WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2025 issue of *CERN Courier*.

Should a Higgs factory be a linear or circular electron–positron collider? Intriguingly, the key strategic technology may be the same in either case. Klystrons consume the majority of power at electron–positron colliders of all mature designs. The trouble is that they are typically only 60% efficient. In our cover feature, Igor Syratchev and Nuria Catalan Lasheras describe CERN's pursuit of 90% efficiency – a feat that would have major implications for the environmental sustainability and cost effectiveness of any Higgs factory (p30).

Klystrons date back to the development of radar in the run-up to World War II. Remarkably, astroparticle physicists are now trying to use radar to detect not enemy aircraft but ultra-high-energy neutrinos. The technology is different, but the underlying principle is the same.

This is just one facet of the ambitious global strategy described by Lu Lu of the University of Wisconsin–Madison in her feature on future neutrino observatories. Only one ultra-high-energy neutrino has been observed so far. Lu describes plans for a worldwide network of observatories offering full-sky coverage. The reward will be cosmic messengers that slice through dust and magnetic fields to point to the most extreme environments in the universe – and energies that are inconceivable in terrestrial colliders (p23).

Elsewhere in these pages: CERN's Verena Kain explains why AI-based automation is the future of accelerator operation (p35); Beate Heinemann describes her strategy for DESY's future (p41); LHC researchers debate an unexpected pseudoscalar excess at the top–antitop threshold (p7); DESI suggests dark energy may be evolving (p11); an analysis of community inputs to the European Strategy for Particle Physics (p8); how to get a job in machine learning (p47); and much more.

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EDITOR: MARK RAYNER

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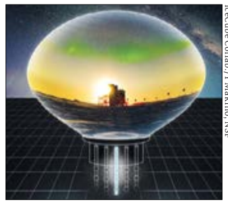

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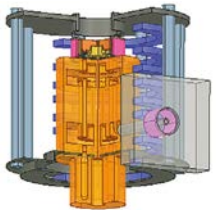

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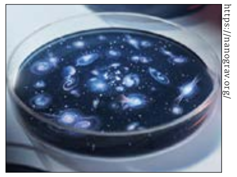

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FROM THE EDITOR

Behind every Higgs boson, a klystron

Mark Rayner
Editor

It's a great time to be a particle physicist. LHC researchers are debating an unexpected pseudoscalar excess at the top–antitop threshold (p7). The Dark Energy Spectroscopic Instrument suggests that dark energy may not be a cosmological constant (p11). And rarely is there a better opportunity to influence the future of the field than now. Community inputs to the ongoing update to the European Strategy for Particle Physics are now in, and all eyes turn to June's open symposium in Venice (p8).

One thing seems certain: there is no higher priority than subjecting the Higgs boson to the unrelenting gaze of an electron–positron collider. That's because the Higgs boson is a uniquely promising portal to new physics. It is the only known fundamental scalar field, with no intrinsic directionality. It is the only elementary field known to allow three particle lines with the same quantum numbers to meet at a single vertex – the simplest possible interaction in nature. It is unique in having a nonzero vacuum expectation value, permeating all of space since the electroweak phase transition. It couples to fermions with arbitrary strengths not fixed by symmetry, giving rise to a hierarchical and unexplained pattern of masses. No one knows what prevents quantum corrections from inflating its mass to vastly higher scales such as that of force unification or quantum gravity. It is the most tempting thread to pull in the tapestry of particle physics.

So should a Higgs factory be a linear or circular electron–positron collider? Intriguingly, the key strategic technology may be the same in either case: a radio-frequency amplifier dating back to the development of radar in the run-up to World War II.

There is no higher priority than subjecting the Higgs boson to the unrelenting gaze of an electron–positron collider

The radio-frequency cavities that put the acceleration into accelerators cannot simply be plugged into the wall. They must be excited by powerful electromagnetic waves generated by miniature particle accelerators called klystrons. These devices can range in size from a pen to a mid-size car, and they consume the majority of power at electron–positron colliders of all mature designs. The trouble is that they are typically only 60% efficient. In our cover feature, Igor Syratchev and Nuria Catalan Lasheras describe CERN's pursuit of 90% efficiency – a feat that would have major implications for the environmental sustainability and cost effectiveness of any Higgs factory (p30). Elsewhere in these pages, CERN's Verena Kain describes another game-changing innovation for future colliders: AI-based automation (p35).

N Eskandari

Sustainable science *CERN's RF engineers seek to boost the energy efficiency of klystrons from 60% to 90%.*

The neutrino sky

If klystrons gave the world radar, astroparticle physicists are now trying to use it to detect neutrinos. This is just one facet of the remarkable story told by Lu Lu of the University of Wisconsin–Madison in her feature on future neutrino observatories.

Only one ultra-high-energy neutrino has been observed so far. Lu describes plans for a global network of observatories offering full sky coverage – a necessity, as the Earth is increasingly opaque to neutrinos at these energies. The reward will be cosmic messengers that slice through dust and magnetic fields to point to the most extreme environments in the universe – and energies that are inconceivable in terrestrial colliders (p23).

Reporting on international high-energy physics

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NEWS ANALYSIS

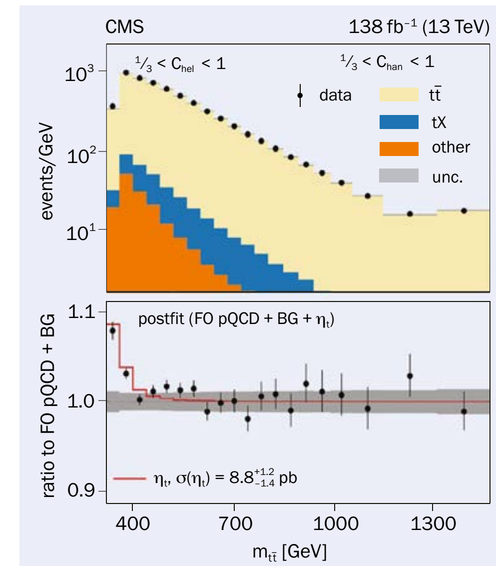
Strong interactions

CMS observes top–antitop excess

CERN's Large Hadron Collider continues to deliver surprises. While searching for additional Higgs bosons, the CMS collaboration may have instead uncovered evidence for the smallest composite particle yet observed in nature – a "quasi-bound" hadron made up of the most massive and shortest-lived fundamental particle known to science and its antimatter counterpart. The findings, which do not yet constitute a discovery claim and could also be susceptible to other explanations, were uploaded to the preprint archive on 28 March, following careful deliberation within the community.

Almost all of the Standard Model's shortcomings motivate the search for additional Higgs bosons. Their properties are usually assumed to be simple. Much as the 125 GeV Higgs boson discovered in 2012 appears to interact with each fundamental fermion with a strength proportional to the fermion's mass, theories postulating additional Higgs bosons generally expect them to couple more strongly to heavier quarks. This puts the singularly massive top quark at centre stage. If an additional Higgs boson has a mass greater than about 345 GeV and can therefore decay to a top quark–antiquark pair, this should dominate the way it decays inside detectors. Hunting for bumps in the invariant mass spectrum of top–antitop pairs is therefore often considered to be the key experimental signature of additional Higgs bosons above the top–antitop production threshold.

The CMS experiment has observed just such a bump. Intriguingly, however, it is located at the lower limit of the search, right at the top-quark pair production threshold itself, leading CMS to also consider an alternative hypothesis long considered difficult to detect: a top–antitop quasi-bound state known as toponium (see "Threshold excess" figure).



Threshold excess *The invariant mass spectrum of top quark–antiquark pairs observed by the CMS experiment in certain domains of the reconstructed spin-correlation observables c_{hel} and c_{han} (top panel) and the signal-to-background ratio (bottom panel). Excess events at threshold can be modelled by including a new top–antitop bound state in the background model (red line).*

"When we started the project, toponium was not even considered as a background to this search," explains CMS physics coordinator Andreas Meyer (DESY). "In our analysis today we are only using a simplified model for toponium – just a generic spin-0 colour-singlet state with a pseudoscalar coupling to top quarks. The toponium hypothesis is very exciting as we previously did not expect to be able to see it at the LHC."

Though other explanations can't be ruled out, CMS finds the toponium hypothesis to be sufficient to explain the observed excess. The size of the excess is consistent with the latest theoretical estimate of the cross section to produce pseudoscalar toponium of around 6.4 pb.

"The cross section we obtain for our simplified hypothesis is 8.8 pb with an uncertainty of about 15%," explains Meyer. "One can infer that this is significantly above five sigma."

The toponium hypothesis is very exciting as we previously did not expect to be able to see it at the LHC

The smallest hadron

If confirmed, toponium would be the final example of quarkonium – a term for quark–antiquark states formed from heavy charm, bottom and perhaps top quarks. Charmonium (charm–anticharm) mesons were discovered at SLAC and Brookhaven National Laboratory in the November Revolution of 1974. Bottomonium (bottom–antibottom) mesons were discovered at Fermilab in 1977. These heavy quarks move relatively slowly compared to the speed of light, allowing the strong interaction to be modelled by a static potential as a function of the separation between them. When the quarks are far apart, the potential is proportional to their separation due to the self-interacting gluons forming an elongating flux tube, yielding a constant force of attraction. At close separations, the potential is due to the exchange of individual gluons and is Coulomb-like in form, and inversely proportional to separation, leading to an inverse-square force of attraction. This is the domain where compact quarkonium states are formed, in a near perfect QCD analogy to positronium, wherein an electron and a positron are bound by photon exchange. The Bohr radii of the ground states of charmonium and bottomonium are approximately 0.3 fm and 0.2 fm, and bottomonium is thought to be the smallest hadron yet discovered. Given its larger mass, toponium's Bohr radius would be an order of magnitude smaller.

For a long time it was thought that toponium bound states were unlikely to be detected in hadron–hadron collisions. The top quark is the most massive and the shortest-lived of the known fundamental particles. It decays into a bottom quark and a real W boson in the time it takes light to travel just 0.1 fm, leaving little time for a hadron to form. Toponium would be unique among quarkonia in that its decay would be triggered by the weak decay of one of its constituent quarks rather than the annihilation of its constituent quarks into photons or gluons. Toponium is expected to decay at twice the rate of the top quark itself, with a width of approximately 3 GeV.

CMS first saw a 3.5 sigma excess in a 2019 search studying the mass range above 400 GeV, based on 35.9 fb^{-1} of proton–proton collisions at 13 TeV from 2016. Now armed with 138 fb^{-1} of collisions from ▷

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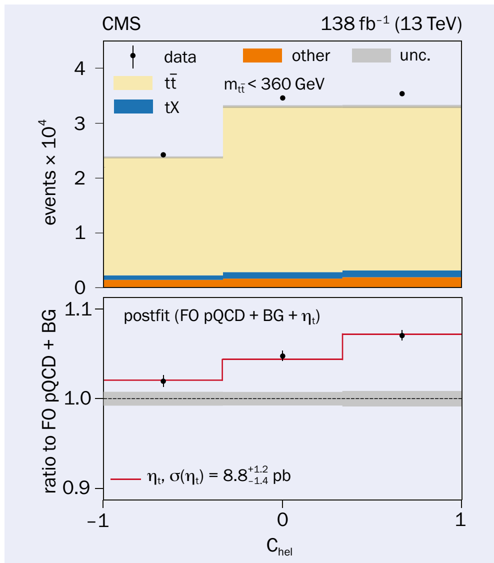
2016 to 2018, the collaboration extended the search down to the top–antitop production threshold at 345 GeV. Searches are complicated by the possibility that quantum interference between background and Higgs signal processes could generate an experimentally challenging peak–dip structure with a more or less pronounced bump.

"The signal reported by CMS, if confirmed, could be due either to a quasi-bound top–antitop meson, commonly called 'toponium', or possibly an elementary spin-zero boson such as appears in models with additional Higgs bosons, or conceivably even a combination of the two," says theorist John Ellis of King's College London. "The mass of the lowest-lying toponium state can be calculated quite accurately in QCD, and is expected to lie just below the nominal top–antitop threshold. However, this threshold is smeared out by the short lifetime of the top quark, as well as the mass resolution of an LHC detector, so toponium would appear spread out as a broad excess of events in the final states with leptons and jets that generally appear in top decays."



Angular analysis *Spin-correlation observables such as c_{hel} favour a pseudoscalar top–antitop bound state (red) over the background-only hypothesis.*

Quantum numbers

An important task of the analysis is to investigate the quantum numbers of the signal. It could be a scalar particle, like the Higgs boson discovered in 2012, or a pseudoscalar particle – a different type of spin-0 object with odd rather than even parity. To measure its spin-parity, CMS studied the angular correlations of the top-quark-pair decay products, which retain information on the original quantum state. The decays bear all the experimental hallmarks of a pseudoscalar particle, consistent with toponium (see "Angular analysis" figure) or the pseudoscalar Higgs bosons common to many theories featuring extended Higgs sectors.

"The toponium state produced at the LHC would be a pseudoscalar boson, whose decays into these final states would have characteristic angular distributions, and the excess of events reported by CMS exhibits the angular correlations expected for such a pseudoscalar state," explains Ellis. "Similar angular correlations would be expected in the decays of an elementary pseudoscalar boson, whereas scalar-boson decays would exhibit different angular correlations that are disfavoured by the CMS analysis."

Two main challenges now stand in the way of definitively identifying the nature of the excess. The first is to improve the modelling of the creation of top-quark pairs at the LHC, including the creation of bound states at the threshold. The second challenge is to obtain consistency with the ATLAS experiment. "ATLAS had similar studies in the past but with a more conservative approach on the systematic uncertainties," says ATLAS physics coordinator Fabio Cerutti (LBNL). "This included, for example, larger uncertainties related to parton showers and other top-modelling effects. To shed more light on the CMS observation, be it a new boson, a top quasi-bound state, or some limited understanding of the modelling of top–antitop production at threshold, further studies are needed on our side. We have several analysis teams working on that. We expect to have new results with improved modelling of the top-pair production at threshold and additional variables sensitive to both a new pseudo-scalar boson or a top quasi-bounded state very soon."

Whatever the true cause of the excess, the analyses reflect a vibrant programme of sensitive measurements at the LHC – and the possibility of a timely discovery.

"Discovering toponium 50 years after the November Revolution would be an unanticipated and welcome golden anniversary present for its charmonium cousin that was discovered in 1974," concludes Ellis. "The prospective observation and measurement of the vector state of toponium in e^+e^- collisions around 350 GeV have been studied in considerable theoretical detail, but there have been rather fewer studies of the observability of pseudoscalar toponium at the LHC. In addition to the angular correlations observed by CMS, the effective production cross section of the observed threshold effect is consistent with non-relativistic QCD calculations. More detailed calculations will be desirable for confirmation that another quarkonium family member has made its appearance, though the omens are promising."

Further reading

CMS Collaboration 2025 arXiv:2503.22382.

POLICY

European strategy update: the community speaks

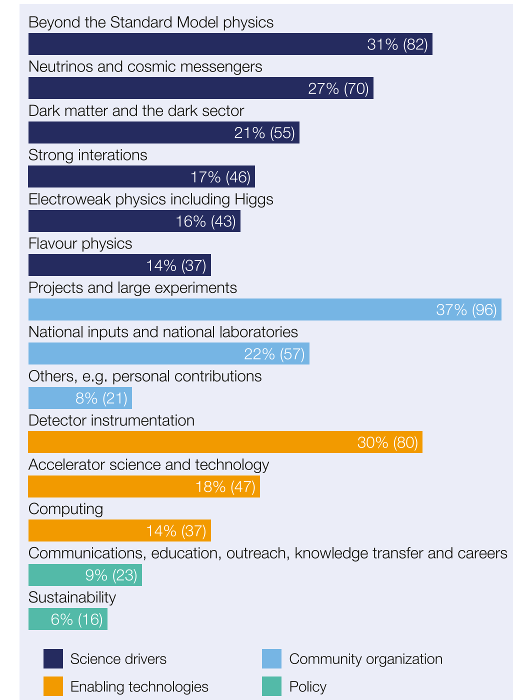
The deadline for submitting inputs to the 2026 update of the European Strategy for Particle Physics (ESPP) passed on 31 March. A total of 263 submissions, ranging from individual to national perspectives, express the priorities of the high-energy physics community (see "Community inputs" figure). These inputs will be distilled by expert panels in preparation for an Open Symposium that will be held in Venice from 23 to 27 June (*CERN Courier* March/April 2025 p11).

Launched by the CERN Council in March 2024, the stated aim of the 2026 update to the ESPP is to develop a visionary and concrete plan that greatly advances human knowledge in fundamental physics, in particular through the realisation of the next flagship project at CERN. The community-wide process, which is due to submit recommendations to Council by the end of the year, is also expected to prioritise alternative options to be pursued if the preferred project turns out not to be feasible or competitive.

We are heartened to see so many rich and varied contributions

"We are heartened to see so many rich and varied contributions, in particular the national input and the various proposals for the next large-scale accelerator project at CERN," says strategy secretary Karl Jakobs of the University of Freiburg, speaking on behalf of the European Strategy Group (ESG). "We thank everyone for their hard work and rigour."

Two proposals for flagship colliders are at an advanced stage: a Future Circular Collider (FCC) and a Linear Collider Facility (LCF). As recommended in the 2020 strategy update, a feasibility study for the FCC was released on 31 March, describing a 91 km-circumference infrastructure that could host an electron–positron Higgs and electroweak factory followed by an energy-frontier hadron collider at a later stage. Inputs for an electron–positron LCF cover potential starting configurations based on Compact Linear Collider (CLIC) or International Linear Collider (ILC) technologies. It is proposed that the latter LCF could be upgraded using CLIC, Cool Copper Collider, plasma-wakefield or energy-recovery technologies and designs. Other proposals outline a muon collider and a possible plasma-wakefield collider, as well as potential "bridging" projects to a future flagship collider. Among the latter are LEP3 and LHeC, which would site an electron–positron and an electron–proton collider, respectively, in the existing LHC tunnel. For the LHeC, an additional energy-recovery linac would need to be added to CERN's accelerator complex.



Community inputs *Self-attributed themes of the 263 community inputs to the European Strategy process. The themes are ordered by umbrella category and percentage of total submissions, with the raw number in parentheses. Multiple themes could be selected.*

Future choices

In probing beyond the Standard Model and more deeply studying the Higgs boson and its electroweak domain, next-generation colliders will pick up where the High-Luminosity LHC (HL-LHC) leaves off. In a joint submission, the ATLAS and CMS collaborations presented physics projections which suggest that the HL-LHC will be able to: observe the $H\to\mu^+\mu^-$ and $H\to Z\gamma$ decays of the Higgs boson; observe Standard Model di-Higgs production; and measure the Higgs' trilinear self-coupling with a precision better than 30%. The joint document also highlights the need for further progress in high-precision theoretical calculations aligned with the demands of the HL-LHC and serves as important input to the discussion on the choice of a future collider at CERN.

Neutrinos and cosmic messengers, dark matter and the dark sector, strong interactions and flavour physics also attracted many inputs, allowing priorities in non-collider physics to complement collider programmes. Underpinning the community's physics aspirations are numerous submissions in the categories of accelerator science and technology, detector instrumentation and computing. Progress in these technologies is vital for the realisation of a post-LHC collider, which was also reflected by the recommendation of the 2020 strategy update to define R&D roadmaps. The scientific and technical inputs will be reviewed by the Physics Preparatory Group (PPG), which will conduct comparative assessments of the scientific potential of various proposed projects against defined physics benchmarks.

Key to the ESPP 2026 update are 57 national and national-laboratory submissions, including some from outside Europe. Most identify the FCC as the preferred project to succeed the LHC. If the FCC is found to be unfeasible, many national communities propose that a linear collider at CERN should be pursued, while taking into account the global context: a 250 GeV linear collider may not be competitive if China decides to proceed with a Circular Electron Positron Collider at a comparable energy on the anticipated timescale, potentially motivating a higher energy electron–positron machine or a proton–proton collider instead.

Complex process

In its review, the ESG will take the physics reach of proposed colliders as well as other factors into account. This complex process will be undertaken by seven working groups, addressing: national inputs; diversity in European particle physics; project comparison; implementation of the strategy and deliverability of large projects; relations with other fields of physics; sustainability and environmental impact; public engagement, education, communication and social and career aspects for the next generation; and knowledge and technology transfer. "The ESG and the PPG have their work cut out and we look forward to further strong participation by the full community, in particular at the Open Symposium," says Jakobs.

A briefing book prepared by the PPG based on the community input and discussions at the Open Symposium will be submitted to the ESG by the end of September for consideration during a five-day-long drafting session, which is scheduled to take place from 1 to 5 December. The CERN Council will then review the final ESG recommendations ahead of a special session to be held in Budapest in May 2026.

FUTURE COLLIDERS

FCC feasibility study complete

The final report of a detailed study investigating the technical and financial feasibility of a Future Circular Collider (FCC) at CERN was released on 31 March. Building on a conceptual design study conducted between 2014 and 2018, the three-volume report is authored by over 1400 scientists and engineers in more than 400 institutes worldwide, and covers aspects of the project ranging from civil engineering to socioeconomic impact. As recommended in the 2020 update to the European Strategy for Particle Physics (ESPP), it was completed in time to serve as an input to the ongoing 2026 update to the ESPP (see p8).

The FCC is a proposed collider infrastructure that could succeed the LHC in the 2040s. Its scientific motivation stems from the discovery in 2012 of the final

A broad and powerful exploratory tool is required in key domains

particle of the Standard Model (SM), the Higgs boson, with a mass of just 125 GeV, and the wealth of precision measurements and exploratory searches during 15 years of LHC operations that have excluded many signatures of new physics at the TeV scale. The report argues that the FCC is particularly well equipped to study the Higgs and associated electroweak sectors in detail and that it provides a broad and powerful exploratory tool that would push the limits of the unknown as far as possible. ▷

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The report describes how the FCC will seek to address key domains formulated in the 2013 and 2020 ESPP updates, including: mapping the properties of the Higgs and electroweak gauge bosons with accuracies orders of magnitude better than today to probe the processes that led to the emergence of the Brout–Englert–Higgs field's nonzero vacuum expectation value; ensuring a comprehensive and accurate campaign of precision electroweak, quantum chromodynamics, flavour and top-quark measurements sensitive to tiny deviations from the SM, probing energy scales far beyond the direct kinematic reach; improving by orders of magnitude the sensitivity to rare and elusive phenomena at low energies, including the possible discovery of light particles with very small couplings such as those relevant to the search for dark matter; and increasing by at least an order of magnitude the direct discovery reach for new particles at the energy frontier.

The FCC research programme outlines two possible stages: an electron–positron collider (FCC-ee) running at several centre-of-mass energies to serve as a Higgs, electroweak and top-quark factory, followed at a later stage by a proton–proton collider (FCC-hh) operating at an unprecedented collision energy. An FCC-ee with four detectors is judged to be "the electroweak, Higgs and top factory project with the highest luminosity proposed to date", able to produce 6×10^{12} Z bosons, 2.4×10^{8} W pairs, almost 3×10^{6} Higgs bosons, and 2×10^{6} top-quark pairs over 15 years of operations. Its versatile RF system would enable flexibility in the running sequence, states the report, allowing experimenters to move between physics programmes and scan through energies at ease. The report also outlines how the FCC-ee injector offers opportunities for other branches of science, including the production of spatially coherent photon beams with a brightness several orders of magnitude higher than any existing or planned light source.

The estimated cost of the construction of the FCC-ee is CHF 15.3 billion. This investment, which would be distributed over a period of about 15 years starting from the early 2030s, includes civil engineering, technical infrastructure, electron and positron accelerators, and four detectors.

CERN

Study complete *Taking geodetic measurements for the FCC.*

Ready for construction

The report describes how key FCC-ee design approaches, such as a double-ring layout, top-up injection with a full-energy booster, a crab-waist collision scheme, and precise energy calibration, have been demonstrated at several previous or presently operating colliders. The FCC-ee is thus "technically ready for construction" and is projected to deliver four-to-five orders of magnitude higher luminosity per unit electrical power than LEP. During operation, its energy consumption is estimated to vary from 1.1 to 1.8 TWh/y depending on the operation mode compared to CERN's current consumption of about 1.3 TWh/y. Decarbonised energy including an ever-growing contribution from renewable sources would be the main source of energy for the FCC. Ongoing technology R&D aims at further increasing FCC-ee's energy efficiency (see p30).

This technology has significant potential for industrial and societal applications

Assuming $14\,T\ Nb_3Sn$ magnet technology as a baseline design, a subsequent hadron collider with a centre-of-mass energy of 85 TeV entering operation in the early 2070s would extend the energy frontier by a factor six and provide an integrated luminosity five to 10 times higher than that of the HL-LHC during 25 years of operation. With four detectors, FCC-hh would increase the mass reach of direct searches for new particles to several tens of TeV, probing a broad spectrum of beyond-the-SM theories and potentially identifying the sources of any deviations found in precision measurements at FCC-ee, especially those involving the Higgs boson. An estimated sample of more than 20 billion Higgs bosons would allow the absolute determination of its couplings to muons, to photons, to the top quark and to $Z\gamma$ below the percent level, while di-Higgs production would bring the uncertainty on the Higgs self-coupling below the 5% level. FCC-hh would also significantly advance understanding of the hot QCD medium by enabling lead–lead and other heavy-ion collisions at unprecedented energies, and could be configured to provide electron–proton and electron–ion collisions, says the report.

The FCC-hh design is based on LHC experience and would leverage a substantial amount of the technical infrastructure built for the first FCC stage. Two hadron injector options are under study involving a superconducting machine in either the LHC or SPS tunnel. For the purpose of a technical feasibility analysis, a reference scenario based on $14\,T\ Nb_3Sn$ magnets cooled to 1.9 K was considered, yielding 2.4 MW of synchrotron radiation and a power consumption of 360 MW or 2.3 TWh/y – a comparable power consumption to FCC-ee.

FCC-hh's power consumption might be reduced below 300 MW if the magnet temperature can be raised to 4.5 K. Outlining the potential use of high-temperature superconductors for 14 to 20 T dipole magnets operating at temperatures between 4.5 K and 20 K, the report notes that such technology could either extend the centre-of-mass energy of FCC-hh to 120 TeV or lead to significantly improved operational sustainability at the same collision energy. "The time window of more than 25 years opened by the lepton-collider stage is long enough to bring that technology to market maturity," says FCC study leader Michael Benedikt (CERN). "High-temperature superconductors have significant potential for industrial and societal applications, and particle accelerators can serve as pilots for market uptake, as was the case with the Tevatron and the LHC for NbTi technology."

Society and sustainability

The report details the concepts and paths to keep the FCC's environmental footprint low while boosting new technologies to benefit society and developing territorial synergies such as energy reuse. The civil construction process for FCC-ee, which would also serve FCC-hh, is estimated to result in about 500,000 $tCO_2(eq)$ over a period of 10 years, which the authors say corresponds to approximately one-third of the carbon budget of the Paris Olympic Games. A socio-economic impact assessment of the FCC integrating environmental aspects throughout its entire lifecycle reveals a positive cost–benefit ratio, even under conservative assumptions and adverse implementation conditions.

A major achievement of the FCC feasibility study has been the development of the layout and placement of the collider ring and related infrastructure, which have been optimised for scientific benefit while taking into account territorial compatibility, environmental and construction constraints, and cost. No fewer than 100 scenarios were developed and analysed before settling on the preferred option: a ring circumference of 90.7 km with shaft depths ranging between 200 and 400 m, with eight surface sites and four experiments. Throughout the study, CERN has been accompanied by its host states, France and Switzerland, working with entities at the local, regional and national levels to ensure a constructive dialogue with territorial stakeholders.

The final report of the FCC feasibility study together with numerous referenced technical documents have been submitted to the ongoing ESPP 2026 update, along with studies of alternative projects proposed by the community. The CERN Council may take a decision around 2028.

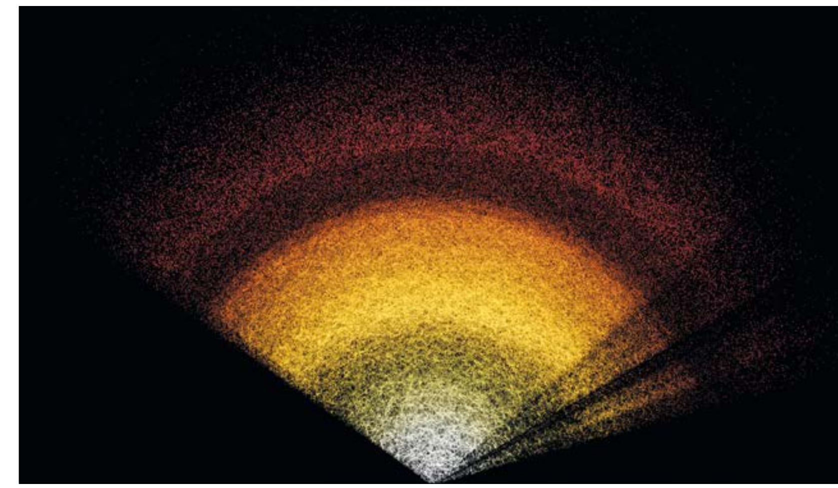
The actual journey towards the realisation of the FCC starts now

"After four years of effort, perseverance and creativity, the FCC feasibility study was concluded on 31 March 2025," says Benedikt. "The actual journey towards the realisation of the FCC starts now and promises to be at least as fascinating as the successive steps that brought us to the present state."

ASTROWATCH

DESI hints at evolving dark energy

The dynamics of the universe depend on a delicate balance between gravitational attraction from matter and the repulsive effect of dark energy. A universe containing only matter would eventually slow down its expansion due to gravitational forces and possibly recollapse. However, observations of Type Ia supernovae in the late 1990s revealed that our universe's expansion is in fact accelerating, requiring the introduction of dark energy. The standard cosmological model, called the Lambda Cold Dark Matter (ΛCDM) model, provides an elegant and robust explanation of cosmological observations by including normal matter, cold dark matter (CDM) and dark energy. It is the foundation of our current understanding of the universe.

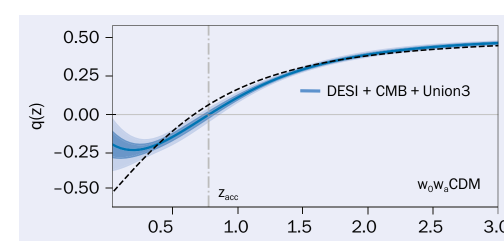


DESI Collaboration and KPNO/NOIRLab/NSF/AURA/R

3D map *A slice of DESI's first three years of data. Each dot represents a galaxy, with colour indicating redshift.*

Cosmological constant

In ΛCDM, Λ refers to the cosmological constant – a parameter introduced by Albert Einstein to counter the effect of gravity in his pursuit of a static universe. With the knowledge that the universe is accelerating, Λ is now used to quantify this acceleration. An important parameter that describes dark energy, and therefore influences the evolution of the universe, is its equation-of-state parameter, w. This value relates the pressure dark energy exerts on the universe, p, to its energy density, ρ, via $p = w\rho$. Within ΛCDM, w is –1 and ρ is constant – a combination that has to date explained observations well. However, new results by the Dark Energy Spectroscopic Instrument (DESI) put these assumptions under increasing stress.



K Lodha *et al.* 2025 arXiv:2503.14743

Tension with ΛCDM *The cosmological deceleration parameter q(z) as a function of redshift z. q(z) > 0 implies deceleration at that redshift and q(z) < 0 acceleration, with increasing redshift corresponding to greater distances and earlier times. The DESI + CMB + Union3 fit and its one- and two-sigma confidence levels (blue) are compared to the ΛCDM model (dashed line).* z_{acc} *(dash–dotted line) corresponds to the onset of cosmic acceleration.*

These new results are part of the second data release (DR2) from DESI. Mounted on the Nicholas U Mayall 4-metre telescope at Kitt Peak National Observatory in Arizona, DESI is optimised to measure the spectra of a large number of objects in the sky simultaneously. Joint observations are possible thanks to 5000 optical fibres controlled through robots, which continuously optimise the focal plane of the detector. Combined with a highly efficient processing pipeline, this allows DESI to perform detailed simultaneous spectrometer measurements of a large number of objects in the sky, resulting in a catalogue of measurements of the distance of objects based on their velocity-induced shift in wavelength, or redshift. For its first data release, DESI used 6 million such redshifts, allowing it to show that w was several sigma away from its expected value of –1 (*CERN Courier* May/June 2024 p11). For DR2, 14 million measurements are used, enough to provide strong hints of w changing with time.

The first studies of the expansion rate of the universe were based on redshift measurements of local objects, such as supernovae. As the objects are relatively close, they provide data on the acceleration at small redshifts. An alternative method is to use the cosmic microwave background (CMB), which allows for measurements of the evolution of the early universe through complex imprints left on the current distribution of the CMB. The significantly smaller expansion rate measured through the CMB compared to local measurements resulted in a "Hubble tension", prompting novel measurements to resolve or explain the observed difference (*CERN Courier* March/April 2025 p28). One such attempt comes from ▷

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DESI, which aims to provide a detailed 3D map of the universe focusing on the distance between galaxies to measure the expansion (see "3D map" figure).

The 3D map produced by DESI can be used to study the evolution of the universe as it holds imprints from small fluctuations in the density of the early universe. These density fluctuations have been studied through their imprint on the CMB, however, they also left imprints in the distribution of baryonic matter until the age of recombination occurred. The variations in baryonic density grew over time into the varying densities of galaxies and other large-scale structures that are observed today.

The regions originally containing higher baryon densities are now those with larger densities of galaxies. Exactly how the matter-density fluctuations evolved into variations in galaxy densities throughout the universe depends on a range of parameters from the ΛCDM model, including w. The detailed map of the universe produced by DESI, which contains a range of objects with redshifts up to 2.5, can therefore be fitted against the ΛCDM model.

The new data release provides significant evidence of a deviation from the Lambda ΛCDM model

Among other studies, the latest data from DESI was combined with that of CMB observations and fitted to the ΛCDM model. This worked relatively well, although it requires a lower matter-density parameter than found from CMB data alone. However, using the resulting cosmological parameters results in a poor match with the data for the early universe coming from supernova measurements. Similarly, fitting the ΛCDM model using the supernova data results in poor agreement with both the DESI and CMB data, thereby putting some strain on the ΛCDM model. Things don't get significantly better when adding some freedom in these analyses by allowing w to differ from −1.

An adaption of the ΛCDM model that results in an agreement with all three datasets requires w to evolve with redshift, or time. The implications for the acceleration of the universe based on these results are shown in the "Tension with ΛCDM" figure, which shows the deceleration rate of the expansion of the universe as a function of redshift. $q<0$ implies an accelerating universe. In the ΛCDM model, acceleration increases with time, as redshift approaches 0. DESI data suggests that the acceleration of the universe started earlier, but is currently less than that predicted by ΛCDM.

Although this model matches the data well, a theoretical explanation is difficult. In particular, the data implies that w(z) was below −1, which translates into an energy density that increases with the expansion; however, the energy density seems to have peaked at a redshift of 0.45 and is now decreasing.

Overall, the new data release provides significant evidence of a deviation from the Lambda ΛCDM model. The exact significance depends on the specific analysis and which data sets are combined, however, all such studies provide similar results. As no 5σ discrepancy is found yet, there is no reason to discard ΛCDM, though this could change with another two years of DESI data coming up, along with data from the European Euclid mission, Vera C Rubin Observatory, and the Nancy Grace Roman Space Telescope. Each will provide new insights into the expansion for various redshift periods.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Tau leptons from light resonances

Among the fundamental particles, tau leptons occupy a curious spot. They participate in the same sort of reactions as their lighter lepton cousins, electrons and muons, but their large mass means that they can also decay into a shower of pions and they interact more strongly with the Higgs boson. In many new-physics theories, Higgs-like particles – beyond that of the Standard Model – are introduced in order to explain the mass hierarchy or as possible portals to dark matter.

Because of their large mass, tau leptons are especially useful in searches for new physics. However, identifying taus is challenging, as in most cases they decay into a final state of one or more pions and an undetected neutrino. A crucial step in the identification of a tau lepton in the CMS experiment is the hadrons-plus-strips (HPS) algorithm. In the standard CMS reconstruction, a minimum momentum threshold of 20 GeV is imposed, such that the taus have enough momentum to make their decay products fall into narrow cones. However, this requirement reduces sensitivity to low-momentum taus. As a result, previous searches for a Higgs-like resonance ϕ decaying into two tau leptons required a ϕ-mass of more than 60 GeV.

The CMS experiment has now been able to extend the ϕ-mass range down to 20 GeV. To improve sensitivity to low-momentum tau decays, machine learning is used to determine a dynamic cone algorithm that expands the cone size as needed. The new algorithm, requiring one tau decaying into a muon and two neutrinos and one tau decaying into hadrons and a neutrino, is implemented in the CMS Scouting trigger system. Scouting extends CMS's reach into previously inaccessible phase space by retaining only the most relevant information about the event, and thus facilitating much higher event rates.

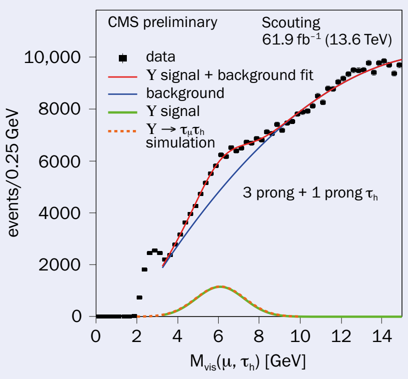

Fig. 1. *The data are consistent with the signal expected from a Υ meson decaying to a pair of tau leptons. The backgrounds are estimated using a polynomial (blue), and the resonance is fit with a Gaussian. The sum of the fitted background and Gaussian is the red line. The expected distribution from Υ mesons (dashed orange) is overlaid on the Gaussian (green), showing consistency.*

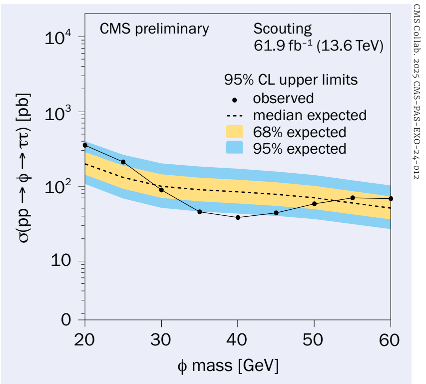

Fig. 2. *Observed limit at 95% confidence level on the production cross-section for $\phi \to \tau\tau$ in pb. The solid line represents the observed limit, while the yellow and blue bands indicate the expectation for the limit in the case of no signal.*

The sensitivity of the new algorithm is so high that even the upsilon (Υ) meson, a bound state of the bottom quark and its antiquark, can be seen. Figure 1 shows the distribution of the mass of the *visible* decay products of tau (M_{vis}), in this case a muon from one tau lepton and either one or three pions from the other. A clear resonance structure is visible at M_{vis} = 6 GeV, in agreement with the expectation for the Υ meson. The peak is not at the actual mass of the Υ meson (9.46 GeV) due to the presence of neutrinos in the decay.

The sensitivity of the new algorithm is so high that even the Υ meson can be seen

While $\Upsilon \to \tau\tau$ decays have been observed at electron–positron colliders, this marks the first evidence at a hadron collider and serves as an important benchmark for the analysis.

Given the high sensitivity of the new algorithm, CMS performed a search for a possible resonance in the range between 20 and 60 GeV using the data recorded in the years 2022 and 2023, and set competitive exclusion limits (see figure 2). For the 2024 and 2025 data taking, the algorithm was further improved, enhancing the sensitivity even more.

Further reading

CMS Collab. 2025 CMS-PAS-EXO-24-012.

ATLAS

Pinpointing polarisation in vector-boson scattering

In the Standard Model (SM), W and Z bosons acquire mass and longitudinal polarisation through electroweak (EW) symmetry breaking, where the Brout–Englert–Higgs mechanism transforms Goldstone bosons into their longitudinal components. One of the most powerful ways to probe this mechanism is through vector-boson scattering (VBS), a rare process represented in figure 1, where two vector bosons scatter off each other. At high (TeV-scale) energies, interactions involving longitudinally polarised W and Z bosons provide a stringent test of the SM. Without the Higgs boson's couplings to these polarisation states, their interaction rates would grow uncontrollably with energy, eventually violating unitarity, indicating a complete breakdown of the SM.

Valuable avenues for uncovering new physics

Measuring the polarisation of same electric charge (same sign) W-boson ▷

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pairs in VBS directly tests the predicted EW interactions at high energies through precision measurements. Furthermore, beyond-the-SM scenarios predict modifications to VBS, some affecting specific polarisation states, rendering such measurements valuable avenues for uncovering new physics.

Using the full proton–proton collision dataset from LHC Run 2 (2015–2018, 140 fb^{-1} at 13 TeV), the ATLAS collaboration recently published the first evidence for longitudinally polarised W bosons in the electroweak production of same-sign W-boson pairs in final states including two same-sign leptons (electrons or muons) and missing transverse momentum, along with two jets (EW $W^\pm W^\pm jj$). This process is categorised by the polarisation states of the W bosons: fully longitudinal ($W^\pm_L W^\pm_L jj$), mixed ($W^\pm_L W^\pm_T jj$), and fully transverse ($W^\pm_T W^\pm_T jj$). Measuring the polarisation states is particularly challenging due to the rarity of the VBS events, the presence of two undetected neutrinos, and the absence of a single kinematic variable that efficiently distinguishes between polarisation states. To overcome this, deep neural networks (DNNs) were trained to exploit the complex correlations between event kinematic variables that characterise different polarisations. This approach enabled the separation of the fully longitudinal $W^\pm_L W^\pm_L jj$ from the combined $W^\pm_T W^\pm jj$ ($W^\pm_L W^\pm_T jj$ plus $W^\pm_T W^\pm_T jj$) processes as well as the combined $W^\pm_L W^\pm jj$ ($W^\pm_L W^\pm_L jj$ plus $W^\pm_L W^\pm_T jj$) from the purely transverse $W^\pm_T W^\pm_T jj$ contribution.

To measure the production of $W^\pm_L W^\pm_L jj$ and $W^\pm_L W^\pm jj$ processes, a first DNN (inclusive DNN) was trained to distinguish EW $W^\pm W^\pm jj$ events from background processes. Variables such as the invariant mass of the two highest-energy jets provide strong discrimination for this classification. In addition, two independent DNNs (signal DNNs) were trained to extract polarisation information, separating either $W^\pm_L W^\pm_L jj$ from $W^\pm_T W^\pm jj$ or $W^\pm_L W^\pm jj$ from $W^\pm_T W^\pm_T jj$, respectively. Angular variables, such as the azimuthal angle difference between the leading leptons and the pseudorapidity difference between the leading and subleading jets, are particularly sensitive to the scattering angles of the W bosons, enhancing the separation power of the signal DNNs. Each DNN is trained using up to 20 kinematic variables, leveraging correlations among them to improve sensitivity.

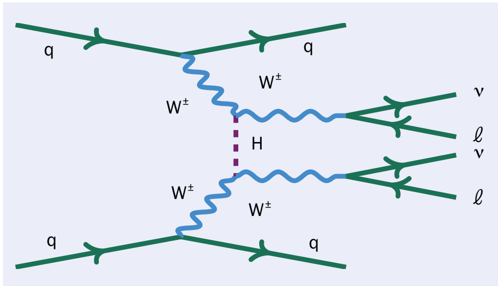

Fig. 1. *A representative diagram for VBS EW $W^\pm W^\pm jj$ production, including the exchange of a Higgs boson.*

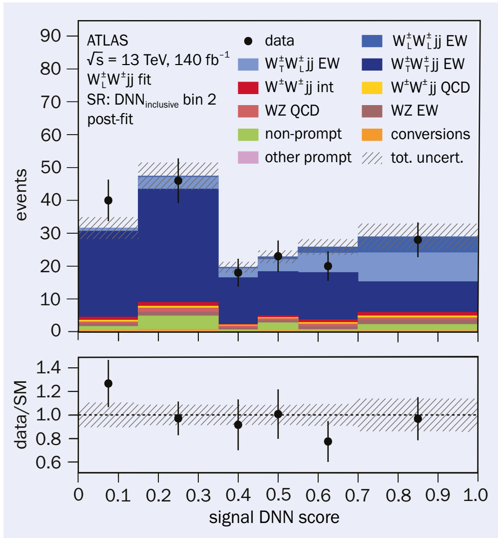

Fig. 2. *Signal DNN score distribution for the $W^\pm_L W^\pm jj$ measurement displayed in the highest EW $W^\pm W^\pm jj$ purity bin of the inclusive DNN. The predicted yields are presented using their best-fit normalisation and shape. The lower panel shows the ratio of the data to the total SM predictions, where the band represents the total uncertainty.*

The signal DNN distributions, within each inclusive DNN region, were used to extract the $W^\pm_L W^\pm_L jj$ and $W^\pm_L W^\pm jj$ polarisation fractions through two independent maximum-likelihood fits. The excellent separation between the $W^\pm_L W^\pm jj$ and $W^\pm_T W^\pm_T jj$ processes can be seen in figure 2 for the $W^\pm_L W^\pm jj$ fit, achieving better separation for higher scores of the signal DNN, represented in the x-axis. An observed (expected) significance of 3.3 (4.0) standard deviations was obtained for $W^\pm_L W^\pm jj$, providing the first evidence of same-sign WW production with at least one of the W bosons longitudinally polarised. No significant excess of events consistent with $W^\pm_L W^\pm_L jj$ production was observed, leading to the most stringent 95% confidence-level upper limits to date on the $W^\pm_L W^\pm_L jj$ cross section: 0.45 (0.70) fb observed (expected).

There is still much to understand about the electroweak sector of the Standard Model, and the measurement presented in this article remains limited by the size of the available data sample. The techniques developed in this analysis open new avenues for studying W- and Z-boson polarisation in VBS processes during the LHC Run 3 and beyond.

Further reading

ATLAS Collab. 2025 arXiv:2503.11317.

ALICE

ALICE measures a rare Ω baryon

Since the discovery of the electron and proton over 100 years ago, physicists have observed a "zoo" of different types of particles. While some of these particles have been fundamental, like neutrinos and muons, many are composite hadrons consisting of quarks bound together by the exchange of gluons. Studying the zoo of hadrons – their compositions, masses, lifetimes and decay modes – allows physicists to understand the details of the strong interaction, one of the fundamental forces of nature.

The Ω(2012) was discovered by the Belle Collaboration in 2018. The ALICE collaboration recently released an observation of a signal consistent with it with a significance of 15σ in proton–proton (pp) collisions at a centre-of-mass energy of 13 TeV. This is the first observation of the Ω(2012) by another experiment.

While the details of its internal structure are still up for debate, the Ω(2012) consists, at minimum, of three strange quarks bound together. It is a heavier, excited version of the ground-state Ω baryon discovered in 1964, which also contains three strange quarks. Multiple theoretical models predicted a spectrum of excited Ω baryons, with some calling for a state with a mass around 2 GeV. Following the discovery of the Ω(2012), theoretical work has attempted to describe its internal structure, with hypotheses including a simple three-quark baryon or a hadronic molecule.

This is the first observation of the Ω(2012) by another experiment

Using a sample of a billion pp collisions, ALICE has measured the decay of Ω(2012) baryons to $\Xi^- K^0_S$ pairs. After traveling a few centimetres, these hadrons decay in turn, eventually producing a proton and four charged pions that are tracked by the ALICE detector.

ALICE's measurements of the mass and width of the Ω(2012) are consistent with Belle's, and superior precision on the mass. ALICE has also confirmed ▷ the rather narrow width of around 6 MeV, which indicates that the Ω(2012) is fairly long-lived for a particle that decays via the strong interaction. Belle and ALICE's width measurements also lend support to the conclusion that the Ω(2012) has a spin-parity configuration of $J^P = 3/2^-$.

ALICE also measured the number of Ω(2012) decays to $\Xi^- K^0_S$ pairs. By comparing this to the total Ω(2012) yield based on statistical thermal model calculations, ALICE has estimated the absolute branching ratio for the $\Omega(2012) \rightarrow \Xi^- K^0$ decay. A branching ratio is the probability of decay to a given mode. The ALICE results indicate that Ω(2012) undergoes two-body ($\Xi\bar{K}$) decays more than half the time, disfavouring models of the Ω(2012) structure that require large branching ratios for three-body decays.

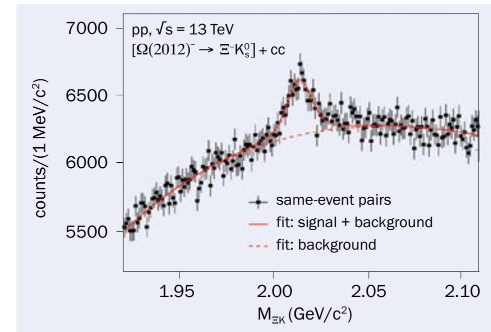

Fig. 1. *Invariant mass distribution of $\Xi^- K^0_S$ pairs in pp collisions at a centre-of-mass energy of 13 TeV. A prominent Ω(2012) peak is visible atop a combinatorial background.*

The present ALICE results will help to improve the theoretical description of the structure of excited baryons. They can also serve as baseline measurements in searches for modifications of Ω-baryon properties in nucleus–nucleus collisions. In the future, Ω(2012) baryons may also serve as new probes to study the strangeness enhancement effect observed in proton–proton and nucleus–nucleus collisions.

Further reading

ALICE Collab. 2025 arXiv: 2502.18063.

LHCb

Clean di-pions reveal vector mesons

Heavy-ion collisions usually have very high multiplicities due to colour flow and multiple nucleon interactions. However, when the ions are separated by greater than about twice their radii in so-called ultra-peripheral collisions (UPC), electromagnetic-induced interactions dominate. In these colour-neutral interactions, the ions remain intact and a central system with few particles is produced whose summed transverse momenta, being the Fourier transform of the distance between the ions, is typically less than 100 MeV/c.

In the photoproduction of vector mesons, a photon, radiated from one of the ions, fluctuates into a virtual vector meson long before it reaches the target and then interacts with one or more nucleons in the other ion. The production of ρ mesons has been measured at the LHC by ALICE in PbPb and XeXe collisions, while J/ψ mesons have been measured in PbPb collisions by ALICE, CMS and LHCb. Now, LHCb has isolated a precisely measured, high-statistics sample of di-pions with backgrounds below 1% in which several vector mesons are seen.

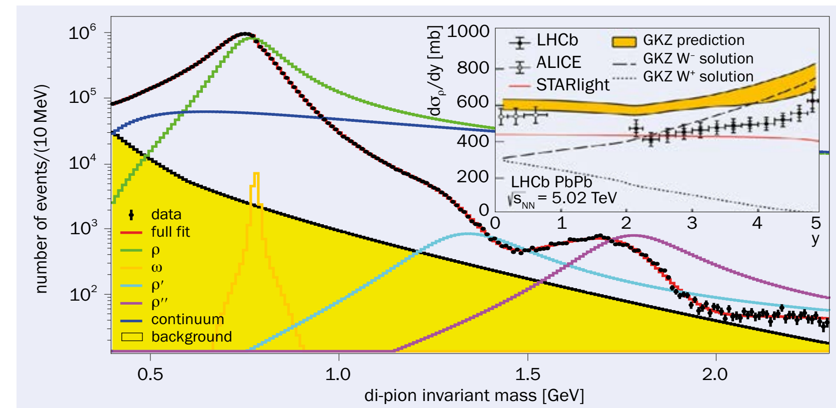

Fig. 1. *The invariant mass of di-pions produced in UPC PbPb collisions. The inset shows the nuclear suppression factor compared to the GKZ model, to the STARlight generator and to ALICE data at central rapidities.*

Figure 1 shows the invariant mass distribution of the pions, and the fit to the data requires contributions from the ρ meson, continuum ππ, the ω meson and two higher mass resonances at about 1.35 and 1.80 GeV, consistent with excited ρ mesons. The higher structure was also discernible in previous measurements by STAR and ALICE. Since its discovery in 1961, the ρ meson has proved challenging to describe because of its broad width and because of interference effects. More data in the di-pion channel, particularly when practically background-free down almost to production threshold, are therefore welcome. These data may help with hadronic corrections to the prediction of muon g-2: the dip and bump structure at high masses seen by LHCb is qualitatively similar to that observed by BaBar in $e^+e^- \rightarrow \pi^+\pi^-$ scattering (*CERN Courier* March/April 2025 p21). From the invariant mass spectrum, LHCb has measured the cross-sections for ρ, ω, ρ′ and ρ″ as a function of rapidity in photoproduction on lead nuclei.

These data may help with hadronic corrections to the prediction of muon g-2

Naively, comparison of the photoproduction on the nucleus and on the proton should simply scale with the number of nucleons, and can be calculated in the impulse approximation that only takes into account the nuclear form factor, neglecting all other potential nuclear effects.

However, nuclear shadowing, caused by multiple interactions as the meson passes through the nucleus, leads to a suppression (*CERN Courier* January/February 2025 p31). In addition, there may be further non-linear QCD effects at play.

Elastic re-scattering is usually described through a Glauber calculation that takes account of multiple elastic scatters. This is extended in the GKZ model using Gribov's formalism to include inelastic scatters. The inset in figure 1 shows the measured differential cross-section for the ρ meson as a function of rapidity for LHCb data compared to the GKZ prediction, to a prediction for the STARlight generator, and to ALICE data at central rapidities. Additional suppression due to nuclear effects is observed above that predicted by GKZ.

Further reading

LHCb Collab. 2025 LHCb-PAPER-2024-042.

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FIELD NOTES

Reports from events, conferences and meetings

QUARK MATTER 2025

Colour information diffuses in Frankfurt

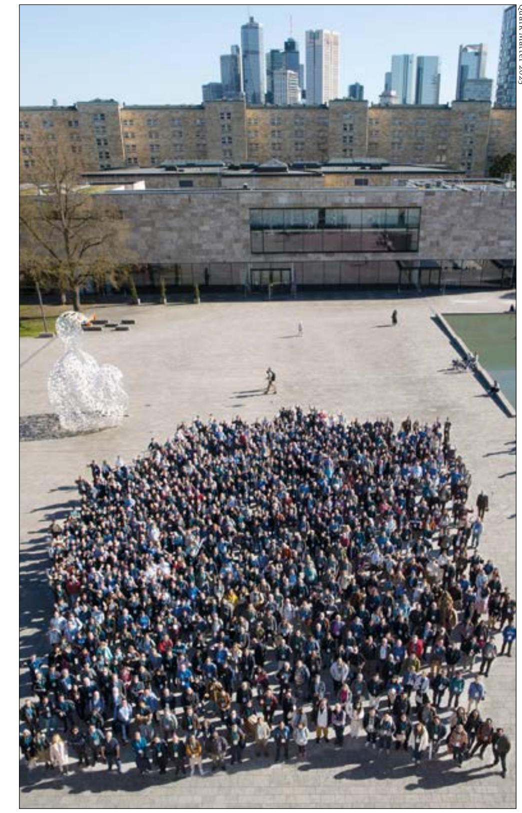
The 31st Quark Matter conference took place from 6 to 12 April at Goethe University in Frankfurt, Germany. This edition of the world's flagship conference for ultra-relativistic heavy-ion physics was the best attended in the series' history, with more than 1000 participants.

A host of experimental measurements and theoretical calculations targeted fundamental questions in many-body QCD. These included the search for a critical point along the QCD phase diagram, the extraction of the properties of the deconfined quark–gluon plasma (QGP) medium created in heavy-ion collisions, and the search for signatures of the formation of this deconfined medium in smaller collision systems.

Probing thermalisation

New results highlighted the ability of the strong force to thermalise the out-of-equilibrium QCD matter produced during the collisions. Thermalisation can be probed by taking advantage of spatial anisotropies in the initial collision geometry which, due to the rapid onset of strong interactions at early times, result in pressure gradients across the system. These pressure gradients in turn translate into a momentum-space anisotropy of produced particles in the bulk, which can be experimentally measured by taking a Fourier transform of the azimuthal distribution of final-state particles with respect to a reference event axis.

An area of active experimental and theoretical interest is to quantify the degree to which heavy quarks, such as charm and beauty, participate in this collective behaviour, which informs on the diffusion properties of the medium. The ALICE collaboration presented the first measurement of the second-order coefficient of the momentum anisotropy of charm baryons in Pb–Pb collisions, showing significant collective behaviour and suggesting that charm quarks undergo some degree of thermalisation. This collective behaviour appears to be stronger in charm baryons than charm mesons, following similar observations for light flavour.



Quark Matter 2025

Ultra-relativistic heavy-ions *Quark Matter 2025 took place in Frankfurt in April.*

A host of measurements and calculations targeted fundamental questions in many-body QCD

Due to the nature of thermalisation and the long hydrodynamic phase of the medium in Pb–Pb collisions, signatures of the microscopic dynamics giving rise to the thermalisation are often washed out in bulk observables. However, local excitations of the hydrodynamic medium, caused by the propagation of a high-energy jet through the QGP, can offer a window into such dynamics. Due to coupling to the coloured medium, the jet loses energy to the QGP, which in turn re-excites the thermalised medium. These excited states quickly decay and dissipate, and the local perturbation can partially thermalise. This results in a correlated response of the medium in the direction of the propagating jet, the distribution of which allows measurement of the thermalisation properties of the medium in a more controlled manner.

In this direction, the CMS collaboration presented the first measurement of an event-wise two-point energy-energy correlator, for events containing a Z boson, in both pp and Pb–Pb collisions. The two-point correlator represents the energy-weighted cross section of the angle between particle pairs in the event and can separate out QCD effects at different scales, as these populate different regions in angular phase space. In particular, the correlated response of the medium is expected to appear at large angles in the correlator in Pb–Pb collisions.

The use of a colourless Z boson, which does not interact in the QGP, allows CMS to compare events with similar initial virtuality scales in pp and Pb–Pb collisions, without incurring biases due to energy loss in the QCD probes. The collaboration showed modifications in the two-point correlator at large angles, from pp to Pb–Pb collisions, alluding to a possible signature of the correlated response of the medium to the traversing jets. Such measurements can help guide models into capturing the relevant physical processes underpinning the diffusion of colour information in the medium.

Looking to the future

The next addition of this conference series will take place in 2027 in Jeju, South Korea, and the new results presented there should notably contain the latest complement of results from the upgraded Run 3 detectors at the LHC and the newly commissioned sPHENIX detector at RHIC. New collision systems like O–O at the LHC will help shed light on many of the properties of the QGP, including its thermalisation, by varying the lifetime of the pre-equilibrium and hydrodynamic phases in the collision evolution.

Nima Zardoshti *CERN.*

Rencontres de Moriond: Electroweak Interactions and Unified Theories

Planning for precision at Moriond

Rencontres de Moriond

Mountain vista *Participants of the 59th Rencontres de Moriond surveyed the landscape of particle physics.*

Since 1966 the Rencontres de Moriond has been one of the most important conferences for theoretical and experimental particle physicists. The Electroweak Interactions and Unified Theories session of the 59th edition attracted about 150 participants to La Thuile, Italy, from 23 to 30 March, to discuss electroweak, Higgs-boson, top-quark, flavour, neutrino and dark-matter physics, and the field's links to astrophysics and cosmology.

Particle physics today benefits from a wealth of high-quality data at the same time as powerful new ideas are boosting the accuracy of theoretical predictions. These are particularly important while the international community discusses future projects, basing projections on current results and technology. The conference heard how theoretical investigations of specific models and "catch all" effective field theories are being sharpened to constrain a broader spectrum of possible extensions of the Standard Model. Theoretical parametric uncertainties are being greatly reduced by collider precision measurements and lattice QCD. Perturbative calculations of short-distance amplitudes are reaching to percent-level precision, while hadronic long-distance effects are being investigated both in B-, D- and K-meson decays, as well as in the modelling of collider events.

Comprehensive searches

Throughout Moriond 2025 we heard how a broad spectrum of experiments at the LHC, B factories, neutrino facilities, and astrophysical and cosmological observatories are planning upgrades to search for new physics at both low- and high-energy scales. Several fields promise qualitative progress in understanding nature in the coming years. Neutrino experiments will measure the neutrino mass hierarchy and CP violation in the neutrino sector. Flavour experiments will exclude or confirm flavour anomalies. Searches for QCD axions and axion-like particles will seek hints to the solution of the strong CP problem and possible dark-matter candidates.

The Standard Model has so far been confirmed to be the theory that describes physics at the electroweak scale (up to a few hundred GeV) to a remarkable level of precision. All the particles predicted by the theory have been discovered, and the consistency of the theory has been proven with high precision, including all calculable quantum effects. No direct evidence of new physics has been found so far. Still, big open questions remain that the Standard Model cannot answer, from understanding the origin of neutrino masses and their hierarchy, to identifying the origin and nature of dark matter and dark energy, and explaining the dynamics behind the baryon asymmetry of the universe.

Several fields promise qualitative progress in understanding nature in the coming years

The discovery of the Higgs boson has been crucial to confirming the Standard Model as the theory of particle physics at the electroweak scale, but it does not explain why the scalar Brout–Englert–Higgs (BEH) potential takes the form of a Mexican hat, why the electroweak scale is set by a Higgs vacuum expectation value of 246 GeV, or what the nature of the Yukawa force is that results in the bizarre hierarchy of masses coupling the BEH field to quarks and leptons. Gravity is also not a component of the Standard Model, and a unified theory escapes us.

At the LHC today, the ATLAS and CMS collaborations are delivering Run 1 and 2 results with beyond-expectation accuracies on Higgs-boson properties and electroweak precision measurements. Projections for the high-luminosity phase of the LHC are being updated and Run 3 analyses are in full swing. The LHCb collaboration presented another milestone in flavour physics for the first time at Moriond 2025: the first observation of CP violation in baryon decays. Its rebuilt Run 3 detector with triggerless readout and full software trigger reported its first results at this conference.

Several talks presented scenarios of new physics that could be revealed in today's data given theoretical guidance of sufficient accuracy. These included models with light weakly interacting particles, vector-like fermions and additional scalar particles. Other talks discussed how revisiting established quantum properties such as entanglement with fresh eyes could offer unexplored avenues to new theoretical paradigms and overlooked new-physics effects.

Johannes Albrecht *TU Dortmund and* **Laura Reina** *Florida State University and INFN University of Rome "La Sapienza".*

PhyStat25

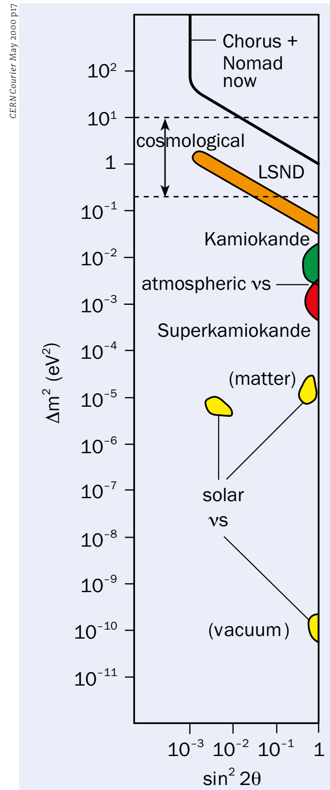
PhyStat conference turns twenty-five

On 16 January, physicists and statisticians met in the CERN Council Chamber to celebrate 25 years of the PhyStat series of conferences, workshops and seminars, which bring together physicists, statisticians and scientists from related fields to discuss, develop and disseminate methods for statistical data analysis and machine learning.

A subfield with distinct problems and methods

The special symposium heard from the founder and primary organiser of the PhyStat series Louis Lyons (Imperial College London and University of Oxford), who together with Fred James and Yves Perrin initiated the movement with the "Workshop on Confidence Limits" in January 2000. According to Lyons, the series was to bring together physicists and statisticians, a philosophy that has been followed and extended throughout the 22 PhyStat workshops and conferences, as well as numerous seminars and "informal reviews". Speakers called attention to recognition from the Royal Statistical Society's pictorial timeline of statistics, starting with the use of averages by Hippias of Elis in 450 BC and culminating with the 2012 discovery of the Higgs boson with 5σ significance.

Lyons and Bob Cousins (UCLA) offered their views on the evolution of statistical practice in high-energy physics, starting in the 1960s bubble-chamber era, strongly influenced by the 1971 book *Statistical Methods in Experimental Physics* by W T Eadie *et al.*, its 2006 second edition by symposium participant Fred James (CERN), as well as *Statistics for Nuclear and Particle Physics* (1985) by Louis Lyons – reportedly the most stolen book from the CERN library. Both Lyons and Cousins noted the interest of the PhyStat community not only in practical solutions to concrete problems but also in foundational questions in statistics, with the focus on frequentist methods setting high-energy physics somewhat apart from the Bayesian approach more widely used in astrophysics.



CERN Courier May 2000 p17

We've come a long way *The first PhyStat workshop discussed confidence intervals, "which may assume bizarre shapes, as happens when a variety of different experiments search for neutrino oscillations".*

Giving his view of the PhyStat era, ATLAS physicist and director of the University of Wisconsin Data Science Institute Kyle Cranmer emphasised the enormous impact that PhyStat has had on the field, noting important milestones such as the ability to publish full likelihood models through the statistical package RooStats, the treatment of systematic uncertainties with profile-likelihood ratio analyses, methods for combining analyses, and the reuse of published analyses to place constraints on new physics models. In regards to the next 25 years, Cranmer predicted the increasing use of methods that have emerged from PhyStat, such as simulation-based inference, and pointed out that artificial intelligence (the elephant in the room) could drastically alter how we use statistics.

Two-way talks

Statistician Mikael Kuusela (CMU) noted that Phystat workshops have provided important two-way communication between the physics and statistics communities, citing simulation-based inference as an example where many key ideas were first developed in physics and later adopted by statisticians. In his view, the use of statistics in particle physics has emerged as "phystatistics", a proper subfield with distinct problems and methods.

Another important feature of the PhyStat movement has been to encourage active participation and leadership by younger members of the community. With its 25th anniversary, the torch is now passed from Louis Lyons to Olaf Behnke (DESY), Lydia Brenner (NIKHEF) and a younger team, who will guide Phystat into the next 25 years and beyond.

Glen Cowan *Royal Holloway, University of London.*

DRD1 Gaseous Detectors School

Gaseous detectors school at CERN

How do wire-based detectors compare to resistive-plate chambers? How well do micropattern gaseous detectors perform? Which gas mixtures optimise operation? How will detectors face the challenges of future more powerful accelerators?

Thirty-two students attended the first DRD1 Gaseous Detectors School at CERN last November. The EP-DT Gas Detectors Development (GDD) lab hosted academic lectures and varied hands-on laboratory exercises. Students assembled their own detectors, learnt about their operating characteristics and explored radiation-imaging methods with state-of-the-art readout approaches – all under the instruction of more than 40 distinguished lecturers and tutors, including renowned scientists, pioneers of innovative technologies and emerging experts.

M Cavazza/CERN

Detector assembly *Future detector experts in action.*

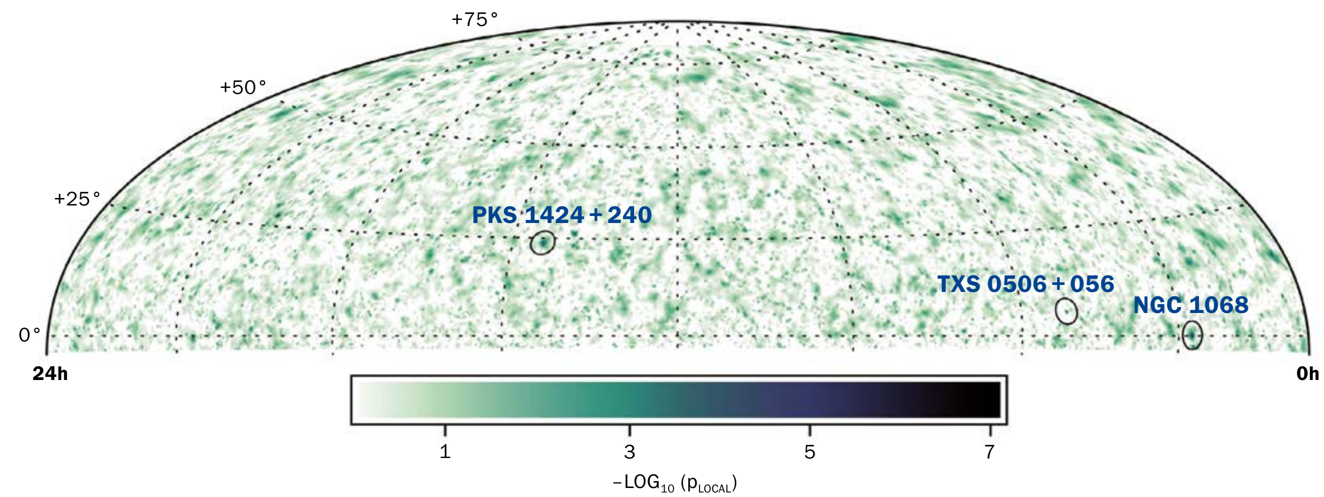
DRD1 is a new worldwide collaborative framework of more than 170 institutes focused on R&D for gaseous detectors. The collaboration focuses on knowledge sharing and scientific exchange, in addition to the development of novel gaseous detector technologies to address the needs of future experiments. This instrumentation school, initiated in DRD1's first year, marks the start of a series of regular training events for young researchers that will also serve to exchange ideas between research groups and encourage collaboration.

The school will take place annually, with future editions hosted at different DRD1 member institutes to reach students from a number of regions and communities.

Florian M Brunbauer, Mauro Iodice *and* **Fabio Sauli** *CERN.*

DISCOVERING THE NEUTRINO SKY

Lu Lu looks forward to the next two decades of neutrino astrophysics, exploring the remarkable detector concepts needed to probe ultra-high energies from 1 EeV to 1 ZeV.



The neutrino sky *IceCube selects neutrinos by using the Earth as a cosmic-ray veto. This map, where 0° is the projection of the Earth's equator onto the sky, shows point-source candidates in the northern hemisphere observed by the IceCube detector at the South Pole. The colour scale represents the statistical significance that a signal is not just a random background. The hottest spot in the northern sky is NGC 1068: a barred spiral galaxy 47 million light-years away that hosts a supermassive black hole surrounded by gamma-ray-attenuating gas and dust. (Credit: IceCub Collab. 2022* Science **378** *538)*

Lake Baikal, the Mediterranean Sea and the deep, clean ice at the South Pole: trackers. The atmosphere: a calorimeter. Mountains and even the Moon: targets. These will be the tools of the neutrino astrophysicist in the next two decades. Potentially observable energies dwarf those of the particle physicist doing repeatable experiments, rising up to 1 ZeV (10^{21} eV) for some detector concepts.

The natural accelerators of the neutrino astrophysicist are also humbling. Consider, for instance, the extraordinary relativistic jets emerging from the supermassive black hole in Messier 87 – an accelerator that stretches for about 5000 light years, or roughly 315 million times the distance from the Earth to the Sun.

Alongside gravitational waves, high-energy neutrinos have opened up a new chapter in astronomy. They point to the most extreme events in the cosmos. They can escape from regions where high-energy photons are attenuated by gas and dust, such as NGC 1068, the first steady neutrino emitter to be discovered (see "The neutrino sky" figure). Their energies can rise orders of magnitude above 1 PeV (10^{15} eV), where the universe becomes opaque to photons due to pair production with the cosmic microwave background. Unlike charged cosmic rays, they are not deflected by magnetic fields, preserving their original direction.

High-energy neutrinos therefore offer a unique window into some of the most profound questions in modern physics. Are there new particles beyond the Standard Model at the highest energies? What acceleration mechanisms allow nature to propel them to such extraordinary energies? And is dark matter implicated in these extreme events? With the observation of a 220^{+570}_{-110} PeV neutrino confounding the limits set by prior observatories and opening up the era of ultra-high-energy neutrino astronomy (*CERN Courier* March/April 2025 p7), the time is ripe for a new generation of neutrino detectors on an even grander scale (see "Thinking big" table).

THE AUTHOR
Lu Lu *University of Wisconsin–Madison.*

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Thinking big Ongoing and future high and ultra-high-energy neutrino observatories

Detection category	Experiments	Energy range	Method
Water Cherenkov (optical)	IceCube, KM3NeT, Baikal-GVD, P-ONE, IceCube-Gen2 (optical), TRIDENT, HUNT	1 TeV–100 PeV	Detects Cherenkov radiation in deep water or ice
Radar-based (radar echo)	RET	PeV–EeV	Detects radar echoes from neutrino-induced cascades in ice
Air-shower-based (ground)	AugerPrime, GRAND, TRINITY, TAMBO, Ashra-NTA, BEACON	10 PeV–EeV	Detects extensive air showers caused by Earth-skimming tau neutrinos
Radio ice (Askaryan effect)	IceCube-Gen2 (radio), RNO-G, ARA, ARIANNA	100 PeV–EeV+	Detects Askaryan radiation in ice
Air-shower-based (space)	POEMMA, PUEO, TAROGE, EUSO-SPB2	EeV+	Detects neutrino-induced air showers from space or balloon-borne platforms
Lunar detectors (lunar Askaryan effect)	NuMoon, LORD, SKA, LUNASKA, RESUN, LuSEE-Night	EeV–ZeV	Uses the Moon as a neutrino target, detecting Askaryan radio bursts via ground-based radio arrays

A cubic-kilometre ice cube

Detecting high-energy neutrinos is a serious challenge. Though the neutrino–nucleon cross section increases a little less than linearly with neutrino energy, the flux of cosmic neutrinos drops as the inverse square or faster, reducing the event rate by nearly an order of magnitude per decade. A cubic-kilometre-scale detector is required to measure cosmic neutrinos beyond 100 TeV, and Earth starts to be opaque as energies rise beyond a PeV or so, when the odds of a neutrino being absorbed as it passes through the planet are roughly even depending on the direction of the event.

The journey of cosmic neutrino detection began off the coast of the Hawaiian Islands in the 1980s, led by John Learned of the University of Hawaii at Mānoa. The DUMAND (Deep Underwater Muon And Neutrino Detector) project sought to use both an array of optical sensors to measure Cherenkov light and acoustic detectors to measure the pressure waves generated by energetic particle cascades in water. It was ultimately cancelled in 1995 due to engineering difficulties related to deep-sea installation, data transmission over long underwater distances and sensor reliability under high pressure.

The next generation of cubic-kilometre-scale neutrino detectors built on DUMAND's experience. The IceCube Neutrino Observatory has pioneered neutrino astronomy at the South Pole since 2011, probing energies from 10 GeV to 100 PeV, and is now being joined by experiments under construction such as KM3NeT in the Mediterranean Sea, which observed the 220 PeV candidate, and Baikal–GVD in Lake Baikal, the deepest lake on Earth. All three experiments watch for the deep inelastic scattering of high-energy neutrinos, using optical sensors to detect Cherenkov photons emitted by secondary particles.

Breaking into the exascale calls for new thinking

A decade of data-taking from IceCube has been fruitful. The Milky Way has been observed in neutrinos for the first time. A neutrino candidate event has been observed that is consistent with the Glashow resonance – the resonant production in the ice of a real W boson by a 6.3 PeV electron–antineutrino – confirming a longstanding prediction from 1960. Neutrino emission has been observed from supermassive black holes in NGC 1068 and TXS 0506+056. A diffuse neutrino flux has been discovered beyond 10 TeV. Neutrino mixing parameters have been measured. And flavour ratios have been constrained: due to the averaging of neutrino oscillations over cosmological distances, significant deviations from a 1:1:1 ratio of electron, muon and tau neutrinos could imply new physics such as the violation of Lorentz invariance, non-standard neutrino interactions or neutrino decay.

The sensitivity and global coverage of water-Cherenkov neutrino observatories is set to increase still further. The Pacific Ocean Neutrino Experiment (P-ONE) aims to establish a cubic-kilometre-scale deep-sea neutrino telescope off the coast of Canada; IceCube will expand the volume of its optical array by a factor eight; and the TRIDENT and HUNT experiments, currently being prototyped in the South China Sea, may offer the largest detector volumes of all. These detectors will improve sky coverage, enhance angular resolution, and increase statistical precision in the study of neutrino sources from 1 TeV to 10 PeV and above.

Breaking into the exascale calls for new thinking.

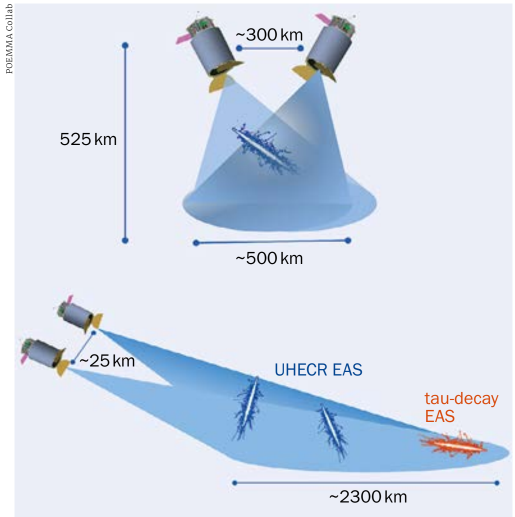
Into the exascale

Optical Cherenkov detectors have been exceptionally successful in establishing neutrino astronomy, however, the attenuation of optical photons in water and ice requires the horizontal spacing of photodetectors to a few hundred metres at most, constraining the scalability of the technology. To achieve sensitivity to ultra-high energies measured in EeV (10^{18} eV), an instrumented area of order 100 km^2 would be required. Constructing an optical-based detector on such a scale is impractical.

One solution is to exchange the tracking volume of IceCube and its siblings with a larger detector that uses the atmosphere as a calorimeter: the deposited energy is sampled on the Earth's surface.

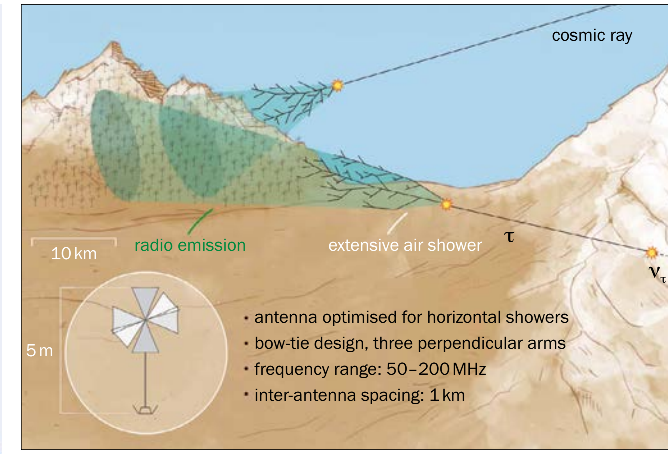
The Pierre Auger Observatory in Argentina epitomises this approach. If IceCube is presently the world's largest

POEMMA Collab



Exascale from above *POEMMA will operate in two distinct observational modes: observing ultra-high-energy cosmic rays (UHECR) "in stereo" using fluorescence light (top); and searching for fast Cherenkov flashes from extensive air showers (EAS) caused by upward-going tau–neutrino interactions in the atmospheric "limb" of Earth as seen from space (bottom).*

GRAND Collab



Earth skimming *The Giant Radio Array for Neutrino Detection experiment proposes to use mountains as targets for ultra-high-energy tau neutrinos.*

detector by volume, the Pierre Auger Observatory is the world's largest detector by area. Over an area of 3000 km^2, 1660 water Cherenkov detectors and 24 fluorescence telescopes sample the particle showers generated when cosmic rays with energies beyond 10 EeV strike the atmosphere, producing billions of secondary particles. Among the showers it detects are surely events caused by ultra-high-energy neutrinos, but how might they be identified?

Out on a limb

One of the most promising approaches is to filter events based on where the air shower reaches its maximum development in the atmosphere. Cosmic rays tend to interact after traversing much less atmosphere than neutrinos, since the weakly interacting neutrinos have a much smaller cross-section than the hadronically interacting cosmic rays. In some cases, tau neutrinos can even skim the Earth's atmospheric edge or "limb" as seen from space, interacting to produce a strongly boosted tau lepton that emerges from the rock (unlike an electron) to produce an upward-going air shower when it decays tens of kilometres later – though not so much later (unlike a muon) that it has escaped the atmosphere entirely. This signature is not possible for charged cosmic rays. So far, Auger has detected no neutrino candidate events of either topology, imposing stringent upper limits on the ultra-high-energy neutrino flux that are compatible with limits set by IceCube. The AugerPrime upgrade, soon expected to be fully operational, will equip each surface detector with scintillator panels and improved electronics.

Experiments in space are being developed to detect these rare showers with an even larger instrumentation volume. POEMMA (Probe of Extreme Multi-Messenger Astrophysics) is a proposed satellite mission designed to monitor the Earth's atmosphere from orbit. Two satellites equipped with fluorescence and Cherenkov detectors will search for ultraviolet photons produced by extensive air showers (see "Exascale from above" figure). EUSO-SPB2 (Extreme Universe Space Observatory on a Super Pressure Balloon 2) will test the same detection methods from the vantage point of high-atmosphere balloons. These instruments can help distinguish cosmic rays from neutrinos by identifying shallow showers and up-going events.

Another way to detect ultra-high-energy neutrinos is by using mountains and valleys as natural neutrino targets. This Earth-skimming technique also primarily relies on tau neutrinos, as the tau leptons produced via deep inelastic scattering in the rock can emerge from Earth's crust and decay within the atmosphere to generate detectable particle showers in the air.

One way to detect ultra-high-energy neutrinos is by using mountains and valleys as natural neutrino targets

The Giant Radio Array for Neutrino Detection (GRAND) aims to detect radio signals from these tau-induced air showers using a large array of radio antennas spread over thousands of square kilometres (see "Earth skimming" figure). GRAND is planned to be deployed in multiple remote, mountainous locations, with the first site in western China, followed by others in South America and Africa. The Tau Air-Shower Mountain-Based Observatory (TAMBO) has been proposed to be deployed on the face of the Colca Canyon in the Peruvian Andes, where an array of scintillators will detect the electromagnetic signals from tau-induced air showers.

Another proposed strategy that builds upon the Earth-skimming principle is the Trinity experiment, which employs an array of Cherenkov telescopes to observe nearby mountains. Ground-based air Cherenkov detectors are known for their excellent angular resolution, allowing for precise pointing to trace back to the origin of the

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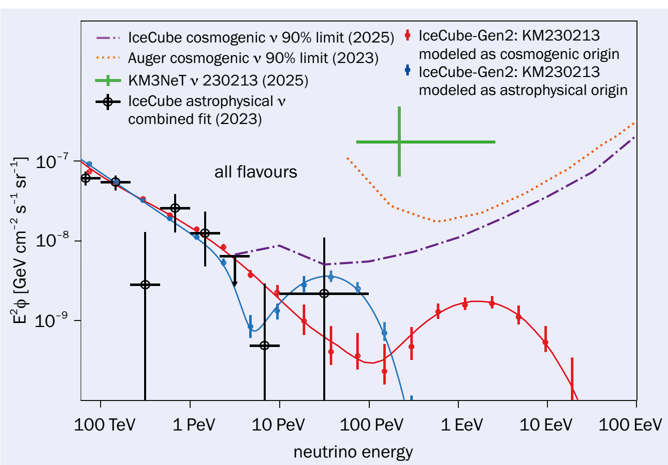
M Wolf, IceCube/NSF

Pole position *The IceCube laboratory in the South pole, where neutrino events are reconstructed in real time.*

L Lu



Diffuse neutrino landscape *All-flavour neutrino-flux measurements (black) and limits (purple) after a decade of IceCube, alongside a measurement by the partially deployed KM3NeT observatory based on a single ultra-high-energy neutrino (green), and limits from the Pierre Auger Observatory (orange). The IceCube flux is seen to diminish faster than a pure $1/E^2$ power law, which would be represented on this plot as a horizontal line, and KM3NeT is in tension with the ultra-high-energy limits. Projections for the future IceCube-Gen2 with 15 years of data taking are shown in blue (assuming the KM3NeT event is of astrophysical origin) and red (assuming the KM3NeT event is of cosmogenic origin).*

high-energy primary particles. Trinity is a proposed system of 18 wide-field Cherenkov telescopes optimised for detecting neutrinos in the 10 PeV–1000 PeV energy range from the direction of nearby mountains – an approach validated by experiments such as Ashra–NTA, deployed on Hawaii's Big Island utilising the natural topography of the Mauna Loa, Mauna Kea and Hualālai volcanoes.

All these ultra-high-energy experiments detect particle showers as they develop in the atmosphere, whether from above, below or skimming the surface. But "Askaryan" detectors operate deep within the ice of the Earth's poles, where both the neutrino interaction and detection occur.

In 1962 Soviet physicist Gurgen Askaryan reasoned that electromagnetic showers must develop a net negative charge excess as they develop, due to the Compton scattering of photons off atomic electrons and the ionisation of atoms by charged particles in the shower. As the charged shower propagates faster than the phase velocity of light in the medium, it should emit radiation in a manner analogous to Cherenkov light. However, there are key differences: Cherenkov radiation is typically incoherent and emitted by individual charged particles, while Askaryan radiation is coherent, being produced by a macroscopic buildup of charge, and is significantly stronger at radio frequencies. The Askaryan effect was experimentally confirmed at SLAC in 2001.

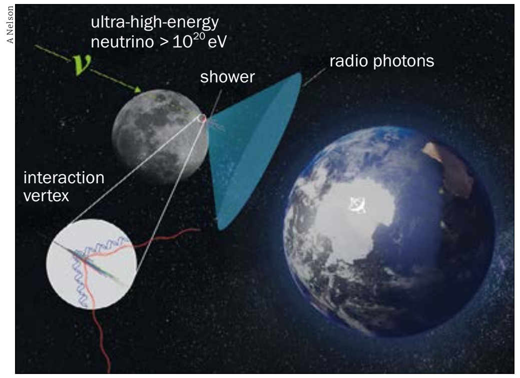
Optimised arrays

Because the attenuation length of radio waves is an order of magnitude longer than for optical photons, it becomes feasible to build much sparser arrays of radio antennas to detect the Askaryan signals than the compact optical arrays used in deep ice Cherenkov detectors. Such detectors are optimised to cover thousands of square kilometres, with typical energy thresholds beyond 100 PeV.

The Radio Neutrino Observatory in Greenland (RNO-G) is a next-generation in-ice radio detector currently under construction on the ~3 km-thick ice sheet above central Greenland, operating at frequencies in the 150–700 MHz range. RNO-G will consist of a sparse array of 35 autonomous radio detector stations, each separated by 1.25 km, making it the first large-scale radio neutrino array in the northern hemisphere.

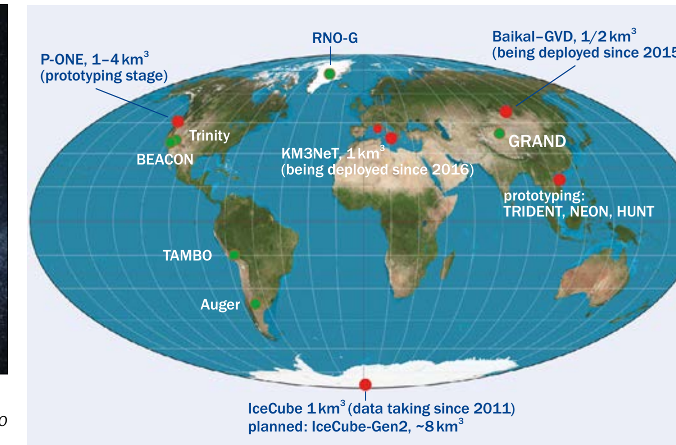
In the southern hemisphere, the proposed IceCube-Gen2 will complement the aforementioned eightfold expanded optical array with a radio component covering a remarkable 500 km^2. The cold Antarctic ice provides an optimal

A Nelson



Moon skimming *The highest possible energies could be probed by seeking signs of Askaryan radiation not from neutrino interactions in polar ice but in the immense target of lunar "regolith" – the loose, dusty, rocky surface material covering the Moon's surface which is thought to have an attenuation length ranging from about 20 m at 1 GHz to 200 m at 100 MHz.*

L Lu based on work by A Karle



Full-sky coverage *The global distribution of operating and proposed optical Cherenkov detectors (red) and ultra-high-energy detectors using alternative detection methods (green).*

medium for radio detection, with radio attenuation lengths of roughly 2 km facilitating cost-efficient instrumentation of the large volumes needed to measure the low ultra-high-energy neutrino flux. The radio array will combine in-ice omnidirectional antennas 150 m below the surface with high-gain antennas at a depth of 15 m and upward-facing antennas on the surface to veto the cosmic-ray background .

The IceCube-Gen2 radio array will have the sensitivity to probe features of the spectrum of astrophysical neutrino beyond the PeV scale, addressing the tension between upper limits from Auger and IceCube, and KM3NeT's 220^{+570}_{-110} PeV neutrino candidate – the sole ultra-high-energy neutrino yet observed. Extrapolating an isotropic and diffuse flux, IceCube should have detected 75 events in the 72–2600 PeV energy range over its operational period. However, no events have been observed above 70 PeV.

If the detected KM3NeT event has a neutrino energy of around 100 PeV, it could originate from the same astrophysical sources responsible for accelerating ultra-high-energy cosmic rays. In this case, interactions between accelerated protons and ambient photons from starlight or synchrotron radiation would produce pions that decay into ultra-high-energy neutrinos. Alternatively, if its true energy is closer to 1 EeV, it is more likely cosmogenic: arising from the Greisen–Zatsepin–Kuzmin process, in which ultra-high-energy cosmic rays interact with cosmic microwave background photons, producing a Δ-resonance that decays into pions and ultimately neutrinos. IceCube-Gen2 will resolve the spectral shape from PeV to 10 EeV and differentiate between these two possible production mechanisms (see "Diffuse neutrino landscape" figure).

Moonshots

Remarkably, the Radar Echo Telescope (RET) is exploring using radar to actively probe the ice for transient signals. Unlike Askaryan-based detectors, which passively listen for radio pulses generated by charge imbalances in particle cascades, RET's concept is to beam a radar signal and watch for reflections off the ionisation caused by particle showers. SLAC's T576 experiment demonstrated the concept in the lab in 2022 by observing a radar echo from a beam of high-energy electrons scattering off a plastic target. RET has now been deployed in Greenland, where it seeks echoes from down-going cosmic rays as a proof of concept.

Perhaps the most ambitious way to observe ultra-high-energy neutrinos foresees using the Moon as a target. When neutrinos with energies above 100 EeV interact near the rim of the Moon, they can induce particle cascades that generate coherent Askaryan radio emission which could be detectable on Earth (see "Moon skimming" figure). Observations could be conducted from Earth-based radio telescopes or from satellites orbiting the Moon to improve detection sensitivity. Lunar Askaryan detectors could potentially be sensitive to neutrinos up to 1 ZeV (10^{21} eV). No confirmed detections have been reported so far.

Neutrino network

Proposed neutrino observatories are distributed across the globe – a necessary requirement for full sky coverage, given the Earth is not transparent to ultra-high-energy neutrinos (see "Full-sky coverage" figure). A network of neutrino telescopes ensures that transient astrophysical events can always be observed as the Earth rotates. This is particularly important for time-domain multi-messenger astronomy, enabling coordinated observations with gravitational wave detectors and electromagnetic counterparts. The ability to track neutrino signals in real time will be key to identifying the most extreme cosmic accelerators and probing fundamental physics at ultra-high energies. ●

Perhaps the most ambitious way to observe ultra-high-energy neutrinos is to use the Moon as a target

Further reading

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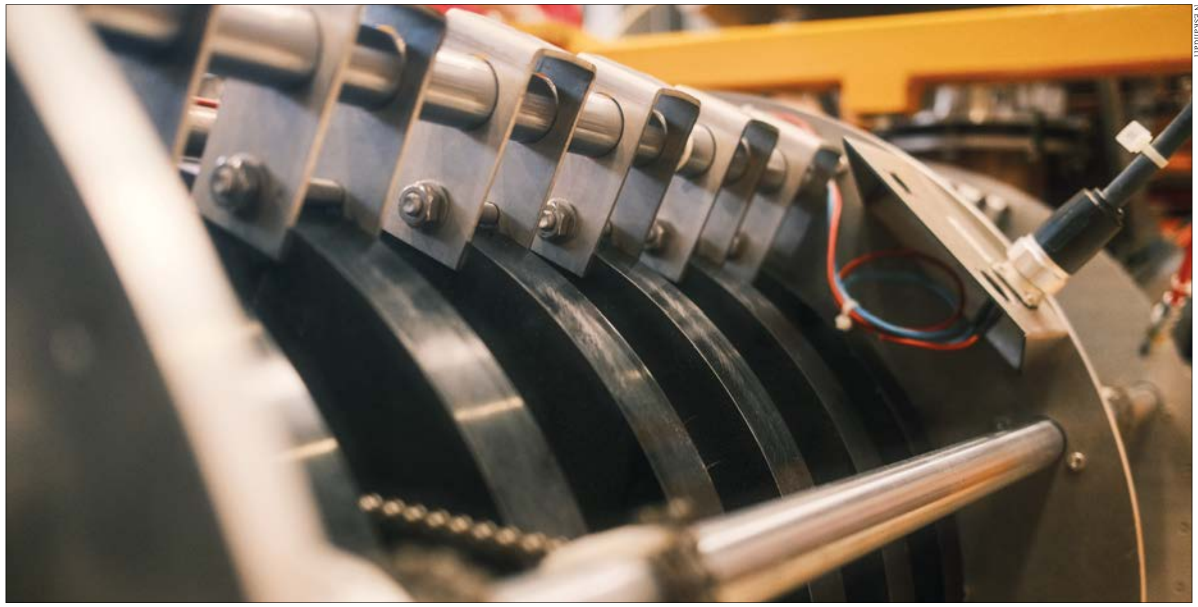


N Eskandari

Generating power *Klystrons are surging in importance thanks to growing interest in Higgs factories. In the pictured LHC klystron, the black ribs of the solenoid encasing the klystron vacuum tube are visible.*

POWERING INTO THE FUTURE

Nuria Catalan Lasheras and Igor Syratchev explain why klystrons are strategically important to the future of the field – and how CERN plans to boost their efficiency above 90%.

The Higgs boson is the most intriguing and unusual object yet discovered by fundamental science. There is no higher experimental priority for particle physics than building an electron–positron collider to produce it copiously and study it precisely. Given the importance of energy efficiency and cost effectiveness in the current geopolitical context, this gives unique strategic importance to developing a humble technology called the klystron – a technology that will consume the majority of site power at every major electron–positron collider under consideration, but which has historically only achieved 60% energy efficiency.

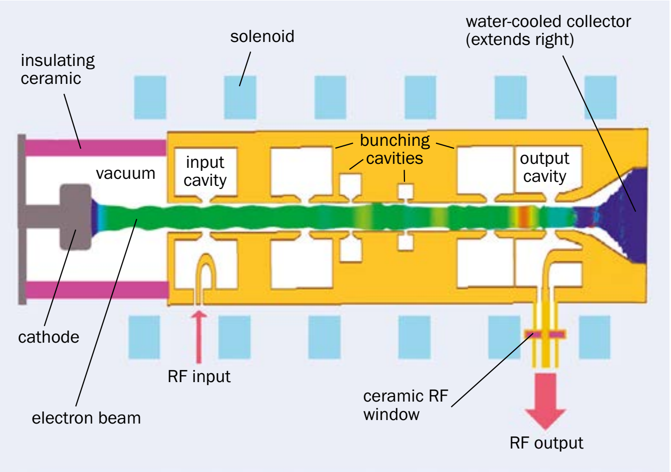
The klystron was invented in 1937 by two American brothers, Russell and Sigurd Varian. The Varians wanted to improve aircraft radar systems. At the time, there was a growing need for better high-frequency amplification to detect objects at a distance using radar, a critical technology in the lead-up to World War II.

The Varian's RF source operated around 3.2 GHz, or a wavelength of about 9.4 cm, in the microwave region of the electromagnetic spectrum. At the time, this was an extraordinarily high frequency – conventional vacuum tubes struggled beyond 300 MHz. Microwave wavelengths promised better resolution, less noise, and the ability to penetrate rain and fog. Crucially, antennas could be small enough to fit on ships and planes. But the source was far too weak for radar.

The Varians' genius was to invent a way to amplify the electromagnetic signal by up to 30 dB, or a factor of 1000. The US and British military used the klystron for airborne radar, submarine detection of U-boats in the Atlantic and naval gun targeting beyond visual range. Radar helped win the Battle of Britain, the Battle of the Atlantic and Pacific naval battles, making surprise attacks harder by giving advance warning. Winston Churchill called radar "the secret weapon of WWII", and the klystron was one of its enabling technologies.

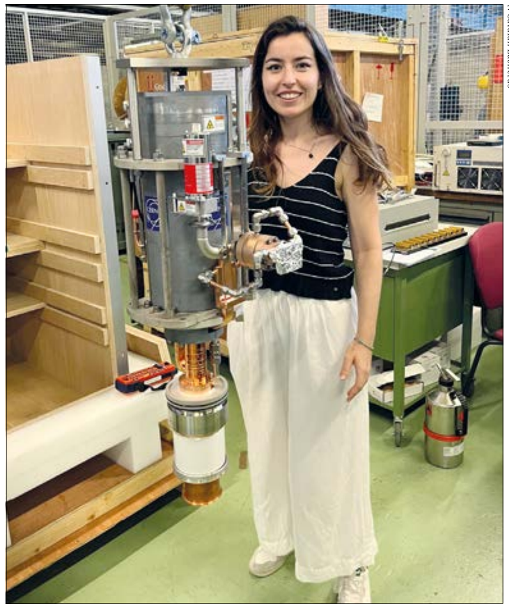
THE AUTHORS

Nuria Catalan Lasheras *and* **Igor Syratchev** *CERN.*



I Syratchev (simulation)/A Epshtein (art)

Operating principle *Simulated longitudinal electron speeds, from blue (stationary) to orange (fast), overlaid on a simplified schematic of a TH2167HE-style klystron. An electron gun (left) emits electrons that are bunched by an input cavity which is excited by an input RF wave (red arrow, left). Four intermediate cavities improve electron bunching, until the output cavity quickly decelerates the now tightly bunched electrons, yielding a strongly amplified RF wave (red arrow, right) through a coaxial waveguide. The vacuum tube is encased within a solenoid to contain the beam.*



N Catalan Lasheras

CLIC klystron *RF engineer next to the X-band E37113, an industrial klystron by CANON ETD that is being retrofitted with increased efficiency for CLIC.*

With its high gain and narrow bandwidth, the klystron was the first practical microwave amplifier and became foundational in radio-frequency (RF) technology. This was the first time anyone had efficiently amplified microwaves with stability and directionality. Klystrons have since been used in satellite communication, broadcasting and particle accelerators, where they power the resonant RF cavities that accelerate the beams. Klystrons are therefore ubiquitous in medical, industrial and research accelerators – and not least in the next generation of Higgs factories, which are central to the future of high-energy physics.

Klystrons and the Higgs

Hadron colliders like the LHC tend to be circular. Their fundamental energy limit is given by the maximum strength of the bending magnets and the circumference of the tunnel. A handful of RF cavities repeatedly accelerate beams of protons or ions after hundreds or thousands of bending magnets force the beams to loop back through them.

Thanks to their clean and precisely controllable collisions, all Higgs factories under consideration are electron–positron colliders. Electron–positron colliders can be either circular or linear in construction. The dynamics of circular electron–positron colliders are radically different as the particles are 2000 times lighter than protons. The strength required from the bending magnets is relatively low for any practical circumference, however, the energy of the particles must be continually replenished, as they radiate away energy in the bends through synchrotron radiation, requiring *hundreds* of RF cavities. RF cavities are equally important in the linear case. Here, all the energy must be imparted in a single pass, with each cavity accelerating the beam only once, requiring either hundreds or even *thousands* of RF cavities.

Either way, 50 to 60% of the total energy consumed by an electron–positron collider is used for RF acceleration, compared to a relatively small fraction in a hadron collider. Efficiently powering the RF cavities is of paramount importance to the energy efficiency and cost effectiveness of the facility as a whole. RF acceleration is therefore of far greater significance at electron–positron colliders than at hadron colliders.

From a pen to a mid-size car

RF cavities cannot simply be plugged into the wall. These finely tuned resonant structures must be excited by RF power – an alternating microwave electromagnetic field that is supplied through waveguides at the appropriate frequency. Due to the geometry of resonant cavities, this excites an on-axis oscillating electrical field. Particles that arrive when the electrical field has the right direction are accelerated. For this reason, particles in an accelerator travel in bunches separated by a long distance, during which the RF field is not optimised for acceleration.

Despite the development of modern solid-state amplifiers, the Varians' klystron is still the most practical technology to generate RF when the power required is in the MW level. They can be as small as a pen or as large and heavy as a mid-size car, depending on the frequency and

Klystrons are ubiquitous in medical, industrial and research accelerators – and not least in the next generation of Higgs factories

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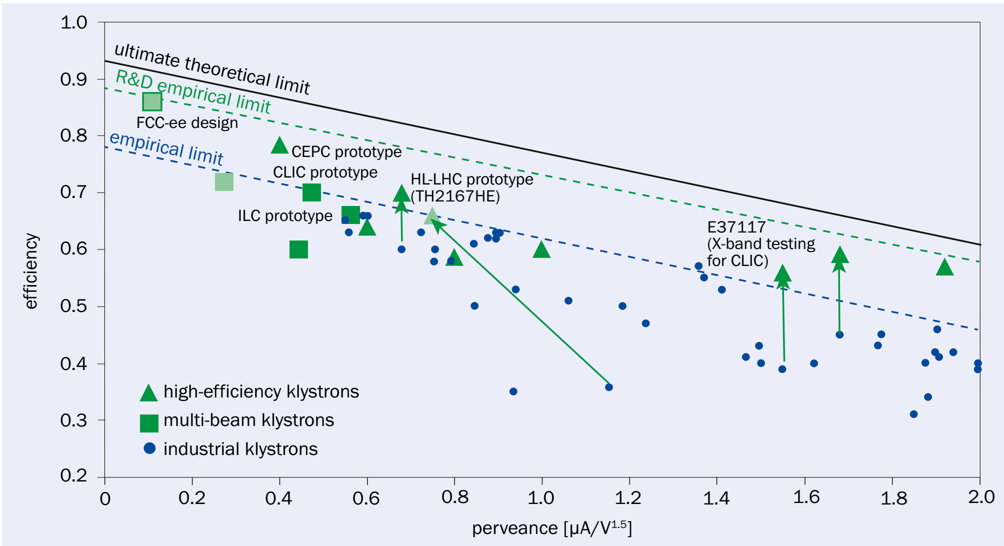
The word klystron is derived from the Greek verb describing the action of waves crashing against the seashore



Battling space charge *The beam-to-RF efficiency of industrial klystrons (blue points) and klystrons designed (green points) or retrofitted (arrows and green points) by the HEK project, as a function of perveance. HEK has improved the industrial empirical limit (blue dashed line) by approximately 10% (dashed green line) as a function of perveance, approaching the ultimate theoretical limit imposed by space-charge effects (solid line). Klystron designs that are in progress are plotted as shaded points. Those that are built but not tested have a solid outline.*

power required. Linear colliders use higher frequency because they also come with higher gradients and make the linac shorter, whereas a circular collider does not need high gradients as the energy to be given each turn is smaller.

Klystrons fall under the general classification of vacuum tubes – fully enclosed miniature electron accelerators with their own source, accelerating path and "interaction region" where the RF field is produced. Their name is derived from the Greek verb describing the action of waves crashing against the seashore. In a klystron, RF power is generated when electrons crash against a decelerating electric field.

Every klystron contains at least two cavities: an input and an output. The input cavity is powered by a weak RF source that must be amplified. The output cavity generates the strongly amplified RF signal generated by the klystron. All this comes encapsulated in an ultra-high vacuum volume inside the field of a solenoid for focusing (see "Operating principle" figure).

Inside the klystron, electrons leave a heated cathode and are accelerated by a high voltage applied between the cathode and the anode. As they are being pushed forward, a small input RF signal is applied to the input cavity, either accelerating or decelerating the electrons according to their time of arrival. After a long drift, late-emitted accelerated electrons catch up with early-emitted decelerated electrons, intersecting with those that did not see any net accelerating force. This is called velocity bunching.

A second, passive accelerating cavity is placed at the location where maximum bunching occurs. Though of a comparable design, this cavity behaves in an inverse fashion to those used in particle accelerators. Rather than converting the energy of an electromagnetic field into the kinetic energy of particles, the kinetic energy of particles is converted into RF electromagnetic waves. This process can be enhanced by the presence of other passive cavities in between the already mentioned two, as well as by several iterations of bunching and de-bunching before reaching the output cavity. Once decelerated, the spent beam finishes its life in a dump or a water-cooled collector.

Optimising efficiency

Klystrons are ultimately RF amplifiers with a very high gain of the order of 30 to 60 dB and a very narrow bandwidth. They can be built at any frequency from a few hundred MHz to tens of GHz, but each operates within a very small range of frequencies called the bandwidth. After broadcasting became reliant on wider bandwidth vacuum tubes, their application in particle accelerators turned into a small market for high-power klystrons. Most klystrons for science are manufactured by a handful of companies which offer a limited number of models that have been in operation for decades. Their frequency, power and duty cycle may not correspond to the specifications of a new accelerator being considered – and in most cases, little or no thought has been given to energy efficiency or carbon footprint.

When searching for suitable solutions for the next particle-physics collider, however, optimising the energy efficiency of klystrons and other devices that will determine the final energy bill and CO_2 emissions is a task of the utmost importance. Therefore, nearly a decade ago, RF experts at CERN and the University of Lancaster began the High-Efficiency Klystron (HEK) project to maximise

Thanks to the efforts made in recent years, high-efficiency klystrons are now approaching the ultimate theoretical limit

beam-to-RF efficiency: the fraction of the power contained in the klystron's electron beam that is converted into RF power by the output cavity.

The complexity of klystrons resides on the very nonlinear fields to which the electrons are subjected. In the cathode and the first stages of electrostatic acceleration, the collective effect of "space-charge" forces between the electrons determines the strongly nonlinear dynamics of the beam. The same is true when the bunching tightens along the tube, with mutual repulsion between the electrons preventing optimal bunching at the output cavity.

For this reason, designing klystrons is not susceptible to simple analytical calculations. Since 2017, CERN has developed a code called KlyC that simulates the beam along the klystron channel and optimises parameters such as frequency and distance between cavities 100 to 1000 times faster than commercial 3D codes. KlyC is available in the public domain and is being used by an ever-growing list of labs and industrial partners.

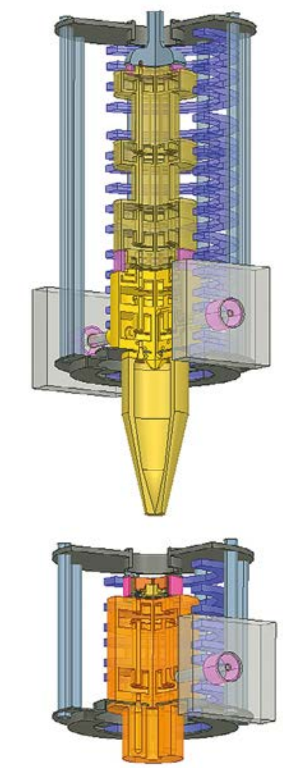
Perveance

The main characteristic of a klystron is an obscure magnitude inherited from electron-gun design called perveance. For small perveances, space-charge forces are small, due to either high energy or low intensity, making bunching easy. For large perveances, space-charge forces oppose bunching, lowering beam-to-RF efficiency. High-power klystrons require large currents and therefore high perveances. One way to produce highly efficient, high-power klystrons is therefore for multiple cathodes to generate multiple low-perveance electron beams in a "multi-beam" (MB) klystron.

Overall, there is an almost linear dependence between perveance and efficiency. Thanks to the efforts made in recent years, high-efficiency klystrons are now outperforming industrial klystrons by 10% in efficiency for all values of perveance, and approaching the ultimate theoretical limit (see "Battling space charge" figure).

One of the first designs to be brought to life was based on the E37113, a pulsed klystron with 6 MW peak power working in the X-band at 12 GHz, commercialised by CANON ETD. This klystron is currently used in the test facility at CERN for validating CLIC RF prototypes, which could greatly benefit from a larger power. As part of a collaboration with CERN, CANON ETD built a new tube, according to the design optimised at CERN, to reach a beam-to-RF efficiency of 57% instead of the original 42% (see "CLIC klystron" image and *CERN Courier* September/October 2022 p9).

High-luminosity gains *The High Efficiency Klystrons team with the TH2167HE prototype, which will offer a 10% gain in efficiency at the High-Luminosity LHC.*



Towards an FCC klystron *Evolution of 400 MHz klystron designs at CERN. Electrons travel from top to bottom, with the square grey conduits at the bottom acting as output waveguides. The TH2167HE (left) retrofits the 60% efficiency of the LHC's klystrons to achieve 70% efficiency for the High-Luminosity LHC, and potentially for the FCC-ee. The MB two-stage klystron (top right) is designed to achieve 86% at the same frequency – a figure that our MB Tristron concept (bottom right) could increase to 93%. By increasing efficiency by 33% compared to the TH2167 used at the LHC, FCC-ee's commensurate reduction in power consumption would save tens of millions of Euros per year in electricity bills.*

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As its interfaces with the high-voltage (HV) source and solenoid were kept identical, one can now benefit from 8 MW of RF power for the same energy consumption as before. As changes in the manufacturing of the tube channel are just a small fraction of the manufacture of the instrument, its price should not increase considerably, even if more accurate production methods are required.

In pursuit of power

Another successful example of re-designing a tube for high efficiency is the TH2167 – the klystron behind the LHC, which is manufactured by Thales. Originally exhibiting a beam-to-RF efficiency of 60%, it was re-designed by the CERN team to gain 10% and reach 70% efficiency, while again using the same HV source and solenoid. The tube prototype has been built and is currently at CERN, where it has demonstrated the capacity to generate 350 kW of RF power with the same input energy as previously required to produce 300 kW. This power will be decisive when dealing with the higher intensity beam expected after the LHC luminosity upgrade. And all this again for a price comparable to previous models (see "High-luminosity gains" image).

The quest for the highest efficiency is not over yet

The quest for the highest efficiency is not over yet. The CERN team is currently working on a design that could power the proposed Future Circular collider (FCC). Using about a hundred accelerating cavities, the electron and positron beams will need to be replenished with 100 MW of RF power, and energy efficiency is imperative.

Although the same tube in use for the LHC, now boosted to 70% efficiency, could be used to power the FCC, CERN is working towards a vacuum tube that could reach an efficiency over 80%. A two-stage multi-beam klystron was initially designed that was capable of reaching 86% efficiency and generating 1 MW of continuous-wave power (see "Towards an FCC klystron" figure).

Motivated by recent changes in FCC parameters, we have rediscovered an old device called a tristron, which is not a conventional klystron but a "gridded tube" where the electron beam bunching mechanism is different. Tristons have a lower power gain but much greater flexibility. Simulations have confirmed that they can reach efficiencies as high as 90%. This could be a disruptive technology with applications well beyond accelerators. Manufacturing a prototype is an excellent opportunity for knowledge transfer from fundamental research to industrial applications. ●

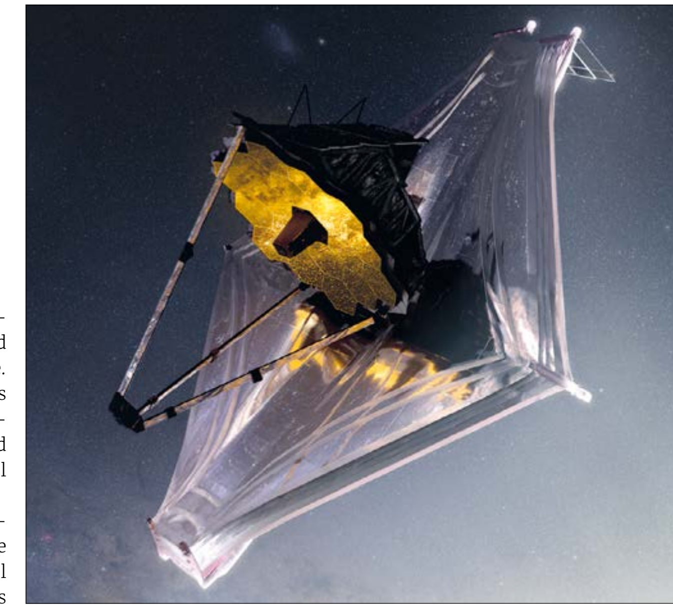
Further reading

D Varian 1983 *The Inventor and the Pilot: Russell and Sigurd Varian* (Cornwall Books, ISBN 0870152375).

N Catalan Lasheras *et al.* 2024 High-efficiency klystrons from a dream to a reality *IPAC'24 Proceedings* (JACoW Publishing), doi: 10.18429/JACoW-IPAC2024-FRYD1.

ACCELERATORS ON AUTOPILOT

Automated space telescopes are inspiring a new generation of particle accelerators that are primarily operated by AI. Verena Kain highlights four ways machine learning is already making the LHC more efficient.



NASA-GSFC, A M Gutierrez (CI Lab)

CERN-PHOTO-201904-108-2/M Brice

Dynamic and adaptive *Inspired by inaccessible instruments such as the James Webb Space Telescope (top), CERN is moving to automate future colliders. Promising initial progress has already been made at multiple stages of the acceleration chain of the LHC (above).*

Particle accelerators can be surprisingly temperamental machines. Expertise, specialisation and experience is needed to maintain their performance. Nonlinear and resonant effects keep accelerator engineers and physicists up late into the night. With so many variables to juggle and fine-tune, even the most seasoned experts will be stretched by future colliders. Can artificial intelligence (AI) help?

Proposed solutions take inspiration from space telescopes. The two fields have been jockeying to innovate since the Hubble Space Telescope launched with minimal automation in 1990. In the 2000s, multiple space missions tested AI for fault detection and onboard decision-making, before the LHC took a notable step forward for colliders in the 2010s by incorporating machine learning (ML) in trigger decisions. Most recently, the James Webb Space Telescope launched in 2021 using AI-driven autonomous control systems for mirror alignment, thermal balancing and scheduling science operations with minimal intervention from the ground. The new Efficient Particle Accelerators project at CERN, which I have led since its approval in 2023, is now rolling out AI at scale across CERN's accelerator complex (see "Dynamic and adaptive" image, right).

AI-driven automation will only become more necessary in the future. As well as being unprecedented in size and complexity, future accelerators will also have to navigate new constraints such as fluctuating energy availability from intermittent sources like wind and solar power, requiring highly adaptive and dynamic machine operation. This would represent a step change in complexity and scale. A new equipment integration paradigm would automate accelerator operation, equipment maintenance, fault analysis and recovery. Every item of equipment will need to be fully digitalised and able to auto-configure, auto-stabilise, auto-analyse and auto-recover. Like a driverless car, instrumentation and software layers must ▷

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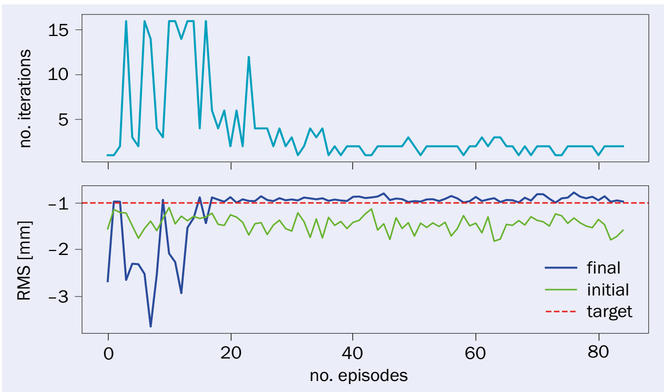


Beam steering *A groundbreaking 2019 experiment used reinforcement learning to reduce the root mean square (RMS) of the horizontal trajectory of the H⁻ beams in LINAC4 from its initial uncalibrated value (green line). As training progressed (horizontal axis), the algorithm soon required three or fewer iterations to select corrector settings that achieve a final RMS (blue line) better than the target of 1 mm (dashed red line).*

also be added for safe and efficient performance.

The final consideration is full virtualisation. While space telescopes are famously inaccessible once deployed, a machine like the Future Circular Collider (FCC) would present similar challenges. Given the scale and number of components, on-site human intervention should be treated as a last resort – or perhaps designed out entirely. This requires a new approach: equipment must be engineered for autonomy from the outset – with built-in margins, high reliability, modular designs and redundancy. Emerging technologies like robotic inspection, automated recovery systems and digital twins will play a central role in enabling this. A digital twin – a real-time, data-driven virtual replica of the accelerator – can be used to train and constrain control algorithms, test scenarios safely and support predictive diagnostics. Combined with differentiable simulations and layered instrumentation, these tools will make autonomous operation not just feasible, but optimal.

The field is moving fast. Recent advances allow us to rethink how humans interact with complex machines – not by tweaking hardware parameters, but by expressing intent at a higher level. Generative pre-trained transformers, a class of large language models, open the door to prompting machines with concepts rather than step-by-step instructions. While further R&D is needed for robust AI copilots, tailor-made ML models have already become standard tools for parameter optimisation, virtual diagnostics and anomaly detection across CERN's accelerator landscape.

Progress is diverse. AI can reconstruct LHC bunch profiles using signals from wall current monitors, analyse camera images to spot anomalies in the "dump kickers" that safely remove beams, or even identify malfunctioning beam-position monitors. In the following, I identify four different types of AI that have been successfully deployed across CERN's accelerator complex. They are merely the harbingers of a whole new way of operating CERN's accelerators.

On-site human intervention of the LHC could be treated as a last resort – or perhaps designed out entirely

1. Beam steering with reinforcement learning

In 2020, LINAC4 became the new first link in the LHC's modernised proton accelerator chain – and quickly became an early success story for AI-assisted control in particle accelerators.

Small deviations in a particle beam's path within the vacuum chamber can have a significant impact, including beam loss, equipment damage or degraded beam quality. Beams must stay precisely centred in the beampipe to maintain stability and efficiency. But their trajectory is sensitive to small variations in magnet strength, temperature, radiofrequency phase and even ground vibrations. Worse still, errors typically accumulate along the accelerator, compounding the problem. Beam-position monitors (BPMs) provide measurements at discrete points – often noisy – while steering corrections are applied via small dipole corrector magnets, typically using model-based correction algorithms.

In 2019, the reinforcement learning (RL) algorithm normalised advantage function (NAF) was trained online to steer the H⁻ beam in the horizontal plane of LINAC4 during commissioning. In RL, an agent learns by interacting with its environment and receiving rewards that guide it toward better decisions. NAF uses a neural network to model the so-called Q-function that estimates rewards in RL and uses this to continuously refine its control policy.

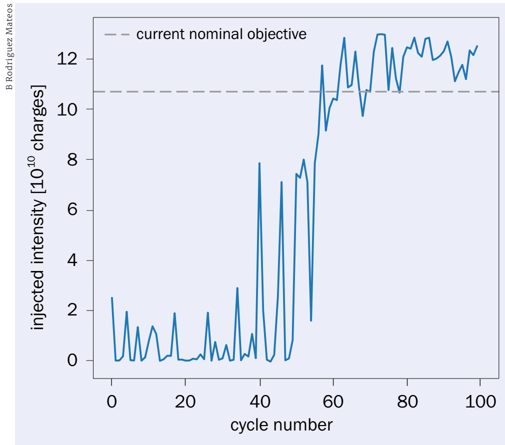
Initially, the algorithm required many attempts to find an effective strategy, and in early iterations it occasionally worsened the beam trajectory, but as training progressed, performance improved rapidly. Eventually, the agent achieved a final trajectory better aligned than the goal of an RMS of 1 mm (see "Beam steering" figure).

This experiment demonstrated that RL can learn effective control policies for accelerator-physics problems within a reasonable amount of time. The agent was fully trained after about 300 iterations, or 30 minutes of beam time, making online training feasible. Since 2019, the use of AI techniques has expanded significantly across accelerator labs worldwide, targeting more and more problems that don't have any classical solution. At CERN, tools such as GeOFF (Generic Optimisation Framework and Frontend) have been developed to standardise and scale these approaches throughout the accelerator complex.

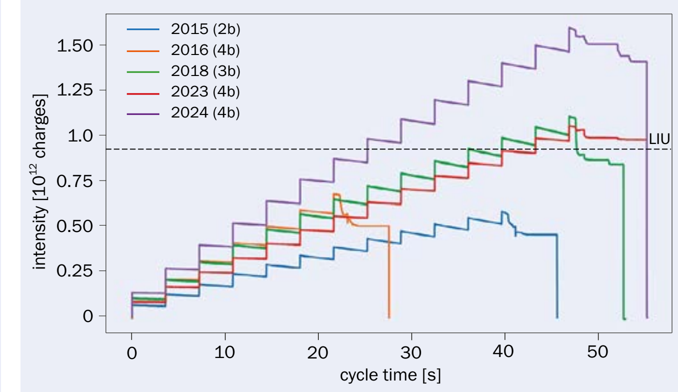
2. Efficient injection with Bayesian optimisation

Bayesian optimisation (BO) is a global optimisation technique that uses a probabilistic model to find the optimal parameters of a system by balancing exploration and exploitation, making it ideal for expensive or noisy evaluations. A game-changing example of its use is the record-breaking LHC ion run in 2024. BO was extensively used all along the ion chain, and made a significant difference in LEIR (the low-energy ion ring, the first synchrotron in the chain) and in the Super Proton Synchrotron (SPS, the last accelerator before the LHC). In LEIR, most processes are no longer manually optimised, but the multi-turn injection process is still non-trivial and depends on various longitudinal and transverse parameters from its injector LINAC3.

In heavy-ion accelerators, particles are injected in a



Quick recovery *Bayesian optimisation is able to restore the beam intensity in LEIR (blue line) to better than nominal values (dashed grey line) within fewer than 100 complete beam shots through the accelerator.*



SPS intensity *Year-on-year improvements in ion-beam performance in the SPS across the duration of one full ion acceleration cycle from injection to extraction. Each staircase shows stepwise injection and accumulation of bunches in the SPS, far exceeding the LHC Injector Upgrade (LIU) design goal in 2024 thanks to ML algorithms in both LEIR and the SPS. The 2024 increase was achieved with the same number of bunches per cycle (four bunches, 4b) as the previous year.*

partially stripped charge state and must be converted to higher charge states at different stages for efficient acceleration. In the LHC ion injector chain, the stripping foil between LINAC3 and LEIR raises the charge of the lead ions from Pb^{27+} to Pb^{54+}. A second stripping foil, between the PS and SPS, fully ionises the beam to Pb^{82+} ions for final acceleration toward the LHC. These foils degrade over time due to thermal stress, radiation damage and sputtering, and must be remotely exchanged using a rotating wheel mechanism. Because each new foil has slightly different stripping efficiency and scattering properties, beam transmission must be re-optimised – a task that traditionally required expert manual tuning.

In 2024 it was successfully demonstrated that BO with embedded physics constraints can efficiently optimise the 21 most important parameters between LEIR and the LINAC3 injector. Following a stripping foil exchange, the algorithm restored the accumulated beam intensity in LEIR to better than nominal levels within just a few dozen iterations (see "Quick recovery" figure).

This example shows how AI can now match or outperform expert human tuning, significantly reducing recovery time, freeing up operator bandwidth and improving overall machine availability.

3. Adaptively correcting the 50 Hz ripple

In high-precision accelerator systems, even tiny perturbations can have significant effects. One such disturbance is the 50 Hz ripple in power supplies – small periodic fluctuations in current that originate from the electrical grid. While these ripples were historically only a concern for slow-extracted proton beams sent to fixed-target experiments, 2024 revealed a broader impact.

In the SPS, adaptive Bayesian optimisation (ABO) was deployed to control this ripple in real time. ABO extends BO by learning the objective not only as a function of the control parameters, but also as a function of time, which then allows continuous control through forecasting.

The algorithm generated shot-by-shot feed-forward corrections to inject precise counter-noise into the voltage regulation of one of the quadrupole magnet circuits. This approach was already in use for the North Area proton beams, but in summer 2024 it was discovered that even for high-intensity proton beams bound for the LHC, the same ripple could contribute to beam losses at low energy.

Thanks to existing ML frameworks, prior experience with ripple compensation and available hardware for active noise injection, the fix could be implemented quickly. While the gains for protons were modest – around 1% improvement in losses – the impact for LHC ion beams was far more dramatic. Correcting the 50 Hz ripple increased ion transmission by more than 15%. ABO is therefore now active whenever ions are accelerated, improving transmission and supporting the record beam intensity achieved in 2024 (see "SPS intensity" figure).

AI can now match or outperform expert human tuning, significantly reducing recovery time and improving overall machine availability

4. Predicting hysteresis with transformers

Another outstanding issue in today's multi-cycling synchrotrons with iron-dominated electromagnets is correcting for magnetic hysteresis – a phenomenon where the magnetic field depends not only on the current but also on its cycling history. Cumbersome mitigation strategies include playing dummy cycles and manually re-tuning parameters after each change in magnetic history.

While phenomenological hysteresis models exist, their accuracy is typically insufficient for precise beam control. ML offers a path forward, especially when supported by high-quality field measurement data. Recent work using temporal fusion transformers – a deep-learning architecture designed for multivariate time-series prediction – has demonstrated that ML-based models can accurately predict field deviations from the programmed transfer function across different SPS magnetic cycles (see "SPS hysteresis" figure). This hysteresis model is now used in

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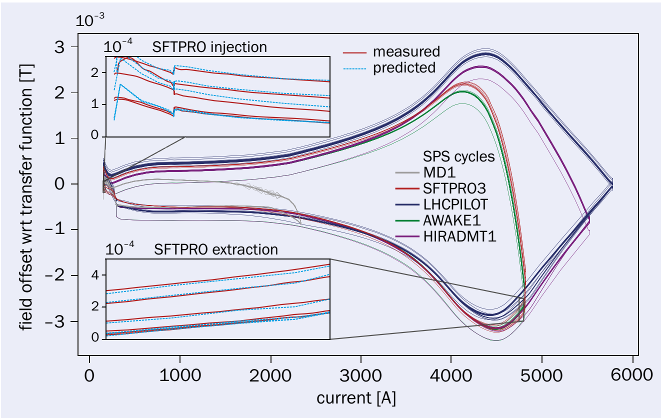

SPS hysteresis *Magnetic field offsets due to hysteresis as a function of current in SPS dipole magnets for different current cycles. ML predictions (dashed lines) model measured values (solid lines) with a precision of the order of 10^{-5} T.*

the SPS control room to provide feed-forward corrections – pre-emptive adjustments to magnet currents based on the predicted magnetic state – ensuring field stability without waiting for feedback from beam measurements and manual adjustments.

THE AUTHOR
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CERN.

A blueprint for the future

With the Efficient Particle Accelerators project, CERN is developing a blueprint for the next generation of autonomous equipment. This includes concepts for continuous self-analysis, anomaly detection and new layers of "Internet of Things" instrumentation that support auto-configuration and predictive maintenance. The focus is on making it easier to integrate smart software layers. Full results are expected by the end of LHC Run 3, with robust frameworks ready for deployment in Run 4.

The goal is ambitious: to reduce maintenance effort by at least 50% wherever these frameworks are applied. This is based on a realistic assumption – already today, about half of all interventions across the CERN accelerator complex are performed remotely, a number that continues to grow. With current technologies, many of these could be fully automated.

Together, these developments will not only improve the operability and resilience of today's accelerators, but also lay the foundation for CERN's future machines, where human intervention during operation may become the exception rather than the rule. AI is set to transform how we design, build and operate accelerators – and how we do science itself. It opens the door to new models of R&D, innovation and deep collaboration with industry. ●

What TOPS means for performance and power

Understanding AI performance metrics for Copilot+ PCs

Copilot+ PCs are here, and they're powered exclusively by Snapdragon® X Series processors! That means more apps are executing AI models locally – rather than in the cloud – delivering better performance, accuracy and privacy benefits. Here's what you need to know about AI performance when matching users with equipment to meet their needs.

What is a Copilot+ PC? In addition to CPUs and GPUs, Copilot+ PCs also have a neural processing unit (NPU). This specialised processor enables apps to run AI workloads on the device, unlocking new experiences while keeping your company data safe.

What is an NPU? An NPU is a specialised processor dedicated to handling AI workloads. Unlike traditional CPUs and GPUs, NPUs are uniquely designed to handle the complex mathematical computations required for AI tasks – offering unparalleled efficiency, performance and power savings. When AI workloads are run on the NPU, the CPU and GPU remain available to handle other tasks.

The Snapdragon X Series processors set new AI performance standards.

What is TOPS?

TOPS, or trillions of operations per second, is the cornerstone performance metric for NPUs. It measures the number of operations (for example additions and multiples) that can be executed within one second. Exploring the parameters of the TOPS equation, such as frequency and precision, can offer a deeper understanding of an NPU's capabilities.

Why does 40 TOPS matter?

AI workloads consume massive amounts of power when executed on the CPU or GPU, but NPUs are designed to efficiently handle AI inferencing. Naturally, AI operations will run faster on devices with higher TOPS values. That's especially true for concurrent app use, such as using Microsoft Copilot while video conferencing. In fact, some AI applications demand so much AI processing power that they may not work at all on devices with lower TOPS capacity.

Are 40 TOPS truly necessary?

Yes. Microsoft requires Copilot+ PCs to have at least 40 TOPS of NPU processing capacity. To ensure the most power and efficiency, the Snapdragon X Series processors go even further, setting a new performance standard at 45 TOPS.

Hardware innovations with Dell AI PCs

Dell's latest lineup of AI PCs, powered by Qualcomm's Snapdragon X Elite and X Plus processors, marks a significant advancement in personal computing. These devices integrate on-device AI capabilities, offering enhanced performance, extended battery life and improved user experiences.

• Learn more about Dell Copilot+ PCs: www.dell.com/en-us/lp/copilotpc

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OPINION
INTERVIEW

Charting DESY's future

DESY's new chair, Beate Heinemann, reflects on the laboratory's evolving role in science and society – from building next-generation accelerators to navigating Europe's geopolitical landscape.

How would you describe DESY's scientific culture?

DESY is a large laboratory with just over 3000 employees. It was founded 65 years ago as an accelerator lab, and at its heart it remains one, though what we do with the accelerators has evolved over time. It is fully funded by Germany.

In particle physics, DESY has performed many important studies, for example to understand the charm quark following the November Revolution of 1974. The gluon was discovered here in the late 1970s. In the 1980s, DESY ran the first experiments to study B mesons, laying the groundwork for core programmes such as LHCb at CERN and the Belle II experiment in Japan. In the 1990s, the HERA accelerator focused on probing the structure of the proton, which, incidentally, was the subject of my PhD, and those results have been crucial for precision studies of the Higgs boson.

Over time, DESY has become much more than an accelerator and particle-physics lab. Even in the early days, it used what is called synchrotron radiation, the light emitted when electrons change direction in the accelerator. This light is incredibly useful for studying matter in detail. Today, our accelerators are used primarily for this purpose: they generate X-rays that image tiny structures, for example viruses.

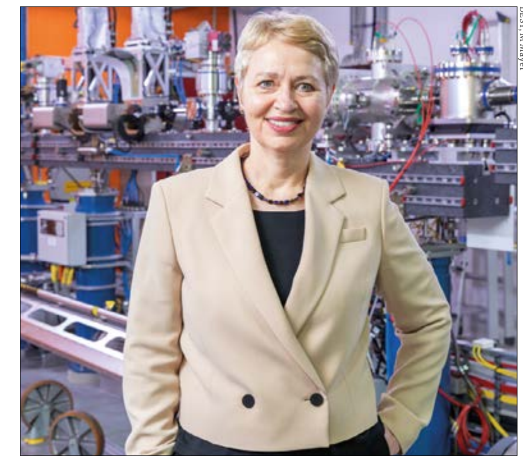
DESY's culture is shaped by its very engaged and loyal workforce. People often call themselves "DESYians" and strongly identify with the laboratory. At its heart, DESY is really an engineering lab. You need an amazing engineering workforce to be able to construct and operate these accelerators.

Which of DESY's scientific achievements are you most proud of?

The discovery of the gluon is, of course, an incredible achievement, but actually I would say that DESY's greatest accomplishment has been building so many cutting-edge accelerators: delivering them on time, within budget, and getting them to work as intended.

Take the PETRA accelerator, for example – an entirely new concept when it was first proposed in the 1970s. The decision to build it was made in 1975; construction was completed by 1978; and by 1979 the gluon was discovered. So in just four years, we went from approving a 2.3 km accelerator to making a fundamental discovery, something that is absolutely crucial to our understanding of the universe. That's something I'm extremely proud of.

I'm also very proud of the European X-ray Free-Electron Laser (XFEL), completed in 2017 and now fully operational. Before that, in 2005 we launched the world's first free-electron laser, FLASH, and of course in the 1990s HERA, another pioneering machine. Again and again, DESY has succeeded in building large, novel and highly valuable accelerators that have pushed the boundaries of science.



DESY, M Mayer

Taking the helm *Beate Heinemann was appointed chairperson of the DESY directorate on 1 April.*

What can we look forward to during your time as chair?

We are currently working on 10 major projects in the next three years alone! PETRA III will be running until the end of 2029, but our goal is to move forward with PETRA IV, the world's most advanced X-ray source. Securing funding for that first, and then building it, is one of my main objectives. In Germany, there's a roadmap process, and by July this year we'll know whether an independent committee has judged PETRA IV to be one of the highest-priority science projects in the country. If all goes well, we aim to begin operating PETRA IV in 2032.

Our FLASH soft X-ray facility is also being upgraded to improve beam quality, and we plan to relaunch it in early September. That will allow us to serve more users and deliver better beam quality, increasing its impact.

In parallel, we're contributing significantly to the HL-LHC upgrade. More than 100 people at DESY are working on building trackers for the ATLAS and CMS detectors, and parts of the forward calorimeter of CMS. That work needs to be completed by 2028.

Astroparticle physics is another growing area for us. Over the next three years we're completing telescopes for the Cherenkov Telescope Array and building detectors for the IceCube upgrade. For the first time, DESY is also constructing a space camera for the satellite UltraSat, which is expected to launch within the next three years.

At the Hamburg site, DESY is diving further into axion research. We're currently running the ALPS II experiment, which has a fascinating "light shining through a wall" setup. Normally, of course, light can't pass through something like a thick concrete wall. But in ALPS II, light inside a magnet can convert into an axion, a hypothetical dark-matter particle that can travel through matter almost unhindered. On the other side, another magnet converts the axion back into light. So, it appears as if the light has passed through the wall, when in fact it was briefly an axion. We started the experiment last year. As with most experiments, we began carefully, because not everything works at once, but two more major upgrades are planned in the next two years, and that's when we expect ALPS II to reach its full scientific potential.

We're also developing additional axion experiments. One of them, in collaboration with CERN, is called BabyIAXO. It's designed to look for axions from the Sun, where you have both light and magnetic fields. We hope to start construction before the end of the decade.

Finally, DESY also has a strong and diverse theory group. Their work spans many areas, and it's exciting to see what ideas will emerge from them over the coming years.

How does DESY collaborate with industry to deliver benefits to society?

We already collaborate quite a lot with industry. The beamlines at PETRA, in particular, are of strong interest. For example, BioNTech conducted some of its research for the COVID-19 vaccine here. We also have a close relationship with the Fraunhofer Society in Germany, which focuses on translating basic research into industrial applications. They famously developed the MP3 format, for instance. Our collaboration with them is quite structured, and there have also been several spinoffs and start-ups based on technology developed at DESY. Looking ahead, we want to significantly strengthen our ties with industry through PETRA IV. With much higher data rates and improved beam quality, it will be far easier to obtain results quickly. Our goal is for 10% of PETRA IV's capacity to be dedicated to industrial use. Furthermore, we are developing a strong ecosystem for innovation on the campus and the surrounding area, with DESY in the centre, called the Science City Hamburg Bahrenfeld.

What's your position on "dual use" research, which could have military applications?

The discussion around dual-use research is complicated. Personally, I find the term "dual use" a bit odd – almost any high-tech equipment can be used for both civilian and military purposes. Take a transistor for example, which has countless applications, including military ones, but it wasn't invented for that reason. At DESY, we're currently having an internal discussion about whether to engage in projects that relate to defence. This is part of an ongoing process where we're trying to define under what conditions, if any, DESY would take on targeted projects related to defence. There are a range of views within DESY, and I think that diversity of opinion is valuable. Some people are firmly against this idea, and I respect that. Honestly, it's probably how I would have felt 10 or 20 years ago. But others believe DESY should play a role. Personally, I'm open to it.

DESY, M Mayer

Hunting axions *ALPS II repurposes a 250 metre stretch of straightened HERA dipole magnets to search for hidden particles beyond the Standard Model.*

If our expertise can help people defend themselves and our freedom in Europe, that's something worth considering. Of course, I would love to live in a world without weapons, where no one attacks anyone. But if I were attacked, I'd want to be able to defend myself. I prefer to work on shields, not swords, like in *Asterix and Obelix*, but, of course, it's never that simple. That's why we're taking time with this. It's a complex and multifaceted issue, and we're engaging with experts from peace and security research, as well as the social sciences, to help us understand all dimensions. I've already learned far more about this than I ever expected to. We hope to come to a decision on this later this year.

You are DESY's first female chair. What barriers do you think still exist for women in physics, and how can institutions like DESY address them?

There are two main barriers, I think. The first is that, in my opinion, society at large still discourages girls from going into maths and science.

Certainly in Germany, if you stopped a hundred people on the street, I think most of them would still say that girls aren't naturally good at maths and science. Of course, there are always exceptions: you do find great teachers and supportive parents who go against this narrative. I wouldn't be here today if I hadn't received that kind of encouragement.

Looking ahead, we want to significantly strengthen our ties with industry

That's why it's so important to actively counter those messages. Girls need encouragement from an early age, they need to be strengthened and supported. On the encouragement side, DESY is quite active. We run many outreach activities for schoolchildren, including a dedicated school lab. Every year, more than 13,000 school pupils visit our campus. We also take part in Germany's "Zukunftstag", where girls are encouraged to explore careers traditionally considered male-dominated, and boys do the same for fields seen as female-dominated.

The second challenge comes later, at a different career stage, and it has to do with family responsibilities. Often, family work still falls more heavily on women than men in many partnerships. That imbalance can hold women back, particularly during the postdoc years, which tend to coincide with the time when many people are starting families. It's a tough period, because you're trying to advance your career.

Workplaces like DESY can play a role in making this easier. We offer good childcare options, flexibility with home-office arrangements, and even shared leadership positions, which help make it more manageable to balance work and family life. We also have mentoring programmes. One example is dynaMENT, where female PhD students and postdocs are mentored by more senior professionals. I've taken part in that myself, and I think it's incredibly valuable.

Do you have any advice for early-career women physicists?

If I could offer one more piece of advice, it's about building a strong professional network. That's something I've found truly valuable. I'm fortunate to have a fantastic international network, both male and female colleagues, including many women in leadership positions. It's so important to have people you can talk to, who understand your challenges, and who might be in similar situations. So if you're a student, I'd really recommend investing in your network. That's very important, I think.

What are your personal reflections on the next-generation colliders?

Our generation has a responsibility to understand the electroweak scale and the Higgs boson. These questions have been around for almost 90 years, since 1935 when Hideki Yukawa explored the idea that forces might be mediated by the exchange of massive particles. While we've made progress, a true understanding is still out of reach. That's what the next generation of machines is aiming to tackle.

The problem, of course, is cost. All the proposed solutions are expensive, and it is very challenging to secure investments for such large-scale projects, even though the return on investment from big science is typically excellent: these projects drive innovation, build high-tech capability and create a highly skilled workforce.

From a scientific point of view, the FCC is the most comprehensive option. As a Higgs factory, it offers a broad and strong programme to analyse the Higgs and electroweak gauge bosons. But who knows if we'll be able to afford it? And it's not just about money. The timeline and the risks also matter. The FCC feasibility report was just published and is still under review by an expert committee. I'd rather not comment further until I've seen the full information. I'm part of the European Strategy Group and we'll publish a new report by the end of the year. Until then, I want to understand all the details before forming an opinion.

It's good to have other options too. The muon collider is not yet as technically ready as the FCC or linear collider, but it's an exciting technology and could be the machine after next. Another could be using plasma-wakefield acceleration, which we're very actively working on at DESY. It could enable us to build high-energy colliders on a much smaller scale. This is something we'll need, as we can't keep building ever-larger machines forever. Investing in accelerator R&D to develop these next-gen technologies is crucial.

Still, I really hope there will be an intermediate machine in the near future, a Higgs factory that lets us properly explore the Higgs boson. There are still many mysteries there. I like to compare it to an egg: you have to crack it open to see what's inside. And that's what we need to do with the Higgs.

One thing that is becoming clearer to me is the growing importance of Europe. With the current uncertainties in the US, which are already affecting health and climate research, we can't assume fundamental research will remain unaffected. That's why Europe's role is more vital than ever.

Europe's role is more vital than ever

I think we need to build more collaborations between European labs. Sharing expertise, especially through staff exchanges, could be particularly valuable in engineering, where we need a huge number of highly skilled professionals to deliver billion-euro projects. We've got one coming up ourselves, and the technical expertise for that will be critical.

I believe science has a key role to play in strengthening Europe, not just culturally, but economically too. It's an area where we can and should come together.

Interview by **Naomi Dinmore** *CERN.*

OPINION REVIEWS

Gravitational remnants in the sky

Relic Gravitons

By Massimo Giovannini

World Scientific

Astrophysical gravitational waves have revolutionised astronomy; the eventual detection of cosmological gravitons promises to open an otherwise inaccessible window into the universe's earliest moments. Such a discovery would offer profound insights into the hidden corners of the early universe and physics beyond the Standard Model. *Relic Gravitons*, by Massimo Giovannini of INFN Milan Bicocca, offers a timely and authoritative guide to the most exciting frontiers in modern cosmology and particle physics.

Giovannini is an esteemed scholar and household name in the fields of theoretical cosmology and early-universe physics. He has written influential research papers, reviews and books on cosmology, providing detailed discussions on several aspects of the early universe. He also authored 2008's *A Primer on the Physics of the Cosmic Microwave Background* – a book most cosmologists are very familiar with.

In *Relic Gravitons*, Giovannini provides a comprehensive exploration of recent developments in the field, striking a remarkable balance between clarity, physical intuition and rigorous mathematical formalism. As such, it serves as an excellent reference – equally valuable for both junior researchers and seasoned experts seeking depth and insight into theoretical cosmology and particle physics.

Relic Gravitons opens with an overview of cosmological gravitons, offering a broad perspective on gravitational waves across different scales and cosmological epochs, while drawing parallels with the electromagnetic spectrum. This graceful introduction sets the stage for a well-contextualised and structured discussion.

J Young for Green Bank Observatory

Cosmic correlations *Radio astronomers use precise timing measurements of ultra-fast millisecond pulsars to search for the distinctive correlation signature created by a background of gravitational waves. The Green Bank Telescope in West Virginia (pictured) is a key instrument in the NANOGrav pulsar timing array.*

Gravitational rainbow

Relic gravitational waves from the early universe span 30 orders of magnitude, from attohertz to gigahertz. Their wavelengths are constrained from above by the Hubble radius, setting a lower frequency bound of 10^{-18} Hz. At the lowest frequencies, measurements of the cosmic microwave background (CMB) provide the most sensitive probe of gravitational waves. In the nanohertz range, pulsar timing arrays serve as powerful astrophysical detectors. At intermediate frequencies, laser and atomic interferometers are actively probing the spectrum. At higher frequencies, only wide-band interferometers such as LIGO and Virgo currently operate, primarily within the audio band spanning from a few hertz to several kilohertz.

World Scientific

The theoretical foundation begins with a clear and accessible introduction to tensor modes in flat spacetime, followed by spherical harmonics and polarisations. With these basics in place, tensor modes in curved spacetime are also explored, before progressing to effective action, the quantum mechanics of relic gravitons and effective energy density. This structured progression builds a solid framework for phenomenological applications.

The second part of the book is about the signals of the concordance paradigm, which includes discussions of Sakharov oscillations, short, intermediate and long wavelengths, before entering technical interludes in the next section. Here, Giovannini emphasises that the evolution of the comoving Hubble radius is uncertain, spectral energy density and other observables require approximate methods. The chapter expands to include conventional results using the Wentzel–Kramers–Brillouin approach, which is particularly useful when early-universe dynamics deviate from standard inflation.

Phenomenological implications are discussed in the final section, starting with the low-frequency branch that covers the analysis of the phenomenological implications in the lowest-frequency domain. Giovannini then examines the intermediate and high-frequency ranges. The concordance paradigm suggests that large-scale inhomogeneities originate from quantum mechanics, where travelling waves transform into standing waves. The penultimate chapter addresses the hot topic of the "quantumness" of relic gravitons, before diving into the conclusion. The book finishes with five appendices covering all sorts of useful topics, from notation to basic related topics in general relativity and cosmic perturbations.

Relic Gravitons is a must-read for anyone intrigued by the gravitational-wave background and its unparalleled potential to unveil new physics. It is an invaluable resource for those interested in gravitational waves and the unique potential to explore the unknown parts of particle physics and cosmology.

Azadeh Maleknejad
King's College London.

Particle Cosmology and Astrophysics

By Dan Hooper

Princeton University Press

In 1989, Rocky Kolb and Mike Turner published *The Early Universe* – a seminal book that offered a comprehensive introduction to the then-nascent field of particle cosmology, laying the groundwork for a generation of physicists to explore the connections between the smallest and largest scales of the universe. Since then, the interfaces between particle physics, astrophysics and cosmology have expanded enormously, fuelled by an avalanche of new data from ground-based and space-borne observatories.

In *Particle Cosmology and Astrophysics*, Dan Hooper follows in their footsteps, providing a much-needed update that captures the rapid developments of the past three decades. Hooper, now a professor at the University of Wisconsin-Madison, addresses the growing need for a text that introduces the fundamental concepts and synthesises the vast array of recent discoveries that have shaped our current understanding of the universe.

Hooper's textbook opens with 75 pages of "preliminaries", covering general relativity, cosmology, the Standard Model of particle physics, thermodynamics and high-energy processes in astrophysics. Each of these disciplines is typically introduced in a full semester of dedicated study, supported by comprehensive texts. For example, students seeking a deeper understanding of high-energy phenomena are likely to benefit from consulting Longair's *High Energy Astrophysics* or Sigl's *Astroparticle Physics*. Similarly, those wishing to advance their knowledge in particle physics will find that more detailed treatments are available in Griffiths' *Introduction to Elementary Particles* or Peskin and Schroeder's *An Introduction to Quantum Field Theory*, to mention just a few textbooks recommended by the author.

By distilling these complex subjects into just enough foundational content, Hooper makes the field accessible to those who have been exposed to only a fraction of the standard coursework. His approach provides an essential stepping stone, enabling students to embark on research in particle cosmology and astrophysics with a well calibrated introduction while still encouraging further study through more specialised texts.

Part II, "Cosmology", follows a similarly pragmatic approach, providing an updated treatment that parallels Kolb and Turner while incorporating a range of topics that have, in the intervening years, become central to modern cosmology. The text now covers areas such as cosmic microwave background (CMB) anisotropies, the evidence for dark matter and its potential particle candidates, the inflationary paradigm, and the evidence and possible nature of dark energy.

Hooper doesn't shy away from complex subjects, even when they resist simple expositions. The discussion on CMB anisotropies serves as a case in point: anyone who has attempted to condense this complex topic into a few graduate lectures is aware of the challenge in maintaining both depth and clarity. Instead of attempting an exhaustive technical introduction, Hooper offers a qualitative description of the evolution of density perturbations and how one extracts cosmological parameters from CMB observations. This approach, while not substituting for the comprehensive analysis found in texts such as Dodelson's *Modern Cosmology* or Baumann's

Princeton University Press

A much-needed update that captures the rapid developments of the past three decades

Cosmology, provides students with a valuable overview that successfully charts the broad landscape of modern cosmology and illustrates the interconnectedness of its many subdisciplines.

Part III, "Particle Astrophysics", contains a selection of topics that largely reflect the scientific interests of the author, a renowned expert in the field of dark matter. Some colleagues might raise an eyebrow at the book devoting 10 pages each to entire fields such as cosmic rays, gamma rays and neutrino astrophysics, and 50 pages to dark-matter candidates and searches. Others might argue that a book titled *Particle Cosmology and Astrophysics* is incomplete without detailing the experimental techniques behind the extraordinary advances witnessed in these fields and without at least a short introduction to the booming field of gravitational-wave astronomy. But the truth is that, in the author's own words, particle cosmology and astrophysics have become "exceptionally multidisciplinary," and it is impossible in a single textbook to do complete justice to domains that intersect nearly all branches of physics and astronomy. I would also contend that it is not only acceptable but indeed welcome for authors to align the content of their work with their own scientific interests, as this contributes to the diversity of textbooks and offers more choice to lecturers who wish to supplement a standard curriculum with innovative, interdisciplinary perspectives.

Ultimately, I recommend the book as a welcome addition to the literature and an excellent introductory textbook for graduate students and junior scientists entering the field.

Gianfranco Bertone
University of Amsterdam.

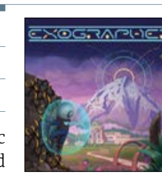
Exographer

Developed by SciFun Games

Published by Abylight Studios

Try lecturing the excitement of subatomic particle discovery to physics students, and you might inspire several future physicists. Lecture physics to a layperson, and you might get a completely different response. Not everyone is excited about particle physics by listening to lectures alone. Sometimes video games can help.

Exographer, the brainchild of Raphael Granier de Cassagnac (*CERN Courier* March/April 2025 p48), puts you in the shoes of an investigator in a world where scientists are fascinated by what their planet is made of, and have made a barrage of apparatus to investigate it. Your role is



Abylight Studios

to traverse through this beautiful realm and solve puzzles that may lead to future discoveries, encountering frustration and excitement along the way.

The puzzles are neither nerve-racking nor too difficult, but solving each one brings immense satisfaction, much like the joy of discoveries in particle physics. These eureka moments make up for the hundreds of times when you fell to your death because you forgot to use the item that could have saved you.

The most important part of the game is taking pictures, particularly inside particle detectors. These reveal the tracks of particles, reminiscent of Feynman diagrams. It's your job to figure out what particles leave these tracks. Is it a known particle? Is it new? Can we add it to our collection?

I am sure that the readers of *CERN Courier* will be familiar with particle discoveries throughout the past century, but as a particle physicist I still found awe and joy in rediscovering them whilst playing the game. It feels like walking through a museum, with each apparatus you encounter more sophisticated than the last. The game also hides an immensely intriguing lore of scientists from our own world. Curious gamers who spend extra time unravelling these stories are rewarded with various achievements.

All in all, this game is a nice introduction to the world of particle-physics discovery – an enjoyable puzzle/platformer game you should try, regardless of whether or not you are a physicist.

Vichayanun Wachirapusitanand
Chulalongkorn University.

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PEOPLE CAREERS

Machine learning in industry

Antoni Shtipliyski offers advice on how early-career researchers can transition into machine-learning roles in industry.

Flying high *Antoni Shtipliyski is an engineering manager at Skyscanner, where he oversees the company's internal machine-learning platform and operations.*

In the past decade, machine learning has surged into every corner of industry, from travel and transport to healthcare and finance. For early-career researchers, who have spent their PhDs and postdocs coding, a job in machine learning may seem a natural next step.

"Scientists often study nature by attempting to model the world around us into mathematical models and computer code," says Antoni Shtipliyski, engineering manager at Skyscanner. "But that's only one part of the story if the aim is to apply these models to large-scale research questions or business problems. A completely orthogonal set of challenges revolves around how people collaborate to build and operate these systems. That's where the real work begins."

Used to large-scale experiments and collaborative problem solving, particle physicists are uniquely well-equipped to step into machine-learning roles. Shtipliyski worked on upgrades for the level-1 trigger system of the CMS experiment at CERN, before leaving to lead the machine-learning operations team in one of the biggest travel companies in the world.

Effective mindset

"At CERN, building an experimental detector is just the first step," says Shtipliyski. "To be useful, it needs to be operated effectively over a long period of time. That's exactly the mindset needed in industry."

During his time as a physicist, Shtipliyski gained multiple skills that continue to help him at work today, but there were also a number of other areas he developed to succeed in machine learning in industry. One critical gap in a physicists' portfolio, he notes, is that many people interpret machine-learning careers as purely algorithmic development and model training.

"At Skyscanner, my team doesn't build models directly," he says. "We look after the platform used to push and serve machine-learning models to our users. We oversee the techno-social machine that delivers these models to travellers. That's the part people underestimate, and where a lot of the challenges lie."

An important factor for physicists transitioning out of academia is to understand the entire lifecycle of a machine-learning project. This includes not only developing an algorithm, but deploying it, monitoring its performance, adapting it to changing conditions and ensuring that it serves business or user needs.

"In practice, you often find new ways that machine-learning models surprise you," says Shtipliyski. "So having flexibility and confidence that the evolved system still works is key. In physics we're used to big experiments like CMS being designed 20 years before being built. By the time it's operational, it's adapted so much from the original spec. It's no different with machine-learning systems."

This ability to live with ambiguity and work through evolving systems is one of the strongest foundations physicists can bring. But large complex systems cannot be built alone, so companies will be looking for examples of soft skills: teamwork, collaboration, communication and leadership.

"Most people don't emphasise these skills, but I found them to be among the most useful," Shtipliyski says. "Learning to write and communicate yourself is incredibly powerful. Being able to clearly express what you're doing and why you're doing it, especially in high-trust environments, makes everything else easier. It's something I also look for when I do hiring."

Industry may not offer the same depth of exploration as academia, but it does offer something equally valuable: breadth, variety and a dynamic environment. Work evolves fast, deadlines come more readily and teams are constantly changing.

"In academia, things tend to move more slowly. You're encouraged to go deep into one specific niche," says Shtipliyski. "In industry, you often move faster and are sometimes more shallow. But if you can combine the depth of thought from academia with the breadth of experience from industry, that's a winning combination."

Applied skills

For physicists eyeing a career in machine learning, the most they can do is to familiarise themselves with tools and practices for building and deploying models. Show that you can use the skills developed in academia and apply them to other environments. This tells recruiters that you have a willingness to learn, and is a simple but effective way of demonstrating commitment to a project from start to finish, beyond your assigned work.

"People coming from physics or mathematics might want to spend more time on implementation," says Shtipliyski. "Even if you follow a guided walkthrough online, or complete classes on Coursera, going through the whole process of implementing things from scratch teaches you a lot. This puts you in a position to reason about the big picture and shows employers your willingness to stretch yourself, to make trade-offs and to evaluate your work critically."

A common misconception is that practicing machine learning outside of academia is somehow less rigorous or less meaningful. But in many ways, it can be more demanding.

Scientific development is often driven by arguments of beauty and robustness. In industry, there's less patience for that," he says. "You have to apply it to a real-world domain – finance, travel, healthcare. That domain shapes everything: your constraints, your models, even your ethics."

Shtipliyski emphasises that the technical side of machine learning is only one half of the equation. The other half is organisational: helping teams work together, navigate constraints and build systems that evolve over time. Physicists would benefit from exploring different business domains to understand how machine learning is used in different contexts. For example, GDPR constraints make privacy a critical issue in healthcare and tech. Learning how government funding is distributed throughout each project, as well as understanding how to build a trusting relationship between the funding agencies and the team, is equally important.

"A lot of my day-to-day work is just passing information, helping people build a shared mental model," he says. "Trust is earned by being vulnerable yourself, which allows others to be vulnerable in turn. Once that happens, you can solve almost any problem."

Taking the lead

Particle physicists are used to working in high-stakes, international teams, so this collaborative mindset is engrained in their training. But many may not have had the opportunity to lead, manage or take responsibility for an entire project from start to finish.

"In CMS, I did not have a lot of say due to the complexity and scale of the project, but I was able to make meaningful contributions in the validation and running of the detector," says Shtipliyski. "But what I did not get much exposure to was the end-to-end experience, and that's something employers really want to see."

This does not mean you need to be a project manager to gain leadership experience. Early-career researchers have the chance to up-skill when mentoring a newcomer, help improve the team's workflow in a proactive way, or network with other physicists and think outside the box.

"Even if you just shadow an existing project, if you can talk confidently about what was done, why it was done and how it might be done differently – that's huge."

Many early-career researchers hesitate prior to leaving academia. They worry about making the "wrong" choice, or being labelled as a "finance person" or "tech person" as soon as they enter another industry. This is something Shtipliyski struggled to reckon with, but eventually realised that such labels do not define you.

"It was tough at CERN trying to anticipate what comes next," he admits. "I thought that I could only have one first job. What if it's the wrong one? But once a scientist, always a scientist. You carry your experiences with you."

Shtipliyski quickly learnt that industry operates under a different set of rules: where everyone comes from a different background, and the levels of expertise differ depending on the person you will speak to next. Having faced intense imposter syndrome at CERN – having shared spaces with world-leading experts – industry offered Shtipliyski a more level playing field.

"In academia, there's a kind of ladder: the longer you stay, the better you get. In industry, it's not like that," says Shtipliyski. "You can be the dedicated expert in the room, even if you're new. That feels really empowering."

Industry rewards adaptability as much as expertise. For physicists stepping beyond academia, the challenge is not abandoning their training, but expanding it – learning to navigate ambiguity, communicate clearly and understand the full lifecycle of real-world systems. Harnessing a scientist's natural curiosity, and demonstrating flexibility, allows the transition to become less about leaving science behind, and more about discovering new ways to apply it.

"You are the collection of your past experiences," says Shtipliyski. "You have the freedom to shape the future."

Interview by Alex Epshtein *CERN.*

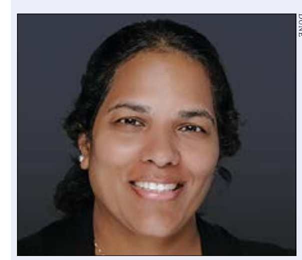
Appointments and awards

New ATLAS leadership team

As of March, Stéphane Willocq (above; University of Massachusetts–Amherst) succeeds Andreas Hoecker as spokesperson of the ATLAS collaboration. Willocq brings extensive leadership experience, having also served as physics coordinator, chair of the publications committee and deputy spokesperson from 2023 to 2025. Over a two-year term, Willocq will steer ATLAS through the final phase of LHC Run 3 and navigate the transition into the High-Luminosity LHC era. Also joining the new management team are deputy spokespersons Anna Sfyrla (University of Geneva) and Guillaume Unal (CERN).

New DUNE co-spokesperson

On 1 April, Sowjanya Gollapinni (below; Los Alamos National Laboratory) was elected as co-spokesperson for the Deep Underground Neutrino Experiment (DUNE), succeeding Mary Bishai (Brookhaven



National Laboratory), and joining continuing co-spokesperson Sergio Bertolucci (University of Bologna) as the head of the collaboration. Gollapinni served as the US scientific coordinator for DUNE's second construction phase and has acted as technical leader for DUNE's calibration and cryogenics since 2015. "The next two years will be a pivotal time for DUNE," she notes. "I look forward to taking DUNE to the next stages of development as the collaboration gets closer to making this project a reality."

Ana María Cetto

On 18 March, Ana María Cetto was awarded the 2025 John Torrence Tate Medal for International Leadership in Physics. She is recognised for "outstanding contributions to the promotion of science, and scientific outreach and cooperation worldwide, including transforming open access through Latindex,

championing gender equity through the Organization for Women in Science for the Developing World, and advancing peaceful progress through science including at the International Atomic Energy Agency and in other international fora."

Big-four breakthrough

In April, the ALICE, ATLAS, CMS and LHCb collaborations were awarded the Breakthrough Prize in Fundamental Physics. The collaborations were recognised for their "detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter–antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider". The collaborations have dedicated their $3 million prize to grants for doctoral students under the auspices of the CERN & Society Foundation.

Heinemann to head DESY

As of April, Beate Heinemann succeeds Helmut Dosch as the chairperson of DESY's board of directors, becoming the first woman to head the German research centre. Her varied career encompasses the H1 experiment at DESY's HERA collider, the CDF experiment at Fermilab's Tevatron, and the ATLAS experiment at CERN's LHC, where she served as deputy spokesperson from 2013 to 2017. In 2018, she initiated the LUXE experiment to explore strong-field quantum electrodynamics at the European XFEL, leading the collaboration until 2023. She served as DESY's director of particle physics from 2022 to her appointment as chair.
● Beate Heinemann is interviewed on p41.

Collide Copenhagen

Polish artist Martyna Marciniak has been awarded the third Collide Copenhagen residency, organised by Arts at CERN in partnership with Copenhagen Contemporary. Marciniak's project will examine

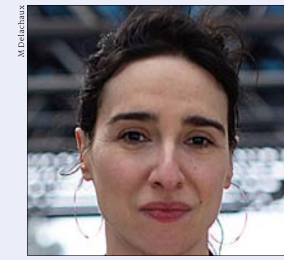
how micro-temporal events, such as a muon's lifespan, reveal connections between human systems and cosmic phenomena.

Wu-Ki Tung Award

ATLAS's Francesco Giuli (University of Rome Tor Vergata) has been awarded the Wu-Ki Tung Award for Early-Career Research on Quantum Chromodynamics. He is cited "for important contributions to the determination of parton distribution functions through a better understanding of the complex issues of experimental systematic uncertainties."

New head of Arts at CERN

Giulia Bini has been appointed curator of Arts at CERN, succeeding Mónica Bello (*CERN Courier* March/April



2025 p41). Bini is the founding head and curator of Enter the Hyper-Scientific, the artist-in-residence programme at EPFL. "I am eager to immerse myself in CERN's extraordinary research and to continue fostering dialogue between artists and the Laboratory's scientific community, brought together by a common drive to explore the frontiers of our understanding."

Alfvén Prize for Keonig

Michel Koenig (Laboratoire pour l'Utilisation des Lasers Intenses) has been awarded the 2025 Hanness Alfvén Prize by the European Physical Society for his outstanding and continuous contributions to bridging the gap between theoretical models and practical applications in fusion energy and astrophysical phenomena through the experimental study of laser–plasma interactions.

Max Planck medal

Reinhard Werner (Leibniz Universität Hannover) was awarded the 2025 Max Planck Medal by the German Physical Society in recognition of his fundamental theoretical contributions to quantum entanglement, quantum nonlocality and quantum information science. Werner's early investigations into quantum structures played a crucial role in the rapid advancement of quantum information theory. His 1989 paper introduced Werner states, foundational in the field.

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PEOPLE OBITUARIES

Walter Oelert 1942–2024

Antimatter experimentalist

Walter Oelert, founding spokesperson of COSY-11 and an experimentalist of rare foresight in the study of antimatter, passed away on 25 November 2024.

Walter was born in Dortmund on 14 July 1942. He studied physics in Hamburg and Heidelberg, achieving his diploma on solid-state detectors in 1969 and his doctoral thesis on transfer reactions on samarium isotopes in 1973. He spent the years from 1973 to 1975 working on transfer reactions of rare-earth elements as a postdoc in Pittsburgh under Bernie Cohen, after which he continued his nuclear-physics experiments at the Jülich cyclotron.

With the decision to build the "Cooler Synchrotron" (COSY) at Forschungszentrum Jülich (FZJ), he terminated his work on transfer reactions, summarised it in a review article, and switched to the field of medium-energy physics. At the end of 1985 he conducted a research stay at CERN, contributing to the PS185 and the JETSET (PS202) experiments at the antiproton storage ring LEAR, while also collaborating with Swedish partners at the CELSIUS synchrotron in Uppsala. In 1986 he habilitated at Ruhr University Bochum, where he was granted an APL professorship in 1996.

With the experience gained at CERN, Oelert proposed the construction of the international COSY-11 experiment as spokesperson, leading the way on studies of threshold production with full acceptance for the reaction products. From first data in 1996, COSY-11 operated successfully for 11 years, producing important results in several meson-production channels.

Walter Oelert led the team that obtained the first antimatter atoms.

At CERN, Walter proposed the production of antihydrogen in the interaction of the antiproton beam with a xenon cluster target – the last experiment before the shutdown of LEAR. The experiment was performed in 1995, resulting in the production of nine antihydrogen atoms. This result was an important factor in the decision by CERN management to build the antiproton-decelerator (AD). In order to continue antihydrogen studies, he received substantial support from Jülich for a partnership in the new ATRAP experiment aiming for CPT violation studies in antihydrogen spectroscopy.

Walter retired in 2008, but kept active in antiproton activities at the AD for more than 10 years, during which time he was affiliated with the Johannes Gutenberg University of Mainz. He was one of the main driving forces on the way to the extra-low-energy antiproton ring (ELENA), which was finally built within time and financial constraints, and drastically improved the performance of the antimatter experiments. He also received a number of honours, notably the Merentibus Medal of the Jagiellonian University of Kraków, and was elected as an external member of the Polish Academy of Arts and Sciences.

Walter's personality – driven, competent, visionary, inspiring, open minded and caring – was the type of glue that made proactive, successful and happy collaborations.

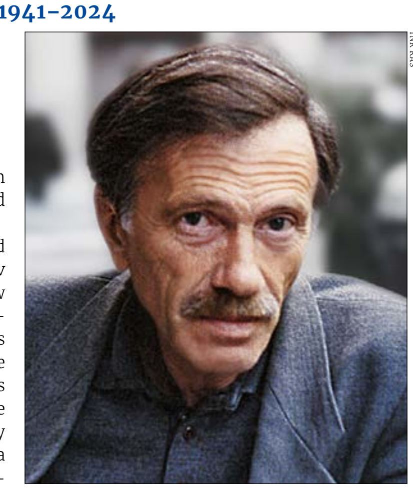
Kurt Kilian *and* **Dieter Grzonka** *FZJ and* **Stefan Ulmer** *HHU Düsseldorf.*

Grigory Vladimirovich Domogatsky 1941–2024

Artistry with neutrinos

Grigory Vladimirovich Domogatsky, spokesman of the Baikal Neutrino Telescope project, passed away on 17 December 2024 at the age of 83.

Born in Moscow in 1941, Domogatsky obtained his PhD in 1970 from Moscow Lomonosov University and then worked at the Moscow Lebedev Institute. There, he studied the processes of the interaction of low-energy neutrinos with matter and neutrino emission during the gravitational collapse of stars. His work was essential for defining the scientific programme of the Baksan Neutrino Observatory. Already at that time, he had put forward the idea of a network of underground detectors to register neutrinos from supernovae, a programme realised decades later by the current SuperNova



Grigory Domogatsky was seen as the father figure of the Baikal Neutrino Telescope project.

He shaped the image of the INR RAS and the field of neutrino astronomy

Early Warning System, SNEWS. Together with his co-author Dmitry Nadyozhin, he showed that neutrinos released in star collapses are drivers in the formation of isotopes such as Li-7, Be-8 and B-11 in the supernova shell, and that these processes play an important role in cosmic nucleosynthesis.

In 1980 Domogatsky obtained his doctor of science (equivalent to the Western habilitation) and in the same year became the head of the newly founded Laboratory of Neutrino Astrophysics at High Energies at the Institute for Nuclear Research of the Russian Academy of Sciences, INR RAS. The central goal of this laboratory was, and is, the construction ▷

of an underwater neutrino telescope in Lake Baikal, a task to which he devoted all his life from that point on. He created a team of enthusiastic young experimentalists, starting site explorations in the following year and obtaining first physics results with test configurations later in the 1980s. At the end of the 1980s, the plan for a neutrino telescope comprising about 200 photomultipliers (NT200) was born, and realised together with German collaborators in the 1990s. The economic crisis following the breakdown of the Soviet Union would surely have ended the project if not for Domogatsky's unshakable will and strong leadership. With the partial configuration of the project deployed in 1994, first neutrino candidates were identified in 1996: the proof of concept for underwater neutrino telescopes had been delivered.

NT200 was shut down a decade ago, by which time a new cubic-kilometre telescope in Lake Baikal was already under construction. This project was christened Baikal–GVD, with GVD standing for gigaton volume telescope, though these letters could equally well denote Domogatsky's initials. Thus far it has reached about half of the size of the IceCube neutrino telescope at the South Pole.

Domogatsky was born to a family of artists and was surrounded by an artistic atmosphere whilst growing up. His grandfather was a famous sculptor, his father a painter, woodcrafter and book illustrator. His brother followed in his father's footsteps, while Grigory himself married Svetlana, an art historian. He possessed an outstanding literary, historical and artistic education, and all who met him were struck by his knowledge, his old-fashioned noblesse and his intellectual charm.

Domogatsky was a corresponding member of the Russian Academy of Sciences and the recipient of many prestigious awards, most notably the Bruno Pontecorvo Prize and the Pavel Cherenkov Prize. With his leadership in the Baikal project, Grigory Domogatsky shaped the scientific image of the INR RAS and the field of neutrino astronomy. He will be remembered as a carefully weighing scientist, as a person of incredible stamina, and as the unforgettable father figure of the Baikal project.

His friends and colleagues.

ELENA ACCOMANDO 1965–2025

A distinguished collider phenomenologist

Elena Accomando, a distinguished collider phenomenologist, passed away on 7 January 2025.

Elena received her laurea in physics from the Sapienza University of Rome in 1993, followed by a PhD from the University of Torino in 1997. Her early career included postdoctoral positions at Texas A&M University and the Paul Scherrer Institute, as well as a staff position at the University of Torino. In 2009 she joined the University of Southampton as a lecturer, earning promotions to associate professor in 2018 and professor in 2022.

Elena Accomando was greatly admired as a scientist, teacher and mentor.

She authored the WPHACT Monte Carlo event generator that remains a valuable tool for precision studies

Elena's research focused on the theory and phenomenology of particle physics at colliders, searching for new forces and exotic supersymmetric particles at the Large Hadron Collider. She explored a wide range of Beyond the Standard Model (BSM) scenarios at current and future colliders. Her work included studies of new gauge bosons such as the Z′, extra-dimensional models, and CP-violating effects in BSM frameworks, as well as dark-matter scattering on nuclei and quantum corrections to vector-boson scattering. She was also one of the authors of "WPHACT", a Monte Carlo event generator developed for four-fermion physics at electron–positron colliders, which remains a valuable tool for precision studies. Elena investigated novel signatures in decays of the Higgs boson, aiming to uncover deviations from Standard Model expectations, and was drawn for connecting theory with experimental applications, proposing phenomenological strategies that were both realistic and impactful. She was well known as a research collaborator at CERN and other international institutions.

Elena played an integral role in shaping the academic community at Southampton and was greatly admired as a teacher. Her remarkable professional achievements were paralleled by strength and optimism in the face of adversity. Despite her long illness, she remained a positive presence, planning ahead for her work and her family. Her colleagues and students remember her as a brilliant scientist, an inspiring mentor and a warm and compassionate person. She will also be missed by her longstanding colleagues from the CMS collaboration at Rutherford Appleton Laboratory.

Elena is survived by her devoted husband, Francesco, and their two daughters.

Alexander Belyaev *and* **Nick Evans** *University of Southampton.*

SHOROKU OHNUMA 1928–2024

Significant contributions to accelerator physics

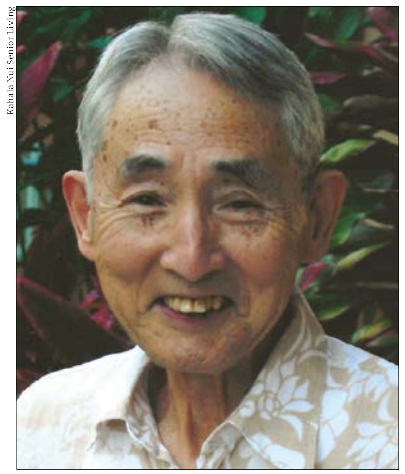
Shoroku Ohnuma, who made significant contributions to accelerator physics in the US and Japan, passed away on 4 February 2024, at the age of 95.

Born on 19 April 1928, in Akita Prefecture, Japan, Ohnuma graduated from the University of Tokyo's Physics Department in 1950. After studying with Yoichiro Nambu at Osaka University, he came to the US as a Fulbright scholar in 1953, obtaining his doctorate from the University of Rochester in 1956. He maintained a lifelong friendship with neutrino astrophysicist Masatoshi Koshiba, who received his degree from Rochester in the same period. A photo published in the Japanese national newspaper *Asahi Shimbun* shows him with Koshiba, Richard Feynman and Nambu when the latter won the Nobel Prize in Physics – Ohnuma would often joke that he was the only one pictured who did *not* win a Nobel.

Ohnuma reviewed accelerator designs and educated students and young researchers in the US and Japan

Ohnuma spent three years doing research at Yale University before returning to Japan to teach at Waseda University. In 1962 he returned to the US with his wife and infant daughter Keiko to work on linear accelerators at Yale. In 1970 he joined the Fermi National Accelerator Laboratory (FNAL), where he contributed significantly to the completion of the Tevatron before moving to the University of Houston in 1986, where he worked on the Superconducting Super Collider (SSC). While he claimed to have moved to Texas because his work at FNAL was done, he must have had high hopes for the SSC, which the first Bush administration slated to be built in Dallas in 1989. Young researchers who worked with him, including me, made up an energetic but inexperienced working team of accelerator researchers. With many FNAL-linked people such as Helen Edwards in the leadership of SSC, we frequently invited professor Ohnuma to Dallas to review the overall design. He was a mentor to me for more than 35 years after our work together at the Texas Accelerator Center in 1988.

Kahala Nui Senior Living



Shoroku Ohnuma had considerable tenacity and dedication in whatever he undertook.

After Congress cancelled the SSC in 1993, Ohnuma continued his research at the University of Houston until 1999. Starting in the late 1990s, he visited the JHF, later J-PARC, accelerator group led by Yoshiharu Mori at the University of Tokyo's Institute for Nuclear Study almost every year. As a member of JHF's first International Advisory Committee, he reviewed the accelerator design and educated students and young researchers, whom he considered his grandchildren. Indeed, his guidance had grown gentler and more grandfatherly.

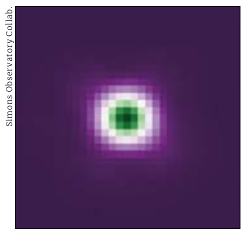
In 2000, in semi-retirement, Ohnuma settled at the University of Hawaii, where he continued to frequent the campus most weekdays until his death. Even after the loss of his wife in 2021, he continued walking every day, taking a bus to the university, doing volunteer work at a senior facility, and visiting the Buddhist temple every Sunday. His interest in Zen Buddhism had grown after retirement, and he resolved to copy the *Heart Sutra* a thousand times on rice paper, with the sumi brush and ink prepared from scratch. We were entertained by his panic at having nearly achieved his goal too soon before his death. The *Heart Sutra* is a foundational text in Zen Buddhism, chanted on every formal occasion. Undertaking to copy it 1000 times exemplified his considerable tenacity and dedication. Whatever he undertook in the way of study, he was unhurried and unworried, optimistic and cheerful, and persistent.

Shinji Machida *Rutherford Appleton Laboratory.*

BACKGROUND

Notes and observations from the high-energy physics community

ACT out, Simons in


Simons Observatory Collab.

On 22 February, the Simons Observatory recorded its first light: an observation of Mars (see image). "This work is the culmination of eight years of effort by dozens of Simons Observatory researchers to make the world's most capable ground-based cosmology telescope," says co-director Mark Devlin of the University of Pennsylvania.

The observatory will study the cosmic microwave background, massive black holes and asteroids. Its 2.4 × 2.6 m large-aperture telescope on the summit of Cerro Toco in the Atacama Desert of northern Chile now joins three small-aperture telescopes at the site, and replaces the now decommissioned Atacama Cosmology Telescope (ACT), which just released its final dataset (https://act.princeton.edu/).

Pierogi in space

In a first for space cuisine, ESA project astronaut and CERN engineer Sławosz Uznański will bring traditional Polish dumplings to the International Space Station during the upcoming Axiom Mission 4. Bonus food catered for specific crew members by chef Mateusz Gessler makes up around 10% of the crew's menu – and the "pierogi" posed a particular engineering challenge. "The first batches kept bursting!" reports Uznański. "It took us a while to master freeze-drying, to remove moisture from the stuffing through the dough and to dispose of the water left after rehydration."

Media corner

"Science management is a bit like herding cats. There are a lot of ideas floating around, but at some point, if you want to build a big project, you have to align people behind it, and you have to push. This is certainly what the FCC community did."

Former CERN Council President **Ursula Bassler** (CNRS) in a *Nature* news feature on community attitudes to the proposed Future Circular Collider (19 March).

"I am a bit worried that the holographic principle has only invited people to be more mysterious because I want the extreme opposite… For me, even quantum mechanics is already too far away from reason."

Gerard 't Hooft on the need for more contrarian thinking in theoretical physics (*Scientific American*, 7 April).

"It's fair to say that this result, taken at face value, appears to be the biggest hint we have about the nature of dark energy in the ~25 years since we discovered it."

Adam Riess (Johns Hopkins University) on suggestions from the Dark Energy Spectroscopic Instrument that dark energy may not be a fixed cosmological constant (*New York Times*, 19 March; see also p11).

"Even if China goes ahead, I hope the decision is to compete. Just like Europe did with the LHC when the US started to build the Superconducting Super Collider."

CERN Council President **Costas Fountas** on the possibility that China could rapidly approve and begin construction on the Circular Election–Positron Collider – a Higgs Factory with a similar design to the proposed Future Circular Collider (*Physics World*, 2 April).

From the archive: June 1985

Abdus Salam on science and development


CERN

Abdus Salam receiving the Lomonosov Gold Medal, the highest annual award of the Academy of the USSR Academy of Sciences, in December 1984.

Despite the recent realisation that science and technology are the sustenance and major hope for economic betterment, the third world has taken to science, as distinct from technology, as only a marginal activity. Policymakers as well as aid-givers speak of the problems of technology transfer, as if that is all that is involved. Very few appear to stress that, for long-term effectiveness, technology transfers must always be accompanied by science transfers, by and to communities of scientists. Further, the high-level scientist must be allowed to play a role in nation building, as an equal partner to the professional planner, economist and technologist.

When Faraday was carrying out his experiments in the 19th century no one could have imagined that the unification of electricity and magnetism would lead to heavy electrical engineering. After Faraday came Maxwell, Hertz, …, leading to radio, television and modern communication systems, as well as X-rays. To see how the climate changed, a hundred years after Maxwell, my colleagues at Harvard, Glashow and Weinberg, and I independently took the next step of postulating a unification of electromagnetism with the weak nuclear force of radioactivity. Even the London '*Economist*' took note and counselled perceptive businessmen not to ignore the likely economic consequences of this new development!

- Text adapted from *CERN Courier* June 1985 pp189–194.

Compiler's note

In today's world, blighted by climate change and war, political leaders, industrialists, educators and indeed all members of society, must be able to recognise misinformation and disinformation and, most of all, to collaborate on solving these existential problems to ensure a sustainable future for life on the planet. Science and technology deal with fact, and multinational research labs propagate collaboration between universities and nations. In the 1980s, Nobel Laureate Leon Lederman, a passionate advocate of education, launched some of the first outreach programmes at Fermilab, initially aimed at pre-college students. Many labs have followed suit.

1/3 **The radius of an LHC-type collider needed to generate a proton with the same energy as the neutrino observed by KM3NeT (p23), in units of the distance to the Moon (Paschal Coyle, CNRS)**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