WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2025 issue of *CERN Courier*.

Protons and charged hadrons deposit energy most rapidly in the final millimetres before they stop. Pinpoint this “Bragg peak” on tumour cells and cancer can be eliminated while sparing healthy tissues. 100 keV/μm is enough to snap DNA’s double helix on both sides. More is overkill. Use heavy ions, and treatments can be particularly precise.

So much for Particle Therapy 101. Progress today depends on matching accelerator solutions to clinical needs (p45). This edition’s cover is a reminder of the complexity of the biological side of the equation. At the bottom, strands of DNA unwind inside the membrane of the cell nucleus, and are copied for repair, replication and repackaging by a sea of organelles submerged in cytoplasm (above right). Mitochondria (top left) stand ready to destroy the cell if damage is detected – a key mechanism by which ionising radiation kills cancer. In this edition, a special feature lists the top five facts physicists need to know about radiobiology to work at the cutting edge of particle therapy (p27), while a retrospective on the inspiring life of Joseph Rotblat adds historical colour (p41).

This issue also marks the passing of Herwig Schopper (p32) and John Peoples (p55), lab directors whose leadership shaped high-energy physics. Today, the future is being shaped once again. China has fired the starting pistol for a new generation of neutrino experiments (p9). The Circular Electron–Positron Collider now boasts a mature design, though approval is on hold (p7). And Europe’s ongoing strategy process has published its physics briefing book – a key resource for deciding CERN’s next flagship collider. ECFA chair Paris Sphicas has distilled hundreds of pages of insights into just four for the *Courier* (p23).

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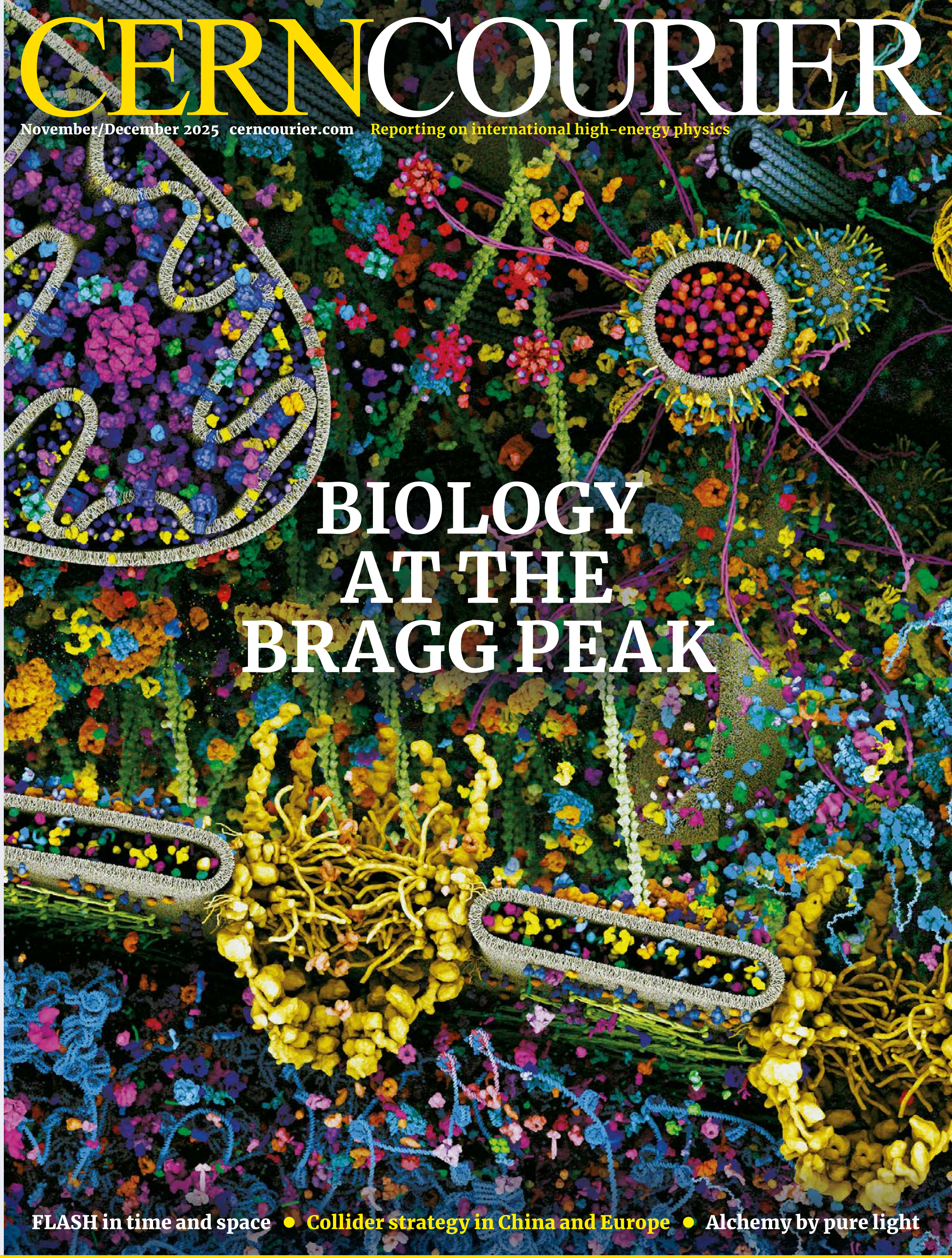
EDITOR: MARK RAYNER



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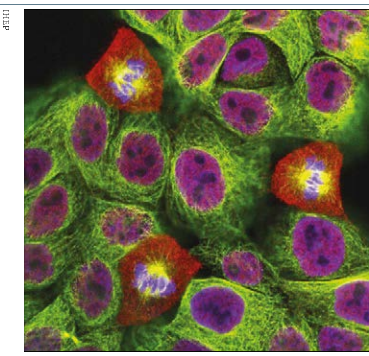
Wild West of the weak interaction *JUNO is the first of a new generation of large neutrino-oscillation experiments to come online.* **9**



Southampton University

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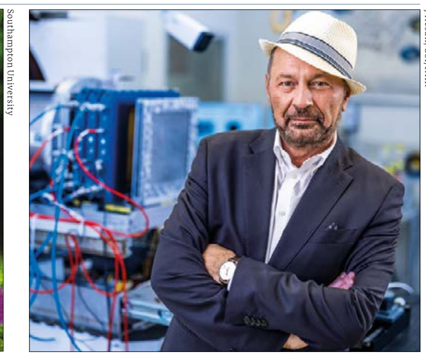

J Hosan, GSI/FAIR

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FROM THE EDITOR

The physics of treating cancer begins with biology

Mark Rayner
Editor

Protons and charged hadrons lose energy most rapidly in the final millimetres before they stop. Pinpoint this "Bragg peak" on tumour cells and you can spare surrounding healthy tissues. An energy deposition of 100 keV/μm is enough to snap DNA's double helix on both sides. More is overkill for cancer cells. Use heavy ions, and your Bragg peak can be exquisitely sharp and precise.

So much for Particle Therapy 101. Progress in the 2020s depends on matching accelerator solutions to clinical needs, argues Particle Therapy Co-Operative Group president Marco Durante (p45). This edition's cover is a reminder of the complexity of the biological side of the equation. This "cellular landscape" is inspired by X-ray, NMR and electron microscopy, and the work of science illustrator David Goodsell. At the bottom, strands of DNA unwind inside the membrane of the cell nucleus, and are copied for repair, replication and repackaging by a sea of organelles submerged in cytoplasm (above right). Mitochondria (top left) stand ready to destroy the cell if damage is detected – a key mechanism by which ionising radiation kills cancer cells. In a special feature, Angelica Facoetti lists the top five facts accelerator physicists need to know about radiobiology to work at the cutting edge of particle therapy (p27).

Cancer treatments have often followed hot on the heels of innovations in particle and accelerator physics. Doctors used X-rays and radium seeds to shrink tumours a mere handful of years after their discovery at the close of the 19th century. In 1928, Ernest Lawrence read Rolf Widerøe's paper on linear accelerators and conceived the cyclotron; by 1936, his brother was using them to produce radio-isotopes to treat leukaemia patients. A decade later, Fermilab-founder Robert Wilson proposed particle therapy using the Bragg peak. But the first accelerator-produced beams to be used for cancer treatment were neutron beams. Research took place first in Berkeley under Ernest Lawrence and later in Liverpool under Joseph Rotblat – an inspiring figure who left the Manhattan Project on moral grounds to divide his life between medical physics and peace activism (p41).

Cancer treatments have often followed hot on the heels of innovations in particle and accelerator physics


INFN

Distilling debate *The physics briefing book of the 2026 update to the European Strategy for Particle Physics has now been published.*

Collider strategy in China and Europe

The future of particle physics is starting to take shape. In October, the Circular Electron–Positron Collider (CEPC) collaboration published a technical design report for their reference detector, capping more than a decade of R&D (see p7). However, CEPC will not be included in the 2026 to 2030 five-year plan of the People's Republic of China, as previously hoped. Attention now turns to Europe. The *Physics Briefing Book* of the ongoing update to the European Strategy for Particle Physics has now been published, distilling 266 community inputs and deliberations at June's Open Symposium in Venice into 250 pages. Paris Sphicas, the chair of the European Committee for Future Accelerators, has further distilled them into just four for the *Courier* (p23).

Elsewhere on these pages: China begins operations at the first of a new generation of neutrino experiments (p9); the passing of Herwig Schopper (p32) and John Peoples (p55), lab directors who shaped CERN and Fermilab; the latest in heavy-ion (p37) and light-ion (p8) physics; and guest Astrowatch correspondents Pratika Dayal and Seiji Fujimoto tackle the excess of bright early galaxies observed by the James Webb Space Telescope (p11). My sincere thanks to departing Astrowatch correspondents Merlin Kole and Arshia Ruina, whose years of service have enriched the conversation between particle physics, astrophysics and cosmology.

Reporting on international high-energy physics

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NEWS ANALYSIS

Policy

CEPC matures, but approval is on hold

In October, the Circular Electron–Positron Collider (CEPC) study group completed its full suite of technical design reports, marking a key step for China's Higgs-factory proposal. However, CEPC will not be considered for inclusion in China's next five-year plan (2026–2030).

"Although our proposal that CEPC be included in the next five-year plan was not successful, IHEP will continue this effort, which an international collaboration has developed for the past 10 years," says study leader Wang Yifang, of the Institute of High Energy Physics (IHEP) in Beijing. "We plan to submit CEPC for consideration again in 2030, unless FCC is officially approved before then, in which case we will seek to join FCC, and give up CEPC."

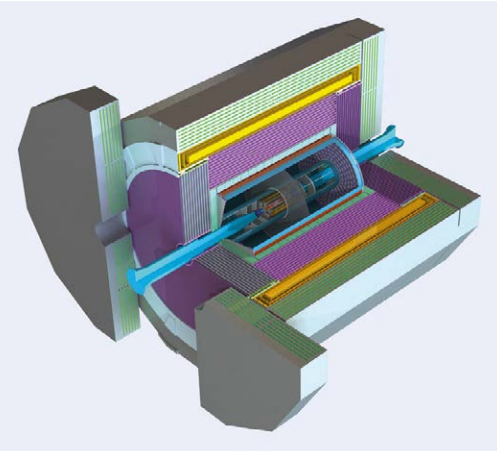
Electroweak precision

CEPC has been under development at IHEP since shortly after the discovery of the Higgs boson at CERN in 2012. To enable precision studies of the new particle, Chinese physicists formally proposed a dedicated electron–positron collider in September 2012. Sharing a concept similar to the Future Circular Collider (FCC) proposed in parallel at CERN, CEPC's high-luminosity collisions would greatly improve precision in measuring Higgs and electroweak processes.

"CEPC is designed as a multi-purpose particle factory," explains Wang. "It would not only serve as an efficient Higgs factory but would also precisely study other fundamental particles, and its tunnel can be re-used for a future upgrade to a more powerful super proton–proton collider."

Following completion of the Conceptual Design Report in 2018, which defined the physics case and baseline layout, the CEPC collaboration entered a detailed technical phase to validate key technologies and complete subsystem designs. The accelerator Technical Design Report (TDR) was released in 2023, followed in October 2025 by the reference detector TDR, providing a mature blueprint for both components.

Compared to the 2018 detector concept, the new technical report proposes several innovations. An electromagnetic calorimeter based on orthogonally oriented crystal bars and a hadronic calorimeter based on high-granularity scintillating glass have been optimised for advanced particle-flow algorithms, improving their energy resolution by a factor of 10 and a factor of two, respectively. A tracking detector employing AC-coupled low-gain avalanche-diode technology will enable simultaneous 10 µm position and 50 ps time measurements, enhancing vertex and flavour tagging. Meanwhile, a readout chip developed in 55 nm technology will achieve state-of-the-art performance at 65% power consumption, enabling better resolution, large-scale integration and reduced cooling-pipe materials. Among other advances, a new type of high-density, high-yield scintillating glass forms the possibility for a full absorption hadronic calorimeter.



CEPC Study Group 2025 arXiv:2510.05260

Mature design *The CEPC Study Group has published a technical design report for its reference detector.*

> **Although our proposal that CEPC be included in the next five-year plan was not successful, IHEP will continue this effort**

To ensure the scientific soundness and feasibility of the design, the CEPC Study Group established an International Detector Review Committee in 2024, chaired by Daniela Bortoletto of the University of Oxford.

Design consolidation

"After three rounds of in-depth review, the committee concluded in September 2025 that the Reference Detector TDR defines a coherent detector concept with a clearly articulated physics reach," says Bortoletto. "The collaboration's ambitious R&D programme and sustained technical excellence have been key to consolidating the major design choices and positioning the project to advance from conceptual design into integrated prototyping and system validation."

CEPC's technical advance comes amid intense international interest in participating in a Higgs factory. Alongside the circular FCC concept at CERN, Higgs factories with linear concepts have been proposed in Europe and Japan, and both Europe and the US have named constructing or participating in a Higgs factory as a strategic priority. Following China's decision to defer CEPC, attention now turns to Europe, where the ongoing update of the European Strategy for Particle Physics will prioritise recommendations for the laboratory's flagship collider beyond the HL-LHC (see p23). Domestically, China will consider other large science projects for the 2026 to 2030 period, including a proposed Super Tau-Charm Facility to succeed the Beijing Electron–Positron Collider II.

With completion of its core technical designs, CEPC now turns to engineering design.

"The newly released detector report is the first dedicated to a circular electron–positron Higgs factory," says Wang. "It showcases the R&D capabilities of Chinese scientists and lays the foundation for turning this concept into reality."

Further reading
CEPC Study Group 2025 arXiv:2510.05260.

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LIGHT-ION PHYSICS

First oxygen and neon collisions at the LHC

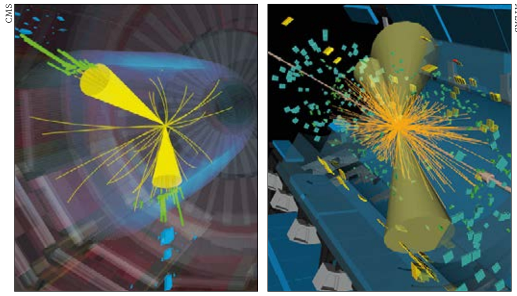
In the first microseconds after the Big Bang, extreme temperatures prevented quarks and gluons from binding into hadrons, filling the universe with a deconfined quark–gluon plasma. Heavy-ion collisions between pairs of gold ($^{197}_{79}$Au^{79+}) or lead ($^{208}_{82}$Pb^{82+}) nuclei have long been observed to produce fleeting droplets of this medium, but light-ion collisions remain relatively unexplored. Between 29 June and 9 July 2025, LHC physicists pushed the study of the quark–gluon plasma into new territory, with the first dedicated studies of collisions between pairs of oxygen ($^{16}_{8}$O^{8+}) and neon ($^{20}_{10}$Ne^{10+}) nuclei, and between oxygen nuclei and protons.

"Early analyses have already helped characterise the geometry of oxygen and neon nuclei, including the latter's predicted prolate 'bowling-pin' shape," says Anthony Timmins of the University of Houston. "More importantly, they appear consistent with the onset of the quark–gluon plasma in light-ion collisions."

As the quark–gluon plasma appears to behave like a near-perfect fluid with low viscosity, the key to modelling heavy-ion collisions is hydrodynamics – the physics of how fluids evolve under pressure gradients, viscous stresses and other forces. When two lead nuclei collide at the LHC, they create a tiny, extremely hot fireball where quarks and gluons interact so frequently they reach local thermal equilibrium within about 10^{-23} s. Measurements of gold–gold collisions at Brookhaven's RHIC and lead–lead collisions at the LHC suggest that the quark–gluon plasma flows with an extraordinarily low viscosity, close to the quantum limit, allowing momentum to move rapidly across the system. But it's not clear whether the same rules apply to the smaller nuclear systems involved in light-ion collisions.

"For hydrodynamics to work, along with the appropriate quark–gluon plasma equation of state, you need a separation of scales between the mean free path of quarks and gluons, the pressure gradients and overall system size," explains Timmins. "As you move to smaller systems, those scales start to overlap. Oxygen and neon are expected to sit near that threshold, close to the limits of plasma formation."

Across the oxygen–oxygen and neon–neon datasets, the ALICE, ATLAS and CMS collaborations decomposed the transverse distribution of emitted particles into Fourier modes – a way to search for collective, fluid-like behaviour. Meas-



CMS ATLAS

Uncharted territory *An oxygen–oxygen collision in the CMS detector (left) and a neon–neon collision in the ATLAS detector (right).*

These initial results are just a smattering of those to come

urements of the "elliptic" and "triangular" Fourier components as functions of event multiplicity support the emergence of a collective flow driven by the initial collision geometry. The collaborations observe signs of energetic-probe suppression in oxygen–oxygen collisions – a signature of the droplet "quenching" jets in a way not observed in proton–proton collisions. Similar features appeared in a one-day xenon–xenon run that took place in October 2017.

CMS compared particle yields in light-ion collisions to a proton–proton reference. After scaling for the number of binary nucleon–nucleon interactions, the collaboration observed a maximum suppression of 0.69 ± 0.04 at a transverse momentum of about 6 GeV, more than five standard deviations from unity. While milder than that observed for lead–lead and xenon–xenon collisions, the data point to genuine medium-induced suppression in the smallest ion–ion system studied to date. Meanwhile, ATLAS reported the first dijet transverse-momentum imbalance in a light-ion system. The reduction in balanced jets is consistent with path-length-dependent energy-loss effects, though apparently weaker than in lead–lead collisions.

In "head-on" collisions, ALICE, ATLAS and CMS all observed a neon–oxygen–lead hierarchy in elliptic flow, suggesting that, if a quark–gluon plasma does form, it exhibits the most pronounced "almond shape" in neon collisions. This pattern reflects the expected nuclear geometries of each species. Lead-208 is a doubly magic nucleus, with complete proton and neutron shells that render it tightly bound and nearly spherical in its ground state. Conversely, neon is predicted to be prolate, with its inherent elongation producing a larger elliptic overlap. Oxygen falls in between, consistent with models describing it as roughly spherical or weakly clustered.

ALICE and ATLAS reported a hierarchy of flow coefficients in light-ion collisions, with elliptic, triangular and quadrangular flows progressively decreasing as their Fourier index rises, in line with hydrodynamic expectations. Like CMS's charged hadron yields, ALICE's preliminary neutral pion yields exhibit a suppression at large momenta.

In a previous fixed-target study, the LHCb collaboration also measured the elliptic and triangular components of the flow in lead–neon and lead–argon collisions, observing the distinctive shape of the neon nucleus. As for proton–oxygen collisions, LHCb's forward-rapidity coverage can probe the partonic structure of nuclei at very small values of Bjorken-x – the fraction of the nucleon's momentum carried by a quark or gluon. Such measurements help constrain nuclear parton distribution functions in the low-x region dominated by gluons and provide rare benchmarks for modelling ultra-high-energy cosmic rays colliding with atmospheric oxygen.

These initial results are just a smattering of those to come. In a whirlwind 11-day campaign, physicists made full use of the brief but precious opportunity to investigate the formation of quark–gluon plasma in the uncharted territory of light ions. Accelerator physicists and experimentalists came together to tackle peculiar problems, such as the appearance of polluting species in the beams due to nuclear transmutation (see p37). Despite the tight schedule, luminosity targets for proton–oxygen, oxygen–oxygen and neon–neon collisions were exceeded by large factors, thanks to high accelerator availability and the high injector intensity delivered by the LHC team.

"These early oxygen and neon studies show that indications of collective flow and parton-energy-loss-like suppression persist even in much smaller systems, while providing new sensitivity to nuclear geometry and valuable prospects for forward-physics studies," concludes Timmins. "The next step is to pin down oxygen's nuclear parton distribution function. That will be crucial for understanding the hadron-suppression patterns we see, with proton–oxygen and ultra-peripheral collisions being great ways to get there."

NEUTRINO PHYSICS

JUNO takes aim at neutrino-mass hierarchy

Compared to the quark sector, the lepton sector is the Wild West of the weak interaction, with large mixing angles and large uncertainties. To tame this wildness, neutrino physicists are set to bring a new generation of detectors online in the next five years, each roughly an order of magnitude larger than its predecessor. The first of these to become operational is the Jiangmen Underground Neutrino Observatory (JUNO) in Guangdong Province, China, which began data taking on 26 August. The new 20 kton liquid-scintillator detector will seek to resolve one of the major open questions in particle physics: whether the third neutrino-mass eigenstate (ν_3) is heavier or lighter than the second (ν_2).

"Building JUNO has been a journey of extraordinary challenges," says JUNO chief engineer Ma Xiaoyan. "It demanded not only new ideas and technologies, but also years of careful planning, testing and perseverance. Meeting the stringent requirements of purity, stability and safety called for the dedication of hundreds of engineers and technicians. Their teamwork and integrity turned a bold design into a functioning detector, ready now to open a new window on the world of neutrinos."

JUNO Collab.

Additional eye *Encompassed by photomultiplier tubes, an engineer shines a light inside the acrylic sphere housing JUNO's liquid-scintillator detector.*

Main goals

Neutrinos interact only via the parity-violating weak interaction, providing direct evidence only for left-handed neutrinos. As a result, right-handed neutrinos are not part of the Standard Model (SM) of particle physics. As the SM explains fermion masses by a coupling of the Higgs field to a left-handed fermion and its right-handed counterpart of the same flavour, neutrinos are predicted to be massless – a prediction still consistent with every effort to directly measure a neutrino mass yet attempted. Yet decades of observations of the flavour oscillations of solar, atmospheric, reactor, accelerator and astrophysical neutrinos have provided incontrovertible indirect evidence that neutrinos must have tiny masses below the sensitivity of instruments to detect. Observations of quantum interference between flavour eigenstates – the electron, muon and tau neutrinos – indicate that there must be a small mass splitting between ν_1 and the slightly more massive ν_2, and a larger mass splitting to ν_3. But it is not yet known whether the mass eigenvalues follow a so-called normal hierarchy, $m_1 < m_2 < m_3$, or an inverted hierarchy, $m_3 < m_1 < m_2$. Resolving this question is the main physics goal of the JUNO experiment.

"Unlike other approaches, JUNO's determination of the mass ordering does not rely on the scattering of neutrinos with atomic electrons in the Earth's crust or the value of the leptonic CP phase, and hence is largely free of parameter degeneracies," explains JUNO spokesperson Wang Yifang. "JUNO will also deliver order-of-magnitude improvements in the precision of several neutrino-oscillation parameters and enable cutting-edge studies of neutrinos from the Sun, supernovae, the atmosphere and the Earth. It will also open new windows to explore unknown physics, including searches for sterile neutrinos and proton decay."

Located 700 m underground near Jiangmen city, JUNO detects antineutrinos produced 53 km away by the Taishan and Yangjiang nuclear power plants. At the heart of the detector is a liquid-scintillator detector inside a 44 m-deep water pool. A stainless-steel truss supports an acrylic sphere housing the liquid scintillator, as well as 20,000 20-inch photomultiplier tubes (PMTs), 25,600 three-inch PMTs, front-end electronics, cabling and anti-magnetic compensation coils. All the PMTs operate simultaneously to capture scintillation light from neutrino interactions and convert it to electrical signals.

To distinguish the extremely fine flavour oscillations that will allow JUNO to observe the neutrino-mass hierarchy, the experiment must achieve an extremely fine energy resolution of almost 50 keV for a typical 3 MeV reactor antineutrino. To attain this, JUNO had to push performance margins in several areas relative to the KamLAND experiment in Japan, which was previously the world's largest liquid-scintillator detector.

"JUNO is a factor 20 larger than KamLAND, yet our required energy resolution is a factor two better," explains Wang. "To achieve this, we have covered the full detector with PMTs with only 3 mm clearance and twice the photo-detection efficiency. By optimising the recipe of the liquid scintillator, we were able to improve its attenuation length by a factor of two to over 20 m, and increase its light yield by 50%."

Go with the flow

Proposed in 2008 and approved in 2013, JUNO began underground construction in 2015. Detector installation started in December 2021 and was completed in December 2024, followed by a phased filling campaign. Within 45 days, the team filled the detector with 60 ktons of ultra-pure water, keeping the liquid-level difference between the inner and outer acrylic spheres within centimetres and maintaining a flow-rate uncertainty below 0.5% to safeguard structural integrity.

Over the next six months, 20 ktons of liquid scintillator progressively filled the 35.4 m diameter acrylic sphere while displacing the water. Stringent requirements on scintillator purity, optical transparency and extremely low radioactivity had to be maintained throughout. In parallel, the collaboration conducted detector debugging, commissioning and optimisation, enabling a seamless transition to full operations at the completion of filling.

JUNO is designed for a scientific lifetime of up to 30 years, with a possible upgrade path allowing a search for neutrinoless double-beta decay, says the team. Such an upgrade would probe the absolute neutrino-mass scale and test whether neutrinos are truly Dirac fermions, as assumed by the SM, or Majorana fermions without distinct antiparticles, as favoured by several attempts to address fundamental questions spanning particle physics and cosmology.

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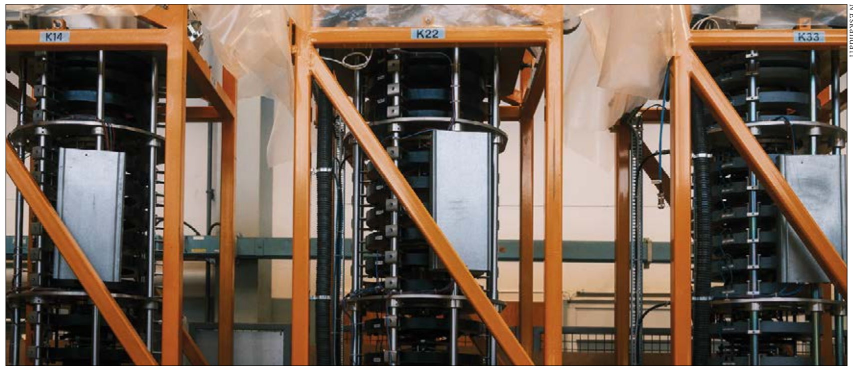
POLICY

Standardising sustainability: step one

For a global challenge like environmental sustainability, the only panacea is international cooperation. In September, the Sustainability Working Group, part of the Laboratory Directors Group (LDG), took a step forward by publishing a report for standardising the evaluation of the carbon impact of accelerator projects. The report challenges the community to align on a common methodology for assessing sustainability and defining a small number of figures of merit that future accelerator facilities must report.

"There's never been this type of report before," says Maxim Titov (CEA Saclay), who co-chairs the LDG Sustainability Working Group. "The LDG Working Group consisted of representatives with technical expertise in sustainability evaluation from large institutions including CERN, DESY, IRFU, INFN, NIKHEF and STFC, as well as experts from future collider projects who signed off on the numbers."



N Eskandari

Powering down *Among other important measures, a new report from the LDG Sustainability Working Group highlights the strategic importance of R&D to improve the energy efficiency of klystrons.*

The report argues that carbon assessment cannot be left to the end of a project. Instead, facilities must evaluate their lifecycle footprint starting from the early design phase, all the way through construction, operation and decommissioning. Studies already conducted on civil-engineering footprints of large accelerator projects outline a reduction potential of up to 50%, says Titov.

In terms of accelerator technology, the report highlights cooling, ventilation, cryogenics, the RF cavities that accelerate charged particles and the klystrons that power them, as the largest sources of inefficiency. The report places particular emphasis on klystrons, and identifies three high-efficiency designs currently under development that could boost the energy efficiency of RF cavities from 60 to 90% (*CERN Courier* May/June 2025 p30).

Carbon assessment cannot be left to the end of a project

The report also addresses the growing footprint of computing and AI. Training algorithms on more efficient hardware and adapting trigger systems to reduce unnecessary computation are identified as ways to cut energy use without compromising scientific output.

"You need to perform a life-cycle assessment at every stage of the project in order to understand your footprint, not just to produce numbers, but to optimise design and improve it in discussions with policymakers," emphasises Titov. "Conducting sustainability assessments is a complex process, as the criteria have to be tailored to the maturity of each project and separately developed for scientists, policymakers, and society applications."

Established by the CERN Council, the LDG is an international coordination body that brings together directors and senior representatives of the world's major accelerator laboratories. Since 2021, the LDG has been composed of five expert panels: high-field magnets, RF structures, plasma and laser acceleration, muon colliders and energy-recovery linacs. The Sustainability Working Group was added in January 2024.

Further reading

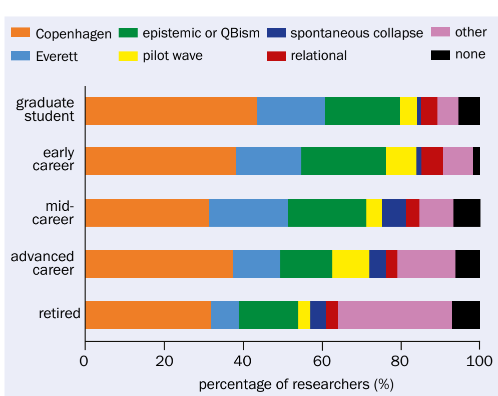
C Bloise *et al.* 2025 arXiv:2509.11705.

INTERPRETATIONS OF QUANTUM MECHANICS

The measurement problem, measured

A century on, physicists still disagree on what quantum mechanics actually means. *Nature* recently surveyed more than a thousand researchers, asking about their views on the interpretation of quantum mechanics. When broken down by career stage, the results show that a diversity of views spans all generations (see "Getting eccentric with age" figure).

The Copenhagen interpretation remains the most widely held view, placing the act of measurement at the core of quantum theory well into the 2020s. Epistemic or QBist approaches, where the quantum state expresses an observer's knowledge or belief, form the next most common group, followed ▷



Nature/D De Blasio

Getting eccentric with age *Preferred interpretation of quantum mechanics by career stage. "Epistemic or QBism" respondents regard the quantum state as representing knowledge or belief rather than an objective property of nature. "Everett" includes many-worlds quantum mechanics and consistent histories. "Other" groups less common responses, such as retrocausal and superdeterministic models, while "none" includes those who selected "Shut up and calculate."*

by Everett's many-worlds framework, in which all quantum outcomes continue to coexist without collapse (*CERN Courier* July/August 2025 p26). Other views maintain small but steady followings, including pilot-wave theory, spontaneous-collapse models and relational quantum mechanics (*CERN Courier* July/August 2025 p21).

Fewer than 10% of physicists surveyed declined to express a view. Though this cohort purports to include proponents of the "shut up and calculate" school of thought, an apparently dwindling cohort of disinterested working physicists may simply be undersampled.

Crucially, confidence is modest. Most respondents view their preferred interpretation as an adequate placeholder or a useful conceptual tool. Only 24% are willing to describe their preferred interpretation as correct, leaving ample room for manoeuvre in the very foundations of fundamental physics.

The Copenhagen interpretation remains the most widely held view

Further reading

nature.com/articles/d41586-025-02342-y.

ASTROWATCH

The puzzle of an excess of bright early galaxies

Since the Big Bang, primordial density perturbations have continually merged and grown to form ever larger structures. This "hierarchical" model of galaxy formation has withstood observational scrutiny for more than four decades. However, understanding the emergence of the earliest galaxies in the first few hundred million years after the Big Bang has remained a key frontier in the field of astrophysics. This is also one of the key science aims of the James Webb Space Telescope (JWST), launched on Christmas Day in 2021.

Its large, cryogenically-cooled mirror and infrared instruments let it capture the faint, redshifted ultraviolet light from the universe's earliest stars and galaxies. Since its launch, the JWST has collected unprecedented samples of astrophysical sources within the first 500 million years of the Big Bang, radically transforming our understanding of early galaxy formation.


Lockheed Martin

Ultraviolet emission, infrared detection *The near-infrared camera of the James Webb Space Telescope.*

Stellar observations

Tantalisingly, JWST's observations hint at an excess of galaxies very bright in the ultra-violet (UV) within the first 400 million years, as compared to expectations from early formation within the standard Lambda Cold Dark matter model. Given that UV photons are a key indicator of young star formation, these observations seem to imply that early galaxies in any given volume of space were overly efficient at forming stars in the infancy of the universe.

However, extraordinary claims demand extraordinary evidence. These puzzling observations have come under immense scrutiny in confirming that the sources lie at the inferred redshifts, and do not just probe over-dense regions that might preferentially host galaxies with high star-formation rates. It could still be the case that the apparent excess of bright galaxies is cosmic variance – a statistical fluctuation caused by the relatively small regions of the sky probed by the JWST so far.

Such observational caveats notwithstanding, theorists have developed a number of distinct "families" of explanations.

UV photons are readily attenuated by dust at low redshifts. If, however, these early galaxies had ejected all of their dust, one might be able to observe almost all of the intrinsic UV light they produced, making them brighter than expected based on lower-redshift benchmarks.

Bias may also arise from detecting only those sources powered by rapid bursts of star formation that briefly elevate galaxies to extreme luminosities.

Several explanations focus on modifying the physics of star formation itself, for example regarding "stellar feedback" – the energy and momentum that newly formed stars inject back into their surrounding gas, that can heat, ionise or expel gas, and slow or shut down further star formation. Early galaxies might have high star-formation rates because stellar feedback was largely inefficient, allowing them to retain most of their gas for further star formation, or perhaps because a larger fraction of gas was able to form stars in the first place.

Extraordinary claims demand extraordinary evidence

While the relative number of low- and high-mass stars in a newly formed stellar population – the initial mass function (IMF) – has been mapped out in the local universe to some extent, its evolution with redshift remains an open question. Since the IMF crucially determines the total UV light produced per unit mass of star formed, a "top-heavy" IMF, with a larger fraction of massive stars compared to that in the local universe, could explain the observations.

Alternatively, the striking ultraviolet light may not arise solely from ordinary young stars – it could instead be powered by accretion onto black holes, which JWST is finding in unexpected numbers.

Alternative cosmologies

Finally, a number of works also appeal to alternative cosmologies to enhance structure formation at such early epochs, invoking an evolving dark-energy equation of state, primordial magnetic fields or even primordial black holes.

A key caveat involved in these observations is that redshifts are often inferred purely from broadband fluxes in different filters – a technique known as photometry. Spectroscopic data are urgently required, not only to verify their exact distances but also to distinguish between different physical scenarios such as bursty star formation, an evolving IMF or contamination by active galactic nuclei, where supermassive black holes accrete gas. Upcoming deep observations with facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) and the Northern Extended Millimeter Array (NOEMA) will be crucial for constraining the dust content of these systems and thereby clarifying their intrinsic star-formation rates. Extremely large surveys with facilities such as Euclid, the Nancy Grace Roman Space Telescope and the Extremely Large Telescope will also be crucial in surveying early galaxies over large volumes and sampling all possible density fields.

Combining these datasets will be critical in shedding light on this unexpected puzzle unearthed by the JWST.

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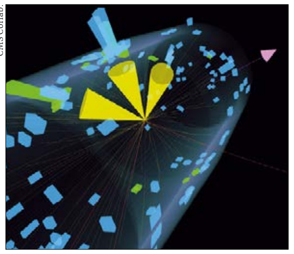
NEWS DIGEST



CMS Collab.

A tWZ candidate in CMS.

One in a trillion
The CMS collaboration has reported the first observation of the production of a top quark together with a W and a Z boson – a process so rare it occurs only once in a trillion proton–proton collisions at the LHC (see above). The measured signal strength of 1.77 ± 0.32 agrees with the Standard Model within 2.3 standard deviations, lifting the statistical sensitivity of the search from an expected 3.5σ to the reported 5.8σ observation (CMS Collab. 2025 CERN-EP-2025-205).

New trials for FLASH therapy
FLASH radiotherapy is one of the most active and promising areas of collaboration between accelerator physicists and medicine, achieving a protective effect for healthy tissues while still damaging tumours (p45). The trick is to deliver ultrahigh dose rates that compress treatment times from minutes to milliseconds – but the protective effect varies by organ and by beam, and questions remain regarding the underlying radiobiology (p27). First proposed in 2014, FLASH was not tested on humans until 2020, when successful clinical trials with proton beams at Cincinnati Children's Hospital in the US suggested that the technique is safe and effective. A new round of clinical trials took place in Cincinnati in August, testing the efficacy of FLASH closer to critical organs such as the lungs and heart – a step that moves the modality nearer to clinical approval.

CLEAR and MEDICIS continue
The CERN Council has granted five-year extensions to the CLEAR electron-beam test facility and the MEDICIS radioisotope facility, ensuring their operation through 2030. Centred around a 20 m linear electron accelerator, CLEAR will continue its work in deep-tissue electron-beam studies, FLASH radiotherapy and testing the radiation hardness of space electronics. Operating within CERN's ISOLDE facility for the study of exotic nuclei, MEDICIS will scale up its production of clinical-grade radionuclides for clinical trials in partner hospitals.

Fusillo on the menu
One way to shrink a magnet's size and make it more energy-efficient can be to make it ridged like fusilli pasta. In August, CERN's Fusillo magnet prototype (pictured)

CERN

Fusillo, the world's first curved-canted-cosine-theta dipole magnet.

successfully passed its first full-scale cryogenic and magnetic performance tests, becoming the world's first operational curved-canted-cosine-theta dipole magnet. The basis of Fusillo's design is a cable wound into two nested coils, which follow the grooves of an outer and inner former; the coils are tilted in opposite directions and produce a dipole field inside the tube, creating a 3 T electromagnet that requires a relatively small 300 A current. At present the magnet must be submerged in liquid helium during operations; the next stage of its R&D will test whether it can be dry-cooled instead. Fusillo is expected to be in use in the new storage ring for High-Intensity-and-Energy ISOLDE within five years, with plans for medical applications in hadron therapy.

Black holes can only grow
On 10 September, the LIGO–Virgo–KAGRA collaboration published the strongest confirmation yet of Stephen Hawking's black-hole area law, which states that the area of event horizons always increases. The team analysed a gravitational-wave event from January this year, finding evidence that the total event-horizon area increased after the merger. The result hinges on the detection of multiple "ringdown modes" – faint, bell-like vibrations emitted as the newly formed black hole settles into a stable state. These oscillations reflect the black hole's final mass and spin, allowing analysts to compare pre- and post-merger areas. While a 2015 study of a near-identical black-hole merger reached 2σ significance for the confirmation of the black-hole area law, the new measurement exceeds 3σ across all models (LIGO–Virgo–KAGRA collab 2025 *Phys. Rev. Lett.* **135** 111403).

First progenitor pinpointed
JWST has been used to identify the progenitor star of a core-collapse supernova for the first time. By comparing JWST infrared images with decades of Hubble observations of host-galaxy NGC 1637 (pictured), the team pinpointed a dust-obscured red supergiant star at the exact site of the blast, confirming it to be

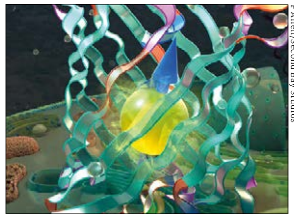
ESA/Hubble & NASA, D Thilker

NGC 1637.

the progenitor. The discovery provides the clearest view yet of a massive star before and after its collapse (C D Kilpatrick *et al.* 2025 *ApJL* **992** L10).

Milky Way's missing wind
Astronomers have found evidence for the long anticipated but previously undetected wind from the Milky Way's central supermassive black hole, Sagittarius A*. Using deep observations from the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile, researchers identified a vast conical cavity in the cold molecular gas surrounding the black hole, stretching at least one parsec and spanning about 45 degrees. The structure's shape and energy suggest it is being actively cleared by a powerful, hot wind driven by Sagittarius A* (M Gorski and E Murchikova 2025 arXiv:2509.10615).

First biological qubit
Molecular engineers at the University of Chicago have shown that fluorescent proteins can act



P Allen/Second Bay Studios

The world's first bioqubit.

as qubits (Jacob S Feder *et al.* 2025 *Nature* **645** 73). "Rather than taking a conventional quantum sensor and trying to camouflage it to enter a biological system, we wanted to explore the idea of using a biological system itself and developing it into a qubit," says David Awschalom, director of the Chicago Quantum Institute. "Fluorescent proteins have become the gold standard for *in vivo* microscopy because of their genetic encodability – a property that we now, for the first time, extend to the quantum world."

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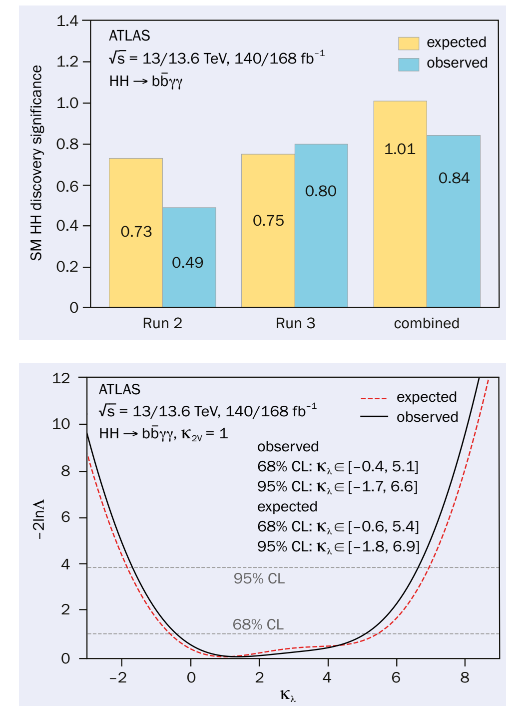
Reports from the Large Hadron Collider experiments

ATLAS

A step towards the Higgs self-coupling

A defining yet unobserved property of the Higgs boson is its ability to couple to itself. The ATLAS collaboration has now set new bounds on this interaction, by probing the rare production of Higgs-boson pairs. Since the self-coupling strength directly connects to the shape of the Higgs potential, any departure from the Standard Model (SM) prediction would have direct implications for electroweak symmetry breaking and the early history of the universe. This makes its measurement one of the most important objectives of modern particle physics.

Higgs-boson pair production is a thousand times less frequent than single-Higgs events, roughly corresponding to a single occurrence every three trillion proton–proton collisions at the LHC. Observing such a rare process demands both vast datasets and highly sophisticated analysis techniques, along with the careful choice of a sensitive probe. Among the most effective is the $HH \rightarrow bb\gamma\gamma$ channel, where one Higgs boson decays into a bottom quark–antiquark pair and the other into two photons. This final state balances the statistical reach of the dominant Higgs decay to bottom quarks with the exceptionally clean signature offered by photon-pair measurements. Despite the small signal branching ratio of about 0.26%, the decay to two photons benefits from the excellent di-photon mass resolution and offers the highest efficiency among the leading HH channels. This provides the $HH \rightarrow bb\gamma\gamma$ channel with an excellent sensitivity to variations in the trilinear self-coupling modifier κ_λ, defined as the ratio of the measured Higgs-boson self-coupling to the SM prediction.



ATLAS Collab, adapted from arXiv: 2507.03495

Fig. 1. *(Top) Observed and expected statistical significances of Higgs-boson pair production in the $HH \rightarrow bb\gamma\gamma$ channel from Run 2 and Run 3 data, and their combination. (Bottom) Likelihood scan of the Higgs-boson self-coupling modifier, showing observed and expected limits at 68% and 95% confidence levels (CL).*

In its new study, the ATLAS collaboration relied on Run 3 data collected between 2022 and 2024, and on the full Run 2 dataset, reaching an integrated luminosity of 308 fb^{-1}. Events were selected with two high-quality photons and at least two b-tagged jets, identified using the latest and most performant ATLAS b-tagging algorithm. To further distinguish signal from background, dominated by non-resonant $\gamma\gamma$+jets and single-Higgs production with $H \rightarrow \gamma\gamma$, a set of machine-learning classifiers called "multivariate analysis discriminants" were trained and used to filter genuine $HH \rightarrow bb\gamma\gamma$ signals.

The collaboration reported an $HH \rightarrow bb\gamma\gamma$ signal significance of 0.84σ under the background-only hypothesis, compared to a SM expectation of 1.01σ (see figure 1). At the 95% confidence level, the self-coupling modifier was constrained to $-1.7 < \kappa_\lambda < 6.6$. These results extend previous Run 2 analyses and deliver a substantially improved sensitivity, comparable to the observed (expected) significance of 0.4σ (1σ) in the combined Run 2 results across all channels. The improvement is primarily due to the adoption of advanced b-tagging algorithms, refined analysis techniques yielding better mass resolution and a larger dataset, more than double that of previous studies.

This result marks significant progress in the search for Higgs self-interactions at the LHC and highlights the potential of Run 3 data. With the full Run 3 dataset and the High-Luminosity LHC on the horizon, ATLAS is set to extend these measurements – improving our understanding of the Higgs boson and searching for possible signs of physics beyond the SM.

Further reading

ATLAS Collab. 2025 arXiv:2507.03495.

ALICE

ALICE observes ρ–proton attraction

The ALICE collaboration recently obtained the first direct measurement of the attraction between a proton and a ρ^0 meson – a particle of particular interest due to its fleeting lifetime and close link to chiral symmetry breaking. The result establishes a technique known as femtoscopy as a new method for studying interactions between vector mesons and baryons, and opens the door to a systematic exploration of how short-lived hadrons behave.

A new method to study how vector mesons and baryons interact

Traditionally, interactions between baryons and vector mesons have been studied indirectly at low-energy facilities, using decay patterns or photo-production measurements. These were mostly interpreted through vector- ▷

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meson-dominance models developed in the 1960s, in which photons fluctuate into vector mesons to interact with hadrons. While powerful, these methods provide only partial information and cannot capture the full dynamics of the interaction. Direct measurements have long been out of reach, mainly because the extremely short lifetime of vector mesons – of the order of 1–10 fm/c – renders conventional scattering experiments impossible.

At the hadronic level, the strong force can be described as arising from the exchange of massive mesons, with the lightest among them, the pion, setting the interaction range to about 1.4 fm. For such a short-range effect to influence the products of a pp collision, the particles must be created close together and with low relative momentum, ensuring sufficient interaction time and a significant wavefunction overlap.

The ALICE collaboration has now studied this mechanism in high-multiplicity proton–proton (pp) collisions, at a centre-of-mass energy of 13 TeV, through femtoscopy, which examines correlations in the relative momentum (k^*) of particle pairs in their rest frame. These were expected to carry information on the size and shape of the particle-emitting source at k^* below about 200 MeV, with any deviations from unity indicating the presence of short-ranged forces.

To study the interaction between protons and ρ^0 vector mesons, candidates were reconstructed via the hadronic decay channel $\rho^0 \to \pi^+\pi^-$, identified from $\pi^+\pi^-$ pairs within the 0.70–0.85 GeV invariant mass window. Since the ρ^0 decays almost instantly into pions, only about 3% of the candidates were genuine ρ^0 mesons. Background corrections were therefore essential to extract the ρ^0–proton correlation function, defined as the ratio of the relative-momentum distribution of same-event pairs to that of mixed-event pairs. The result is consistent with unity at large relative momenta (k^* > 200 MeV), as expected in the absence of strong forces. At lower values, however, a suppression with significance of about four standard deviations clearly signals ρ^0–proton final-state interactions (see figure 1).

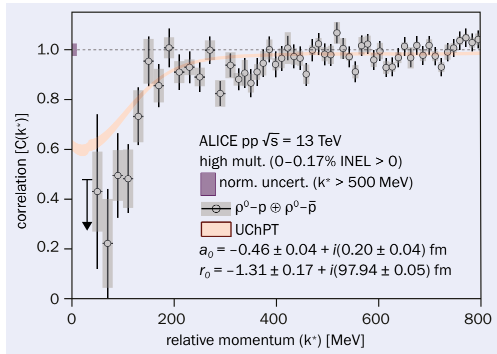

Fig. 1. *The measured ρ^0–proton correlation in high-multiplicity pp collisions. The suppression of ρ^0–proton pairs at low relative momenta indicates an attractive interaction consistent with theoretical predictions.*

To interpret these results, ALICE used an effective field model based on chiral perturbation theory, which predicted two resonance states consistent with the formation of excited nucleon states. Because some pairs linger in these quasi-bound states instead of flying out freely, fewer emerge with nearly the same momentum. This results in a correlation suppression at low k^* consistent with observations. Unlike photoproduction experiments and QCD sum rules, femtoscopy delivers the complete phase information of the ρ^0–proton interaction. By analysing both ρ–proton and ϕ–proton pairs, ALICE extracted precise scattering parameters that can now be incorporated into theoretical models.

This measurement sets a benchmark for vector-meson-dominance models and establishes femtoscopy as a tool to probe interactions involving the shortest-lived hadrons, while providing essential input for understanding ρ–nucleon interactions in vacuum and describing the meson's properties in heavy-ion collisions. Pinning down how the ρ meson behaves is crucial for interpreting dilepton spectra and the restoration of chiral symmetry, as differences between light quark masses become negligible at high energies. For example, the mass gap between the ρ and its axial counterpart, a_1, comes from spontaneous chiral-symmetry breaking.

Further reading
ALICE Collab. 2025 arXiv:2508.09867.

LHCb

Neural networks boost B-tagging

The LHCb collaboration has developed a new inclusive flavour-tagging algorithm for neutral B-mesons. Compared to standard approaches, it can correctly identify 35% more B^0 and 20% more B^0_s decays, expanding the dataset available for analysis. This increase in tagging power will allow for more accurate studies of charge-parity (CP) violation and B-meson oscillations.

In the Standard Model (SM), neutral B-mesons oscillate between particle and antiparticle states via second-order weak interactions involving a pair of W-bosons. Flavour-tagging techniques determine whether a neutral B-meson was initially produced as a B^0 or its antiparticle $\bar{B}^0$, thereby enabling the measurement of time-dependent CP asymmetries. As the initial flavour can only be inferred indirectly from noisy, multi-particle correlations in the busy hadronic environment of the LHC, mistag rates have traditionally been high.

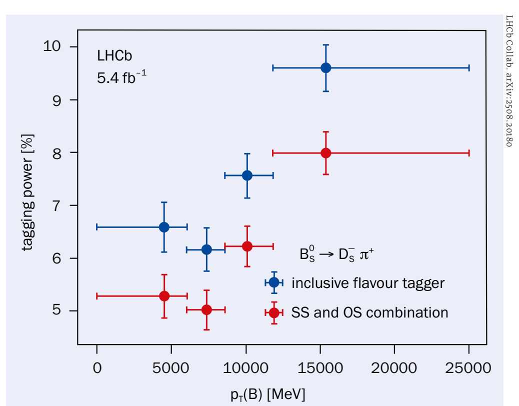

Fig. 1. *Tagging power as a function of the transverse momentum of the neutral B-meson, measured with 5.4 fb^{-1} of LHCb data for $B^0_s \to D^-_s\pi^+$ decays. The inclusive flavour tagger (blue) outperforms the combination of opposite- and same-side taggers (red).*

Until now, the LHCb collaboration has relied on two complementary flavour-tagging strategies. One infers the signal meson's flavour by analysing the decay of the other b-hadron in the event, whose existence follows from $b\bar{b}$ pair production in the original proton-proton collision. Since the two hadrons originate from oppositely-charged, early-produced bottom quarks, the method is known as "opposite-side" (OS) tagging. The other strategy, or "same-side" (SS) tagging, uses tracks from the fragmentation process that produced the signal meson. Each provides only part of the picture, and their combination defined the state of the art in previous analyses.

The new algorithm adopts a more comprehensive approach. Using a deep neural network based on the "DeepSets" ▷ architecture, it incorporates information from all reconstructed tracks associated with the hadronisation process, rather than preselecting a subset of candidates. By considering the global structure of the event, the algorithm builds a more detailed inference of the meson's initial flavour. This inclusive treatment of the available information increases both the sensitivity and the statistical reach of the tagging procedure.

The model was trained and calibrated using well-established B^0 and B^0_s meson decay channels. When compared with the combination of opposite-side and same-side taggers, the inclusive algorithm displayed a 35% increase in tagging power for B^0 mesons and 20% for B^0_s mesons (see figure 1). The improvement stems from gains in both the fraction of events that receive a flavour tag and how often the tag is correct. Tagging power is a critical figure of merit, as it determines the effective amount of usable data. Therefore, even modest gains can dramatically reduce statistical uncertainties in CP-violation and B-oscillation measurements, enhancing the experiment's precision and discovery potential.

This development illustrates how algorithmic innovation can be as important as detector upgrades in pushing the boundaries of precision. The improved tagging power effectively expands the usable data sample without requiring additional collisions, enhancing the experiment's capacity to test the SM and seek signs of new physics within the flavour sector. The timing is particularly significant as LHCb enters Run 3 of the LHC programme, with higher data rates and improved detector components. The new algorithm is designed to integrate smoothly with existing reconstruction and analysis frameworks, ensuring immediate benefits while providing scalability for the much larger datasets expected in future runs.

> **This illustrates how algorithmic innovation can be as important as detector upgrades in pushing the boundaries of precision**

As the collaboration accumulates more data, the inclusive flavour-tagging algorithm is likely to become a central tool in data analysis. Its improved performance is expected to reduce uncertainties in some of the most sensitive measurements carried out at the LHC, strengthening the search for deviations from the SM.

Further reading
LHCb Collab. 2025 arXiv:2508.20180.

CMS

Machine learning and the search for the unknown

In particle physics, searches for new phenomena have traditionally been guided by theory, focusing on specific signatures predicted by models beyond the Standard Model. Machine learning offers a different way forward. Instead of targeting known possibilities, it can scan the data broadly for unexpected patterns, without assumptions about what new physics might look like. CMS analysts are now using these techniques to conduct model-independent searches for short-lived particles that could escape conventional analyses.

Dynamic graph neural networks operate on graph-structured data, processing both the attributes of individual nodes and the relationships between them. One such model is ParticleNet, which represents large-radius-jet constituents as networks to identify N-prong hadronic decays of highly boosted particles, predicting their parent's mass. The tool recently aided a CMS search for the single production of a heavy vector-like quark (VLQ) decaying into a top quark and a scalar boson, either the Higgs or a new scalar particle. Alongside ParticleNet, a custom deep neural network was trained to identify leptonic top-quark decays by distinguishing them from background processes over a wide range of momenta. With this approach, the analysis achieved sensitivity to VLQ production cross-sections as small as 0.15 fb. Emerging methods such as transformer networks can provide even more sensitivity in future searches (see figure 1).

Another novel approach combined two distinct machine-learning tools in the search for a massive scalar X decaying into a Higgs boson and a second scalar Y.

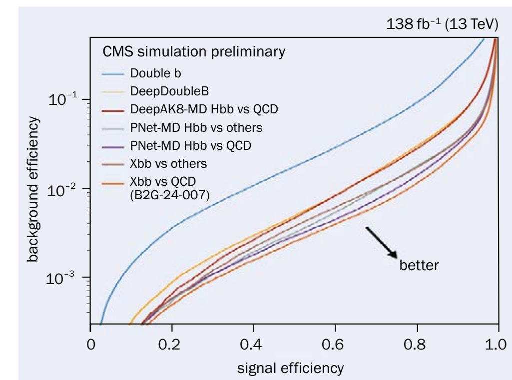

Fig. 1. *The performance of a transformer network tagger for identifying large-radius jets containing two b-quarks (for example, from an $X \to b\bar{b}$ decay), compared with earlier algorithms.*

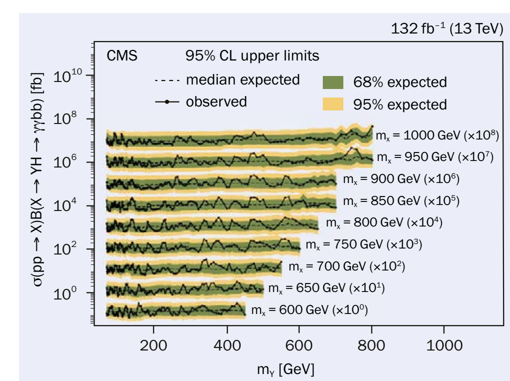

Fig. 2. *Upper limits on the production cross-section times branching fraction, $\sigma \times B(X \to YH \to \gamma\gamma b b)$, as a function of the masses m_X and m_Y.*

While ParticleNet identified Higgs-boson decays to two bottom quarks, potential Y signals were assigned an "anomaly score" by an autoencoder – a neural network trained to reproduce its input and highlight atypical features in the data. This technique provided sensitivity to a wide range of unexpected decays without relying on specific theoretical models. By combining targeted identification with model-independent anomaly detection, the analysis achieved both enhanced performance and broad applicability.

Searches at the TeV scale sit at the frontier where not only more and more data but also algorithmic innovation drives experimental discovery. Tools such as targeted deep neural networks, parametric neural networks (PNNs) – which efficiently scan multi-dimensional mass landscapes (see figure 2) – and model-independent anomaly detection, are opening new ways to search for deviations from the Standard Model. Analyses of the full LHC Run 2 dataset have already revealed intriguing hints, with several machine-learning studies reporting local excesses – including a 3.6σ excess in a search for $V' \to VV$ or $VH \to$ jets, and deviations up to 3.3σ in various $X \to HY$ searches. While no definitive signal has yet emerged, the steady evolution of neural-network techniques is already changing how new phenomena are sought, and anticipation is high for what they may reveal in the larger Run 3 dataset.

Further reading
CMS Collab. CMS-PAS-B2G-23-009.
CMS Collab. CMS-PAS-B2G-24-015.

FIELD NOTES

Reports from events, conferences and meetings

THE INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS

NuFact prepares for a precision era

The 26th edition of the International Workshop on Neutrinos from Accelerators (NuFact) attracted more than 200 physicists to Liverpool from 1 to 6 September. There was no shortage of topics to discuss. Delegates debated oscillations, scattering, accelerators, muon physics, beyond-PMNS physics, detectors, and inclusion, diversity, equity, education and outreach (IDEEO).

Neutrino physics has come a long way since the discovery of neutrino oscillations in 1998. Experiments now measure oscillation parameters with a precision of a few per cent. At NuFact 2025, the IceCube collaboration reported new oscillation measurements using atmospheric neutrinos from 11 years of observations at the South Pole. The measurements achieve world-leading sensitivity on neutrino mixing angles, alongside new constraints on the unitarity of the neutrino mixing matrix. Meanwhile, the JUNO experiment in China celebrated the start of data-taking with its liquid-scintillator detector (see p9). JUNO will determine the neutrino mass ordering by observing the fine oscillation patterns of antineutrinos produced in nuclear reactors.

University of Liverpool

Angles on mixing *Neutrino physicists gathered in Liverpool in September.*

Neutrino physics is one of the most vibrant and global areas of particle physics today

Neutrino scattering

Beyond oscillations, a major theme of the conference was neutrino scattering. Although neutrinos are the most abundant massive particles in the universe, their interactions with matter remain poorly understood. Measuring and modelling these processes is essential: they probe nuclear structure and hadronic physics in a novel way, while also providing the foundation for oscillation analyses in current and next-generation experiments. Exciting advances were reported across the field. The SBND experiment at Fermilab announced the collection of around three million neutrino interactions using the Booster Neutrino Beam. ICARUS presented its first neutrino–argon cross-section measurement. MicroBooNE, MINERvA and T2K showcased new results on neutrino–nucleus interaction and compared them with theoretical models. The e4ν collaboration highlighted electron beams as potential sources of data to refine neutrino-scattering models, supporting efforts to achieve the detailed interaction picture needed for the coming precision era of oscillation physics. At higher energies, FASER and SND@LHC showcased their LHC neutrino observations with both emulsion and electronic detectors.

CERN's role in neutrino physics was on display throughout the conference. Beyond the results from ICARUS, FASER and SND@LHC, other contributions included the first observation of neutrinos in the ProtoDUNE detectors, the status of the MUonE experiment – aimed at measuring the hadronic contribution to the muon anomalous magnetic moment – and the latest results from NA61. The role of CERN's Neutrino Platform was also highlighted in contributions about the T2K ND280 near-detector upgrade and the WAGASCI–BabyMIND detector, both of which were largely assembled and tested at CERN. Discussions featured the results of the Water Cherenkov Test Experiment, which operated in the T9 beamline to prototype technology for Hyper-Kamiokande, and other novel CERN-based ideas, such as nuSCOPE – a proposal for a short-baseline experiment that would "tag" individual neutrinos at production, formed from the merging of ENUBET and NuTag. Building on a proof-of-principle result from NA62, which identified a neutrino candidate via its parent kaon decay, this technique could represent a paradigm shift in neutrino beam characterisation.

NuFact 2025 reinforced the importance of diversity and inclusion in science. The IDEEO working group led discussions on how varied perspectives and equitable participation strengthen collaboration, improve problem solving and attract the next generation of researchers. Dedicated sessions on education and outreach also highlighted innovative efforts to engage wider communities and ensure that the future of neutrino physics is both scientifically robust and socially inclusive. From precision oscillation measurements to ambitious new proposals, NuFact 2025 demonstrated that neutrino physics is one of the most vibrant and global areas of particle physics today.

Laura Munteanu, **Pierre Granger** *and* **Stephen Dolan** *CERN.*

KAONS 2025

Mainz muses on future of kaon physics

The 13th KAONS conference convened almost 100 physicists in Mainz from 8 to 12 September. Since the first edition took place in Vancouver in 1988, the conference series has returned roughly every three years to bring together the global kaon-physics community. This edition was particularly significant, being the first since the decision not to continue CERN's kaon programme with the proposed HIKE experiment (*CERN Courier* May/June 2024 p7).

CERN's current NA62 effort was nevertheless present in force. Eight presentations spanned its wide-ranging programme, from precision studies of rare kaon decays to searches for lepton-flavour and lepton-number violation, and explorations beyond the Standard Model (SM). Complementary perspectives came from Japan's KOTO experiment at J-PARC, from multipurpose facilities such as KLOE-2, Belle II and CERN's LHCb experiment, as well as from a large and engaged theoretical community. Together, these contributions underscored the vitality of kaon physics: a field that continues to test the SM at the highest levels of precision, with a strong potential to uncover new physics.

Kaons 2025

Independent cross-checks *Kaon physics is in a particularly dynamic phase.*

NA62 reported a big success on the so-called "golden mode" ultra-rare decay $K^+ \to \pi^+ \nu \bar{\nu}$, a process that is highly sensitive to new physics (*CERN Courier* July/August 2024 p30). NA62 has already delivered remarkable progress in this domain: by analysing data up to 2022, the collaboration more than doubled its sample from 20 to 51 candidate events, achieving the first 5σ observation of the decay (*CERN Courier* November/December 2024 p11). This is the smallest branching fraction ever measured, and, intriguingly, shows a mild 1.7σ tension with the Standard Model prediction, which itself is known with a 2% theoretical uncertainty. With the experiment continuing to collect data until CERN's next long shutdown (LS3), NA62's final dataset is expected to triple the current statistics, sharpening what is already one of the most stringent tests of the SM.

Another major theme was the study of rare B-meson decays where kaons often appear in the final state, for example $B \to K^* (\to K\pi)\, \ell^+ \ell^-$. Such processes are central to the long-debated "B anomalies," in which certain branching fractions of rare semileptonic B decays show persistent tensions between experimental results and SM predictions (*CERN Courier* January/February 2025 p14). On the experimental front, CERN's LHCb experiment continues to lead the field, delivering branching-fraction measurements with unprecedented precision. Progress is also being made on the theoretical side, though significant challenges remain in matching this precision. The conference highlighted new approaches reducing uncertainties and biases, based both on phenomenological techniques and lattice QCD.

Kaon physics is in a particularly dynamic phase. Theoretical predictions are reaching unprecedented precision, and two dedicated experiments are pushing the frontiers of rare kaon decays. At CERN, NA62 continues to deliver impactful results, even though plans for a next-stage European successor did not advance this year. Momentum is building in Japan, where the proposed KOTO-II upgrade, if approved, would secure the long-term future of the programme. Just after the conference, the KOTO-II collaboration held its first in-person meeting, bringing together members from both KOTO and NA62 – a promising sign for continued cross-fertilisation. Looking ahead, sustaining two complementary experimental efforts remains highly desirable: independent cross-checks and diversified systematics. Both will be essential to fully exploit the discovery potential of rare kaon decays.

Felix Erben *CERN.*

THE INTERNATIONAL COMMITTEE FOR FUTURE ACCELERATORS

ICFA meets in Madison

Once a year, the International Committee for Future Accelerators (ICFA) assembles for an in-person meeting, typically attached to a major summer conference. The 99th edition took place on 24 August at the Wisconsin IceCube Particle Astrophysics Center in downtown Madison, one day before Lepton–Photon 2025.

While the ICFA is neither a decision-making body nor a representation of funding agencies, its mandate assigns to the committee the important task of promoting international collaboration and coordination in all phases of the construction and exploitation of very-high-energy accelerators. This role is especially relevant in today's context of strategic planning and upcoming decisions – with the ongoing European Strategy update, the Chinese decision process on CEPC in full swing, and the new perspectives emerging on the US-American side with the recent National Academy of Sciences report (*CERN Courier* September/October 2025 p10).

Consequently, the ICFA heard presentations on these important topics and discussed priorities and timelines.

Maintaining scientific diversity in an era of potentially vast and costly flagship projects featured prominently

In addition, the theme of "physics beyond colliders" – and with it, the question of maintaining scientific diversity in an era of potentially vast and costly flagship projects – featured prominently. In this context, the importance of national laboratories capable of carrying out mid-sized particle-physics experiments was underlined. This also featured in the usual ICFA regional reports.

An important part of the work of the committee is carried out by the ICFA panels – groups of experts in specific fields of high relevance. The ICFA heard reports from the various panel chairs at the Wisconsin meeting, with a focus on the Instrumentation, Innovation and ▷

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Development panel, where Stefan Söldner-Rembold (Imperial College London) recently took over as chair, succeeding the late Ian Shipsey. Among other things, the panel organises several schools and training events, such as the EDIT schools, as well as prizes that increase recognition for senior and early-career researchers working in the field of instrumentation.

Another focus was the recent work of the Data Lifecycle panel chaired by Kati Lassila-Perini (University of Helsinki). This panel, together with numerous expert stakeholders in the field, recently published recommendations for best practices for data preservation and open science in HEP, advocating the application of the FAIR principles of findability, accessibility, interoperability and reusability at all levels of particle-physics research. The document provides guidance for researchers, experimental collaborations and organisations on implementing best-practice routines. It will now be distributed as broadly as possible and will hopefully contribute to the establishment of open and FAIR science practices.

CERN

Along the Beamline *The "Physics beyond colliders" theme featured heavily at the 99th ICFA meeting.*

Formally, the ICFA is a working group of the International Union for Pure and Applied Physics (IUPAP) and is linked to Commission C11, Particles and Fields. IUPAP has recently begun a "rejuvenation" effort that also involves rethinking the role of its working groups. Reflecting the continuity and importance of the ICFA's work, Marcelo Gameiro Munhoz, chair of C11, presented a proposal to transform the ICFA into a standing committee under C11 – a new type of entity within IUPAP. This would allow ICFA to overcome its transient nature as a working group.

Finally, there were discussions on plans for a new set of ICFA seminars – triennial events in different world regions that assemble up to 250 leaders in the field. Following the 13th ICFA Seminar on Future Perspectives in High-Energy Physics, hosted by DESY in Hamburg in late 2023, the baton has now passed to Japan, which is finalising the location and date for the next edition, scheduled for late 2026.

Thomas Schörner *DESY.*

INVISIBLES25

Invisibles, in sight

CERN

The energetic Invisibles community *The network assembled at CERN, continuing a decade-long conversation on the unseen sectors of the universe.*

Around 150 researchers gathered at CERN from 1 to 5 September to discuss the origin of the observed matter–antimatter asymmetry in the universe, the source of its accelerated expansion, the nature of dark matter and the mechanism behind neutrino masses. The vibrant atmosphere of the annual meeting of the Invisibles research network encouraged lively discussions, particularly among early-career researchers.

Marzia Bordone (University of Zurich) highlighted central questions in flavour physics, such as the tensions in the determinations of quark flavour-mixing parameters and the anomalies in leptonic and semileptonic B-meson decays (*CERN Courier* January/February 2025 p14). She showed that new bosons beyond the Standard Model that primarily interact with the heaviest quarks are theoretically well motivated and could be responsible for these flavour anomalies. Bordone emphasised that collaboration between experiment and theory, as well as data from future colliders like FCC-ee, will be essential to understand whether these effects are genuine signs of new physics.

Lina Necib (MIT) shared impressive new results on the distribution of galactic dark matter. Though invisible, dark matter interacts gravitationally and is present in all galaxies across the universe. Her team used exquisite data from the ESA Gaia satellite to track stellar trajectories in the Milky Way and determine the local dark-matter distribution to within 20–30% precision – which means about 300,000 dark-matter particles per cubic metre assuming they have mass similar to that of the proton. This is a huge improvement over what could be done just one decade ago, and will aid experiments in their direct search for dark matter in laboratories worldwide.

The most quoted dark-matter candidates at Invisibles25 were probably axions: particles once postulated to explain why the strong interactions that bind protons and neutrons behave in the same way for particles and antiparticles. Nicole Righi (King's College London) discussed how these particles are ubiquitous in string theory. According to Righi, their detection may imply a hot Big Bang, with a rather late thermal stage, or hint at some special feature of the geometry of ultracompact dimensions related to quantum gravity.

The most intriguing talk was perhaps the CERN colloquium given by the 2011 Nobel laureate Adam Riess (Johns Hopkins University). By setting up an impressive system of distance measurements to extragalactic systems, Riess and his team have measured the expansion rate of the universe – the Hubble constant – with per cent accuracy. Their results indicate a value about 10% higher than that inferred from the cosmic microwave background within the standard ΛCDM model, a discrepancy known as the "Hubble tension". After more than a decade of scrutiny, no single systematic error appears sufficient to account for it, and theoretical explanations remain tightly constrained (*CERN Courier* March/April 2025 p28). In this regard, Julien Lesgourgues (RWTH Aachen University) pointed out that, despite the thousands of papers written on the Hubble tension, there is no compelling extension of ΛCDM that could truly accommodate it.

While 95% of the universe's energy density is invisible, the community studying it is very real. Invisibles now has a long history and is based on three innovative training networks funded by the European Union, as well as two Marie Curie exchange networks. The network includes more than 100 researchers and 50 PhD students spread across key beneficiaries in Europe, as well as America, Asia and Africa – CERN being one of their long-term partners. The energy and enthusiasm of the participants at this conference were palpable, as nature continues to offer deep mysteries that the Invisibles community strives to unravel.

Miguel Escudero *CERN.*

HIGGS HUNTING 2025

Higgs hunters revel in Run 3 data

L Fayard

Higgs hunters *Researchers discussed Higgs couplings, di-Higgs production and the future of particle accelerators.*

The 15th Higgs Hunting workshop took place from 15 to 17 July at IJCLab in Orsay and LPNHE in Paris. It offered an opportunity to about 100 participants to step back and review the most recent LHC Run 2 and 3 Higgs-boson results, together with some of the latest theoretical developments.

One of the highlights concerned the Higgs boson's coupling to the charm quark, with the CMS collaboration presenting a new search using Higgs production in association with a top–antitop pair. The analysis, targeting Higgs decays into charm–quark pairs, reached a sensitivity comparable to the best existing direct constraints on this elusive interaction. New ATLAS analyses showcased the impact of the large Run 3 dataset, hinting at great potential for Higgs physics in the years to come – for example, Run 3 data has reduced the uncertainties on the coupling of the Higgs boson to muons and Zγ by 30% and 38%, respectively. On the di-Higgs front, the expected upper limit on the signal-strength modifier, measured in the bbγγ final state only, has now surpassed in sensitivity the combination of all Run 2 HH channels (see p15). The sensitivity to di-Higgs production is expected to improve significantly during Run 3, raising hopes of seeing a signal before the next long shutdown, from mid-2026 to the end of 2029.

Juan Rojo (Vrije Universiteit Amsterdam) discussed parton distribution functions for Higgs processes at the LHC, while Thomas Gehrmann (University of Zurich) reviewed recent developments in general Higgs theory. Mathieu Pellen (University of Freiburg) provided a review of vector-boson fusion, Jose Santiago Perez (University of Granada) summarised the effective field theory framework and Oleksii Matsedonskyi (University of Cambridge) reviewed progress on electroweak phase transitions. In his "vision" talk, Alfredo Urbano (INFN Rome) discussed the interplay between Higgs physics and early-universe cosmology. Finally, Benjamin Fuks (LPTHE, Sorbonne University) presented a toponium model, bringing the elusive romance of top–quark pairs back into the spotlight (*CERN Courier* September/October 2025 p9).

After a cruise on the Seine in the light of the Olympic Cauldron, participants were propelled toward the future during the European Strategy for Particle Physics session. The ESPPU secretary Karl Jakobs (University of Freiburg) and various session speakers set the stage for spirited and vigorous discussions of the options before the community – in particular, the scenarios to pursue should the FCC programme, the clear plan A, not be realised. The next Higgs Hunting workshop will be held in Orsay and Paris from 16 to 18 September 2026.

Nicolas Berger *LAPP Annecy,* **Luca Cadamuro** *IJCLab,* **Anne-Catherine Le Bihan** *IPHC.*

WORKSHOP ON THE IMPACT OF HIGGS STUDIES ON NEW THEORIES OF FUNDAMENTAL INTERACTIONS

All aboard the scalar adventure

E Rosi

Untapped potential *Researchers met on the island of Capri, discussing how precision Higgs measurements could probe physics beyond the Standard Model.*

Since the discovery of the Higgs boson in 2012, the ATLAS and CMS collaborations have made significant progress in scrutinising its properties and interactions. So far, measurements are compatible with an elementary Higgs boson, originating from the minimal scalar sector required by the Standard Model. However, current experimental precision leaves ample room for this picture to change. In particular, the full potential of the LHC and its high-luminosity upgrade to search for a richer scalar sector beyond the Standard Model (BSM) is only beginning to be tapped.

The first Workshop on the Impact of Higgs Studies on New Theories of Fundamental Interactions, which took place on the Island of Capri, Italy, from 6 to 10 October 2025, gathered around 40 experimentalists and theorists to explore the pivotal role of the Higgs boson in exploring BSM physics. Participants discussed the implications of extended scalar sectors and the latest ATLAS and CMS searches, including current potential anomalies in LHC data.

"The Higgs boson has moved from the realm of being just a new particle to becoming a tool for searches for BSM particles," said Greg Landsberg (Brown University) in an opening talk. ▷

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An extended scalar sector can address several mysteries in the SM. For example, it could serve as a mediator to a hidden sector that includes dark-matter particles, or play a role in generating the observed matter–antimatter asymmetry during an electroweak phase transition. Modified or extended Higgs sectors also arise in supersymmetric and other BSM models that address why the 125 GeV Higgs boson is so light compared to the Planck mass – despite quantum corrections that should drive it to much higher scales – and might shed light on the perplexing pattern of fermion masses and flavours.

One way to look for new physics in the scalar sector is modifications in the decay rates, coupling strengths and CP-properties of the Higgs boson. Another is to look for signs of additional neutral or charged scalar bosons, such as those predicted in longstanding two-Higgs-doublet or Higgs-triplet models. The workshop saw ATLAS and CMS researchers present their latest limits on extended Higgs sectors, which are based on an increasing number of model-independent or signature-based searches. While the data so far are consistent with the SM, a few mild excesses have attracted the attention of some theorists.

The High-Luminosity LHC will enable us to explore the scalar sector in detail

In diphoton final states, a slight excess of events persists in CMS data at a mass of 95 GeV. Hints of a small excess at a mass of 152 GeV are also present in ATLAS data, while a previously reported excess at 650 GeV has faded after full examination of Run 2 data. Workshop participants also heard suggestions that the Brout–Englert–Higgs potential could allow for a second resonance at 690 GeV.

"We haven't seen concrete evidence for extended Higgs sectors, but intriguing features appear in various mass scales," said CMS collaborator Sezen Sekmen (Kyungpook National University). "Run 3 ATLAS and CMS searches are in full swing, with improved triggering, object reconstruction and analysis techniques."

Di-Higgs production, the rate of which depends on the strength of the Higgs boson's self-coupling, offers a direct probe of the shape of the Brout–Englert–Higgs potential and is a key target of the LHC Higgs programme. Multiple SM extensions predict measurable effects on the di-Higgs production rate. In addition to non-resonant searches in di-Higgs production, ATLAS and CMS are pursuing a number of searches for BSM resonances decaying into a pair of Higgs bosons, which were shown during the workshop.

Rich exchanges between experimentalists and theorists in an informal setting gave rise to several new lines of attack for physicists to explore further. Moreover, the critical role of the High-Luminosity LHC to probe the scalar sector of the SM at the TeV scale was made clear.

"Much discussed during this workshop was the concern that people in the field are becoming demotivated by the lack of discoveries at the LHC since the Higgs, and that we have to wait for a future collider to make the next advance," says organiser Andreas Crivellin (University of Zurich). "Nothing could be further from the truth: the scalar sector is not only the least explored of the SM and the one with the greatest potential to conceal new phenomena, but one that the High-Luminosity LHC will enable us to explore in detail."

Matthew Chalmers *CERN.*

TEN WINDOWS ON THE FUTURE OF PARTICLE PHYSICS

The briefing book of the 2026 update of the European Strategy for Particle Physics was published in October. Paris Sphicas highlights key takeaways from each of its 10 themes in fundamental science and technology.

INFN

Community inputs *The briefing book of the 2026 update of the European Strategy for Particle Physics summarises 266 written submissions and the deliberations of the Open Symposium in Venice, pictured.*

A major step toward shaping the future of European particle physics was reached on 2 October, with the release of the *Physics Briefing Book* of the 2026 update of the European Strategy for Particle Physics. Despite its 250 pages, it is a concise summary of the vast amount of work contained in the 266 written submissions to the strategy process and the deliberations of the Open Symposium in Venice in June (*CERN Courier* September/October 2025 p24).

The briefing book compiled by the Physics Preparatory Group is an impressive distillation of our current knowledge of particle physics, and a preview of the exciting prospects offered by future programmes. It provides the scientific basis for defining Europe's long-term particle-physics priorities and determining the flagship collider that will best advance the field. To this end, it presents comparisons of the physics reach of the different candidate machines, which often have different strengths in probing new physics beyond the Standard Model (SM).

Condensing all this in a few sentences is difficult, though two messages are clear: if the next collider at CERN is an electron–positron collider, the exploration of new physics will proceed mainly through high-precision measurements; and the highest physics reach into the structure of physics beyond the SM via indirect searches will be provided by the combined exploration of the Higgs, electroweak and flavour domains.

Following a visionary outlook for the field from theory, the briefing book divides its exploration of the future of particle physics into seven sectors of fundamental physics and three technology pillars that underpin them.

THE AUTHOR
Paris Sphicas *is the chair of the European Committee for Future Accelerators and a member of the Strategy Secretariat of the 2026 update to the European Strategy for Particle Physics.*

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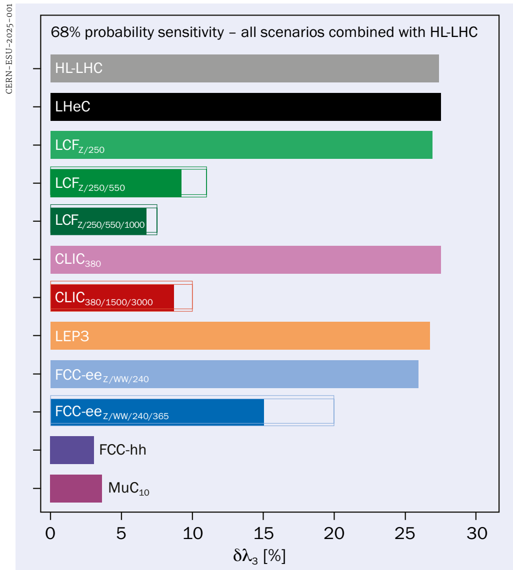

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Higgs self-coupling *The projected sensitivities of future colliders to modifications of the Higgs self-coupling (λ_3). Unshaded bars reflect the effect of theory uncertainties in the determination of λ_3 from single-Higgs-boson measurements.*

1. Higgs and electroweak physics

In the new era that has dawned with the discovery of the Higgs boson, numerous fundamental questions remain, including whether the Higgs boson is an elementary scalar, part of an extended scalar sector, or even a portal to entirely new phenomena. The briefing book highlights how precision studies of the Higgs boson, the W and Z bosons, and the top quark will probe the SM to unprecedented accuracy, looking for indirect signs of new physics.

Addressing these requires highly precise measurements of its couplings, self-interaction and quantum corrections. While the High-Luminosity LHC (HL-LHC) will continue to improve several Higgs and electroweak measurements, the next qualitative leap in precision will be provided by future electron–positron colliders, such as the FCC-ee, the Linear Collider Facility (LCF), CLIC or LEP3. And while these would provide very important information, it would fall upon the shoulders of an energy-frontier machine like the FCC-hh or a muon collider to access potential heavy states. Using the absolute HZZ coupling from the FCC-ee, such machines would measure the single-Higgs-boson couplings with a precision better than 1%, and the Higgs self-coupling at the level of a few per cent (see "Higgs self-coupling" figure).

This anticipated leap in experimental precision will necessitate major advances in theory, simulation and detector technology. In the coming decades, electroweak physics and the Higgs boson in particular will remain a cornerstone of particle physics, linking the precision and energy frontiers in the search for deeper laws of nature.

The book highlights how precision studies of the Higgs boson, the W and Z bosons, and the top quark will probe the SM to unprecedented accuracy

2. Strong interaction physics

Precise knowledge of the strong interaction will be essential for understanding visible matter, exploring the SM with precision, and interpreting future discoveries at the energy frontier. Building upon advanced studies of QCD at the HL-LHC, future high-luminosity electron–positron colliders such as FCC-ee and LEP3 would, like LHeC, enable per-mille precision on the strong coupling constant, and a greatly improved understanding of the transition between the perturbative and non-perturbative regimes of QCD. The LHeC would bring increased precision on parton-distribution functions that would be very useful for many physics measurements at the FCC-hh. FCC-hh would itself open up a major new frontier for strong-interaction studies.

A deep understanding of the strong interaction also necessitates the study of strongly interacting matter under extreme conditions with heavy-ion collisions. ALICE and the other experiments at the LHC will continue to illuminate this physics, revealing insights into the early universe and the interiors of neutron stars.

3. Flavour physics

With high-precision measurements of quark and lepton processes, flavour studies test the SM at energy scales far above those directly accessible to colliders, thanks to their sensitivity to the effects of virtual particles in quantum loops. Small deviations from theoretical predictions could signal new interactions or particles influencing rare processes or CP-violating effects, making flavour physics one of the most sensitive paths toward discovering physics beyond the SM.

Global efforts are today led by the LHCb, ATLAS and CMS experiments at the LHC and by the Belle II experiment at SuperKEKB. These experiments have complementary strengths: huge data samples from proton–proton collisions at CERN and a clean environment in electron–positron collisions at KEK. Combining the two will provide powerful tests of lepton-flavour universality, searches for exotic decays and refinements in the understanding of hadronic effects.

The next major step in precision flavour physics would require "tera-Z" samples of a trillion Z bosons from a high-luminosity electron–positron collider such as the FCC-ee, alongside a spectrum of focused experimental initiatives at a more modest scale.

4. Neutrino physics

Neutrino physics addresses open fundamental questions related to neutrino masses and their deep connections to the matter–antimatter asymmetry in the universe and its cosmic evolution. Upcoming experiments including long-baseline accelerator-neutrino experiments (DUNE and Hyper-Kamiokande), reactor experiments such as JUNO (see p9) and astroparticle observatories (KM3NeT and IceCube, see also *CERN Courier* May/June 2025 p23) will likely unravel the neutrino mass hierarchy and discover leptonic CP violation.

In parallel, the hunt for neutrinoless-double-beta decay continues. A signal would indicate that neutrinos are Majorana fermions, which would be indisputable evidence for new physics! Such efforts extend the reach of particle physics beyond accelerators and deepen connections between disciplines. Efforts to determine the absolute mass of neutrinos are also very important.

The chapter highlights the growing synergy between neutrino experiments and collider, astrophysical and

cosmological studies, as well as the pivotal role of theory developments. Precision measurements of neutrino interactions provide crucial support for oscillation measurements, and for nuclear and astroparticle physics. New facilities at accelerators explore neutrino scattering at higher energies, while advances in detector technologies have enabled the measurement of coherent neutrino scattering, opening new opportunities for new physics searches. Neutrino physics is a truly global enterprise, with strong European participation and a pivotal role for the CERN neutrino platform.

5. Cosmic messengers

Astroparticle physics and cosmology increasingly provide new and complementary information to laboratory particle-physics experiments in addressing fundamental questions about the universe. A rich set of recent achievements in these fields includes high-precision measurements of cosmological perturbations in the cosmic microwave background (CMB) and in galaxy surveys, a first measurement of an extragalactic neutrino flux, accurate antimatter fluxes and the discovery of gravitational waves (GWs).

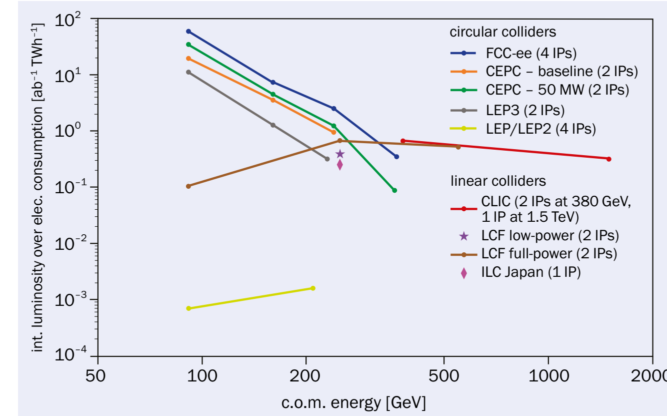
Leveraging information from these experiments has given rise to the field of multi-messenger astronomy. The next generation of instruments, from neutrino telescopes to ground- and space-based CMB and GW observatories, promises exciting results with important clues for particle physics.

6. Beyond the Standard Model

The landscape for physics beyond the SM is vast, calling for an extended exploration effort with exciting prospects for discovery. It encompasses new scalar or gauge sectors, supersymmetry, compositeness, extra dimensions and dark-sector extensions that connect visible and invisible matter.

Many of these models predict new particles or deviations from SM couplings that would be accessible to next-generation accelerators. The briefing book shows that future electron–positron colliders such as FCC-ee, CLIC, LCF and LEP3 have sensitivity to the indirect effects of new physics through precision Higgs, electroweak and flavour measurements. With their per-mille precision measurements, electron–positron colliders will be essential tools for revealing the virtual effects of heavy new physics beyond the direct reach of colliders. In direct searches, CLIC would extend the energy frontier to 1.5 TeV, whereas FCC-hh would extend it to tens of TeV, potentially enabling the direct observation of new physics such as new gauge bosons, supersymmetric particles and heavy scalar partners. A muon collider would combine precision and energy reach, offering a compact high-energy platform for direct and indirect discovery.

This chapter of the briefing book underscores the complementarity between collider and non-collider experiments. Low-energy precision experiments, searches for electric dipole moments, rare decays and axion or dark-photon experiments probe new interactions at extremely small couplings, while astrophysical and cosmological observations constrain new physics over sprawling mass scales.



N Mounet, CERN

Energy efficiency *The nominal annual integrated luminosity delivered by future electron–positron colliders per unit of electrical energy consumed.*

7. Dark matter and the dark sector

The nature of dark matter, and the dark sector more generally, remains one of the deepest mysteries in modern physics. A broad range of masses and interaction strengths must be explored, encompassing numerous potential dark-matter phenomenologies, from ultralight axions and hidden photons to weakly interacting massive particles, sterile neutrinos and heavy composite states. The theory space of the dark sector is just as crowded, with models involving new forces or "portals" that link visible and invisible matter.

As no single experimental technique can cover all possibilities, progress will rely on exploiting the complementarity between collider experiments, direct and indirect searches for dark matter, and cosmological observations. Diversity is the key aspect of this developing experimental programme!

8. Accelerator science and technology

The briefing book considers the potential paths to higher energies and luminosities offered by each proposal for CERN's next flagship project: the two circular colliders FCC-ee and FCC-hh, the two linear colliders LCF and CLIC, and a muon collider; LEP3 and LHeC are also considered as colliders that could potentially offer a physics programme to bridge the time between the HL-LHC and the next high-energy flagship collider. The technical readiness, cost and timeline of each collider are summarised, alongside their environmental impact and energy efficiency (see "Energy efficiency" figure).

The two main development fronts in this technology pillar are high-field magnets and efficient radio-frequency (RF) cavities. High-field superconducting magnets are essential for the FCC-hh, while high-temperature superconducting magnet technology, which presents unique opportunities and challenges, might be relevant to the FCC-hh as a second-stage machine after the FCC-ee. Efficient RF systems are required by all accelerators (*CERN Courier* May/June 2025 p30). Research and development (R&D) on advanced acceleration concepts, such as plasma-wakefield acceleration and muon colliders, also present much promise but necessitate significant work

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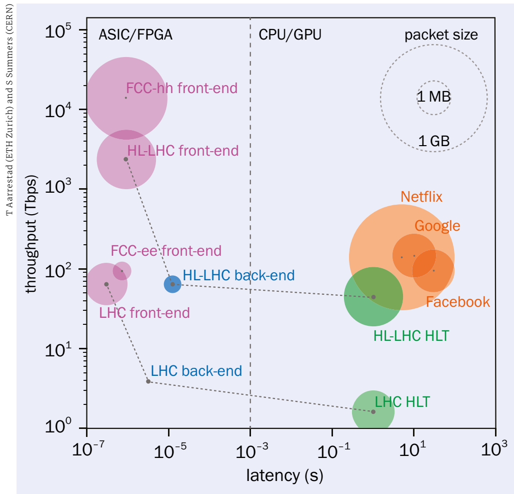
If detectors are the eyes that explore nature, computing is the brain that deciphers the signals they receive



T Aarrestad (ETH Zurich) and S Summers (CERN)

Data challenge *Front-end systems at future colliders will operate at high throughput and low latency, surpassing some of the most demanding computing infrastructures in industry. Throughput is the rate at which data is processed, plotted here in terabits-per-second. Latency is the period available for data processing, plotted here in seconds. The area of the circles represents the logarithm of the average packet or event size in bytes.*

before they can present a viable solution for a future collider.

Preserving Europe's leadership in accelerator science and technology requires a broad and extensive programme of work with continuous support for accelerator laboratories and test facilities. Such investments will continue to be very important for applications in medicine, materials science and industry.

9. Detector instrumentation

A wealth of lessons learned from the LHC and HL-LHC experiments are guiding the development of the next generation of detectors, which must have higher granularity, and – for a hadron collider – a higher radiation tolerance, alongside improved timing resolution and data throughput.

As the eyes through which we observe collisions at accelerators, detectors require a coherent and long-term R&D programme. Central to these developments will be the detector R&D collaborations, which have provided a structured framework for organising and steering the work since the previous update to the European Strategy for Particle Physics. These span the full spectrum of detector systems, with high-rate gaseous detectors, liquid detectors and high-performance silicon sensors for precision timing, precision particle identification, low-mass tracking and advanced calorimetry.

All these detectors will also require advances in readout electronics, trigger systems and real-time data processing. A major new element is the growing role of AI and quantum sensing, both of which already offer innovative methods for analysis, optimisation and detector design (*CERN Courier* July/August 2025 p31). As in computing, there are high hopes and well-founded expectations that these technologies will transform detector design and operation.

To maintain Europe's leadership in instrumentation, it is important to maintain sustained investments in test-beam infrastructures and engineering. This supports a mutually beneficial symbiosis with industry. Detector R&D is a portal to sectors as diverse as medical diagnostics and space exploration, providing essential tools such as imaging technologies, fast electronics and radiation-hard sensors for a wide range of applications.

10. Computing

If detectors are the eyes that explore nature, computing is the brain that deciphers the signals they receive. The briefing book pays much attention to the major leaps in computation and storage that are required by future experiments, with simulation, data management and processing at the top of the list (see "Data challenge" figure). Less demanding in resources, but equally demanding of further development, is data analysis. Planning for these new systems is guided by sustainable computing practices, including energy-efficient software and data centres. The next frontier is the HL-LHC, which will be the testing ground and the basis for future development, and serves as an example for the preservation of the current wealth of experimental data and software (*CERN Courier* September/October 2025 p41).

Several paradigm shifts hold great promise for the future of computing in high-energy physics. Heterogeneous computing integrates CPUs, GPUs and accelerators, providing hugely increased capabilities and better scaling than traditional CPU usage. Machine learning is already being deployed in event simulation, reconstruction and even triggering, and the first signs from quantum computing are very positive. The combination of AI with quantum technology promises a revolution in all aspects of software and of the development, deployment and usage of computing systems.

Some closing remarks

Beyond detailed physics summaries, two overarching issues appear throughout the briefing book.

First, progress will depend on a sustained interplay between experiment, theory and advances in accelerators, instrumentation and computing. The need for continued theoretical development is as pertinent as ever, as improved calculations will be critical for extracting the full physics potential of future experiments.

Second, all this work relies on people – the true driving force behind scientific programmes. There is an urgent need for academia and research institutions to attract and support experts in accelerator technologies, instrumentation and computing by offering long-term career paths. A lasting commitment to training the new generation of physicists who will carry out these exciting research programmes is equally important.

Revisiting the briefing book to craft the current summary brought home very clearly just how far the field of particle physics has come – and, more importantly, how much more there is to explore in nature. The best is yet to come! ●

Further reading

R Forty *et al.* (The Physics Preparatory Group) 2025 CERN-ESU-2025-001.

BIOLOGY AT THE BRAGG PEAK

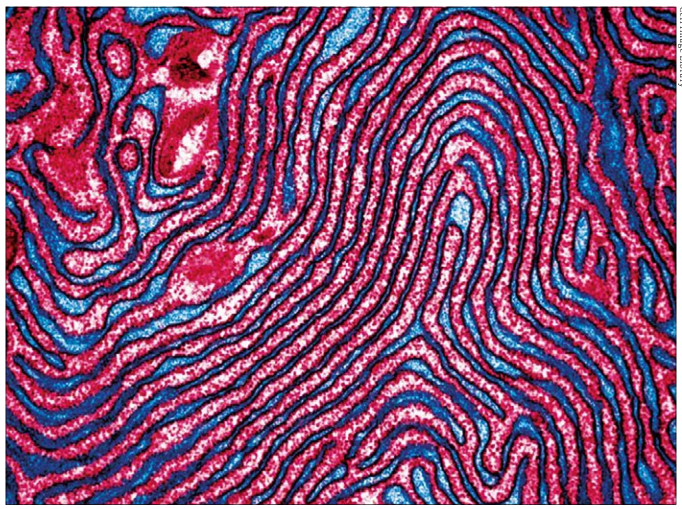
Angelica Facoetti explains five facts accelerator physicists need to know about radiobiology to work at the cutting edge of particle therapy.

In 1895, mere months after Wilhelm Röntgen discovered X-rays, doctors explored their ability to treat superficial tumours. Today, the X-rays are generated by electron linacs rather than vacuum tubes, but the principle is the same, and radiotherapy is part of most cancer treatment programmes.

Charged hadrons offer distinct advantages. Though they are more challenging to manipulate in a clinical environment, protons and heavy ions deposit most of their energy just before they stop, at the so-called Bragg peak, allowing medical physicists to spare healthy tissue and target cancer cells precisely. Particle therapy has been an effective component of the most advanced cancer therapies for nearly 80 years, since it was proposed by Robert R Wilson in 1946.

With the incidence of cancer rising across the world, research into particle therapy is more valuable than ever to human wellbeing – and the science isn't slowing down. Today, progress requires adapting accelerator physics to the demands of the burgeoning field of radiobiology. This is the scientific basis for developing and validating a whole new generation of treatment modalities, from FLASH therapy to combining particle therapy with immunotherapy.

Here are the top five facts accelerator physicists need to know about biology at the Bragg peak.



Cell Image Library

Repair shop *The endoplasmic reticulum (pictured) creates proteins necessary for DNA replication and repair.*

1. 100 keV/µm optimises damage to DNA

Almost every cell's control centre is contained within its nucleus, which houses DNA – your body's genetic instruction manual. If the cell's DNA becomes compromised, it can mutate and lose control of its basic functions, leading the cell to die or multiply uncontrollably. The latter results in cancer.

For more than a century, radiation doses have been effective in halting the uncontrollable growth of cancerous cells. Today, the key insight from radiobiology is that for the same radiation dose, biological effects such as cell death, genetic instability and tissue toxicity differ significantly based on both beam parameters and the tissue being targeted.

Biologists have discovered that a "linear energy transfer" of roughly 100 keV/µm produces the most significant biological effect. At this density of ionisation, the distance between energy deposition events is roughly equal to the diameter of the DNA double helix, creating complex, repair-resistant DNA lesions that strongly reduce cell survival. Beyond 100 keV/µm, energy is wasted.

DNA is the main target of radiotherapy because it holds the genetic information essential for the cell's survival and proliferation. Made up of a double helix that looks like a twisted ladder, DNA consists of two strands of nucleotides held together by hydrogen bonds. The sequence of these nucleotides forms the cell's unique genetic code. A poorly repaired lesion on this ladder leaves a permanent mark on the genome.

When radiation induces a double-strand break, repair is primarily attempted through two pathways: either by rejoining the broken ends of the DNA, or by replacing the break with an identical copy of healthy DNA (see "Repair shop" image). The efficiency of these repairs decreases dramatically when the breaks occur in close spatial proximity or if they are chemically complex. Such scenarios frequently result in lethal mis-repair events or severe alterations in the genetic code, ultimately compromising cell survival.

THE AUTHOR
Angelica Facoetti *CNAO.*

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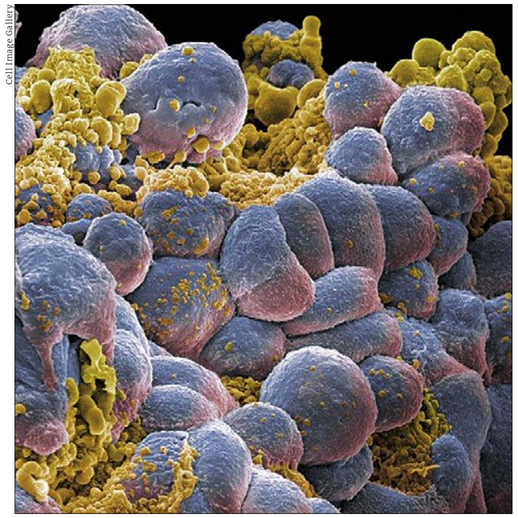
DNA is the main target of radiotherapy because it holds the genetic information essential for the cell's survival and proliferation

This fundamental aspect of radiobiology strongly motivates the use of particle therapy over conventional radiotherapy. Whereas X-rays deliver less than 10 keV/μm, creating sparse ionisation events, protons deposit tens of keV/μm near the Bragg peak, and heavy ions 100 keV/μm or more.

2. Mitochondria and membranes matter too

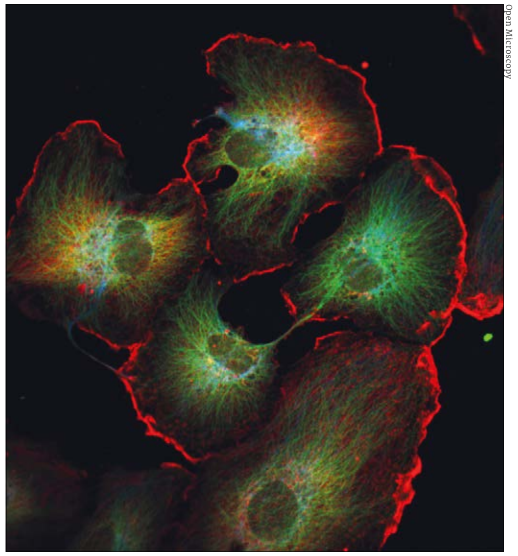
For decades, radiobiology revolved around studying damage to DNA in cell nuclei. However, mounting evidence reveals that an important aspect of cellular dysfunction can be inflicted by damage to other components of cells, such as the cell membrane and the collection of "organelles" inside it. And the nucleus is not the only organelle containing DNA.

Mitochondria generate energy and serve as the body's cellular executioners. If a mitochondrion recognises that its cell's DNA has been damaged, it may order the cell membrane to become permeable. Without the structure of the cell membrane, the cell breaks apart, its fragments carried away by immune cells. This is one mechanism behind "programmed cell death" – a controlled form of death, where the cell essentially presses its own self-destruct button (see "Self-destruct" image).


Cell Image Gallery

Self-destruct *A scanning-electron-microscope image of breast-cancer cells (purple) and cells that have undergone programmed cell death (yellow).*

Irradiated mitochondrial DNA can suffer from strand breaks, base-pair mismatches and deletions in the code. In space-radiation studies, damage to mitochondrial DNA is a serious health concern as it can lead to mutations, premature ageing and even the creation of tumours. But programmed cell death can prevent a cancer cell from multiplying into a tumour. By disrupting the mitochondria of tumour cells, particle irradiation can compromise their energy metabolism and amplify cell death, increasing the permeability of the cell membrane and encouraging the tumour cell to self-destruct. Though a less common occurrence, membrane damage by irradiation can also directly lead to cell death.


Open Microscopy

Communication *Five animal cells with visible nuclei (dark ovals) and cell membranes (red). The middle two cells are exchanging molecular signals (green).*

3. Bystander cells exhibit their own radiation response

For many years, radiobiology was driven by a simple assumption: only cells directly hit by radiation would be damaged. This view started to change in the 1990s, when researchers noticed something unexpected: even cells that had not been irradiated showed signs of stress or injury when they were near the irradiated cells. This phenomenon, known as the bystander effect, revealed that irradiated cells can send biochemical signals to their neighbours, which may in turn respond as if they themselves had been exposed, potentially triggering an immune response (see "Communication" image).

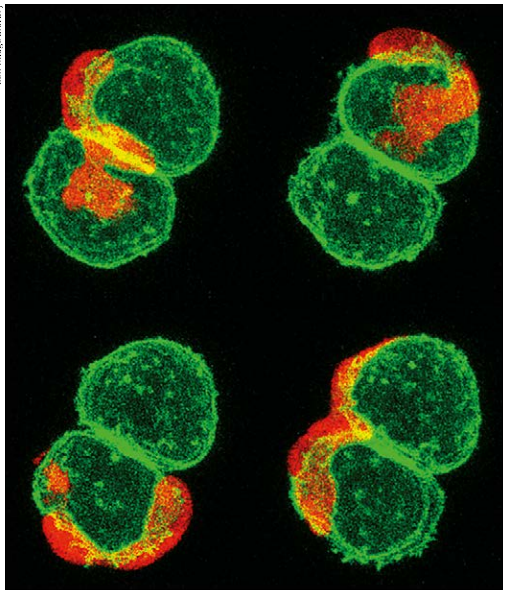
"Non-targeted" effects propagate not only in space, but also in time, through the phenomenon of radiation-induced genomic instability. This temporal dimension is characterised by the delayed appearance of genomic alterations across multiple cell generations. Radiation damage propagates across cells and tissues, and over time, adding complexity beyond the simple dose–response paradigm.

Although the underlying mechanisms remain unclear, the clustered ionisation events produced by carbon ions generate complex DNA damage and cell death, while largely preserving nearby, unirradiated cells.

4. Radiation damage activates the immune system

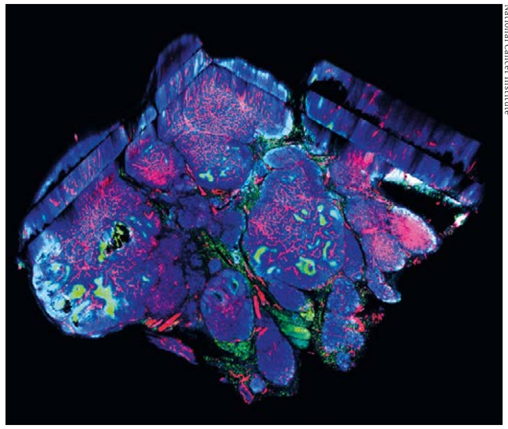
Cancer cells multiply because the immune system fails to recognise them as a threat (see "Immune response" image). The modern pharmaceutical-based technique of immunotherapy seeks to alert the immune system to the threat posed by cancer cells it has ignored by chemically tagging them. Radiotherapy seeks to activate the immune system by inflicting recognisable cellular damage, but long courses of photon radiation can also weaken overall immunity.

This negative effect is often caused by the exposure of circulating blood and active blood-producing organs to radiation doses. Fortunately, particle therapy's ability to tightly conform the dose to the target and subject surrounding tissues to a minimal dose can significantly mitigate the reduction of immune blood cells, better preserving systemic immunity. By inflicting complex, clustered DNA lesions, heavy ions have the strongest potential to directly trigger programmed cell death, even in the most difficult-to-treat cancer cells, bypassing some of the molecular tricks that tumours use to survive, and amplifying the immune response beyond conventional radiotherapy with X-rays. This is linked to the complex, clustered DNA lesions induced by high-energy-transfer radiation, which triggers the DNA damage-repair signals strongly associated with immune activation.


Cell Image Library

Immune response *An immune cell (red) glides over a pair of tumour-precursor cells (green) in a live three-day-old zebrafish embryo.*

These biological differences provide a strong rationale for the rapidly emerging research frontier of combining particle therapy with immunotherapy. Particle therapy's key advantage is its ability to amplify immunogenic cell death, where the cell's surface changes, creating "danger tags" to recruit immune cells to come and kill it, recognise others like it, and kill those too. This ability for particle therapy to mitigate systemic immunosuppression makes it a theoretically superior partner for immunotherapy compared to conventional X-rays.


National Cancer Institute

Oxygen depletion *A mouse model of a breast-cancer tumour. Hypoxic regions are stained green.*

FLASH radiotherapy appears to minimise damage to healthy tissues while maintaining at least the same level of tumour control as conventional methods

5. Ultra-high dose rates protect healthy tissues

In recent years, the attention of clinicians and researchers has focused on the "FLASH" effect– a groundbreaking concept in cancer treatment where radiation is delivered at an ultra-high dose rate in excess of 40 J/kg/s. FLASH radiotherapy appears to minimise damage to healthy tissues while maintaining at least the same level of tumour control as conventional methods. Inflammation in healthy tissues is reduced, and the number of immune cells entering the tumour increased, helping the body fight cancer more effectively. This can significantly widen the therapeutic window – the optimal range of radiation doses that can successfully treat a tumour while minimising toxicity to healthy tissues.

Though the radiobiological mechanisms behind this protective effect remain unclear, several hypotheses have been proposed. A leading theory focuses on oxygen depletion or "hypoxia".

As tumours grow, they outpace the surrounding blood vessels' ability to provide oxygen (see "Oxygen depletion" image). By condensing the dose in a very short time, it is thought that FLASH therapy may induce transient hypoxia within normal tissues too, reducing oxygen-dependent DNA damage there, while killing tumour cells at the same rate. Using a similar mechanism, FLASH therapy may also preserve mitochondrial integrity and energy production in normal tissues.

It is still under investigation whether a FLASH effect occurs with carbon ions, but combining the biological benefits of high-energy-transfer radiation with those of FLASH could be very promising. ●

POLYMATH, HUMANITARIAN, GENTLEMAN

Herwig Schopper, Director-General of CERN from 1981 to 1988, passed away on 19 August at the age of 101. A brilliant scientist, manager and diplomat, Herwig set the course for CERN to become the pre-eminent laboratory for particle physics.

Towards LEP and the LHC *Through farsighted and principled scientific leadership, Herwig Schopper shaped decades of progress in particle physics.*

Herwig Schopper was born on 28 February 1924 in the German-speaking town of Landskron (today, Lanškroun) in the then young country of Czechoslovakia. He enjoyed an idyllic childhood, holidaying at his grandparents' hotel in Abbazia (today, Opatija) on what is now the Croatian Adriatic coast. It was there that his interest in science was awakened through listening in on conversations between physicists from Budapest and Belgrade. In Landskron, he developed an interest in music and sport, learning to play both piano and double bass, and skiing in the nearby mountains. He also learned to speak English, not merely to read Shakespeare as was the norm at the time, but to be able to converse, thanks to a Jewish teacher who had previously spent time in England. This skill was to prove transformational later in life.

The idyll began to crack in 1938 when the Sudetenland was annexed by Germany. War broke out the following year, but the immediate impact on Herwig was limited. He remained in Landskron until the end of his high-school education, graduating as a German citizen – and with no choice but to enlist. Joining the Luftwaffe signals corps, because he thought that would help him develop his knowledge of physics, he served for most of the war on the Eastern Front ensuring that communication lines remained open between military headquarters and the troops on the front lines. As the war drew to a close in March 1945, he was transferred west, just in time to see the Western Allies cross the Rhine at Remagen. Recalled to Berlin and given orders to head further west, Herwig instructed his driver to first make a short detour via Potsdam. This was a sign of the kind of person Herwig was that, amidst the chaos of the fall of Berlin, he wanted to see Schloss Sanssouci, Frederick the Great's temple to the enlightenment, while he had the chance.

By the time Herwig arrived in Schleswig-Holstein, the war was over, and he found himself a prisoner of the British. He later recalled, with palpable relief, that he had managed to negotiate the war without having to shoot at anyone. On discovering that Herwig spoke English, the British military administration engaged him as a translator. This came as a great consolation to Herwig since many of his compatriots were dispatched to the mines to extract the coal that would be used to reconstruct a shattered Germany. Herwig rapidly struck up a friendship with the English captain he was assigned to. This in turn eased his passage to the University of Hamburg, where he began his research career studying optics, and later enabled him to take the first of his scientific sabbaticals when travel restrictions on German academics were still in place (see "Academic overture" image).

THE AUTHORS

James Gillies, Rolf Heuer *and* **Rüdiger Voss** *CERN.*

Virtuosi *Lifelong friends Chien-Shiung Wu and Herwig Schopper, most likely pictured at the Atoms for Peace conference in Geneva in 1958.*

Academic overture *Herwig Schopper while a student studying for his PhD at the University of Hamburg.*

In 1951, Herwig left for a year in Stockholm, where he worked with Lise Meitner on beta decay. He described this time as his first step up in energy from the eV-energies of visible light to the keV-energies of beta-decay electrons. A later sabbatical, starting in 1956, would see him in Cambridge, where he worked under Meitner's nephew, Otto Frisch, in the Cavendish laboratory. As Austrian Jews, both Meitner and Frisch had sought exile before the war. By this time, Frisch had become director of the Cavendish's nuclear physics department and a fellow of the Royal Society.

Initial interactions

While at Cambridge, Herwig took his first steps in the emerging field of particle physics, and became one of the first to publish an experimental verification of Lee and Yang's proposal that parity would be violated in weak interactions. His single-author paper was published soon after that by Chien-Shiung Wu and her team, leading to a lifelong friendship between the two (see "Virtuosi" image).

Following Wu's experimental verification of parity violation, cited by Herwig in his paper, Lee and Yang received the Nobel Prize. Wu was denied the honour, ostensibly on the basis that she was one of a team and the prize can only be shared three ways. It remains in the realm of speculation whether Herwig would have shared the prize had his paper been the first to appear.

A third sabbatical, arranged by Willibald Jentschke, who wanted Herwig to develop a user group for the newly established DESY laboratory, saw the Schopper family move to Ithaca, New York in 1960. At Cornell, Herwig learned the ropes of electron synchrotrons from Bob Wilson. He also learned a valuable lesson in the hands-on approach to leadership. Arriving in Ithaca on a Saturday, Herwig decided to look around the deserted lab. He found one person there, tidying up. It turned out not to be the janitor, but the lab's founder and director, Wilson himself. For Herwig, Cornell represented another big jump in energy, cementing Schopper as an experimental particle physicist.

Herwig's three sabbaticals gave him the skills he would later rely on in hardware development and physics analysis, but it was back in Germany that he honed his management skills and established himself a skilled science administrator.

At the beginning of his career in Hamburg, Herwig worked under Rudolf Fleischmann, and when Fleischmann was offered a chair at Erlangen, Herwig followed. Among the research he carried out at Erlangen was an experiment to measure the helicity of gamma rays, a technique that he'd later deploy in Cambridge to measure parity violation.

It was not long before Herwig was offered a chair himself, and in 1958, at the tender age of 34, he parted from his mentor to move to Mainz. In his brief tenure there, he set wheels in motion that would lead to the later establishment of the Mainz Microtron laboratory, today known as MAMI. By this time, however, Herwig was much in demand, and he soon moved to Karlsruhe, taking up a joint position between the university and the Kernforschungszentrum, KfK. His plan was to merge the two under a single management structure as the Karlsruhe Institute for Experimental Nuclear Physics. In doing so, he laid the seeds for today's Karlsruhe Institute of Technology, KIT.

Pioneering research

At Karlsruhe, Herwig established a user group for DESY, as Jentschke had hoped, and another at CERN. He also initiated a pioneering research programme into superconducting RF and had his first personal contacts with CERN, spending a year there in 1964. In typical Herwig fashion, he pursued his own agenda, developing a device he called a sampling total absorption counter, STAC, to measure neutron energies. At the time, few saw the need for such a device, but this form of calorimetry is now an indispensable part of any experimental particle physicists' armoury.

In 1970, Herwig again took leave of absence from Karlsruhe to go to CERN. He'd been offered the position of head of the laboratory's Nuclear Physics Division, but his stay was to be short lived (see "Prélude" image). The following year, Jentschke took up the position of Director-General

Cornell represented another big jump in energy, cementing Schopper as an experimental particle physicist

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It fell to Herwig both to implement a new management structure for CERN and to see the LEP proposal through to approval

CERN

Prélude *Herwig's first formal role at CERN was in the early 1970s, when he served as head of the Nuclear Physics Division.*

CERN

Architects of LEP *Herwig with Large Electron–Positron collider project leader Emilio Picasso.*

of CERN alongside John Adams. Jentschke was to run the original CERN laboratory, Lab I, while Adams ran the new CERN Lab II, tasked with building the SPS. This left a vacancy at Germany's national laboratory, and the job was offered to Herwig. It was too good an offer to refuse.

As chair of the DESY directorate, Herwig witnessed from afar the discovery of both charm and bottom quarks in the US. Although missing out on the discoveries, DESY's machines were perfect laboratories to study the spectroscopy of these new quark families, and DESY went on to provide definitive measurements. Herwig also oversaw DESY's development in synchrotron light science, repurposing the DORIS accelerator as a light source when its physics career was complete and it was succeeded by PETRA.

The ambition of the PETRA project put DESY firmly on course to becoming an international laboratory, setting the scene for the later HERA model. PETRA experiments went on to discover the gluon in 1979.

The following year, Herwig was named as CERN's next Director-General, taking up office on 1 January 1981. By this time, the CERN Council had decided to call time on its experiment with two parallel laboratories, leaving Herwig with the task of uniting Lab I and Lab II. The Council was also considering plans to build the world's most powerful accelerator, the Large Electron–Positron collider, LEP.

It fell to Herwig both to implement a new management structure for CERN and to see the LEP proposal through to approval (see "Architects of LEP" image). Unpopular decisions were inevitable, making the early years of Herwig's mandate somewhat difficult. In order to get LEP approved, he had to make sacrifices. As a result, the Intersecting Storage Rings (ISR), the world's only hadron collider, collided its final beams in 1984 and cuts had to be made across the research programme. Herwig was also confronted with a period of austerity in science funding, and found himself obliged to commit CERN to constant funding in real terms throughout the construction of LEP, and as it turns out, in perpetuity.

Herwig's battles were not only with the lab's governing body; he also went against the opinions of some of his scientific colleagues concerning the size of the new accelerator. True to form, Herwig stuck with his instinct, insisting that the LEP tunnel should be 27 km around, rather than the more modest 22 km that would have satisfied the immediate research goals while avoiding the difficult geology beneath the Jura mountains. Herwig, however, was looking further ahead – to the hadron collider that would follow LEP. His obstinacy was fully vindicated with the discovery of the Higgs boson in 2012, confirming the Brout–Englert–Higgs mechanism, which had been proposed almost 50 years earlier. This discovery earned the Nobel Prize for Peter Higgs and François Englert in 2013 (see "Towards LEP and the LHC" image, p32).

The CERN blueprint

Difficult though some of his decisions may have been, there is no doubt that Herwig's 1981 to 1988 mandate established the blueprint for CERN to this day. The end of operations of the ISR may have been unpopular, and we'll never know what it may have gone on to achieve, but the world's second hadron collider at the SPS delivered CERN's first Nobel prize during Herwig's mandate, awarded to Carlo Rubbia and Simon van der Meer in 1984 for the discovery of W and Z bosons.

Herwig turned 65 two months after stepping down as CERN Director-General, but retirement was never on his mind. In the years that followed, he carried out numerous roles for UNESCO, applying his diplomacy and foresight to new areas of science. UNESCO was in many ways a natural step for Herwig, whose diplomatic skills had been honed by the steady stream of high-profile visitors to CERN during his mandate as Director-General. At one point, he engineered a meeting at UNESCO between Jim Cronin, who was lobbying for the establishment of a cosmic-ray observatory in Argentina, and the country's president, Carlos Menem. The following day, Menem announced the start of construction of the Pierre Auger Observatory. On another occasion, Herwig was tasked with developing the Soviet gift to Cuba of a small particle accelerator into a working laboratory. That initiative would ultimately come to nothing, but it helped Herwig prepare the groundwork for perhaps his greatest

post-retirement achievement: SESAME, a light-source laboratory in Jordan that operates as an intergovernmental organisation following the CERN model (see "Science diplomacy" image). Mastering the political challenge of establishing an organisation that brings together countries from across the Middle East – including long-standing rivals – required a skill set that few possess.

Although the roots of SESAME can be traced to a much earlier date, by the end of the 20th century, when the idea was sufficiently mature for an interim organisation to be established, Herwig was the natural candidate to lead the new organisation through its formative years. His experience of running international science coupled with his post-retirement roles at UNESCO made him the obvious choice to steer SESAME from idea to reality. It was Herwig who modelled SESAME's governing document on the CERN convention, and it was Herwig who secured the site in Jordan for the laboratory. Today, SESAME is producing world-class research – a shining example of what can be achieved when people set aside their differences and focus on what they have in common.

Herwig never stopped working for what he believed in. When CERN's current Director-General convened a meeting with past Directors-General in 2024, along with the president of the CERN Council, Herwig was present. When initiatives were launched to establish an international research centre in the Balkans, Herwig stepped up to the task. He never lost his sense of what is right, and he never

SESAME/CERN

Science diplomacy *Ground breaking at the SESAME light source in 2003.*

lost his mischievous sense of humour. Following an interview at his house in 2024 for the film *The Peace Particle*, the interviewer asked whether he still played the piano. Herwig stood up, walked to the piano and started to play a very simple arrangement of Christian Sinding's "Rustle of Spring". Just as curious glances started to be exchanged, he transitioned, with a twinkle in his eye, to a beautifully nuanced rendition of Liszt's "Liebestraum No. 3".

Herwig Schopper was a rare combination of genius, polymath, humanitarian and gentleman. Always humble, he could make decisions with nerves of steel when required. His legacy spans decades and disciplines, and has shaped the field of particle physics in many ways. With his passing, the world has lost a truly remarkable individual. He will be sorely missed. ●

Establishing an organisation that brings together countries from across the Middle East required a skill set few possess

Radioactive gold *Isotopes travel hundreds of metres down the LHC beampipe (pictured) following ultraperipheral collisions in ALICE and the other LHC experiments.*

ALCHEMY BY PURE LIGHT

In lead collisions at the LHC, some of the strongest electromagnetic fields in the universe bombard the inside of the beam pipe with radioactive gold. By following the collision fragments, John Jowett explores a little-known link between nuclear physics and the performance limits of heavy-ion colliders.

New results in fundamental physics can be a long time coming. Experimental discoveries of elementary particles have often occurred only decades after their prediction by theory.

Still, the discovery of the fundamental particles of the Standard Model has been speedy in comparison to another longstanding quest in natural philosophy: chrysopoeia, the medieval alchemists' dream of transforming the "base metal" lead into the precious metal gold. This may have been motivated by the observation that the dull grey, relatively abundant metal lead is of similar density to gold, which has been coveted for its beautiful colour and rarity for millennia.

The quest goes back at least to the mythical, or mystical, notion of the philosopher's stone and Zosimos of Panopolis around 300 CE. Its evolution, in various cultures, through medieval times and up to the 19th century, is a fascinating thread in the emergence of modern empirical science from earlier ways of thinking. Some of the leaders of this transition, such as Isaac Newton, also practised alchemy. While the alchemists pioneered many of the techniques of modern chemistry, it was only much later that it became clear that lead and gold are distinct chemical elements and that chemical methods are powerless to transmute one into the other.

With the dawn of nuclear physics in the 20th century, it

THE AUTHOR
John Jowett *CERN and GSI.*

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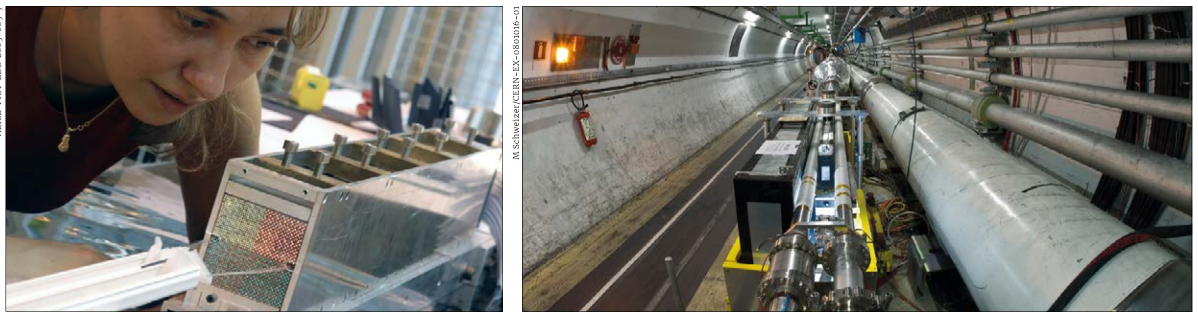
Historic gold *Nuclear physicists transformed other elements into gold at the Harvard Cyclotron in 1940 (left), at Berkely's Bevalac in 1980 (middle, pictured in its Bevatron era, before a new injector transformed it into the world's first relativistic heavy-ion accelerator) and in 2022 at CERN's ISOLDE facility (right).*



Spotting spectators *Fibre bundles from one of ALICE's zero degree calorimeters (left), and their installation 100 metres downstream from the experimental cavern (right).*

was discovered that elements could transform into others through nuclear reactions, either naturally by radioactive decay or in the laboratory. In 1940, gold was produced at the Harvard Cyclotron by bombarding a mercury target with fast neutrons. Some 40 years ago, tiny amounts of gold were produced in nuclear reactions between beams of carbon and neon, and a bismuth target at the Bevalac in Berkeley. Very recently, gold isotopes were produced at the ISOLDE facility at CERN by bombarding a uranium target with proton beams (see "Historic gold" images).

Now, tucked away discreetly in the conclusions of a paper recently published by the ALICE collaboration, one can find the observation, originating from Igor Pshenichnov, Uliana Dmietrieva and Chiara Oppedisano, that "the transmutation of lead into gold is the dream of medieval alchemists which comes true at the LHC."

ALICE has finally measured the transmutation of lead into gold, not via the crucibles and alembics of the alchemists, nor even by the established techniques of nuclear bombardment used in the experiments mentioned above, but in a novel and interesting way that has become possible in "near-miss" interactions of lead nuclei at the LHC.

The transmutation of lead into gold is the dream of medieval alchemists which comes true at the LHC

At the LHC, lead has been transformed into gold by light.

Since the first announcement, this story has attracted considerable attention in the media. Here I would like to put this assertion in scientific context and indicate its relevance in testing our understanding of processes that can limit the performance of the LHC and future colliders such as the FCC.

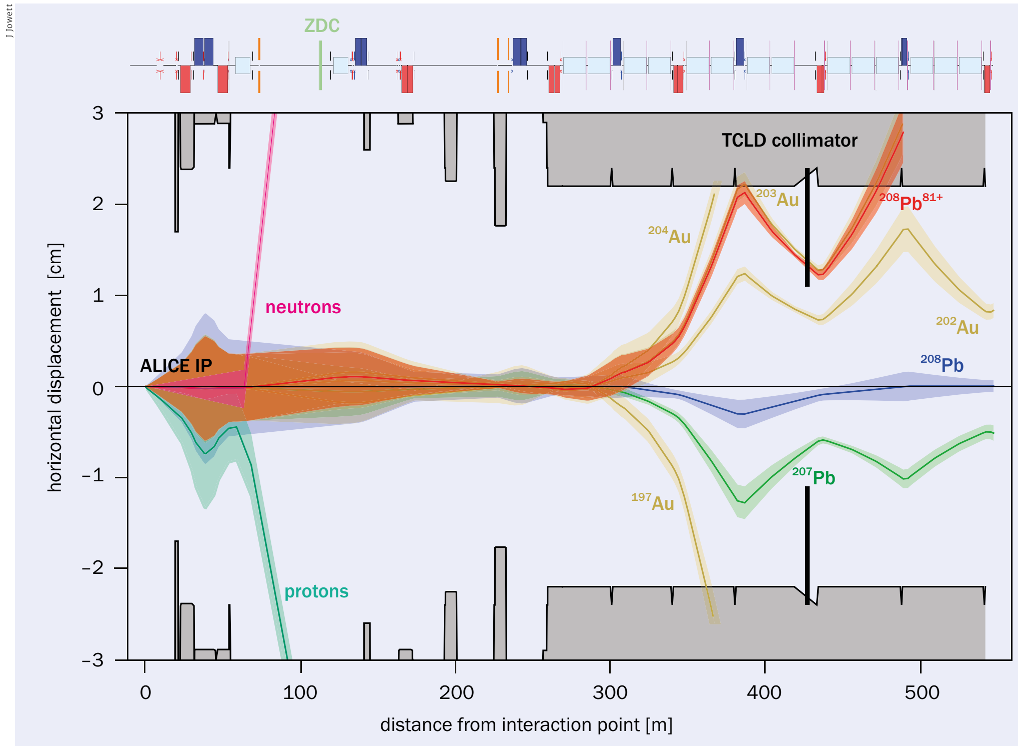
Electromagnetic pancakes

Any charged particle at rest is surrounded by lines of electric fields radiating outwards in all directions. These fields are particularly strong close to a lead nucleus because it contains 82 protons, each with one elementary charge. In the LHC, the lead nuclei travel at 99.999994% of the speed of light, squeezing the field lines into a thin pancake transverse to the direction of motion in the laboratory frame of reference. This compression is so strong that, in the vicinity of the nucleus, we find the strongest magnetic and electric fields known in the universe, trillions of times stronger than even the prodigiously powerful superconducting magnets of the LHC, and orders of magnitude greater than the Schwinger limit where the vacuum polarises or the magnetic fields found in rare, rapidly spinning neutron stars called magnetars. Of course, these fields extend only over a very short time as one nucleus passes by the other. Quantum mechanics, via a famous insight of Fermi, Weizsäcker and Williams, tells us that this electromagnetic flash is equivalent to a pulse of quasi-real photons whose intensity and energy are greatly boosted by the large charge and the relativistic compression.

When two beams of nuclei are brought into collision in the LHC, some hadronic interactions occur. In the unimaginable temperatures and densities of this ultimate crucible we create droplets of the quark–gluon plasma, the main subject of study of the heavy-ion programme. However, when nuclei "just miss" each other, the interactions of these electromagnetic fields amount to photon–photon and photon–nucleus collisions. Some of the processes occurring in these so-called ultra-peripheral collisions (UPCs) are so strong that they would limit the performance of the collider, were it not for special measures implemented in the last 10 years.

The ALICE paper is one among many exploring the rich field of fundamental physics studies opened up by UPCs at the LHC (*CERN Courier* January/February 2025 p31). Among them are electromagnetic dissociation processes where a photon interacting with a nucleus can excite oscillations of its internal structure and result in the ejection of small numbers of neutrons and protons that are detected by ALICE's zero degree calorimeters (ZDCs). The ALICE experiment is unique in having calorimeters to detect spectator protons as well as neutrons (see "Spotting spectators" figure). The residual nuclei are not detected although they contribute to the signals measured by the beam-loss monitor system of the LHC.

Each ^{208}Pb nucleus in the LHC beams contains 82 protons and 208–82 = 126 neutrons. To create gold, a nucleus with a charge of 79, three protons must be removed, together with a variable number of neutrons.



Ultraperipheral products *Calculations of the trajectories of "secondary beams" created by ultraperipheral lead-lead collisions in the ALICE detector. The beams are tracked within the beam pipe (grey) over a distance of 550 m to the right of the interaction point (IP). Beamline elements (top) are shown symbolically: light blue boxes for bending magnets, and dark blue and red boxes for quadrupoles. The primary beam of ^{208}Pb nuclei that did not collide is shown in blue.*

Alchemy in ALICE

While less frequent than the creation of the elements thallium (single-proton emission) or mercury (two-proton emission), the results of the ALICE paper show that each of the two colliding lead-ion beams contribute a cross section of 6.8 ± 2.2 barns to gold production, implying that the LHC now produces gold at a maximum rate of about 89 kHz from lead–lead collisions at the ALICE collision point, or 280 kHz from all the LHC experiments combined. During Run 2 of the LHC (2015–2018), about 86 billion gold nuclei were created at all four LHC experiments, but in terms of mass this was only a tiny 2.9×10^{-11} g of gold. Almost twice as much has already been produced in Run 3 (since 2023).

Strikingly, this gold production is somewhat larger than the rate of hadronic nuclear collisions, which occur at about 50 kHz for a total cross section of 7.67 ± 0.25 barns.

Different isotopes of gold are created according to the number of neutrons that are emitted at the same time as the three protons. To create ^{197}Au, the only stable isotope and the main component of natural gold, a further eight neutrons must be removed – a very unlikely process. Most of the gold produced is in the form of unstable isotopes with lifetimes of the order of a minute.

Although the ZDC signals confirm the proton and neutron emission, the transformed nuclei are not themselves detected by ALICE and their fate is not discussed in the paper. These interaction products nevertheless propagate hundreds of metres through the beampipe in several secondary beams whose trajectories can be calculated, as seen in the "Ultraperipheral products" figure.

The ordinate shows horizontal displacement from the central path of the outgoing beam. This coordinate system is commonly used in accelerator physics as it suppresses the bending of the central trajectory – downwards in the figure – and its separation into the beam pipes of the LHC arcs.

The "5σ" envelope of the intense main beam of ^{208}Pb

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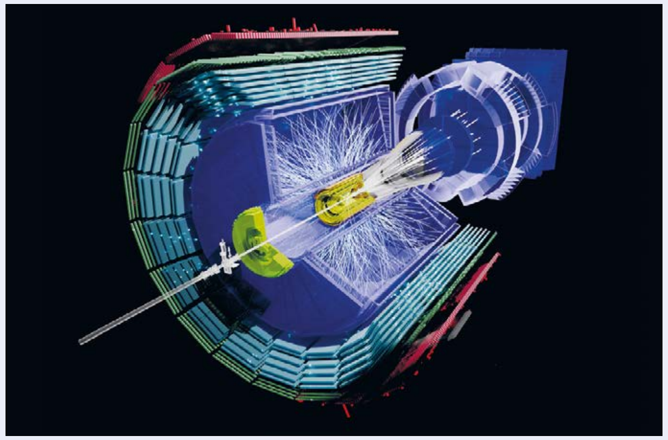
Light-ion collider



A first at the LHC *An oxygen–oxygen collision in the ALICE detector in July 2025.*

Besides lead, the LHC has recently collided beams of ^{16}O and ^{20}Ne (see p8), and nuclear transmutation has manifested itself in another way. In hadronic or electromagnetic events where equal numbers of protons and neutrons are emitted, the outgoing nucleus has almost the same charge-to-mass ratio, since nuclear binding energies are very small at the top of the periodic table. It may then continue to circulate with the original beam, resulting in a small contamination that increases during the several hours of an LHC fill. Hybrid collisions can then occur, for example including a ^{14}N nucleus formed by the ejection of a proton and a neutron from ^{16}O. Fortunately, the momentum spread introduced by the interactions puts many of these nuclei outside the acceptance of the radio-frequency cavities that keep the beams bunched as they circulate around the ring, so the effect is smaller than had first been expected.

nuclei that did not collide is shown in blue. Neutrons from electromagnetic dissociation and other processes are plotted in magenta. They begin with a certain divergence and then travel down the LHC beam pipe in straight lines, forming a cone, until they are detected by the ALICE ZDC, some 114 m away from the collision, after the place where the beam pipe splits in two. Because of the coordinate system, the neutron cone appears to bend sharply at the first separation dipole magnet.

Protons are shown in green. As they only have 40% of the magnetic rigidity of the main beam, they bend quickly away from the central trajectory in the first separation magnet, before being detected by a different part of the ZDC on the other side of the beam pipe.

Photon–photon interactions in UPCs copiously produce electron–positron pairs. In a small fraction of them, corresponding nevertheless to a large cross-section of about 280 barns, the electron is created in a bound state of one of the ^{208}Pb nuclei, generating a secondary beam of ^{208}Pb^{81+} single-electron ions. The beam from this so-called bound-free pair production (BFPP), shown in red, carries a power of about 150 W – enough to quench the superconducting coils of the LHC magnets, causing them to transition from the superconducting to the normal resistive state. Such quenches can seriously disrupt accelerator operation, as the stored magnetic energy is rapidly released as heat within the affected magnet.

To prevent this, new "TCLD" collimators were installed on either side of ALICE during the second long shutdown of the LHC. Together with a variable-amplitude bump in the beam orbit, which pulls the BFPP beam away from the first impact point so that it can be safely absorbed on the TCLD, this allowed the luminosity to be increased to more than six times the original LHC design, just in time to exploit the full capacity of the upgraded ALICE detector in Run 3.

The most powerful beam from an electromagnetic-dissociation process is ^{207}Pb from single neutron emission, plotted in green. It has comparable intensity to ^{208}Pb^{81+} but propagates through the LHC arc to the collimation system at Point 3.

Similar electromagnetic-dissociation processes occur elsewhere, notably in beam interactions with the LHC collimation system. The recent ALICE paper, together with earlier ones on neutron emissions in UPCs, helps to test our understanding of the nuclear interactions that are an essential ingredient of complex beam-physics simulations. These are used to understand and control beam losses that might otherwise provoke frequent magnet quenches or beam dumps. At the LHC, a deep symbiosis has emerged between the fundamental nuclear physics studied by the experiments and the accelerator physics limiting its performance as a heavy-ion collider – or even as a light-ion collider (see "Light-ion collider" panel).

The figure also shows beams of the three heaviest gold isotopes in gold. ^{204}Au has an impact point in a dipole magnet but is far too weak to quench it. ^{203}Au follows almost the same trajectory as the BFPP beam. ^{202}Au propagates through the arc to Point 3. The extremely weak flux of ^{197}Au, the only stable isotope of gold, is also shown.

Worth its weight in gold

Prospecting for gold at the LHC looks even more futile when we consider that the gold nuclei emerge from the collision point with very high energies. They hit the LHC beam pipe or collimators at various points downstream where they immediately fragment in hadronic showers of single protons, neutrons and other particles. The gold exists for tens of milliseconds at most.

And finally, the isotopically pure lead used in CERN's ion source costs more by weight than gold, so realising the alchemists' dream at the LHC was a poor business plan from the outset.

The moral of this story, perhaps, is that among modern-day natural philosophers, LHC physicists take issue with the designation of lead as a "base" metal. We find, on the contrary, that ^{208}Pb, the heaviest stable isotope among all the elements, is worth far more than its weight in gold for the riches of the physics discoveries that it has led us to. ●

Further reading

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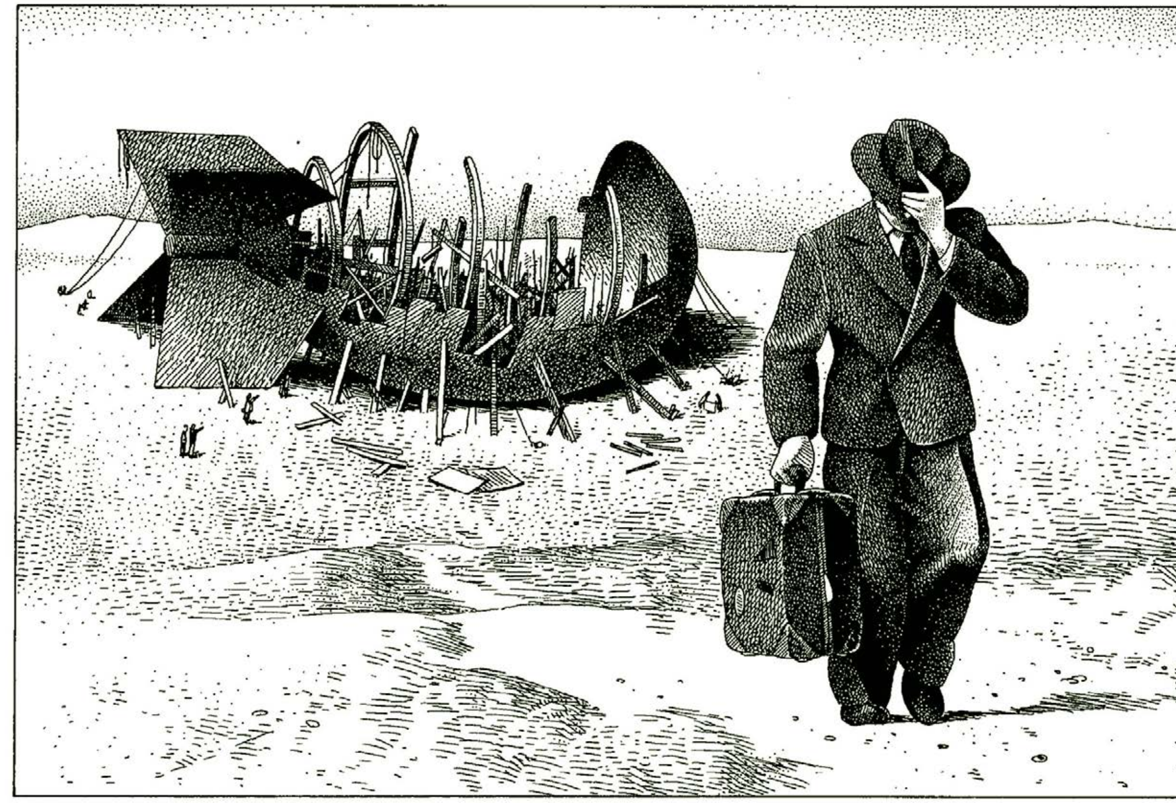
THE PHYSICIST WHO FOUGHT WAR AND CANCER

Subatomic physics has shaped both the conduct of war and the treatment of cancer. Joseph Rotblat, who left the Manhattan Project on moral grounds and later advanced radiotherapy, embodies this dual legacy, as his biographer Andrew Brown recounts.



The courage of his convictions *Joseph Rotblat worked for a short period on the Manhattan Project, before switching from neutron to medical physics and becoming a tireless opponent of nuclear weapons.*

Joseph Rotblat's childhood was blighted by the destruction visited on Warsaw, first by the Tsarist Army, followed by the Central Powers and completed by the Red Army from 1918 to 1920. His father's successful paper-importing business went bankrupt in 1914, and the family became destitute. After a short course in electrical engineering, Joseph and a teenaged friend became jobbing electricians. A committed autodidact, Rotblat found his way into the Free University, where he studied physics under Ludwik Wertenstein. Wertenstein had worked with Marie Skłodowska-Curie in Paris and was the chief of the Radiological Institute in Warsaw as well as teaching at the Free University. He was the first to recognise Rotblat's brilliance and retained him as a researcher at the Institute. Rotblat's main research was neutron-induced artificial radioactivity: he was among the first to induce cobalt-60, which became a standard source in radiotherapy machines before reliable linear accelerators were available.

By the late 1930s, Rotblat had published more than a dozen papers, some in English journals after translation by Wertenstein; the name Rotblat was becoming known in neutron physics. The professor regarded him as the likely

THE AUTHOR

A British radiation oncologist now based in the US, **Andrew Brown** *is the principal biographer of James Chadwick and Joseph Rotblat.*

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LANL

James Chadwick *When already renowned for discovering the neutron, James Chadwick invited Joseph Rotblat to collaborate on neutron physics and nuclear fission at the University of Liverpool, and then to join the British mission to the Manhattan Project in Los Alamos.*

next head of the Radiological Institute and thought he should prepare by working outside Poland. Rotblat wanted to gain experience of the cyclotron and, although he could have joined the Joliot–Curie group in Paris, elected to go to Liverpool where James Chadwick was overseeing a machine expected to produce a proton beam within months. He arrived in Liverpool in April 1939 and was shocked by the city's filth. He also found the scouse dialect of its citizens incomprehensible. Despite the trying circumstances, Rotblat soon impressed Chadwick with his experimental skill and was rewarded with a prestigious fellowship. Chadwick wrote to Wertenstein in June describing Rotblat as "very intelligent and very quick".

Brimming with enthusiasm

Chadwick had formed a long-distance friendship with Ernest Lawrence, the cyclotron's inventor, who kept him apprised of developments in Berkeley. At the time of Rotblat's arrival, Lawrence was brimming with enthusiasm about the potential of neutrons and radioactive isotopes from cyclotrons for medical research, especially in cancer treatment. Chadwick hired Bernard Kinsey, a Cambridge graduate who spent three years with Lawrence, to take charge of the Liverpool cyclotron, and he befriended Rotblat. Liverpool had limited funding: Chadwick complained to Lawrence that the money "this laboratory has been running on in the past few years – is less than some men spend on tobacco." Chadwick served on a Cancer Commission in Liverpool under the leadership of Lord Derby, which planned to bring cancer research to the Liverpool Radium Institute using products from the cyclotron.

Chadwick described Rotblat as "very intelligent and very quick"

The small stipend from the Oliver Lodge fellowship encouraged Rotblat to return to Warsaw in August 1939 to collect his wife, Tola, and bring her to England. She was recovering from acute appendicitis; her doctors persuaded Joseph that she was not fit to travel. So he returned alone on the last train allowed to pass through Berlin before the Germans attacked Poland once more. Tola wrote her last letter to Joseph in December 1939. While he was in Warsaw, Rotblat confided in Wertenstein about his belief that a uranium fission bomb was feasible using fast neutrons, and he repeated this argument to Chadwick when he returned to Liverpool. Chadwick eventually became the leader of the British contingent on the Manhattan Project and arranged for Rotblat to come to Los Alamos in 1944 while remaining a Polish citizen. Rotblat worked in Robert Wilson's cyclotron group and survived a significant radiation accident, receiving an estimated dose of 1.5 J/kg to his upper torso and head. The circumstances of his leaving the project in December 1944 were far more complicated than the moralistic account he wrote in *The Bulletin of the Atomic Scientists* 40 years later, but no less noble.

Tragedy and triumph

As Chadwick wrote to Rotblat in London, he saw "very obvious advantages" for the future of nuclear physics in Britain from Rotblat's return to Liverpool. For one thing, "Rotblat has a wider experience on the cyclotron than anyone now in England," and he also possessed "a mass of information on the equipment used in Project Y [Los Alamos] and Chicago." Chadwick had two major roles in mind for Rotblat. One was to revitalise the depleted Liverpool department and to stimulate cyclotron research in England; and the second to collate the detailed data on nuclear physics brought by British scientists returning from the Manhattan Project. In 1945, Rotblat discovered that six members of his family had miraculously survived the war in Poland, but tragically not Tola. His state of despair deepened after the news of the atomic bombs being used against Japan: he knew about the possibility of a hydrogen bomb, and remembered conversations with Niels Bohr in Los Alamos about the risks of a nuclear arms race. He made two resolutions: to campaign against nuclear weapons and to leave academic nuclear physics and become a medical physicist to use his scientific knowledge for the direct benefit of people.

When Chadwick returned to Liverpool from the US, he found the department in a much better state than he expected. The credit for this belonged largely to Rotblat's leadership; Chadwick wrote to Lawrence praising his outstanding ability, combined with a truly remarkable concern for the staff and students. Chadwick and Rotblat then agreed to build a synchrocyclotron in Liverpool. Rotblat selected the abandoned crypt of an unbuilt Catholic cathedral as the best site, since the local topography would provide some radiation protection. The post-war shortages, especially of steel, made this an extremely ambitious project. Rotblat presented a successful application for the largest university grant to the Department of Science and Industrial Research, and despite design and construction problems resulting in spiralling costs, the machine was in active research use from 1954 to 1968.

With the encouragement of physicians at Liverpool Royal Infirmary, Rotblat started to dabble in nuclear medicine to image thyroid glands and treat haematological disorders. In

Rotblat resolved to campaign against nuclear weapons and use his scientific knowledge for the direct benefit of people

1949 he saw an advert for the chair in physics at the Medical College of St. Bartholomew's Hospital (Bart's) in London and applied. While Rotblat was easily the most accomplished candidate, there was a long delay in his appointment on spurious grounds, such as being over-qualified to teach physics to medical students, likely to be a heavy consumer of research funds and xenophobia. Bart's was a closed, reactionary institution. There was a clear division between the Medical College, with its links to London University, and the hospital, where the post-war teaching was suboptimal as it struggled to recover from the war and adjusted reluctantly to the new National Health Service (NHS). The Medical College, in Charterhouse Square, was severely bombed in the Blitz and the physics department completely destroyed. Rotblat attempted to thwart his main opponent, the dean (described as "secretive and manipulative" in one history), by visiting the hospital and meeting senior clinicians and governors. There was also a determined effort, orchestrated by Chadwick, to retain him in the ranks of nuclear physicists.

When I interviewed Rotblat in 1994, he told me that Chadwick's final tactic was to tell him that he was close to being elected as a fellow of the Royal Society, but if he took the position at Bart's, it would never happen. Rotblat poignantly observed: "He was right." I mentioned this to Lorna Arnold, the nuclear historian, who thought it was a shame. She said she would take it up with her friend Rudolf Peierls. Despite being in poor health, Peierls vowed to correct this omission, and the next year the Royal Society elected Rotblat a fellow at the age of 86.

Full-time medical physicist

Rotblat's first task at Bart's, when he finally arrived in 1950, was to prepare a five-year departmental plan: a task he was well-qualified for after his experience with the synchrocyclotron in Liverpool. With wealthy, centuries-old hospitals such as Bart's allowed to keep their endowments after the advent of the NHS, he also became an active committee member for the new Research Endowment Fund that provided internal grants and hired research assistants. The physics department soon collaborated with the biochemistry, pharmacology and physiology departments that required radioisotopes for research. He persuaded the Medical College to buy a 15 MV linear accelerator from Mullard, an English electronics company, which never worked for long without problems.

During his first two years, in addition to the radioisotope work, he studied the passage of electrons through biological tissue and the energy dissipation of neutrons in tissue – the 1950s were a golden age for radiobiology in England, and Rotblat forged close relationships with Hal Gray and his group at the Hammersmith Hospital. In the mid-1950s, he was approached by Patricia Lindop, a newly qualified Bart's physician who had also obtained a first-class degree in physiology. Lindop had a five-year grant from the Nuffield Foundation to study ageing and, after discussions with Rotblat, it was soon arranged that she would study the acute and long-term effects of radiation in mice at different ages. This was a massive, prospective study that would eventually involve six research assistants and a colony of 30,000 mice. Rotblat acted as the supervisor for her PhD, and they published multiple papers together. In terms of acute death (within 30 days of a high, whole-body dose), she found that mice that were one-day old at exposure could tolerate the highest doses, whereas four-week-old mice were the most vulnerable. The interpretation of long-term

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Joseph Rotblat *Pictured here in his identity-badge photograph at Los Alamos, Rotblat left the Manhattan Project in 1944, once it became clear from Allied intelligence that Germany had abandoned its nuclear programme.*

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Robert Wilson *After working with Joseph Rotblat on the Manhattan Project, Robert Wilson went on to propose proton therapy, which benefits from the localised energy transfer of charged hadrons as they come to a halt at the Bragg peak, and to found Fermilab.*

The Pugwash Conference

Patricia Lindop *A brilliant radiobiologist and physician, Patricia Lindop was Joseph Rotblat's close collaborator in medical physics and peace advocacy for five decades. Lindop (second left) and Rotblat (to her left) are pictured here at the 1958 Pugwash Conference on Science and World Affairs.*

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effects was much less clearcut and provoked major disagreements within the radiobiology community. In a 1994 letter, Rotblat mused on the number of Manhattan Project scientists still alive: "According to my own studies on the effects of radiation on lifespan, I should have been dead a long time, having received a sub-lethal dose in Los Alamos. But here I am, advocating the closure of Los Alamos, Livermore and Sandia, instead of promoting them as health resorts!"

According to my own studies on the effects of radiation on lifespan, I should have been dead a long time

In 1954, the US Bravo test obliterated the Bikini atoll and layered a Japanese fishing boat (*Lucky Dragon No. 5*) that was outside the exclusion zone in the South Pacific with radioactive dust. American scientists realised that the weapon massively exceeded its designed yield, and there was an unconvincing attempt to allay public fear. Rotblat was invited onto BBC's flagship current-affairs programme, *Panorama*, to explain to the public the difference between the original fission bombs and the H-bomb. His lucid delivery impressed Bertrand Russell, a mathematical philosopher and a leading pacifist in World War I, who also spoke on *Panorama*. The two became close friends. When Rotblat went to a radiobiology conference a few months later, he met a Japanese scientist who had analysed the dust recovered from *Lucky Dragon No. 5*. The dust was comprised of about 60% rare-earth isotopes, leading Rotblat to believe that most of the explosive energy was due to fission not fusion. He wrote his own report, not based on any inside knowledge and despite official opposition, concluding this was a fission–fusion–fission bomb and that his TV presentation had underestimated its power by orders of magnitude. Rotblat's report became public just as the British Cabinet decided in secret to develop thermonuclear weapons. The government was concerned that the Americans would view this as another breach of security by an ex-Manhattan Project physicist. Rotblat's reputation as a man of the political left grew within the conservative institution of Bart's.

Russell made a radio address at the end of 1954 to address the global existential threat posed by thermonuclear weapons and urged the public to "remember your humanity and forget the rest". Six months later, Russell announced the Russell–Einstein Manifesto with Rotblat as one of the signatories, and relied upon by Russell to answer questions from the press. The first Pugwash conference followed in 1957 with Rotblat as a prominent contributor. His active involvement, closely supported by Lindop, would last for the rest of his life, as he encouraged communication across the East–West divide and pushed for international arms control agreements. Much of this work took place in his office at Bart's. Rotblat and the Pugwash conference then shared the 1995 Nobel Peace Prize. ●

Further reading

A Brown 2012 *Keeper of the Nuclear Conscience: The Life and Work of Joseph Rotblat* Oxford University Press.

The future of particle therapy

When targeting tumours, protons and heavy ions offer distinct advantages compared to conventional X-ray radiotherapy. PTCOG president Marco Durante describes an exciting future for the technology and shares his vision for closer international cooperation between medicine, academia and industry.

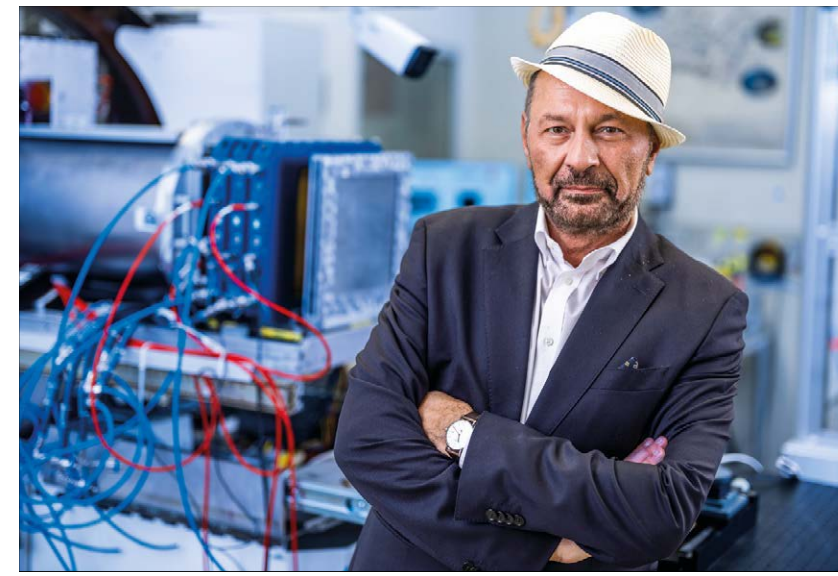
What excites you most about your research in 2025?

2025 has been a very exciting year. We just published a paper in *Nature Physics* about radioactive ion beams.

I also received an ERC Advanced Grant to study the FLASH effect with neon ions. We plan to go back to the 1970s, when Cornelius Tobias in Berkeley thought of using very heavy ions against radio-resistant tumours, but now using FLASH's ultrahigh dose rates to reduce its toxicity to healthy tissues. Our group is also working on the simultaneous acceleration of different ions: carbon ions will stop in the tumour, but helium ions will cross the patient, providing an online monitor of the beam's position during irradiation. The other big news in radiotherapy is vertical irradiation, where we don't rotate the beam around the patient, but rotate the patient around the beam. This is particularly interesting for heavy-ion therapy, where building a rotating gantry that can irradiate the patient from multiple angles is almost as expensive as the whole accelerator. We are leading the Marie Curie UPLIFT training network on this topic.

Why are heavy ions so compelling?

Close to the Bragg peak, where very heavy ions are very densely ionising, the damage they cause is difficult to repair. You can kill the tumours much better than with protons. But carbon, oxygen and neon run the risk of inducing toxicity in healthy tissues. In Berkeley, more than 400 patients were treated with heavy ions. The results were not very good, and it was realised that these ions can be very toxic for normal tissue. The programme was stopped in 1992, and since then there has been no more heavy-ion therapy in the US, though carbon-ion therapy was established in Japan not long after. Today, most of the 130 particle-therapy centres worldwide use protons, but 17 centres across Asia and Europe offer carbon-ion therapy, with one now under construction at the Mayo Clinic in the US. Carbon is very convenient, because the plateau of the Bragg curve is similar to X-rays, while the peak is much more effective than protons. But still, there is evidence that it's not heavy enough, that the charge is not high enough to get rid of very radio-resistant hypoxic tumours – tumours where you don't have enough oxygenation. So that's why we want to go heavier: neon. If we show that you can manage the toxicity using FLASH, then this is something that can be translated into the clinics.



J Hosan, GSI/FAIR

Global leadership *Marco Durante is an internationally recognised radiobiologist and medical physicist, specialising in particle therapy and space-radiation protection. As well as being director of biophysics at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, he currently serves as president of the international Particle Therapy Co-Operative Group (PTCOG).*

There seems to be a lot of research into condensing the dose either in space, in microbeams or, in time, in the FLASH effect…

Absolutely.

Why does that spare healthy tissue at the expense of cancer cells?

That is a question I cannot answer. To be honest, nobody knows. We know that it works, but I want to make it very clear that we need more research to translate it completely to the clinic. It is true that if you either fractionate in space or compress in time, normal tissue is much more resistant, while the effect on the tumour is approximately the same, allowing you to increase the dose

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without harming the patient. The problem is that the data are still controversial.

So you would say that it is not yet scientifically established that the FLASH effect is real?
There is an overwhelming amount of evidence for the strong sparing of normal tissue at specific sites, especially for the skin and for the brain. But, for example, for gastrointestinal tumours the data is very controversial. Some data show no effect, some data show a protective effect, and some data show an increased effectiveness of FLASH. We cannot generalise.

Is it surprising that the effect depends on the tissue?
In medicine this is not so strange. The brain and the gut are completely different. In the gut, you have a lot of cells that are quickly duplicating, while in the brain, you almost have the same number of neurons that you had when you were a teenager – unfortunately, there is not much exchange in the brain.

So, your frontier at GSI is FLASH with neon ions. Would you argue that microbeams are equally promising?
Absolutely, yes, though millibeams more so than microbeams, because microbeams are extremely difficult to go into clinical translation. In the micron region, any kind of movement will jeopardise your spatial fractionation. But if you have millimetre spacing, then this becomes credible and feasible. You can create millibeams using a grid. Instead of having one solid beam, you have several stripes. If you use heavier ions, they don't scatter very much and remain spatially fractionated. There is mounting evidence that fractionated irradiation of the tumour can elicit an immune response and that these immune cells eventually destroy the tumour. Research is still ongoing to understand whether it's better to irradiate with a spatial fractionation of 1 millimetre or to only radiate the centre of the tumour, allowing the immune cells to migrate and destroy the tumour.

What's the biology of the body's immune response to a tumour?
To become a tumour, a cell has to fool the immune system, otherwise our immune system will destroy it. So, we are desperately trying to find a way to teach the immune system to say: "look, this is not a friend – you have to kill it, you have to destroy it." This is immunotherapy, the subject of the Nobel Prize in medicine in 2018 and also related to the 2025 Nobel Prize in medicine on regulation of the immune system. But these drugs don't work for every tumour. Radiotherapy is very useful in this sense, because you kill a lot of cells, and when the immune system sees a lot of dead cells, it activates. A combination of immunotherapy and radiotherapy is now being used more and more in clinical trials.

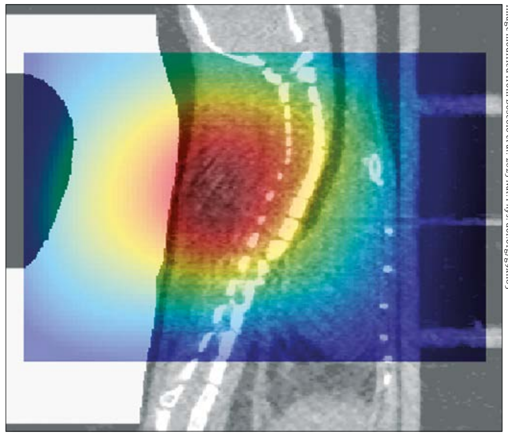


Image modified from Boscolo *et al.* 2025 *Nat. Phys.* doi.org/g9xh83

Radioactive-ion therapy *The activity distribution of a ^{11}C ion beam measured by PET, overlaid on a CT scan of a mouse.*

Accelerator and detector physicists have to learn to speak the language of the non-specialist

You also mentioned radioactive ion beams and the simultaneous acceleration of carbon and helium ions. Why are these approaches advantageous?
The two big problems with particle therapy are cost and range uncertainty. Having energy deposition concentrated at the Bragg peak is very nice, but if it's not in the right position, it can do a lot of damage. Precision is therefore much more important in particle therapy than in conventional radiotherapy, as X-rays don't have a Bragg peak – even if the patient moves a little bit, or if there is an anatomical change, it doesn't matter. That's why many centres prefer X-rays. To change that, we are trying to create ways to see the beam while we irradiate. Radioactive ions decay while they deposit energy in the tumour, allowing you to see the beam using PET. With carbon and helium, you don't see the carbon beam, but you see the helium beam. These are both ways to visualise the beam during irradiation.

How significantly does radiation therapy improve human well-being in the world today?
When I started to work in radiation therapy at Berkeley, many people were telling me: "Why do you waste your time in radiation therapy? In 10 years everything will be solved." At that time, the trend was gene therapy. Other trends have come and gone, and after 35 years in this field, radiation therapy is still a very important tool in a multidisciplinary strategy for killing tumours. More than 50% of cancer patients need radiotherapy, but, even in Europe, it is not available to all patients who need it.

What are the most promising initiatives to increase access to radiotherapy in low- and middle-income countries?
Simply making the accelerators cheaper. The GDP of most countries in Africa, South America and Asia is also steadily increasing, so you can expect that – let's say – in 20 or 30 years from now, there will be a big demand for advanced medical technologies in these countries, because they will have the money to afford it.

Is there a global shortage of radiation physicists?
Yes, absolutely. This is true not only for particle therapy, which requires a high number of specialists to maintain the machine, but also for conventional X-ray radiotherapy with electron linacs. It's also true for diagnostics because you need a lot of medical physicists for CT, PET and MRI.

What is your advice to high-energy physicists who have just completed a PhD or a postdoc, and want to enter medical physics?
The next step is a specialisation course. In about four years, you will become a specialised medical physicist and can start to work in the clinics. Many who take that path continue to do research alongside their clinical work, so you don't have to give up your research career, just reorient it toward medical applications.

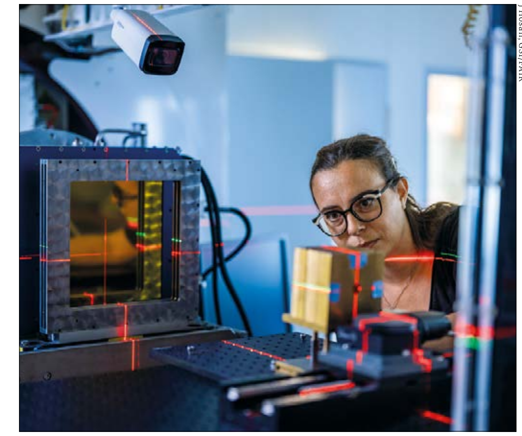
How does PTCOG exert leadership over global research and development?
The Particle Therapy Co-Operative Group (PTCOG) is a very interesting association. Every particle-therapy centre is represented in its steering committee. We have two big roles. One is research, so we really promote

international research in particle therapy, even with grants. The second is education. For example, Spain currently has 11 proton therapy centres under construction. Each will need maybe 10 physicists. PTCOG is promoting education in particle therapy to train the next generation of radiation-therapy technicians and medical oncologists. It's a global organisation, representing science worldwide, across national and continental branches.

Do you have a message for our community of accelerator physicists and detector physicists? How can they make their research more interdisciplinary and improve the applications?
Accelerator physicists especially, but also detector physicists, have to learn to speak the language of the non-specialist. Sometimes they are lost in translation. Also, they have to be careful not to oversell what they are doing, because you can create expectations that are not matched by reality. Tabletop laser-driven accelerators are a very interesting research topic, but don't oversell them as something that can go into the clinics tomorrow, because then you create frustration and disappointment. There is a similar situation with linear accelerators for particle therapy. Since I started to work in this field, people have been saying "Why do we use circular accelerators? We should use linear accelerators." After 35 years, not a single linear accelerator has been used in the clinics. There must also be a good connection with industry, because eventually clinics buy from industry, not academia.

Are there missed opportunities in the way that fundamental physicists attempt to apply their research and make it practically useful with industry and medicine?
In my opinion, it should work the other way around. Don't say "this is what I am good at"; ask the clinical environment, "what do you need?" In particle therapy, we want accelerators that are cheaper and with a smaller footprint. So in whatever research you do, you have to prove to me that the footprint is smaller, and the cost lower.

Do forums exist where medical doctors can tell researchers what they need?
PTCOG is definitely the right place for that. We keep medicine, physics and



J Hosan, GSI/FAIR

Cave M *The beamline for radiobiology and medical physics research at GSI.*

biology together, and it's one of the meetings with the highest industry participation. All the industries in particle therapy come to PTCOG. So that's exactly the right forum where people should talk. We expect 1500 people at the next meeting, which will take place in Deauville, France, from 8 to 13 June 2026, shortly after IPAC.

Are accelerator physicists welcome to engage in PTCOG even if they've not previously worked on medical applications?
Absolutely. This is something that we are missing. Accelerator physicists mostly go to IPAC but not to PTCOG. They should also come to PTCOG to speak more with medical physicists. I would say that PTCOG is 50% medical physics, 30% medicine and 20% biology. So, there are a lot of medical physicists, but we don't have enough accelerator physicists and detector physicists. We need more particle and nuclear physicists to come to PTCOG to see what the clinical and biology community want, and whether they can provide something.

We need more particle and nuclear physicists to come to PTCOG to see what the clinical and biology community want

Do you have a message for policymakers and funding agencies about how they can help push forward research in radiotherapy?
Unfortunately, radiation therapy and even surgery are wrongly perceived as old technologies. There is not much investment in them, and that is a big problem for us. What we miss is good investment at the level of cooperative programmes that develop particle therapy in a collaborative fashion. At the moment, it's becoming increasingly difficult. All the money goes into prevention and pharmaceuticals for immunotherapy and targeted therapy, and this is something that we are trying to revert.

Are large accelerator laboratories well placed to host cooperative research projects?
Both GSI and CERN face the same challenge: their primary mission is nuclear and particle physics. Technological transfer is fine, but they may jeopardise their funding if they stray too far from their primary goal. I believe they should invest more in technological transfer, lobbying their funding agencies to demonstrate that there is a translation of their basic science into something that is useful for public health.

How does your research in particle therapy transfer to astronaut safety?
Particle therapy and space-radiation research have a lot in common. They use the same tools and there are also a lot of overlapping topics, for example radiosensitivity. One patient is more sensitive, one patient is more resistant, and we want to understand what the difference is. The same is true of astronauts – and radiation is probably the main health risk for long-term missions. Space is also a hostile environment in terms of microgravity and isolation, but here we understand the risks, and we have countermeasures. For space radiation, the problem is that we don't understand the risk very well, because the type of radiation is so exotic. We don't have that type of radiation on Earth, so we don't know exactly how big the risk is. Plus, we don't have effective countermeasures, because the radiation is so energetic that shielding will not be enough to protect the crews effectively. We need more research to reduce the uncertainty on the risk, and most of this research is done in ground-based accelerators, not in space.

I understand that you're even looking into cryogenics…
Hibernation is considered science fiction, but it's not science fiction at all – it's something we can recreate in the lab. We call it synthetic torpor. This can be induced in animals that are non-hibernating. Bears and squirrels hibernate; humans and rats don't, but we can induce it. And when

you go into hibernation, you become more radioresistant, providing a possible countermeasure to radiation exposure, especially for long missions. You don't need much food, you don't age very much, metabolic processes are slowed down, and you are protected from radiation. That's for space. This could also be applied to therapy. Imagine you have a patient with multiple metastasis and no hope for treatment. If you can induce synthetic torpor, all the tumours will stop, because when you go into a low temperature and hibernation, the tumours don't grow. This is not the solution, because when you wake the patient up, the tumours will grow again, but what you can do is treat the tumours while you are in hibernation, while healthy tissue is more radiation resistant. The number of research groups working on this is low, so we're quite far from considering synthetic torpor for spaceflight or clinical trials for cancer treatment. First of all, we have to see how long we can keep an animal in synthetic torpor. Second, we should translate into bigger animals like pigs or even non-human primates.

Radiation therapy is probably the best interdisciplinary field that you can work in

In the best-case scenario, what can particle therapy look like in 10 years' time?

Ideally, we should probably at least double the amount of particle-therapy centres that are now available, and expand into new regions. We finally have a particle-therapy centre in Argentina, which is the first one in South America. I would like to see many more in South America and in Africa. I would also like to see more centres that try to tackle tumours where there is no treatment option, like glioblastoma or pancreatic cancer, where the mortality is the same as the incidence. If we can find ways to treat such cancers with heavy ions and give hope to these patients, this would be really useful.

Is there a final thought that you'd like to leave with readers?

Radiation therapy is probably the best interdisciplinary field that you can work in. It's useful for society and it's intellectually stimulating.

I really hope that big centres like CERN and GSI commit more and more to the societal benefits of basic research. We need it now more than ever. We are living in a difficult global situation, and we have to prove that when we invest money in basic research, this is very well invested money. I'm very happy to be a scientist, because in science, there are no barriers, there is no border. Science is really, truly international. I'm an advocate of saying scientific collaboration should never stop.

It didn't even stop during the Cold War. At that time, the cooperation between East and West at the scientist level helped to reduce the risk of nuclear weapons. We should continue this. We don't have to think that what is happening in the world should stop international cooperation in science: it eventually brings peace.

Interview by **Mark Rayner** *editor.*

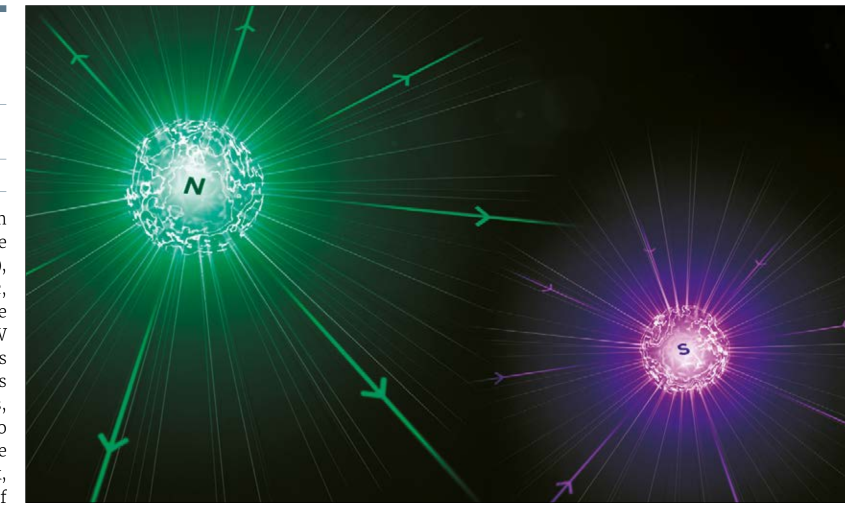
OPINION REVIEWS

Subtleties of quantum fields

Uncovering Quantum Field Theory and the Standard Model: From Fundamental Concepts to Dynamical Mechanisms

By Wolfgang Bietenholz and Uwe-Jens Wiese

Cambridge University Press



D Dominguez, CERN

Not for the faint of heart *In their new book, Wolfgang Bietenholz and Uwe-Jens Wiese discuss subtleties of quantum field theory such as the Witten effect, which would require magnetic monopoles to be electrically charged.*

Quantum field theory unites quantum physics with special relativity. It is the framework of the Standard Model (SM), which describes the electromagnetic, weak and strong interactions as gauge forces, mediated by photons, gluons and W and Z bosons, plus additional interactions mediated by the Higgs field. The success of the SM has exceeded all expectations, and its mathematical structure has led to a number of impressive predictions. These include the existence of the charm quark, discovered in 1974, and the existence of the Higgs boson, discovered in 2012.

Uncovering Quantum Field Theory and the Standard Model by Wolfgang Bietenholz of the National Autonomous University of Mexico and Uwe-Jens Wiese from the University of Bern, explains the foundations of quantum field theory in great depth, from classical field theory and canonical quantisation to regularisation and renormalisation, via path integrals and the renormalisation group. What really makes the book special are frequently discussed relations to statistical mechanics and condensed-matter physics.

Riding a wave

The section on particles and "wavicles" is highly original. In quantum field theory, quantised excitations of fields cannot be interpreted as point-like particles. Unlike massive particles in non-relativistic quantum mechanics, these excitations have non-trivial localisation properties, which apply to photons and electrons alike. To emphasise the difference between non-relativistic particles and wave excitations in a relativistic theory, one may refer to them as "wavicles", following Frank Wilczek. As discussed in chapter 3, an intuitive understanding of wavicles can be gained by the analogy to phonons in a crystal.

The number of quark colours, which is three in nature, plays a prominent role in this book

Another remarkable feature of charged fields is the infinite extension of their excitations due to their Coulomb field. This means that any charged state necessarily includes an infrared cloud of soft gauge bosons. As a result, they cannot be described by ordinary one-particle states and are referred to as "infraparticles". Their properties, along with the related "superselection sectors," are explained in the section on scalar quantum electrodynamics.

The SM can be characterised as a non-abelian chiral gauge theory. Bietenholz and Wiese explain the various aspects of chirality in great detail. Anomalies in global and local symmetries are carefully discussed in the continuum as well as on a space–time lattice, based on the Ginsparg–Wilson relation and Lüscher's lattice chiral symmetry. Confinement of quarks and gluons, the hadron spectrum, the parton model and hard processes, chiral perturbation theory and deconfinement at high temperatures uncover perturbative and non-perturbative aspects of quantum chromodynamics (QCD), the theory of strong interactions. Numerical simulations of strongly coupled lattice Yang–Mills theories are very demanding. During the past four decades, much progress has been made in turning lattice QCD into a quantitative reliable tool by controlling statistical and systematic uncertainties, which is clearly explained to the critical reader. The treatment of QCD is supplemented by an introduction to the electroweak theory covering the Higgs mechanism, electroweak symmetry breaking and flavour physics of quarks and leptons.

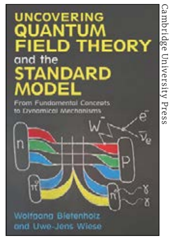
The number of quark colours, which is three in nature, plays a prominent role in this book. At the quantum level, gauge symmetries can fail due to anomalies, rendering a theory inconsistent. The SM is free of anomalies, but this only works because of a delicate interplay between quark and lepton charges and the number of colours. An important example of this interplay is the decay of the neutral pion into two photons. The subtleties of this process are explained in chapter 24.

Most remarkably, the SM predicts baryon-number-violating processes. This arises from the vacuum structure of the weak SU(2) gauge fields, which involves topologically distinct field configurations. Quantum tunnelling ▷

between them, together with the anomaly in the baryon–number current, leads to baryon–number violating transitions, as discussed in chapter 26. Similarly, in QCD a non-trivial topology of the gluon field leads to an explicit breaking of the flavour-singlet axial symmetry and, subsequently, to the mass of the η' meson. Moreover, the gauge field topology gives rise to an additional parameter in QCD, the vacuum-angle θ. Since this parameter induces an electric dipole moment of the neutron that satisfies a strong upper bound, this confronts us with the strong-CP problem: what constrains θ to be so tiny that the experimental upper bound on the neutron dipole moment is satisfied? A solution may be provided by the Peccei–Quinn symmetry and axions, as discussed in a dedicated chapter.

By analogy with the QCD vacuum angle, one can introduce a CP-violating electromagnetic parameter θ into the SM – even though it has no physical effect in pure QED. This brings us to a gem of the book: its discussion of the Witten effect. In the presence of such a θ, the electric charge of a magnetic monopole becomes $\theta/2\pi$ plus an integer. This leads to the remarkable conclusion that for non-zero θ, all monopoles become dyons, carrying both electric and magnetic charge.

The SM is an effective low-energy theory and we do not know at what energy scale elements of a more fundamental theory will become visible. Its gauge structure and quark and lepton content hint at a possible unification of the interactions into a larger gauge group, which is discussed in the final chapter. Once gravity is included, one is confronted with a hierarchy problem: the question of why the electroweak scale is so small compared to the Planck mass, at which the Compton wavelength of a particle and its Schwarzschild radius coincide. Hence, at Planck energies quantum gravitational effects cannot be ignored. Perhaps, solving the electroweak hierarchy puzzle requires working with supersymmetric theories. For all students and scientists struggling with the SM and exploring possible extensions, the nine appendices will be a very valuable source of information for their research.



Cambridge University Press

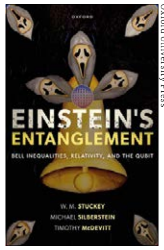
Wilfried Buchmüller *DESY.*

Einstein's Entanglement: Bell Inequalities, Relativity, and the Qubit

By William Stuckey, Michael Silberstein and Timothy McDevitt

Oxford University Press

Why is entanglement so puzzling to physicists, and what has been employed to explain the phenomenon?



Oxford University Press

Quantum entanglement is the quantum phenomenon par excellence. Our world is a quantum world: the matter that we see and touch is the most obvious consequence of quantum physics and it wouldn't really exist the way it is in a purely classical world. However, in our modern parlance when we talk about quantum sensors or quantum computing, what makes these things "quantum" is the employment of entanglement. Entanglement was first discussed by Einstein and Schrödinger, and later became famous with the celebrated EPR (Einstein–Podolsky–Rosen) paper of 1935.

The magic of entanglement

In an entangled particle system, some properties have to be assigned to the system itself and not to individual particles. When a neutral pion decays into two photons, for example, conservation of angular momentum requires their total spin to be zero. Since the photons travel in opposite directions in the pion's rest frame, in order for their spins to cancel they must share the same "helicity". Helicity is the spin projection along the direction of motion, and only two states are possible: left- or right-handed. If one photon is measured to be left-handed, the other must be left-handed as well. The entangled photons must be thought of as a single quantum object: neither do the individual particles have predefined spins nor does the measurement performed on one cause the other to pick a spin orientation. Experiments in more complicated systems have ruled these possibilities out, at least in their simplest incarnations, and this is exactly where the magic of entanglement begins.

Quantum entanglement is the main topic of *Einstein's Entanglement* by William Stuckey, Michael Silberstein and Timothy McDevitt, all currently teaching at Elizabethtown College, Pennsylvania. The trio have complementary expertise in physics, philosophy and maths, and this is not their first book on the foundations of physics. They aim to explain why entanglement is so puzzling to physicists and the various ways that have been employed over the years to explain (or even explain away) the phenomenon. They also want to introduce the readers to their own idea on how to solve the riddle and argue about its merits.

General readers may struggle in places. The book does have accessible chapters, for example one at the start with a quantum-gloves experiment – a nice way to introduce the reader to the problem – as well as a chapter on special relativity. Much of the discussion about quantum mechanics, however, uses advanced concepts such as Hilbert space and the Bloch sphere, that belong to an undergraduate course in quantum mechanics. Philosophical terminology, such as "wave-function realism", is also used copiously. The explanations and the discussion provided are of good quality and an interested reader in the interpretations of quantum mechanics with some background in physics has a lot to gain. The authors quote copiously from a superb list of references and include many interesting historical facts that make reading the book very entertaining.

In general, the book criticises constructive approaches to interpreting quantum mechanics that explicitly postulate physical phenomena. In the example of neutral-pion decay that I gave previously, the case in which the measurement of one photon causes the other photon to pick a spin would require a constructive explanation. These can be contrasted with principle explanations, which may involve, for example, invoking an overarching symmetry. To quote an example that is used many times in the book, the relativity principle can be used to explain Lorentz length contraction without the need for a physical mechanism to contract the bodies, which would require a constructive explanation.

The authors make the claim that the conceptual issues with entanglement can be solved by sticking to principle explanations and, in particular, with the demand that Planck's constant is measured to be the same in all inertial reference frames. Whether this simple suggestion is adequate to explain the mysteries of quantum mechanics, I will leave to the reader. Seneca wrote in his *Natural Questions* that "our descendants will be astonished at our ignorance of what to them is obvious". If the authors are correct, entanglement may prove to be a case in point.

Nikolaos Rompotis *University of Liverpool.*

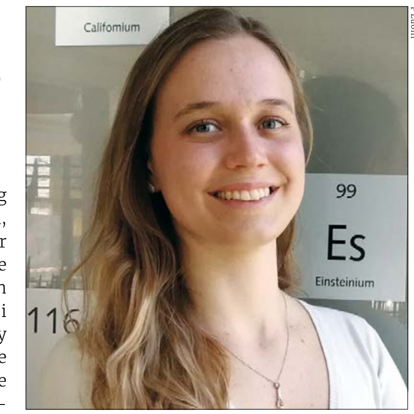
PEOPLE CAREERS

Prepped for re-entry

Francesca Luoni advises early-career researchers on how to shield their career while transitioning from research to engineering, and back again.

When Francesca Luoni logs on each morning at NASA's Langley Research Center in Virginia, she's thinking about something few of us ever consider: how to keep astronauts safe from the invisible hazards of space radiation. As a research scientist in the Space Radiation Group, Luoni creates models to understand how high-energy particles from the Sun and distant supernovae interact with spacecraft structures and the human body – work that will help future astronauts safely travel deeper into space.

But Luoni is not a civil servant for NASA. She is contracted through the multinational engineering firm Analytical Mechanics Associates, continuing a professional slingshot from pure research to engineering and back again. Her career is an intriguing example of how to balance research with industrial engagement – a holy grail for early-career researchers in the late 2020s.



Francesca Luoni *is a senior research scientist in the Space Radiation Group at NASA Langley.*

Leveraging expertise

Luoni's primary aim is to optimise NASA's Space Radiation Cancer Risk Model, which maps out the cancer incidence and mortality risk for astronauts during deep-space missions, such as NASA's planned mission to Mars. To make this work, Luoni's team leverages the expertise of all kinds of scientists, from engineers, statisticians and physicists, to biochemists, epidemiologists and anatomists.

"I'm applying my background in radiation physics to estimate the cancer risk for astronauts," she explains. "We model how cosmic rays pass through the structure of a spacecraft, how they interact with shielding materials, and ultimately, what reaches the astronauts and their tissues."

Before arriving in Virginia early this year, Luoni had already built a formidable career in space-radiation physics. After a physics PhD in Germany, she joined the GSI Helmholtz Centre for Heavy Ion Research, where she spent long nights at particle accelerators testing new shielding materials for spacecraft. "We would run experiments after the medical facility closed for the day," she says. "It was precious work because there are so few facilities worldwide where you can acquire experimental data on how matter responds to space-like radiation."

Her experiments combined experimental measurement data with Monte Carlo simulations to compare model predictions with reality – skills she honed during her time in nuclear physics that she still uses daily at NASA. "Modelling is something you learn gradually, through university, postgrads and research," says Luoni. "It's really about understanding physics, maths, and how things come together."

In 2021 she accepted a fellowship in radiation protection at CERN. The work was different from the research she'd done before. It was more engineering-oriented, ensuring the safety of both scientists and surrounding communities from the intense particle beams of the LHC and SPS. "It may sound surprising, but at CERN the radiation is far more energetic than we see in space. We studied soil and water activation, and shielding geometries, to protect everyone on site. It was much more about applied safety than pure research."

Luoni's path through academia and research was not linear, to say the least. From being an experimental physicist collecting data at GSI, to working as an engineer and helping physicists conduct their own experiments at CERN, Luoni is excited to be diving back into pure research, even if it wasn't her initially intended field.

Despite her industry-contractor title, Luoni's day-to-day work at NASA is firmly research-driven. Most of her time is spent refining computational models of space-radiation-induced cancer risk. While the coding skills she honed at CERN apply to her role now, Luoni still experienced a steep learning curve when transitioning to NASA.

"I am learning biology and epidemiology, understanding how radiation damages human tissues, and also deepening my statistics knowledge," she says. Her team codes primarily in Python and MATLAB, with legacy routines in Fortran. "You have to be patient with Fortran," she remarks. "It's like building with tiny bricks rather than big built-in functions."

Luoni is quick to credit not just the technical skills but the personal resilience gained from moving between countries and disciplines. Born in Italy, she has worked in Germany, Switzerland and now the US. "Every move teaches you something unique," she says. "But it's emotionally demanding. You face bureaucracy, new languages, distance from family and friends. You need to be at peace with yourself, because there's loneliness too."

Bravery and curiosity

But in the end, she says, it's worth the price. Above all, Luoni counsels bravery and curiosity. "Be willing to step out of your comfort zone," she says. "It takes strength to move to a new country or field, but it's worth it. I feel blessed to have experienced so many cultures and to work on something I love."

While she encourages travel, especially at the PhD and postdoc stages in a researcher's career, Luoni advises caution when presenting your experience on applications. Internships and shorter placements are welcome, but employers want to see that you have stayed somewhere long enough to really understand and harness that company's training.

"Moving around builds a unique skill set," she says. "Like it or not, big names on your CV matter – GSI, CERN, NASA – people notice. But stay in each place long enough to really learn from your mentors, a year is the minimum. Take it one step at a time and say yes to every opportunity that comes your way."

Luoni had been looking for a way to enter space-research throughout her career, building up a diverse portfolio of skills throughout her various roles in academia and engineering. "Follow your heart and your passions," she says. "Without that, even the smartest person can't excel."

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

CERNCOURIER
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Appointments and awards

DESY

Wiik Prize
Andreas Maier has been awarded the Bjørn H. Wiik Prize by a committee at DESY, recognising his contributions to laser-driven plasma wakefield acceleration (LPA). Maier is leading the Plasma Acceleration group at DESY's accelerator division, with the goal of making LPA viable for scientific and technological applications. Under his leadership, plasma accelerators advanced from single-shot demonstrations to continuous operation for more than 24 hours. A significant milestone was achieved with an energy compression stage, improving the energy spread and stability to better than 0.1%; comparable to conventional accelerators (*CERN Courier* July/August 2025 p8).

ICTP Dirac Medal
Gary Gibbons (University of Cambridge), Gary Horowitz (University of California, Santa Barbara), Roy Kerr (University of Canterbury) and Robert Wald (University of Chicago) have received the 2025 ICTP Dirac Medal for their theoretical contributions to gravitational physics. Gibbons played a key role in developing the Euclidean approach to quantum gravity and applying it to the thermodynamic properties of black holes. Horowitz advanced the study of gravitational objects in string theory and holography, contributing to the understanding of black branes and the microscopic description of black-hole entropy. Kerr discovered the solution describing a rotating black hole, now central to both theoretical and observational astrophysics. Wald refined the mathematical framework of black-hole physics, clarifying their thermodynamic laws and advancing the theory of quantum fields in curved spacetime.

Nobel Prize to quantum physics
On 7 October, the 2025 Nobel Prize in Physics was awarded to John Clarke (University of California, Berkley), Michel Devoret and John Martinis (both of University of California, Santa Barbara), "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit". In 1984 and 1985, the three scientists conducted a series of experiments using a superconducting circuit incorporating a Josephson junction to show that quantum effects, such as tunnelling and discrete energy levels, could manifest in a macroscopic system. Their experiments laid the foundations for superconducting quantum electronics and the development of quantum technologies.

Quantum industry prize to BASE
Barbara Maria Latacz (CERN) has been awarded the 2025 Boeing Quantum Creators Prize. The award recognises early-career researchers who have made significant contributions to quantum physics and technology. Latacz's work involves the demonstration of the first antimatter-based quantum bit (qubit) at CERN's BASE experiment in July. Researchers successfully maintained a single

CERN/P Traczyk

trapped antiproton oscillating coherently between two spin states for approximately 50 seconds, using coherent quantum transition spectroscopy to overcome previously limiting magnetic-field oscillations. Latacz receives $3500 and an invitation to present her research at the upcoming Chicago Quantum Summit.

Shaw Prize
The Shaw Prize in Astronomy was awarded to John Richard Bond (University of Toronto) and George Efstathiou (University of Cambridge) for their work in cosmology, particularly their studies of fluctuations in the cosmic microwave background (CMB). These minute temperature and polarisation variations in the CMB provide a snapshot of the universe's infancy, offering insights into its age, geometry, and the distribution of mass and energy. Bond and Efstathiou's theoretical models predicted patterns in baryon oscillations, which were subsequently confirmed by a range of observational instruments, including NASA's Wilkinson Microwave Anisotropy Probe and ESA's Planck satellite. The Shaw Prize in Astronomy has been awarded once a year since 2004. Each prize carries a monetary award, which was set at $1.2 million in 2016.

Gruber Cosmology Prize
The 2025 Gruber Cosmology Prize has been awarded to Ryan Cooke and Max Pettini for their work in precision cosmology. The two University of Cambridge physicists developed methods to measure the primordial deuterium-to-hydrogen ratio in quasar absorption-line systems, allowing a 1% determination of the universe's baryon density shortly after the Big Bang. Their results, obtained using some of the largest ground-based telescopes, closely match those from the cosmic microwave background by the ESA Planck satellite and NASA's Wilkinson Microwave Anisotropy Probe, validating Big Bang nucleosynthesis as a precise tool for understanding the early universe. The award highlights their transformative contribution to establishing the composition and fundamental parameters of the cosmos. The ceremony took place on 3 October at Yale University during the Sixth Gruber Cosmology Conference.

Hidden Figures award
Maria Alandes Pradillo, a software engineer at CERN, has won the Hidden Figures award 2025 in the non-profit category, presented by TechFace. TechFace is a company dedicated to diversifying the hiring pool in technology companies, and its annual Hidden Figures awards recognise women whose work has increased access to STEM fields. As a steering committee member of CERN's Women in Technology (WIT) community, Pradillo has

techface.ch/hidden-figures-award

co-developed workshops for young children to introduce them to computing and ICT, and led initiatives for events focused on diversifying STEM, like the WIT mentoring programme. Her efforts aim to address the underrepresentation of women in technical roles in STEM by sparking early interest and making the field more accessible.

Carlos Hernandez Garcia award
On 22 July, Frank Zimmermann, accelerator physicist at CERN, received the Carlos Hernandez Garcia Prize for his contributions to accelerator physics and the training of accelerator physicists in Mexico and beyond. The Mexican Community of Particle Accelerators (CMAP) established the award to recognise researchers who have significantly contributed to the advancement and consolidation of the field of particle accelerators in Mexico and worldwide. Zimmermann's collaboration with the Mexican high-energy physics community began around 2006, when the need for national accelerator expertise was first identified, and in 2008 he welcomed the first Mexican student to CERN for hands-on training. Over the next few years the collaboration was strengthened and became the Mexican–CERN Beam programme in 2014, which facilitated the creation of CMAP the following year.

PEOPLE OBITUARIES

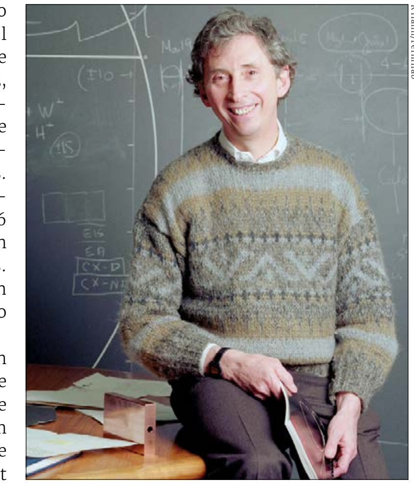
JOHN PEOPLES 1933–2025

A pillar of US particle physics

John Peoples, the third director of Fermilab, who guided the lab through one of the most critical periods in its history, passed away on 25 June 2025. Born in New York City on 22 January 1933, John received his bachelor's degree in electrical engineering from the Carnegie Institute of Technology (now Carnegie Mellon University) in 1955. After several years at the Glen L. Martin Company, John entered Columbia University where he received his PhD in physics in 1966 for the measurement of the Michel parameter in muon decay under the direction of Allan Sachs. This was followed by a teaching and research position at Cornell University and relocation to Fermilab, initially on sabbatical, in 1971.

John officially joined the Fermilab staff in 1975 as head of the Research Division. His tenure included the discovery of the upsilon particle (b-quark bound state) by Leon Lederman's team in 1977. He also held responsibilities for the upgrading of the experimental areas to accept beams of up to 1 TeV in anticipation of the completion of the Fermilab Tevatron.

In 1981, following Lederman's decision to utilise the Tevatron as a proton–antiproton collider, John was appointed head of the TeV-I Project, with responsibility for the construction of the Antiproton Source and the collision hall for the CDF detector. Under John's leadership, a novel design was developed, building on the earlier pioneering work done at CERN for antiproton accumulation based on stochastic cooling, and proton–antiproton collisions were achieved in the Tevatron four years later, in 1985.



R Hahn/Fermilab

John Peoples generated a flood of ideas for improving Fermilab.

His leadership both enhanced international collaboration and retained a prominent role for Fermilab in collider physics

Tireless commitment

John succeeded Lederman to become Fermilab's third director in July 1989, shortly after the decision to locate the Superconducting Super Collider (SSC) in Waxahachie, Texas, creating immense challenges to Fermilab's future. John guided the US community to a plan for a new accelerator, the Main Injector (and ultimately the Recycler), that could support a high-luminosity collider programme for the decade of SSC construction while simultaneously providing high-intensity extracted beams for a future neutrino programme that could sustain Fermilab well beyond the SSC's startup. The cancellation of the SSC in 1993 was a seismic event for US and global high-energy physics, and ensured the Tevatron's role as the highest energy collider in the world for the next almost two decades. John was asked to lead the termination phase of the SSC lab. In 1994/1995, as director of both Fermilab and the SSC, he worked on this painful task with a special emphasis on helping the many suddenly unemployed people find new career paths.

During John's tenure as director, Fermilab produced many important physics results. In 1995, the Tevatron Collider experiments, CDF and DØ, announced the discovery of the top quark, the final quark predicted in the Standard Model of particle physics at the mass of more than 175 times that of the proton. To ensure that the experiments could analyse their data quickly and efficiently, John supported replacing costly mainframe computers with "clusters" of inexpensive microprocessors developed in industry for personal computers and later laptops and phones. The final fixed-target run with 800 GeV extracted beam in 1997 and 1998 helped resolve an important and long-standing problem in CP violation in kaon decays and discovered the tau neutrino.

From 1993–1997, John served as chair of the International Committee for Future Accelerators (ICFA). He stepped down after two terms as Fermilab director in 1999. In 2010, he received the Robert R. Wilson Prize for Achievement in the Physics of Particle Acceleration from the American Physical Society.

Under John's influence, there were frequent personnel exchanges between Fermilab and CERN throughout the 1980s, as Fermilab staff benefited from CERN's experience with antiproton production and CERN benefited from Fermilab's experience with the operations of a superconducting accelerator. These exchanges extended into the 1990s, and following the termination of the SSC, John was instrumental in securing support for US participation in the LHC accelerator and detector projects. His leadership both enhanced international collaboration and retained a prominent role for Fermilab in collider physics after the Tevatron completed operations in 2011.

During the 1980s, astrophysics became an important contributor to our knowledge of particle physics and required more ambitious experiments with strong synergies with the latest round of HEP experiments. In 1991, John formed the Experimental Astrophysics Group at Fermilab. This led to its strong participation in the Sloan Digital Sky Survey (SDSS), the Pierre Auger Cosmic Ray Observatory, the Cryogenic Dark Matter Search (CDMS) and the Dark Energy Survey (DES), of which John became director in 2003. John's vision of a vibrant community of particle physicists, astrophysicists and cosmologists exploring the inner space–outer space connection is now reality.

Those of us who had the privilege of knowing and working with John were challenged by his intense work ethic and by the equally intense flood of new ideas for running and improving our programmes. He was a gifted and dedicated experimental physicist, skilled in accelerator science, an expert in superconducting magnet design and technology, a superb manager, and a great recruiter and mentor of young engineers and scientists, including the authors of this article. We will miss him!

Joel Butler *and* **Stephen Holmes** *Fermilab.*

CERNCOURIER
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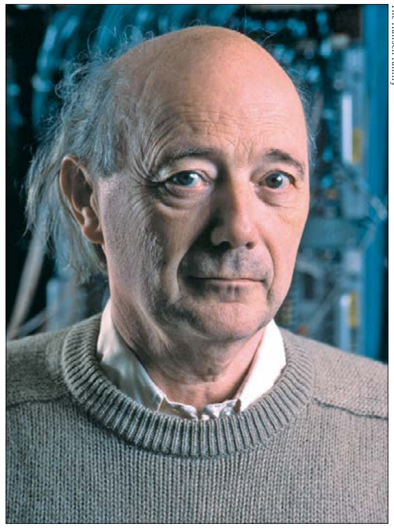
Ole Hansen 1934–2025

A leading Danish nuclear physicist

Ole Hansen, a leading Danish nuclear-reaction physicist, passed away on 11 May 2025, three days short of his 91st birthday. His studies of nucleon transfer between a projectile nucleus and a target nucleus made it possible to determine the bound states in either or both nuclei and confront it with the framework for which the Danish Nobel Prize winners Aage Bohr and Ben Mottelson had developed a unified theory. He conducted experiments at Los Alamos in the US and Aldermaston in the UK, among others, and developed a deep intuitive relationship with Clebsch–Gordan coefficients.

Together with Ove Nathan, Ole oversaw a proposal to build a large tandem accelerator at the Niels Bohr Institute department located at Risø, near Roskilde. The government and research authorities had supported the costly project, but it was scrapped on an afternoon in August 1978 as a last-minute saving to help establish a coalition between the two parties across the centre of Danish politics. Ole's disappointment was enormous: he decided to take up an offer at Brookhaven National Laboratory (BNL) to continue his nuclear work there, while Nathan threw himself into university politics and later became rector of the University of Copenhagen.



The Hansen family

Ole Hansen was an open-minded, energetic and visionary man with an irreverent sense of humour.

> **Ole will be remembered as the first director of the unified Niels Bohr Institute and for establishing the Danish National Research Foundation**

Deep exploration

Ole sent his resignation as a professor at the University of Copenhagen to the Queen – a civil servant had to do so at the time – but was almost immediately confronted with demands for cutbacks at BNL, which would stop the research programme with the tandem accelerator there. Ole did not withdraw his resignation, but together with US colleagues proposed a research programme at very high energies by injecting ions from the tandem into the existing particle accelerator, AGS, thereby achieving energies in the nucleon–nucleon centre-of-mass system of up to 5 GeV. This was the start of the exploration of the deeper structure of nuclear matter, which is revealed as a system consisting of quarks and gluons at temperatures of billions of degrees. This later led to the construction of the first atomic nucleus collision machine, the Relativistic Heavy Ion Collider (RHIC) in the US. Ole himself participated in the E802 and E866 experiments at BNL/AGS, and in the BRAHMS experiment at RHIC.

Ole will also be remembered as the first director, called back from the US, of the unified Niels Bohr Institute, which was established in 1993 as a fusion of the physics, astronomy and geophysics departments surrounding the Fælledparken commons in Copenhagen after an international panel chaired by him had recommended a merger. Ole realised the necessity of merging the departments in order to create the financial room for manoeuvre needed to be able to hire new and younger researchers again. He left his mark on the construction, which initially had to deal with the very different cultures of the Blegdamsvej, Ørsted and Geophysics institutes. He approached the task efficiently but with a good understanding and respect for the scientific perspectives and the individual researchers.

Back in Denmark, Ole played a significant role in the establishment of the competitive research system we know today, including the establishment of the Danish National Research Foundation (DNRF), of which he was vice-chair in the first years, and with the streamlining of the institute's research and the establishment of several new areas.

Strong interests

Despite the scale of all his administrative tasks, Ole maintained a lively interest in research and actively supported the establishment of the Centre for CERN Research (now the NICE National Instrument Center) together with the author of this obituary. He was also a member of the CERN Council during the exciting period when the LHC took shape.

Ole will be remembered as an open-minded, energetic and visionary man with an irreverent sense of humour that some feared but others greatly appreciated. Despite his modest manner, he influenced his colleagues with his strong interest in new physics and his sharp scepticism. If consulted, he would probably turn his nose up at the word "loyal", but he was ever a good and loyal friend. He is survived by his wife, Ruth, and four children.

Jens Jørgen Gaardhøje *Niels Bohr Institute.*

Michele Arneodo 1959–2025

A central figure in diffractive physics

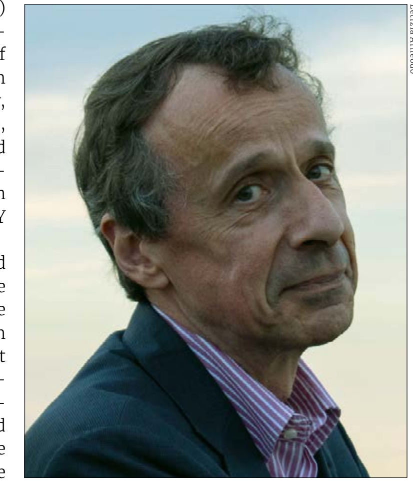
Michele Arneodo, professor of physics at the University of Piemonte Orientale and chairperson elect of the CMS Collaboration Board, passed away on 12 August 2025. He was 65.

Born in Turin in 1959, Michele graduated in physics from the University of Torino in 1982. He was awarded a Fulbright Fellowship to pursue graduate studies at Princeton University, where he received his MA in 1985 and his PhD in 1992. He began his career as a staff researcher at INFN Torino, before moving to academia as an associate professor at the University of Calabria and then, from 1995, at the University of Piemonte Orientale in Novara, where he became full professor in 2002.

Michele's research career began with the European Muon Collaboration (NA2 and NA9) and the New Muon Collaboration (NA37) at CERN, investigating the structure of nucleons through the deep inelastic scattering of muons. He went on to play a leading role in the ZEUS experiment at DESY's HERA collider, focusing on the diffractive physics programme, coordinating groups in Torino and Novara, and overseeing the operation of the Leading Proton Spectrometer. Awarded an Alexander von Humboldt fellowship, he worked at DESY between 1996 and 1999.

With the start of the LHC era, Michele devoted his efforts to CMS, becoming a central figure in diffractive physics and the relentless force behind the construction of the CMS Precision Proton Spectrometer (PPS) and the subsequent merging of the TOTEM and CMS collaborations. He was convener of the diffractive physics group, served on the CMS Publication and Style committees, and from 2014 chaired the Institution Board of the CMS PPS, where he was also resource manager and INFN national coordinator. He had been appointed as chairperson of the CMS Collaboration Board, a role that he was due to begin this year.

Teaching was central to Michele's vocation. At the University of Piemonte Orientale, he developed courses on radiation physics for medical students and radiology specialists, building bridges between particle physics and medical applications. He was also widely recognised as a dedicated mentor, always attentive to the careers of younger collaborators.



Letizia Arneodo

Michele Arneodo had the style and generosity of a bygone era.

> **A central figure in diffractive physics and the relentless force behind the construction of the Precision Proton Spectrometer**

We will remember Michele as a very talented physicist and a genuinely kind person, who had the style and generosity of a bygone era. Always approachable, he could be found with a smile, a sincere interest in others' well-being, and a delicate sense of humour that brought lightness to professional exchanges. His students and collaborators valued his constant encouragement and his passion for transmitting enthusiasm for physics and science.

While leaving a lasting mark on physics and on the institutions he served, Michele also cultivated enduring friendships and dedicated himself fully to his family, to whom the thoughts of the CMS and wider CERN communities go at this difficult time.

Michele, "Rest forever here in our hearts".

His Torino colleagues.

Miro Preger 1946–2025

A pioneer of electron–positron colliders

Miro Andrea Preger, a distinguished accelerator physicist in the Accelerator Division of the Frascati National Laboratories (LNF), passed away on 1 September 2025.

Originally an employee of the Italian National Committee for Nuclear Energy (CNEN), Miro had a long career as a key figure in the INFN institutions.

He made his mark at the pioneering ADONE collider in the 1970s, optimising its performance, developing an innovative luminosity monitor, and improving the machine optics and injection system. Later he served as the director of ADONE, participating in all second-generation experiments, colliding beams for particle physics and producing synchrotron radiation and gamma rays for nuclear physics.

Beyond LNF, Miro played an important role in the design of the Italian synchrotron radiation source ELETTRA in Trieste, and the ESRF in Grenoble; he also collaborated on many other accelerator projects, including CTF3 and CLIC at CERN.

Miro held many institutional roles, and as head of the Accelerator Physics Service, he taught the art and science of accelerators to many young scientists, with clarity, patience and dedication. As a mentor, he leaves a legacy of accelerator experts who have ensured the success of many LNF initiatives.

The Preger family

Miro Preger leaves a legacy of accelerator experts at the Frascati National Laboratories.

> **Miro made outstanding contributions to the DAΦNE collider project, leading the realisation of the electron–positron injection system**

Miro made outstanding contributions to the DAΦNE collider project from the beginning, leading the design and realisation of the entire electron–positron injection system. He was deeply involved in the very challenging commissioning and achieving the high luminosity that was required by the experiments.

Besides his characteristic dynamism, one of Miro's distinctive traits was his ability to foster harmonious collaboration among technicians, technologists and researchers.

Away from physics, Miro was an excellent tennis player and skier, along with being a skilled sailor, activities that he often shared with colleagues.

His colleagues and friends.

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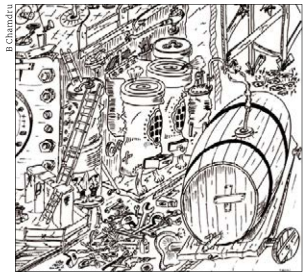
BACKGROUND

Notes and observations from the high-energy physics community

Digital revival



Bubble trouble *An artist's impression of the CERN 2 m liquid-hydrogen bubble chamber published in the January 1965 edition of* CERN Courier.

An effort is underway to digitally preserve thousands of beam exposures from the CERN 2 m hydrogen bubble chamber, which operated from 1965 to 1977: bubblechamber.web.cern.ch. "Beyond representing a highly intuitive pedagogical resource with applications in particle-physics education and public engagement, we are also investigating the feasibility of recovering quantitative scientific information from the images," says Andy Chisholm of the University of Birmingham.

6100

Neutral-atom qubits trapped in a grid by lasers at Caltech – the largest qubit array ever assembled (H Manetsch *et al.* 2025 *Nature*; see also *CERN Courier* July/August 2025 p35)

Media corner

"It could have been that the solar system was a weird fluke."
Jessie Christiansen (Caltech) reflects on the preponderance of exoplanet discoveries, with more than 6000 confirmed since astronomers found the first planets outside our solar system in 1992 (19 September, *Scientific American*).

"This would be utterly catastrophic for astronomy. All the international effort that has been put into the design, development and operation of these telescopes, which are the best on Earth, would basically be wasted."
Itziar de Gregorio, head of office for the European Southern Observatory in Chile, reacts to plans to build a renewable energy facility in the Atacama Desert (12 September, *New York Times*).

"These results are a paradigm change."
Roberto Maiolino (University of Cambridge) on the James Webb Space Telescope's observations of a gargantuan black hole, QSO1, which he suggests "formed without much of a galaxy" (2 September, *The Guardian*).

"Happy birthday, LIGO. Now drop dead."
A ***New York Times*** headline commemorates 10 years of data taking at LIGO – and the potential cancellation of the project (10 September).

"It is hard to imagine a big tech company agreeing to share the World Wide Web for no commercial reward, like CERN allowed me to."
Tim Berners-Lee on the need for a "CERN-like not-for-profit body driving forward international AI research." (28 September, *The Guardian*).

"For us, this represents the greatest award to creativity in science."
Giacomo Bartolucci (University of Barcelona) on winning the Ig Nobel Prize for studying a phase transition in the preparation of *cacio e pepe*, a Roman pasta dish (19 September, *Scientific American*).

From the archive: November/December 1985

Echoes of a report

Happier times *During a visit on 3 September, CERN Director-General Herwig Schopper introduces Queen Beatrix of the Netherlands to Dutch accelerator physicist Simon van der Meer (back to camera), who shared the 1984 Nobel Prize in Physics with Carlo Rubbia.*

In March 1984, two bodies responsible for science research policy and funding in the United Kingdom asked for a Committee to investigate the UK's participation in high-energy physics in general and in CERN in particular. This was in the context of continually reduced levels of public-sector expenditure in the UK. The Committee, under the chairmanship of Sir John Kendrew, published its 150-page report on 18 June this year. The bulk of it is highly complimentary towards high-energy physics and also about the way in which the research is managed, and CERN's role as an international scientific enterprise. One of the Committee members said 'CERN should be regarded as one of the brightest jewels in the scientific crown'.

Despite this fulsome praise, the report's major conclusions included that the UK should remain a Member State of CERN on the present basis until 1989 but should continue its membership beyond 1989 only at significantly lower cost; and that progressive reduction of the UK total expenditure on particle physics should attain at least 25% by 1991.

The report met a great deal of criticism in the UK Press. *Nature* commented 'The decision that there should now be a reconsideration of continued British membership of CERN will further reinforce the impression that the British have concluded that their sceptred isle north of the white cliffs of Dover would be better off on its own'.

● Text adapted from *CERN Courier* November 1985 pp375–376.

Compiler's note

In 1985, Herwig Schopper, who recently died aged 101 (p32), was in the fifth year of his mandate as CERN Director-General, a period that saw pressure on the CERN budget as a result of the economic situation in various Member States. Schopper had secured Council's approval for the new Large Electron-Positron collider in 1981, but within a constant budget. Four years later, a UK report threatened withdrawal from CERN unless the subscription was reduced by 25%. Happily for UK particle physicists, this never came to pass, although Nature's comments about the 'sceptred isle' resonated some 30 years later when the UK voted to leave the European Union – a decision that did not affect the country's membership of CERN but which does affect science funding more generally.

Corrections and clarifications

The September/October edition pictured Yuval Ne'eman (left) next to Murray Gell-Mann following the discovery of the Ω^- baryon in 1964 (p32), but failed to note that both physicists independently predicted its existence in 1961. On p42, the data abstraction levels achieved by HERA experiments are inverted.

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