WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2025 issue of *CERN Courier*.

One hundred years ago, Werner Heisenberg retreated to the island of Helgoland, where he built the foundations of the first full formulation of quantum mechanics. Finding its matrices repugnant, Erwin Schrödinger developed a mathematically equivalent formulation with a wavefunction and a wave equation. Either way, physics would never be the same again: in quantum mechanics, measurement affects what can be known and predictions can only ever be probabilistic.

A century has not sufficed to fully understand or exploit the theory – and high-energy physicists today find themselves at an interesting juncture. Detector designs are beginning to push quantum limits (p31). Quantum computing is in its “noisy intermediate-scale” era, poised to apply its remarkable parallelism to simulations beyond the reach of classical supercomputers (p35). And with efforts to move beyond the Standard Model at least temporarily frustrated, increasing numbers of theorists are returning to grapple with the foundational assumptions of quantum mechanics. In this special edition, Carlo Rovelli (p21) and David Wallace (p26) explore a jungle of ideas to resolve questions that have defied consensus since the earliest days of the theory.

Elsewhere in these pages: Fermilab’s last word on muon g-2 (p7); DESY brings practical plasma-wakefield acceleration a step closer (p8); ATLAS and ALICE make the first differential measurements of the radial flow of quark–gluon plasma (p13); a farewell to Mary K Gaillard (p47); and much more.

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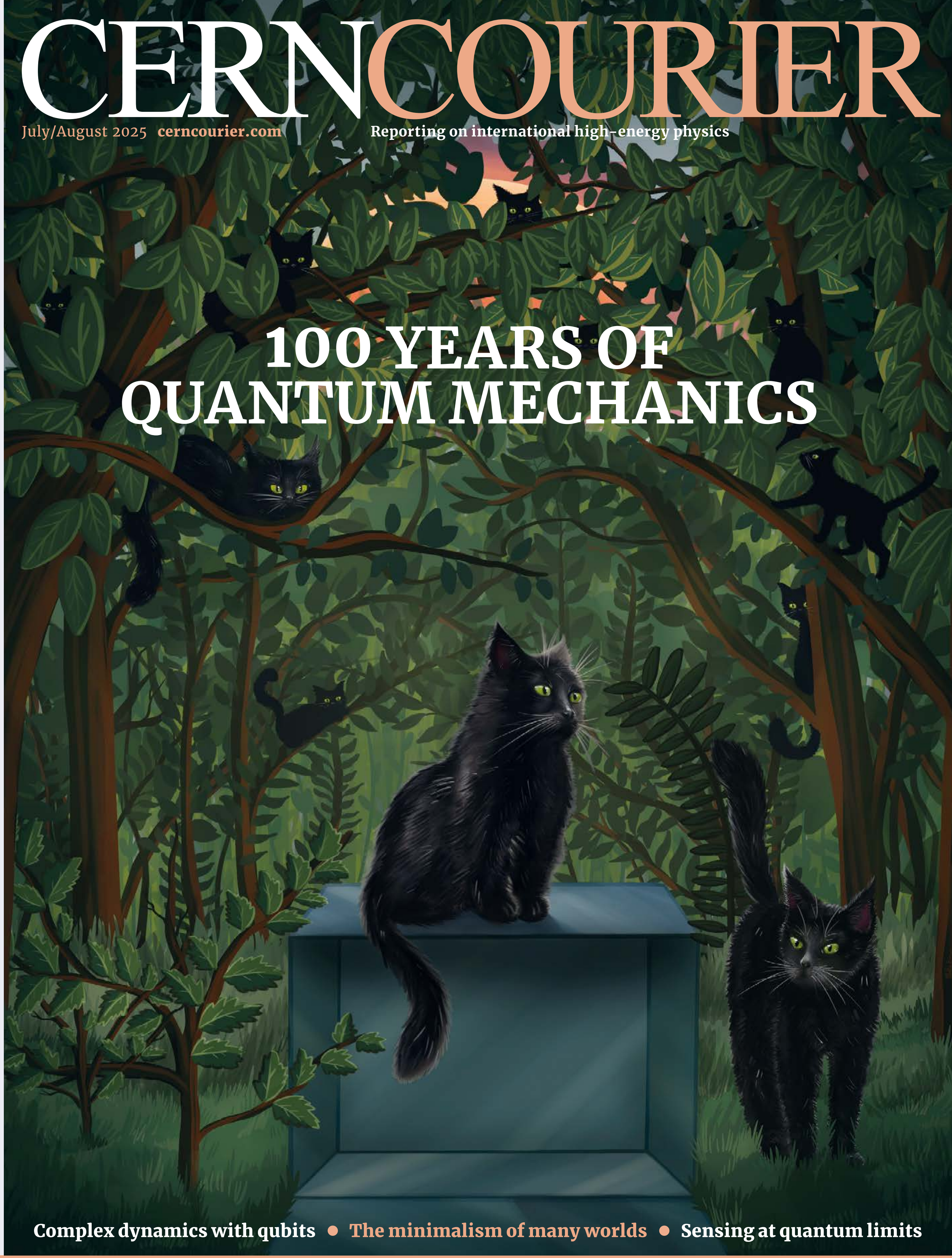
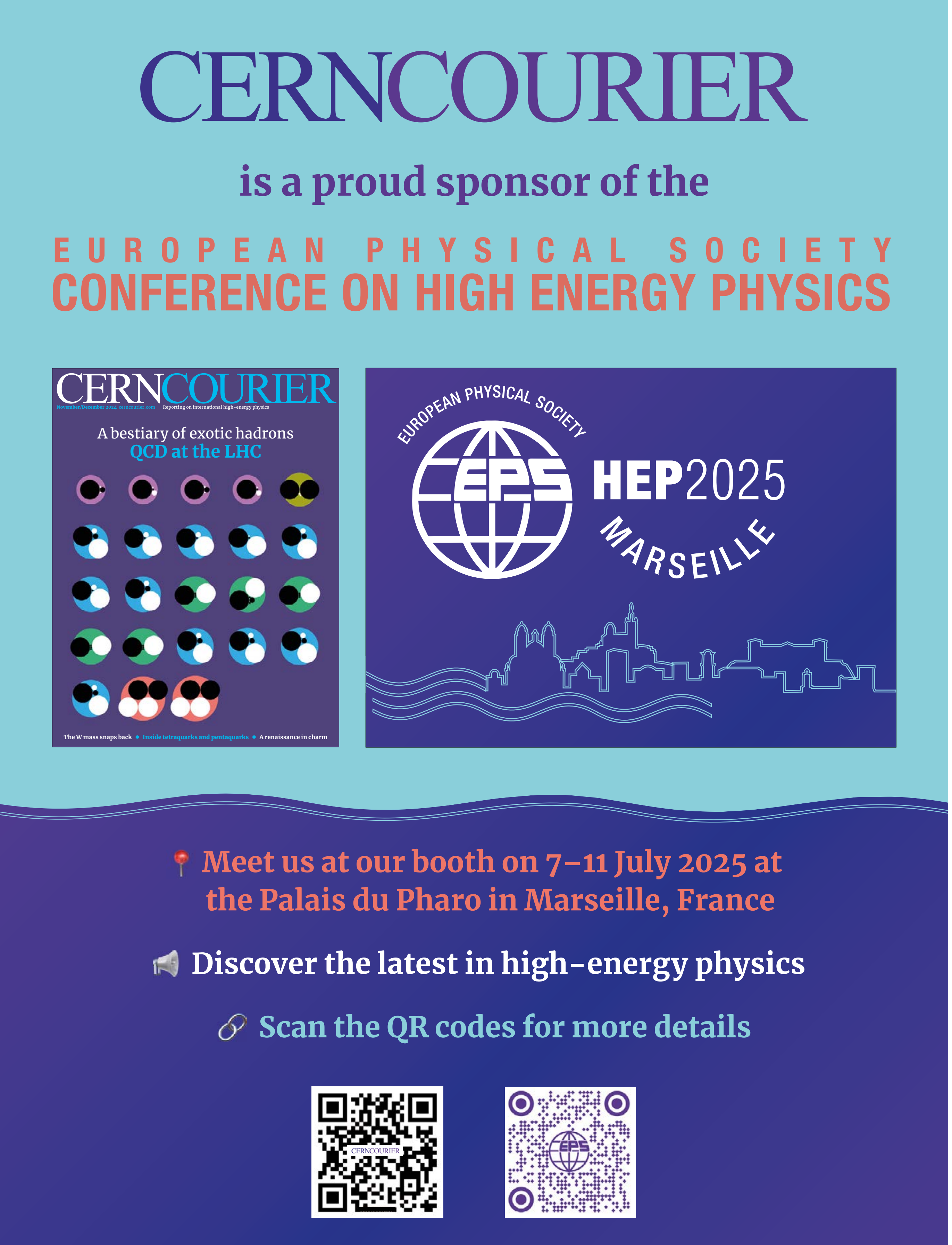
EDITOR: MARK RAYNER





IN THIS ISSUE

VOLUME 65 NUMBER 4 JULY/AUGUST 2025

FROM THE EDITOR

100 years of quantum mechanics

Mark Rayner
Editor

Does this edition of *CERN Courier* stray into controversial territory? "Shut up and calculate" may once have been the response to articles on the interpretation of quantum mechanics. Quantum sensing (p31) and quantum simulation (p35) may still seem futuristic. But our features explore subjects whose importance is increasingly recognised within high-energy physics. This month's anniversary is the perfect moment to bring the latest thinking to the attention of a wider audience.

One hundred years ago, Werner Heisenberg retreated to the island of Helgoland, where he drew up the foundations of the first full formulation of quantum mechanics (p16). Finding its matrices repugnant, Erwin Schrödinger developed a mathematically equivalent formulation with a wavefunction and a wave equation. Either way, physics would never be the same again: in quantum mechanics, the act of observing alters reality, and predictions can only ever be probabilistic.

Who were these wild beasts who muddied the concept of objective reality? The revolution that culminated in 1925 was seeded two decades earlier, in 1905, when Einstein explained the photoelectric effect with quanta. He viewed the quantum revolution he launched with suspicion, but currents undercutting the portrayal of the physical world as aloof and objective were becoming difficult to ignore, not only in physics but also in philosophy and art. A few months after Einstein's paper on the photoelectric effect, Henri Rousseau exhibited *Le lion, ayant faim, se jette sur l'antilope* (see image) in Paris, alongside innovative works by younger artists such as Matisse and Derain, and classical sculpture in the traditional representational style. "*Donatello parmi les fauves!*" (Donatello among the wild beasts) mocked critic Louis Vauxcelles, and a free-thinking new generation defiantly claimed the name Fauvist.

Who were these wild beasts who muddied the concept of objective reality?

The primacy of the observer

Fauvism made the observer's experience the primary truth of painting. Quantum mechanics made observer measurements the primary truth of physics. Was the increasing convergence of science, art and philosophy on this point a coincidence? Perhaps, perhaps not, but science and the arts influence each other more than we may realise (p39). Rousseau's painting, which can now be found at the Fondation Beyeler in Basel, is the inspiration for our cover. Artist Nika Eskandari portrays Schrödinger's cat escaping into a jungle of quantum possibilities.

A century after Heisenberg's visit to Helgoland, there is still no consensus on how to interpret quantum mechanics. Its interpretations are too many to number. While appreciating their impressive diversity, we have commissioned articles by leading proponents of two that seem to be growing in influence. While surveying the whole scene, Carlo Rovelli introduces an idea he originated: a relativity principle for observers (p21). And while Rovelli's "relational" interpretation may be said to take inspiration from Heisenberg's matrix mechanics, the Everettian or "many worlds" interpretation takes Schrödinger's wave equation to its logical limit. David Wallace argues that many worlds – so apparently maximalist in claiming that all possibilities really exist – is actually a minimalist and even conservative way to interpret the basic facts of quantum mechanics (p26).

R Bayer, Basel

Wild beasts Le lion, ayant faim, se jette sur l'antilope *(the hungry lion throws itself on the antelope), by Henri Rousseau, 1905.*

Reporting on international high-energy physics

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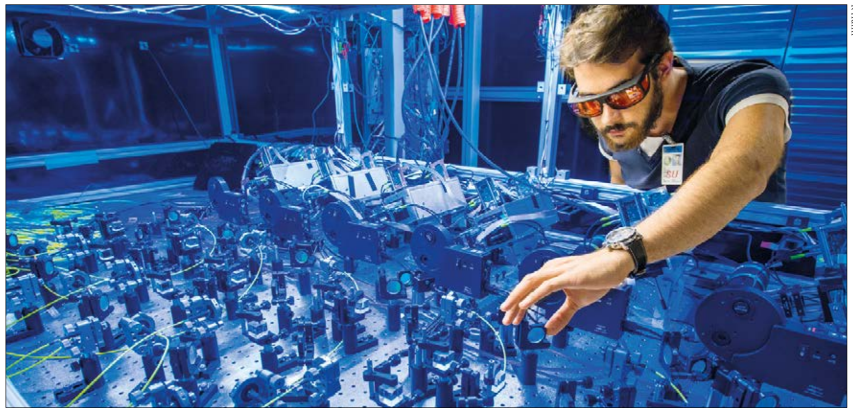
NEWS ANALYSIS

Tests of the Standard Model

Fermilab's final word on muon g–2

Fermilab's Muon g–2 collaboration has given its final word on the magnetic moment of the muon. The new measurement agrees closely with a significantly revised Standard Model (SM) prediction. Though the experimental measurement will likely now remain stable for several years, theorists expect to make rapid progress to reduce uncertainties and resolve tensions underlying the SM value. One of the most intriguing anomalies in particle physics is therefore severely undermined, but not yet definitively resolved.

The muon g–2 anomaly dates back to the late 1990s and early 2000s, when measurements at Brookhaven National Laboratory (BNL) uncovered a possible discrepancy by comparison to theoretical predictions of the so-called muon anomaly, $a_\mu = (g-2)/2$. a_μ expresses the magnitude of quantum loop corrections to the leading-order prediction of the Dirac equation, which multiplies the classical gyromagnetic ratio of fundamental fermions by a "g-factor" of precisely two. Loop corrections of $a_\mu \sim 0.1\%$ quantify the extent to which virtual particles emitted by the muon further increase the strength of its interaction with magnetic fields. Were measurements to be shown to deviate from SM predictions, this would indicate the influence of virtual fields beyond the SM.


R Hahn

Laser calibration *Technical improvements by Fermilab's Muon g–2 collaboration achieved a systematic uncertainty of 78 ppb on quantum corrections to the magnetic moment of the muon.*

Move on up

In 2013, the BNL experiment's magnetic storage ring was transported from Long Island, New York, to Fermilab in Batavia, Illinois. After years of upgrades and improvements, the new experiment began in 2017. It now reports a final precision of 127 parts per billion (ppb), bettering the experiment's design precision of 140 ppb, and a factor of four more sensitive than the BNL result.

"First and foremost, an increase in the number of stored muons allowed us to reduce our statistical uncertainty to 98 ppb compared to 460 ppb for BNL," explains co-spokesperson Peter Winter of Argonne National Laboratory, "but a lot of technical improvements to our calorimetry, tracking, detector calibration and magnetic-field mapping were also needed to improve on the systematic uncertainties from 280 ppb at BNL to 78 ppb at Fermilab."

This formidable experimental precision throws down the gauntlet to the theory community

The final Fermilab measurement is $(116592070.5 \pm 11.4\,(\text{stat.}) \pm 9.1(\text{syst.}) \pm 2.1\,(\text{ext.})) \times 10^{-11}$, fully consistent with the previous BNL measurement. This formidable precision throws down the gauntlet to the Muon g–2 Theory Initiative (TI), which was founded to achieve an international consensus on the theoretical prediction.

The calculation is difficult, featuring contributions from all sectors of the SM (*CERN Courier* March/April 2025 p21). The TI published its first whitepaper in 2020, reporting $a_\mu = (116591810 \pm 43) \times 10^{-11}$, based exclusively on a data-driven analysis of cross-section measurements at electron–positron colliders (WP20). In May, the TI updated its prediction, publishing a value $a_\mu = (116592033 \pm 62) \times 10^{-11}$, statistically incompatible with the previous prediction at the level of three standard deviations, and with an increased uncertainty of 530 ppb (WP25). The new prediction is based exclusively on numerical SM calculations. This was made possible by rapid progress in the use of lattice QCD to control the dominant source of uncertainty, which arises due to the contribution of so-called hadronic vacuum polarisation (HVP). In HVP, the photon representing the magnetic field interacts with the muon during a brief moment when a virtual photon erupts into a difficult-to-model cloud of quarks and gluons.

Significant shift

"The switch from using the data-driven method for HVP in WP20 to lattice QCD in WP25 results in a significant shift in the SM prediction," confirms Aida El-Khadra of the University of Illinois, chair of the TI, who believes that it is not unreasonable to expect significant error reductions in the next couple of years. "There still are puzzles to resolve, particularly around the experimental measurements that are used in the data-driven method for HVP, which prevent us, at this point in time, from obtaining a new prediction for HVP in the data-driven method. This means that we also don't yet know if the data-driven HVP evaluation will agree or disagree with lattice–QCD calculations. However, given the ongoing dedicated efforts to resolve the puzzles, we are confident we will soon know what the data-driven method has to say about HVP. Regardless of the outcome of the comparison with lattice QCD, this will yield profound insights."

On the experimental side, attention now turns to the Muon g–2/EDM experiment at J-PARC in Tokai, Japan. ▷

While the Fermilab experiment used the "magic gamma" method first employed at CERN in the 1970s to cancel the effect of electric fields on spin precession in a magnetic field (*CERN Courier* September/October 2024 p53), the J-PARC experiment seeks to control systematic uncertainties by exercising particularly tight control of its muon beam. In the Japanese experiment, antimatter muons will be captured by atomic electrons to form muonium, ionised using a laser, and reaccelerated for a traditional precession measurement with sensitivity to both the muon's magnetic moment and its electric dipole moment (*CERN Courier* July/August 2024 p8).

"We are making plans to improve experimental precision beyond the Fermilab experiment, though their precision is quite tough to beat," says spokesperson Tsutomu Mibe of KEK. "We also plan to search for the electric dipole moment of the muon with an unprecedented precision of roughly 10^{-21} e cm, improving the sensitivity of the last results from BNL by a factor of 70."

We are making plans to improve experimental precision beyond the Fermilab experiment

With theoretical predictions from high-order loop processes expected to be of the order 10^{-38} e cm, any observation of an electric dipole moment would be a clear indication of new physics.

"Construction of the experimental facility is currently ongoing," says Mibe. "We plan to start data taking in 2030."

Further reading

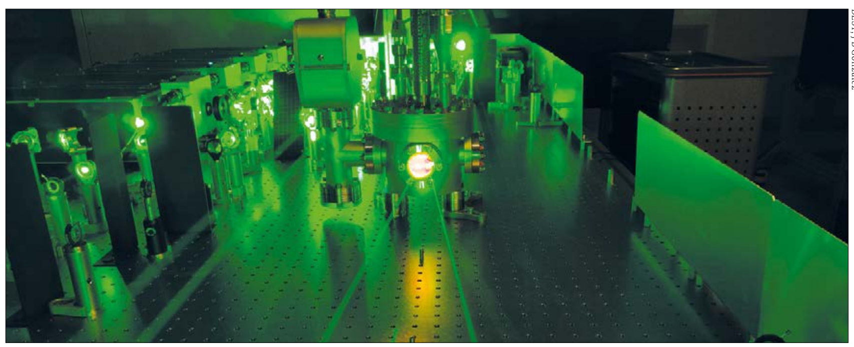
The Muon g-2 Collaboration 2025 arXiv:2506.03069.
R Aliberti *et al.* 2025 arXiv:2505.21476.
S Aritome *et al.* 2025 *Phys. Rev. Lett.* **134** 245001.

Accelerator physics

Double plasma progress at DESY

What if, instead of using tonnes of metal to accelerate electrons, they were to "surf" on a wave of charge displacements in a plasma? This question, posed in 1979 by Toshiki Tajima and John Dawson, planted the seed for plasma wakefield acceleration (PWA). Scientists at DESY now report some of the first signs that PWA is ready to compete with traditional accelerators at low energies. The results tackle two of the biggest challenges in PWA: beam quality and bunch rate.

"We have made great progress in the field of plasma acceleration," says Andreas Maier, DESY's lead scientist for plasma acceleration, "but this is an endeavour that has only just started, and we still have a bit of homework to do to get the system integrated with the injector complexes of a synchrotron, which is our final goal."



DESY/J B Gonzalez

Beam quality and bunch rate *DESY has reported progress with laser-driven plasma-wakefield accelerators, including the acceleration of 100 electron bunches per second using the KALDERA laser system pictured here.*

Riding a wave

PWA has the potential to radically miniaturise particle accelerators. Plasma waves are generated when a laser pulse or particle beam ploughs through a millimetres-long hydrogen-filled capillary, displacing electrons and creating a wake of alternating positive and negative charge regions behind it. The process is akin to flotsam and jetsam being accelerated in the wake of a speedboat, and the plasma "wakefields" can be thousands of times stronger than the electric fields in conventional accelerators, allowing particles to gain hundreds of MeV in just a few millimetres. But beam quality and intensity are significant challenges in such narrow confines.

In a first study, a team from the LUX experiment at DESY and the University of Hamburg demonstrated, for the first time, a two-stage correction system to dramatically reduce the energy spread of accelerated electron beams. The first stage stretches the longitudinal extent of the beam from a few femtoseconds to several picoseconds using a series of four zigzagging bending magnets called a magnetic chicane. Next, a radio-frequency cavity reduces the energy variation to below 0.1%, bringing the beam quality in line with conventional accelerators.

"We basically trade beam current for energy stability," explains Paul Winkler, lead author of a recent publication on active energy compression. "But for the intended application of a synchrotron injector, we would need to stretch the electron bunches anyway. As a result, we achieved performance levels so far only associated with conventional accelerators."

But producing high-quality beams is only half the battle. To make laser-driven PWA a practical proposition, bunches must be accelerated not just once a second, like at LUX, but hundreds or thousands of times per second. This has now been demonstrated by KALDERA, DESY's new high-power laser system (see "Beam quality and bunch rate" image).

"Already, on the first try, we were able to accelerate 100 electron bunches per second," says principal investigator Manuel Kirchen, who emphasises the complementarity of the two advances. The team now plans to scale up the energy and deploy "active stabilisation" to improve beam quality. "The next major goal is to demonstrate that we can continuously run the plasma accelerators with high stability," he says.

With the exception of CERN's AWAKE experiment (*CERN Courier* May/June 2024 p25), almost all plasma-wakefield accelerators are designed with medical or industrial applications in mind. Medical applications are particularly promising as they require lower beam energies and place less demanding constraints on beam quality. Advances such as those reported by LUX and KALDERA raise confidence in this new technology and could eventually open the door to cheaper and more portable X-ray equipment, allowing medical imaging and cancer therapy to take place in university labs and hospitals.

Further reading

P Winkler *et al.* 2025 *Nature* **640** 907.

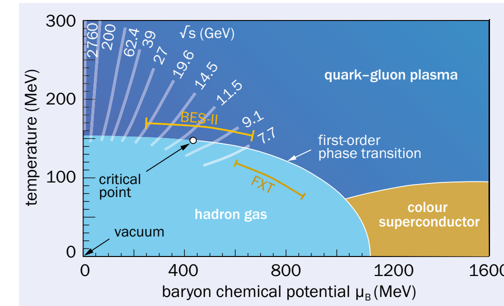
Quark–gluon plasma

STAR hunts QCD critical point

Just as water takes the form of ice, liquid or vapour, QCD matter exhibits distinct phases. But while the phase diagram of water is well established, the QCD phase diagram remains largely conjectural. The STAR collaboration at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) recently completed a new beam-energy scan (BES-II) of gold–gold collisions. The results narrow the search for a long-sought-after "critical point" in the QCD phase diagram.

"BES-II precision measurements rule out the existence of a critical point in the regions of the QCD phase diagram accessed at LHC and top RHIC energies, while still allowing the possibility at lower collision energies," says Bedangadas Mohanty of the National Institute of Science Education and Research in India, who co-led the analysis. "The results refine earlier BES-I indications, now with much reduced uncertainties."

At low temperatures and densities, quarks and gluons are confined within hadrons. Heating QCD matter leads to the formation of a deconfined quark–gluon plasma (QGP), while increasing the density at low temperatures is expected to give rise to more exotic states such as colour superconductors. Above a certain threshold in baryon density, the transition from hadron gas to QGP is expected to be first-order – a sharp, discontinuous change akin to water boiling. As density decreases, this boundary gives way to a smooth crossover where the two phases blend. A hypothetical critical point marks the shift between these regimes, much like the endpoint of the liquid–gas coexistence line in the phase diagram of water (see "Phases of QCD" figure).



Adapted from L Du *et al.* 2024 *Int. J. Mod. Phys.* **33** 2430008

Phases of QCD *Conjectured QCD phase diagram showing hadronisation trajectories as a function of centre-of-mass energy (√s). The baryon chemical potential is a measure of baryon density.*

Heavy-ion collisions offer a way to observe this phase transition directly. At the Large Hadron Collider, the QGP created in heavy-ion collisions transitions smoothly to a hadronic gas as it cools, but the lower energies explored by RHIC probe the region of phase space where the critical point may lie.

To search for possible signatures of a critical point, the STAR collaboration measured gold–gold collisions at centre-of-mass energies between 7.7 and 27 GeV per nucleon pair. The collaboration reports that their data deviate from frameworks that do not include a critical point, including the hadronic transport model, thermal models with canonical ensemble treatment, and hydrodynamic approaches with excluded-volume effects. Depending on the choice of observable and non-critical baseline model, the significance of the deviations ranges from two to five standard deviations, with the largest effects seen in head-on collisions when using peripheral collisions as a reference.

"None of the existing theoretical models fully reproduce the features observed in the data," explains Mohanty. "To interpret these precision measurements, it is essential that dynamical model calculations that include critical-point physics be developed." The STAR collaboration is now mapping lower energies and higher baryon densities using a fixed target (FXT) mode, wherein a 1 mm gold foil sits 2 cm below the beam axis.

"The FXT data are a valuable opportunity to explore QCD matter at high baryon density," says Mohanty. "Data taking will conclude later this year when RHIC transitions to the Electron–Ion Collider. The Compressed Baryonic Matter experiment at FAIR in Germany will then pick up the study of the QCD critical point towards the end of the 2020s."

Further reading

STAR Collab. 2025 arXiv:2504.00817.

Policy

Slovenia, Ireland and Chile tighten ties with CERN

Slovenia became CERN's 25th Member State on 21 June, formalising a relationship of over 30 years. Full membership confers voting rights in the CERN Council and opportunities for Slovenian enterprises and citizens.

"Slovenia's full membership in CERN is an exceptional recognition of our science and researchers," said Igor Papič, Slovenia's Minister of Higher Education, Science and Innovation. "Furthermore, it reaffirms and strengthens Slovenia's reputation as a nation building its future on knowledge and science. Indeed, apart from its beautiful natural landscapes, knowledge is the only true natural wealth of our country. For this reason, we have allocated record financial resources to science, research and innovation. Moreover, we have enshrined the obligation to increase these funds annually in the Scientific Research and Innovation Activities Act."

CERN

International collaboration *Slovenia has become CERN's 25th Member State.*

"On behalf of the CERN Council, I warmly welcome Slovenia as the newest Member State of CERN," said Costas Fountas, president of the CERN Council. "Slovenia has a longstanding relationship with CERN, with continuous involvement of the Slovenian science community over many decades in the ATLAS experiment in particular."

On 8 and 16 May, respectively, Ireland and Chile signed agreements to become Associate Member States of CERN, pending the completion of national ratification processes. They join Türkiye, Pakistan, Cyprus, Ukraine, India, Lithuania, Croatia, Latvia and Brazil as Associate Members – a status introduced by the CERN Council in 2010. In this period, the Organization has also concluded international cooperation agreements with Qatar, Sri Lanka, Nepal, Kazakhstan, the Philippines, Thailand, Paraguay, Bosnia and Herzegovina, Honduras, Bahrain and Uruguay.

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ASTROWATCH

Exceptional flare tests blazar emission models

Active galactic nuclei (AGNs) are extremely energetic regions at the centres of galaxies, powered by accretion onto a supermassive black hole. Some AGNs launch plasma outflows moving near light speed. Blazars are a subclass of AGNs whose jets are pointed almost directly at Earth, making them appear exceptionally bright across the electromagnetic spectrum. A new analysis of an exceptional flare of BL Lacertae by NASA's Imaging X-ray Polarimetry Explorer (IXPE) has now shed light on their emission mechanisms.

The spectral energy distribution of blazars generally has two broad peaks. The low-energy peak from radio to X-rays is well explained by synchrotron radiation from relativistic electrons spiraling in magnetic fields, but the origin of the higher-energy peak from X-rays to γ-rays is a longstanding point of contention, with two classes of models, dubbed hadronic and leptonic, vying to explain it. Polarisation measurements offer a key diagnostic tool, as the two models predict distinct polarisation signatures.

Ball Aerospace

Pre-launch checks *The Imaging X-ray Polarimetry Explorer.*

Model signatures

In hadronic models, high-energy emission is produced by protons, either through synchrotron radiation or via photo-hadronic interactions that generate secondary particles. Hadronic models predict that X-ray polarisation should be as high as that in the optical and millimetre bands, even in complex jet structures.

Leptonic models are powered by inverse Compton scattering, wherein relativistic electrons "upscatter" low-energy photons, boosting them to higher energies with low polarisation. Leptonic models can be further subdivided by the source of the inverse-Compton-scattered photons. If initially generated by synchrotron radiation in the AGN (synchrotron self-Compton, SSC), modest polarisation (~50%) is expected due to the inherent polarisation of synchrotron photons, with further reductions if the emission comes from inhomogeneous or multiple emitting regions. If initially generated by external sources (external Compton, EC), isotropic photon fields from the surrounding structures are expected to average out their polarisation.

IXPE launched on 9 December 2021, seeking to resolve such questions. It is designed to have 100-fold better sensitivity to the polarisation of X-rays in astrophysical sources than the last major X-ray polarimeter, which was launched half a century ago (*CERN Courier* July/August 2022 p10). In November 2023, it participated in a coordinated multiwavelength campaign spanning radio, millimetre and optical, and X-ray bands targeted the blazar BL Lacertae, whose X-ray emission arises mostly from the high-energy component, with its low-energy synchrotron component mainly at infrared energies. The campaign captured an exceptional flare, providing a rare opportunity to test competing emission models.

A key feature of the flare was the rapid rise and fall of optical polarisation

Optical telescopes recorded a peak optical polarisation of 47.5 ± 0.4%, the highest ever measured in a blazar. The short-mm (1.3 mm) polarisation also rose to about 10%, with both bands showing similar trends in polarisation angle. IXPE measured no significant polarisation in the 2 to 8 keV X-ray band, placing a 3σ upper limit of 7.4%.

The striking contrast between the high polarisation in optical and mm bands, and a strict upper limit in X-rays, effectively rules out all single-zone and multi-region hadronic models. Had these processes dominated, the X-ray polarisation would have been comparable to the optical. Instead, the observations strongly support a leptonic origin, specifically the SSC model with a stratified or multi-zone jet structure that naturally explains the low X-ray polarisation.

A key feature of the flare was the rapid rise and fall of optical polarisation. Initially, it was low, of order 5%, and aligned with the jet direction, suggesting the dominance of poloidal or turbulent fields. A sharp increase to nearly 50%, while retaining alignment, indicates the sudden injection of a compact, toroidally dominated magnetic structure.

The authors of the analysis propose a "magnetic spring" model wherein a tightly wound toroidal field structure is injected into the jet, temporarily ordering the magnetic field and raising the optical polarisation. As the structure travels outward, it relaxes, likely through kink instabilities, causing the polarisation to decline over about two weeks. This resembles an elastic system, briefly stretched and then returning to equilibrium.

A magnetic spring would also explain the multiwavelength flaring. The injection boosted the total magnetic field strength, triggering an unprecedented mm-band flare powered by low-energy electrons with long cooling times. The modest rise in mm-wavelength polarisation (green points) suggests emission from a large, turbulent region. Meanwhile, optical flaring (black points) was suppressed due to the rapid synchrotron cooling of high-energy electrons, consistent with the observed softening of the optical spectrum. No significant γ-ray enhancement was observed, as these photons originate from the same rapidly cooling electron population.

Turning point

These findings mark a turning point in high-energy astrophysics. The data definitively favour leptonic emission mechanisms in BL Lacertae during this flare, ruling out efficient proton acceleration and thus any associated high-energy neutrino or cosmic-ray production. The ability of the jet to sustain nearly 50% polarisation across parsec scales implies a highly ordered, possibly helical magnetic field extending far from the supermassive black hole.

The results cement polarimetry as a definitive tool in identifying the origin of blazar emission. The dedicated Compton Spectrometer and Imager (COSI) γ-ray polarimeter is soon set to complement IXPE at even higher energies when launched by NASA in 2027. Coordinated campaigns will be crucial for probing jet composition and plasma processes in AGNs, helping us understand the most extreme environments in the universe.

Further reading

I Agudo 2025 arXiv:2505.01832.

NEWS DIGEST

LuSEE-Night

Testing a LuSEE-Night antenna.

Far side of the Moon

LuSEE-Night has begun final integration and testing at the Space Sciences Laboratory (SSL) in Berkeley. The US-led project aims to deploy a pathfinder radio telescope on the far side of the Moon. Four three-metre antennas will use the Moon to block out radio interference from Earth and observe the low-frequency sky. Similar techniques have been proposed for observing ultra-high-energy neutrinos, via the lunar Askaryan effect (*CERN Courier* May/June 2025 p23). After testing at BNL and SSL, the integrated payload will be launched by Firefly Aerospace, which just completed the first fully successful soft landing on the Moon by a commercial enterprise.

Future colliders, compared

On 26 May, CERN's Future Colliders Comparative Evaluation group added its input to community submissions to the ongoing European Strategy for Particle Physics (*CERN Courier* May/June 2025 p8). The working group brought together project leaders and domain experts to conduct a consistent evaluation of the Future Circular Collider and alternative scenarios based on shared assumptions and standardised criteria. The report evaluates physics performance, environmental aspects, technical maturity, construction and operation costs, required human resources and realistic implementation timelines.

Untangled web

On 6 June, the OpenWebSearch.eu project, funded by the European Union, launched a pilot of the first-ever federated pan-European "Open Web Index". The index, which the team describe as being designed to promote transparency and European sovereignty online, is now open to academic and independent teams, with a public release set for mid-2025. CERN contributed to the project's federated data infrastructure, ensuring openness and security for scientific and public use (*CERN Courier* January/February 2024 p45). Large-scale web indexing is also hosted in the US, China and Russia.

'Blank sky' axion search

Elena Pinetti (Flatiron Institute) has used data from the James Webb Space Telescope (JWST) to set new constraints on QCD axions and axion-like particles (ALPs). Pinetti repurposed "blank-sky" observations, which accumulate vast amounts of deep observational data but are typically only used to subtract background noise from measurements. A negative search for infrared lines from axion decay into two photons in the Milky Way halo led to world-best limits on axion–photon coupling in the 0.1 to 4 eV range (E Pinetti 2025 arXiv:2503.11753). Initially proposed to solve the strong CP problem, axions and ALPs are popular dark-matter candidates.

NASA/D Stover

JWST's folding, segmented mirror.

Canada and CERN collaborate

In March, Canada and CERN signed a statement of intent to strengthen collaboration and expand cooperation on accelerator, detector and computing technologies. The agreement highlights Canada's key role in the High-Luminosity LHC and builds on decades of involvement in the LHC and other CERN programmes. Should member states elect to build the FCC, Canada intends to collaborate on its construction and physics exploitation, subject to domestic approvals.

CERN Director-General Fabiola Gianotti with Canadian Ambassador Patrick Wittmann.

Superheavy shell effects

GSI researchers are closing in on the "isotopic border" of seaborgium (Sg), beyond which nuclei of the superheavy element are expected to decay in under 10^{-14} s. The team detected 22 Sg-257 nuclei, 21 of which decayed via spontaneous fission, and one via alpha decay (P Mosat *et al.* 2025 *Phys. Rev. Lett.* **134** 232501). This new, lightest Sg isotope has a half-life of 12.6 ms and is one step away from the shell closure at 152 neutrons (Sg-258). Its lighter cousin Sg-256 – one step in the other direction – could decay as quickly as 1 ns unless shell-stabilised. "Our findings on Sg-257 provide exciting hints on the impact of shell effects on the fission properties of superheavy nuclei," says Pavol Mosat (GSI).

Boost for US theory

Larry Leinweber, founder and president of the Leinweber Foundation, has donated $90 million to theoretical physics at the University of Chicago, MIT and UC Berkeley. The money will be used to provide funding for postdocs and graduate students, as well as to host workshops and conferences at the recipient universities. The new Leinweber Institute for Theoretical Physics will join an existing institute at the University of Michigan. "Compared to experimental physics, theoretical physics is relatively cheap," said Michigan institute director Fred Adams, "so a modest amount of money goes a longer way."

Missing baryons, found

Cosmological models predict that baryons should account for 4 to 5% of the total energy density of the universe – but when astronomers tally up all the baryonic matter in stars, galaxies and gas clouds, they have historically found evidence for only about half of the expected ordinary matter. The "missing baryons" problem may now have been resolved thanks to new data from the Deep Synoptic Array in California, which has mapped the distribution of baryonic matter in the universe using fast radio bursts (FRBs). By analysing dispersion from 69 localised FRBs with known redshifts, researchers found 76% of baryons in the diffuse intergalactic medium, 15% in halos and clusters, and the rest in galaxies (L Connor *et al. Nat. Astron.* 16 June 2025/ doi:10.1038/s41550-025-02566-y).

G Hallinan

The Deep Synoptic Array-110.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ALICE AND ATLAS

A new probe of radial flow

The ATLAS and ALICE collaborations have announced the first results of a new way to measure the "radial flow" of quark–gluon plasma (QGP). The two analyses offer a fresh perspective into the fluid-like behaviour of QCD matter under extreme conditions, such as those that prevailed after the Big Bang. The measurements are highly complementary, with ALICE drawing on their detector's particle-identification capabilities and ATLAS leveraging the experiment's large rapidity coverage.

At the Large Hadron Collider, lead-ion collisions produce matter at temperatures and densities so high that quarks and gluons momentarily escape their confinement within hadrons. The resulting QGP is believed to have filled the universe during its first few microseconds, before cooling and fragmenting into mesons and baryons. In the laboratory, these streams of particles allow researchers to reconstruct the dynamical evolution of the QGP, which has long been known to transform anisotropies of the initial collision geometry into anisotropic momentum distributions of the final-state particles.

Compelling evidence

Differential measurements of the azimuthal distributions of produced particles over the last decades have provided compelling evidence that the outgoing momentum distribution reflects a collective response driven by initial pressure gradients. The isotropic expansion component, typically referred to as radial flow, has instead been inferred from the slope of particle spectra (see figure 1). Despite its fundamental role in driving the QGP fireball, radial flow lacked a differential probe comparable to those of its anisotropic counterparts.

That situation has now changed. The ALICE and ATLAS collaborations recently employed the novel observable $v_0(p_T)$ to investigate radial flow directly. Their independent results demonstrate, for the first time, that the isotropic expansion of the QGP in heavy-ion collisions exhibits clear signatures of collective behaviour. The isotropic expansion of the QGP and its azimuthal modulations ultimately depend on the hydrodynamic properties of the QGP, such as shear or bulk viscosity, and can thus be measured to constrain them.

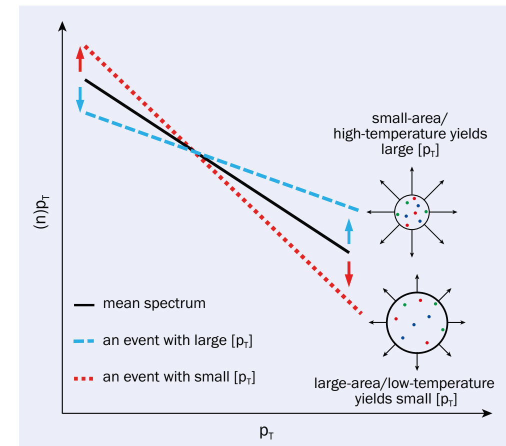

Fig. 1. *Schematic illustration of how radial-flow fluctuations lead to correlations between the differential yield $n(p_T)$ and transverse momentum p_T. Blue indicates a smaller-than-average initial area and a larger integral radial flow, whereas red indicates a larger-than-average initial area and a smaller integral radial flow.*

The results demonstrate that the isotropic expansion of the QGP in heavy-ion collisions exhibits clear signatures of collective behaviour

Traditionally, radial flow has been inferred from the slope of p_T-spectra, with the p_T-integrated radial-flow extracted via fits to "blast wave" models. The newly introduced differential observable $v_0(p_T)$ captures fluctuations in spectral shape across p_T bins. $v_0(p_T)$ retains differential sensitivity, since it is defined as the correlation (technically the normalised covariance) between the fraction of particles in a given p_T-interval and the mean transverse momentum of the collision products within a single event, $[p_T]$. Roughly speaking, a fluctuation raising $[p_T]$ produces a positive $v_0(p_T)$ at high p_T due to the fractional yield increasing; conversely, the fractional yield decreasing at low p_T causes a negative $v_0(p_T)$. A pseudorapidity gap between the measurement of mean p_T and the particle yields is used to suppress short-range correlations and isolate the long-range, collective signal. Previous studies observed event-by-event fluctuations in $[p_T]$, related to radial flow over a wide p_T range and quantified by the coefficient v_0^{ref}, but they could not establish whether these fluctuations were correlated across different p_T intervals – a crucial signature of collective behaviour.

Origins

The ATLAS collaboration performed a measurement of $v_0(p_T)$ in the 0.5 to 10 GeV range, identifying three signatures of the collective origin of radial flow (see figure 2, p14). First, correlations between the particle yield at fixed p_T and the event-wise mean $[p_T]$ in a reference interval show that the two-particle radial flow factorises into single-particle coefficients as $v_0(p_T) \times v_0^{ref}$ for $p_T < 4$ GeV, independent of the reference choice (left panel). Second, the data display no dependence on the rapidity gap between correlated particles, suggesting a long-range effect intrinsic to the entire system (middle panel). Finally, the centrality dependence of the ratio $v_0(p_T)/v_0^{ref}$ followed a consistent trend from head-on to peripheral collisions, effectively cancelling initial geometry effects and supporting the interpretation of a collective QGP response (right panel). At higher p_T, a decrease in $v_0(p_T)$ and a splitting with respect to centrality suggest the onset of non-thermal effects such as jet quenching. This may reveal fluctuations in jet energy loss – an area warranting further investigation.

Using more than 80 million collisions at a centre-of-mass energy of 5.02 TeV, ALICE extracted $v_0(p_T)$ for identified pions, kaons and protons across ▷

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a broad range of centralities. ALICE observes $v_0(p_T)$ to be negative at low p_T, reflecting the influence of mean-p_T fluctuations on the spectral shape (see figure 3). The data display a clear mass ordering at low p_T, from protons to kaons to pions, consistent with expectations from collective radial expansion. This mass ordering reflects the greater "push" heavier particles experience in the rapidly expanding medium. The picture changes above 3 GeV, where protons have larger $v_0(p_T)$ values than pions and kaons, perhaps indicating the contribution of recombination processes in hadron production.

The two collaborations' measurements of the new $v_0(p_T)$ observable highlight its sensitivity to the bulk-transport properties of the QGP medium. Comparisons with hydrodynamic calculations show that $v_0(p_T)$ varies with bulk viscosity and the speed of sound, but that it has a weaker dependence on shear viscosity. Hydrodynamic predictions reproduce the data well up to about 2 GeV, but diverge at higher momenta. The deviation of non-collective models like HIJING from the data underscores the dominance of final-state, hydrodynamic-like effects in shaping radial flow.

These results advance our understanding of one of the most extreme regimes of QCD matter, strengthening the case for the formation of a strongly interacting, radially expanding QGP medium in heavy-ion collisions. Differential measurements of radial flow offer a new tool to probe this fluid-like expansion in detail, establishing its collective origin and complementing decades of studies of anisotropic flow.

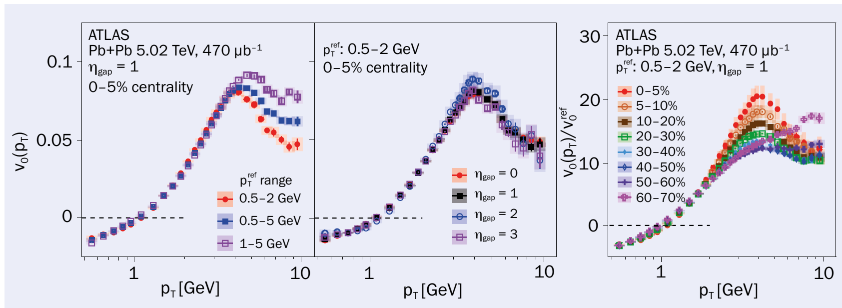

Fig. 2. *ATLAS measurements of radial flow as a function of p_T, for various reference momenta (left), pseudorapidity gaps (middle) and centrality ranges from head-on (0–5% centrality) to peripheral (60–70% centrality) collisions (right). The scaling at low p_T suggests that radial flow is a collective phenomenon.*

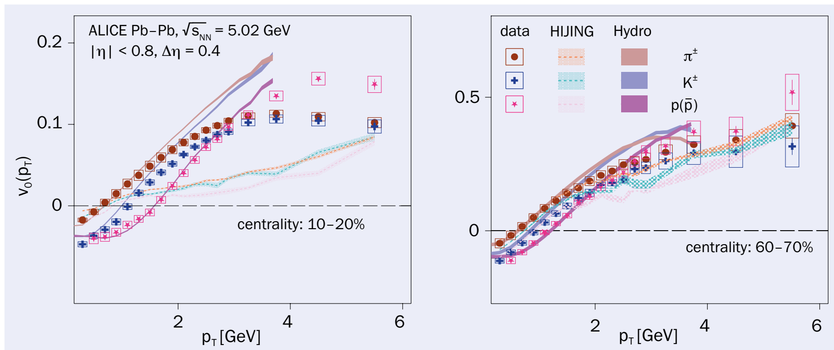

Fig. 3. *ALICE measurements of radial flow as a function of p_T for pions, kaons and protons in mid-central (left) and peripheral (right) Pb–Pb collisions at a centre-of-mass energy of 5.02 TeV. The measurements are compared to state-of-the-art hydrodynamic-based model calculations (Hydro) and a non-collective model (HIJING).*

Further reading

ATLAS Collab. 2025 arXiv:2503.24125.
ALICE Collab. 2025 arXiv:2504.04796.

CMS

Decoding the Higgs mechanism with vector bosons

The discovery of the Higgs boson at the LHC in 2012 provided strong experimental support for the Brout–Englert–Higgs mechanism of spontaneous electroweak symmetry breaking (EWSB) as predicted by the Standard Model. The EWSB explains how the W and Z bosons, the mediators of the weak interaction, acquire mass: their longitudinal polarisation states emerge from the Goldstone modes of the Higgs field, linking the mass generation of vector bosons directly to the dynamics of the process.

Yet, its ultimate origins remain unknown and the Standard Model may only offer an effective low-energy description of a more fundamental theory. Exploring this possibility requires precise tests of how EWSB operates, and vector boson scattering (VBS) provides a particularly sensitive probe. In VBS, two electroweak gauge bosons scatter off one another. The cross section remains finite at high energies only because there is an exact cancellation between the pure gauge-boson interactions and the Higgs-boson mediated contributions, an effect analogous to the role of the Z boson propagator in WW production at electron–positron colliders. Deviations from the expected behaviour could signal new dynamics, such as anomalous couplings, strong interactions in the Higgs sector or new particles at higher energy scales.

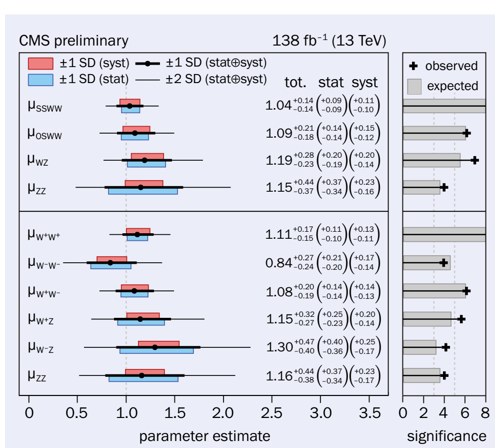

Fig. 1. *Measured VBS signal strengths (μ) from the combined data, compared to Standard Model predictions. Left: μ values with 1σ (thick) and 2σ (thin) intervals; the red and blue bands show systematic and statistical uncertainties, respectively. Right: observed (black) and expected (grey) significances of the electroweak signal relative to the background-only hypothesis.*

VBS interactions are among the rarest observed so far at the LHC, with cross sections as low as one femtobarn. To disentangle them from the background, researchers rely on the distinctive experimental signature of two high-energy jets in the forward detector regions produced by the initial quarks that radiate the bosons, with minimal hadronic activity between them. Using the full data set from Run 2 of the LHC at a centre-of-mass energy of 13 TeV, the CMS collaboration carried out a comprehensive set of VBS measurements across several production modes: WW (with both same and opposite charges), WZ and ZZ, studied in five final states where both bosons decay leptonically and in two semi-leptonic configurations where one boson decays into leptons and the other into quarks. To enhance sensitivity further, the data from all the measurements have now been combined in a single joint fit, with a complete treatment of uncertainty correlations and a careful handling of events selected by more than one analysis.

This result lays the groundwork for future searches for new physics hidden within the electroweak sector

All modes, one analysis

To account for possible deviations from the expected predictions, each process is characterised by a signal strength parameter (μ), defined as the ratio of the measured production rate to the cross section predicted by the Standard Model. A value of μ near unity indicates consistency with the Standard Model, while significant deviations may suggest new physics. The results, summarised in figure 1, display good agreement with the Standard Model predictions: all measured signal strengths are consistent with unity within their respective uncertainties. A mild excess with respect to the leading-order theoretical predictions is observed across several channels, highlighting the need for more accurate modelling, in particular for the measurements that have reached a level of precision where systematic effects dominate. By presenting the first evidence for all charged VBS production modes from a single combined statistical analysis, this CMS result lays the groundwork for future searches for new physics hidden within the electroweak sector.

Further reading

CMS Collab. 2025 CMS-PAS-SMP-24-013.

LHCb

Hadronic decays confirm long-lived Ω_c^0 baryon

In 2018 and 2019, the LHCb collaboration published surprising measurements of the Ξ_c^0 and Ω_c^0 baryon lifetimes, which were inconsistent with previous results and overturned the established hierarchy between the two. A new analysis of their hadronic decays now confirms this observation, promising insights into the dynamics of baryons.

The Λ_c^+, Ξ_c^+, Ξ_c^0 and Ω_c^0 baryons – each composed of one charm and two lighter up, down or strange quarks – are the only ground-state singly charmed baryons that decay predominantly via the weak interaction. The main contribution to this process comes from the charm quark transitioning into a strange quark, with the other constituents acting as passive spectators. Consequently, at leading order, their lifetimes should be the same. Differences arise from higher-order effects, such as W-boson exchange between the charm and spectator quarks and quantum interference between identical particles, known as "Pauli interference". Charm hadron lifetimes are more sensitive to these effects than beauty hadrons because of the smaller charm quark mass compared to the bottom quark, making them a promising testing ground to study these effects.

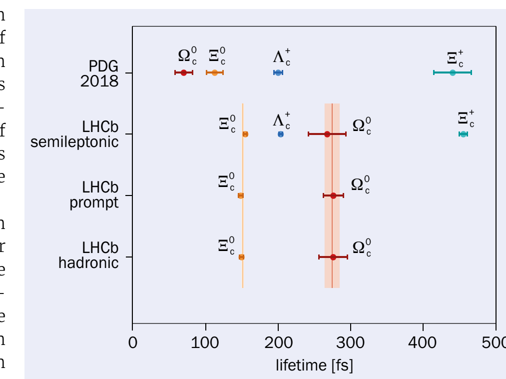

Fig. 1. *Average charm baryon lifetimes determined by the PDG in 2018, and the three lifetime measurements performed by the LHCb experiment in 2018 and 2019 (semileptonic), 2021 (prompt) and 2025 (hadronic). The coloured bands indicate the average of the LHCb measurements.*

Measurements of the Ξ_c^0 and Ω_c^0 lifetimes prior to the start of the LHCb experiment resulted in the PDG averages shown in figure 1. The first LHCb analysis, using charm baryons produced in semi-leptonic decays of beauty baryons, was in tension with the established values, giving a Ω_c^0 lifetime four times larger than the previous average. The inconsistencies were later confirmed by another LHCb measurement, using an independent data set with charm baryons produced directly (prompt) in the pp collision (*CERN Courier* July/August 2021 p17). These results changed the ordering of the four single-charm baryons when arranged according to their lifetimes, triggering a scientific discussion on how to treat higher-order effects in decay rate calculations.

Using the full Run 1 and 2 datasets, LHCb has now measured the Ξ_c^0 and Ω_c^0 lifetimes with a third independent data sample, based on fully reconstructed $\Xi_b^- \to \Xi_c^0 (\to pK^-K^-\pi^+)\pi^-$ and $\Omega_b^- \to \Omega_c^0 (\to pK^-K^-\pi^+)\pi^-$ decays. The selection of these hadronic decay chains exploits the long lifetime of the beauty baryons, such that the selection efficiency is almost independent of the charm baryon decay time. To cancel out the small remaining acceptance effects, the measurement is normalised to the kinematically and topologically similar $B^- \to D^0(\to K^+K^-\pi^+\pi^-)\pi^-$ channel, minimising the uncertainties with only a small additional correction from simulation.

The signal decays are separated from the remaining background by fits to the $\Xi_c^0\,\pi^-$ and $\Omega_c^0\,\pi^-$ invariant mass spectra, providing 8260 ± 100 Ξ_c^0 and 355 ± 26 Ω_c^0 candidates. The decay time distributions are obtained with two independent methods: by determining the yield in each of a specific set of decay time intervals, and by employing a statistical technique that uses the covariance matrix from the fit to the mass spectra. The two methods give consistent results, confirming LHCb's earlier measurements. Combining the three measurements from LHCb, while accounting for their correlated uncertainties, gives $\tau(\Xi_c^0) = 150.7 \pm 1.6$ fs and $\tau(\Omega_c^0) = 274.8 \pm 10.5$ fs. These new results will serve as experimental guidance on how to treat higher-order effects in weak baryon decays, particularly regarding the approach-dependent sign and magnitude of Pauli interference terms.

Further reading

LHCb Collab. 2025 arXiv:2506.13334.

FIELD NOTES

Reports from events, conferences and meetings

HELGOLAND 2025

Quantum theory returns to Helgoland

In June 1925, Werner Heisenberg retreated to the German island of Helgoland seeking relief from hay fever and the conceptual disarray of the old quantum theory. On this remote, rocky outpost in the North Sea, he laid the foundations of matrix mechanics. Later, his "island epiphany" would pass through the hands of Max Born, Wolfgang Pauli, Pascual Jordan and several others, and become the first mature formulation of quantum theory. From 9 to 14 June 2025, almost a century later, hundreds of researchers gathered on Helgoland to mark the anniversary – and to deal with pressing and unfinished business.

Alfred D Stone (Yale University) called upon participants to challenge the folklore surrounding quantum theory's birth. Philosopher Elise Crull (City College of New York) drew overdue attention to Grete Hermann, who hinted at entanglement before it had a name and anticipated Bell in identifying a flaw in von Neumann's no-go theorem, which had been taken as proof that hidden-variable theories are impossible. Science writer Philip Ball questioned Heisenberg's epiphany itself: he didn't invent matrix mechanics in a flash, claims Ball, nor immediately grasp its relevance, and it took months, and others, to see his contribution for what it was (see "Lend me your ears" image).

Lend me your ears *Heisenberg collaborated with colleagues including Born and Pauli, pictured here in autumn 1925 (Born left; Pauli right), to decipher his island epiphany.*

The foundations of quantum mechanics remain open to interpretation, and any future progress will depend on excavating them directly

Building on a strong base

A clear takeaway from Helgoland 2025 was that the foundations of quantum mechanics, though strongly built on Helgoland 100 years ago, nevertheless remain open to interpretation, and any future progress will depend on excavating them directly (see p21).

Does the quantum wavefunction represent an objective element of reality or merely an observer's state of knowledge? On this question, Helgoland 2025 could scarcely have been more diverse. Christopher Fuchs (UMass Boston) passionately defended quantum Bayesianism, which recasts the Born probability rule as a consistency condition for rational agents updating their beliefs. Wojciech Zurek (Los Alamos National Laboratory) presented the Darwinist perspective, for which classical objectivity emerges from redundant quantum information encoded across the environment. Although Zurek himself maintains a more agnostic stance, his decoherence-based framework is now widely embraced by proponents of many-worlds quantum mechanics (see p26).

Markus Aspelmeyer (University of Vienna) made the case that a signature of gravity's long-speculated quantum nature may soon be within experimental reach. Building on the "gravitational Schrödinger's cat" thought experiment proposed by Feynman in the 1950s, he described how placing a massive object in a spatial superposition could entangle a nearby test mass through their gravitational interaction. Such a scenario would produce correlations that are inexplicable by classical general relativity alone, offering direct empirical evidence that gravity must be described quantum-mechanically. Realising this type of experiment requires ultra-low pressures and cryogenic temperatures to suppress decoherence, alongside extremely low-noise measurements of gravitational effects at short distances. Recent advances in optical and optomechanical techniques for levitating and controlling nanoparticles suggest a path forward – one that could bring evidence for quantum gravity not from black holes or the early universe, but from laboratories on Earth.

Information insights

Quantum information was never far from the conversation. Isaac Chuang (MIT) offered a reconstruction of how Heisenberg might have arrived at the principles of quantum information, had his inspiration come from Shannon's Mathematical Theory of Communication. He recast his original insights into three broad principles: observations act on systems; local and global perspectives are in tension; and the order of measurements matters. Starting from these ingredients, one could in principle recover the structure of the qubit and the foundations of quantum computation. Taking the analogy one step further, he suggested that similar tensions between measurements and generalisation – or robustness and adaptability – may one day give rise to a quantum theory of learning.

Helgoland 2025 illustrated just how much quantum mechanics has diversified since its early days. No longer just a framework for explaining atomic spectra, the photoelectric effect and black-body radiation, it is at once a formalism describing high-energy particle scattering, a handbook for controlling the most exotic states of matter, the foundation for information technologies now driving national investment plans, and a source of philosophical conundrums that, after decades at the margins, has once again taken centre stage in theoretical physics.

Davide De Biasio *associate editor.*

FCC WEEK 2025

A new phase for the FCC

FCC Week 2025 gathered more than 600 participants from 34 countries together in Vienna from 19 to 23 May. The meeting was the first following the submission of the FCC's feasibility study to the European Strategy for Particle Physics (*CERN Courier* May/June 2025 p9). Comprising three volumes – covering physics and detectors, accelerators and infrastructure, and civil engineering and sustainability – the study represents the most comprehensive blueprint to date for a next-generation collider facility. The next phase will focus on preparing a robust implementation strategy, via technical design, cost assessment, environmental planning and global engagement.

Shining lights *The FCC is not only about pushing the frontiers of knowledge, but also about enabling a new generation of ideas, collaborations and societal progress.*

CERN Director-General Fabiola Gianotti estimated the integral FCC programme to offer unparalleled opportunities to explore physics at the shortest distances, and noted growing support and enthusiasm for the programme within the community. That enthusiasm is reflected in the growing collaboration: the FCC collaboration now includes 162 institutes from 38 countries, with 28 new Memoranda of Understanding signed in the past year. These include new partnerships in Latin America, Asia and Ukraine, as well as Statements of Intent from the US and Canada. The FCC vision has also gained visibility in high-level policy dialogues, including the Draghi report on European competitiveness. Scientific plenaries and parallel sessions highlighted updates on simulation tools, rare-process searches and strategies to probe beyond the Standard Model. Detector R&D has progressed significantly, with prototyping, software development and AI-driven simulations advancing rapidly.

Design developments

In accelerator design, developments included updated lattice and optics concepts involving global "head-on" compensation (using opposing beam interactions) and local chromaticity corrections (to the dependence of beam optics on particle energy). Refinements were also presented to injection schemes, beam collimation and the mitigation of collective effects. A central tool in these efforts is the Xsuite simulation platform, whose capabilities now include spin tracking and modelling based on real collider environments such as SuperKEKB.

Technical innovations also came to the fore. The superconducting RF system for FCC-ee includes 400 MHz Nb/Cu cavities for low-energy operation and 800 MHz Nb cavities for higher-energy modes. The introduction of reverse-phase operation and new RF source concepts – such as the tristron, with energy efficiencies above 90% (*CERN Courier* May/June 2025 p30) – represent major design advances.

FCC Week 2025 extended well beyond the conference venue, turning Vienna into a vibrant hub for public science outreach

Cost control

Vacuum technologies based on ultrathin NEG coating and discrete photon stops, as well as industrialisation strategies for cost control, are under active development. For FCC-hh, high-field magnet R&D continues on both Nb_3Sn prototypes and high-temperature superconductors.

Sessions on technical infrastructure explored everything from grid design, cryogenics and RF power to heat recovery, robotics and safety systems. Sustainability concepts, including renewable energy integration and hydrogen storage, showcased the project's interdisciplinary scope and long-term environmental planning.

The Early Career Researchers forum drew nearly 100 participants for discussions on sustainability, governance and societal impact. The session culminated in a commitment to inclusive collaboration, echoed by the quote from Austrian-born artist, architect and environmentalist Friedensreich Hundertwasser (1928–2000): "Those who do not honour the past lose the future. Those who destroy their roots cannot grow."

This spirit of openness and public connection also defined the week's city-wide engagement. FCC Week 2025 extended well beyond the conference venue, turning Vienna into a vibrant hub for public science outreach. In particular, the "Big Science, Big Impact" session – co-organised with the Austrian Federal Economic Chamber (WKO) – highlighted CERN's broader role in economic development. Daniel Pawel Zawarczynski (WKO) shared examples of small and medium enterprise growth and technology transfer, noting that CERN participation can open new markets, from tunnelling to aerospace. Economist Gabriel Felbermayr referred to a recent WIFO analysis indicating a benefit-to-cost ratio for the FCC greater than 1.2 under conservative assumptions. The FCC is not only a tool for discovery, observed Johannes Gutleber (CERN), but also a platform enabling technology development, open software innovation and workforce training.

The FCC awards celebrate the creativity, rigour and passion that early-career researchers bring to the programme. This year, Tsz Hong Kwok (University of Zürich) and Audrey Piccini (CERN) won poster prizes, Sara Aumiller (TU München) and Elaf Musa (DESY) received innovation awards, and Ivan Karpov (CERN) and Nicolas Vallis (PSI) were honoured with paper prizes sponsored by *Physical Review Accelerators and Beams*. As CERN Council President Costas Fountas reminded participants, the FCC is not only about pushing the frontiers of knowledge, but also about enabling a new generation of ideas, collaborations and societal progress.

Frank Zimmermann *and* **Panagiotis Charitos** *CERN.*

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NEUTRON-STAR WORKSHOP

Neutron stars as fundamental physics labs

Neutron stars are truly remarkable systems. They pack between one and two times the mass of the Sun into a radius of about 10 kilometres. Teetering on the edge of gravitational collapse into a black hole, they exhibit some of the strongest gravitational forces in the universe. They feature extreme densities in excess of atomic nuclei. And due to their high densities they produce weakly interacting particles such as neutrinos. Fifty experts on nuclear physics, particle physics and astrophysics met at CERN from 9 to 13 June to discuss how to use these extreme environments as precise laboratories for fundamental physics.

CERN

Dense discussions *An intriguing question that the workshop left open is whether the canonical QCD axion could condense inside neutron stars.*

Perhaps the most intriguing open question surrounding neutron stars is what is actually inside them. Clearly they are primarily composed of neutrons, but many theories suggest that other forms of matter should appear in the highest density regions near the centre of the star, including free quarks, hyperons and kaon or pion condensates. Diverse data can constrain these hypotheses, including astronomical inferences of the masses and radii of neutron stars, observations of the mergers of neutron stars by LIGO, and baryon production patterns and correlations in heavy-ion collisions at the LHC. Theoretical consistency is critical here. Several talks highlighted the importance of low-energy nuclear data to understand the behaviour of nuclear matter at low densities, though also emphasising that at very high densities and energies any description should fall within the realm of QCD – a theory that beautifully describes the dynamics of quarks and gluons at the LHC.

Another key question for neutron stars is how fast they cool. This depends critically on their composition. Quarks, hyperons, nuclear resonances, pions or muons would each lead to different channels to cool the neutron star. Measurements of the temperatures and ages of neutron stars might thereby be used to learn about their composition.

The workshop revealed that research into neutron stars has progressed so rapidly in recent years that it allows key tests of fundamental physics including tests of particles beyond the Standard Model, including the axion: a very light and weakly coupled dark-matter candidate that was initially postulated to explain the "strong CP problem" of why strong interactions are identical for particles and antiparticles. The workshop allowed particle theorists to appreciate the various possible uncertainties in their theoretical predictions and propagate them into new channels that may allow sharper tests of axions and other weakly interacting particles. An intriguing question that the workshop left open is whether the canonical QCD axion could condense inside neutron stars.

Research into neutron stars has progressed so rapidly in recent years that it allows key tests of fundamental physics

While many uncertainties remain, the workshop revealed that the field is open and exciting, and that upcoming observations of neutron stars, including neutron-star mergers or the next galactic supernova, hold unique opportunities to understand fundamental questions from the nature of dark matter to the strong CP problem.

Miguel Escudero Abenza *CERN.*

HADRONS 2025

Hadrons in Porto Alegre

The 16th International Workshop on Hadron Physics (Hadrons 2025) welcomed 135 physicists to the Federal University of Rio Grande do Sul (UFRGS) in Porto Alegre, Brazil. Delayed by four months due to a tragic flood that devastated the city, the triennial conference took place from 10 to 14 March, despite adversity maintaining its long tradition as a forum for collaboration among Brazilian and international researchers at different stages of their careers.

Hadrons 2025

QCD questions *Despite flooding in the city, a successful Hadrons 2025 took place in Porto Alegre in March.*

The workshop's scientific programme included field theoretical approaches to QCD, the behaviour of hadronic and quark matter in astrophysical contexts, hadronic structure and decays, lattice QCD calculations, recent experimental developments in relativistic heavy-ion collisions, and the interplay of strong and electroweak forces within the Standard Model.

Fernanda Steffens (University of Bonn) explained how deep-inelastic-scattering experiments and theoretical developments are revealing the internal structure of the proton. Kenji Fukushima (University of Tokyo) addressed the theoretical framework and phase structure of strongly interacting matter, with particular emphasis on the QCD phase diagram and its relevance to heavy-ion collisions and neutron stars. Chun Shen (Wayne State University) presented a comprehensive overview of the state-of-the-art techniques used to extract the transport properties of quark–gluon plasma from heavy-ion collision data, emphasising the role of Bayesian inference and machine learning in constraining theoretical models. Li-Sheng Geng (Beihang University) explored exotic hadrons through the lens of hadronic molecules, highlighting symmetry multiplets such as pentaquarks, the formation of multi-hadron states and the role of femtoscopy in studying unstable particle interactions.

This edition of Hadrons was dedicated to the memory of two individuals who left a profound mark on the Brazilian hadronic-physics community: Yogiro Hama, a distinguished senior researcher and educator whose decades-long contributions were foundational to the development of the field in Brazil, and Kau Marquez, an early-career physicist whose passion for science remained steadfast despite her courageous battle with spinal muscular atrophy. Both were remembered with deep admiration and respect, not only for their scientific dedication but also for their personal strength and impact on the community.

Since its creation in 1988, the Hadrons workshop has played a central role in developing Brazil's scientific capacity in particle and nuclear physics. Its structure facilitates close interaction between master's and doctoral students, and senior researchers, thus enhancing both technical training and academic exchange. This model continues to strengthen the foundations of research and collaboration throughout the Brazilian scientific community.

Its mission is to cultivate a vibrant and inclusive scientific environment

This is the main event for the Brazilian particle- and nuclear-physics communities, reflecting a commitment to advancing research in this highly interactive field. By circulating the venue across multiple regions of Brazil, each edition further renews its mission to cultivate a vibrant and inclusive scientific environment. This edition was closed by a public lecture on QCD by Tereza Mendes (University of São Paolo), who engaged local students with the foundational questions of strong-interaction physics.

The next edition of the Hadrons series will take place in Bahia in 2028.

Fernando S Navarra *University of São Paulo,* **Patrícia C Magalhães** *University of Campinas and* **Mariana Dutra** *Aeronautics Institute of Technology.*

FLAVOR PHYSICS AND CP VIOLATION

Muons under the microscope in Cincinnati

The 23rd edition of Flavor Physics and CP Violation (FPCP) attracted 100 physicists to Cincinnati, USA, from 2 to 6 June 2025. The conference reviews recent experimental and theoretical developments in CP violation, rare decays, Cabibbo–Kobayashi–Maskawa matrix elements, heavy-quark decays, flavour phenomena in charged leptons and neutrinos, and the interplay between flavour physics and high-p_T physics at the LHC.

Manuel Franco Sevilla

Flavour physics *FPCP 2025 took place in Cincinnati.*

The highlight of the conference was new results on the muon magnetic anomaly. The Muon g-2 experiment at Fermilab released its final measurement of $a_\mu = (g-2)/2$ on 3 June, while the conference was in progress, reaching a precision of 127 ppb on the published value. This uncertainty is more than four times smaller than that reported by the previous experiment. One week earlier, on 27 May, the Muon g-2 Theory Initiative published their second calculation of the same quantity, following that published in summer 2020. A major difference between the two calculations is that the earlier one used experimental data and the dispersion integral to evaluate the hadronic contribution to a_μ, whereas the update uses a purely theoretical approach based on lattice QCD. The strong tension with the experiment of the earlier calculation is no longer present, with the new calculation compatible with experimental results. Thus, no new physics discovery can be claimed, though the reason for the difference between the two approaches must be understood (see p7).

The MEG II collaboration presented an important update to their limit on the branching fraction for the lepton-flavour-violating decay $\mu \to e\gamma$. Their new upper bound of 1.5×10^{-13} is determined from data collected in 2021 and 2022. The experiment recorded additional data from 2023 to 2024 and expects to continue data taking for two more years. These data will be sensitive to a branching fraction four to five times smaller than the current limit.

LHCb, Belle II, BESIII and NA62 all discussed recent results in quark flavour physics. Highlights include the first measurement of CP violation in a baryon decay by LHCb and improved limits on CP violation in D-meson decay to two pions by Belle II. With more data, the latter measurements could potentially show that the observed CP violation in charm is from a non-Standard-Model source.

The Belle II collaboration now plans to collect a sample between 5 to 10 ab^{-1} by the early 2030s before undergoing an upgrade to collect a 30 to 50 ab^{-1} sample by the early 2040s. LHCb plan to run to the end of the High-Luminosity LHC and collect 300 fb^{-1}. LHCb recorded almost 10 fb^{-1} of data last year – more than in all their previous running, and now with a fully software-based trigger with much higher efficiency than the previous hardware-based first-level trigger. Future results from Belle II and the LHCb upgrade are eagerly anticipated.

The 24th FPCP conference will be held from 18 to 22 May 2026 in Bad Honnef, Germany.

Marco Incagli *INFN and University of Pisa and* **Jim Libby** *Indian Institute of Technology Madras.*

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HIGGS PAIRS 2025

Plotting the discovery of Higgs pairs on Elba

Precise measurements of the Higgs self-coupling and its effects on the Higgs potential will play a key role in testing the validity of the Standard Model (SM). 150 physicists discussed the required experimental and theoretical manoeuvres on the serene island of Elba from 11 to 17 May at the Higgs Pairs 2025 workshop.

The conference mixed updates on theoretical developments in Higgs-boson pair production, searches for new physics in the scalar sector, and the most recent results from Run 2 and Run 3 of the LHC. Among the highlights was the first Run 3 analysis released by ATLAS on the search for di-Higgs production in the bbγγ final state – a particularly sensitive channel for probing the Higgs self-coupling. This result builds on earlier Run 2 analyses and demonstrates significantly improved sensitivity, now comparable to the full Run 2 combination of all channels. These gains were driven by the use of new b-tagging algorithms, improved mass resolution through updated analysis techniques, and the availability of nearly twice the dataset.

L Brost

Escape to Elba *Theorists and experimentalists found a valuable discussion forum at Higgs Pairs.*

Complementing this, CMS presented the first search for ttHH production – a rare process that would provide additional sensitivity to the Higgs self-coupling and Higgs–top interactions. Alongside this, ATLAS presented first experimental searches for triple Higgs boson production (HHH), one of the rarest processes predicted by the SM. Work on more traditional final states such as bbττ and bbbb is ongoing at both experiments, and continues to benefit from improved reconstruction techniques and larger datasets.

Beyond current data, the workshop featured discussions of the latest combined projection study by ATLAS and CMS, prepared as part of the input to the upcoming European Strategy Update. It extrapolates results of the Run 2 analyses to expected conditions of the High-Luminosity LHC (HL-LHC), estimating future sensitivities to the Higgs self-coupling and di-Higgs cross-section in scenarios with vastly higher luminosity and upgraded detectors. Under these assumptions, the combined sensitivity of ATLAS and CMS to di-Higgs production is projected to reach a significance of 7.6σ, firmly establishing the process.

These projections provide crucial input for analysis strategy planning and detector design for the next phase of operations at the HL-LHC. Beyond the HL-LHC, efforts are already underway to design experiments at future colliders that will enhance sensitivity to the production of Higgs pairs, and offer new insights into electroweak symmetry breaking.

Rea Thornberry *Southern Methodist University.*

FOUR WAYS TO INTERPRET QUANTUM MECHANICS

Orthodox quantum mechanics is empirically flawless, but founded on an awkward interface between quantum systems and classical probes. In this feature, Carlo Rovelli – himself the originator of the relational interpretation – describes the major schools of thought on how to make sense of a purely quantum world.

Unknown

A century of debate *Werner Heisenberg conceived the first complete formulation of quantum mechanics on the German island of Helgoland in 1925. There is still no consensus on how to interpret the theory.*

One hundred years after its birth, quantum mechanics is the foundation of our understanding of the physical world. Yet debates on how to interpret the theory – especially the thorny question of what happens when we make a measurement – remain as lively today as during the 1930s.

The latest recognition of the fertility of studying the interpretation of quantum mechanics was the award of the 2022 Nobel Prize in Physics to Alain Aspect, John Clauser and Anton Zeilinger. The motivation for the prize pointed out that the bubbling field of quantum information, with its numerous current and potential technological applications, largely stems from the work of John Bell at CERN the 1960s and 1970s, which in turn was motivated by the debate on the interpretation of quantum mechanics.

The majority of scientists use a textbook formulation of the theory that distinguishes the quantum system being studied from "the rest of the world" – including the measuring apparatus and the experimenter, all described in classical terms. Used in this orthodox manner, quantum theory describes how quantum systems react when probed by the rest of the world. It works flawlessly.

Sense and sensibility

The problem is that the rest of the world is quantum mechanical as well. There are of course regimes in which the behaviour of a quantum system is well approximated by classical mechanics. One may even be tempted to think that this suffices to solve the difficulty. But this leaves us in the awkward position of having a general theory of the world that only makes sense under special approximate conditions. Can we make sense of the theory in general?

THE AUTHOR
Carlo Rovelli *Aix-Marseille University.*

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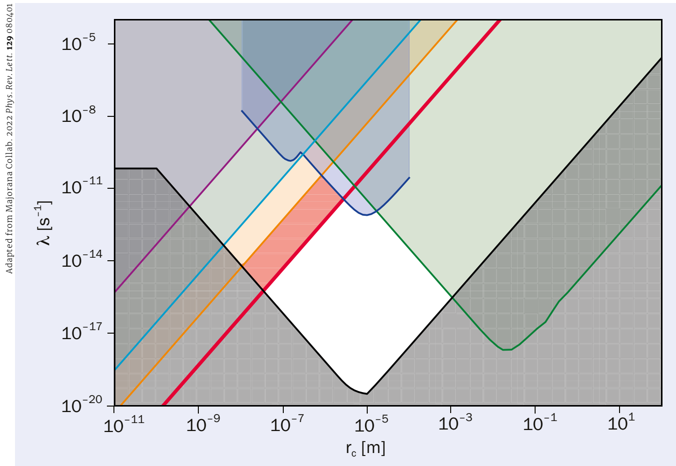
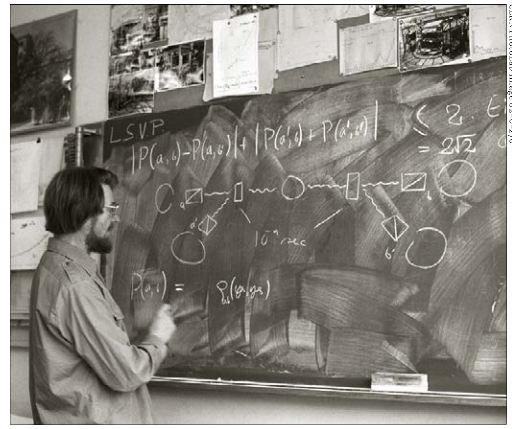


Adapted from Majorana Collab. 2022 *Phys. Rev. Lett.* **129** 080401

Probing physical collapse *Upper limits on a "mass proportional" physical-collapse model where the wavefunction is localised with a length r_c at a rate λ. Shaded regions are excluded by cold-atom interferometry (magenta), gravitational-wave detectors (green), cantilever experiments (blue), bulk heating constraints (cyan) and searches for spontaneous X-ray emission by the Majorana Demonstrator at the Sanford Underground Research Facility (red). Prior limits from spontaneous X-ray emission are shown in orange. The theoretical lower bounds are indicated by the solid black curve.*



CERN PhotoLab Image 82-6-270

Non-locality *In the 1960s and 1970s, John Bell reignited interest in the foundations of quantum mechanics, laying the groundwork for the now-vibrant field of quantum information. On the blackboard, entangled particles are shown emerging from a central source and travelling to distant detectors. Their spacelike separation ensures that no signal travelling at or below the speed of light could pass between them. Bell's theorem suggests that no theory based on local hidden variables alone can fully account for the correlations predicted by quantum mechanics and since confirmed by experiment.*

Four main ideas stand at the forefront of efforts to make quantum mechanics more conceptually robust

Today, variants of four main ideas stand at the forefront of efforts to make quantum mechanics more conceptually robust. They are known as physical collapse, hidden variables, many worlds and relational quantum mechanics. Each appears to me to be viable *a priori*, but each comes with a conceptual price to pay. The latter two may be of particular interest to the high-energy community as the first two do not appear to fit well with relativity.

The idea of the physical collapse is simple: we are missing a piece of the dynamics. There may exist a yet-undiscovered physical interaction that causes the wavefunction to "collapse" when the quantum system interacts with the classical world in a measurement. The idea is empirically testable. So far, all laboratory attempts to find violations of the textbook Schrödinger equation have failed (see "Probing physical collapse" figure), and some models for these hypothetical new dynamics have been ruled out by measurements.

The second possibility, hidden variables, follows on from Einstein's belief that quantum mechanics is incomplete. It posits that its predictions are exactly correct, but that there are additional variables describing what is going on, besides those in the usual formulation of the theory: the reason why quantum predictions are probabilistic is our ignorance of these other variables.

The work of John Bell shows that the dynamics of any such theory will have some degree of non-locality (see "Non-locality" image). In the non-relativistic domain, there is a good example of a theory of this sort, that goes under the name of de Broglie–Bohm, or pilot-wave theory. This theory has non-local but deterministic dynamics capable of reproducing the predictions of non-relativistic quantum-particle dynamics. As far as I am aware, all existing theories of this kind break Lorentz invariance, and the extension of hidden variable theories to quantum-field theoretical domains appears cumbersome.

Relativistic interpretations

Let me now come to the two ideas that are naturally closer to relativistic physics. The first is the many-worlds interpretation – a way of making sense of quantum theory without either changing its dynamics or adding extra variables. It is described in detail in this edition of *CERN Courier* by one of its leading contemporary proponents (see p26), but the main idea is the following: being a genuine quantum system, the apparatus that makes a quantum measurement does not collapse the superposition of possible measurement outcomes – it becomes a quantum superposition of the possibilities, as does any human observer.

If we observe a singular outcome, says the many-worlds interpretation, it is not because one of the probabilistic alternatives has actualised in a mysterious "quantum measurement". Rather, it is because we have split into a quantum superposition of ourselves, and we just happen to be in one of the resulting copies. The world we see around us is thus only one of the branches of a forest of parallel worlds in the overall quantum state of everything. The price to pay to make sense of quantum theory in this manner is to accept the idea that the reality we see is just a branch in a vast collection of possible worlds that include innumerable copies of ourselves.

Relational interpretations are the most recent of the four kinds mentioned. They similarly avoid physical collapse or hidden variables, but do so without multiplying worlds. They stay closer to the orthodox textbook interpretation, but with no privileged status for observers. The idea is to think of quantum theory in a manner closer to the way it was initially conceived by Born, Jordan, Heisenberg and Dirac: namely in terms of transition amplitudes between observations rather than quantum states evolving continuously in time, as emphasised by Schrödinger's wave mechanics (see "A matter of taste" image).

American Institute of Physics

A matter of taste *Relational quantum mechanics develops the perspectives of Dirac (left) and Heisenberg (centre), while the many worlds interpretation leans more heavily on Schrödinger's (right) conception of the wave function as primitive.*

Observer relativity

The alternative to taking the quantum state as the fundamental entity of the theory is to focus on the information that an arbitrary system can have about another arbitrary system. This information is embodied in the physics of the apparatus: the position of its pointer variable, the trace in a bubble chamber, a person's memory or a scientist's logbook. After a measurement, these physical quantities "have information" about the measured system as their value is correlated with a property of the observed systems.

Quantum theory can be interpreted as describing the relative information that systems can have about one another. The quantum state is interpreted as a way of coding the information about a system available to another system. What looks like a multiplicity of worlds in the many-worlds interpretation becomes nothing more than a mathematical accounting of possibilities and probabilities.

The relational interpretation reduces the content of the physical theory to be about how systems affect other systems. This is like the orthodox textbook interpretation, but made democratic. Instead of a preferred classical world, any system can play a role that is a generalisation of the Copenhagen observer. Relativity teaches us that velocity is a relative concept: an object has no velocity by itself, but only relative to another object. Similarly, quantum mechanics, interpreted in this manner, teaches us that all physical variables are relative. They are not properties of a single object, but ways in which an object affects another object.

The QBism version of the interpretation restricts its attention to observing systems that are rational agents: they can use observations and make probabilistic predictions about the future. Probability is interpreted subjectively, as the expectation of a rational agent. The relational interpretation proper does not accept this restriction: it considers the information that any system can have about any other system. Here, "information" is understood in the simple physical sense of correlation described above.

Like many worlds – to which it is not unrelated – the relational interpretation does not add new dynamics or new variables. Unlike many worlds, it does not ask us to think about parallel worlds either. The conceptual price to pay is a radical weakening of a strong form of realism: the theory does not give us a picture of a unique objective sequence of facts, but only perspectives on the reality of physical systems, and how these perspectives interact with one another. Only quantum states of a system relative to another system play a role in this interpretation. The many-worlds interpretation is very close to this. It supplements the relational interpretation with an overall quantum state, interpreted realistically, achieving a stronger version of realism at the price of multiplying worlds. In this sense, the many worlds and relational interpretations can be seen as two sides of the same coin.

I have only sketched here the most discussed alternatives, and have tried to be as neutral as possible in a field of lively debates in which I have my own strong bias (towards the fourth solution). Empirical testing, as I have mentioned, can only test the physical collapse hypothesis.

There is nothing wrong, in science, in using different pictures for the same phenomenon. Conceptual flexibility is itself a resource. Specific interpretations often turn out to be well adapted to specific problems. In quantum optics it is sometimes convenient to think that there is a wave undergoing interference, as well as a particle that follows a single trajectory guided by the wave, as in the pilot-wave hidden-variable theory. In quantum computing, it is convenient to think that different calculations are being performed in parallel in different worlds. My own field of loop quantum gravity treats spacetime regions as quantum processes: here, the relational interpretation merges very naturally with general relativity, because spacetime regions themselves become quantum processes, affecting each other.

Richard Feynman famously wrote that "every theoretical physicist who is any good knows six or seven different theoretical representations for exactly the same physics. He knows that they are all equivalent, and that nobody is ever going to be able to decide which one is right at that level, but he keeps them in his head, hoping that they will give him different ideas for guessing." I think that this is where we are, in trying to make sense of our best physical theory. We have various ways to make sense of it. We do not yet know which of these will turn out to be the most fruitful in the future. ●

Every theoretical physicist who is any good knows six or seven different theoretical representations for exactly the same physics

Further reading

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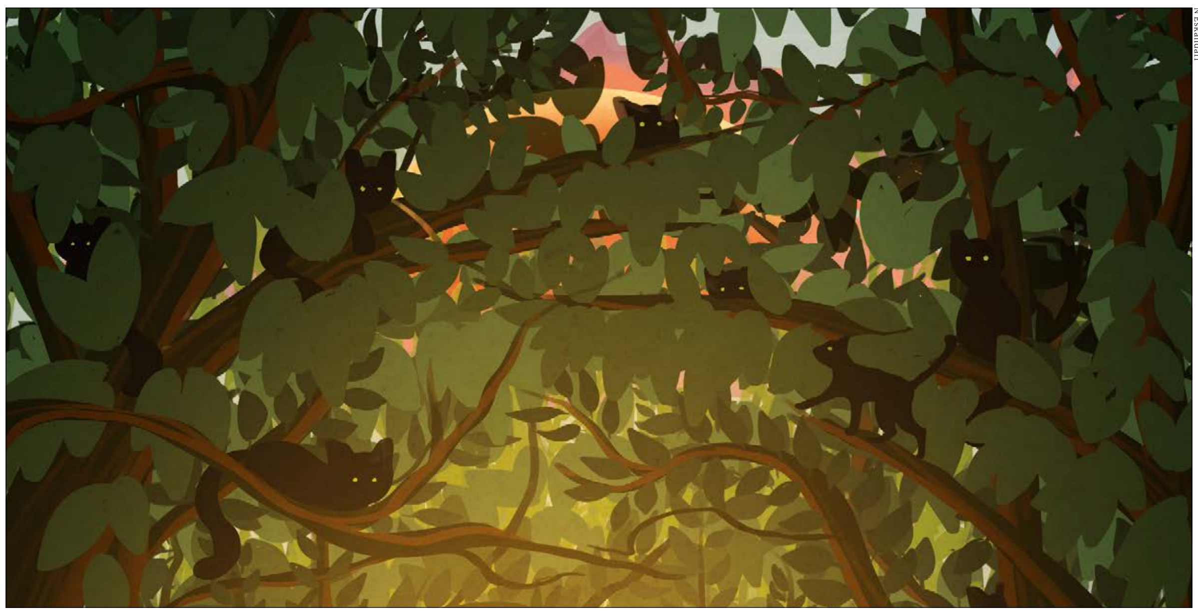
THE MINIMALISM OF MANY WORLDS

David Wallace argues for the 'decoherent view' of quantum mechanics, where at the fundamental level there is neither probability nor wavefunction collapse – and for its purest incarnation, the many-worlds interpretation of Hugh Everett III.



N Eskandari

Escaping Schrödinger's box *According to Hugh Everett III, the world we see around us is only one of the branches of a forest of parallel worlds in the overall quantum state of everything.*

Physicists have long been suspicious of the "quantum measurement problem": the supposed puzzle of how to make sense of quantum mechanics. Everyone agrees (don't they?) on the formalism of quantum mechanics (QM); any additional discussion of the interpretation of that formalism can seem like empty words. And Hugh Everett III's infamous "many-worlds interpretation" looks more dubious than most: not just unneeded words but unneeded worlds. Don't waste your time on words or worlds; shut up and calculate.

But the measurement problem has driven more than philosophy. Questions of how to understand QM have always been entangled, so to speak, with questions of how to apply and use it, and even how to formulate it; the continued controversies about the measurement problem are also continuing controversies in how to apply, teach and mathematically describe QM. The Everett interpretation emerges as the natural reading of one strategy for doing QM, which I call the "decoherent view" and which has largely supplanted the rival "lab view", and so – I will argue – the Everett interpretation can and should be understood not as a useless adjunct to modern QM but as part of the development in our understanding of QM over the past century.

The view from the lab

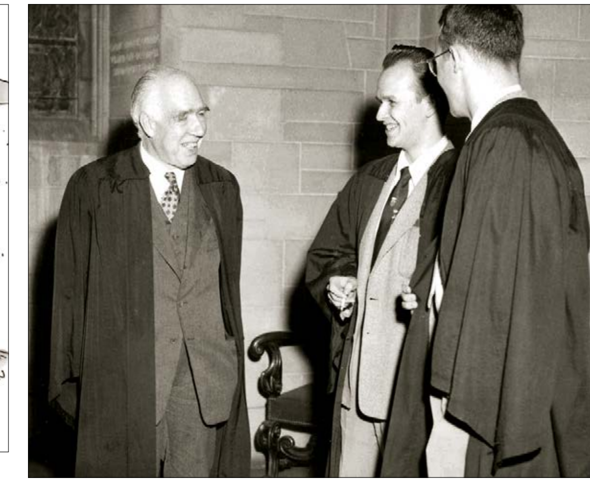
The lab view has its origins in the work of Bohr and Heisenberg, and it takes the word "observable" that appears in every QM textbook seriously. In the lab view, QM is not a theory like Newton's or Einstein's that aims at an objective description of an external world subject to its own dynamics; rather, it is essentially, irreducibly, a theory of observation and measurement. Quantum states, in the lab view, do not represent objective features of a system in the way that (say) points in classical phase space do: they represent the experimentalist's partial knowledge of that system. The process of measurement is not something to describe within QM: ultimately it is external to QM. And the so-called "collapse" of quantum states upon measurement represents not a mysterious stochastic process but simply the updating of our knowledge upon gaining more information.

THE AUTHOR

David Wallace *University of Pittsburgh.*

A Epstein

Dynamical probes *Experimental kit isn't found scattered across the desert, stamped by the gods with the self-adjoint operator it measures; it is built using physical principles.*



A Richards/AIP Emilio Segrè Visual Archives

Origins *While Bohr (left) was the main proponent of the lab view, Everett (centre) was foundational to the decoherent view.*

Valued measurements

The lab view has led to important physics. In particular, the "positive operator valued measure" idea, central to many aspects of quantum information, emerges most naturally from the lab view. So do the many extensions, total and partial, to QM of concepts initially from the classical theory of probability and information. Indeed, in quantum information more generally it is arguably the dominant approach. Yet outside that context, it faces severe difficulties. Most notably: if quantum mechanics describes not physical systems in themselves but some calculus of measurement results, if a quantum system can be described only relative to an experimental context, what theory describes those measurement results and experimental contexts themselves?

One popular answer – at least in quantum information – is that measurement is primitive: no dynamical theory is required to account for what measurement is, and the idea that we should describe measurement in dynamical terms is just another Newtonian prejudice. (The "QBist" approach to QM fairly unapologetically takes this line.)

One can criticise this answer on philosophical grounds, but more pressingly: that just isn't how measurement is actually done in the lab. Experimental kit isn't found scattered across the desert (each device perhaps stamped by the gods with the self-adjoint operator it measures); it is built using physical principles (see "Dynamical probes" figure). The fact that the LHC measures the momentum and particle spectra of various decay processes, for instance, is something established through vast amounts of scientific analysis, not something simply posited. We need an account of experimental practice that allows us to explain how measurement devices work and how to build them.

Bohr had such an account: quantum measurements are to be described through classical mechanics. The classical is ineliminable from QM precisely because it is to classical mechanics we turn when we want to describe the experimental context of a quantum system. To Bohr, the quantum–classical transition is a conceptual and philosophical matter as much as a technical one, and classical ideas are unavoidably required to make sense of any quantum description.

Perhaps this was viable in the 1930s. But today it is not only the measured systems but the measurement devices themselves that essentially rely on quantum principles, beyond anything that classical mechanics can describe. And so, whatever the philosophical strengths and weaknesses of this approach – or of the lab view in general – we need something more to make sense of modern QM, something that lets us apply QM itself to the measurement process.

Practice makes perfect

We can look to physics practice to see how. As von Neumann glimpsed, and Everett first showed clearly, nothing prevents us from modelling a measurement device itself inside unitary quantum mechanics. When we do so, we find that the measured system becomes entangled with the device, so that (for instance) if a measured atom is in a weighted superposition of spins with respect to some axis, after measurement then the device is in a similarly-weighted superposition of readout values.

In principle, this courts infinite regress: how is that new superposition to be interpreted, save by a still-larger measurement device? In practice, we simply treat the mod-squared amplitudes of the various readout values

Perhaps this was viable in the 1930s, but today measurement devices rely on quantum principles

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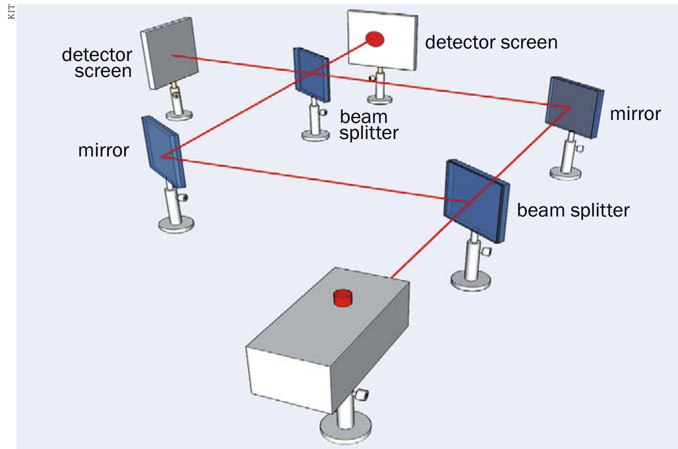

Superpositions are not probabilities *A Mach–Zehnder interferometer splits a particle beam in two and then re-interferes it. It can be tuned to trigger each detector in any proportion.*

It is the decoherent view that underlies the way quantum theory is for the most part used in the 21st century

as probabilities, and compare them with observed frequencies. This sounds a bit like the lab view, but there is a subtle difference: these probabilities are understood not with respect to some hypothetical measurement, but as the actual probabilities of the system being in a given state.

Of course, if we could always understand mod-squared amplitudes that way, there would be no measurement problem! But interference precludes this. Set up, say, a Mach–Zehnder interferometer, with a particle beam split in two and then re-interfered, and two detectors after the re-interference (see "Superpositions are not probabilities" figure). We know that if either of the two paths is blocked, so that any particle detected must have gone along the other path, then each of the two outcomes is equally likely: for each particle sent through, detector A fires with 50% probability and detector B with 50% probability. So whichever path the particle went down, we get A with 50% probability and B with 50% probability. And yet we know that if the interferometer is properly tuned and both paths are open, we can get A with 100% probability or 0% probability or anything in between. Whatever microscopic superpositions are, they are not straightforwardly probabilities of classical goings-on.

Unfeasible interference

But macroscopic superpositions are another matter. There, interference is unfeasible (good luck reinterfering the two states of Schrödinger's cat); nothing formally prevents us from treating mod-squared amplitudes like probabilities.

And decoherence theory has given us a clear understanding of just why interference is invisible in large systems, and more generally when we can and cannot get away with treating mod-squared amplitudes as probabilities. As the work of Zeh, Zurek, Gell-Mann, Hartle and many others (drawing inspiration from Everett and from work on the quantum/classical transition as far back as Mott) has shown, decoherence – that is, the suppression of interference – is simply an aspect of non-equilibrium statistical mechanics. The large-scale, collective degrees of freedom of a quantum system, be it the needle on a measurement device or the centre-of-mass of a dust mote, are constantly interacting with a much larger number of small-scale degrees of freedom: the short-wavelength phonons inside the object itself; the ambient light; the microwave background radiation. We can still find autonomous dynamics for the collective degrees of freedom, but because of the constant transfer of information to the small scale, the coherence of any macroscopic superposition rapidly bleeds into microscopic degrees of freedom, where it is dynamically inert and in practice unmeasurable.

Emergence and scale

Decoherence can be understood in the familiar language of emergence and scale separation. Quantum states are not fundamentally probabilistic, but they are emergently probabilistic. That emergence occurs because for macroscopic systems, the timescale by which energy is transferred from macroscopic to residual degrees of freedom is very long compared to the timescale of the macroscopic system's own dynamics, which in turn is very long compared to the timescale by which information is transferred. (To take an extreme example, information about the location of the planet Jupiter is recorded very rapidly in the particles of the solar wind, or even the photons of the cosmic background radiation, but Jupiter loses only an infinitesimal fraction of its energy to either.) So the system decoheres very rapidly, but having done so it can still be treated as autonomous.

On this decoherent view of QM, there is ultimately only the unitary dynamics of closed systems; everything else is a limiting or special case. Probability and classicality emerge through dynamical processes that can be understood through known techniques of physics: understanding that emergence may be technically challenging but poses no problem of principle. And this means that the decoherent view can address the lab view's deficiencies: it can analyse the measurement process quantum mechanically; it can apply quantum mechanics even in cosmological contexts where the "measurement" paradigm breaks down; it can even recover the lab view within itself as a limited special case. And so it is the decoherent view, not the lab view, that – I claim – underlies the way quantum theory is for the most part used in the 21st century, including in its applications in particle physics and cosmology (see "Two views of quantum mechanics" table).

But if the decoherent view is correct, then at the fundamental level there is neither probability nor wavefunction collapse; nor is there a fundamental difference between a microscopic superposition like those in interference experiments and a macroscopic superposition like Schrödinger's cat.

Two views of quantum mechanics

Quantum phenomenon	Lab view	Decoherent view
Dynamics	Unitary (i.e. governed by the Schrödinger equation) only between measurements	Always unitary
Quantum/classical transition	Conceptual jump between fundamentally different systems	Purely dynamical: classical physics is a limiting case of quantum physics
Measurements	Cannot be treated internal to the formalism	Just one more dynamical interaction
Role of the observer	Conceptually central	Just one more physical system

The differences are differences of degree and scale: at the microscopic level, interference is manifest; as we move to larger and more complex systems it hides away more and more effectively; in practice it is invisible for macroscopic systems. But even if we cannot detect the coherence of the superposition of a live and dead cat, it does not thereby vanish. And so according to the decoherent view, the cat is simultaneously alive and dead in the same way that the superposed atom is simultaneously in two places. We don't need a change in the dynamics of the theory, or even a reinterpretation of the theory, to explain why we don't see the cat as alive and dead at once: decoherence has already explained it. There is a "live cat" branch of the quantum state, entangled with its surroundings to an ever-increasing degree; there is likewise a "dead cat" branch; the interference between them is rendered negligible by all that entanglement.

Many worlds

At last we come to the "many worlds" interpretation: for when we observe the cat ourselves, we too enter a superposition of seeing a live and a dead cat. But these "worlds" are not added to QM as exotic new ontology: they are discovered, as emergent features of collective degrees of freedom, simply by working out how to use QM in contexts beyond the lab view and then thinking clearly about its content. The Everett interpretation – the many-worlds theory – is just the decoherent view taken fully seriously. Interference explains why superpositions cannot be understood simply as parameterising our ignorance; unitarity explains how we end up in superpositions ourselves; decoherence explains why we have no awareness of it.

(Forty-five years ago, David Deutsch suggested testing the Everett interpretation by simulating an observer inside a quantum computer, so that we could recohere them after they made a measurement. Then, it was science fiction; in this era of rapid progress on AI and quantum computation, perhaps less so!)

Could we retain the decoherent view and yet avoid any commitment to "worlds"? Yes, but only in the same sense that we could retain general relativity and yet refuse to commit to what lies behind the cosmological event horizon: the theory gives a perfectly good account of the other Everett worlds, and the matter beyond the horizon, but perhaps epistemic caution might lead us not to overcommit. But even so, the content of QM includes the other worlds, just as the content of general relativity includes beyond-horizon physics, and we will only confuse ourselves if we avoid even talking about that content. (Thus Hawking, who famously observed that when he heard about Schrödinger's cat he reached for his gun, was nonetheless happy to talk about Everettian branches when doing quantum cosmology.)

Alternative views

Could there be a different way to make sense of the decoherent view? Never say never; but the many-worlds perspective results almost automatically from simply taking that view as a literal description of quantum systems and how they evolve, so any alternative would have to be philosophically subtle, taking a different and less literal reading of QM. (Perhaps relationalism, discussed in this issue by Carlo Rovelli, see p21, offers a way to do it, though in many ways it seems more a version of the lab view. The physical collapse and hidden variables interpretations modify the formalism, and so fall outside either category.)

Does the apparent absurdity, or the ontological extravagance, of the Everett interpretation force us, as good scientists, to abandon many-worlds, or if necessary the decoherent view itself? Only if we accept some scientific principle that throws out theories that are too strange or that postulate too large a universe. But physics accepts no such principle, as modern cosmology makes clear.

Are there philosophical problems for the Everett interpretation? Certainly: how are we to think of the emergent ontology of worlds and branches; how are we to understand probability when all outcomes occur? But problems of this kind arise across all physical theories. Probability is philosophically contested even apart from Everett, for instance: is it frequency, rational credence, symmetry or something else? In any case, these problems pose no barrier to the use of Everettian ideas in physics.

The case for the Everett interpretation is that it is the conservative, literal reading of the version of quantum mechanics we actually use in modern physics, and there is no scientific pressure for us to abandon that reading. We could, of course, look for alternatives. Who knows what we might find? Or we could shut up and calculate – within the Everett interpretation. ●

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The Everett interpretation is just the decoherent view taken fully seriously

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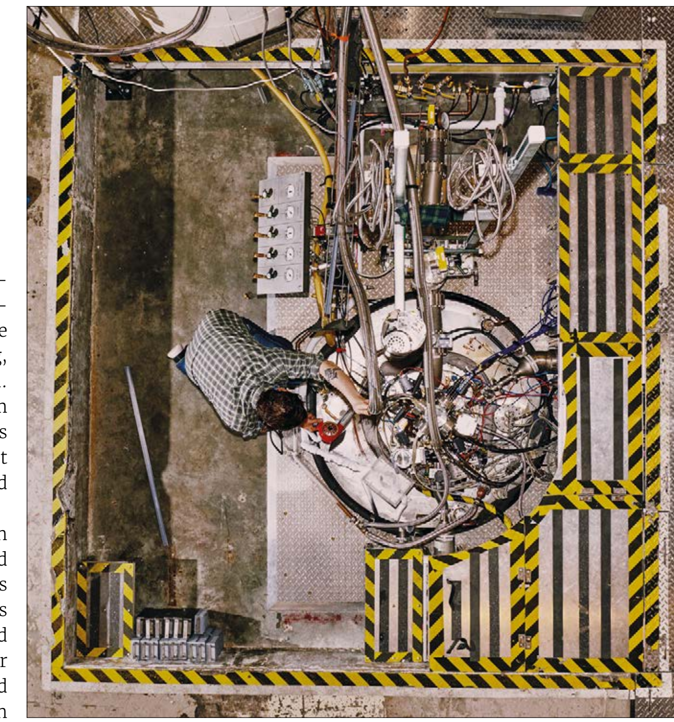
SENSING AT QUANTUM LIMITS

Quantum sensors have become important tools in low-energy particle physics. Michael Doser explores opportunities to exploit their unparalleled precision at higher energies.



T Luong

Quantum sensitivity *The Axion Dark Matter Experiment (ADMX) searches for ultra-light bosonic dark matter in the 1 to 40 μeV mass range by detecting possible conversions of axions into microwave photons inside a high-quality-factor superconducting cavity. Quantum-limited amplifiers, cooled to millikelvin temperatures, push the detector's sensitivity toward the limits set by quantum measurement noise.*

Atomic energy levels. Spin orientations in a magnetic field. Resonant modes in cryogenic, high-quality-factor radio-frequency cavities. The transition from superconducting to normal conducting, triggered by the absorption of a single infrared photon. These are all simple yet exquisitely sensitive quantum systems with discrete energy levels. Each can serve as the foundation for a quantum sensor – instruments that detect single photons, measure individual spins or record otherwise imperceptible energy shifts.

Over the past two decades, quantum sensors have taken on leading roles in the search for ultra-light dark matter and in precision tests of fundamental symmetries. Examples include the use of atomic clocks to probe whether Earth is sweeping through oscillating or topologically structured dark-matter fields, and cryogenic detectors to search for electric dipole moments – subtle signatures that could reveal new sources of CP violation. These areas have seen rapid progress, as challenges related to detector size, noise, sensitivity and complexity have been steadily overcome, opening new phase space in which to search for physics beyond the Standard Model. Could high-energy particle physics benefit next?

Low-energy particle physics

Most of the current applications of quantum sensors are at low energies, where their intrinsic sensitivity and characteristic energy scales align naturally with the phenomena being probed. For example, within the Project 8 experiment at the University of Washington, superconducting sensors are being developed to tackle a longstanding challenge: to distinguish the tiny mass of the neutrino from zero (see "Quantum-noise limited" image, p32). Inward-looking phased arrays of quantum-noise-limited microwave receivers allow spectroscopy of cyclotron radiation from beta-decay electrons as they spiral in a magnetic field. The shape of the endpoint of the spectrum is sensitive to the mass of the neutrino and such sensors have the potential to be sensitive to neutrino masses as low as 40 meV.

Beyond the Standard Model, superconducting sensors play a central role in the search for dark matter. At the lowest mass scales (peV to meV), experiments search for ultralight bosonic dark-matter candidates such as axions and axion-like particles (ALPs) through excitations of the vacuum field inside high-quality-factor microwave and millimetre-wave cavities (see "Quantum sensitivity" image above). In the meV range, light-shining-through-wall experiments aim to reveal brief oscillations into weakly coupled hidden-sector particles such as dark photons or ALPs, and may employ quantum sensors for detecting reappearing photons, depending on the detection strategy. In the MeV to sub-GeV mass range, superconducting sensors are used to detect individual photons and phonons in cryogenic scintillators, enabling sensitivity to

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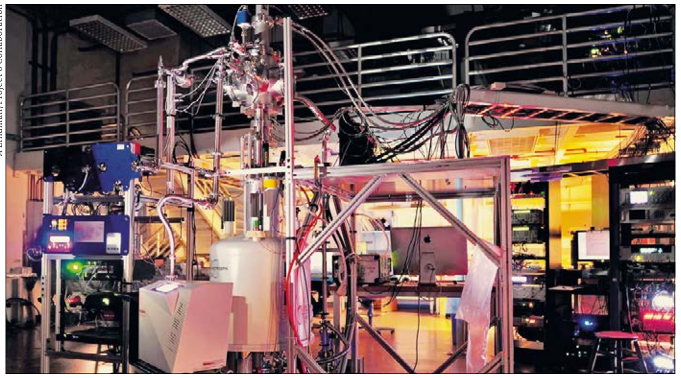


Quantum-noise limited *In a bid to measure the mass of the neutrino, the Project 8 collaboration uses superconducting sensors to study the endpoint of beta-decay spectra.*

dark-matter interactions via electron recoils. At higher masses, reaching into the GeV regime, superfluid helium detectors target nuclear recoils from heavier dark matter particles such as WIMPs.

These technologies also find broad application beyond fundamental physics. For example, in superconducting and other cryogenic sensors, the ability to detect single quanta with high efficiency and ultra-low noise is essential. The same capabilities are the technological foundation of quantum communication.

Raising the temperature

While many superconducting quantum sensors require ultra-low temperatures of a few mK, some spin-based quantum sensors can function at or near room temperature. Spin-based sensors, such as nitrogen-vacancy (NV) centres in diamonds and polarised rubidium atoms, are excellent examples.

NV centres are defects in the diamond lattice where a missing carbon atom – the vacancy – is adjacent to a lattice site where a carbon atom has been replaced by a nitrogen atom. The electronic spin states in NV centres have unique energy levels that can be probed by laser excitation and detection of spin-dependent fluorescence.

Rubidium is promising for spin-based sensors because it has unpaired electrons. In the presence of an external magnetic field, its atomic energy levels are split by the Zeeman effect. When optically pumped with laser light, spin-polarised "dark" sublevels – those not excited by the light – become increasingly populated. These aligned spins precess in magnetic fields, forming the basis of atomic magnetometers and other quantum sensors.

Researchers are increasingly exploring how quantum-control techniques can be integrated into high-energy-physics detectors

Being exquisite magnetometers, both devices make promising detectors for ultralight bosonic dark-matter candidates such as axions. Fermion spins may interact with spatial or temporal gradients of the axion field, leading to tiny oscillating energy shifts. The coupling of axions to gluons could also show up as an oscillating nuclear electric dipole moment. These interactions could manifest as oscillating energy-level shifts in NV centres, or as time-varying NMR-like spin precession signals in the atomic magnetometers.

Large-scale detectors

The situation is completely different in high-energy physics detectors, which require numerous interactions between a particle and a detector. Charged particles cause many ionisation events, and when a neutral particle interacts it produces charged particles that result in similarly numerous ionisations. Even if quantum control were possible within individual units of a massive detector, the number of individual quantum sub-processes to be monitored would exceed the possibilities of any realistic device.

Increasingly, however, researchers are exploring how quantum-control techniques – such as manipulating individual atoms or spins using lasers or microwaves – can be integrated into high-energy-physics detectors. These methods could enhance detector sensitivity, tune detector response or enable entirely new ways of measuring particle properties. While these quantum-enhanced or hybrid detection approaches are still in their early stages, they hold significant promise.

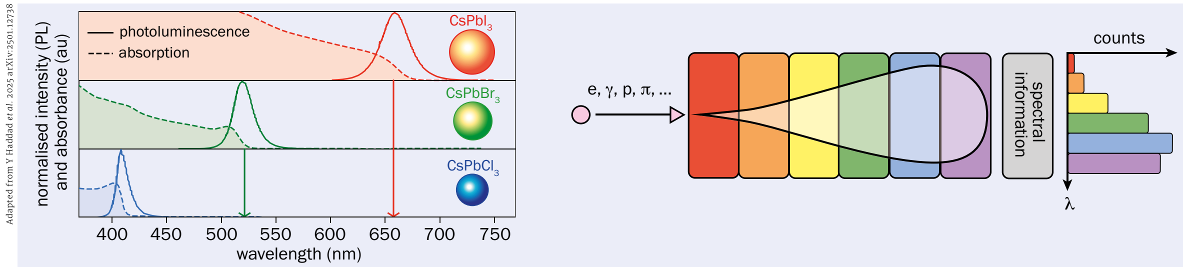
Quantum dots

Quantum dots are nanoscale semiconductor crystals – typically a few nanometres in diameter – that confine charge carriers (electrons and holes) in all three spatial dimensions. This quantum confinement leads to discrete, atom-like energy levels and results in optical and electronic properties that are highly tunable with size, shape and composition. Originally studied for their potential in optoelectronics and biomedical imaging, quantum dots have more recently attracted interest in high-energy physics due to their fast scintillation response, narrow-band emission and tunability. Their emission wavelength can be precisely controlled through nanostructuring, making them promising candidates for engineered detectors with tailored response characteristics.

While their radiation hardness is still under debate and needs to be resolved, engineering their composition, geometry, surface and size can yield very narrow-band (20 nm) emitters across the optical spectrum and into the infrared. Quantum dots such as these could enable the design of a "chromatic calorimeter": a stack of quantum-dot layers, each tuned to emit at a distinct wavelength; for example red in the first layer, orange in the second and progressing through the visible spectrum to violet. Each layer would absorb higher energy photons quite broadly but emit light in a narrow spectral band. The intensity of each colour would then correspond to the energy absorbed in that layer, while the emission wavelength would encode the position of energy deposition, revealing the shower shape (see "Chromatic calorimetry" figure). Because each layer is optically distinct, hermetic isolation would be unnecessary, reducing the overall material budget.

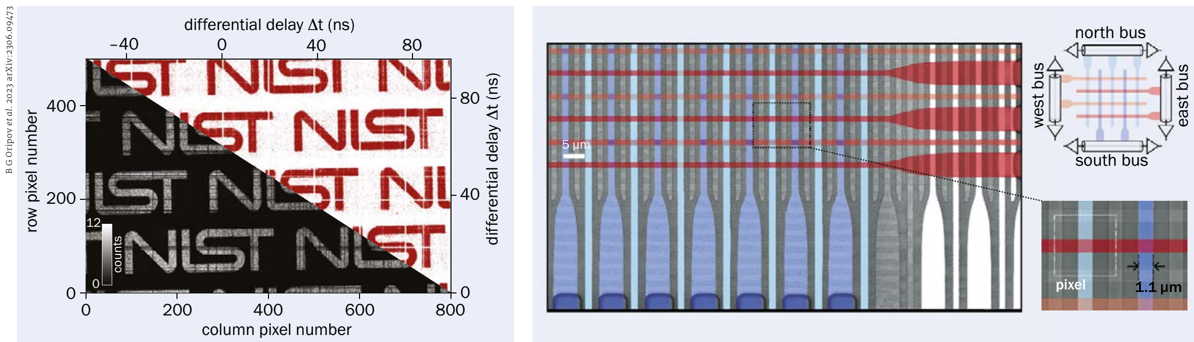
Rather than improving the energy resolution of existing calorimeters, quantum dots could provide additional information on the shape and development of particle showers if embedded in existing scintillators. Initial simulations and beam tests by CERN's Quantum Technology Initiative (QTI) support the hypothesis that the spectral intensity of quantum-dot emission can carry information about the energy and species of incident particles. Ongoing work

Adapted from Y Haddad *et al.* 2025 arXiv:2501.12738



Chromatic calorimetry *Left: the absorption (dashed lines) and emission (solid lines) spectra of quantum dots depend on their composition, geometry, surface treatment and size, with smaller dots (~2 nm) emitting blue light and larger dots (~4 nm) emitting red light. Right: a novel calorimeter could be designed by stacking materials embedded with different sized, narrow-band quantum dots adjacent to a spectrally sensitive photon detector.*

B G Oripov *et al.* 2023 arXiv:2306.09473



Single-photon phase transitions *Left: a sample image taken at 370 nm by a large-scale superconducting-nanowire single-photon detector pixel array with multi-bus readout. Raw time-delay (red) and binned (black and white) data is shown across 400,000 (800 × 500) pixels. Right: a false-colour scanning electron micrograph of a corner of the sensor shows bus connections alongside a simplified schematic (top right) and a zoom into a single 5 × 5 μm pixel (inset). The sensor operates by registering when individual photons induce nanowires to change state from superconducting to normal conducting.*

aims to explore their capabilities and limitations.

Beyond calorimetry, quantum dots could be formed within solid semiconductor matrices, such as gallium arsenide, to form a novel class of "photonic trackers". Scintillation light from electronically tunable quantum dots could be collected by photodetectors integrated directly on top of the same thin semiconductor structure, such as in the DoTPiX concept. Thanks to a highly compact, radiation-tolerant scintillating pixel tracking system with intrinsic signal amplification and minimal material budget, photonic trackers could provide a scintillation-light-based alternative to traditional charge-based particle trackers.

Living on the edge

Low temperatures also offer opportunities at scale – and cryogenic operation is a well-established technique in both high-energy and astroparticle physics, with liquid argon (boiling point 87 K) widely used in time projection chambers and some calorimeters, and some dark-matter experiments using liquid helium (boiling point 4.2 K) to reach even lower temperatures. A range of solid-state detectors, including superconducting sensors, operate effectively at these temperatures and below, and offer significant advantages in sensitivity and energy resolution.

Magnetic microcalorimeters (MMCs) and transition-edge sensors (TESs) operate in the narrow temperature range where a superconducting material undergoes a rapid transition from zero resistance to finite values. When a particle deposits energy in an MMC or TES, it slightly raises the temperature, causing a measurable increase in resistance. Because the transition is extremely steep, even a tiny temperature change leads to a detectable resistance change, allowing precise calorimetry.

Functioning at millikelvin temperatures, TESs provide much higher energy resolution than solid-state detectors made from high-purity germanium crystals, which work by collecting electron–hole pairs created when ionising radiation interacts with the crystal lattice. TESs are increasingly used in high-resolution X-ray spectroscopy of pionic, muonic or antiprotonic atoms, and in photon detection for observational astronomy, despite the technical challenges associated with maintaining ultra-low operating temperatures.

By contrast, superconducting nanowire and microwire single-photon detectors (SNSPDs and SMSPDs) register only a change in state – from superconducting to normal conducting – allowing them to operate at higher temperatures than traditional low-temperature sensors. When made from high-critical-temperature (T_c) superconductors, operation at temperatures as high as 10 K is feasible, while maintaining excellent sensitivity to energy deposited by charged particles and ultrafast switching times on the order of a few picoseconds. Recent advances include the development of large-area devices with up to 400,000 micron-scale pixels (see "Single-photon phase transitions" figure), fabrication of high-T_c SNSPDs and successful beam tests of SMSPDs. These technologies are promising candidates for detecting milli-charged particles – hypothetical particles arising in "hidden sector" extensions of the Standard Model – or for high-rate beam monitoring at future colliders.

Partnering with neighbouring fields such as quantum computing, quantum communication and manufacturing is of paramount importance

Rugged, reliable and reproducible

Quantum sensor-based experiments have vastly expanded the phase space that has been searched for new physics. This is just the beginning of the journey, as larger-scale efforts build on the initial gold rush and new quantum devices are developed, perfected and brought to bear on the many open questions of particle physics.

To fully profit from their potential, a vigorous R&D programme is needed to scale up quantum sensors for future detectors. Ruggedness, reliability and reproducibility are key – as well as establishing "proof of principle" for the numerous imaginative concepts that have already been conceived. Challenges range from access to test infrastructures, to standardised test protocols for fair comparisons. In many cases, the largest challenge is to foster an open exchange of ideas given the numerous local developments that are happening worldwide. Finding a common language to discuss developments in different fields that at first glance may have little in common, builds on a willingness to listen, learn and exchange.

The European Committee for Future Accelerators (ECFA) detector R&D roadmap provides a welcome framework for addressing these challenges collaboratively through the Detector R&D (DRD) collaborations established in 2023 and now coordinated at CERN. Quantum sensors and emerging technologies are covered within the DRD5 collaboration, which ties together 112 institutes worldwide, many of them leaders in their particular field. Only a third stem from the traditional high-energy physics community.

These efforts build on the widespread expertise and enthusiastic efforts at numerous institutes and tie in with the quantum programmes being spearheaded at high-energy-physics research centres, among them CERN's QTI. Partnering with neighbouring fields such as quantum computing, quantum communication and manufacturing is of paramount importance. The best approach may prove to be "targeted blue-sky research": a willingness to explore completely novel concepts while keeping their ultimate usefulness for particle physics firmly in mind. ●

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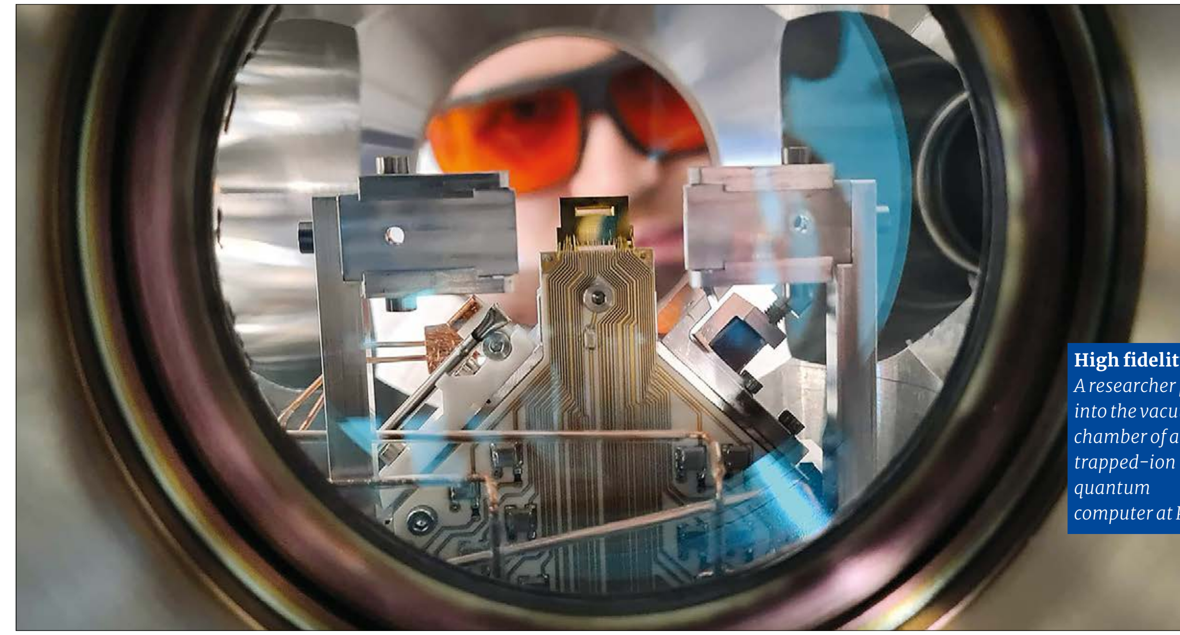

High fidelity *A researcher peers into the vacuum chamber of a trapped-ion quantum computer at PSI.*

QUANTUM SIMULATORS IN HIGH-ENERGY PHYSICS

From black-hole evaporation to neutron-star interiors, extreme environments and complex dynamics often outpace even the most powerful supercomputers. Enrique Rico Ortega and Sofia Vallecorsa explain how quantum computing will change that.

In 1982 Richard Feynman posed a question that challenged computational limits: can a classical computer simulate a quantum system? His answer: not efficiently. The complexity of the computation increases rapidly, rendering realistic simulations intractable. To understand why, consider the basic units of classical and quantum information.

A classical bit can exist in one of two states: $|0\rangle$ or $|1\rangle$. A quantum bit, or qubit, exists in a superposition $\alpha|0\rangle + \beta|1\rangle$, where α and β are complex amplitudes with real and imaginary parts. This superposition is the core feature that distinguishes quantum bits and classical bits. While a classical bit is either $|0\rangle$ or $|1\rangle$, a quantum bit can be a blend of both at once. This is what gives quantum computers their immense parallelism – and also their fragility.

The difference becomes profound with scale. Two classical bits have four possible states, and are always in just one of them at a time. Two qubits simultaneously encode a complex-valued superposition of all four states.

Resources scale exponentially. N classical bits encode N boolean values, but N qubits encode 2^N complex amplitudes. Simulating 50 qubits with double-precision real numbers for each part of the complex amplitudes would require more than a petabyte of memory, beyond the reach of even the largest supercomputers.

Direct mimicry

Feynman proposed a different approach to quantum simulation. If a classical computer struggles, why not use one quantum system to emulate the behaviour of another? This was the conceptual birth of the quantum simulator: a device that harnesses quantum mechanics to solve quantum problems. For decades, this visionary idea remained in the realm of theory, awaiting the technological breakthroughs that are now rapidly bringing it to life. Today, progress in quantum hardware is driving two main approaches: analog and digital quantum simulation, in direct analogy to the history of classical computing.

In analog quantum simulators, the physical parameters of the simulator directly correspond to the parameters

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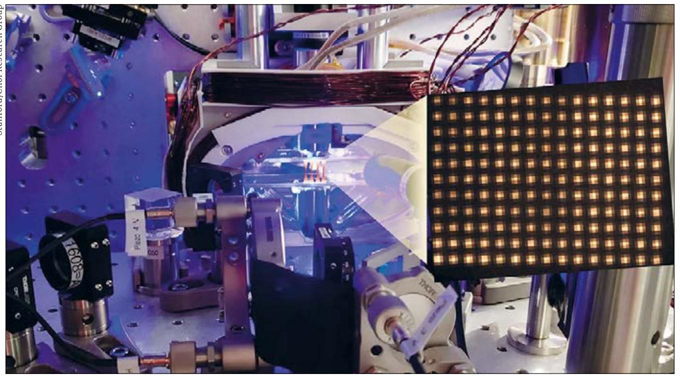

Optical tweezers *In this neutral-atom experiment at Stanford University, atoms are confined in a lattice by highly focused laser beams (see inset).*

A philosophical dimension

The discretisation of space by quantum simulators echoes the rise of lattice QCD in the 1970s and 1980s. Confronted with the non-perturbative nature of the strong interaction, Kenneth Wilson introduced a method to discretise spacetime, enabling numerical solutions to quantum chromodynamics beyond the reach of perturbation theory. Simulations on classical supercomputers have since deepened our understanding of quark confinement and hadron masses, catalysed advances in high-performance computing, and inspired international collaborations. It has become an indispensable tool in particle physics (see p7).

In classical lattice QCD, the discretisation of spacetime is just a computational trick – a means to an end. But in quantum simulators this discretisation becomes physical. The simulator is a quantum system governed by the same fundamental laws as the target theory.

This raises a philosophical question: are we merely modelling the target theory or are we, in a limited but genuine sense, realising it? If an array of neutral atoms faithfully mimics the dynamical behaviour of a specific gauge theory, is it "just" a simulation, or is it another manifestation of that theory's fundamental truth? Feynman's original proposal was, in a sense, about using nature to compute itself. Quantum simulators bring this abstract notion into concrete laboratory reality.

of the quantum system being studied. Think of it like a wind tunnel for aeroplanes: you are not calculating air resistance on a computer but directly observing how air flows over a model.

A striking example of an analog quantum simulator traps excited Rydberg atoms in precise configurations using highly focused laser beams known as "optical tweezers". Rydberg atoms have one electron excited to an energy level far from the nucleus, giving them an exaggerated electric dipole moment that leads to tunable long-range dipole–dipole interactions – an ideal setup for simulating particle interactions in quantum field theories (see "Optical tweezers" figure).

The positions of the Rydberg atoms discretise the space inhabited by the quantum fields being modelled. At each point in the lattice, the local quantum degrees of freedom of the simulated fields are embodied by the internal states of the atoms. Dipole–dipole interactions simulate the dynamics of the quantum fields. This technique has been used to observe phenomena such as string breaking, where the force between particles pulls so strongly that the vacuum spontaneously creates new particle–antiparticle pairs. Such quantum simulations model processes that are notoriously difficult to calculate from first principles using classical computers (see "A philosophical dimension" panel).

Universal quantum computation

Digital quantum simulators operate much like classical digital computers, though using quantum rather than classical logic gates. While classical logic manipulates classical bits, quantum logic manipulates qubits. Because quantum logic gates obey the Schrödinger equation, they preserve information and are reversible, whereas most classical gates, such as "AND" and "OR", are irreversible. Many quantum gates have no classical equivalent, because they manipulate phase, superposition or entanglement – a uniquely quantum phenomenon in which two or more qubits share a combined state. In an entangled system, the state of each qubit cannot be described independently of the others, even if they are far apart: the global description of the quantum state is more than the combination of the local information at every site.

By applying sequences of quantum logic gates, a digital quantum computer can model the time evolution of any target quantum system. This makes them flexible and scalable in pursuit of universal quantum computation – logic able to run any algorithm allowed by the laws of quantum mechanics, given enough qubits and sufficient time. Universal quantum computing requires only a small subset of the many quantum logic gates that can be conceived, for example Hadamard, T and CNOT. The Hadamard gate creates a superposition: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$. The T gate applies a 45° phase rotation: $|1\rangle \rightarrow e^{i\pi/4}|1\rangle$. And the CNOT gate entangles qubits by flipping a target qubit if a control qubit is $|1\rangle$. These three suffice to prepare any quantum state from a trivial reference state: $|\psi\rangle = U_1 U_2 U_3 \ldots U_N |0000\ldots000\rangle$.

To bring frontier physics problems within the scope of current quantum computing resources, the distinction between analog and digital quantum simulations is often blurred. The complexity of simulations can be reduced by combining digital gate sequences with analog quantum hardware that aligns with the interaction patterns relevant to the target problem. This is feasible as quantum logic gates usually rely on native interactions similar to those used in analog simulations. Rydberg atoms are a common choice. Alongside them, two other technologies are becoming increasingly dominant in digital quantum simulation: trapped ions and superconducting qubit arrays.

Trapped ions offer the greatest control. Individual charged ions can be suspended in free space using electromagnetic fields. Lasers manipulate their quantum states, inducing interactions between them. Trapped-ion systems are renowned for their high fidelity (meaning operations are accurate) and long coherence times (meaning they maintain their quantum properties for longer), making them excellent candidates for quantum simulation (see "Trapped ions" figure).

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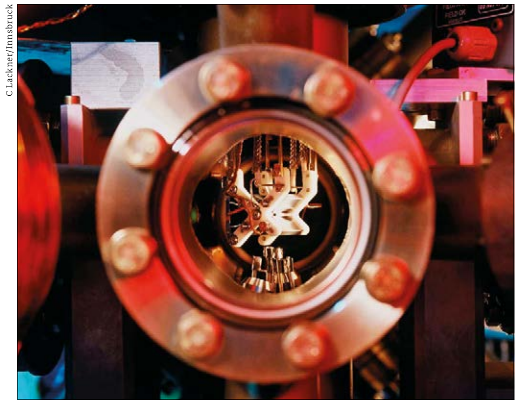


Trapped ions *A quantum simulator at the University of Innsbruck.*

Superconducting qubit arrays promise the greatest scalability. These tiny superconducting circuit materials act as qubits when cooled to extremely low temperatures and manipulated with microwave pulses. This technology is at the forefront of efforts to build quantum simulators and digital quantum computers for universal quantum computation (see "Superconducting qubits" figure).

The noisy intermediate-scale quantum era

Despite rapid progress, these technologies are at an early stage of development and face three main limitations.

The first problem is that qubits are fragile. Interactions with their environment quickly compromise their superposition and entanglement, making computations unreliable. Preventing "decoherence" is one of the main engineering challenges in quantum technology today.

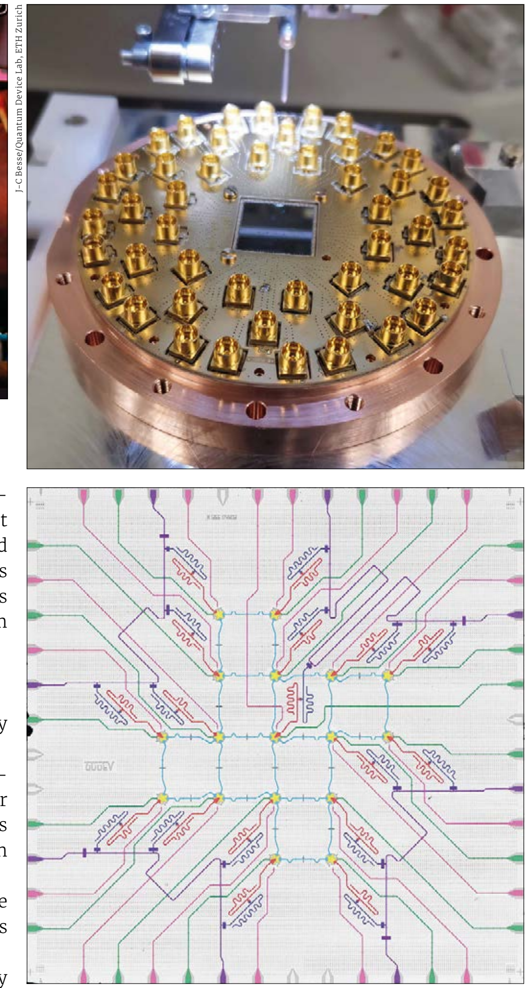
The second challenge is that quantum logic gates have low fidelity. Over a long sequence of operations, errors accumulate, corrupting the result.

Finally, quantum simulators currently have a very limited number of qubits – typically only a few hundred. This is far fewer than what is needed for high-energy physics (HEP) problems.

This situation is known as the noisy "intermediate-scale" quantum era: we are no longer doing proof-of-principle experiments with a few tens of qubits, but neither can we control thousands of them. These limitations mean that current digital simulations are often restricted to "toy" models, such as QED simplified to have just one spatial and one time dimension. Even with these constraints, small-scale devices have successfully reproduced non-perturbative aspects of the theories in real time and have verified the preservation of fundamental physical principles such as gauge invariance, the symmetry that underpins the fundamental forces of the Standard Model.

Quantum simulators may chart a similar path to classical lattice QCD, but with even greater reach. Lattice QCD struggles with real-time evolution and finite-density physics due to the infamous "sign problem", wherein quantum interference between classically computed amplitudes causes exponentially worsening signal-to-noise ratios.

J-C Besse/Quantum Device Lab, ETH Zurich



Superconducting qubits *A 17-qubit quantum computer at ETH Zurich (top). A schematic of the printed circuit board (black square) is shown on the schematic above, where qubits (yellow) are connected by wires that control the qubits by generating microwave pulses (red and blue lines). The gold ports in the photograph connect signal lines to the outside of the chip. During operation, the device is suspended below a cryostat and cooled to 10 mK.*

This renders some of the most interesting problems unsolvable on classical machines.

Quantum simulators do not suffer from the sign problem because they evolve naturally in real-time, just like the physical systems they emulate. This promises to open new frontiers such as the simulation of early-universe dynamics, black-hole evaporation and the dense interiors of neutron stars.

Quantum simulators will powerfully augment traditional theoretical and computational methods, offering profound insights when Feynman diagrams become intractable, when dealing with real-time dynamics and

Quantum simulators will powerfully augment traditional theoretical and computational methods

when the sign problem renders classical simulations exponentially difficult. Just as the lattice revolution required decades of concerted community effort to reach its full potential, so will the quantum revolution, but the fruits will again transform the field. As the aphorism attributed to Mark Twain goes: history never repeats itself, but it often rhymes.

Quantum information

One of the most exciting and productive developments in recent years is the unexpected, yet profound, convergence between HEP and quantum information science (QIS). For a long time these fields evolved independently. HEP explored the universe's smallest constituents and grandest structures, while QIS focused on harnessing quantum mechanics for computation and communication. One of the pioneers in studying the interface between these fields was John Bell, a theoretical physicist at CERN.

Just as the lattice revolution needed decades of concerted community effort to reach its full potential, so will the quantum revolution

HEP and QIS are now deeply intertwined. As quantum simulators advance, there is a growing demand for theoretical tools that combine the rigour of quantum field theory with the concepts of QIS. For example, tensor networks were developed in condensed-matter physics to represent highly entangled quantum states, and have now found surprising applications in lattice gauge theories and "holographic dualities" between quantum gravity and quantum field theory. Another example is quantum error correction – a vital QIS technique to protect fragile quantum information from noise, and now a major focus for quantum simulation in HEP.

This cross-disciplinary synthesis is not just conceptual; it is becoming institutional. Initiatives like the US Department of Energy's Quantum Information Science Enabled Discovery (QuantISED) programme, CERN's Quantum Technology Initiative (QTI) and Europe's Quantum Flagship are making substantial investments in collaborative research. Quantum algorithms will become indispensable for theoretical problems just as quantum sensors are becoming indispensable to experimental observation (see p31).

The result is the emergence of a new breed of scientist: one equally fluent in the fundamental equations of particle physics and the practicalities of quantum hardware. These "hybrid" scientists are building the theoretical and computational scaffolding for a future where quantum simulation is a standard, indispensable tool in HEP. ●

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Quantum culture

Kanta Dihal explores why quantum mechanics captures the imagination of writers – and how 'quantum culture' affects the public understanding of science.

How has quantum mechanics influenced culture in the last 100 years?
Quantum physics offers an opportunity to make the impossible seem plausible. For instance, if your superhero dies dramatically but the actor is still on the payroll, you have a few options available. You could pretend the hero miraculously survived the calamity of the previous instalment. You could also pretend the events of the previous instalment never happened. And then there is *Star Wars*: "Somehow, Palpatine returned."

These days, however, quantum physics tends to come to the rescue. Because quantum physics offers the wonderful option to maintain that all previous events really happened, and yet your hero is still alive… in a parallel universe. Much is down to the remarkable cultural impact of the many-worlds interpretation of quantum physics, which has been steadily growing in fame (or notoriety) since Hugh Everett introduced it in 1957.

Is quantum physics unique in helping fiction authors make the impossible seem possible?
Not really! Before the "quantum" handwave, there was "nuclear": think of Dr Atomic from *Watchmen*, or *Godzilla*, as expressions of the utopian and dystopian expectations of that newly discovered branch of science. Before nuclear, there was electricity, with Frankenstein's monster as perhaps its most important product. We can go all the way back to the invention of hydraulics in the ancient world, which led to an explosion of tales of liquid-operated automata – early forms of artificial intelligence – such as the bronze soldier Talos in ancient Greece. We have always used our latest discoveries to dream of a future in which our ancient tales of wonder could come true.

K Dihal

Sociology of science *Kanta Dihal is a lecturer in science communication at Imperial College London. An expert in the cultural narratives of science and technology, she is currently researching the impact of quantum mechanics on popular culture.*

Is the many-worlds interpretation the most common theory used in science fiction inspired by quantum mechanics?
Many-worlds has become Marvel's favourite trope. It allows them to expand on an increasingly entangled web of storylines that borrow from a range of remakes and reboots, as well as introducing gender and racial diversity into old stories. Marvel may have mainstreamed this interpretation, but the viewers of the average blockbuster may not realise exactly how niche it is, and how many alternatives there are. With many interpretations vying for acceptance, every once in a while a brave social scientist ventures to survey quantum-physicists' preferences. These studies tend to confirm the dominance of the Copenhagen interpretation, with its collapse of the wavefunction rather than the branching universes characteristic of the Everett interpretation. In a 2016 study, for instance, only 6% of quantum physicists claimed that Everett was their favourite interpretation. In 2018 I looked through a stack of popular quantum-physics books published between 1980 and 2017, and found that more than half of these books endorse the many-worlds interpretation. A non-physicist might be forgiven for thinking that quantum physicists are split between two equal-sized enemy camps of Copenhagenists and Everettians.

What makes the many-worlds interpretation so compelling?
Answering this brings us to a fundamental question that fiction has enjoyed exploring since humans first told each other stories: what if? "What if the Nazis won the Second World War?" is pretty much an entire genre by itself these days. Before that, there were alternate histories of the American Civil War and many other key historical events. This means that the many-worlds interpretation fits smoothly into an existing narrative genre. It suggests that these alternate histories may be real, that they are potentially accessible to us and simply happening in a different dimension. Even the specific idea of branching alternative universes existed in fiction before Hugh Everett applied it to quantum mechanics. One famous example is the 1941 short story *The Garden of Forking Paths* by the Argentinian writer Jorge Luis Borges, in which a writer tries to create a novel in which everything that could happen, happens. His story anticipated the many-worlds interpretation so closely that Bryce DeWitt used an extract from it as the epigraph to his 1973 edited collection *The Many-Worlds Interpretation of*

Quantum Mechanics. But the most uncanny example is, perhaps, Andre Norton's science-fiction novel *The Crossroads of Time*, from 1956 – published when Everett was writing his thesis. In her novel, a group of historians invents a "possibility worlds" theory of history. The protagonist, Blake Walker, discovers that this theory is true when he meets a group of men from a parallel universe who are on the hunt for a universe-travelling criminal. Travelling with them, Blake ends up in a world where Hitler won the Battle of Britain. Of course, in fiction, only worlds in which a significant change has taken place are of any real interest to the reader or viewer. (Blake also visits a world inhabited by metal dinosaurs.) The truly uncountable number of slightly different universes Everett's theory implies are extremely difficult to get our heads around. Nonetheless, our storytelling mindsets have long primed us for a fascination with the many-worlds interpretation.

Have writers put other interpretations to good use?

For someone who really wants to put their physics degree to use in their spare time, I'd recommend the works of Greg Egan: although his novel *Quarantine* uses the controversial conscious collapse interpretation, he always ensures that the maths checks out. Egan's attitude towards the scientific content of his novels is best summed up by a quote on his blog: "A few reviewers complained that they had trouble keeping straight [the science of his novel *Incandescence*]. This leaves me wondering if they've really never encountered a book that benefits from being read with a pad of paper and a pen beside it, or whether they're just so hung up on the idea that only non-fiction should be accompanied by note-taking and diagram-scribbling that it never even occurred to them to do this."

What other quantum concepts are widely used and abused?

We have Albert Einstein to thank for the extremely evocative description of quantum entanglement as "spooky action at a distance". As with most scientific phenomena, a catchy nickname such as this one is extremely effective for getting a concept to stick in the popular imagination. While Einstein himself did not initially believe quantum entanglement could be a real phenomenon, as it would violate local causality, we now have both evidence and applications of entanglement in the real world, most notably in quantum cryptography. But in science fiction, the most common application of quantum entanglement is in faster-than-light communication. In her 1966 novel *Rocannon's World*, Ursula K Le Guin describes a device called the "ansible", which interstellar travellers use to instantaneously communicate with each other across vast distances. Her term was so influential that it now regularly appears in science fiction as a widely accepted name for a faster-than-light communications device, the same way we have adopted the word "robot" from the 1920 play *R.U.R.* by Karel Čapek.

Fiction may get the science wrong, but that is often because the story it tries to tell existed long before the science

How were cultural interpretations of entanglement influenced by the development of quantum theory?

It wasn't until the 1970s that no-signalling theorems conclusively proved that entanglement correlations, while instantaneous, cannot be controlled or used to send messages. Explaining why is a lot more complex than communicating the notion that observing a particle here has an effect on a particle there. Once again, quantum physics seemingly provides just enough scientific justification to resolve an issue that has plagued science fiction ever since the speed of light was discovered: how can we travel through space, exploring galaxies, settling on distant planets, if we cannot communicate with each other? This same line of thought has sparked another entanglement-related invention in fiction: what if we can send not just messages but also people, or even entire spaceships, across faster-than-light distances using entanglement? Conveniently, quantum physicists had come up with another extremely evocative term that fit this idea perfectly: quantum teleportation. Real quantum teleportation only transfers information. But the idea of teleportation is so deeply embedded in our storytelling past that we can't help extrapolating it. From stories of gods that could appear anywhere at will to tales of portals that lead to strange new worlds, we have always felt limited by the speeds of travel we have managed to achieve – and once again, the speed of light seems to be a hard limit that quantum teleportation might be able to get us around. In his 2003 novel *Timeline*, Michael Crichton sends a group of researchers back in time using quantum teleportation, and the videogame *Half-Life 2* contains teleportation devices that similarly seem to work through quantum entanglement.

What quantum concepts have unexplored cultural potential?

Clearly, interpretations other than many worlds have a PR problem, so is anyone willing to write a chart topper based on the relational interpretation or QBism? More generally, I think that any question we do not yet have an answer to, or any theory that remains untestable, is a potential source for an excellent story. Richard Feynman famously said, "I think I can safely say that nobody understands quantum mechanics." Ironically, it is precisely because of this that quantum physics has become such a widespread building block of science fiction: it is just hard enough to understand, just unresolved and unexplained enough to keep our hopes up that one day we might discover that interstellar communication or inter-universe travel might be possible. Few people would choose the realities of theorising over these ancient dreams. That said, the theorising may never have happened without the dreams. How many of your colleagues are intimately acquainted with the very science fiction they criticise for having unrealistic physics? We are creatures of habit and convenience held together by stories, physicists no less than everyone else. This is why we come up with catchy names for theories, and stories about dead-and-alive cats. Fiction may often get the science wrong, but that is often because the story it tries to tell existed long before the science.

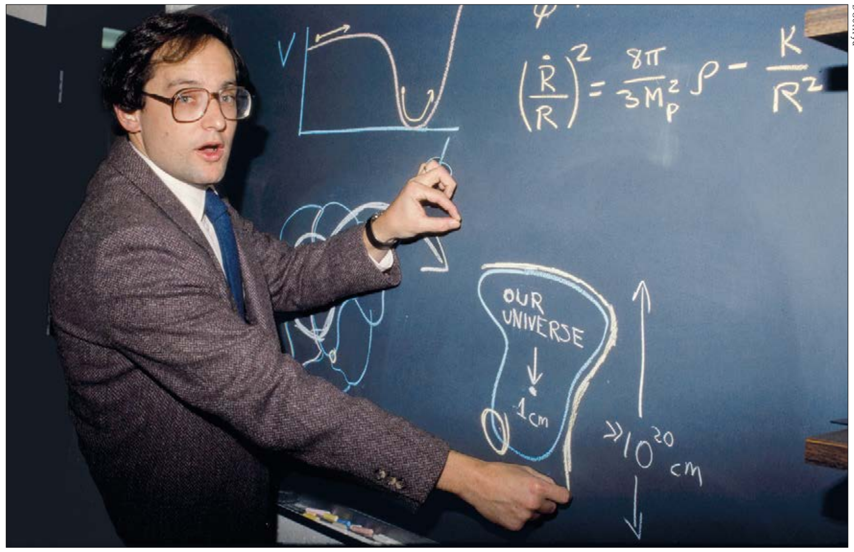
OPINION REVIEWS

The battle of the Big Bang

Battle of the Big Bang: The New Tales of Our Cosmic Origins

By Niayesh Afshordi and Phil Halper

University of Chicago Press



Originator turned sceptic *Paul Steinhardt, pictured here at the University of Pennsylvania in the 1980s, today argues that cosmic inflation has become so adaptable that it can be adjusted to accommodate any observational outcome.*

As Arthur Koestler wrote in his seminal 1959 work *The Sleepwalkers*, "The history of cosmic theories … may without exaggeration be called a history of collective obsessions and controlled schizophrenias; and the manner in which some of the most important individual discoveries were arrived at, reminds one more of a sleepwalker's performance than an electronic's brain." Koestler's trenchant observation about the state of cosmology in the first half of the 20th century is perhaps even more true of cosmology in the first half of the 21st, and *Battle of the Big Bang: The New Tales of Our Cosmic Origins* provides an entertaining – and often refreshingly irreverent – update on the state of current collective obsessions and controlled schizophrenias in cosmology's effort to understand the origin of the universe. The product of a collaboration between a working cosmologist (Afshordi) and a science communicator (Halper), *Battle of the Big Bang* tells the story of our modern efforts to comprehend the nature of the first moments of time, back to the moment of the Big Bang and even before.

Rogues' gallery

The story told by the book combines lucid explanations of a rogues' gallery of modern cosmological theories, some astonishingly successful, others less so, interspersed with anecdotes culled from Halper's numerous interviews with key players in the game. These stories of the real people behind the theories add humanistic depth to the science, and the balance between Halper's engaging storytelling and Afshordi's steady-handed illumination of often esoteric scientific ideas is mostly a winning combination; the book is readable, without sacrificing too much scientific depth. In this respect, *Battle of the Big Bang* is reminiscent of Dennis Overbye's 1991 *Lonely Hearts of the Cosmos*. As with Overbye's account of the famous conference-banquet fist fight between Rocky Kolb and Gary Steigman, there is no shortage here of renowned scientists behaving like children, and the "mean girls of cosmology" angle makes for an entertaining read. The story of University of North Carolina professor Paul Frampton getting catfished by cocaine smugglers posing as model Denise Milani and ending up in an Argentine prison, for example, is not one you see coming.

Afshordi and Halper ably lead the reader through a wild mosaic of alternative theories to inflation

A central conflict propelling the narrative is the longstanding feud between Andrei Linde and Alan Guth, both originators of the theory of cosmological inflation, and Paul Steinhardt, also an originator of the theory who later transformed into an apostate and bitter critic of the theory he helped establish.

Inflation – a hypothesised period of exponential cosmic expansion by more than 26 orders of magnitude that set the initial conditions for the hot Big Bang – is the gorilla in the room, a hugely successful theory that over the past several decades has racked up win after win when confronted by modern precision cosmology. Inflation is rightly considered by most cosmologists to be a central part of the "standard" cosmology, and its status as a leading theory inevitably makes it a target of critics like Steinhardt, who argue that inflation's inherent flexibility means that it is not a scientific theory at all. Inflation is introduced early in the book, and for the remainder, Afshordi and Halper ably lead the reader through a wild mosaic of alternative theories to inflation: multiverses, bouncing universes, new universes birthed from within black holes, extra dimensions, varying light speed and "mirror" universes with reversed time all make appearances, a dizzying inventory of our most recent collective obsessions and schizophrenias.

In the later chapters, Afshordi describes some of his own efforts to formulate an alternative to inflation, and it is here that the book is at its strongest; the voice of a master of the craft confronting his own unconscious assumptions and biases makes for compelling reading. I have known Niayesh as a friend and colleague for more than 20 years. He is a fearlessly creative theorist with deep technical skill, but he has the heart of a rebel and a poet, ▷

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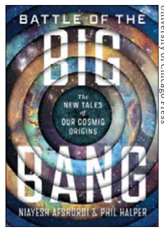
OPINION REVIEWS

and I found myself wishing that the book gave his unique voice more room to shine, instead of burying it beneath too many mundane pop-science tropes; the book could have used more of the science and less of the “science communication”. At times the pop-culture references come so thick that the reader feels as if he is having to shake them off his leg.



University of Chicago Press

Compelling arguments

Anyone who reads science blogs or follows science on social media is aware of the voices, some of them from within mainstream science and many from further out on the fringe, arguing that modern theoretical physics suffers from a rigid orthodoxy that serves to crowd out worthy alternative ideas to understand problems such as dark matter, dark energy and the unification of gravity with quantum mechanics. This has been the subject of several books such as Lee Smolin’s *The Trouble with Physics* and Peter Woit’s *Not Even Wrong*. A real value in *Battle of the Big Bang* is to provide a compelling counter-argument to that pessimistic narrative. In reality, ambitious scientists like nothing better than overturning a standard paradigm, and theorists have put the standard model of cosmology in the cross hairs with the gusto of assassins gunning for John Wick. Despite – or perhaps because of – its focus on conflict, this book ultimately paints a picture of a vital and healthy scientific process, a kind of controlled chaos, ripe with wild ideas, full of the clash of egos and littered with the ashes of failed shots at glory.

What the book is not is a reliable scholarly work on the history of science. Not only was the manuscript rather haphazardly copy-edited (the renowned Mount Palomar telescope, for example, is not “two hundred foot”, but in fact 200 *inches*), but the historical details are sometimes smoothed over to fit a coherent narrative rather than presented in their actual messy accuracy. While I do not doubt the anecdote of David Spergel saying “we’re dead”, referring to cosmic strings when data from the COBE satellite was first released, it was not COBE that killed cosmic strings. The blurry vision of COBE could accommodate either strings or inflation as the source of fluctuations in the cosmic microwave background (CMB), and it took a clearer view to make the distinction. The final nail in the coffin came from BOOMERanG nearly a decade later, with the observation of the second acoustic peak in the CMB. And it was not, as claimed here, BOOMERanG that provided the first evidence for a flat geometry to the cosmos; that happened a few years earlier, with the Saskatoon and CAT experiments.

The book makes a point of the premature death of Dave Wilkinson, when in fact he died at age 67, not (as is implied in the text) in his 50s. Wilkinson – who was my freshman physics professor – was a great scientist and a gifted teacher, and it is appropriate to memorialise him, but he had a long and productive career.

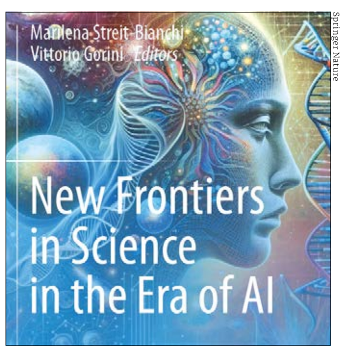
Besides these points of detail, there are some more significant omissions. The book relates the story of how the Ukrainian physicist Alex Vilenkin, blacklisted from physics and working as a zookeeper in Kharkiv, escaped the Soviet Union. Vilenkin moved to SUNY Buffalo, where I am currently a professor, because he had mistaken Mendel Sachs, a condensed matter theorist, for Ray Sachs, who originally predicted fluctuations in the CMB. It’s a funny story, and although the authors note that Vilenkin was blacklisted for refusing to be an informant for the KGB, they omit the central context that he was Jewish, one of many Jews banished from academic life by Soviet authorities who escaped the stifling anti-Semitism of the Soviet Union for scientific freedom in the West. This history resonates today in light of efforts by some scientists to boycott Israeli institutes and even blacklist Israeli colleagues. Unlike the minutiae of CMB physics, this matters, and *Battle of the Big Bang* should have been more careful to tell the whole story.

Will Kinney *University at Buffalo*.

New Frontiers in Science in the Era of AI

Edited by Marilena Streit-Bianchi and Vittorio Gorini

Springer Nature



Springer Nature

A broad and ambitious survey spanning particle physics, evolutionary biology, neuroscience and AI ethics

At a time when artificial intelligence is more buzzword than substance in many corners of public discourse, *New Frontiers in Science in the Era of AI* arrives with a clear mission: to contextualise AI within the long arc of scientific thought and current research frontiers. This book is not another breathless ode to ChatGPT or deep learning, nor a dry compilation of technical papers. Instead, it’s a broad and ambitious survey, spanning particle physics, evolutionary biology, neuroscience and AI ethics, that seeks to make sense of how emerging technologies are reshaping not only the sciences but knowledge and society more broadly.

The book’s chapters, written by established researchers from diverse fields, aim to avoid jargon while attracting non-specialists, without compromising depth. The book offers an insight into how physics remains foundational across scientific domains, and considers the social, ethical and philosophical implications of AI-driven science.

The first section, “New Physics World”, will be the most familiar terrain for physicists. Ugo Moschella’s essay, “What Are Things Made of? The History of Particles from Thales to Higgs”, opens with a sweeping yet grounded narrative of how metaphysical questions have persisted alongside empirical discoveries. He draws a bold parallel between the ancient idea of mass emerging from a cosmic vortex and the Higgs mechanism, a poetic analogy that holds surprising resonance. Thales, who lived roughly from 624 to 545 BCE, proposed that water is the fundamental substance out of which all others are formed. Following his revelation, Pythagoras and Empedocles added three more items to complete the list of the elements: earth, air and fire. Aristotle added a fifth element: the “aether”. The physical foundation of the standard cosmological model of the ancient world is then rooted in the Aristotelian conceptions of movement and gravity, argues Moschella. His essay lays the groundwork for future chapters that explore entanglement, computation and the transition from thought experiments to quantum technology and AI.

The second and third sections venture into evolutionary genetics, epigenetics (the study of heritable changes in gene expression) and neuroscience – areas more peripheral to physics, but timely nonetheless. Contributions by Eva Jablonka, evolutionary theorist and geneticist from Tel Aviv University, and Telmo Pievani, a biologist from the University of Padua, explore the biological implications of gene editing, environmental inheritance and self-directed evolution, as well as the ever-blurring boundaries between what is considered “natural” versus “artificial”. The authors propose that the human ability to edit genes is itself an evolutionary agent – a novel and unsettling idea, as this would be an evolution driven by a will and not by chance. Neuroscientist Jason D Runyan reflects compellingly on free will in the age of AI, blending empirical work with philosophical questions. These chapters enrich the central inquiry of what it means to be a “knowing agent”: someone who acts on nature according to its will, influenced by biological, cognitive and social factors. For physicists, the lesson may be less about adopting specific methods and more about recognising how their own field’s assumptions – about determinism, emergence or complexity – are echoed and challenged in the life sciences.

Perspectives on AI

The fourth section, “Artificial Intelligence Perspectives”, most directly addresses the book’s central theme. The quality, scientific depth and rigour are not equally distributed between these chapters, but are stimulating nonetheless. Topics range from the role of open-source AI in student-led AI projects at CERN’s IdeaSquare and real-time astrophysical discovery. Michael Coughlin and colleagues’ chapter on accelerated AI in astrophysics stands out for its technical clarity and relevance, a solid entry point for physicists curious about AI beyond popular discourse. Absent is an in-depth treatment of current AI applications in high-energy physics, such as anomaly detection in LHC triggers or generative models for simulation. Given the book’s CERN affiliations, this omission is surprising and leaves out some of the most active intersections of AI and high-energy physics (HEP) research.

The final sections address cosmological mysteries and the epistemological limits of human cognition. David H Wolpert’s epilogue, “What Can We Know About That Which We Cannot Even Imagine?”, serves as a reminder that even as AI expands our modelling capacity, the epistemic limits of human cognition – including conceptual blind spots and unprovable truths – may remain permanent. This tension is not a contradiction but a sobering reflection on the intrinsic boundaries of scientific – and more widely human – knowledge.

Even as AI expands our modelling capacity, the epistemic limits of human cognition may remain permanent

This eclectic volume is best read as a reflective companion to one’s own work. For advanced students, postdocs and researchers open to thinking beyond disciplinary boundaries, the book is an enriching, if at times uneven, read.

To a professional scientist, the book occasionally romanticises interdisciplinary exchange between specialised fields without fully engaging with the real methodological difficulties of translating complex concepts to the other sciences. Topics including the limitations of current large-language models, the reproducibility crisis in AI research, and the ethical risks of data-driven surveillance would have benefited from deeper treatment. Ethical questions in HEP may be less prominent in the public eye, but still exist. To mention a few, there are the environmental impact of large-scale facilities, the question of spending a substantial amount of public money on such mega-science projects, the potential dual-use concerns of the technologies developed, the governance of massive international collaborations and data transparency. These deserve more attention, and the book could have explored them more thoroughly.

A timely snapshot

Still, the book doesn’t pretend to be exhaustive. Its strength lies in curating diverse voices and offering a timely snapshot of science, as well as shedding light on ethical and philosophical questions associated with science that are less frequently discussed.

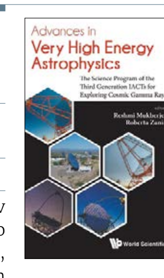
There is a vast knowledge gap in today’s society. Researchers often become so absorbed in their specific domains that they lose sight of their work’s broader philosophical and societal context and the need to explain it to the public. Meanwhile, public misunderstanding of science, and the resulting confusion between fact, theory and opinion, is growing. This gulf provides fertile ground for political manipulation and ideological extremism. *New Frontiers in Science in the Era of AI* has the immense merit of trying to bridge that gap. The editors and contributors deserve credit for producing a work of both scientific and societal relevance.

Federico Carminati *Société Internationale de Psychanalyse Multidisciplinaire*.

Advances in Very High Energy Astrophysics: The Science Program of the Third Generation IACTs for Exploring Cosmic Gamma Rays

Edited by Reshmi Mukherjee and Roberta Zanin

World Scientific



World Scientific

Imaging atmospheric Cherenkov telescopes (IACTs) are designed to detect very-high-energy gamma rays, enabling the study of a range of both galactic and extragalactic gamma-ray sources. By capturing Cherenkov light from gamma-ray-induced air showers, IACTs help trace the origins of cosmic rays and probe fundamental physics, including questions surrounding dark matter and Lorentz invariance. Since the first gamma-ray source detection by the Whipple telescope in 1989, the field has rapidly advanced through instruments like HESS, MAGIC and VERITAS. Building on these successes, the Cherenkov Telescope Array Observatory (CTAO) represents the next generation of IACTs, with greatly improved sensitivity and energy coverage. The northern CTAO site on La Palma is already collecting data, and major infrastructure development is now underway at the southern site in Chile, where telescope construction is set to begin soon.

Considering the looming start to CTAO telescope construction, *Advances in Very High Energy Astrophysics*, edited by Reshmi Mukherjee of Barnard College and Roberta Zanin, from the University of Barcelona, is very timely. World-leading experts tackle the almost impossible task of summarising the progress made by the third-generation IACTs: HESS, MAGIC and VERITAS.

The range of topics covered is vast, spanning the last 20 years of progress in the areas of IACT instrumentation, data-analysis techniques, all aspects of high-energy astrophysics, cosmic-ray astrophysics and gamma-ray cosmology. The authors are necessarily selective, so the depth into each sector is limited, but I believe that the essential concepts were properly introduced and the most important highlights captured. The primary focus of the book lies in discussions surrounding gamma-ray astronomy and high-energy physics, cosmic rays and ongoing research into dark matter.

It appears, however, that the individual chapters were all written independently of each other by different authors, leading to some duplications. Source classes and high-energy radiation mechanisms are introduced multiple times, sometimes with different terminology and notation in the different chapters, which could lead to confusion for novices in the field. But though internal coordination could have been improved, a positive aspect of this independence is that each chapter is self-contained and can be read on its own. I recommend the book to emerging researchers looking for a broad overview of this rapidly evolving field.

Markus Böttcher *North-West University*.

A scientist in sales

In the face of tight labour markets for highly skilled talent, Massimiliano Pindo wants to blur the boundaries between academia and industry.

The boundary between industry and academia can feel like a chasm. Opportunity abounds for those willing to bridge the gap.

Massimiliano Pindo began his career working on silicon pixel detectors at the DELPHI experiment at the Large Electron–Positron Collider. While at CERN, Pindo developed analytical and technical skills that would later become crucial in his career. But despite his passion for research, doubts clouded his hopes for the future.

"I wanted to stay in academia," he recalls. "But at that time, it was getting really difficult to get a permanent job." Pindo moved from his childhood home in Milan to Geneva, before eventually moving back in with his parents while applying for his next research grant. "The golden days of academia where people got a fixed position immediately after a postdoc or PhD were over."

The path forward seemed increasingly unstable, defined by short-term grants, constant travel and an inability to plan long-term. There was always a constant stream of new grant applications, but permanent contracts were few and far between. With competition increasing, job stability seemed further and further out of reach. "You could make a decent living," Pindo says, "but the real problem was you could not plan your life."

Translatable skills

Faced with the unpredictability of academic work, Pindo transitioned into industry – a leap that eventually led him to his current role as marketing and sales director at Renishaw, France, a global engineering and scientific technology company. Pindo was confident that his technical expertise would provide a strong foundation for a job beyond academia, and indeed he found that "hard" skills such as analytical thinking, problem-solving and a deep understanding of technology, which he had honed at CERN alongside soft skills such as teamwork, languages and communication, translated well to his work in industry.

"When you're a physicist, especially a particle physicist, you're used to breaking down complex problems, selecting what is really meaningful amongst all the noise, and addressing these issues directly," Pindo says. His experience in academia gave him the confidence that industry challenges would pale in comparison. "I was telling myself that in the academic world, you are dealing with things that, at least on paper, are more complex and difficult than what you find in industry."

M Pindo

From silicon to sales *Massimiliano Pindo is the marketing and sales director at global engineering and scientific technology firm Renishaw, France.*

Initially, these technical skills helped Pindo become a device engineer for a hardware company, before making the switch to sales. The gradual transition from academia to something more hands-on allowed him to really understand the company's product on a technical level, which made him a more desirable candidate when transitioning into marketing.

"When you are in B2B [business-to-business] mode and selling technical products, it's always good to have somebody who has technical experience in the industry," explains Pindo. "You have to have a technical understanding of what you're selling, to better understand the problems customers are trying to solve."

However, this experience also allowed him to recognise gaps in his knowledge. As he began gaining more responsibility in his new, more business-focused role, Pindo decided to go back to university and get an MBA. During the programme, he was able to familiarise himself with the worlds of human resources, business strategy and management – skills that aren't typically the focus in a physics lab.

Pindo's journey through industry hasn't been a one-way ticket out of academia. Today, he still maintains a foothold in the academic world, teaching strategy as an affiliated professor at the Sorbonne. "In the end you never leave the places you love," he says. "I got out through the door – now I'm getting back in through the window!"

Transitioning between industry and academia was not entirely seamless. Misconceptions loomed on both sides, and it took Pindo a while to find a balance between the two.

"There is a stereotype that scientists are people who can't adapt to industrial environments – that they are too abstract, too theoretical," Pindo explains. "People think scientists are always in the clouds, disconnected from reality. But that's not true. The science we make is not the science of cartoons. Scientists can be people who plan and execute practical solutions."

The misunderstanding, he says, goes both ways. "When I talk to alumni still in academia, many think that industry is a nightmare – boring, routine, uninteresting. But that's also false," Pindo says. "There's this wall of suspicion. Academics look at industry and think, 'What do they want? What's the real goal? Are they just trying to make more money?' There is no trust."

Tight labour markets

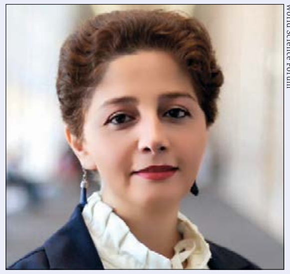
For Pindo, this divide is frustrating and entirely unnecessary. Now with years of experience navigating both worlds, he envisions a more fluid connection between academia and industry – one that leverages the strengths of both. "Industry is currently facing tight labour markets for highly skilled talent, and academia doesn't have access to the money and practical opportunities that industry can provide," says Pindo. "Both sides need to work together."

To bridge this gap, Pindo advocates a more open dialogue and a revolving door between the two fields – one that allows both academics and industry professionals to move fluidly back and forth, carrying their expertise across boundaries. Both sides have much to gain from shared knowledge and collaboration. One way to achieve this, he suggests, is through active participation in alumni networks and university events, which can nurture lasting relationships and mutual understanding. If more professionals embraced this mindset, it could help alleviate the instability that once pushed him out of academia, creating a landscape where the boundaries between science and industry blur to the benefit of both.

"Everything depends on active listening. You always have to learn from the person in front of you, so give them the chance to speak. We have a better world to build, and that comes only from open dialogue and communication."

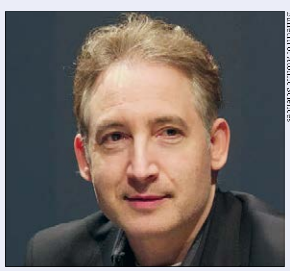
Interview by Alex Epshtein *CERN.*

Appointments and awards



World Science Forum

AAAS awards
Encieh Erfani (above), now of the Perimeter Institute, has received the American Association for the Advancement of Science (AAAS) Award for Scientific Freedom and Responsibility. The award honours individuals or organisations whose exemplary actions – sometimes taken at significant personal cost – have served to foster and protect those ideals. Erfani was an assistant professor of physics whose research focused on cosmology in her native Iran, but following the death of Mahsa Amini, she resigned her faculty position and engaged in advocacy with fellow Iranian academics. Also recognised in 2025 by the AAAS is Brian Greene (below), of Columbia University, who received the Mani L Bhaumik



Bulletin of Atomic Sciences

Award for Public Engagement with Science. Greene is known for his work on mirror symmetry and spatial topology change – two key ideas of superstring theory – and for popularising science through bestselling books like *The Elegant Universe* and *The Fabric of the Cosmos*, reaching millions worldwide.

New IceCube spokesperson
Erin O'Sullivan, from Uppsala University, has been appointed the new spokesperson of the IceCube Collaboration, taking over from Ignacio Taboada. O'Sullivan brings extensive experience to the role, having served as chair of the publications committee and co-led the low-energy astrophysics working group at IceCube. Her research has significantly contributed to the study of supernova neutrinos, including leading a project funded by the Swedish Research Council to investigate neutrino emissions from supernovae using IceCube and to help prepare Hyper-Kamiokande to detect the diffuse supernova neutrino background. In her new role,

IceCube

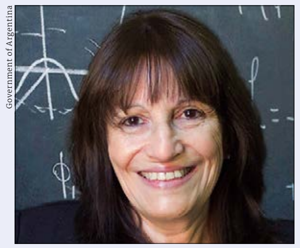
O'Sullivan will oversee the upcoming IceCube Upgrade, which involves deploying seven new strings of advanced optical sensors to enhance the detector's sensitivity and calibration capabilities. O'Sullivan began her term on 1 May.

EPS-HEP prizes awarded
The 2025 European Physical Society (EPS) High Energy and Particle Physics Prize honours Jürg Gasser and Heinrich Leutwyler (University of Bern) and Martin Lüscher (CERN) for pioneering theoretical methods that deepen our understanding of strong interactions in the non-perturbative regime. The Giuseppe and Vanna Cocconi Prize recognises the Fermi-LAT and Fermi-GBM collaborations for transforming gamma-ray astronomy with thousands of new source detections, including pulsars, gamma-ray bursts and key electromagnetic counterparts to neutrino and gravitational-wave events. Lorenz Eberhardt (University of Amsterdam) received the Gribov Medal for groundbreaking advances in string theory, notably proving the AdS/CFT correspondence in three dimensions and progressing string-amplitude calculations. The Young Experimental Physicist Prize is awarded to Thea Klaeboe Aarrestad (ETH Zurich) for integrating machine learning into particle-physics detector systems and leading novel anomaly-detection methods, and to Laura Zani (INFN Pisa) for outstanding searches beyond the Standard Model and contributions to the Belle II experiment. The Outreach Prize goes to the Beamline for Schools Project for its innovative global competitions enabling high-school teams to conduct experiments at leading accelerator labs such as CERN and DESY.

Röntgen Medal for X-ray safety
On 10 May, Reinhard Loose of the Institute of Medical Physics at Nuremberg Hospital was awarded the 2025 Röntgen Medal by the City of Remscheid for his contributions to medical and technical radiation protection. Loose is an expert in the safe application of X-rays and played a significant role in advancing clinical protocols and technological innovations that enhance radiation safety. Loose's proposed regulations introduced several key protocols, including mandatory involvement of medical physics experts in high-dose procedures such as CT and fluoroscopic intervention. His efforts have been pivotal in establishing a robust framework for radiation safety in medical settings, ensuring both patient and staff protection.

Roentgen Museum

UNESCO women in science
María Teresa Dova (National University of La Plata and CONICET) is the laureate for Latin America and the Caribbean in the 2025 L'Oréal–UNESCO For Women in Science International



Government of Argentina

Awards. Dova was rewarded for her contributions to high-energy physics, including the discovery and ongoing characterisation of the Higgs boson, searches for new physics with the ATLAS experiment and the study of cosmic rays with the Pierre Auger Observatory. The jury acknowledged her central role as a mentor and inspiration for a new generation of Argentinian physicists.

Accelerator prizes
The 2025 ACFA/IPAC'25 Accelerator Prizes recognise outstanding contributions in accelerator science and technology. Hitoshi Tanaka of RIKEN SPring-8 Center received the Xie Jialin Prize for his work on photon source accelerators, including the design of SACLA and energy-efficient upgrades at SPring-8. Liangting Sun from the Institute of Modern Physics of the Chinese Academy of Sciences was awarded the Nishikawa Tetsuji Prize for advancements in high-charge-state superconducting electron-cyclotron-resonance ion sources. The Hogil Kim Prize went to Riccardo Pompili of LNF-INFN for his efforts in plasma-based accelerator diagnostics and leadership in the Plasma Working Area of the EuPRAXIA@SPARC_LAB project. Adam Steinberg, of the University of Melbourne and the University of Manchester, received the Mark Oliphant Prize for developing fixed-field accelerator technologies aimed at enhancing hadron-therapy beam delivery.

PEOPLE OBITUARIES

Mary K Gaillard 1939–2025

A theoretical physicist of great power

AIP Emilio Segrè Visual Archives

Mary K Gaillard was gifted with deep physical intuition and a very high level of technical mastery.

Mary K Gaillard, a key figure in the development of the Standard Model of particle physics, passed away on 23 May 2025. She was born in 1939 to a family of academics who encouraged her inquisitiveness and independence. She graduated in 1960 from Hollins College, a small college in Virginia, where her physics professor recognised her talent, helping her get jobs in the Ringuet laboratory at l'École Polytechnique during a junior year abroad and for two summers at the Brookhaven National Laboratory. In 1961 she obtained a master's degree from Columbia University and in 1968 a doctorate in theoretical physics from the University of Paris at Orsay. Mary K was a research scientist with the French CNRS and a visiting scientist at CERN for most of the 1970s. From 1981 until she retired in 2009, she was a senior scientist at the Lawrence Berkeley National Laboratory and a professor of physics at the University of California at Berkeley, where she was the first woman in the department.

Mary K was a theoretical physicist of great power, gifted both with a deep physical intuition and a very high level of technical mastery. She used her gifts to great effect and made many important contributions to the development of the Standard Model of elementary particle physics that was established precisely during the course of her career. She pursued her love of physics with powerful determination, in the face of overt discrimination that went well beyond what may still exist today. She fought these battles and produced beautiful, important physics, all while raising three children as a devoted mother.

Undeniable impact

After obtaining her master's degree at Columbia, Mary K accompanied her first husband, Jean-Marc Gaillard, to Paris, where she was rebuffed in many attempts to obtain a position in an experimental group. She next tried and failed, multiple times, to find an advisor in theoretical physics, which she actually preferred to experimental physics but had not pursued because it was regarded as an even more unlikely career for a woman. Eventually, and fortunately for the development of elementary particle physics, Bernard d'Espagnat agreed to supervise her doctoral research at the University of Paris. While she quickly succeeded in producing significant results in her research, respect and recognition were still slow to come. She suffered many slights from a culture that could not understand or countenance the possibility of a woman theoretical physicist and put many obstacles in her way. Respect and recognition did finally come in appropriate measure, however, by virtue of the undeniable impact of her work.

Her contributions to the field are numerous. During an intensely productive period in the mid-1970s, she completed a series of projects that established the framework for the decades to follow that would culminate in the Standard Model. Famously, during a one-year visit to Fermilab in 1973, using the known properties of the "strange" K mesons, she successfully predicted the mass scale of the fourth "charm" quark a few months prior to its discovery. Back at CERN a few years later, she also predicted, in the framework of grand unified theories, the mass of the fifth "bottom" quark – a successful though still speculative prediction. Other impactful work, extracting the experimental consequences of theoretical constructs, laid down the paths that were followed to experimentally validate the charm-quark discovery and to search for the Higgs boson required to complete the Standard Model. Another key contribution showed how "jets", streams of particles created in high-energy accelerators, could be identified as manifestations of the "gluon" carriers of the strong force of the Standard Model.

In the 1980s in Berkeley, when the Superconducting Super Collider and the Large Hadron Collider were under discussion, she showed that they could successfully uncover the mechanism of electroweak symmetry breaking required to understand the Standard Model weak force, even if it was "dynamical" – an experimentally much more challenging possibility than breaking by a Higgs boson. For the remainder of her career, she focused principally on work to address issues that are still unresolved by the Standard Model. Much of this research involved "supersymmetry" and its extension to encompass the gravitational force, theoretical constructs that originated in the work of her second husband, the late Bruno Zumino, who also moved from CERN to Berkeley.

Mary K's accomplishments were recognised by numerous honorary societies and awards, including the National Academy of Sciences, the American Academy of Arts and Sciences, and the J. J. Sakurai Prize for Theoretical Particle Physics of the American Physical Society. She served on numerous governmental and academic advisory panels, including six years on the National Science Board. She tells her own story in a memoir, *A Singularly Unfeminine Profession*, published in 2015. Mary K Gaillard will surely be remembered when the final history of elementary particle physics is written.

Michael Chanowitz *Lawrence Berkeley National Laboratory.*

CERNCOURIER

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FRITZ CASPERS 1950–2025

A master of beam cooling

Friedhelm "Fritz" Caspers, a master of beam cooling, passed away on 12 March 2025.

Born in Bonn, Germany in 1950, Fritz studied electrical engineering at RWTH Aachen. He joined CERN in 1981, first as a fellow and then as a staff member. During the 1980s Fritz contributed to stochastic cooling in CERN's antiproton programme. In the team of Georges Carron and Lars Thorndahl, he helped devise ultra-fast microwave stochastic cooling systems for the then new antiproton cooler ring. He also initiated the development of power field-effect transistors that are still operational today in CERN's Antiproton Decelerator ring. Fritz conceived novel geometries for pickups and kickers, such as slits cut into ground plates, as now used for the GSI FAIR project, and meander-type electrodes. From 1988 to 1995, Fritz was responsible for all 26 stochastic-cooling systems at CERN. In 1990 he became a senior member of the Institute of Electrical and Electronics Engineers (IEEE), before being distinguished as an IEEE Life Fellow later in his career.

Fritz Caspers was kind and willing to help anyone who needed his support.

Pioneering diagnostics

In the mid-2000s, Fritz proposed enamel-based clearing electrodes and initiated pertinent collaborations with several German companies. At about the same time, he carried out ultrasound diagnostics on soldered junctions on LHC interconnects. Among the roughly 1000 junctions measured, he and his team found a single non-conform junction. In 2008 Fritz suggested non-elliptical superconducting crab cavities for the HL-LHC. He also proposed and performed pioneering electron-cloud diagnostics and mitigation-using microwaves. For the LHC, he predicted a "magnetron effect", where coherently radiating cloud electrons might quench the LHC magnets at specific values of their magnetic field. His advice was highly sought after on laboratory-impedance measurements and electromagnetic interference.

He helped develop the power field-effect transistors still operational today in CERN's AD ring

Throughout the past three decades, Fritz was active and held in high esteem not only at CERN but all around the world. For example, he helped develop the stochastic cooling systems for GSI in Darmstadt, Germany, where his main contact was Fritz Nolden. He contributed to the construction and commissioning of stochastic cooling for GSI's Experimental Storage Ring, including the successful demonstration of the stochastic cooling of heavy ions in 1997. Fritz also helped develop the stochastic cooling of rare isotopes for the RI Beam Factory project at RIKEN, Japan.

Fritz was a long-term collaborator of IMP Lanzhou at the Chinese Academy of Sciences (CAS). In 2015, stochastic cooling was commissioned at the Cooling Storage Ring with his support. Always kind and willing to help anyone who needed him, Fritz also provided valuable suggestions and hands-on experience with impedance measurements for IMP's HIAF project, especially the titanium-alloy-loaded thin-wall vacuum chamber and magnetic-alloy-loaded RF cavities. In 2021, Fritz was elected as a Distinguished Scientist of the CAS President's International Fellowship Initiative and awarded the Dieter Möhl Award by the International Committee for Future Accelerators for his contributions to beam cooling.

In 2013, the axion dark-matter research centre IBS-CAPP was established at KAIST, Korea. For this new institute, Fritz proved to be just the right lecturer. Every spring, he visited Korea for a week of intensive lectures on RF techniques, noise measurements and much more. His lessons, which were open to scientists from all over Korea, transformed Korean researchers from RF amateurs into professionals, and his contributions helped propel IBS-CAPP to the forefront of research.

Fritz was far more than just a brilliant scientist. He was a generous mentor, a trusted colleague and a dear friend who lit up a room when he entered, and his absence will be deeply felt by all of us who had the privilege of knowing him. Always on the hunt for novel ideas, Fritz was a polymath and a fully open-minded scientist. His library at home was a visit into the unknown, containing "dark matter", as we often joked. We will remember Fritz as a gentleman who was full of inspiration for the young and the not-so-young alike. His death is a loss to the whole accelerator world.

Frank Zimmermann *CERN*, **Takeshi Katayama** *RIKEN*, **Yannis Semertzidis** *IBS-CAPP*, **Konstantin Zioutas** *University of Patras and* **Junxia Wu** *IMP*.

FRITZ A FERGER 1933–2025

A multi-talented engineer

Fritz Ferger, a multi-talented engineer who had a significant impact on the technical development and management of CERN, passed away on 22 March 2025.

Born in Reutlingen, Germany, on 5 April 1933, Fritz obtained his electrical engineering degree in Stuttgart and a doctorate at the University of Grenoble. A contract with General Electric in his pocket, he visited CERN, curious about the 25 GeV Proton Synchrotron, the construction of which was receiving the finishing touches in the late 1950s. He met senior CERN staff and was offered a contract that he, impressed by the visit, accepted in early 1959.

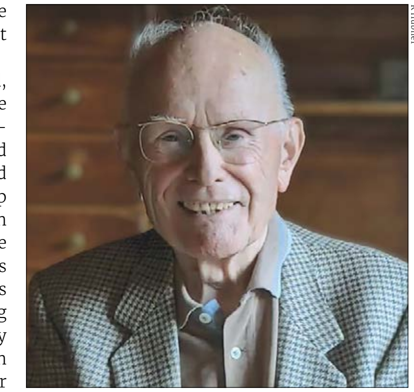
Under his ISR leadership CERN acquired the confidence that colliders were the way to go

Fritz's first assignment was the development of a radio-frequency (RF) accelerating cavity for a planned fixed-field alternating-gradient (FFAG) accelerator. This was abandoned in early 1960 in favour of the study of a 2×25 GeV proton–proton collider, the Intersecting Storage Rings (ISR). As a first step, the CERN Electron Storage and Accumulation Ring (CESAR) was constructed to test high-vacuum technology and RF accumulation schemes; Fritz designed and constructed the RF system. With CESAR in operation, he ▷

moved on to the construction and tests of the high-power RF system of the ISR, a project that was approved in 1965.

After the smooth running-in of the ISR and, for a while having been responsible for the General Engineering Group, he became division leader of the ISR in 1974, a position he held until 1982. Under his leadership the ISR unfolded its full potential with proton beam currents up to 50 A and a luminosity 35 times the design value, leading CERN to acquire the confidence that colliders were the way to go. Due to his foresight, the development of new technologies was encouraged for the accelerator, including superconducting quadrupoles and pumping by cryo- and getter surfaces. Both were applied on a grand scale in LEP and are still essential for the LHC today.

When the resources of the ISR Division were refocussed on LEP in 1983, Fritz became the leader of the Technical Inspection and Safety Commission. This absorbed the activities of the previous health and safety groups, but its main task was to scrutinise the LEP project from all technical and safety aspects. Fritz's responsibility widened considerably when he became leader of the Technical Support Division in 1986. All of the CERN civil engineering, the tunnelling for the 27 km circumference LEP ring, its auxiliary tunnels, the concreting of the enormous caverns for the experiments and the construction of a dozen surface buildings were in full swing and brought to a successful conclusion in the following years. New buildings on the Meyrin site were added, including the attractive Building 40 for the large experimental groups, in which he took particular pride. At the same time, and under pressure to reduce expenditure, he had to manage several difficult outsourcing contracts.



The ISR unfolded its full potential under Fritz Ferger's leadership.

When he retired in 1997, he could look back on almost 40 years dedicated to CERN; his scientific and technical competence paired with exceptional organisational and administrative talent. We shall always remember him as an exacting colleague with a wide range of interests, and as a friend, appreciated for his open and helpful attitude.

We grieve his loss and offer our sincere condolences to his widow Catherine and their daughters Sophie and Karina.

His friends and colleagues.

SANDY DONNACHIE 1936–2025

Particle theory and scientific leadership

Sandy Donnachie, a particle theorist and scientific leader, passed away on 7 April 2025.

Born in 1936 and raised in Kilmarnock, Scotland, Sandy received his BSc and PhD degrees from the University of Glasgow before taking up a lectureship at University College London in 1963. He was a CERN research associate from 1965 to 1967, and then senior lecturer at the University of Glasgow until 1969, when he took up a chair at the University of Manchester and played a leading role in developing the scientific programme at NINA, the electron synchrotron at the nearby Daresbury National Laboratory. Sandy then served as head of the Department of Physics and Astronomy at the University from 1989 to 1994, and as dean of the Faculty of Science and Engineering from 1994 to 1997. He had a formidable reputation – if a staff member or student asked to see him, he would invite them to come at 8 a.m., to test whether what they wanted to discuss was truly important.

Sandy Donnachie was renowned for his work on elastic and diffractive scattering.

Sandy played a leading role in the international scientific community, maintaining strong connections with CERN throughout his career, as scientific delegate to the CERN Council from 1989 to 1994, chair of the SPS committee from 1988 to 1992, and member of the CERN Scientific Policy Committee from 1988 to 1993. In the UK, he chaired the UK's Nuclear Physics Board from 1989 to 1993, and served as a member of the Science and Engineering Research Council from 1989 to 1994. He also served as an associate editor for *Physical Review Letters* from 2010 to 2016. In recognition of his leadership and scientific contributions, he was awarded the UK's Institute of Physics Glazebrook Medal in 1997.

The "Donnachie–Landshoff pomeron" is known to all those working in the field

Sandy is perhaps best known for his body of work with Peter Landshoff on elastic and diffractive scattering: the "Donnachie–Landshoff pomeron" is known to all those working in the field. The collaboration began half a century ago and when email became available, they were among its early and most enthusiastic users. Sandy only knew Fortran and Peter only knew C, but somehow they managed to collaborate and together wrote more than 50 publications, including a book *Pomeron Physics and QCD* with Günter Dosch and Otto Nachtmann published in 2004. The collaboration lasted until, so sadly, Sandy was struck with Parkinson's disease and was no longer able to use email. Earlier in his career, Sandy had made significant contributions to the field of low-energy hadron scattering, in particular through a collaboration with Claud Lovelace, which revealed many hitherto unknown baryon states in pion–nucleon scattering, and through a series of papers on meson photoproduction, initially with Graham Shaw and then with Frits Berends and other co-workers.

Throughout his career, Sandy was notable for his close collaborations with experimental physics groups, including a long association with the Omega Photon Collaboration at CERN, with whom he co-authored 27 published papers. He and Shaw also produced three books, culminating in *Electromagnetic Interactions and Hadronic Structure* with Frank Close, which was published in 2007.

In his leisure time, Sandy was a great lover of classical music and a keen sailor, golfer and country walker.

Peter Landshoff *University of Cambridge*, **Graham Shaw** *and* **Jeff Forshaw** *University of Manchester.*

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BACKGROUND

Notes and observations from the high-energy physics community

A galactic masterpiece


www.eso.org/public/news/eso2510/

The Very Large Telescope in Chile has produced one of the most detailed surveys of a star-forming galaxy to date. Stitched together from more than 100 exposures, the image of the Sculptor Galaxy covers an area 65,000 light-years wide, revealing around 500 planetary nebulae, regions of gas and dust cast off from dying sun-like stars (E Congiu *et al.* 2025 arXiv:2506.14921). "The Sculptor Galaxy is in a sweet spot," says Enrico Congiu of the European Southern Observatory. "It is close enough that we can resolve its internal structure and study its building blocks with incredible detail, but at the same time, big enough that we can still see it as a whole system."

Media corner

"The Fermilab experiment is hugely successful; they did their job. We theorists; we still need to follow up."

Chair of the Muon g-2 Theory Initiative **Aida El-Khadra** (University of Illinois Urbana-Champaign) in *The New York Times* (3 June).

"This is a puzzling situation for everyone. People have made checks against each other. The [experiments] have been scrutinised in detail; we had sessions that lasted five hours… Nothing wrong was found."

Gilberto Colangelo (University of Bern) on the Muon g-2 Theory Initiative's inability to square lattice QCD predictions with calculations based on electron–positron data (*Scientific American*, 8 June).

"The dream of 17th-century alchemists has been realised by physicists at the LHC, who have turned lead into gold – albeit for only a fraction of a second and at tremendous cost."

Nature's **Elizabeth Gibney** reacts to the ALICE collaboration's analysis of proton emission in ultraperipheral Pb–Pb collisions (9 May).

"They assumed the effect they were trying to prove, and achieved this through massaging of data and theory gymnastics."

Former collaborator **Vincent Mourik** (Forschungszentrum Jülich) sharply disputes recent claims to have discovered a new state of matter known as a topological superconductor – a possible foundation for error-resistant quantum computing (*Science*, 6 May).

From the archive: July/August 1985

Collision course


CERN

Colleagues enjoy champagne after the peak proton–antiproton collision luminosity in the SPS was increased tenfold in the 1982 run, with Lyn Evans at centre.

On 10 July 1981, Carlo Rubbia burst into the Lisbon Particle Physics Conference clutching the first recordings of high-energy collisions of matter and antimatter in the CERN SPS ring. His announcement was greeted with spontaneous applause. More than three years later, the SPS Collider's performance has improved more than a hundred fold.

The Collider's peak luminosity (a measure of the instantaneous proton–antiproton collision rate) has been pushed up from $5\times10^{27}\,\mathrm{cm^{-2}s^{-1}}$ in 1981 to $3.5\times10^{29}\,\mathrm{cm^{-2}s^{-1}}$ in 1984. More importantly, the daily average performance (integrated luminosity) has increased by more than an order of magnitude. The first physics run took place at the end of 1981, when 2×10^{32} per cm^2 ($0.2\,\mathrm{nb^{-1}}$) of integrated luminosity was produced. In the second run at the end of 1982, the peak luminosity was increased to $5\times10^{28}\,\mathrm{cm^{-2}s^{-1}}$ and a total integrated luminosity of $28\,\mathrm{nb^{-1}}$ was produced, enough to reveal the long-awaited W particle. In the latest big run (end of 1984), the peak luminosity was further increased and a total of $395\,\mathrm{nb^{-1}}$ was produced in each of the two experiments.

The steady improvement in Collider performance reflects a gradual mastering of a complex chain of accelerators. While this is impressive, the ingenuity and resourcefulness of the operating teams is far from exhausted. We can hope to see many more antiproton milestones in the years to come.

● Text adapted from *CERN Courier* July/August 1985 pp 229–233.

Compiler's note

Running CERN's Super Proton Synchrotron (SPS) as a proton–antiproton collider allowed the discovery of the W and Z bosons, as announced in 1983. Three decades later, in 2012, teams at the Large Hadron Collider (LHC) announced their discovery of the Higgs boson, thus confirming the mechanism proposed for endowing the W and Z with their mass. As with the SPS collider, the year-on-year improvement in luminosity at the LHC has been key in enabling the experiments there to make many discoveries. Lyn Evans, co-author of the article quoted here, played a major role at both machines, becoming well known as the LHC project leader.

Twenty years of looking back

"From the archive" began life at the start of 2005, the year of CERN's 50th anniversary. The aim was to highlight aspects of the organisation's first half-century through short extracts from past issues of *CERN Courier*. During 2006 it passed into the hands of a regular compiler, Peggie Rimmer. Already known to the *Courier*'s editor through her book reviews, she was the ideal person for the role. With a doctorate in physics from Oxford, Peggie joined CERN in 1967 and went on to work on front-end data acquisition and networking for a quarter of a century, supervising World Wide Web inventor Tim Berners-Lee from 1984 to 1990. Later she joined and then ran the public-relations group, before her final role at CERN as the scientific secretary to the Research Review Board, which oversaw preparations for the four big LHC experiments. She has drawn on all of this experience in compiling her entertaining archive column for almost two decades. Many thanks, Peggie, yours is a hard act to follow. *Chapeau!*

● Christine Sutton, *CERN Courier* editor from 2003 to 2015, now takes up the archive column.

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