WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2024 issue of *CERN Courier*.

Uncovering the fundamental laws and constituents of the universe is not just a source of fascination for particle physicists. Engineers, chemists and materials scientists draw similar motivation in meeting the challenging and strange requirements of cutting-edge accelerator and detector technologies. The interdisciplinary materials, metrology and non-destructive testing section at CERN supports projects such as the HL-LHC magnet development with state-of-the-art equipment and analysis, and its services are increasingly in demand from projects outside – including the ITER fusion experiment (p37).

Also explored in depth in this issue are the next steps for the AWAKE plasma-wakefield experiment (p25), the new-physics implications of neutrino masses (p29) and a lesser-known approach to quantum gravity called asymptotic safety (p43). Advanced triggers for the HL-LHC experiments (p8), the selection of the SHiP experiment for CERN's North Area (p7) and DESI's first cosmology results (p11) are among other highlights, along with the latest LHC results (p15), conference reports (p19), news in brief (p13), opinion (p49), reviews (p52), careers (p55) and more.

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DIGITAL EDITION CREATED BY IOP PUBLISHING

CERNCOURIER
Volume 64 Number 3 May/June 2024
IOP Publishing

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J M Ordan/CERN-PHOTO-201910-349-7

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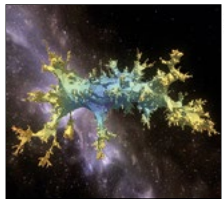
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FROM THE EDITOR

From materials science to quantum gravity

Matthew Chalmers
Editor

Uncovering the fundamental laws and constituents of the universe is not just a source of fascination for particle physicists. Engineers, chemists and materials scientists draw similar motivation in meeting the challenging and strange requirements of cutting-edge accelerator and detector technologies. The interdisciplinary materials, metrology and non-destructive testing section at CERN supports projects such as the HL-LHC magnet development with state-of-the-art equipment and analysis, and its services are increasingly in demand from outside (p37).

Also explored in depth in this issue are the AWAKE experiment (p25), the profound implications of neutrino masses (p29) and a lesser-known approach to quantum gravity called asymptotic safety (p43). Advanced triggers for the HL-LHC (p8), the SHiP experiment (p7) and DESI's first cosmology results (p11) are among other highlights, along with the latest LHC results (p15), conference reports (p19) and news in brief (p13), plus opinion (p49), reviews (p52), careers (p55) and more.

From materials science to quantum gravity, the *Courier* has been capturing developments in global high-energy physics and related fields for 65 years. A de facto journal of record, you might say, that enables readers to keep up with developments beyond their specialist fields in an accessible and hopefully enjoyable way. The magazine has undergone several changes, the most recent in 2019 involving a full print redesign and the launch of a new website and social-media presence. It has also tested the mettle of eight editors. Alas, after eight years and almost 60 issues, it is time to make way for the ninth.

Future colliders, and the impressive progress towards the proposed FCC in particular, have been a recurring topic in these pages

Privileged view

A whirlwind tour of the past eight years would note the astounding growth in the LHC's capabilities, both in terms of performance and experimental precision (p13). Searches for hidden and feebly interacting particles have climbed agendas. More than 50 new hadrons have been discovered. Neutrino and dark-matter experiments have carved out swathes of new parameter space. Antihydrogen spectroscopy has taken off. Deep learning is on the rise and quantum technologies are all the rage. The discovery of gravitational waves has opened new research programmes that further blur the boundaries between particle physics and cosmology (p19).

Gell-Mann, Weinberg, Higgs (p61) and other architects of the Standard Model have left us, but the theory stands as strong as ever. Early LHC Run 2 excitement about 750 GeV blips was dashed. Hints that lepton flavour universality is violated rose and fell. The muon g-2 anomaly persists but its interpretation remains unclear. Neutrino anomalies have been squeezed. The absence of evidence for non-Standard Model particles, yet the existence of several mysteries that require them, has brought healthy disharmony about how to progress to the next level of understanding in fundamental physics. The terrain might be poorly lit, but there is no time for despondency.

Over and out

Future colliders, and the impressive progress towards the proposed Future Circular Collider in particular, have been a recurring topic in these pages. Increasingly, so have calls for greater unity and better communication within the community regarding the field's future. The *Courier* offers a professional, informal forum in which to explore and debate such weighty matters, which the next European strategy update is about to bring into sharp focus (p8). This relies on the continued efforts of individuals to take precious time out of their routines to get in touch with news and views.

Another pillar of the *Courier* to be guarded closely is its editorial independence from CERN's organisational hierarchy: supported by a seasoned advisory board, the editor's decision is final. Among the changes made to the magazine in 2019 was the introduction of this page, allowing the editor to bring context to the articles in each issue. It's now over to former deputy editor Mark Rayner to embrace global high-energy physics in all its shapes, sizes and wonder.

Reporting on international high-energy physics

CERN Courier is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

IOP Publishing

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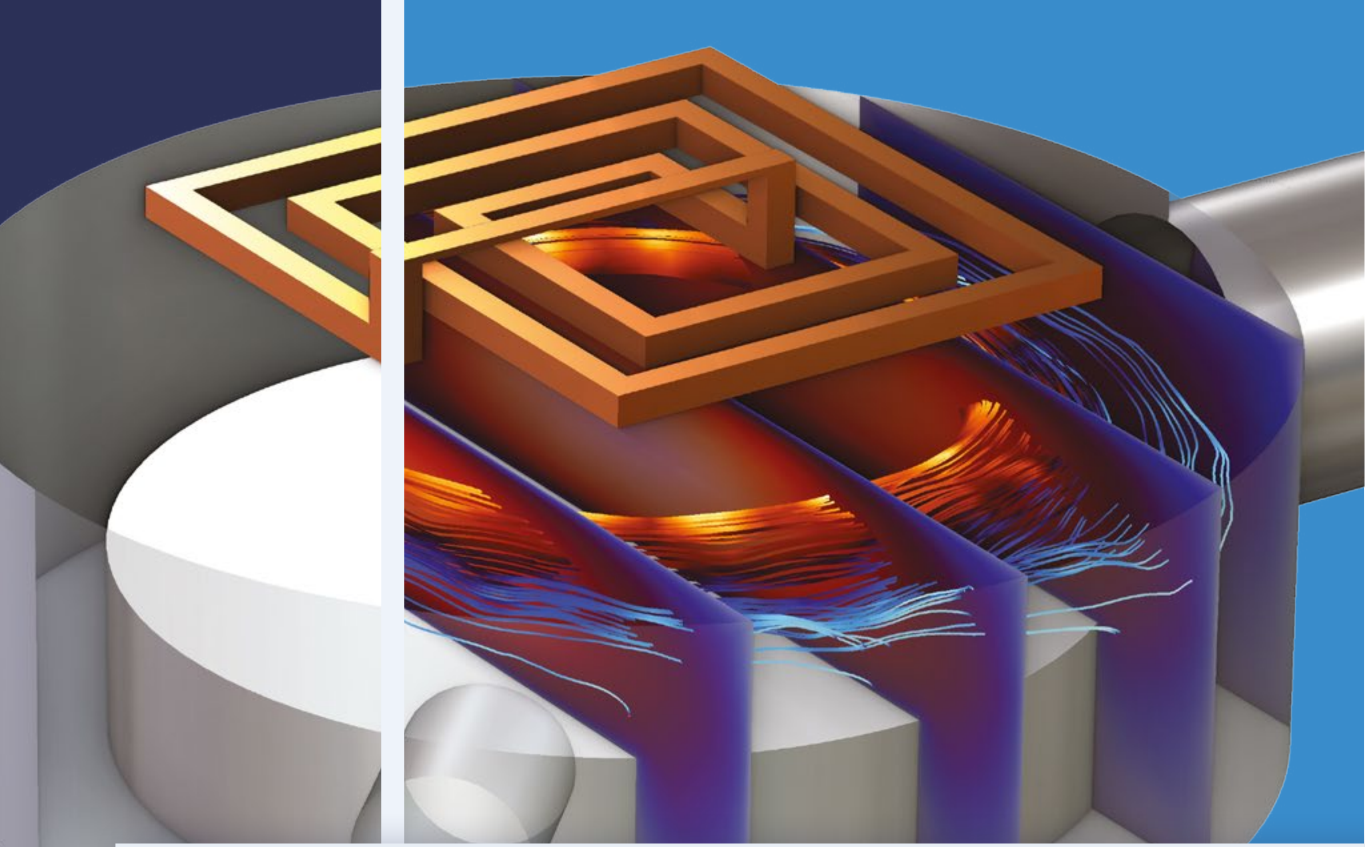
General distribution
Courrier Adressage, CERN, 1211 Geneva 23, Switzerland; e-mail courrier-adressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

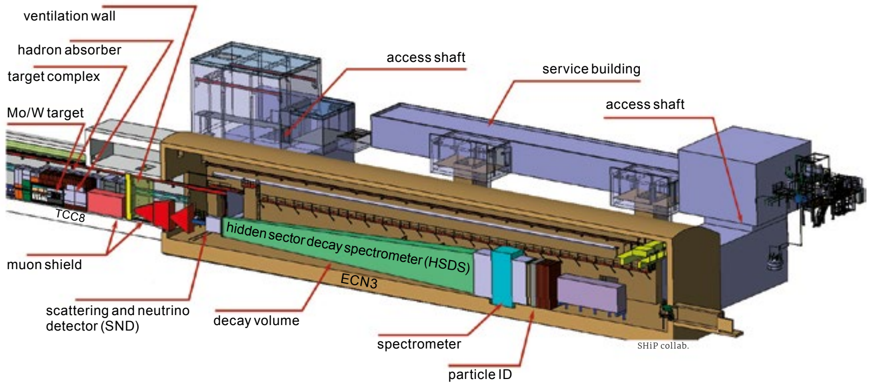
ISSN 0304-288X



NEWS ANALYSIS

NORTH AREA

SHiP to chart hidden sector



Full speed ahead *Layout of the SHiP experiment, with the target on the left and the experiment in the ECN3 hall.*

In March, CERN selected a new experiment called SHiP to search for hidden particles using high-intensity proton beams from the SPS. First proposed in 2013, SHiP is scheduled to operate in the North Area's ECN3 hall from 2031, where it will enable searches for new physics at the "coupling frontier" complementary to those at high-energy and precision-flavour experiments.

Interest in hidden sectors has grown in recent years, given the absence of evidence for non-Standard Model particles at the LHC, yet the existence of several phenomena (such as dark matter, neutrino masses and the cosmic baryon asymmetry) that require new particles or interactions. It is possible that the reason why such particles have not been seen is not that they are too heavy but that they are light and extremely feebly interacting. With such small couplings and mixings, and thus long lifetimes, hidden particles are extremely difficult to constrain. Operating in a beam-dump configuration that will produce copious quantities of photons and charm and beauty hadrons, SHiP will generically explore hidden-sector particles in the MeV to multiple-GeV mass range.

Optimised searching

SHiP is designed to search for signatures of models with hidden-sector particles, which include heavy neutral leptons, dark photons and dark scalars, by full reconstruction and particle identification of Standard Model final states. It will also search for light-dark-matter scattering signatures via the direct detection of atomic-electron or nuclear recoils in a high-density medium, and is optimised to make measurements of tau neutrinos and of neutrino-induced charm production by all three neutrinos species.

The experiment will be built in the existing TCC8/ECN3 experimental facility in the North Area. The beam-dump setup consists of a high-density proton target located in the target bunker, followed by a hadron stopper and a muon shield. Sharing the SPS beam time with other fixed-target experiments and the LHC should allow around 6×10^{20} protons on target to be produced during 15 years of nominal operation. The detector itself consists of two parts that are designed to be sensitive to as many physics models and final states as possible. The scattering and neutrino detector will search for light dark matter and perform neutrino measurements. Further downstream is the much larger hidden-sector decay spectrometer, which is designed to reconstruct the decay vertex of a hidden-sector particle, measure its mass and provide particle identification of the decay products in an extremely low-background environment.

One of the most critical and challenging components of the facility is the proton target

One of the most critical and challenging components of the facility is the proton target, which has to sustain an energy of 2.6 MJ impinging on it every 7.2 s. Another is the muon shield. To control the beam-induced background from muons, the flux in the detector acceptance must be reduced by some six orders of magnitude over the shortest possible distance, for which an active muon shield entirely based on magnetic deflection has been developed.

The focus of the SHiP collaboration now is to produce technical design reports. "Given adequate funding, we believe that the TDR phase for BDF/SHiP will take us about three years, followed by production and construction, with the aim to commission the facility towards the end of 2030 and the detector in 2031," says SHiP spokesperson Andrey Golutvin of Imperial College London. "This will allow up to two years of data-taking during Run 4, before the start of Long Shutdown 4, which would be the obvious opportunity to improve or consolidate, if necessary, following the experience of the first years of data taking."

The decision to proceed with SHiP concluded a process that took more than a year, involving the Physics Beyond Colliders study group and the SPS and PS experiments committee. Two other experiments, HIKE and SHADOWS, were proposed to exploit the high-intensity beam from the SPS. Continuing the successful tradition of kaon experiments in the ECN3 hall, which currently hosts the NA62 experiment, HIKE (high-intensity kaon experiment) proposed to search for new physics in rare charged and neutral kaon decays while also allowing on-axis searches for hidden particles. For SHADOWS (search for hidden and dark objects with the SPS), which would have taken data concurrently with HIKE when the beamline is operated in beam-dump mode, the focus was low-background searches for off-axis hidden-sector particles in the MeV-GeV region.

"In terms of their science, SHiP and HIKE/SHADOWS were ranked equally by the relevant scientific committees," explains CERN director for research and computing Joachim Mnich. "But a decision had to be made, and SHiP was a strategic choice for CERN."

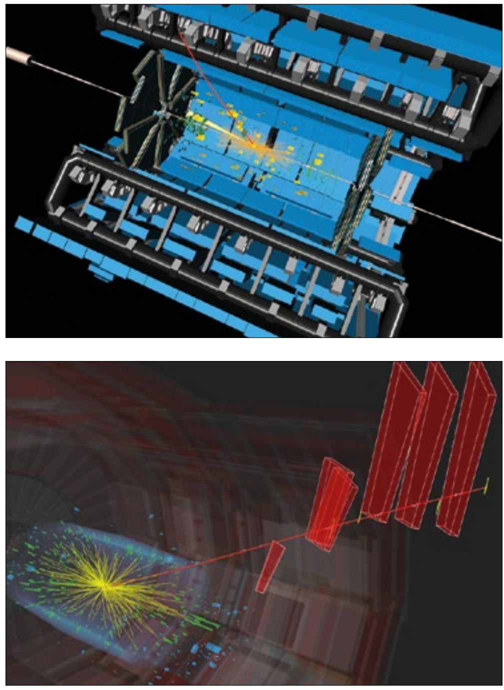
COMPUTING

Next-generation triggers for HL-LHC and beyond

The LHC experiments have surpassed expectations in their ability to squeeze the most out of their large datasets, also demonstrating the wealth of scientific understanding to be gained from improvements to data-acquisition pipelines. Colliding proton bunches at a rate of 40 MHz, the LHC produces a huge quantity of data that must be filtered in real-time to levels that are manageable for offline computing and ensuing physics analysis. When the High-Luminosity LHC (HL-LHC) enters operation from 2029, the data rates and event complexity will further increase significantly.

To meet this challenge, the general-purpose LHC experiments ATLAS and CMS are preparing significant detector upgrades, which include improvements in the online filtering or trigger-selection processes. In view of the importance of this step, the collaborations seek to further enhance their trigger and analysis capabilities, and thus their scientific potential, beyond their currently projected scope.

Following a visit by a group of private donors, in 2023 CERN, in close collaboration with the ATLAS and CMS collaborations, submitted a proposal to the Eric and Wendy Schmidt Fund for Strategic Innovation, which resulted in the award of a $48 million grant. The donation laid the foundations of the Next Generation Triggers project, which kicked off in January 2024. The five-year-long project aims to accelerate novel computing, engineering and scientific ideas for the ATLAS and CMS upgrades, also taking advantage of advanced AI techniques, not only in large-scale data analysis and simulation but also embedded in front-end detector electronics. These include quantum-inspired algorithms to improve simulations, and heterogeneous computing architectures and new strategies to optimise the performance of GPU-accelerated experiment code. The project will also provide insight to detectors and data flows for future projects, such as experiments at the proposed Future Circular Collider, while the associated infrastructure will support the advancement of software and algorithms for simulations that are vital to the HL-LHC and future-collider physics programmes. Through the direct involvement of the CERN experimental physics, information technology and theory departments, it is expected that results from the project will bring benefits across the lab's scientific programme.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CMS-PHO-EVENTS-2024-019-3

On your marks *ATLAS (top) and CMS (above) events recorded at a collision energy of 13.6 TeV on 5 April, marking the beginning of physics data-taking for 2024.*

The Next Generation Triggers project is broken down into four work packages: infrastructure, algorithms and theory (to improve machine learning-assisted simulation and data collection, develop common frameworks and tools, and better leverage available and new computing infrastructures and platforms); enhancing the ATLAS trigger and data acquisition (to focus on improved and accelerated filtering and exotic signature detection); rethinking the CMS real-time data processing (to extend the use of heterogeneous computing to the whole online reconstruction and to design a novel AI-powered real-time processing workflow to analyse every collision); and education programmes and outreach to engage the community, industry and academia in the ambitious goals of the project, foster and train computing skills in the next generation of high-energy physicists, and complement existing successful community programmes with multi-disciplinary subjects across physics, computing science and engineering.

"The Next Generation Triggers project builds upon and further enhances the ambitious trigger and data acquisition upgrades of the ATLAS and CMS experiments to unleash the full scientific potential of the HL-LHC," says ATLAS spokesperson Andreas Hoecker.

"Its work packages also benefit other critical areas of the HL-LHC programme, and the results obtained will be valuable for future particle-physics experiments at the energy frontier," adds Patricia McBride, CMS spokesperson.

CERN will have sole discretion over the implementation of the Next Generation Triggers scientific programme and how the project is delivered overall. In line with its Open Science Policy, CERN also pledges to release all IP generated as part of the project under appropriate open licences.

POLICY

European strategy update

On 21 March the CERN Council decided to launch the process for updating the European strategy for particle physics – the cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the CERN Council, the European strategy is formed through a broad consultation of the particle-physics community and in close coordination with similar processes in the US and Japan, to ensure coordination between regions and optimal use of resources globally.

CERN-HOMEWEB-PHO-2019-118-3

Setting priorities *The third update of the European strategy for particle physics gets under way.*

The deadline for submitting written input for the next strategy update has been set for 31 March 2025, with a view to concluding the process in June 2026. The strategy process is managed by the strategy secretariat, which the Council will establish during its June 2024 session. ▷

The European strategy process was initiated by the CERN Council in 2005, placing the LHC at the top of particle physics' scientific priorities, with a significant luminosity upgrade already being mooted. A ramp-up of R&D for future accelerators also featured high on the priority list, followed by coordination with a potential International Linear Collider and participation in a global neutrino programme.

The first strategy update in 2013, which kept the LHC as a top priority and attached increasing importance to its high-luminosity upgrade, stated that Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next strategy update. The latter charge was formulated in more detail in the second strategy update, completed in 2020, which recommended a Higgs factory as the highest priority to follow the LHC and that a technical and financial feasibility study should be pursued in parallel for a next-generation hadron collider at the highest achievable energy. A mid-term report on the resulting Future Circular Collider feasibility study was submitted for review at the end of 2023 (*CERN Courier* March/April 2024 pp25–38) and the final report, expected in March 2025, will be a key input for the next strategy update.

The final report of the FCC feasibility study will be a key input for the next strategy update

More information about the third update of the European strategy, together with the call for input, will be issued by the strategy secretariat in due course.

NUCLEAR MATTER

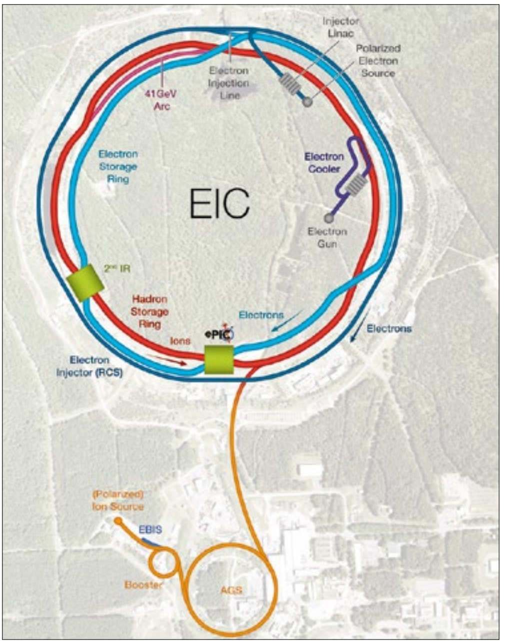
EIC steps towards construction

The Electron–Ion Collider (EIC), located at Brookhaven National Laboratory and being built in partnership with Jefferson Lab, has taken a step closer to construction. In April the US Department of Energy (DOE) approved "Critical Decision 3A", which gives the formal go-ahead to purchase long-lead procurements for the facility.

The EIC will offer the unique ability to collide a beam of polarised high-energy electrons with polarised protons, polarised lightweight ions, or heavy ions. Its aim is to produce 3D snapshots or "nuclear femtography" of the inner structure of nucleons to gain a deeper understanding of how quarks and gluons give rise to properties such as spin and mass (*CERN Courier* October 2018 p31). The collider, which will make use of infrastructure currently used for the Relativistic Heavy Ion Collider and is costed at between $1.7 and 2.8 billion, is scheduled to enter construction in 2026 and to begin operations in the first half of the next decade.

By passing the latest DOE project milestone, the EIC project partners can now start ordering key components for the accelerator, detector and infrastructure. These include superconducting wires and other materials, cryogenic equipment, the experimental solenoid, lead-tungstate crystals and scintillating fibres for detectors, electrical substations and support buildings. "The EIC project can now move forward with the execution of contracts with industrial partners that will significantly reduce project technical and schedule risk," said EIC project director Jim Yeck.

More than 1500 physicists from nearly 300 laboratories and institutes worldwide are members of the EIC user group. Earlier this year the DOE and the CNRS signed a statement of interest concerning the contribution of researchers in France, while the UK announced that it will invest £58.8 million to develop the necessary detector and accelerator technologies.



BNL/T Bowman

Shaping up *A schematic of the future Electron–Ion Collider at Brookhaven National Laboratory.*

FLAVOUR PHYSICS

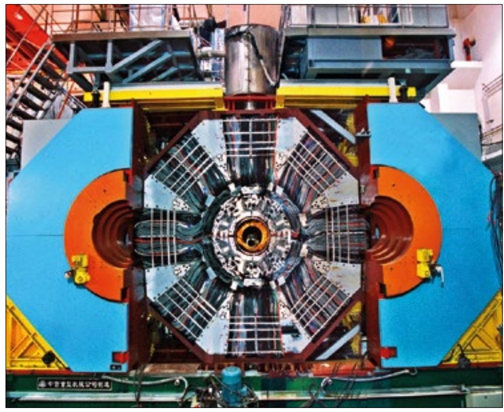
BESIII passes milestone at the charm threshold

The BESIII collaboration has marked a significant milestone: the completion of its 15-year campaign to collect 20 fb^{-1} of e$^+$e$^-$ collision data at the $\psi(3770)$ resonance. The sample, collected in two main running periods, 2010–2011 and 2022–2024, is more than 20 times larger than the world's previous charm-threshold data set collected by the CLEO-c experiment in the US.

BESIII is an experiment situated on the BEPCII storage ring at IHEP in Beijing. It involves more than 600 physicists drawn not only from China but also other nations, including Germany, Italy, Poland, the Netherlands, Sweden and the UK from the CERN member states. The detector has collected data at a range of running points with centre-of-mass energies from 1.8 to 4.95 GeV, most of which are inaccessible to other operating colliders. This energy regime allows researchers to make largely unique studies of physics above and below the charm threshold, and has led to important discoveries and measurements in light-meson spectroscopy, non-perturbative QCD, and charm and tau physics.

The sample is more than 20 times larger than the world's previous charm-threshold data set

The $\psi(3770)$, discovered at SLAC in 1977, is the lightest charmonium state above the open-charm threshold. Charmonium consists of a bound charm quark and anti-charm quark, whereas open-charm states such as D^0 and D$^+$ mesons are systems in which the charm quark co-exists with a different anti-quark. The $\psi(3770)$ can decay into D and anti-D mesons, whereas charmonium states below threshold, such as the J/ψ, are too light to do so, and must instead decay through annihilation of the charm and anticharm quarks. ▷



J Liu

Charming *The BESIII detector at the BEPCII storage ring at IHEP Beijing.*

Open-charm mesons are also produced in copious quantities at the LHC and at Belle II. However, in $\psi(3770)$ decays at BESIII they are produced in pairs, with no accompanying particles. This makes the BESIII sample a uniquely clean laboratory in which to study the properties of D mesons. If one meson is reconstructed, or tagged, in a known charm decay, the other meson in the event can be analysed in an unbiased manner. When reconstructed in a decay of interest, the unbiased sample of mesons can be used to measure absolute branching fractions and the relative phases between any intermediate resonances in the D decay.

"Both sets of information are not only interesting in themselves, but also vital for studies with charm and beauty mesons at LHCb and Belle II," explains Guy Wilkinson of the University of Oxford. "For example, measurements of phase information performed by BESIII with the first tranche of $\psi(3770)$ data have been essential input in the world-leading determination of the CP-violating angle γ of the unitarity triangle by LHCb in events where a beauty meson decays into a D meson and an accompanying kaon." Exploitation of the full $20\,\mathrm{fb}^{-1}$ sample will be essential in helping LHCb and Belle II realise their full potential in CP-violation measurements with larger data sets in the future, he adds. "Hence BESIII is very complementary to the higher energy experiments, demonstrating the strong synergies that exist between particle-physics facilities worldwide."

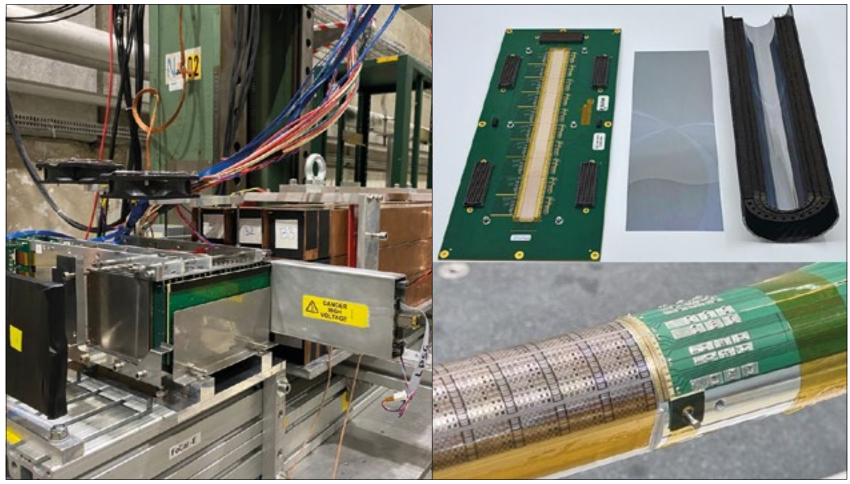
This summer, BEPCII will undergo an upgrade that will increase its luminosity. Over the rest of the decade more data will be taken above and below the charm threshold. In the longer term, there are plans, elsewhere in China, for a Super Tau Charm Facility – an accelerator that would build on the BEPCII and BESIII programme with datasets that are two orders of magnitude larger.

HEAVY-ION PHYSICS

New subdetectors to extend ALICE's reach

The LHC's dedicated heavy-ion experiment, ALICE, is to be equipped with an upgraded inner tracking system and a new forward calorimeter to extend its physics reach. The upgrades have been approved for installation during the next long shutdown from 2026 to 2028.

With $10\,\mathrm{m}^2$ of active silicon and nearly 13 billion pixels, the current ALICE inner tracker, which has been in place since 2021, is the largest pixel detector ever built. It is also the first detector at the LHC to use monolithic active pixel sensors (MAPS) instead of the more traditional hybrid pixels and silicon microstrips. The new inner tracking system, ITS3, uses a novel stitching technology to construct MAPS of $50\,\mu\mathrm{m}$ thickness and up to $26 \times 10\,\mathrm{cm}^2$ in area that can be bent around the beampipe in a truly cylindrical shape. The first layer will be placed just 2 mm from the beampipe and 19 mm from the interaction point, with a much lighter support structure that significantly reduces the material volume and therefore its effect on particle trajectories. Overall, the new system will boost the pointing resolution of the tracks by a factor of two compared to the present ITS detector, strongly enhancing measurements of thermal radiation emitted by the quark–gluon plasma and enabling insights into the interactions of charm and beauty quarks as they propagate through it.



ALICE

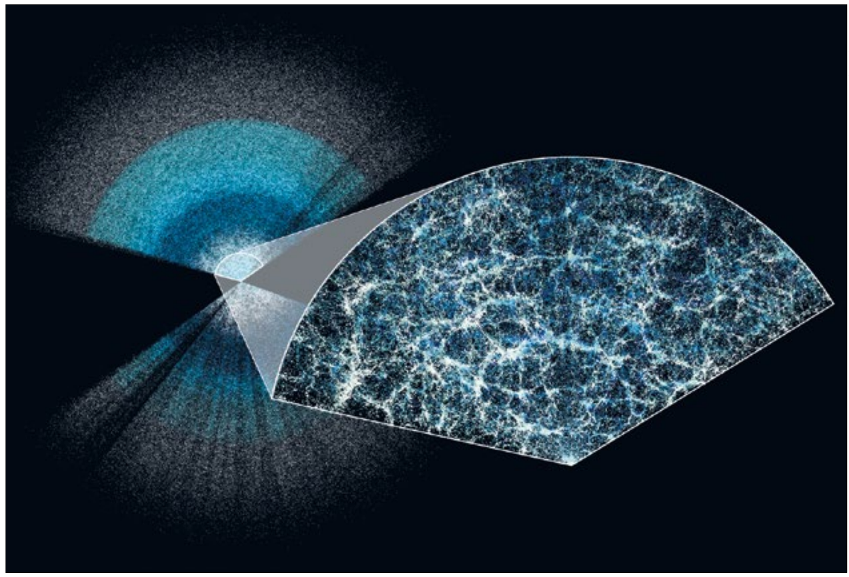
Upgrade ahead *ALICE's new forward calorimeter (left) and the components of the Inner Tracker System 3.*

The new forward calorimeter, FoCal, is optimised for photon detection in the forward direction. It consists of a highly granular electromagnetic calorimeter, composed of 18 layers of $1 \times 1\,\mathrm{cm}^2$ silicon-pad sensors paired with tungsten converter plates and two additional layers of $30 \times 30\,\mu\mathrm{m}^2$ pixels, and a hadronic calorimeter made of copper capillary tubes and scintillating fibres. By measuring inclusive photons and their correlations with neutral mesons, as well as the production of jets and charmonia, FoCal will add new capabilities to explore the small Bjorken-x parton structure of nucleons and nuclei.

Technical design reports for the ITS3 and FoCal projects were endorsed by the relevant CERN review committees in March. The construction phase has now started, with the detectors due to be installed in early 2028 in order to be ready for data taking in 2029. The upgrades, in particular ITS3, are also an important step on the way to ALICE 3 – a major proposed upgrade of ALICE that, if approved, would enter operation in the mid-2030s.

ASTROWATCH

First DESI results shine a light on Hubble tension



C Lamman/DESI/cmastro

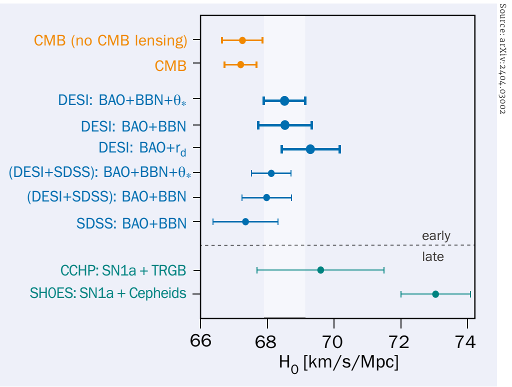
Wide open *DESI's map of the universe is the largest to date, showing delicate bubble-like structures in the distribution of galaxies (inset) that contain clues to the expansion history of the universe.*

The expansion of the universe has been a well-established fact of physics for almost a century. By the turn of the millennium the rate of this expansion, referred to as the Hubble constant (H_0), had converged to a value of around $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. However, more recent measurements have given rise to a tension: whereas those derived from the cosmic microwave background (CMB) cluster around a value of $67\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, direct measurements using a local distance-ladder (such as those based on Cepheids) mostly prefer larger values around $73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This disagreement between early- and late-universe measurements, respectively, stands at the 4–5σ level, thereby calling for novel measurements.

One such source of new information are large galaxy surveys, such as the one currently being performed by the Dark Energy Spectroscopic Instrument (DESI). This Arizona-based instrument uses 5000 individual robots that optimise the focal plane of the detector to allow it to measure 5000 galaxies at the same time. The goal of the survey is to provide a detailed 3D map, which can be used to study the evolution of the universe by focussing on the distance between galaxies. During its first year of observation, the results of which have now been released, DESI has provided a catalogue of millions of objects.

Primordial imprints

Small fluctuations in the density of the early universe resulted not only in signatures in the CMB, as measured for example by the Planck probe, but also left imprints in the distribution of baryonic matter. Each over-dense region is thought to contain dark matter, baryonic matter and photons. The gravitational force from dark matter on the baryons is countered by radiation pressure from the photons. From the small over-densities, baryons are dragged along by photon pressure until these two types of particles decoupled during the recombination era. The original location of the over-density is surrounded by a sphere of baryonic matter, which typically is at a distance referred to as the sound horizon. The sound horizon at the moment of decoupling, denoted r_d, leaves an imprint that has since evolved to produce the density fluctuations in the universe that seeded large-scale structures.



Source: arXiv:2404.03002

Hubble tension *68% credible-interval constraints on the Hubble constant assuming the flat ΛCDM model, showing: DESI baryon acoustic oscillation measurements in combination with other data (blue, bold); corresponding results from the Sloan Digital Sky Survey and combinations thereof (blue); CMB anisotropy measurements from Planck and the Atacama Cosmology Telescope (orange); and measurements using Cepheids or tip-of-the-red-giant branch distance ladders (green).*

This imprint, and how it has evolved over the last 13 billion years, depends on a number of parameters in the standard ΛCDM model of cosmology. Measuring the baryon distribution therefore allows many of the ΛCDM parameters to be constrained. Since the DESI data measure the combination of H_0 and r_d, a direct measurement of H_0 is not possible. However, by using additional data for the sound horizon, taken from CMB measurements and Big Bang nucleosynthesis theory, the team finds values of H_0 that cluster around $67.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (see "Hubble tension" figure). This is consistent with early-universe measurements and differs by more than 3σ from late-universe measurements.

Although these new results do not directly resolve the Hubble tension, they do hint at one potential solution: the need to revise the ΛCDM model. The measurements also allow constraints to be placed on the acceleration of the universe, which depends on the dark-energy equation of state, w. While this is naturally assumed to be constant at $w = -1$, the DESI first-year results better match a time-evolving equation of state. Although highly dependent on the analysis, the DESI data so far provide results that differ from ΛCDM predictions by more than 2.5σ. The data from the remaining four years of the survey are therefore highly anticipated as these will show whether a change to the standard cosmological model is required.

Further reading

DESI Collab. *et al.* 2024 arXiv:2404.03000, 2404.03001 and 2404.03002.

CERNCOURIER

VOLUME 64 NUMBER 3 MAY/JUNE 2024

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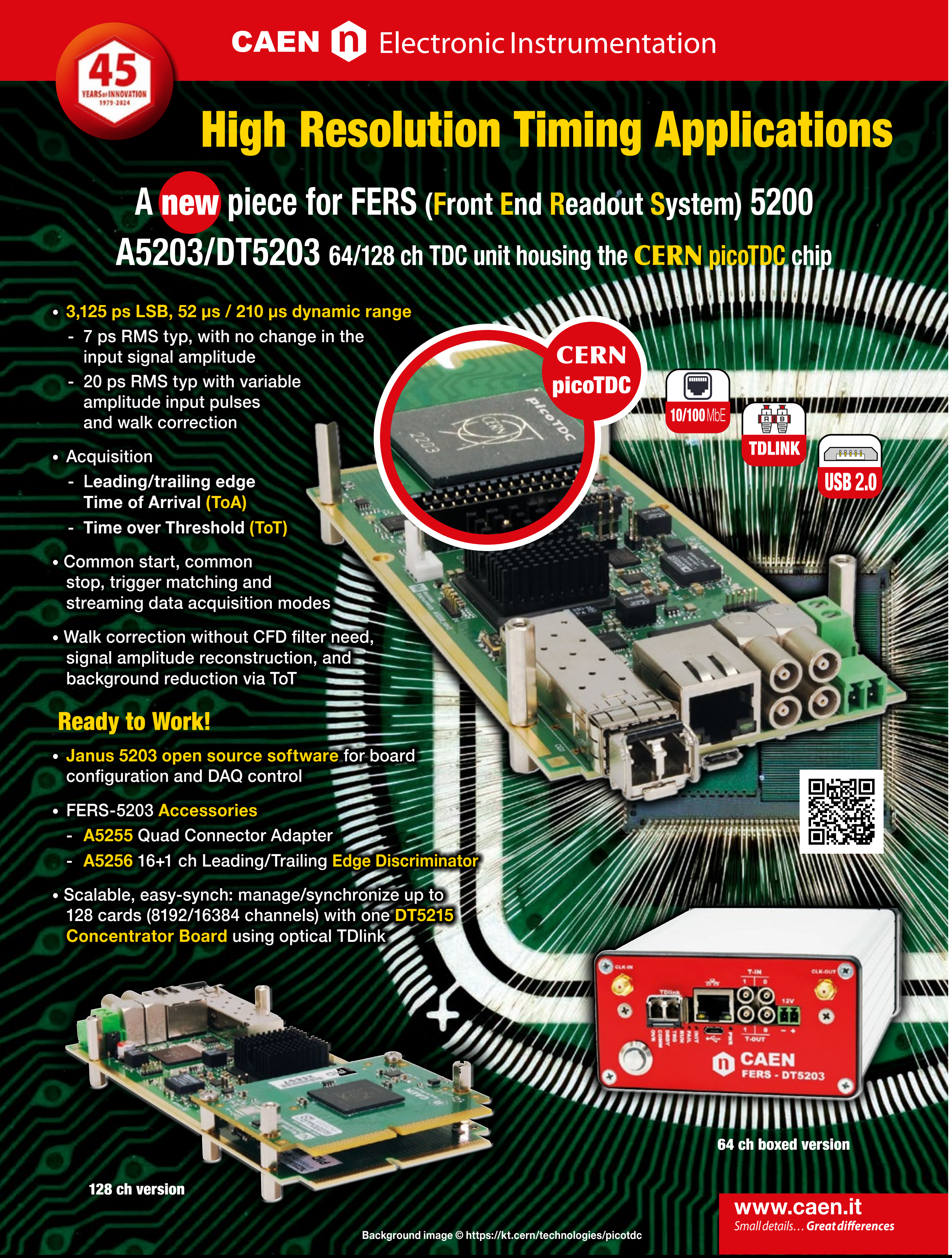


NEWS DIGEST


A bird's eye view of LHAASO.

LHAASO

LHAASO studies cosmic knee

Researchers at the Large High Altitude Air Shower Observatory (LHAASO) in Sichuan Province, China have shed light on the origin of the "knee" in the energy spectrum of cosmic rays – a puzzle that has perplexed researchers for almost seven decades. The spectrum of cosmic rays follows a descending power law that extends from 1 GeV all the way to 100 EeV, with a steeper descent starting at 4 PeV. LHAASO's square kilometre array of 5000 electromagnetic calorimeters and 1000 muon detectors examined the composition of this kink by measuring the energy and mean mass of cosmic-ray showers hitting the detector between 2021 and 2022. The team found that the knee coincides with a shift in the mix of cosmic rays towards lighter elements (*Phys. Rev. Lett.* **132** 131002). Cosmic rays above the knee are thought to originate from outside the galaxy.

CMS measures Weinberg angle

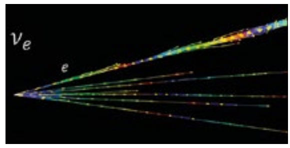
The CMS collaboration has presented the most precise measurement of the effective leptonic electroweak mixing angle yet performed at a hadron collider (CMS-PAS-SMP-22-010). Also known as the Weinberg angle, the electroweak mixing angle mixes the fundamental W^3 and B fields to generate photons and Z bosons in electroweak symmetry breaking, and links the masses of the W and Z bosons. CMS's measurement is effective and leptonic as it includes quantum corrections and is extracted from forward–backward asymmetries in dimuon and dielectron events. Differing measurements at LEP and by the SLD experiment at SLAC have puzzled physicists for more than a decade. "This result shows that precision physics can be carried out at hadron colliders," says CMS spokesperson Patricia McBride.

ATLAS measures W width

Continuing the theme of electroweak precision at hadron colliders, the ATLAS collaboration has released a preprint detailing the first measurement of the width of the W boson at the LHC (arXiv:2403.15085). At 2202 ± 47 MeV, the new measurement is the most precise made by a single experiment to date. The W boson's width had previously been measured at LEP and the Tevatron to be 2085 ± 42 MeV, consistent with the Standard Model prediction of 2088 ± 1 MeV. Deviations could potentially reveal decays into yet-to-be-discovered new particles.

FASER firsts

The FASER collaboration has measured neutrino-interaction cross sections in a previously unprobed energy domain around 1 TeV (arXiv:2403.12520). Eight muon–neutrino candidates and four electron–neutrino candidates were found in a tungsten-emulsion detector placed 480 m forward of the ATLAS collision point at the LHC. Given an expected background of $0.025^{+0.015}_{-0.010}$ electron–neutrino candidates, this constitutes the first direct observation of electron neutrinos at a collider, following FASER's first observation of collider neutrinos last year. Planned upgrades for the High-Luminosity LHC promise substantial increases in sensitivity, says the team (see p20).

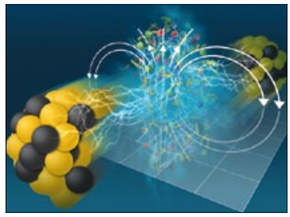


A candidate electron–neutrino interaction in FASERν.

FASER

STAR targets QGP conductivity

Peripheral collisions between heavy ions are thought to produce magnetic fields of order 10^{14} T that dissipate within 10^{-23} seconds. The rapid decay of such ultra-strong magnetic fields should deflect particles and antiparticles in the resulting quark–gluon plasma (QGP) differently, with the magnitude of the collective effect probing the electrical conductivity of this deconfined phase of nuclear matter. The STAR collaboration in February reported evidence for this effect in the motion of final-state particles (*Phys. Rev. X* **14** 011028). The effect was strongest in gold collisions at 27 GeV, but was also observed at 200 GeV in collisions of gold, zirconium and ruthenium ions. The team reports that the data are consistent with the electrical conductivity predicted by lattice-QCD calculations.


Artist's impression of a peripheral collision at RHIC.

BNL

Thorium-reactor investment

Geneva-based startup Transmutex, which counts former CERN physicists on its scientific committee, has received a CHF 21 million injection of funds by two US investment firms, marking a step towards the realisation of accelerator-driven thorium reactors. Though not itself fissile, thorium-232 can be converted to uranium-233 through neutron bombardment; like the uranium-235 present in uranium ore, uranium-233 can then sustain a chain reaction, though generating fewer undesirable waste products, say the team. This process has the potential to reduce the radiotoxicity of long-lived waste from 300,000 years to 300 years, they claim, with reduced risks of proliferation and safety features allowing the reactor to be shut down within two milliseconds. With uranium prices at their highest level since the Fukushima disaster in 2011, thorium's greater abundance also makes the technology more sustainable than traditional reactors.

Fermilab boosts local economy

Fermilab contributed $1.6 billion to the US economy and supported more than 7000 jobs in FY2022, says a new report by the lab. The study models direct economic impacts as well as business-to-business and consumer spending resulting from procurement and employment. Fermilab's home state of Illinois received 33% of the $286 million spent on new contracts. South Dakota received 4% as excavation and engineering activities continued at the Sanford Underground Research Facility, in preparation for the DUNE experiment. Economic output due to DUNE and related projects is expected to peak between 2025 and 2028.

Majorana fermions emerge

In the latest example of fundamental symmetries being unearthed in condensed-matter systems, emergent quasiparticle excitations resembling Majorana fermions may have been observed in a "spin liquid" – in this case, a honeycomb lattice of ruthenium atoms whose magnetic moments cannot arrange themselves into a stable configuration even at low temperatures. The study exploits the thermal Hall effect, whereby a heat current is generated perpendicular to a temperature gradient when an orthogonal magnetic field is applied. Researchers in Japan and Korea claim conclusive evidence that their experiment's current carriers resemble Majorana fermions (*Sci. Adv.* **10** 11).

ENERGY FRONTIERS

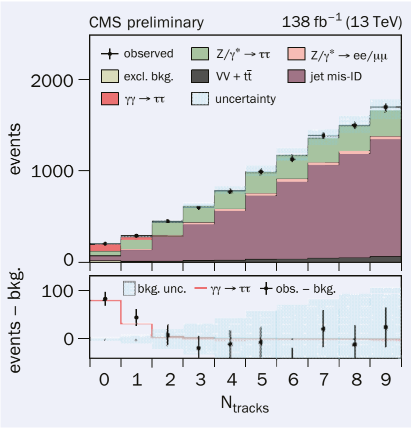
Reports from the Large Hadron Collider experiments

CMS

CMS closes in on tau g–2

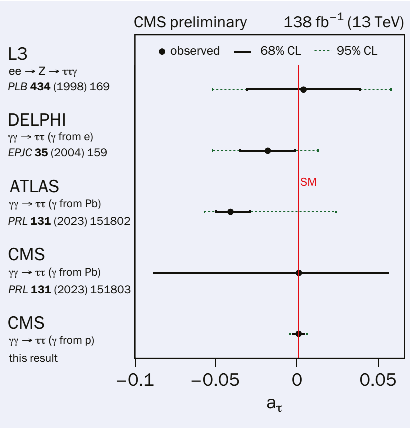
The CMS collaboration has reported the first observation of $\gamma\gamma \to \tau\tau$ in pp collisions. The results set a new benchmark for the tau lepton's magnetic moment, surpassing previous constraints and paving the way for studies probing new physics.

For the tau lepton's less massive cousins, measurements of magnetic moments offer exceptional sensitivity to beyond-the-Standard Model (BSM) physics. In quantum electrodynamics (QED), quantum effects modify the Dirac equation, which predicts a gyromagnetic factor g precisely equal to two. The first-order correction, an effect of only $\alpha/2\pi$, was calculated by Julian Schwinger in 1948. Taking into account higher orders too, the electron anomalous magnetic moment, $a = (g-2)/2$, is one of the most precisely measured quantities in physics and is in remarkable agreement with QED predictions. The g–2 of the muon has also been measured with high precision and shows a persistent discrepancy with certain theoretical predictions. By contrast, however, the tau lepton's g–2 suffers from a lack of precision, given that its short lifetime makes direct measurements very challenging. If new-physics effects scale with the squared lepton mass, deviations from QED predictions in this measurement would be about 280 times larger than in the muon g–2 measurement.



Source: CMS Collab. 2024 CMS-PAS-SMP-23-005

Fig. 1. *Observed and expected distributions of the number of additional tracks within 1 mm of the di-tau vertex. The* $\gamma\gamma \to \tau\tau$ *signal is visible at low multiplicities.*



Source: CMS Collab. 2024 CMS-PAS-SMP-23-005

Fig. 2. *Constraints set by the new CMS result on the anomalous magnetic moment of the tau lepton, in comparison with past measurements.*

Experimental insights on g–2 can be indirectly obtained by measuring the exclusive production of tau-lepton pairs created in photon–photon collisions. As charged particles pass each other at relativistic velocities in the LHC beampipe, they generate intense electromagnetic fields, leading to photon–photon collisions. The production of tau-lepton pairs in photon collisions was first observed by the ATLAS and CMS collaborations in Pb–Pb runs. The CMS collaboration has now observed the same process in proton–proton (pp) data. When photon collisions occur in pp runs, the protons can remain intact. As a result, final-state particles can be produced exclusively, with no other particles coming from the same production vertex.

Separating these low particle multiplicity events from ordinary pp collisions is extremely challenging, as events "pile up" within the same bunch crossing. Thanks to the precise tracking capabilities of the CMS detector, tau-lepton tracks were isolated within just a millimetre around the interaction vertex. Figure 1 shows the resulting excess of $\gamma\gamma \to \tau\tau$ events rising above the estimated backgrounds when few additional tracks were observed within the selected 1mm window.

Tau-lepton tracks were isolated within just a millimetre around the interaction vertex

This process was used to constrain a_τ using an effective-field-theory approach. BSM physics affecting g–2 would modify the expected number of $\gamma\gamma \to \tau\tau$ events, with the effect increasing with the di-tau invariant mass. Compared to Pb–Pb collisions, the pp data sample provides a more precise g–2 value because of the larger number of events and higher invariant masses probed, thanks to the higher energy of the photons. Using the invariant-mass distributions collected in pp collisions during the full LHC Run 2, the CMS collaboration has not observed any statistically significant deviations from the Standard Model. The tightest constraint ever on a_τ was set, as shown in figure 2. The uncertainty is only three times larger than the value of Schwinger's correction.

Further reading

CMS Collab. 2024 CMS-PAS-SMP-23-005.

ATLAS

ATLAS turbocharges event simulation

As the harvest of data from the LHC experiments continues to increase, so does the required number of simulated collisions. This is a resource-intensive task as hundreds of particles must be tracked through complex detector geometries for each simulated physics collision – and Monte Carlo statistics must typically exceed experimental statistics by a factor of 10 or more, to minimise uncertainties when measured distributions are compared with theoretical predictions. To support data taking in Run 3 (2022–2025), the ATLAS collaboration therefore developed, evaluated and deployed a wide array of detailed optimisations to its detector-simulation software.

AtlFast3 offers fast, high-precision physics simulations

The production of simulated data ▷

begins with the generation of particles produced within the LHC's proton–proton or heavy-ion collisions, followed by the simulation of their propagation through the detector and the modelling of the electronics signals from the active detection layers. Considerable computing resources are incurred when hadrons, photons and electrons enter the electromagnetic calorimeters and produce showers with many secondary particles whose trajectories and interactions with the detector material must be computed. The complex accordion geometry of the ATLAS electromagnetic calorimeter makes the Geant4 simulation of the shower development in the calorimeter system particularly compute-intensive, accounting for about 80% of the total simulation time for a typical collision event.

Since computing costs money and consumes electrical power, it is highly desirable to speed up the simulation of collision events without compromising accuracy. For example, considerable CPU resources were previously spent in the transportation of photons and neutrons; this has been mitigated by randomly removing 90% of the photons (neutrons) with energy below 0.5 (2) MeV and scaling up the energy deposited from the remaining 10% of low-energy particles. The simulation of photons in the finely segmented electromagnetic calorimeter took considerable time because the probabilities for each possible interaction process were calculated every time photons crossed a material boundary. That calculation time has been greatly reduced by using a uniform geometry with no photon transport boundaries and by determining the position of simulated interactions using the ratio of the cross sections in the various material layers. The combined effect of the optimisations brings an average speed gain of almost a factor of two.

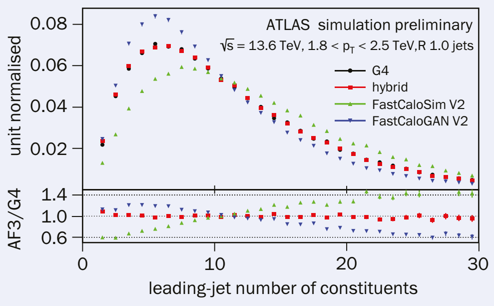


Fig. 1. *The number of constituents of high-p_T reconstructed large-radius jets with the hybrid AtlFast3 configuration, and with the two separate components FastCaloSim and FastCaloGAN. The lower panel shows the ratio with respect to the Geant4 simulation.*

Source: *ATLAS Collab. 2022 Comput. Softw. Big Sci.* **6** 7

ATLAS has also successfully used fast-simulation algorithms to leverage the available computational resources. Fast simulation aims at avoiding the compute-expensive Geant4 simulation of calorimeter showers by using parameterised models that are significantly faster and retain most of the physics performance of the more detailed simulation. However, one of the major limitations of the fast simulation employed by ATLAS during Run 2 was the insufficiently accurate modelling of physics observables such as the detailed description of the substructure of jets reconstructed with large-radius clustering algorithms.

For Run 3, ATLAS has developed a completely redesigned fast simulation toolkit, known as AtlFast3, which performs the simulation of the entire ATLAS detector. While the tracking systems continue to be simulated using Geant4, the energy response in the calorimeters is simulated using a hybrid approach that combines two new tools: FastCaloSim and FastCaloGAN.

FastCaloSim parametrises the longitudinal and lateral development of electromagnetic and hadronic showers, while the simulated energy response from FastCaloGAN is based on generative adversarial neural networks that are trained on pre-simulated Geant4 showers. AtlFast3 effectively combines the strengths of both approaches by selecting the most appropriate algorithm depending on the properties of the shower-initiating particles, tuned to optimise the performance of reconstructed observables, including those exploiting jet substructure. As an example, figure 1 shows that the hybrid AtlFast3 approach models the number of constituents of reconstructed jets as simulated with Geant4 very accurately.

With its significantly improved physics performance and a speedup between a factor of 3 (for Z → ee events) and 15 (for high-p_T di-jet events), AtlFast3 will play a crucial role in delivering high-precision physics simulations of ATLAS for Run 3 and beyond, while meeting the collaboration's budgetary compute constraints.

Further reading

ATLAS Collab. 2022 *Comput. Softw. Big Sci.* **6** 7.

LHCb

LHCb targets rare radiative decay

Rare radiative b-hadron decays are powerful probes of the Standard Model (SM) sensitive to small deviations caused by potential new physics in virtual loops. One such process is the decay of $B_s^0 \to \mu^+\mu^-\gamma$. The dimuon decay of the B_s^0 meson is known to be extremely rare and has been measured with unprecedented precision by LHCb and CMS. While performing this measurement, LHCb also studied the $B_s^0 \to \mu^+\mu^-\gamma$ decay, partially reconstructed due to the missing photon, as a background component of the $B_s^0 \to \mu^+\mu^-$ process and set the first upper limit on its branching fraction to 2.0×10^{-9} at 95% CL (red arrow in figure 1). However, this search was limited to the high-dimuon-mass region, whereas several theoretical extensions of the SM could manifest themselves in lower regions of the dimuon-mass spectrum. Reconstructing the photon is therefore essential to explore the spectrum thoroughly and probe a wide range of physics scenarios.

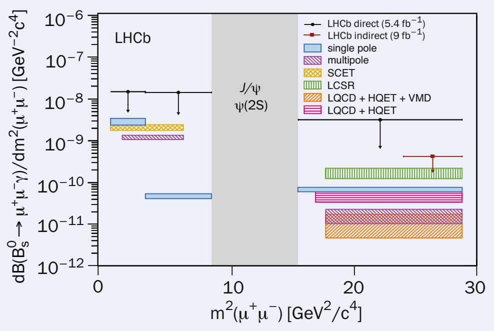


Fig. 1. *95% confidence limits on differential branching fractions for $B_s^0 \to \mu^+\mu^-\gamma$ in intervals of dimuon mass squared (q^2). The shaded boxes illustrate SM predictions for the process, according to different calculations.*

Source: LHCb

The LHCb collaboration now reports the first search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay with a reconstructed photon, exploring the full dimuon mass spectrum. Photon reconstruction poses additional experimental challenges, such as degrading the mass resolution of the B_s^0 candidate and introducing additional background contributions. To cope with this ambitious search, machine-learning algorithms and new variables have been specifically designed with the aim of discriminating the signal among background processes with similar signatures. The analysis ▷ is performed separately for three dimuon mass ranges to exploit any differences along the spectrum, such as the φ(1020) meson contribution in the low invariant mass region. The $\mu^+\mu^-\gamma$ invariant mass distributions of the selected candidates are fitted, including all background contributions and the $B_s^0 \to \mu^+\mu^-\gamma$ signal component. Figure 2 shows the fit for the lowest dimuon mass region.

No significant signal of $B_s^0 \to \mu^+\mu^-\gamma$ is found in any of the three dimuon mass regions, consistent with the background-only hypothesis. Upper bounds on the branching fraction are set and can be seen as the black arrows in figure 1. The mass fit is also performed for the combined candidates of the three dimuon mass regions to set a combined upper limit on the branching fraction to 2.8×10^{-8} at 95% CL.

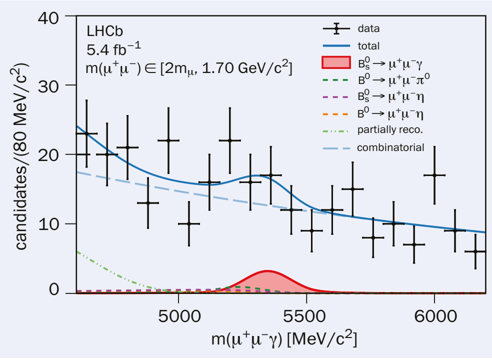


Fig. 2. *Mass distribution of $B_s^0 \to \mu^+\mu^-\gamma$ candidates for the lowest dimuon mass region, below 1.7 GeV/c^2, with the total fit overlaid (blue line). The signal component (solid red line) is displayed with its total uncertainty (red band). The various background contributions are also displayed.*

Source: LHCb Collab 2024 arXiv:2404.03375

The SM theoretical predictions of b decays becomes particularly difficult to calculate when a photon is involved, and they have large uncertainties due to the $B_s^0 \to \gamma$ local form factors. The $B_s^0 \to \mu^+\mu^-\gamma$ decay provides a unique opportunity to validate the different theoretical approaches, which do not agree with each other, as shown by the coloured bands in figure 1. Theoretical calculations of the branching fractions are currently below the experimental limits. The upgraded LHCb detector and the increased luminosity of the LHC's Run 3 is currently providing conditions for studying rare radiative b-hadron decays with greater precision and, eventually, for finding evidence for the $B_s^0 \to \mu^+\mu^-\gamma$ decay.

Further reading

LHCb Collab 2024 arXiv:2404.03375.

ALICE

Shy charm mesons confound predictions

In the past two decades, it has become clear that three-quark baryons and quark–antiquark mesons cannot describe the full spectrum of hadrons. Dozens of exotic states have been observed in the charm sector alone. These states are either interpreted as compact objects with four or five valence quarks or as hadron molecules, however, their inner structures remain uncertain due to the complexity of calculations in quantum chromodynamics (QCD) and the lack of direct experimental measurements of the residual strong interaction between charm and light hadrons. New femtoscopy measurement by the ALICE collaboration challenge theoretical expectations and the current understanding of QCD.

Femtoscopy is a well-established method for studying the strong interactions between hadrons. Experimentally, this is achieved by studying particle pairs with small relative momentum. In high-energy collisions of protons at the LHC, the distance between such hadrons at the time of production is about one femtometre, which is within the range of the strong nuclear force. From the momentum correlations of particle pairs, one extracts the scattering length, a_0, which quantifies the final-state strong interaction between the two hadrons. By studying the momentum correlations of emitted particle pairs, it is possible to access the final-state interactions of even short-lived hadrons such as D mesons.

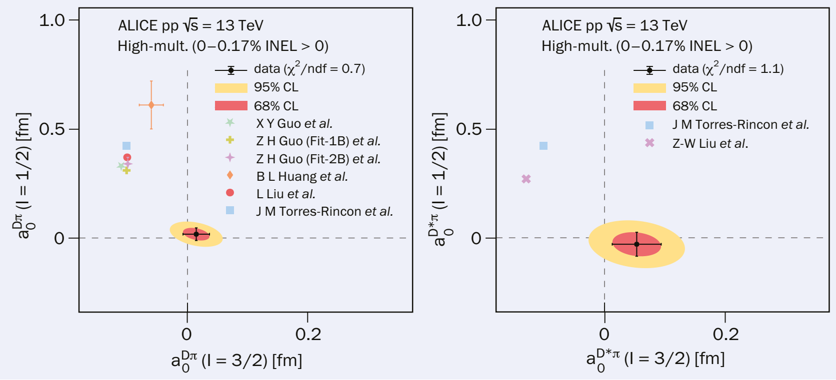


Fig. 1. *Scattering lengths of $D\pi$ (left) and $D^*\pi$ (right) for the two total-isospin configurations $I = 1/2$ and $I = 3/2$. These parameters are extracted via a combined fit to the femtoscopic correlation functions of the same- and opposite-charge pairs. Theoretical predictions are also plotted.*

Source: ALICE Collab. 2024 arXiv:2401.13541

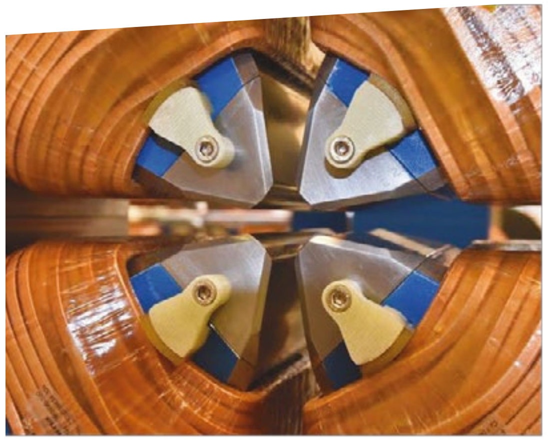
The ALICE collaboration has now, for the first time, measured the interaction of open-charm mesons (D^+ and D^{*+}) with charged pions and kaons for all the charge combinations. The momentum correlation functions of each system were measured in proton–proton collisions in the LHC at a centre-of-mass energy of 13 TeV. As predicted by heavy-quark spin symmetry, the scattering lengths of $D\pi$ and $D^*\pi$ agree with each other, but they are found to be significantly smaller than the theoretical predictions (figure 1). This implies that the interaction between these mesons can be fully explained by the Coulomb force, and the contribution from strong interactions is negligible within experimental precision. The small measured values of the scattering length challenge our understanding of the residual strong force of heavy-flavour hadrons in the non-perturbative limit of QCD.

These results also have an important impact on the study of the quark–gluon plasma (QGP) – a deconfined state of matter created in ultra-relativistic heavy-ion collisions. The rescattering of D mesons with the other hadrons (mostly pions and kaons) created in such collisions was thought to modify the D-meson spectra, in addition to the modification expected from the QGP formation. The present ALICE measurement demonstrates, however, that the effect of rescattering is expected to be very small.

More precise and systematic studies of charm–hadron interactions will be carried out with the upgraded ALICE detector in the upcoming years.

Further reading

ALICE Collab. 2024 arXiv:2401.13541.



FIELD NOTES

Reports from events, conferences and meetings

ULTRA-HIGH-FREQUENCY GRAVITATIONAL WAVES

The inventive pursuit of UHF gravitational waves

Since their first direct detection in 2015, gravitational waves (GWs) have become pivotal in our quest to understand the universe. The ultra-high-frequency (UHF) band offers a window to discover new physics beyond the Standard Model (*CERN Courier* March/April 2022 p22). Unleashing this potential requires theoretical work to investigate possible GW sources and experiments with far greater sensitivities than those achieved today.

A workshop at CERN from 4 to 8 December 2023 leveraged impressive experimental progress in a range of fields. Attended by nearly 100 international scientists – a noteworthy increase from the 40 experts who attended the first workshop at ICTP Trieste in 2019 – the workshop showcased the field's expanded research interest and collaborative efforts. Concretely, about 10 novel detector concepts have been developed since the first workshop.


CERN

Pioneers *Detecting ultra-high-frequency gravitational waves remains a visionary goal.*

One can look for GWs in a few different ways: observing changes in the space between detector components, exciting vibrations in detectors, and converting GWs into electromagnetic radiation in strong magnetic fields. Substantial progress has been made in all three experimental directions.

Levitating concepts

The leading concepts for the first approach involve optically levitated sensors such as high-aspect-ratio sodium–cyttrium–fluoride prisms, and semi-levitated sensors such as thin silicon or silicon–nitride nanomembranes in long optical resonators. These technologies are currently under study by various groups in the Levitated Sensor Detectors collaboration and at DESY.

For the second approach, the main focus is on millimetre-scale quartz cavities similar to those used in precision clocks. A network of such detectors, known as GOLDEN, is being planned, involving collaborations among UC Davis, University College London and Northwestern University. Superconducting radio-frequency cavities also present a promising technology. A joint effort between Fermilab and DESY is leveraging the existing MAGO prototype to gain insights and design further optimised cavities.

The workshop showcased the field's expanded research interest and collaborative efforts

Regarding the third approach, a prominent example is optical high-precision interferometry, combined with a series of accelerator dipole magnets similar to those used in the light-shining-through-a-wall axion-search experiment, ALPS II (Any Light Particle Search II) or the axion helioscope CAST and its planned successor IAXO. In fact, ALPS II is anticipated to commence a dedicated GW search in 2028. Additionally, other notable concepts inspired by axion dark-matter searches involve toroidal magnets, exemplified by experiments like ABRACADABRA, or solenoidal magnets such as BASE or MADMAX.

All three approaches stand to benefit from burgeoning advances in quantum sensing, which promise to enhance sensitivities by orders of magnitude. In this landscape, axion dark-matter searches and UHF GW detection are poised to work in close collaboration, leveraging quantum sensing to achieve unprecedented results. Concepts that demonstrate synergies with axion-physics searches are crucial at this stage, and can be facilitated by incremental investments. Such collaboration builds awareness within the scientific community and presents UHF searches as an additional, compelling science case for their construction.

Cross-disciplinary research is also crucial to understand cosmological sources and constraints on UHF GWs. For the former, our understanding of primordial black holes has significantly matured, transitioning from preliminary estimates to a robust framework. Additional sources, such as parabolic encounters and exotic compact objects, are also gaining clarity. For the latter, the workshop highlighted how strong magnetic fields in the universe, such as those in extragalactic voids and planetary magnetospheres, can help set limits on the conversion between electromagnetic and gravitational waves.

Despite much progress, the sensitivity needed to detect UHF GWs remains a visionary goal, requiring the constant pursuit of inventive new ideas. To aid this, the community is taking steps to be more inclusive. The living review produced after the first workshop (arXiv:2011.12414) will be revised to be more accessible for people outside our community, breaking down detector concepts into fundamental building blocks for easier understanding. Plans are also underway to establish a comprehensive research repository and standardise data formats. These initiatives are crucial for fostering a culture of open innovation and expanding the potential for future breakthroughs in UHF GW research. Finally, a new, fully customisable and flexible GW plotter including the UHF frequency range is being developed to benefit the entire GW community.

The journey towards detecting UHF GWs is just beginning. While current sensitivities are not yet sufficient, the community's commitment to developing innovative ideas is unwavering. With the collective efforts of a dedicated scientific community, the next leap in gravitational-wave research is on the horizon. Limits exist to be surpassed!

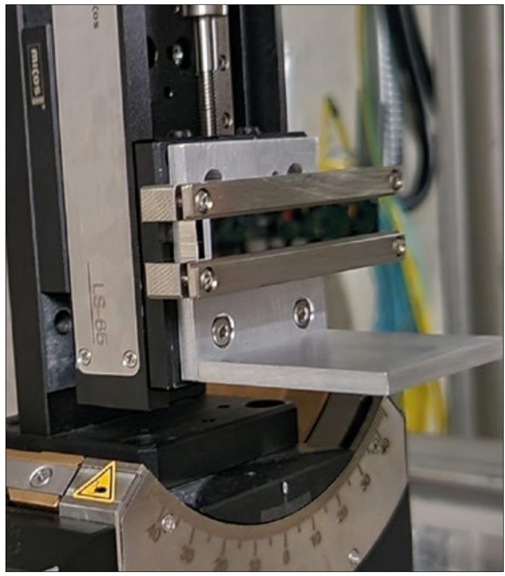
Axel Lindner *DESY*, **Francesco Muia** *University of Cambridge*, **Joachim Kopp** *CERN and Mainz University, and* **Valerie Domcke** *CERN.*

Physics Beyond Colliders

Boosting physics with precision and intensity

The Physics Beyond Colliders (PBC) initiative has diversified the landscape of experiments at CERN by supporting smaller experiments and showcasing their capabilities. Its fifth annual workshop convened around 175 physicists from 25 to 27 March to provide updates on the ongoing projects and to explore new proposals to tackle the open questions of the Standard Model and beyond.

This year, the PBC initiative has significantly strengthened CERN's dark-sector searches, explained Mike Lamont and Joachim Mnich, directors for accelerators and technology, and research and computing, respectively. In particular, the newly approved SHiP proton beam-dump experiment (see p7) will complement the searches for light dark-sector particles that are presently conducted with NA64's versatile setup, which is suitable for electron, positron, muon and hadron beams.


K Dewhurst/CERN

TWOCRYST crystal *A 7 cm-long prototype precession crystal with a bending angle of 7 mrad.*

First-phase success

The FASER and SND experiments, now taking data in the LHC tunnel, are two of the successes of the PBC initiative's first phase. Both search for new physics and study high-energy neutrinos along the LHC collision axis. FASER's successor, FASER2, promises a 10,000-fold increase in sensitivity to beyond-the-Standard Model physics, said Jonathan Feng (UC Irvine). With the potential to detect thousands of TeV-scale neutrinos a day, it could also measure parton distribution functions and thereby enhance the physics reach of the high-luminosity LHC (HL-LHC). FASER2 may form part of the proposed Forward Physics Facility, set to be located 620 m away, along a tangent from the HL-LHC's interaction point 1. A report on the facility's technical infrastructure is scheduled for mid-2024, with a letter of intent foreseen in early 2025. By contrast, the CODEX-b and ANUBIS experiments are being designed to search for feebly interacting particles transverse to LHCb and ATLAS, respectively. In all these endeavours, the Feebly Interacting Particle Physics Centre will act as a hub for exchanges between experiment and theory.

Francesco Terranova (Milano-Bicocca) and Marc Andre Jebramcik (CERN) explained how ENUBET and NuTAG have been combined to optimise a "tagged" neutrino beam for cross-section measurements, where the neutrino flavour is known by studying the decay process of its parent hadron. In the realm of quantum chromodynamics, SPS experiments with lead ions (the new NA60+ experiment) and light ions (NA61/SHINE) are aiming to decode the phases of nuclear matter in the non-perturbative regime. Meanwhile, AMBER is proposing to determine the charge radii of kaons and pions, and to perform meson spectroscopy, in particular with kaons.

New ideas ranged from the measurement of molecular electric dipole moments at ISOLDE to measuring the gravitational field of the LHC beam

The LHCspin collaboration presented a plan to open a new frontier of spin physics at the LHC building upon the successful operation of the SMOG2 gas cell that is upstream of the LHCb detector. Studying collective phenomena at the LHC in this way could probe the structure of the nucleon in a so-far little-explored kinematic domain and make use of new probes such as charm mesons, said Pasquale Di Nezza (INFN Frascati).

Measuring moments

The TWOCRYST collaboration aims to demonstrate the feasibility and the performance of a possible fixed-target experiment in the LHC to measure the electric and magnetic dipole moments (EDMs and MDMs) of charmed baryons, offering a complementary probe of searches for CP violation in the Standard Model. The technique would use two bent crystals: the first to deflect protons from the beam halo onto a target, with the resulting charm baryons then deflected by the second (precession) crystal onto a detector such as LHCb, while at the same time causing their spins to precess in the strong electric and magnetic fields of the deformed crystal lattice, explained Pascal Hermes (CERN).

Several projects to detect axion-like particles were discussed, including a dedicated superconducting cavity for heterodyne detection being jointly developed by PBC and CERN's Quantum Technology Initiative. Atom interferometry is another subject of common interest, with PBC demonstrating the technical feasibility of installing an atom interferometer with a baseline of 100 m in one of the LHC's access shafts. Other new ideas ranged from the measurement of molecular EDMs at ISOLDE to measuring the gravitational field of the LHC beam.

With the continued determination to fully exploit the scientific potential of the CERN accelerator complex and infrastructure for projects that are complementary to high-energy-frontier colliders testified by many fruitful discussions, the annual meeting concluded as a resounding success. The PBC community ended the workshop by thanking co-founder Claude Vallée (CPPM Marseille), who retired as a PBC convener after almost a decade of integral work, and welcomed Gunar Schnell (Ikerbasque and UPV/EHU Bilbao), who will take over as convener.

Kristiane Bernhard-Novotny *CERN.*

Ultra-peripheral collisions 2023

Ultra-peripheral conference debuts in Mexico

Ultra-peripheral collisions (UPCs) involving heavy ions and protons represent the energy frontier for photon-induced reactions. These high-energy photons can be used to study unique features of quarks and gluons inside nuclei, and can probe electromagnetic and electroweak interactions without the usual backgrounds associated with quantum-chromodynamic processes. The first edition of the international workshop on this subject took place from 10 to 15 December 2023 in Playa del Carmen, Mexico, bringing together about 90 participants, more than a third of whom were early-career researchers. This is the first time that the international UPC community has gathered together, establishing a new international conference series on this active and expanding area of research.


M Rennells

Ultra peripheral *The UPC23 conference took place in Playa del Carmen, Mexico.*

The conference highlighted the impressive progress and diversity of UPC physics, which goes far beyond the initial studies of exclusive processes. UPC23 covered the latest results from experiments at RHIC and the LHC, and prospects for the future Electron-Ion Collider (EIC) at Brookhaven National Laboratory. Discussions delved into the intricacies of inelastic photo-nuclear events, including the exciting programme of open charm that is yet to be explored, and examined how UPCs serve as a novel lens for investigating the quark-gluon plasma and other final-state nuclear effects. Lots of attention was devoted to the physics of low-x parton densities – a fundamental aspect of protons and nuclei that photons can probe in a unique way.

Enriched understanding

Among the conference's theoretical highlights, Farid Salazar (UCLA) showed how vector-meson photoproduction could be a powerful method to detect gluon saturation across different collision systems, from proton-nucleus to electron-nucleus to UPCs. Zaki Panjsheeri (Virginia) put forth innovative ideas to study double-parton correlations, linking UPC vector-meson studies to generalised parton distributions, enhancing our understanding of the proton's structure. Ashik Ikbal (Kent State), meanwhile, introduced exciting proposals to investigate quantum entanglement through exclusive J/ψ photoproduction at RHIC.

Delegates discussed the future opportunities for UPC physics with the large integrated luminosity expected for Runs 3 and 4 at the LHC

The conference also provided a platform for discussing the active exploration of light-by-light scattering and two-photon processes for probing fundamental physics and searches for axion-like particles, and for putting constraints on the anomalous magnetic moment of the tau lepton (see p15).

Energy exploration

Physicists at the LHC have effectively repurposed the world's most powerful particle accelerator into a high-energy photon collider. This innovative approach, traditionally the domain of electron beams in colliders like LEP and HERA, and anticipated at the EIC, allows the LHC to explore photon-induced interactions at energies never before achieved. David Grund (Czech Technical University in Prague), Georgios Krintiras (Kansas) and Cesar Luiz Da Silva (Los Alamos) shared the latest LHC findings on the energy dependence of UPC J/ψ events. These results are crucial for understanding the onset of gluon saturation – a state where gluons become so dense reaching saturation, the dynamical equilibrium where the emission and recombination occurs. However, the data also align with the nuclear phenomenon known as gluon shadowing, which arises from multiple-scattering processes. David Tlusty (Creighton) presented the latest findings from the STAR Collaboration, which has recently expanded its UPC programme, complementing the energy exploration at the LHC.

Carlos Bertulani (Texas A&M) paid tribute to Gerhard Baur, who passed away on June 16 last year. Bertulani and Baur co-authored "Electromagnetic processes in relativistic heavy ion collisions" – a seminal paper with more than 1000 citations. Bertulani invited delegates to consider the untapped potential of UPCs in the study of anti-atoms and exotic atoms.

Delegates also discussed the future opportunities for UPC physics with the large integrated luminosity expected for Run 3 and Run 4 at the LHC, with the planned detector upgrades for Run 4 such as FoCal, the recent upgrades by STAR, the sPHENIX programme and at the EIC. Delegates are expecting event selection and instrumentation close to the beam line, for example using "zero degree" calorimeters, to offer the greatest experimental opportunities in the coming years.

The next edition of the UPC conference will take place in Saariselka, Finland in June 2025.

Daniel Tapia Takaki *The University of Kansas.*

Herwig Schopper – a century in physics

CERN celebrates 100 years of science and diplomacy

Since his birth in Bohemia in 1924, Herwig Schopper has been a prisoner of war, an experimentalist with pioneering contributions in nuclear, accelerator and detector physics, director general (DG) of DESY and then CERN during a golden age for particle physics, and a celebrated science diplomat. Shortly after his centenary, his colleagues, family and friends gathered on 1 March to celebrate the life of the first DG in either institution to reach 100.

"He is a restless person," noted Albrecht Wagner (DESY), who presented a whistlestop tour of Schopper's 35 years working in Germany, following his childhood in Bohemia. Whether in Hamburg, Erlangen, Mainz or Karlsruhe, he never missed out on an opportunity to see new places – though always maintaining the Austrian diet to which his children attribute his longevity. On one occasion, Schopper took a sabbatical to work with Lise Meitner in Stockholm's Royal Institute of Technology. At the time, the great physicist was performing the first nuclear-physics studies in the keV range, said Wagner, and directed Schopper to measure the absorption rate of beta-decay electrons in various materials using radioactive sources and a Geiger–Müller counter. Schopper is one of the last surviving physicists to have worked with her, observed Wagner.

Schopper's scientific contributions have included playing a major part in the world's first polarised proton source, Europe's first R&D programme for superconducting accelerators and the development of hadronic calorimeters as precision instruments, explained Christian Fabjan (TU Vienna/HEPHY). Schopper dubbed the latter the sampling total absorption calorimeter, or STAC, playing on the detector's stacked design, but the name didn't stick. In recognition of his contributions, hadronic calorimeters might now be renamed Schopper total absorption calorimeters, joked Fabjan.

As CERN DG from 1981 to 1988, Schopper oversaw the lion's share of the construction of the LEP, before it began operations in July 1989. To accomplish this, he didn't shy away from risks, budget cuts or unpopular opinions when the situation called for it, said Chris Llewellyn Smith, who would himself serve as DG from 1994 to 1998. Llewelyn Smith credited Schopper with making decisions that would benefit not only LEP, but also the LHC. "Watching Herwig deal with these reviews was a wonderful apprenticeship, during which I learned a lot about the management of CERN," he recalled.


C Fernandez/CERN-PHOTO-202403-048-31

Centenarian *Herwig Schopper receives the Heisenberg medal.*

After passing CERN's leadership to Carlo Rubbia, Schopper became a fulltime science diplomat, notably including 20 years in senior roles at UNESCO between 1997 and 2017, and significant contributions to SESAME, the Synchrotron-light for Experimental Science and Applications in the Middle East (see *CERN Courier* January/February 2023, p28). Khaled Toukan of Jordan's Atomic Energy Commission, CERN Council president Eliezer Rabinovici and Maciej Nałecz (Polish Academy of Science, formerly of UNESCO) all spoke of Schopper's skill in helping to develop SESAME as a blueprint for science for peace and development. "Herwig likes building rings," Toukan fondly recounted.

As with any good birthday party, Herwig received gifts: a first copy of his biography, a NASA hoodie emblazoned with "Failure is not an option" from Sam Ting (MIT), who is closely associated with Schopper since their time together at DESY, and the Heisenberg medal. "You've even been in contact with the man himself," noted Heisenberg Society president Johannes Blümer, referring to several occasions Schopper met Heisenberg at conferences and even once discussed politics with him.

Schopper continues to counsel DGs to this day – and not only on physics. Confessing to occasionally being intimidated by his lifetime of achievements, CERN DG Fabiola Gianotti intimated that they often discuss music. "Herwig likes all composers, but not baroque ones. For him, they are too rational and intellectual." For this, he will always have physics.

Sanje Fenkart *CERN.*

MENU 2023

Slim, charming protons on the menu in Mainz

The triennial international conference on meson–nucleon physics and the structure of the nucleon (MENU) attracted more than 140 participants to the historic centre of Mainz from 16 to 20 October 2023.

Among MENU 2023's highlights on nucleon structure, a preliminary analysis by the NNPDF collaboration suggests that the proton contains more charm than anticharm, with Niccolò Laurenti (Università degli Studi di Milano) showing evidence of a non-vanishing intrinsic valence charm contribution to the proton's wavefunction. Meanwhile, Michael Kohl (Hampton University) concluded that the proton-radius puzzle is still not resolved. To make progress, form-factor measurements in electron scattering must be scrutinised, and the use of atomic spectroscopy data clarified, he said.

W Gradl

Structural issues *MENU 2023 took place in the historic centre of Mainz.*

Hadron physics

A large part of this year's conference was dedicated to hadron spectroscopy, with updates from Belle II, BESIII, GlueX, Jefferson Lab, JPAC, KLOE/KLOE-2 and LHCb, as well as theoretical overviews covering everything from lattice quantum chromodynamics to effective-field theories. Special emphasis was also given to future directions in hadron physics at future facilities such as FAIR, the Electron-Ion Collider and the local Mainz Energy-Recovering Superconducting Accelerator (MESA) facility – a future low-energy but high-intensity electron accelerator that will make it possible to carry out experiments in nuclear astrophysics, dark-sector searches and tests of the SM. Among upgrade plans at Jefferson Lab, Eric Voutier (Paris-Saclay) presented a future experimental programme with positron beams at CEBAF, the institute's Continuous Electron Beam Accelerator Facility. The upgrade will allow for a rich physics programme covering two-photon exchange, generalised polarisabilities, generalised parton distribution functions and direct dark-matter searches.

Highlights on nucleon structure include a preliminary analysis suggesting that the proton contains more charm than anticharm

Hadron physics is also closely related to searches for new physics, as precision observables of the Standard Model are in many cases limited by the non-perturbative regime of quantum chromodynamics. A prime example is the physics of the anomalous magnetic moment of the muon, for which a puzzling discrepancy between data-driven dispersive and lattice-quantum chromodynamics calculations of hadronic contributions to the Standard Model prediction persists (*CERN Courier* May/June 2021 p25). The upcoming collaboration meeting of the Muon g-2 Theory Initiative in September 2024 at KEK will provide important new insights from lattice QCD and e^+e^- experiments. It remains to be seen whether the eventual theoretical consensus will confirm a significant deviation from the experimental value, which is currently being updated by Fermilab's Muon g-2 experiment using their last three years of data.

Sabine Alebrand, **Achim Denig**, **Franziska Hagelstein** *and* **Linda York** *Mainz University.*

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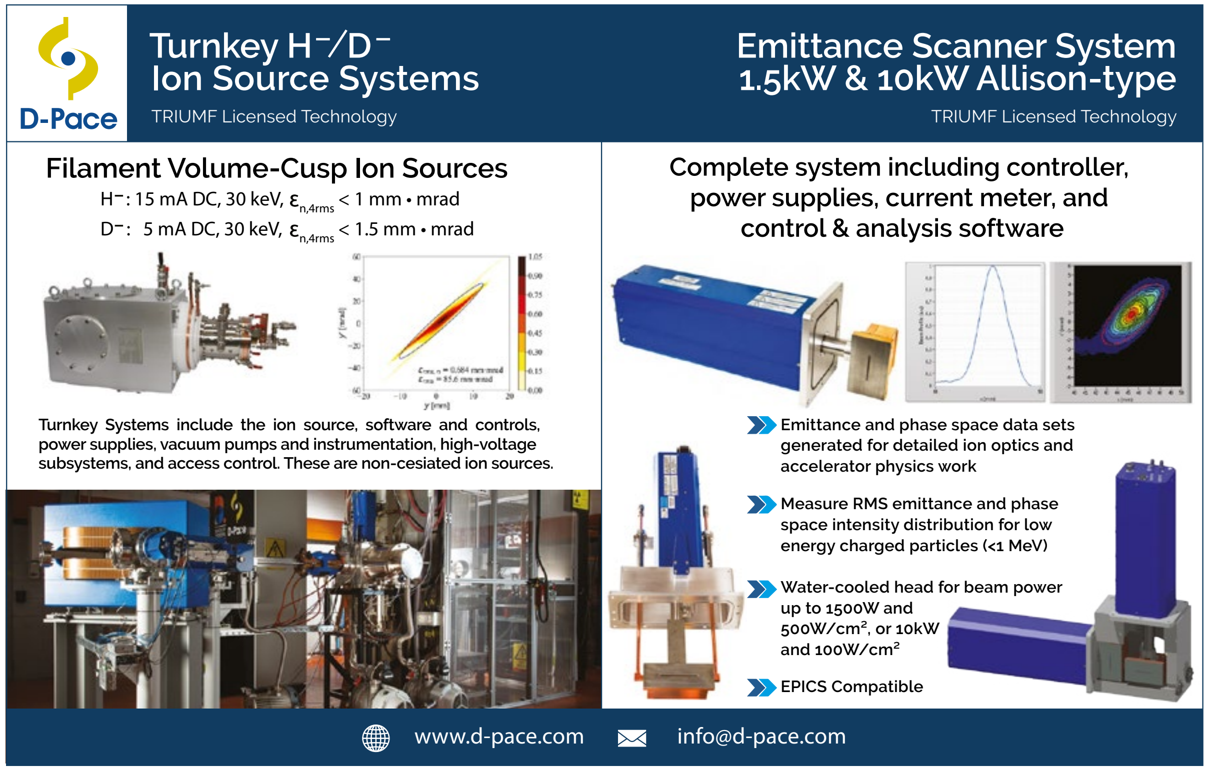

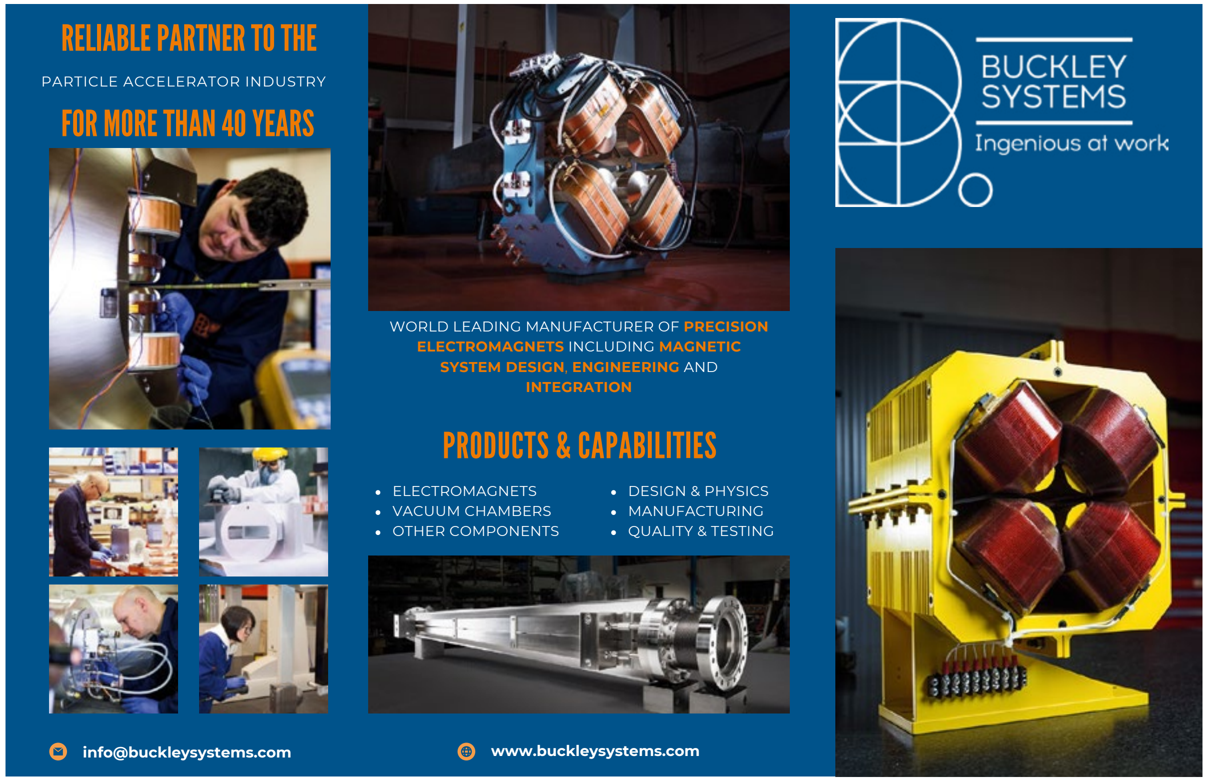

HOW TO SURF TO HIGH ENERGIES

The AWAKE experiment is adapting plasma-wakefield acceleration for applications in particle physics.

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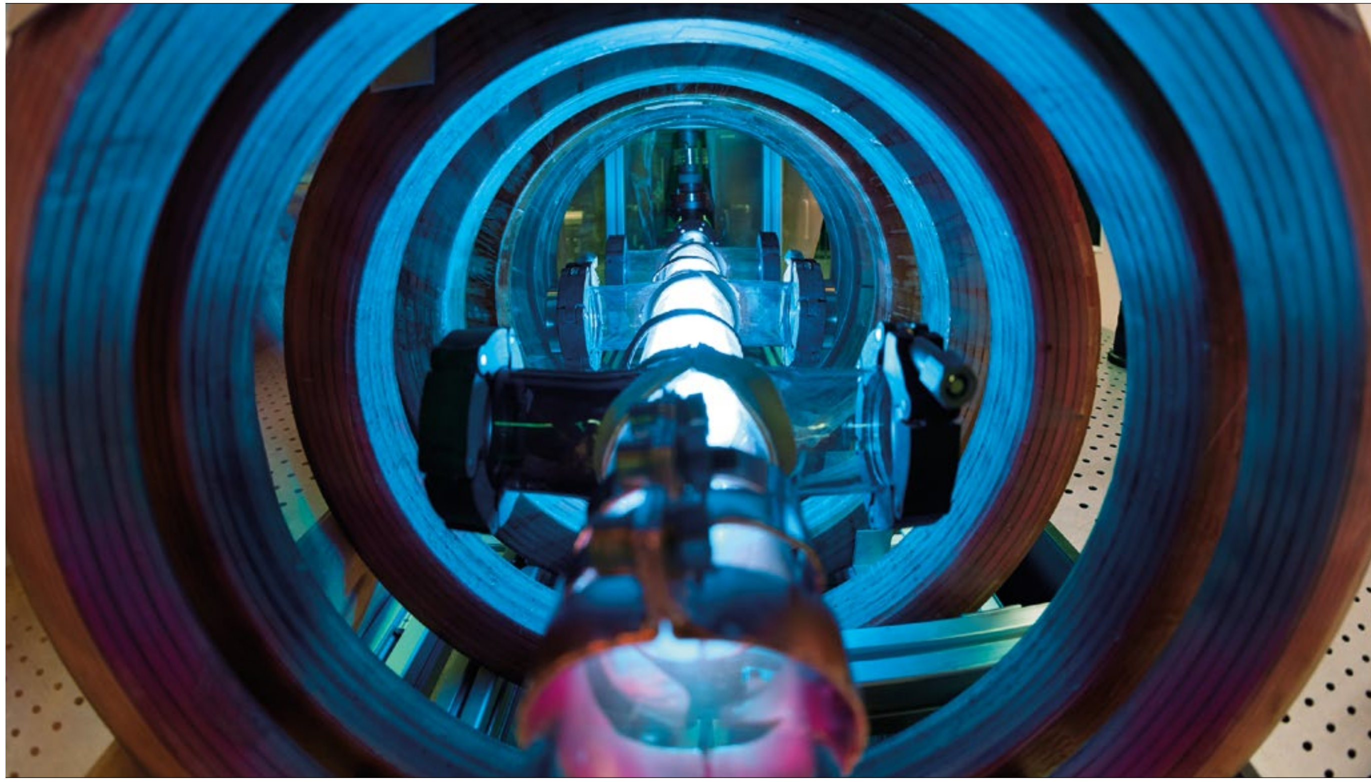

Helicon plasma source *AWAKE is experimenting with plasma technologies to scale proton-driven wakefields to greater lengths.*

A laser ionises rubidium vapour, turning it into plasma. A proton bunch plunges inside, evolving into millimetre-long microbunches. The microbunches pull the plasma's electrons, forming wakes in the plasma, like a speedboat displacing water. Crests and troughs of the plasma's electric field trail the proton microbunches at almost the speed of light. If injected at just the right moment, relativistic electrons surf on the accelerating phase of the field over a distance of metres, gaining energy up to a factor of 1000 times faster than can be achieved in conventional accelerators.

Plasma wakefield acceleration is a cutting-edge technology that promises to revolutionise the field of particle acceleration by paving the way for smaller and more cost-effective linear accelerators. The technique traces back to a seminal paper published in 1979 by Toshiki Tajima and John Dawson which laid the foundations for subsequent breakthroughs. At its core, the principle involves using a driver to generate wakefields in a plasma, upon which a witness beam surfs to undergo acceleration. Since the publication of the first paper, the field has demonstrated remarkable success in achieving large accelerating gradients.

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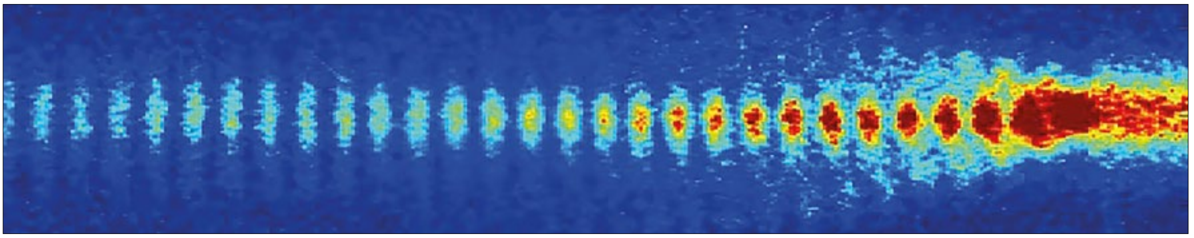
Edda Gschwendtner *CERN* **Patric Muggli** *Max Planck Institute for Physics* **Marlene Turner** *CERN.*


AWAKE Collaboration

Self-modulation *A proton bunch train formed in plasma by the self-modulation instability. The bunch train is propagating to the right.*


M Cavazza/CERN-PHOTO-202307-176-34

Rubidium source *AWAKE's 10 m-long rubidium vapour source.*

AWAKE technology promises to bridge the gap between global developments at small scales and possible future electron–positron colliders

Traditionally, only laser pulses and electron bunches have been used as drive beams. However, since 2016 the Advanced Wakefield Experiment (AWAKE) at CERN has used proton bunches from the Super Proton Synchrotron (SPS) as drive beams – an innovative approach with profound implications. Thanks to their high stored energy, proton bunches enable AWAKE to accelerate an electron bunch to energies relevant for high-energy physics in a single plasma, circumventing the need for the multiple accelerating stages that are required when using lasers or electron bunches.

Bridging the divide

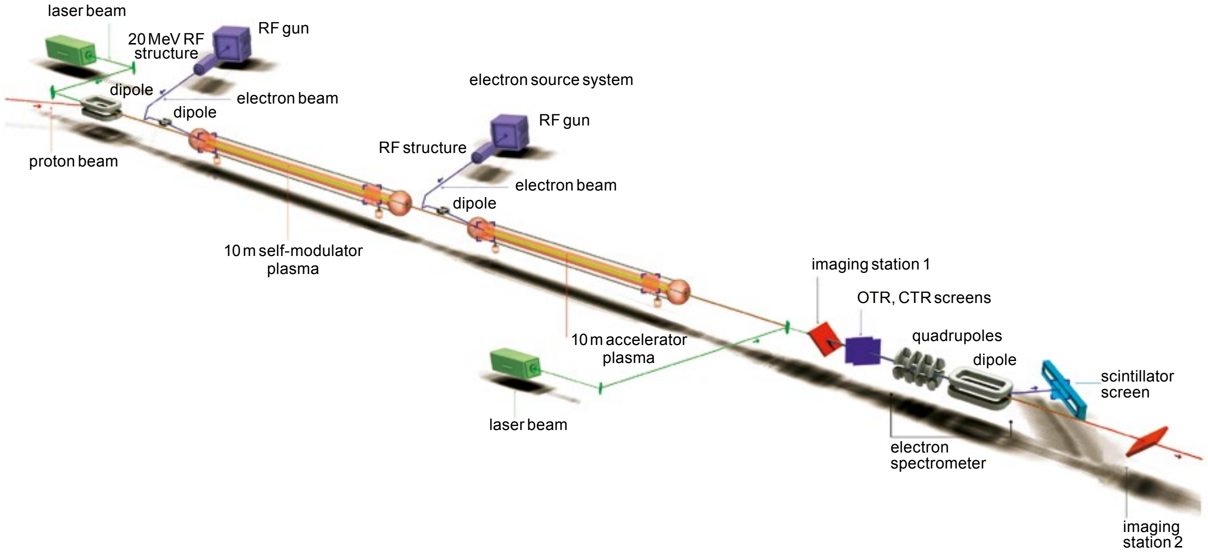
Relevant to any accelerator concept based on plasma wakefields, AWAKE technology promises to bridge the gap between global developments at small scales and possible future electron–positron colliders. The experiment is therefore an integral component of the European strategy for particle physics' plasma roadmap, aiming to advance the concept to a level of technological maturity that would allow their application to particle-physics experiments. An international collaboration of approximately 100 people across 22 institutes worldwide, AWAKE has already published more than 90 papers, many in high-impact journals, alongside significant efforts to train the next generation, culminating in the completion of over 28 doctoral theses to date.

In the experiment, a 400 GeV proton bunch from the SPS is sent into a 10 m-long plasma source containing rubidium vapour at a temperature of around 200 °C (see "Rubidium source" figure). A laser pulse accompanies the proton bunch, ionising the vapour and transforming it into a plasma.

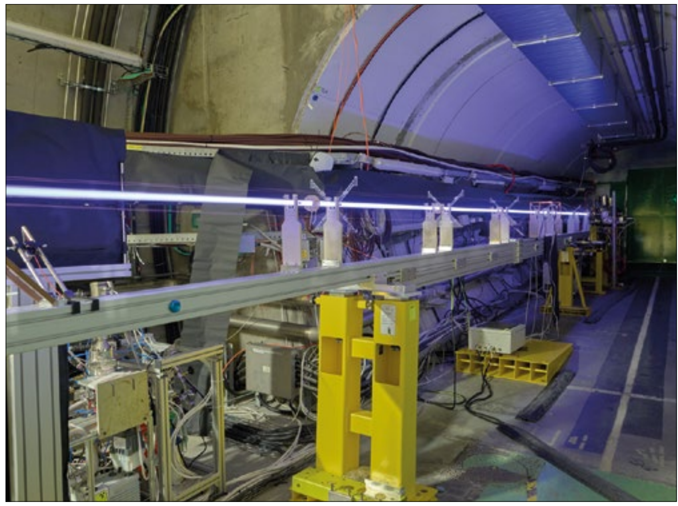
To induce the necessary wakefields, the drive bunch length must be of the order of the plasma wavelength, which corresponds to the natural oscillation period of the plasma. However, the length of the SPS proton bunch is around 6 cm, significantly longer than the 1 mm plasma wavelength in AWAKE, and short wavelengths are required to reach large accelerating gradients.

The solution is to take advantage of a beam-plasma instability, which transforms long particle bunches into microbunches with the period of the plasma through a process known as self-modulation. In other words, as the long proton bunch traverses the plasma, it can be coaxed into splitting into a train of shorter "microbunches". The bunch train resonantly excites the plasma wave, like a pendulum or a child on a swing, being pushed with small kicks at its natural oscillation interval or resonant frequency. If applied at the right time, each kick increases the oscillation amplitude or height of the wave. When the amplitude is sufficiently high, a witness electron bunch from an external source is injected into the plasma wakefields, to ride the wakefields and gain energy.

The first phase of AWAKE (Run 1, from 2016 to 2018) served as a proof-of-concept demonstration of the acceleration scheme. First, it was shown that a plasma can be used as a compact device to self-modulate a highly relativistic and highly energetic proton bunch (see "Self-modulation" figure). Second, it was shown that the resulting bunch train resonantly excites strong wakefields. Third – the most direct demonstration – it was shown that externally injected electrons can be captured, focused and accelerated to GeV energies by the wakefields. The addition of a percent-level positive gradient in density along the plasma led to 20% boosts in the energy gained by the accelerated electrons.



Modulation and acceleration *Plasma wakefield acceleration in AWAKE Run 2. A self-modulator plasma (left) divides the proton bunch into microbunches before a second plasma (right) accelerates electrons in their wakefields. (Credit: AWAKE Collaboration)*


M Cavazza/CERN-PHOTO-202305-118

Discharge source *A 10 m-long prototype discharge plasma source was tested in 2023. The technology is a promising means to scale AWAKE's acceleration plasma to greater lengths.*

Based on these proof-of-principle experimental results and expertise at CERN and in the collaboration, AWAKE developed a well-defined programme for Run 2, which launched in 2021 following Long Shutdown 2, and which will run for several more years from now. The goal is to achieve electron acceleration with GeV/m energy gain and beam quality similar to a normalised emittance of 10 mm-mrad and a relative energy spread of a few per cent. In parallel, scalable plasma sources are being developed that can be extended up to hundreds of metres in length (see "Helicon plasma source" and "Discharge source" figures). Once these goals are reached, the concepts of AWAKE could be used in particle-physics applications such as using electron beams with energy between 40 and 200 GeV impinging on a fixed target to search for new phenomena related to dark matter.

Controlled instability

The first Run 2 milestone, on track for completion by the end of the year, is to complete the self-modulator – the plasma that transforms the long proton bunch into a train of microbunches. The demonstration has been staged in two experimental phases.

The first phase was completed in 2022. The results prove that wakefields driven by a full proton bunch can have a reproducible and tunable timing. This is not at all a trivial demonstration given that the experiment is based on an instability!

Techniques to tune the instability are similar to those used with free-electron lasers: provide a controlled initial signal for the instability to grow from and operate in the saturated regime, for example. In AWAKE, the self-modulation instability is initiated by the wakefields driven by an electron bunch placed ahead of the proton bunch. The wakefields from the electron bunch imprint themselves on the proton bunch right from the start, leading to a well defined bunch train. This electron bunch is distinct from the witness bunches, which are later accelerated.

The second experimental phase for the completion of the self-modulator is to demonstrate that high-amplitude wakefields can be maintained over long distances. Numerical simulations predict that self-modulation can be optimised by tailoring the plasma's density profile. For example, introducing a step in the plasma density should lead to higher accelerating fields that can be maintained over long distances. First measurements are very encouraging, with density steps already leading to increased energy gains for externally injected electrons. Work is ongoing to globally optimise the self-modulator.

The second experimental milestone of Run 2 will be the acceleration of an electron bunch while demonstrat-

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ing its sustained beam quality. The experimental setup designed to reach this milestone includes two plasmas: a self-modulator that prepares the proton bunch train, and a second "accelerator plasma" into which an external electron bunch is injected (see "Modulation and acceleration" figure). To make space for the installation of the additional equipment, CERN will in 2025 and 2026 dismantle the CNGS (CERN Neutrinos to Gran Sasso) target area that is installed in a 100m-long tunnel cavern downstream from the AWAKE experimental facility.

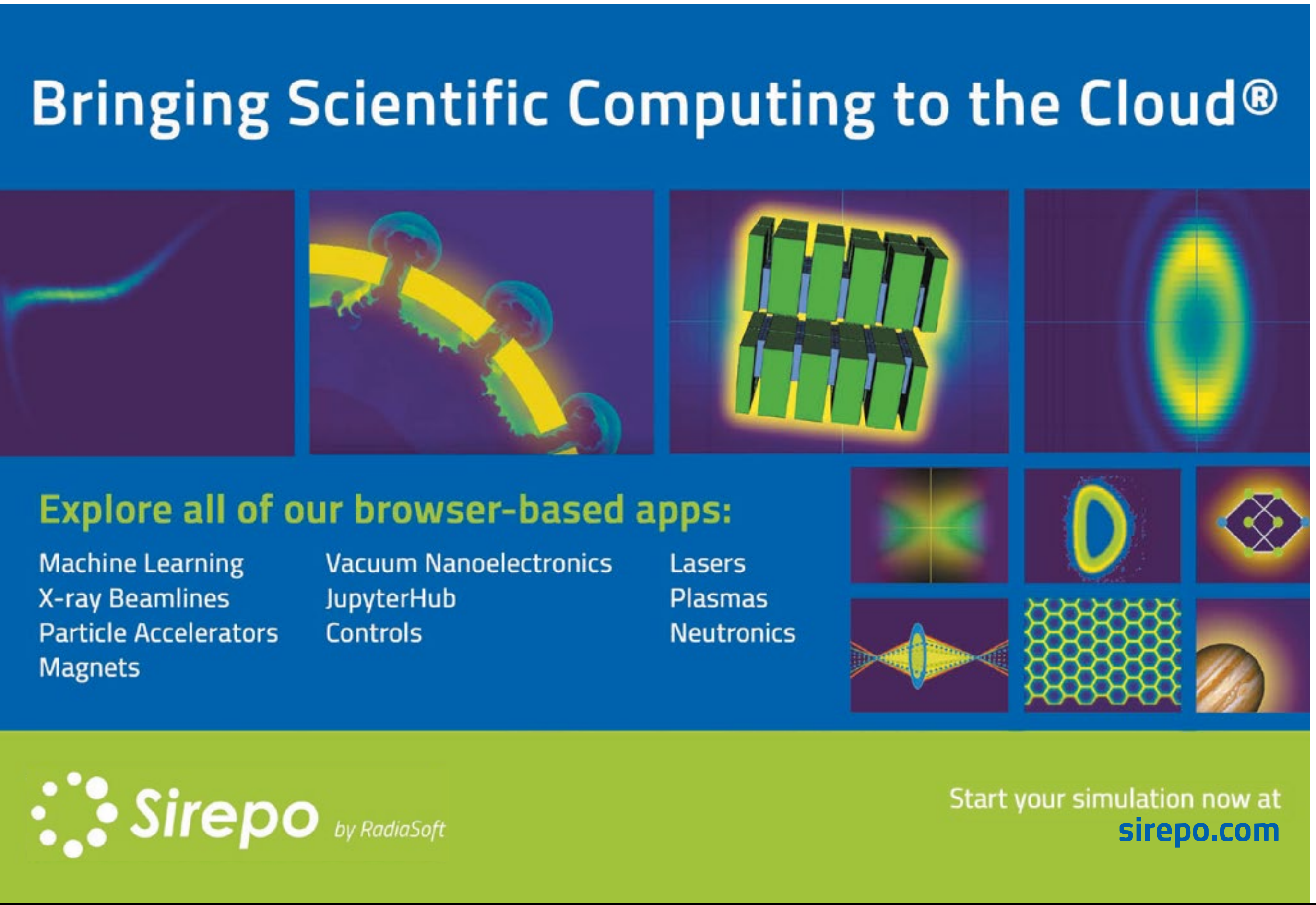
Two enabling technologies are needed to achieve high-quality electron acceleration

Accelerate ahead

Two enabling technologies are needed to achieve high-quality electron acceleration. The first is a source and transport line to inject the electron bunch on-axis into the accelerator plasma. A radio-frequency (RF) injector source was chosen because of the maturity of the technology, though the combination of S-band and X-band structures is novel, and forms a compact accelerator with possible medical applications. It is followed by a transport line that preserves the parameters of the 150 MeV 100 pC bunch, and allows for its tight focusing (5 to 10 μm) at the entrance of the accelerator plasma. External injection into plasma-based accelerators is challenging because of the high frequency (about 235 GHz in AWAKE) and thus small structure size (roughly 200 μm) at which they operate. The main goal is to demonstrate that the electron bunch can be accelerated to 4 to 10 GeV, with a relative energy spread of 5 to 8%, and emerge with approximately the same normalised emittance as at the entrance of the plasma (2–30 mm mrad).

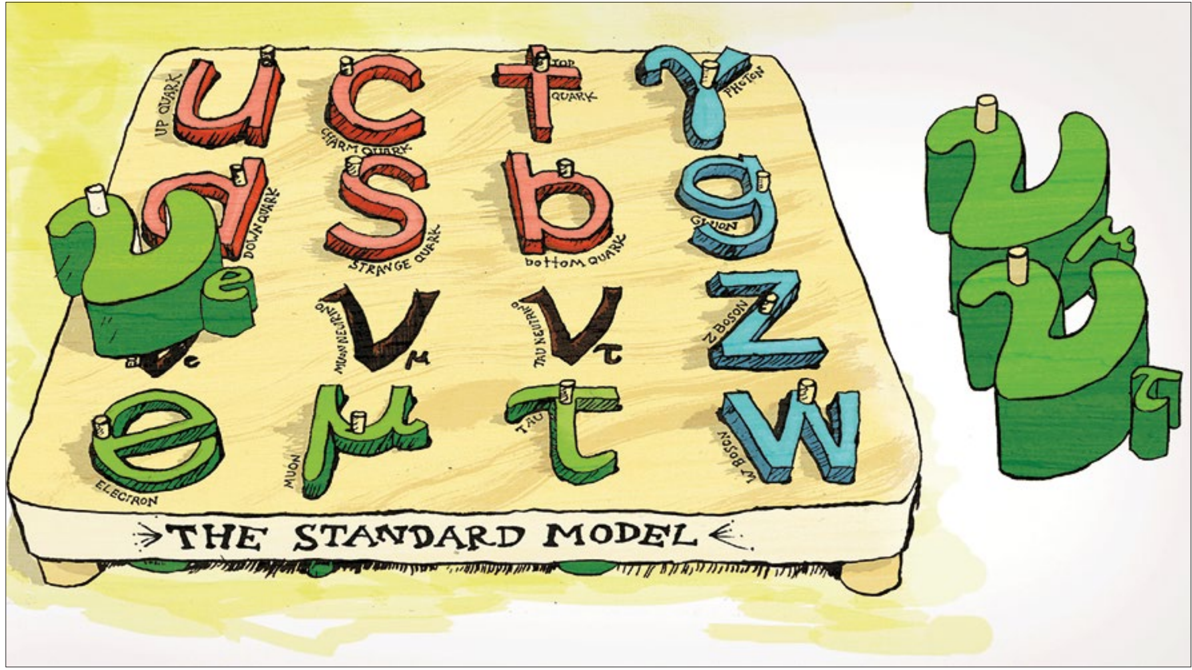
For these experiments, rubidium vapour sources will be used for both the self-modulator and accelerator plasmas, as they provide the uniformity, tunability and reproducibility required for the acceleration process. However, the laser-ionisation process of the rubidium vapour does not scale to lengths beyond 20 m. The alternative enabling technology is therefore a plasma source whose length can be scaled to the 50 to 100 metres required for the bunch to reach 50–100 GeV energies. To achieve this, a laboratory to develop discharge and helicon-plasma sources has been set up at CERN (see "Discharge source" figure). Multiple units can in principle be stacked to reach the desired plasma length. The challenge with such sources is to demonstrate that they can produce required plasma parameters other than length.

The third and final experimental milestone for Run 2 will then be to replace the 10 m-long accelerator plasma with a longer source and achieve proportionally larger energy gains. The AWAKE acceleration concept will then essentially be mature to propose particle-physics experiments, for example with bunches of a billion or so 50 GeV electrons. ●



THE NEUTRINO MASS PUZZLE

André de Gouvêa explains why neutrino masses imply the existence of new fundamental fields.



Symmetry

After all these years, neutrinos remain extraordinary – and somewhat deceptive. The experimental success of the three-massive-neutrino paradigm over the past 25 years makes it easy to forget that massive neutrinos are not part of the Standard Model (SM) of particle physics.

The problem lies with how neutrinos acquire mass. Nonzero neutrino masses are not possible without the existence of new fundamental fields, beyond those that are part of the SM. And we know virtually nothing about the particles associated with them. They could be bosons or fermions, light or heavy, charged or neutral, and experimentally accessible or hopelessly out of reach.

This is the neutrino mass puzzle. At its heart is the particle's uniquely elusive nature, which is both the source of the problem and the main challenge in resolving it.

Mysterious and elusive

Despite outnumbering other known massive particles in the universe by 10 orders of magnitude, neutrinos are the least understood of the matter particles. Unlike electrons, they do not participate in electromagnetic interactions. Unlike quarks, they do not participate in the strong interactions that bind protons and neutrons together. Neutrinos participate only in aptly named weak interactions. Out of the trillions of neutrinos that the Sun beams through you each second, only a handful will interact with your body during your lifetime.

Neutrino physics has therefore had a rather tortuous and slow history. The existence of neutrinos was postulated in 1930 but only confirmed in the 1950s. The hypothesis that there are different types of neutrinos was first raised in the 1940s but only confirmed in the 1960s. And the

Misfits

Massive neutrinos are not part of the Standard Model.

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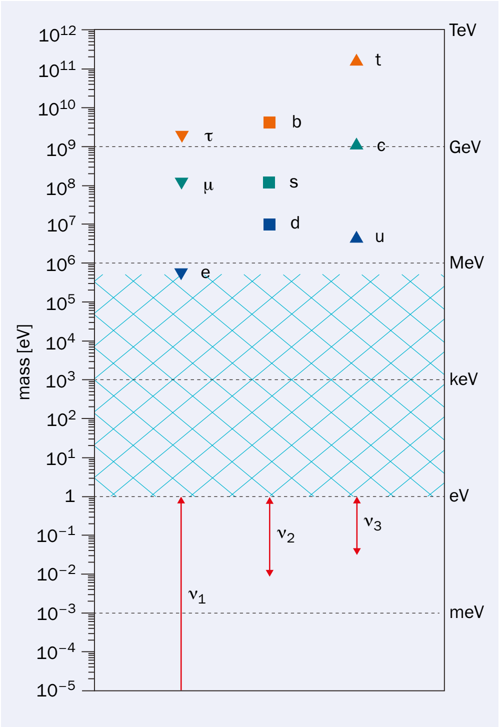
Massive puzzle *Neutrinos have small but undeniably nonzero masses.*



A de Gouvêa

Chasm *The masses of all known matter particles. The allowed ranges for the neutrino masses are indicated by red arrows. These are heavily correlated since we know the differences of the neutrino masses-squared with good precision. The 1 eV upper bound is very generous as there is strong observational evidence pointing to an upper bound to the three neutrino masses that is smaller than 0.1 eV. There is no lower bound on the mass of the lightest neutrino.*

third neutrino type, postulated when the tau lepton was discovered in the 1970s, was only directly observed in the year 2000. Nonetheless, over the years neutrino experiments have played a decisive role in the development of the most successful theory in modern physics: the SM. And at the turn of the 21st century, neutrino experiments revealed that there is something missing in its description of particle physics.

Neutrinos are fermions with spin one-half that interact with the charged leptons (the electron, muon and tau lepton) and the particles that mediate the weak interactions (the W and Z bosons). There are three neutrino types, or flavours: electron-type (ν_e), muon-type (ν_μ) and tau-type (ν_τ), and each interacts exclusively with its namesake charged lepton. One of the predictions of the SM is that neutrino masses are exactly zero, but a little over 25 years ago, neutrino experiments revealed that this is not exactly true. Neutrinos have tiny but undeniably nonzero masses.

The search for neutrino masses is almost as old as Pauli's 93-year-old postulate that neutrinos exist

Mixing it up

The search for neutrino masses is almost as old as Pauli's 93-year-old postulate that neutrinos exist. They were ultimately discovered around the turn of the millennium through the observation of neutrino flavour oscillations. It turns out that we can produce one of the neutrino flavours (for example ν_μ) and later detect it as a different flavour (for example ν_e) so long as we are willing to wait for the neutrino flavour to change. The probability associated with this phenomenon oscillates in spacetime with a characteristic distance that is inversely proportional to the differences of the squares of the neutrino masses. Given the tininess of neutrino masses and mass splittings, these distances are frequently measured in hundreds of kilometres in particle-physics experiments.

Neutrino oscillations also require the leptons to mix. This means that the neutrino flavour states are not particles with a well defined mass but are quantum superpositions of different neutrino states with well defined masses. The three mass eigenstates are related to the three flavour eigenstates via a three-dimensional mixing matrix, which is usually parameterised in terms of mixing angles and complex phases.

In the last few decades, precision measurements of neutrinos produced in the Sun, in the atmosphere, in nuclear reactors and in particle accelerators in different parts of the world, have measured the mixing parameters at the several percent level. Assuming the mixing matrix is unitary, all but one have been shown to be nonzero. The measurements have revealed that the three neutrino mass eigenvalues are separated by two different mass-squared differences: a small one of order $10^{-4}\,\text{eV}^2$ and a large one of order $10^{-3}\,\text{eV}^2$. Data therefore reveal that at least two of the neutrino masses are different from zero. At least one of the neutrino masses is above 0.05 eV, and the second lightest is at least 0.008 eV. While neutrino oscillation experiments cannot measure the neutrino masses directly, precise measurements of beta-decay spectra and constraints from the large-scale structure of the universe offer complementary upper limits. The nonzero neutrino masses are constrained to be less than roughly 0.1 eV.

These masses are tiny when compared to the masses of all the other particles (see "Chasm" figure). The mass of the lightest charged fermion, the electron, is of order 10^6 eV. The mass of the heaviest fermion, the top quark, is of order 10^{11} eV, as are the masses of the W, Z and Higgs bosons. These particle masses are all at least seven orders of magnitude heavier than those of the neutrinos. No one knows why neutrino masses are dramatically smaller than those of all other massive particles.

Neutrino masses require the existence of new fields, and hence new particles, beyond those in the Standard Model

Image generated by AI

Different fit *Additional Higgs fields allow solutions to the neutrino mass puzzle that predict the neutrinos to be Majorana fermions.*

The Standard Model and mass

To understand why the SM predicts neutrino masses to be zero, it is necessary to appreciate that particle masses are complicated in this theory. The reason is as follows. The SM is a quantum field theory. Interactions between the fields are strictly governed by their properties: spin, various "local" charges, which are conserved in interactions, and – for fermions like the neutrinos, charged leptons and quarks – another quantum number called chirality.

In quantum field theories, mass is the interaction between a right-chiral and a different left-chiral field. A naive picture is that the mass-interaction constantly converts left-chiral states into right-chiral ones (and vice versa) and the end result is a particle with a nonzero mass. It turns out, however, that for all known fermions, the left-chiral and right-chiral fermions have different charges. The immediate consequence of this is that you can't turn one into the other without violating the conservation of some charge so none of the fermions are allowed to have mass: the SM naively predicts that all fermion masses are zero!

The Higgs field was invented to fix this shortcoming. It is charged in such a way that some right-chiral and left-chiral fermions are allowed to interact with one another plus the Higgs field which, uniquely among all known fields, is thought to have been turned on everywhere since the phase transition that triggered electroweak symmetry breaking very early in the history of the universe. In other words, so long as the vacuum configuration of the Higgs field is not trivial, fermions acquire a mass thanks to these interactions.

This is not only a great idea; it is also at least mostly correct, as spectacularly confirmed by the discovery of the Higgs boson a little over a decade ago. It has many verifiable consequences. One is that the strength with which the Higgs boson couples to different particles is proportional to the particle 's mass – the Higgs prefers to interact with the top quark or the Z or W bosons relative to the electron or the light quarks. Another consequence is that all masses are proportional to the value of the Higgs field in the vacuum (10^{11} eV) and, in the SM, we naively expect all particle masses to be similar.

Neutrino masses are predicted to be zero because, in the SM, there are no right-chiral neutrino fields and hence none for the left-chiral neutrinos – the ones we know about – to "pair up" with. Neutrino masses therefore require the existence of new fields, and hence new particles, beyond those in the SM.

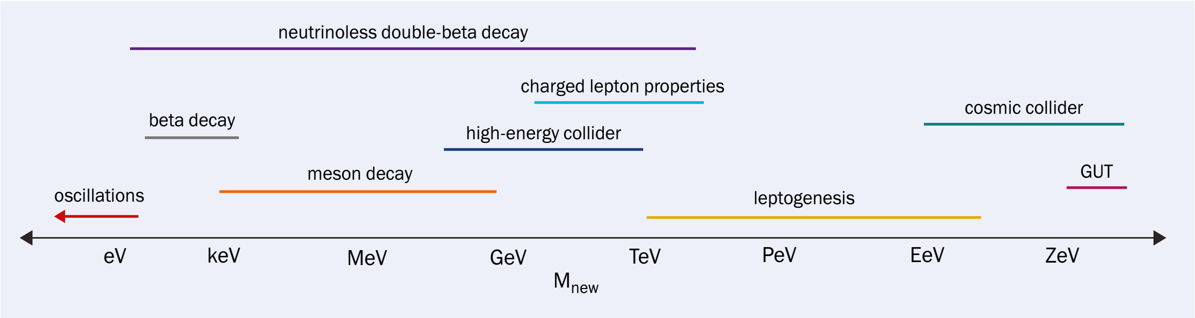
Wanted: new fields

The list of candidate new fields is long and diverse. For example, the new fields that allow for nonzero neutrino masses could be fermions or bosons; they could be neutral or charged under SM interactions, and they could be related to a new mass scale other than the vacuum value of the SM Higgs field (10^{11} eV), which could be either much smaller or much larger. Finally, while these new fields might be "easy" to discover with the current and near-future generation of experiments, they might equally turn out to be impossible to probe directly in any particle-physics experiment in the foreseeable future.

Though there are too many possibilities to list, they can be classified into three very broad categories: neutrinos acquire mass by interacting with the same Higgs field that gives mass to the charged fermions; by interacting with a similar Higgs field with different properties; or through a different mechanism entirely.

At first glance, the simplest idea is to postulate the existence of right-chiral neutrino fields and further assume they interact with the Higgs field and the left-chiral neutrinos, just like right-chiral and left-chiral charged leptons and quarks. There is, however, something special about right-chiral neutrino fields: they are completely neutral relative to all local SM charges. Returning to the rules of quantum field theory, completely neutral chiral fermions are allowed to interact "amongst themselves" independent of whether there are other right-chiral or left-chiral fields around. This means the right-chiral neutrino fields should come along with a different mass that is independent from the vacuum value of the Higgs field of 10^{11} eV.

To prevent this from happening, the right-chiral neu-



A de Gouvêa

eV to ZeV *The new physics responsible for nonzero neutrino masses could be anywhere between eV and ZeV (10^{21} eV) in scale, with a plethora of different possible experimental signatures and new physics connections.*

trinos must possess some kind of conserved charge that is shared with the left-chiral neutrinos. If this scenario is realised, there is some new, unknown fundamental conserved charge out there. This hypothetical new charge is called lepton number: electrons, muons, tau leptons and neutrinos are assigned charge plus one, while positrons, antimuons, tau antileptons and antineutrinos have charge minus one. A prediction of this scenario is that the neutrino and the antineutrino are different particles since they have different lepton numbers. In more technical terms, the neutrinos are massive Dirac fermions, like the charged leptons and the quarks. In this scenario, there are new particles associated with the right-chiral neutrino field, and a new conservation law in nature.

Accidental conservation

As of today, there is no experimental evidence that lepton number is not conserved, and readers may question if this really is a new conservation law. In the SM, however, the conservation of lepton number is merely "accidental" – once all other symmetries and constraints are taken into account, the theory happens to possess this symmetry. But lepton number conservation is no longer an accidental symmetry when right-chiral neutrinos are added, and these chargeless and apparently undetectable particles should have completely different properties if it is not imposed.

If lepton number conservation is imposed as a new symmetry of nature, making neutrinos pure Dirac fermions, there appears to be no observable consequence other than nonzero neutrino masses. Given the tiny neutrino masses, the strength of the interaction between the Higgs boson and the neutrinos is predicted to be at least seven orders of magnitude smaller than all other Higgs couplings to fermions. Various ideas have been proposed to explain this remarkable chasm between the strength of the neutrino's interaction with the Higgs field relative to that of all other fermions. They involve a plurality of theoretical concepts including extra-dimensions of space, mirror copies of our universe and dark sectors.

A second possibility is that there are more Higgs fields in nature and that the neutrinos acquire a mass by interacting with a Higgs field that is different from the one that gives a mass to the charged fermions. Since the neutrino mass is proportional to the vacuum value of a different Higgs field, the fact that the neutrino masses are so small is easy to tolerate: they are simply proportional to a different mass scale that could be much smaller than 10^{11} eV. Here, there are no right-chiral neutrino fields and the neutrino masses are interactions of the left-chiral neutrino fields amongst themselves. This is possible because, while the neutrinos possess weak-force charge they have no electric charge. In the presence of the nontrivial vacuum of the Higgs fields, the weak-force charge is effectively not conserved and these interactions may be allowed. The fact that the Higgs particle discovered at the LHC – associated with the SM Higgs field – does not allow for this possibility is a consequence of its charges. Different Higgs fields can have different weak-force charges and end up doing different things. In this scenario, the neutrino and the antineutrino are, in fact, the same particle. In more technical terms: the neutrinos are massive Majorana fermions.

One way to think about this is as follows: the mass interaction transforms left-chiral objects into right-chiral objects. For electrons, for example, the mass converts left-chiral electrons into right-chiral electrons. It turns out that the antiparticle of a left-chiral object is right-chiral and vice versa, and it is tempting to ask whether a mass interaction could convert a left-chiral electron into a right-chiral positron. The answer is no: electrons and positrons are different objects and converting one into the other would violate the conservation of electric charge. But this is no barrier for the neutrino, and we can contemplate the possibility of converting a left-chiral neutrino into its right-chiral antiparticle without violating any known law of physics. If this hypothesis is correct, the hypothetical lepton-number charge, discussed earlier, cannot be conserved. This hypothesis is experimentally neither confirmed nor contradicted but could soon be confirmed with the observation of neutrinoless double-beta decays – nuclear decays which can only occur if lepton-number symmetry is violated. There is an ongoing worldwide campaign to search for the neutrinoless double-beta decay of various nuclei.

A new source of mass

In the third category, there is a source of mass different from the vacuum value of the Higgs field, and the neutrino masses are an amalgam of the vacuum value of the Higgs field and this new source of mass. A very low new mass scale might be discovered in oscillation experiments, while consequences of heavier ones may be detected in other types of particle-physics experiments, including measurements of beta and meson decays, charged-lepton properties, or the hunt for new particles at high-energy colliders. Searches for neutrinoless double-beta decay can reveal different sources for lepton-number violation, while ultraheavy particles can leave indelible footprints in the structure of the universe through cosmic collisions. The new physics responsible for nonzero neutrino masses might also be related to grand-unified theories or the origin of the matter–antimatter asymmetry of the universe, through a process referred to as leptogenesis. The range of possibilities spans 22 orders of magnitude (see "eV to ZeV" figure).

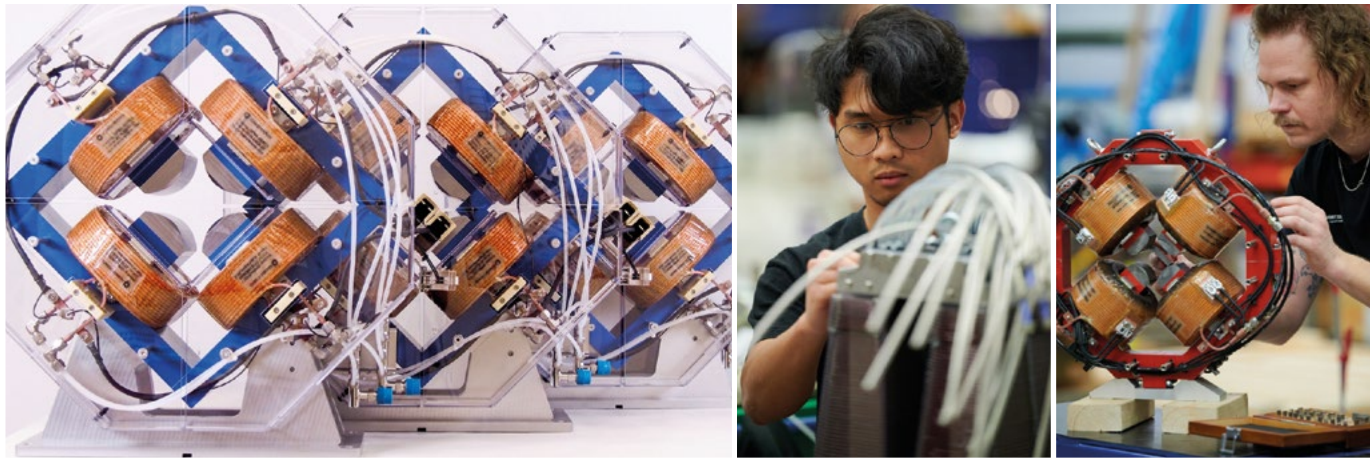
Challenging scenarios

Since the origin of the neutrino masses here is qualitatively different from that of all other particles, the values of the neutrino masses are expected to be qualitatively different. Experimentally, we know that neutrino masses are much smaller than all charged-fermion masses, so many physicists believe that the tiny neutrino masses are strong indirect evidence for a source of mass beyond the vacuum value of the Higgs field. In most of these scenarios, the neutrinos are also massive Majorana fermions. The challenge here is that if a new mass scale exists in fundamental physics, we know close to nothing about it. It could be within direct reach of particle-physics experiments, or it could be astronomically high, perhaps as large as 10^{12} times the vacuum value of the SM's Higgs field.

How do we hope to learn more? We need more experimental input. There are many outstanding questions that can only be answered with oscillation experiments. These could provide evidence for new neutrino-like particles or new neutrino interactions and properties. Meanwhile, searching for neutrinoless double-beta decay is the most promising avenue to experimentally reveal whether neutrinos are Majorana or Dirac fermions. Other activities include high-energy collider searches for new Higgs bosons that like to talk to neutrinos and new heavy neutrino-like particles that could be related to the mechanism of neutrino mass generation. Charged-lepton probes, including measurements of the anomalous magnetic moment of muons and searches for lepton-flavour violation, may provide invaluable clues, while surveys of the cosmic microwave background and the distribution of galaxies could also reveal footprints of the neutrino masses in the structure of the universe.

We still know very little about the new physics uncovered by neutrino oscillations. Only a diverse experimental programme will reveal the nature of the new physics behind the neutrino mass puzzle. ●

Searching for neutrinoless double-beta decay is the most promising avenue to reveal whether neutrinos are Majorana or Dirac fermions



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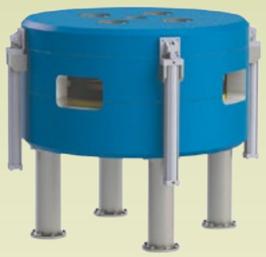
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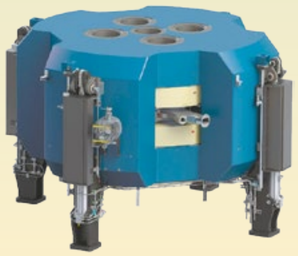
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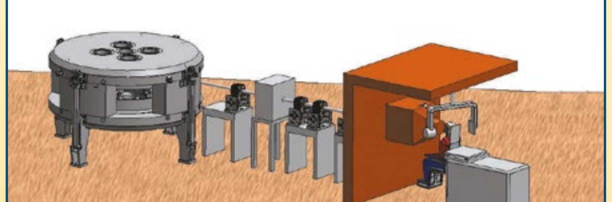
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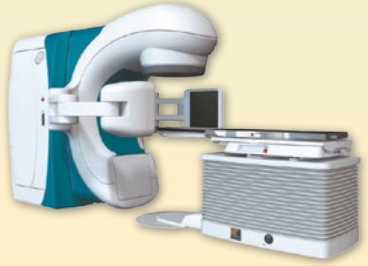
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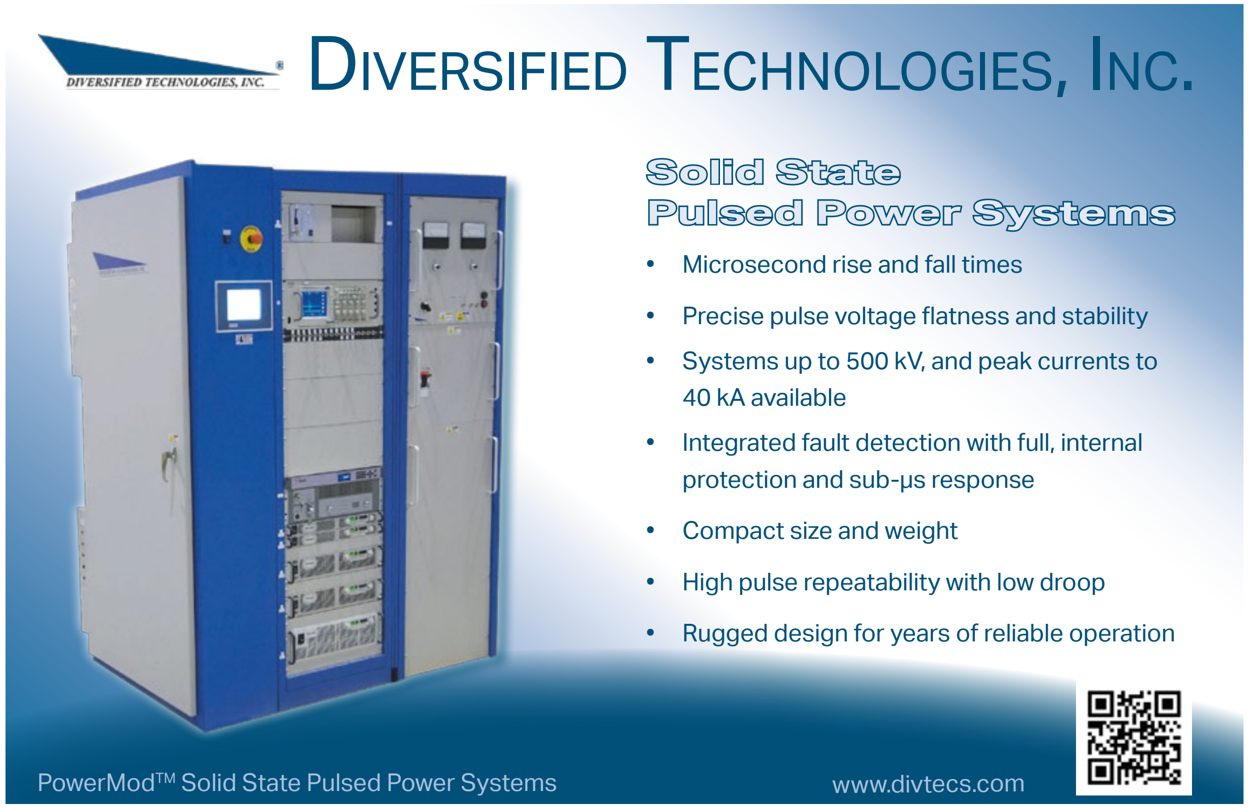
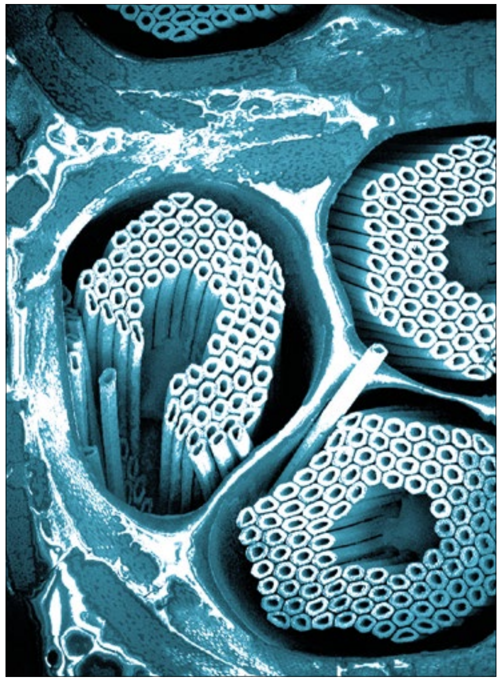


ENGINEERING MATERIALS FOR BIG SCIENCE

From the HL-LHC magnets to the ITER fusion project, Stefano Sgobba, Katie Buchanan and Ana Teresa Perez Fontenla describe how CERN deals with complex demands for mechanical design, production facilities and material science at CERN and beyond.


M Crouvizier/CERN EN-MME-MM

HL-LHC coils up close *Total breakage of Nb_3Sn filaments in a magnet coil for the HL-LHC observed by scanning electron microscopy after deep etching of the copper supports.*

The nature of CERN's research often demands unusual and highly complex materials to be developed and tested. A good example is the LHC beam screen that limits the energy transfer from the beam to the cold mass of the magnets, for which a new non-magnetic stainless steel had to be developed in the mid-1990s to meet the physical and mechanical requirements at cryogenic temperatures. The same is true of the external cylinder of the CMS solenoid magnet, for which a process enabling the production of 7 m-diameter high-strength seamless aluminium-alloy rings had to be identified and qualified. Another breakthrough at the LHC has been the solution adopted for the end covers of the cold masses of the dipole magnets, for which 2500 stainless-steel powder metallurgy-hot isostatic pressed covers were produced – qualifying this innovative shaping solution for the first time for massive, fully reliable leak-tight operation at cryogenic temperatures.

Similar challenges apply today for the High-Luminosity LHC (HL-LHC), which is due to operate from 2029. For the HL-LHC radio-frequency crab cavities, which will tilt the beams at the collision points to maximise the luminosity, niobium and niobium-titanium alloy products have been carefully identified and qualified. Niobium additive-manufactured at CERN achieved a record purity and conductivity for this kind of product. For the new HL-LHC magnets, which are necessary to focus the beams more tightly at the collision points, detailed qualifications of the soundness of niobium-tin (Nb_3Sn) coils have been critical, as has the development and qualification of methods to test the weld of the quadrupole magnet cold masses.

These and numerous other projects are the domain of the CERN materials, metrology and non-destructive testing (EN-MME-MM) section, whose mission is to provide material sciences for accelerators and detectors spanning the whole CERN community, in close coordination with the mechanical design and production facilities of the EN-MME group. The interdisciplinary, expert-staffed section guarantees a full life-cycle management of materials – from functional requirements to prototyping, series production, inspection and end-of-life – and includes the identification or development of material solutions, the specification and qualification of suppliers, the definition of manufacturing and inspection plans, and inspections of received materials and parts before and after their integration into the machines and experiments. This challenging mission requires advanced microscopic materials analysis, high-precision optical metrology, mechanical static and cyclic measurements, including at cryogenic temperatures, and, last but not least, state of the art non-destructive testing techniques (see "Section facilities" figure).

High-field magnets

The future of particle accelerators is strongly linked to the development of high-field superconducting magnets that enable higher energies and luminosities to be attained. The HL-LHC will be the first operational facility to employ high-performance Nb_3Sn accelerator

THE AUTHORS

Stefano Sgobba, **Katie Elizabeth Buchanan** *and* **Ana Teresa Perez Fontenla** *CERN.*


CERN EN-MME-MM

Section facilities *The comprehensive facilities of the EN–MME–MM section provide full life-cycle management of materials and parts.*

The future of particle accelerators is strongly linked to the development of high-field superconducting magnets

magnets, surpassing the intrinsic performance limitations of NbTi-based magnets as used for the LHC. The fabrication of Nb_3Sn magnets is a challenging process because the conductor is an extremely brittle intermetallic phase. While the difficulty of working with brittle compounds is reduced using the traditional wind-react-and-impregnate approach, uncertainties remain due to volume changes associated with phase transformations occurring during the reaction heat treatment necessary to form the Nb_3Sn phase.

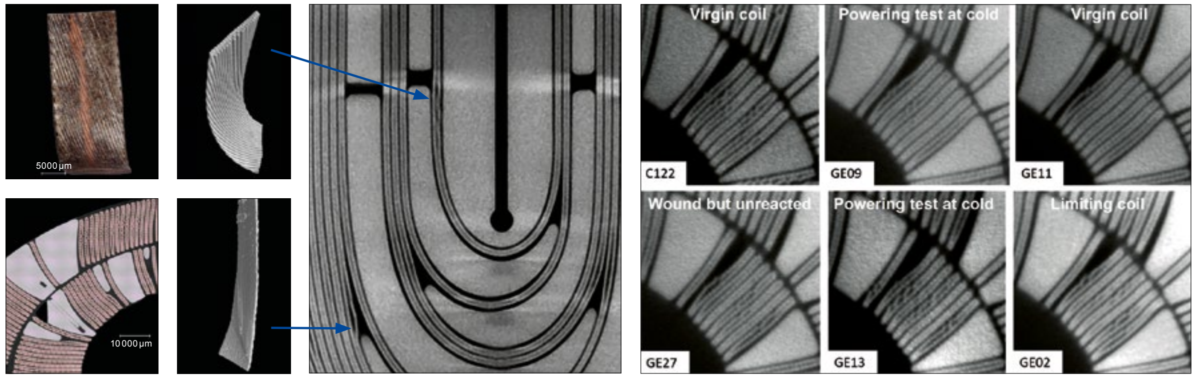
Needle in a haystack

To investigate the root causes of performance limitation or degradation observed on early magnets, several HL-LHC dipole and quadrupole magnet coils were examined. This project has been one of the most complex failure analyses ever undertaken by the MM section, demanding an innovative investigation methodology to be identified and performed at several fabrication stages and after cool-down and powering. Internal shear and bending loads on unsupported superconducting wires, which can cause their dislocation as well as cracks in the aggregates of Nb_3Sn filaments, were suspected to be the main cause of limitation or degradation. Like hunting for a needle within a massive haystack, the challenge was to find microscopic damage at the level of the filaments in the large volume of coils covering a length up to 7.2 m.

Starting in 2020 with 11 T magnet-coil ends, a sequence of mesoscale observations of whole coil sections was carried out non-destructively using innovative high-energy X-ray computed tomography (CT). This enabled the critical volumes to be identified and was followed up with a microscopic assessment of internal events, geometrical distortions and potential flaws using advanced microscopy. As a result, the MM section was able to unequivocally identify strands with transversely broken elements (see "Dipole diagnostics" and "Cracking niobium tin" figures). Techniques such as scanning electron microscopy (SEM) and focussed ion beam (FIB) were used to analyse damage to strands or sub-elements at particular localised positions as well as failure modes. In addition, a deep-etching technique allowed a decisive observation of completely broken filaments (see "HL-LHC coils up close" figure). Taken together, this comprehensive approach provided an in-depth view of the examined coils by identifying and characterising atypical features and imperfections in both the superconducting phase of the strands and the glass fibre/resin insulation system. It also clearly associated the quenches (a sudden loss of the superconducting state) experienced by the coils with physical events, namely broken superconducting filaments or damaged strands. The successful analysis of the CERN coil limitations led the MM section to receive several coils from different non-conforming quadrupole magnets, fabricated in the US in the framework of the Accelerator Upgrade Project collaboration, and successfully carry out the same type of investigations.

Effective recovery

This highly effective approach and key results on Nb_3Sn accelerator magnets were made possible thanks to the wide experience gained with previous applications of CT techniques to the magnet system of the ITER fusion experiment, which employs the Nb_3Sn conductor on a massive scale. The aim of such investigations is not only to understand what went wrong, no matter how difficult and complex that might be, but also to identify remedial actions. For the HL-LHC magnets, the MM section has contributed widely to the introduction of effective recovery measures, improved coil manufacturing



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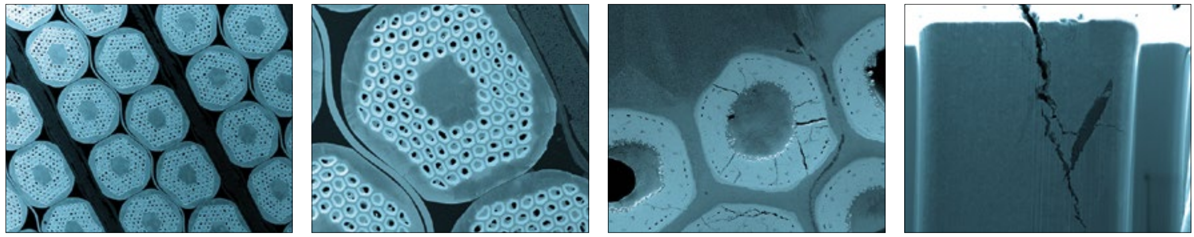
Dipole diagnostics *Left: issues internal to a 11 T Nb_3Sn coil are identified by linac computed tomography (CT) and further confirmed by X-ray microtomography and microscopic observations, which prove the suspected presence of misaligned strands and bulging in the cables (events identified by arrows). Right: winding imperfections confirmed by linac CT for several other coils in consistent positions at different steps of the processing and testing (six coils are compared in equivalent positions).*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Cracking niobium tin *Volumetric cracks confirmed by SEM-FIB in the brittle Nb_3Sn superconducting phase.*

and cold-mass assembly processes, and the production of magnets with reproducible behaviour and no sign of degradation. These results led to the conclusion that the root cause of the performance limitation of previous long CERN magnets has been identified and can now be overcome for future applications, as is the case for Nb_3Sn quadrupole magnets.

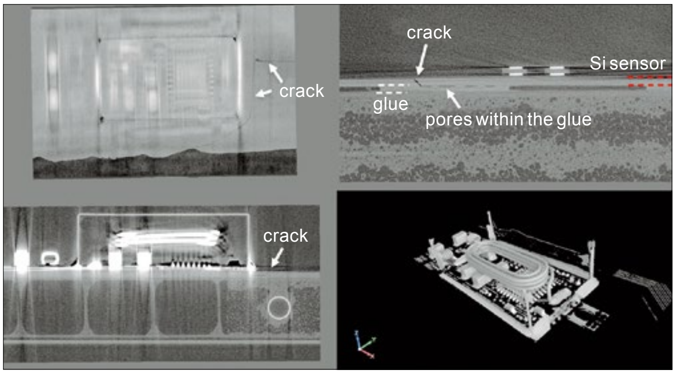
Structural support

Investigating the massive HL-LHC coils required a high-energy (6 MeV) linac CT that was subcontracted to TEC Eurolab in Italy and Diondo GmbH in Germany, two of only a few companies in the world that are equipped with this technique. However, the MM section also has an X-ray CT facility with an energy of 225 keV, which enables sufficient penetration for less massive samples. One of the most recent of countless examples employing this technique concerns the staves for the future ATLAS tracker (ITk) for the HL-LHC upgrade. During 2023 a significant fraction of the ITk modules suffered from early high-voltage breakdowns, despite appearing to perform satisfactorily during earlier stages of quality control. A subset of these modules exhibited breakdowns following thermal cycling, with some failing during the cold phases of the cycle. Additionally, others experienced breakdowns after being loaded onto their supporting staves. High-resolution CT scans at CERN combined with other techniques confirmed the presence and propagation of cracks through the entire sensor thickness, and enabled the MM team to identify the gluing process between the carbon structure and the sensors as the root cause of the vulnerability, which is now being addressed by the ATLAS project team (see "ATLAS modules" figure). Also for the HL-LHC, the section is working on the internalisation process of the beryllium vacuum-chamber fabrication technology required for the experiments.

While carrying out failure analyses of extremely high-tech components is the core business of the MM section, in some cases understanding the failure of the most basic objects can be paramount. This does not necessarily mean that the investigations are simpler. At 11 a.m. on 13 October 2022, a pipe supplying CERN with water burst under the main road near the French–Swiss border, which was closed until early afternoon. The damage was quickly repaired by the Swiss services, and the road re-opened. But it was critical to understand if this was an isolated incident of an individual pipe, in service for 20 years, or if there was the potential risk of bursts in other ducts of the same type.

The damaged portion of the duct, measuring 1.7 m in length and 0.5 m in diameter, is the largest sample ever brought to the MM facilities for root-cause analysis (see "Water pipe" figure). As such, it required most of the available techniques to be deployed. For the receiving inspections, visual and radiographic testing and high-precision optical dimensional metrology in a volume of almost 17 m^3 were used. For microstructural examinations, tests by CT, microoptical and SEM observations on

The services of the MM section, provided via cooperation agreements with CERN, are in wide demand externally



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ATLAS modules *CT scan of a sample from the ATLAS ITk stave modules, showing the detail of the crack and its propagation in the sensor as well as imperfections in the glue.*

CERN EN-MME-MM

Water pipe *A failure analysis of a water pipe near CERN in 2022 required a complete set of SEM (top left), CT (top right) and other advanced inspections, revealing the sequence of the failure (bottom): circumferential/radial rupture at midpoint by flexural strength acting between supported ends (1), longitudinal meandering (2), branching of the crack into spiral cracks (3), weakening of the pipe and fast progression towards the opposite end (4) and branching of the crack into spiral cracks (5).*

the samples surrounding the crack – including a post-resin burn-off test – were carried out. The cracking (one of the most common found in water and sewer pipes) turned out to be the result of bending forces due to local soil movement. This generated a flexural constraint between the supported ends of the failing section, consisting of a concrete base on one side and a connection sleeve to the next pipe section on the opposite side. The change of boundary conditions may have been due to droughts during summer periods that altered the soil conditions. To the great relief of all, the composite material of the pipe or its constituents were not the main cause of the failure.

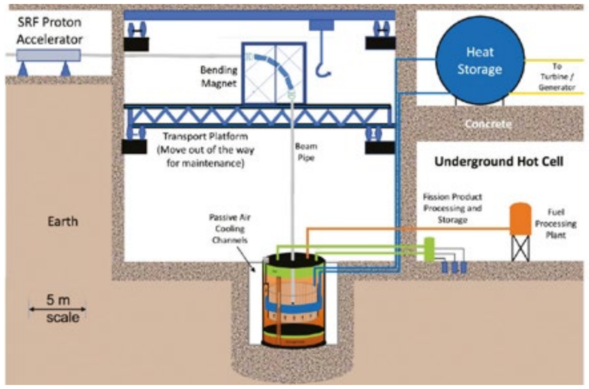
Beyond CERN

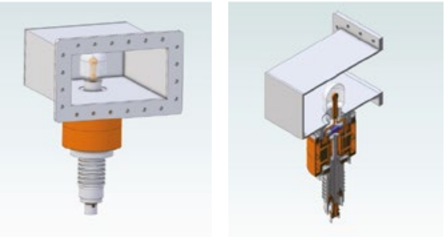
The services of the MM section, provided via cooperation agreements with CERN, are also in wide demand externally. ITER is a strong example. As of 2009, a major multi-year cooperation agreement is in place specifically covering metallurgical and material testing for the construction of the ITER magnet and vacuum systems. The many results and achievements of this long-lasting cooperation include: the qualification of high-strength stainless-steel jacket material for the conductor of the ITER central solenoid, including their cryogenic properties; the development and application of advanced examination techniques to assess the vacuum pressure impregnation process used in the correction coils and their critical welds, which are not inspectable with conventional techniques; and the assessment of a high-strength austenitic stainless steel for the precompression structure of the central solenoid, involving forgings featuring an unprecedented combination of size and aspect ratio. The section has also been fully entrusted by the ITER organisation for major failure analysis, such as the root-cause analysis of a heavy gauge fastener of the toroidal-field gravity support system and, more recently, the analysis of leakage events in the thermal-shield cooling pipes of the ITER magnet system. Several agreements are also in place via the CERN knowledge transfer group for the assessment of structural materials for a fusion project beyond ITER, and for a subcritical fission reactor project.

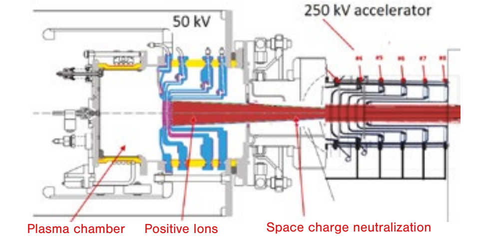
Also not to be forgotten is the major involvement of CERN in the Einstein Telescope project, for example in assessing suitable materials and fabrication solutions for its vacuum system, one of the largest ultra-high vacuum systems ever built. A three-year-long project that started in September 2022 aims to deliver the main technical design report for the Einstein Telescope beampipes, in which CERN's contribution is structured in eight work packages spanning design and materials choice to logistics, installation and surface treatments (*CERN Courier* September/October 2023 p45).

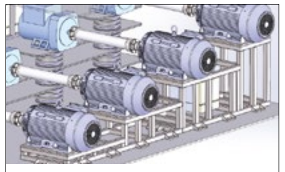
Beyond fundamental physics, the section is also working on the selection of materials for a future hydrogen economy, namely the definition of the proper specification and procedures for operation in a liquid-hydrogen environment. The watchmaking industry, which places high requirements on materials, also cooperates in this field. It is expected that the section will also receive requests for even more collaboration projects for different fields.

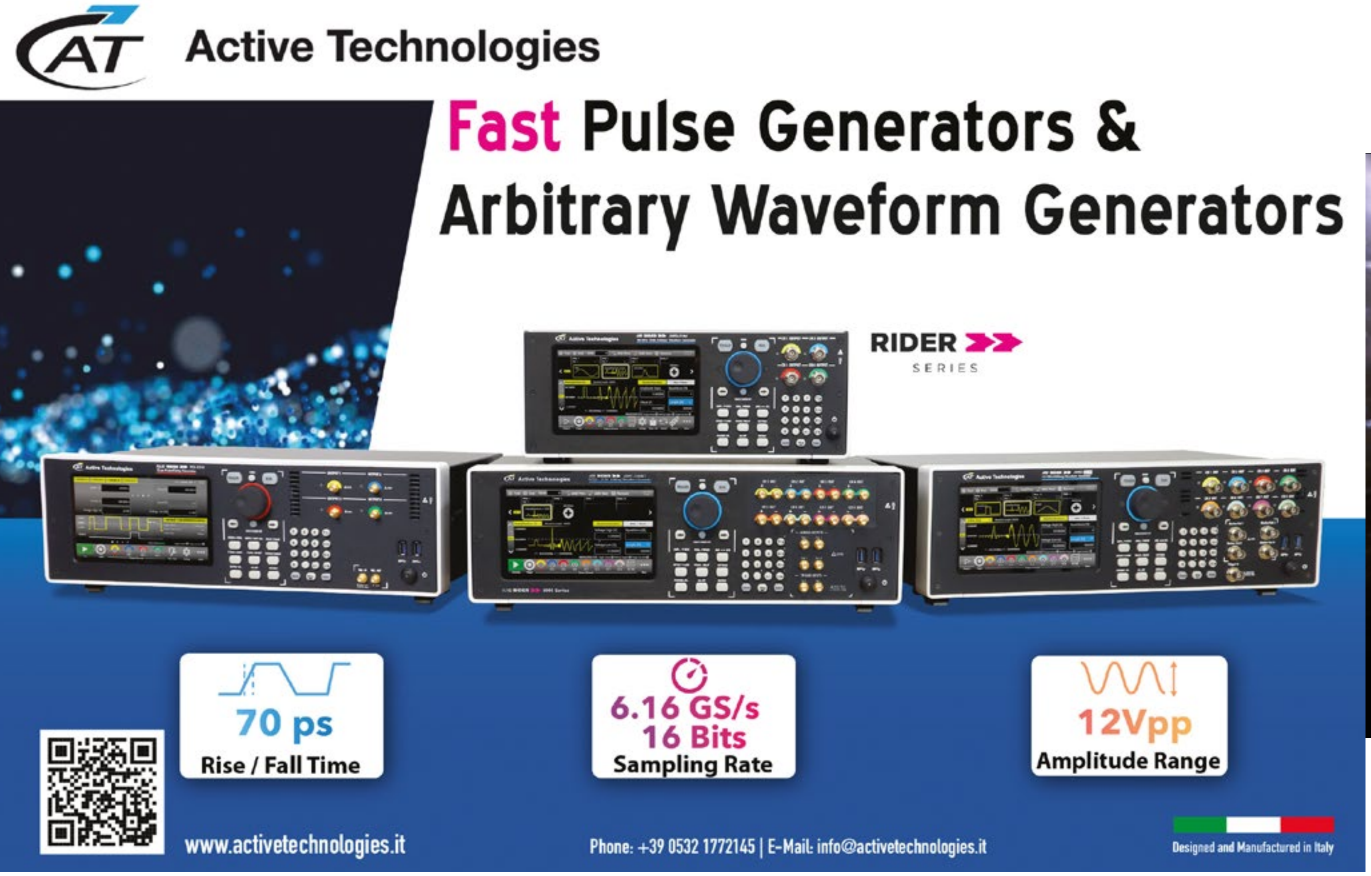
It is quite true to say that materials are everywhere. The examples given here clearly show that in view of the ambitious goals of CERN, a highly interdisciplinary effort from materials and mechanical engineers is paramount to the proper selection and qualification of materials, parts and processes to enable the creation of the giant colliders and detectors that allow physicists to explore the fundamental constituents of the universe. ●

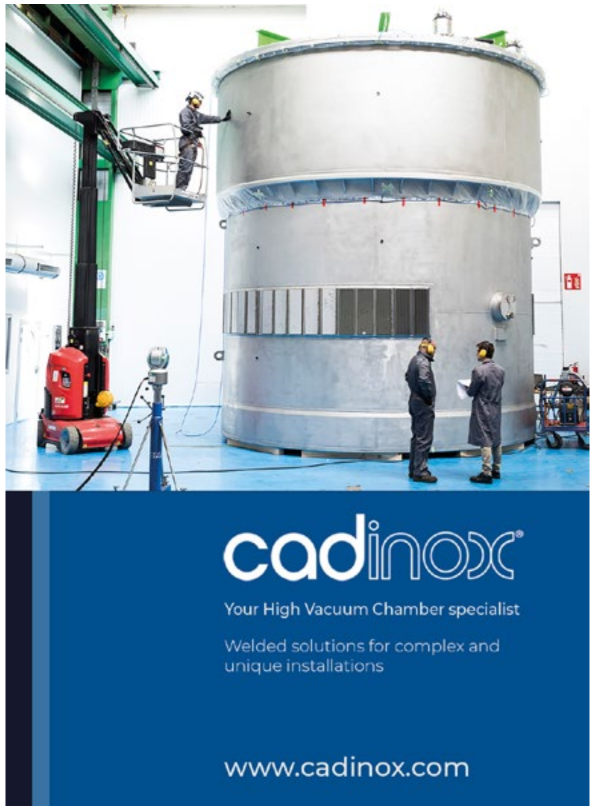


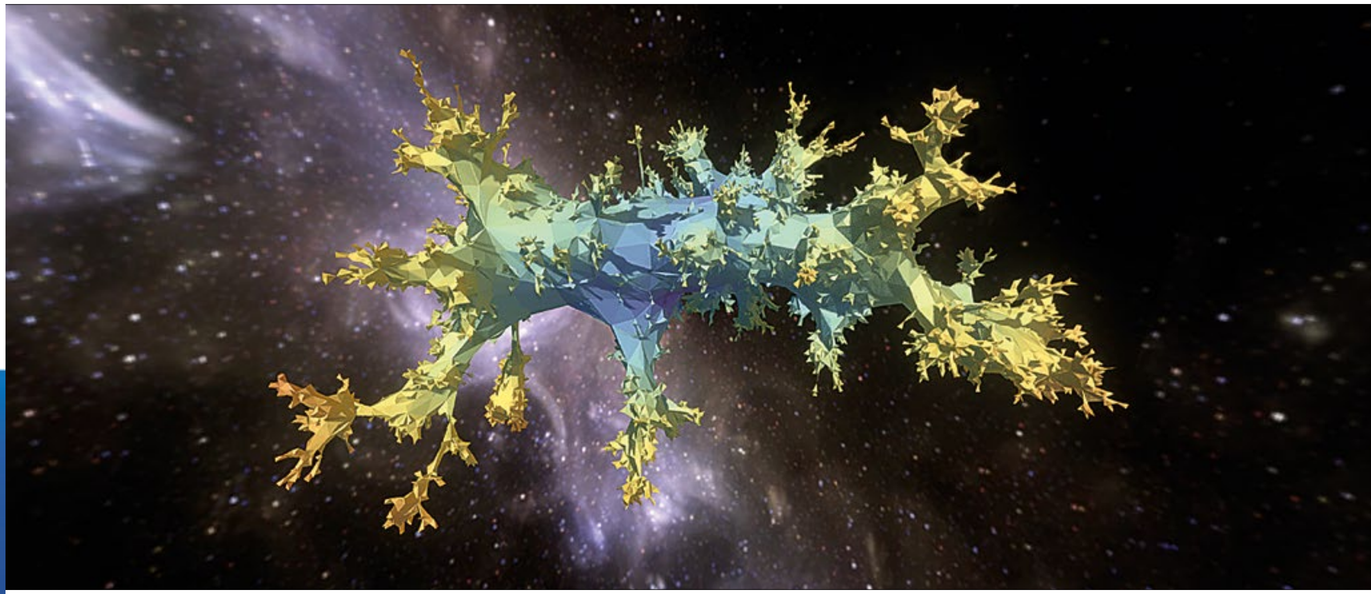












Under the microscope *A snapshot of a quantum spacetime obtained from Monte Carlo simulations (front). If the quantum spacetime is not resolved with sufficient resolution, only the spacetime of classical general relativity (background) is observed. (Credit: T Budd).*

A SAFE APPROACH TO QUANTUM GRAVITY

After 25 years of steady progress, recent advances in theory and computing are enabling researchers to connect an approach to quantum gravity called asymptotic safety to the Standard Model. Frank Saueressig and Maximilian Becker explain the power and potential of this approach.

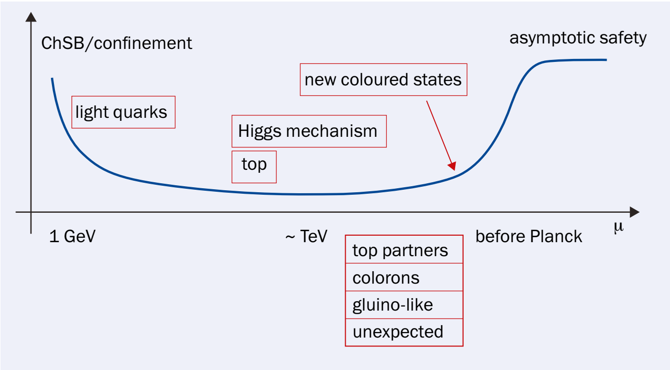
The LHC experiments at CERN have been extremely successful in verifying the Standard Model (SM) of particle physics to very high precision. From the theoretical perspective, however, this model has two conceptual shortcomings. One is that the SM appears to be an "effective field theory" that is valid up to a certain energy scale only; the other is that gravity is not part of the model. This raises the question of what a theory comprising particle physics and gravity that is valid for all energy scales might look like. This directly leads to the domain of quantum gravity.

The typical scale associated with quantum-gravity effects is the Planck scale: 10^{15} TeV, or 10^{-35} m. This exceeds the scales accessible at the LHC by approximately 14 orders of magnitude, forcing us to ask: what can theorists possibly gain from investigating physics at energies beyond the Planck scale? The answer is simple: the SM includes many free parameters that must be fixed by experimental data. Since the number of these parameters proliferates when higher order interactions are included, one would like to constrain this high-dimensional parameter space.

At low energies, this can be done by implementing bounds derived from demanding unitarity and causality of physical processes. Ideally, one would like to derive similar constraints from consistency at trans-Planckian scales where quantum-gravity effects may play a major role. At first sight, this may seem counterintuitive. It is certainly true that gravity treated as an effective field theory itself does not yield any effect measurable at LHC scales due to its weakness; the additional constraints then arise from requiring that the effective field theories underlying the SM and gravity can be combined and extended into a

THE AUTHORS

Frank Saueressig *and* **Maximilian Becker** *Radboud University Nijmegen.*



F Sannino

Safety belt *An illustration showing what the QCD running coupling α_S could look like when moving from the infrared to the ultraviolet.*

framework that is valid at all energy scales. Presumably, this will not work for all effective field theories. Taking a "bottom-up" approach (identifying the set of theories for which this extension is possible) may constrain the set of free parameters. Conversely, to be phenomenologically viable, any theory describing trans-Planckian physics must be compatible with existing knowledge at the scales probed by collider experiments. This "top-down" approach may then constrain the potential physics scenarios happening at the quantum-gravity scale – a trajectory that has been followed, for example, by the swampland programme initiated from string theory at all scales.

From the theoretical viewpoint, the SM is formulated in the language of relativistic quantum field theories. On this basis, it is possible that the top-down route becomes more realistic the closer the formulation of trans-Planckian physics sticks to this language. For example, string theory is a promising candidate for a consistent description of trans-Planckian physics. However, connecting the theory to the SM has proven to be very difficult, mainly due to the strong symmetry requirements underlying the formulation. In this regard, the "asymptotic safety" approach towards quantum gravity may offer a more tractable option for implementing the top-down idea since it uses the language of relativistic quantum field theory.

Asymptotic safety

What is the asymptotic-safety scenario, and how does it link quantum gravity to particle physics? Starting from the gravity side, we have a successful classical theory: Einstein's general relativity. If one tries to upgrade this to a quantum theory, things go wrong very quickly. In the early 1970s, it was shown by Gerard 't Hooft and Martinus Veltman that applying the perturbative quantisation techniques that have proved highly successful for particle-physics theories fail for general relativity. In short, it introduces an infinite number of parameters (one for each allowed local interaction) and thus requires an infinite number of independent measurements to determine what the values of those parameters are. Although this path leads us to a quantum theory of gravity valid at all scales, the construction lacks predictive power. Still, it results in a perfectly predictive effective field theory describing gravity up to the Planck scale.

The asymptotic-safety approach towards quantum gravity may offer a more tractable option for implementing the top-down idea

This may seem discouraging when attempting to formulate a quantum field theory of gravity without introducing new symmetry principles, for example supersymmetry, to remove additional free parameters. A loophole is provided by Kenneth Wilson's modern understanding of renormalisation. Here, the basic idea is to organise quantum fluctuations according to their momentum and integrate-out these fluctuations, starting from the most energetic ones and proceeding towards lower energy modes. This creates what is called the Wilsonian renormalisation-group "flow" of a theory. Healthy high-energy completions are provided by renormalisation-group fixed points. At these special points the theory becomes scale-invariant, which ensures the absence of divergences. The fixed point also provides predictive power via the condition that the renormalisation-group flow hits the fixed point at high energies (see "Safety belt" figure). For asymptotically-free theories, where all interactions switch off at high energies, the underlying renormalisation-group fixed point is the free theory. This can be seen in the example of quantum chromodynamics (QCD): if the QCD gauge coupling diminishes when going to higher and higher energies, it approaches a fixed point at arbitrary high energies that is non-interacting. One can also envision high-energy completions based on a renormalisation-group fixed point with non-vanishing interactions, which is commonly referred to as asymptotic safety.

Forces of nature

In the context of gravity, the asymptotic-safety scenario was first proposed by Steven Weinberg in the late 1970s. Starting with the seminal work by Martin Reuter (University of Mainz) in 1998, the existence of a renormalisation-group fixed point suitable for rendering gravity asymptotically safe – the so-called Reuter fixed point – is supported by a wealth of first-principle computations. While similar constructions are well known in condensed-matter physics, the Reuter fixed point is distinguished by the fact that it may provide a unified description of all forces of nature. As such, it may have profound consequences for our understanding of the physics inside a black hole, give predictions for parameters of the SM such as the Higgs-boson mass, or disfavour certain types of physics beyond the SM.

The predictive power of the fixed point arises as follows. Only a finite set of parameters exist that describe consistent quantum field theories emanating from the fixed point. One then starts to systematically integrate-out quantum fluctuations (from high to low energy), resulting in a family of effective descriptions in which the quantum fluctuations are taken into account. In practice, this process is implemented by the running of the theory's couplings, generating what are known as renormalisation-group trajectories. To be phenomenologically viable, the endpoint of the renormalisation group trajectory must be compatible with observations. In the end, only one (or potentially none) of the trajectories emanating from the fixed point will provide a description of nature (see "Going with the flow" image). According to the asymptotic-safety principle, this trajectory must be identified by fixing the free parameters left by the fixed point based on experiments. Once this process is completed, the construction fixes all couplings in the effective field theory in terms of a few free parameters. Since this entails an infinite number of relations that can be probed experimentally, the construction is falsifiable.

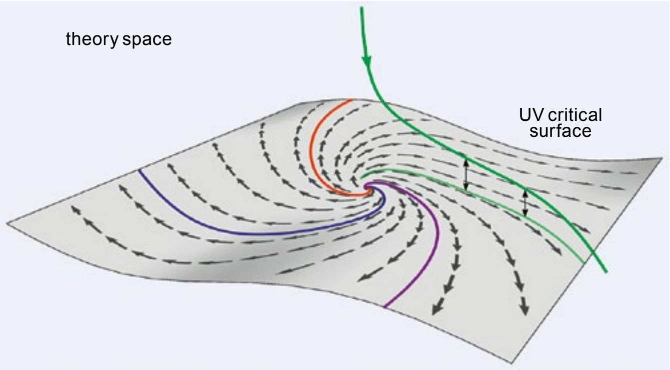
Particle physics link

The link to particle physics follows from the observation that the asymptotic-safety construction remains operative once gravity is supplemented by the matter fields of the SM. Non-abelian gauge groups – such as those underlying the electroweak and strong forces, Yukawa interactions and fermion masses – are readily accommodated. A wide range of proof-of-concepts show that this is feasible, gradually bringing the ultimate computation involving the full SM into reach. The fact that gravity remains interacting at the smallest length scales too implies that the construction will feature non-minimal couplings between matter and the gravitational field as well as matter self-interactions of a very specific type. The asymptotic-safety mechanism may then provide the foundation for a realistic quantum field theory unifying all fundamental forces of nature.

Can particle physics tell us whether this specific idea about quantum gravity is on the right track? After all there still exists the vast hierarchy between the energy scales probed by collider experiments and the Planck scale. Surprisingly, the answer is positive! Conceptually, the interacting renormalisation-group fixed point for the gravity–matter theory again gives a set of viable quantum field theories in terms of a fixed number of free parameters. First estimates conducted by Jan Pawlowski and coworkers at Heidelberg University suggest that this number is comparable to the number of free parameters in the SM.

In practice, one may then be tempted to make the following connection. Currently, observables probed by collider physics are derived from the SM effective field theory. Hence, they depend on the couplings of the effective field theory. The asymptotic-safety mechanism expresses these couplings in terms of the free parameters associated with the interacting fixed point. Once the SM effective field theory is extended to include operators of sufficiently high mass dimension, the asymptotic-safety dictum predicts highly non-trivial relations between the couplings parameterising the effective field theory. These relations can be confronted with observations that test whether the observables measured experimentally are subject to these constraints. This can either be provided by matching to existing particle-physics data obtained at the LHC, or by astrophysical observations probing the strong-gravity regime. The theoretical programme of deriving such relations is currently under development. A feasible benchmark, showing that the underlying physics postulates are on the right track, would then be to "post-dict" the experimental results already available. Showing that a theory formulated at the Planck scale is compatible with the SM effective field theory would be a highly non-trivial achievement in itself.

This line of testing quantum gravity experimentally may be seen as orthogonal to more gravity-focused tests that attempt to decipher the quantum nature of gravity. Recent ideas in these directions have evolved around developing tabletop experiments that probe the quantum superposition of macroscopic objects at sub-millimetre scales, which could ultimately be developed into a quantum-Cavendish experiment that probes the gravitational field of source masses in spatial quantum superposition states. The emission of a graviton could then lead to decoherence effects which give hints that gravity indeed has a force carrier similar to the other fundamental forces. Of course, one could also hope that experiments probing gravity in the strong-gravity regime find deviations from general relativity. So far, this has not been the case. This is why particle physics may be a prominent and fruitful arena in which to also test quantum-gravity theories such as asymptotic safety in the future.



&reasNink/Wikipedia

Going with the flow *A visualisation of a 3D space of couplings with an interacting renormalisation group fixed point and its ultraviolet (UV) critical surface.*

For decades, quantum-gravity research has been disconnected from directly relevant experimental data. As a result, the field has developed a vast variety of approaches that aim to understand the laws of physics at the Planck scale. These include canonical quantisation, string theory, the AdS/CFT correspondence, loop quantum gravity and spin foams, causal dynamical triangulations, causal set theory, group field theory and asymptotic safety. The latter has recently brought a new perspective on the field: supplementing the quantum-gravity sector of the theory by the matter degrees of freedom of the SM opens an exciting window through which to confront the construction with existing particle-physics data. As a result, this leads to new avenues of research at the intersection between particle physics and gravity, marking the onset of a new era in quantum-gravity research in which the field travels from a purely theoretical to an observationally guided endeavour. ●

Showing that a theory formulated at the Planck scale is compatible with the SM effective field theory would be a highly non-trivial achievement in itself

Further reading

M Reuter and F Saueressig 2019 *Quantum Gravity and the Functional Renormalization Group: The Road towards Asymptotic Safety* (Cambridge University Press).
F Saueressig 2023 In *Handbook of Quantum Gravity* (eds C Bambi, L Modesto and I L Shapiro; Springer) arXiv:232.14152.
A Eichhorn and M Schiffer 2023 In *Handbook of Quantum Gravity* (eds C Bambi, L Modesto and I L Shapiro; Springer) arXiv:2212.07456.
Á Pastor-Gutiérrez *et al.* 2023 *SciPost Phys.* **15** 105; arXiv:2207.09817.

CERNCOURIER
Volume 64 Number 3 May/June 2024
www.
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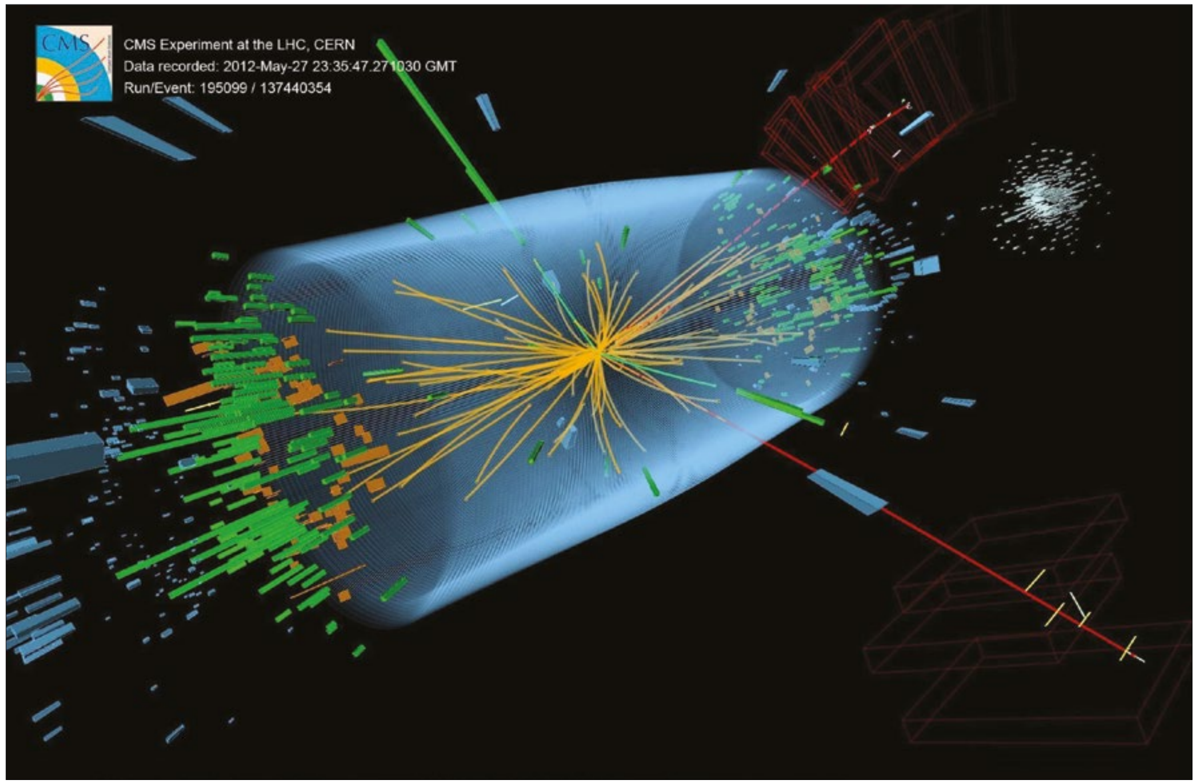
Element Six Synthetic Diamond Protects CERN Particle Detectors in Higgs boson Experiment Results



Back in 2012, CERN (European Organization for Nuclear Research) particle detection systems used Element Six synthetic diamond in their first line of defence against beam-induced radiation damage in their Higgs boson experiment results.

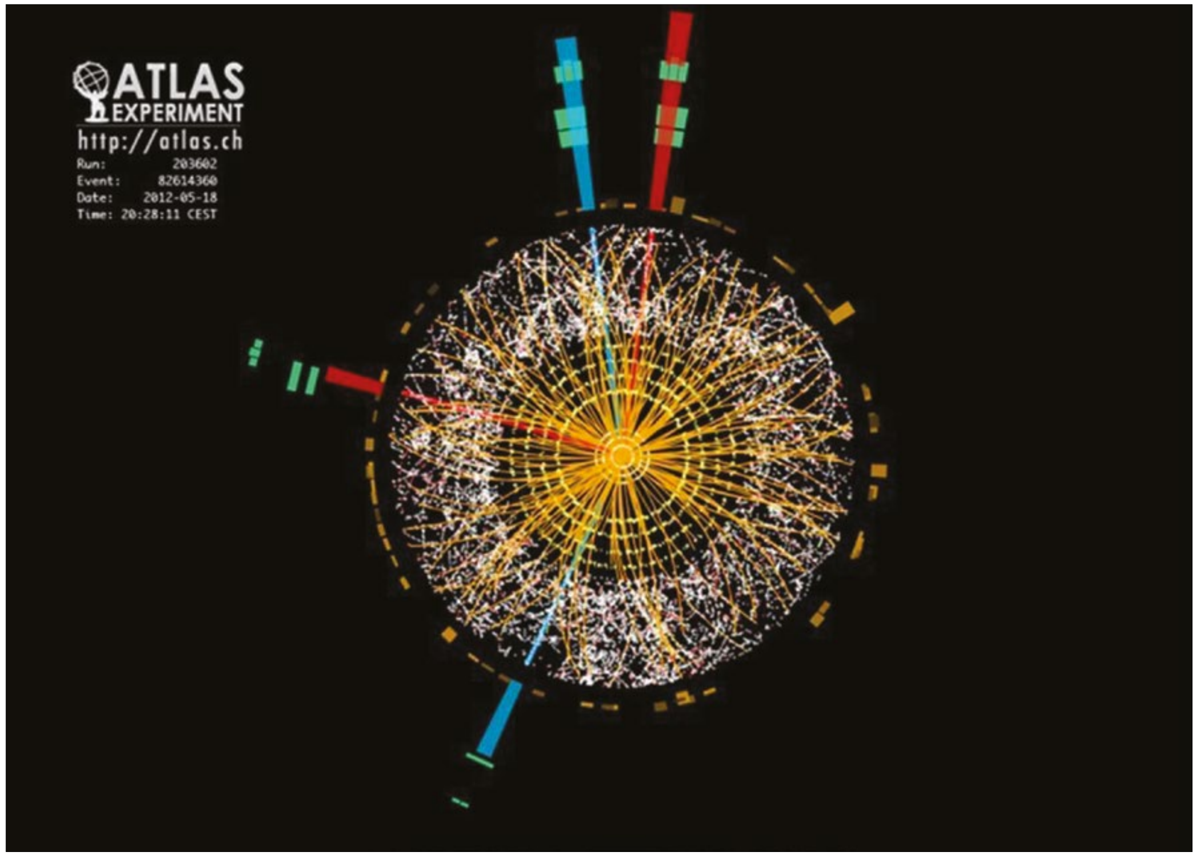
Element Six, a world leader in synthetic diamond supermaterials, supplied its highest purity synthetic diamond as an integral part of the CERN LHC (Large Hadron Collider) CMS (Compact Muon Solenoid) and ATLAS Beam Condition Monitoring Systems, used in the milestone experiments which revealed the discovery of the Higgs boson.

"The diamond synthesised by Element Six measures LHC beam conditions in key areas of the main experiments that have been used in the search for the Higgs boson," said Heinz Pernegger, CERN scientist at the ATLAS experiment.

"The CMS experiment relies on the stability of the synthetic diamond sensors produced by Element Six to monitor the LHC beam arriving to the CMS experiment and the particles created in the collision. The robustness of this synthetic diamond-based system is crucial in protecting the most sensitive components of the 66 million channel pixel-tracking detector," said Anna Dabrowski, CERN scientist at the CMS experiment.

"The use of synthetic diamond sensors was essential for a smooth operation of the LHC and the collection of high quality data by the LHC experiments, making the observation of the new particle possible," concluded Professor Wolfgang Lohmann from the Brandenburg University of Technology.

Element Six electronic grade synthetic diamond was selected as the optimum detector material by CERN scientists over the decade-long development of CERN's CMS and ATLAS Beam Condition Monitoring Systems. Synthetic diamond was shown to be the most robust sensor material available which could withstand the harsh, high radiation environment and react almost instantaneously to be able to protect the advanced measurement systems.



Element Six manufactures the synthetic diamond used in the detectors using a process called chemical vapour deposition (CVD). This process takes a mixture of gases and forms plasma with the extreme high temperature of a sun spot to allow carbon to precipitate onto a substrate layer as synthetic diamond.

The purpose of the CERN CMS and ATLAS experiments was to count, track and characterise the different particles produced from the particle collisions inside the LHC. The synthetic diamond detectors in the monitoring system protected the experiments from adverse beam conditions and contributed to the luminosity measurement, which was crucial for obtaining the five sigma result.

Leveraging Element Six's over 70 years of innovation leadership and patented technology, the grades of synthetic diamond used in these monitoring systems are grown to ultra high levels of purity, incorporating less than one part per billion of boron, and less than 50 parts per billion of nitrogen. When diamond is synthesised with these levels of purity, it becomes an ideal radiation detector material. It can exhibit properties such as very low leakage current with negligible temperature dependence, a fast signal response and a vastly improved radiation hardness and reduction of leakage-current compared to silicon, the material traditionally used for detectors.

Dr Daniel Twitchen, Chief Technologist at Element Six, said:

"We are incredibly proud of the small, but important, contribution our synthetic diamond has made in helping the CMS and ATLAS experiments that enabled the team at CERN realise their milestone discoveries."

"This is yet another demonstration of why synthetic diamond is an ideal advanced engineering material capable of delivering extreme performance in the toughest environments. At Element Six, we are committed to engineering and manufacturing the highest purity synthetic diamond to help our partners meet their scientific and technology application challenges."

Professor Dr. Erich Griesmayer, CEO at CIVIDEC, with more than 20 years' experience of working at CERN, added:

"Beam condition monitoring is critical to the safe operation of the LHC at CERN. The diamond synthesised by Element Six was able to provide that protection in key areas of the main experiments that have been used in the search for the Higgs boson. Now that the synthetic diamond has been proven in this application, there is scope for its further use in medicine such as radiation therapy and diagnostic imaging."

To find out more about Element Six's collaboration with CIVIDEC, read the related case study here

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OPINION
INTERVIEW

Strengthening science in Europe

Theoretical cosmologist Mairi Sakellariadou discusses her goals as president of the European Physical Society and the importance of supporting curiosity-driven research.

Why theoretical cosmology?
I was first trained as a mathematician, and then as a physicist. I've always worked at the interface between theory and data, where one of the most interesting things is to test cosmological models inspired by some fundamental theory. For example, you can create a model based on string theory or on a non-perturbative approach to quantum gravity, and then use data to constrain the quantum gravity theory. Today we receive a wealth of data from different kinds of experiments, which allows us to test early-universe models without relying on *ad hoc* ideas. Although it is not something I directly work on, the current tension in the value of the Hubble constant serves as an example. This of course could be telling us something about new physics, but it seems to me it is more likely to be an issue with the way we interpret data and apply the same models across different scales. Supernovae are taken as "standard candles" when measuring the expansion rate of the universe, for example, and one may wonder how correct this assumption is. It is important to perform systematic studies of the raw data before we rush to new theories.

My current work mainly bears on gravitational waves. I am also editor-in-chief of the journal *General Relativity and Gravitation*. I joined the LIGO collaboration the year of the discovery, studying the implications of gravitational-wave background searches for new physics. I am working on similar studies for the proposed Einstein Telescope. Gravitational waves allow us to test high-energy models beyond the Standard Model at energy scales that are above those that can be reached by accelerators. There are also new results coming from pulsar timing arrays. We live in a time where many exciting results are coming fast.

Clear goals *Mairi Sakellariadou, professor of theoretical physics at King's College London, became EPS president on 30 March 2024.*

CMW

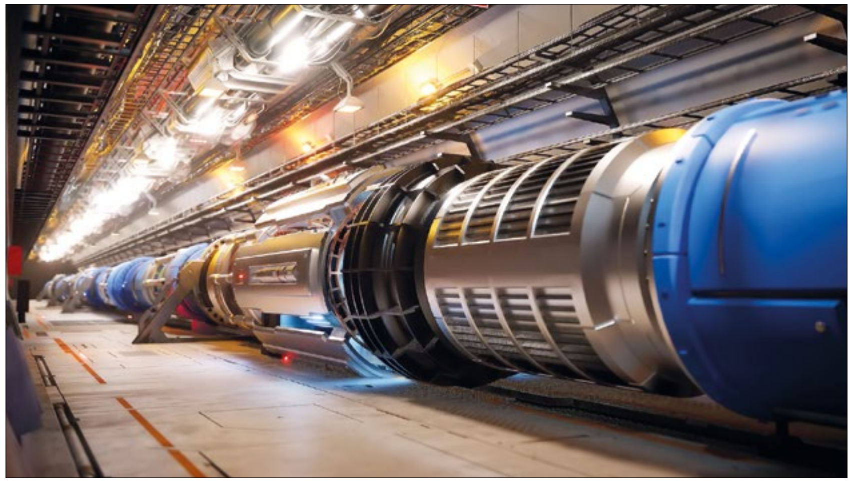
How big is the European Physical Society, and what led you to be elected president?
The European Physical Society (EPS) is the federation of all national physics societies in Europe. It was founded in 1968 by particle physicist Gilberto Bernardini, who contributed to the foundation of CERN and later became director of the Synchrocyclotron division and directorate member for research.

Several years ago, following the LIGO/Virgo discoveries, I initiated the gravitational physics division of the EPS and, in doing so, entered the EPS council. Then I was elected a member of the executive committee and was eventually contacted to run for election. I admit that I was reluctant at first because it's another task with a lot of responsibilities. But it turned out I was elected, and I took up the position formally on April 27th. I am proud to have been elected as president and I will do my best to serve the EPS and respect the confidence that representatives of so many European national societies have put in me.

What do you hope to achieve during your two-year mandate?
I have several goals as president. The most important one is to strengthen the position of Europe. What do I mean by that? There are important issues that we all face together, such as our economic independence (for instance, sources of energy, technological advances in electronics, biophysics and medical applications) and the preservation of the environment. The EPS can play a role by building teams of experts to address these issues, to be in a position to advise policy makers at the European level.

Scientific policy is another example. We live in an era with very large changes in the scale of experiments, the size of datasets, as well as advanced data-analysis techniques such as artificial intelligence. We should be able to have a say about how these things are dealt with and what the priorities are. The EPS can have a solid dialogue with large experimental teams and important research centres such as CERN. We can pass the message, for example via the national physics societies, and provide lists of experts to advise politicians on such matters.

Last but not least is education. We need to adapt the programmes offered to the students because there is huge demand for soft skills, and I am not sure they are adequately provided. We also need to offer opportunities to welcome students and early-career researchers from regions around the world that need support. We should collaborate with them and provide scholarships to enable them to spend time at a facility such as CERN or DESY and develop key skills.


Pixel Rise

Collider talk *The EPS can support constructive dialogue about major projects such as the proposed Future Circular Collider at CERN.*

> Money can't go to everyone in equal amounts, so we need a way to set scientific priorities in Europe

To achieve all that, we should strengthen the links between the EPS and the national societies (be they small or large). We represent the interest of all physicists in Europe equally. We also need to have a more active dialogue with our colleagues in North America and Asia because we share common challenges. Of course, to do that requires hard work and commitment.

How can the EPS support fundamental research such as particle physics?

We have a high-energy physics division, of course. From my point of view, we need to accentuate the motivation for exploring the laws of the universe. CERN obviously plays a key role in this because colliders are one of the basic experimental devices to do so. Gravitational-wave observatories are another example. These experiments have to go hand-in-hand because they have a common ambition. The EPS can give an extra voice to the scientific aspects of this enterprise. Of course, the question of financing next-generation experiments remains to be solved, as well as the balance between fundamental science and applied research. For me there is no doubt that such experiments should continue. Unfortunately, today one often has to state the implications for industry and the applications for society. This can sometimes be difficult to square with curiosity-driven science.

If approved, would a new collider at CERN take away funding from other fields?

This is a very simplistic view. Science funding is not a zero-sum game. As CERN did for the LHC, it's good to find external sources. Money can't go to everyone in equal amounts, so we need a way to set scientific priorities in Europe. First and foremost, this should take into account the scientific case. Then we should look at the number of countries that are interested and the level of investments that have been made – for example, also involving industry.

Is the scientific case for the Future Circular Collider sufficiently clear in this respect?

If the argument is to find supersymmetry, or particles predicted by some other framework of physics beyond the Standard Model, then I'm afraid it will fail. Of course, in scientific working groups you need to go into specifics such as which hypotheses will be tested, and which signatures are possible. But such detail is a trap when engaging with broader audiences because we can't be sure that such things exist at the energies we can explore. Instead, the argument should be that we try to understand better the elementary particles and laws. We need to pass the message to politicians, to the person on the street and to scientists that there are some important questions that can only be addressed with future colliders. While CERN and particle physicists should not be defensive, they should be clearer about what the role and ultimate hope of a collider is. Then there is no argument that can go against it. This is something that could be elaborated by the high-energy physics division of the EPS, for example by providing a document stating the views of particle physicists. We should also be prepared for a critical dialogue, to identify the strengths and weaknesses of the arguments. One should in any case ensure that anyone invited to give their views should have an established scientific reputation within their field, a prerequisite that is not met in some high-level discussions and media outlets.

Does the existence of several future-collider options pose a problem from a communications perspective?

I think it's problematic if, scientifically, a consensus cannot be reached. There is something similar going on in the gravitational-wave community, where divisions exist about where to build the Einstein Telescope and which configuration it should have. This may lead to a healthy process of course, but discussions should be kept between experts. Indeed, it can weaken the case for a new experiment if scientists are seen to be disagreeing strongly.

What effects are current political shifts in Europe having on physics?

I'm afraid that there could be very negative effects. To this we have to add the risks created by the conflicts we see expanding. One effect could also be the changes in priorities for funding. As one of the largest scientific societies, we need to keep supporting collaborations among scientists no matter their country of origin, ethnicity, gender, or any other discriminating factor. We also need to provide financial support where possible, for example as we have done recently for Ukrainian colleagues to participate in our activities, and to make statements in response to events going way beyond the world of physics.

Interview by **Matthew Chalmers** *editor.*

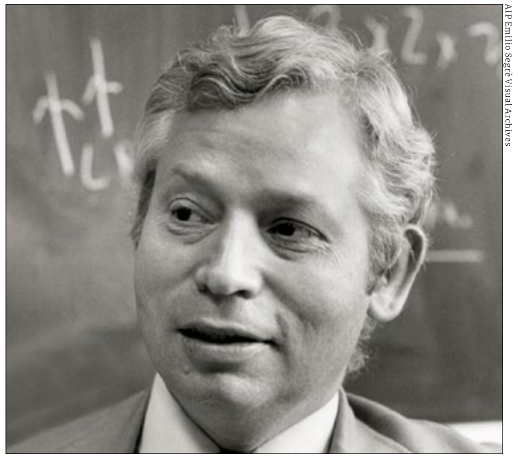
OPINION REVIEWS

A logical freight train

Steven Weinberg – Selected Papers

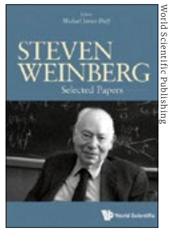
Edited by Michael Duff

World Scientific



AIP Emilio Segrè Visual Archives

Steven Weinberg *Required reading for graduate students in particle theory.*



World Scientific Publishing

Steven Weinberg was a logical freight train – for many, the greatest theorist of the second half of the 20th century. It is timely to reflect on his legacy, the scientific component of which is laid out in a new collection of his publications selected by theoretical physicist Michael Duff (Imperial College).

Six chapters cover Weinberg's most consequential contributions to effective field theory, the Standard Model, symmetries, gravity, cosmology and short-form popular science writing. I can't identify any notable omissions and I doubt many others would, though some may raise an eyebrow at the exclusion of his paper deriving the Lee–Weinberg bound. Duff brings each chapter to life with first-hand anecdotes and details that will delight those of us most greatly separated from historical events. I am relatively young, and only had one meaningful interaction with Steven Weinberg. Though my contemporaries and I inhabit a scientific world whose core concepts are interwoven with, if not formed by, Steven Weinberg's scientific legacy, unlike Michael Duff we are poorly qualified to comment historically on the ecosystem in which this legacy grew, nor on aspects of personality. This makes his commentary particularly valuable to younger readers.

I can envisage three distinct audiences for this new collection. The first is the lay theorist – those who are widely enough read to recognise the depth of Weinberg's impact in theoretical physics and would like to know more. Such readers will find Duff's introductions to be insightful and entertaining – helpful preparation for the more technical aspects of the papers, though expertise is required to fully grapple with many of them. There are also a few hand-picked non-technical articles one would otherwise not encounter without some serious investigative effort, including some accessible articles on quantum field theory, effective field theory and life in the multiverse, in addition to the dedicated section on popular writings. These will delight any theory aficionado.

The second audience is practising theorists. If you're going to invest in a printed collection of publications, then Weinberg is an obvious protagonist. Particle theorists consult his articles so often that they may as well have them close at hand. This collection contains those most often revisited and ought to be useful in this respect. Duff's introductions also expose technical interconnections between the articles that might otherwise be missed.

The third audience I have in mind are beginning graduate students in particle theory, cosmology and beyond. It would not be a mistake to put this collection on recommended reading lists. In due course, most students should read many of these papers multiple times, so why not get on with it from the get-go? The section on effective field theories (EFTs) contains many valuable key ideas and perspectives. Plenty of those concepts are still commonly encountered more by osmosis than with any rigour, and this can lead to confused notions around the general approach of EFT. Perhaps an incomplete introduction to EFT could be avoided for graduate students by cutting straight to the fundamentals contained here? The cosmology section also reveals many important modern concepts alongside lucid and fearless wrestling with big questions. The papers on gravity detail techniques that are frequently encountered in any first foray into modern amplitudology, as well as strategies to infer general lessons in quantum field theory from symmetries and self-consistency alone.

In my view, however, the most important section for beginning graduate students is that on the construction of the Standard Model (SM). It may be said that a collective amnesia has emerged regarding the scientific spirit that drove its development. The SM was built by model builders. I don't say this facetiously. They made educated guesses about the structure of the "ultraviolet" (microscopic) world based on the "infrared" (long-distance) breadcrumbs embedded within low-energy experimental observations. Decades after this swashbuckling era came to an end, there is a growing tendency to view the SM as something rigid, providentially bestowed and permanent. The academic bravery and risk-taking that was required to take the necessary leaps forward then, and which may be required now, is no better demonstrated than in "A Model of Leptons". All young theorists should read this multiple times. A Model of Leptons exemplifies that not only was Steven Weinberg an unstoppable force of logic, but also a plucky risk taker. It's inspirational that its final paragraph, which laid out the structure of nature at the electroweak scale, ends with doubt and speculation: "And if this model is renormalisable, then what happens when we extend it to include the couplings of A and B to the hadrons?" By working their way through this collection, graduate students may be inspired to similar levels of ambition and jeopardy.

In the weeks that followed the passing of Stephen Weinberg, I sensed amongst a number of colleagues of all generations some moods that I could have anticipated; of the loss of not only a *bona fide* truth-seeker, but also of a leader, frequently *the* leader. I also perceived a feeling that transcended the scientific realm alone, of someone whose ▷

creative genius ought to be recognised amongst the greatest of scientists, musicians, artists and humanity of the last century. How can we productively reflect on that? I imagine we would all do well to learn not only of Weinberg's important individual scientific insights, but also to attempt to absorb his overall methodology in identifying interesting questions, in breaking new trails in fundamental physics, and in pursuing logic and clarity wherever they may take you. This collection is not a bad place to start.

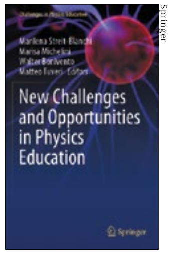
Amongst the greatest scientists of the last century

Matthew McCullough *CERN.*

New Challenges and Opportunities in Physics Education

Edited by Marilena Streit-Bianchi, Marisa Michelini, Walter Bonivento and Matteo Tuveri

Springer



Springer

New Challenges and Opportunities in Physics Education presents itself as a guidebook for high-school physics educators who are navigating modern challenges in physics education. But whether you're teaching the next generation of physicists, exploring the particles of the universe, or simply interested in the evolution of physics education, this book promises valuable insights. It doesn't aim to cater to all equally, but rather to offer a spark of inspiration to a broad spectrum of readers.

The book is structured in two distinctive sections on modern physics topics and the latest information and communication technologies (ICTs) for classrooms. The editors bring together a diverse blend of expertise in modern physics, physics education and interdisciplinary approaches. Marilena Streit-Bianchi and Walter Bonivento are well known names in high-energy physics, with long and successful careers at CERN. In parallel, Marisa Michelini and Matteo Tuveri are pushing the limits of physics education with modern educational approaches and contemporary topics. All four are committed to making physics education engaging and relevant to today's students.

The first part presents the core concepts of contemporary physics through a variety of narrative techniques, from historical recounting to imaginary dialogues, providing educators with a toolbox of resources to engage students in various learning scenarios. Does the teacher want to "flip the classroom" and assign some reading? They can read about the scientific contributions of Enrico Fermi by Salvatore Esposito. Does the teacher want to encourage discussions? Mariano Cadoni and Mauro Dorato have got their back with a unique piece "Gravity between Physics and Philosophy", which can support interdisciplinary classroom discussions.

The second half of the book starts with an overview of ICT resources and classical physics examples on how to use them in a classroom setting. The authors then explore the skills that teachers and students need to effectively use ICTs. The transition to ICT feels a bit too long, and the book struggles to weave the two sections into a cohesive narrative, but the second half nevertheless captures the title of the book perfectly – ICTs are the epitome of new opportunities in physics education. While much has been said about them in other works, this book offers a cherry-picked but well rounded collection of ideas for enhancing educational experiences.

The authors not only emphasise modern physics and technology, but also another a very important characteristic of modern science: collaboration. This is an important message that we need to convey to students, as mere historical examples from classical physics sometimes show an elitist view of physics. Lone-genius narratives are often explicitly transitioned to a collaborative understanding of breakthroughs.

The book would not be complete without input from actual teachers. One notable contribution is by Michael Gregory, a particle-physics educator who shares his experiences with distance learning together with Steve Goldfarb, the former IPPOG co-chair. During the pandemic, he used online tools to convey physics concepts not only to his own students, but to students and teachers around the world. As such, his successful virtual science camps and online particle-physics courses reached frequently overlooked audiences in remote locations.

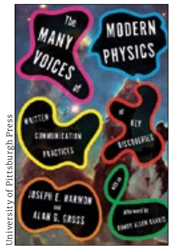
Overall, *New Challenges and Opportunities in Physics Education* emerges as a valuable resource for a diverse audience. It is a guidebook for educators searching for innovative strategies to spice up their physics teachings or to better weave modern science into their lessons. Although it might fall short of flawlessly joining the modern-physics content with educational elements in the second half, its value is undeniable. The first part, in particular, serves as a treasure trove not only for educators but also for science communicators and even particle physicists seeking to engage with the public, using the common ground of high-school physics knowledge.

Anja Kranjc Horvat *CERN.*

The Many Voices of Modern Physics: Written Communication Practices of Key Discoveries

By Joseph E Harmon and Alan G Gross

University of Pittsburgh Press



University of Pittsburgh Press

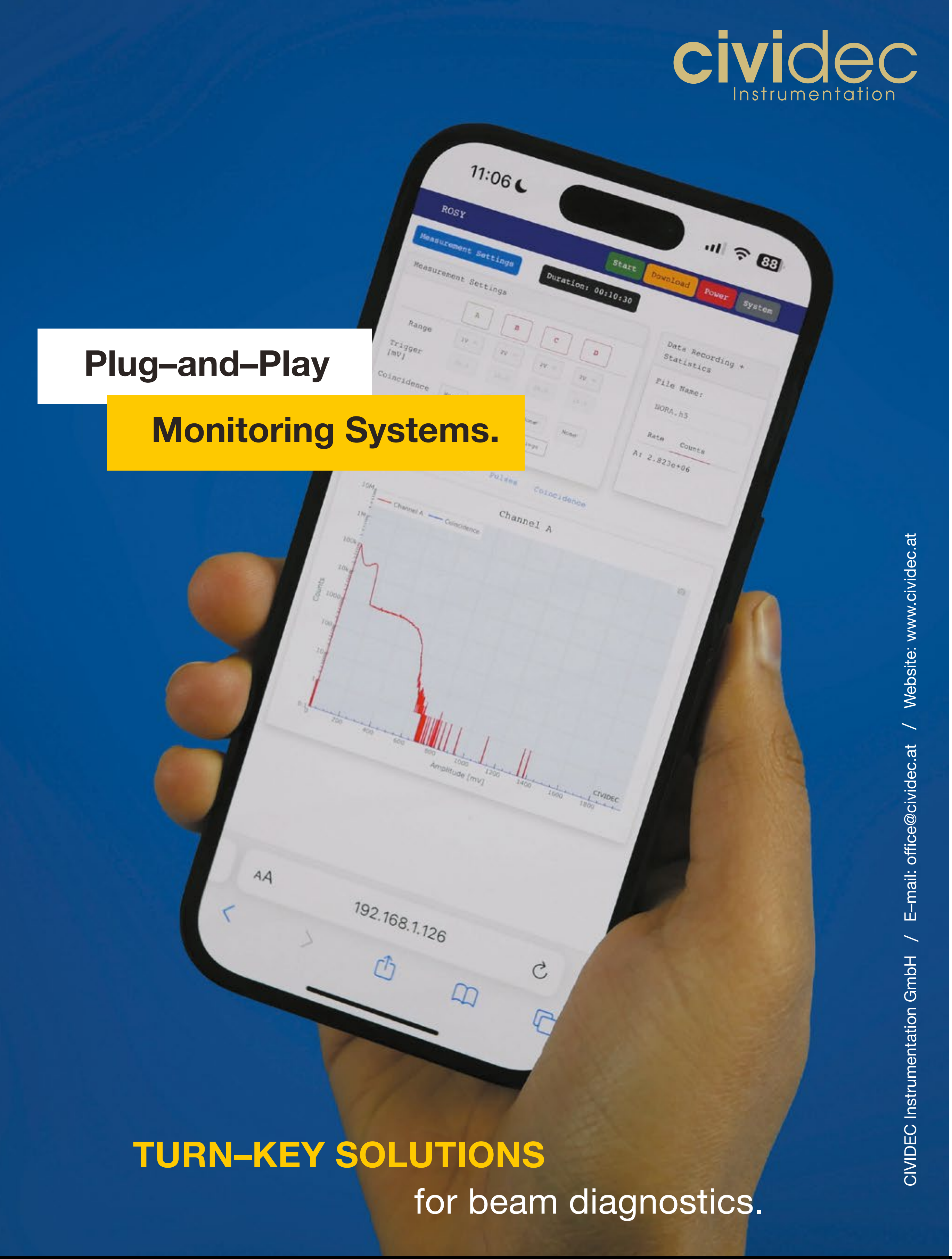
This book provides a rich glimpse into written science communication throughout a century that introduced many new and abstract concepts in physics. It begins with Einstein's 1905 paper "On the Electrodynamics of Moving Bodies", in which he introduced special relativity. Atypically, the paper starts with a thought experiment that helps the reader follow a complex and novel physical mechanism. Authors Harmon and Gross analyse and explain the terminological text and bring further perspective by adding comments made by other scientists or science writers during that time. They follow this analysis style throughout the book, covering science from the smallest to the largest scales and addressing the controversies surrounding atomic weapons.

The only exception from written evaluations of scientific papers is the chapter "Astronomical value", in which the authors revisit the times of great astronomers such as Galileo Galilei or the Herschel siblings William and Caroline. Even back then, researchers were in need of sponsors and supporters to fund their research. In Galilei's case, he regularly presented his findings to the Medici family and fuelled fascination in his patrons so that he was able to continue his work.

While writing the book, Gross, a rhetoric and communications professor, died unexpectedly, leaving Harmon, a science writer and editor at Argonne National Laboratory in communications, to complete the work.

While somewhat repetitive in style, readers can pick a topic from the contents and see how scientists and communicators interacted with their audiences. While in-depth scientific knowledge is not required, the book is best targeted at those familiar with the basics of physics who want to gain new perspectives on some of the most important breakthroughs during the past century and beyond. Indeed, by casting well-known texts in a communication context, the book offers analogies and explanations that can be used by anyone involved in public engagement.

Sanje Fenkart *CERN.*



Sabbatical in space

Project astronaut and CERN engineer Sławosz Uznański points to the growing opportunities for high-energy physicists and engineers in space.


P Traczyk/CERN

From CERN to ESA *Project astronaut Sławosz Uznański.*

Sławosz Uznański had to bide his time. Since its foundation in 1975, the European Space Agency (ESA) had only opened four selection rounds for new astronauts. When a fresh opportunity arose in 2021, Uznański's colleagues in CERN's electric power converters group were supportive of his ambitions to take an extended sabbatical in space. Now confirmed as one of 17 astronauts selected from among more than 22,000 applicants, Uznański is in training for future missions to the International Space Station (ISS).

His new colleagues are a diverse bunch, including geologists, medical doctors, astrophysicists, biologists, biotechnologists, jet fighter pilots and helicopter pilots. His own background is as a physicist and systems engineer. Following academic work studying the effect of radiation on semiconductors, Uznański spent 12 years at CERN working on powering existing infrastructure and future projects such as the Future Circular Collider. He's most proud of being a project leader in reliability engineering and helping to design and deploy a new radiation-tolerant power-converter control system to the entire LHC accelerator complex.

Preparing for orbit

For now, Uznański's astronaut training is mostly theoretical, preparing him for the ISS's orbit-trajectory control, thermal control, communications, data handling, guidance, navigation and power generation, where he has deep expertise. But lift-off may not be far away, and one of his reserve-astronaut colleagues, Marcus Wandt, is already sitting up in the ISS capsule.

"I had the chance, in January, to see him launch from Cape Canaveral. And then, thanks to my operational experience at CERN, being in the control room, I came back directly to Columbus Control Center in Munich. Throughout the whole mission, I was in the control room, to support the mission and learn what I might live through one day."

Rather than expertise or physical fitness, Uznański sees curiosity as the golden thread for astronauts – not least because they have to be able to perform any type of experiment that is assigned to them. As a Polish astronaut, he will have responsibility for the scientific experiments that are intended to accompany his country's first mission to the ISS, most likely in late 2024 or early 2025. Among 66 proposals from Polish institutes, a dozen or more are currently being considered to fly.

The experiments are as diverse as the astronauts' professional backgrounds. One will non-invasively monitor astronauts' brain activity to help develop human–machine interfaces for artificial limbs. Another – a radiation monitor developed at CERN – plays on the fact that shielded high-energy physics environments have a similar radiation environment to the ISS in low-earth orbit. Uznański hopes that this technology can be commercialised and become another example of the opportunities out there for budding space entrepreneurs.

CERN is extremely open in terms of technologies and I very much identify myself with that

"I think we are in a fascinating moment for space exploration," he explains, pointing to the boom in the commercial sector since 2014. "Space technology has gotten really democratised and commercialised. And I think it opens up possibilities for all types of engineers who build systems with great ideas and great science."

Open science is a hot topic here. It's increasingly possible to access venture capital to develop related technologies, notes Uznański, and the challenge is to ensure that the science is used in an open manner. "There is a big overlap between CERN culture and ESA culture in this respect. CERN is extremely open in terms of technologies and I very much identify myself with that."

However societies choose to shape the future of open science in space, the two organisations are already partnering on several projects devoted to the pure curiosity that is dear to Uznański's heart. These range from Euclid's study of dark energy (*CERN Courier* May/June 2023 p7) to the ongoing study of cosmic rays by the Alpha Magnetic Spectrometer (AMS). With AMS due for an upgrade in 2026 (*CERN Courier* March/April 2024 p7), he cannot help but hope to be on that flight.

"If the opportunity arises, it's a clear yes from me."

Mark Rayner *CERN.*

Appointments and awards

University & INFN Bologna

New leadership for EuCAPT
Silvia Pascoli (above, University & INFN Bologna) has taken over as director of the European Consortium for Astroparticle Theory (EuCAPT), succeeding founding director Gianfranco Bertone (GRAPPA). EuCAPT brings together European astroparticle-physics researchers and has CERN as its home institution. It was formally established by the Astroparticle Physics European Consortium, APPEC. During her mandate, Pascoli will work on the strategic development of EuCAPT aided by David Marsh (Stockholm University) in his role as EuCAPT vice-president. Marsh is a cosmologist focusing on string compactifications, inflation theory and astronomical signals from axions. The last new addition is Francesca Calore (CNRS-LAPTh) as chair of EuCAPT council. Calore started out as a theoretical particle physicist and now works on searches for dark matter with astrophysical experiments.

EPS new president
Mairi Sakellariadou (King's College London) started her mandate as president of the European Physical Society (EPS) on 30 March, taking over from Luc Bergé (CEA). Sakellariadou specialises in theoretical cosmology, with an emphasis on the early universe. She is a member of the LIGO consortium that made the first direct detection of gravitational waves in 2015. During her time as president, Sakellariadou will lead the EPS executive committee and will work on promoting EPS activities as well strengthening scientific collaboration in Europe (see p49), placing a special focus on scientifically underrepresented countries and the visibility of women in physics.

VUB

Second term at J-PARC
Takashi Kobayashi (KEK) began a second term as director of the Japan Proton Accelerator Research Complex (J-PARC) on 1 April. A neutrino physicist and member of the long-baseline T2K experiment since 1999, Kobayashi will lead the lab for the next three years as it proceeds with a major beam-power upgrade. "Going forward, I see it as my mission to transform J-PARC into a research facility that contributes more to the advancement of humanity," he said in a statement.

J-PARC

ATLAS thesis awards
During the February ATLAS week, the collaboration celebrated the seven winners of the 2023 ATLAS PhD thesis awards. Joshua Beirer (CERN, University of Göttingen), Prajita Bhattarai (Brandeis University), Savannah Clawson (University of Manchester), Hassnae El Jarrari (Université Mohammed-V de Rabat), Nicole Hartman (Stanford & SLAC), Samuel Van Stroud (UCL) and Xiao Yang (University of Science and Technology of China) were awarded for their outstanding contributions to the ATLAS collaboration as doctoral students. Their theses span a wide range from the electroweak sector, via exotic physics to performance studies and detector R&D.

Wu-Ki Tung award
The 2024 Wu-Ki Tung award goes to theoretical physicist Ian Moult (Yale) "for his pioneering work on QCD energy correlators, including their all-order factorisation, multi-loop structure, phenomenological applications and connections to conformal field theory". After graduating from the University of British Columbia, Moult obtained his PhD in 2016 from MIT and worked as a postdoctoral fellow at UC Berkeley and SLAC before moving to Yale. Moult's research is focused on the development of new quantum field theory techniques for improving the understanding of high-energy particle-physics experiments, ranging from dark matter detection to collisions at the LHC.

private

Alfvén plasma-physics prize
Tünde Fülöp (below, Chalmers University of Technology) and Per Helander (MPI for Plasma Physics) are the winners of the 2024 EPS Hannes Alfvén Prize for "outstanding contributions to theoretical plasma physics, yielding groundbreaking results that significantly impact the understanding and optimisation of magnetically confined fusion plasma". Fülöp explored the physics of runaway electrons in tokamaks and elsewhere, and their associated electromagnetic instabilities, while Helander made seminal contributions to the theory of stellarator plasmas by investigating how the properties of a magnetically confined plasma depend on the magnetic field geometry.

J Wingborg

La Fondation pour Genève
In recognition of her exceptional commitment to Geneva's international reputation, CERN Director-General Fabiola Gianotti will be awarded the 30th prize of La Fondation pour Genève during a ceremony on 13 May. From the realisation of the ATLAS experiment at the LHC, to the discovery of the Higgs boson and the creation of CERN Science Gateway, Gianotti has contributed to a number of major projects that have made Geneva a leading player in the world of science and in the diplomatic arena, states the citation: "Her dynamism, passion for the transmission of knowledge, democratisation of science and openness to all the public make her a real inspiration for the younger generations."

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Top-end user award
At a conference of the Cloud Native Computing Foundation (CNCF) in Paris (19–22 March), CERN was presented as winner of the top-end user award. Cited for its "forward looking approach to leveraging cloud native technologies to address future scientific and operational challenges", CERN joins the ranks of previous awardees including Spotify and Apple. Cloud native technologies are software solutions that allow system engineers to improve basic cloud features such as scalability, flexibility and data resiliency. This award is a special CNCF community award that recognises major contributions to the cloud native ecosystem.

RECRUITMENT

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Jožef Stefan Institute, Ljubljana, Slovenia

FMF | UNIVERSITY OF LJUBLJANA
Faculty of Mathematics and Physics

Title: Five PhD Positions in Experimental Particle Physics

Location: Jožef Stefan Institute, Ljubljana, Slovenia

Doctoral Study: Faculty of Mathematics and Physics at the University of Ljubljana

Start Date: October 1st, 2024

Duration: 4 years

Application Deadline: May 31st, 2024

About Us:
The Jožef Stefan Institute (JSI) is a leading research institution in Ljubljana, Slovenia, committed to excellence in scientific research and innovation. We are seeking highly motivated and talented students to join our team working on cutting-edge experiments, including the ATLAS and LHCb experiments at CERN, and the Belle II Experiment at KEK. Ljubljana is a vibrant, easy-to-navigate capital with easy road access to the Alps, the Adriatic, and cities such as Venice, Vienna, and Munich.

The Experimental Particle Physics Department (F9 - https://www-f9.ijs.si/en/) at JSI is currently comprised of over 20 faculty members and staff scientists and over 10 PhD students and postdocs. A significant part of the group is involved in detector R&D: Cherenkov detectors and their applications in medical imaging (https://photodetectors.ijs.si), and solid-state detectors for the ATLAS Phase-II upgrade (ITk, HGTD, BCM). The group also plays a leading role in the newly formed DRD3 (https://drd3.web.cern.ch) and DRD4 (https://drd4.web.cern.ch) collaborations. The group is strongly involved in physics data analysis at Belle II and ATLAS experiments, ranging from measurements of rare processes with B meson decays at Belle II to direct searches for new phenomena and Higgs and Standard Model precision measurements at the ATLAS Experiment. The group has recently won two ERC projects: FAIME (https://faime.ijs.si) and its spin-off CherPET, a proof-of-concept ERC project aiming to apply the detectors developed in particle physics to advances in medical imaging methods.

Position Overview:
As a PhD student, you will have the opportunity to contribute to groundbreaking research in experimental particle physics. Several positions are available, spanning the analysis of experimental data within the framework of the ATLAS and Belle II collaborations to detector research and development for the ATLAS and LHCb experiments. The workplace for all positions will be the JSI, Ljubljana, with possible shorter or longer periods at CERN, Geneva, or KEK, Japan. Your doctoral studies will be conducted at the Faculty of Mathematics and Physics at the University of Ljubljana, with guidance from experienced supervisors from both institutions.

ATLAS Experiment Positions:

Topic: Machine learning-assisted data analysis at ATLAS

Contacts: Miha Muškinja (miha.muskinja@ijs.si), Borut Kerševan (borut.kersevan@ijs.si)

Topic: Development of semiconductor detectors for charged particle tracking for future experiments at particle colliders

Contact: Igor Mandić (igor.mandic@ijs.si)

Belle II & LHCb Experiment Positions:

Topic: Measurements of rare processes at B meson decays at the Belle II experiment

Contact: Marko Bračko (marko.bracko@ijs.si)

Topic: Particle identification system upgrade at LHCb

Contact: Rok Pestotnik (rok.pestotnik@ijs.si)

Benefits:
- Competitive salary commensurate with experience.
- Full doctoral scholarship at the Faculty of Mathematics and Physics at the University of Ljubljana.
- Full health coverage plan.
- Opportunity for professional development and networking within the international particle physics community.
- Supportive and collaborative work environment.

General Inquiries:
f9-jobs@ijs.si or respective contacts listed above for specific inquiries.

Application Process:
Send your motivation letter and CV to f9-jobs@ijs.si and arrange for up to three reference letters to be sent to the same address.

PEOPLE OBITUARIES

Peter Higgs 1929–2024

A massive legacy for particle physics

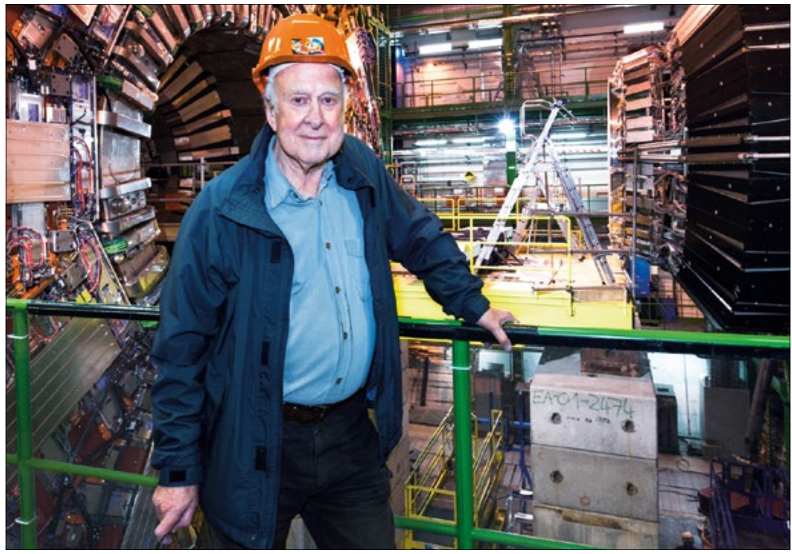
Peter Higgs, an iconic figure in modern science who in 1964 postulated the existence of the eponymous Higgs boson, passed away on 8 April 2024 at the age of 94.

Peter Higgs was born in Newcastle upon Tyne in the UK on 29 May 1929. His family moved around when he was young and he suffered from childhood asthma, so he was often taught at home. However, from 1941 to 1946 he attended Cotham Grammar School in Bristol, one of whose alumni was Paul Dirac. He went on to study physics at King's College London, where he got his bachelor's degree in 1950 and his PhD for research in molecular physics in 1954. After periods at the University of Edinburgh, Imperial College and University College London, in 1960 he settled at the University of Edinburgh where he remained for the rest of his career.

Seeds of success

Following his PhD, Higgs's research interests shifted to field theory, with a first paper on vacuum expectation values of fields in 1956, followed by a couple of papers on general relativity. Then, in 1964, came his two famous papers introducing spontaneous gauge symmetry breaking into relativistic quantum field theory and showing how a vector boson could acquire a mass in a consistent manner – as long as it was accompanied by a massive scalar boson.

Related ideas had been discussed previously by Phillip Anderson and Yoichiro Nambu in the context of non-relativistic condensed-matter physics, namely in models of superconductivity, where a condensate of electron pairs enables a photon to acquire an effective mass. Anderson conjectured that a similar mechanism should be possible in a relativistic theory, but he did not develop the idea. On the other hand, Nambu used spontaneous symmetry breaking to describe the properties of the pion, but also did not discuss the extension to a relativistic vector boson.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Peter Higgs during a visit to the CMS experiment in April 2008.

In early 1964 Walter Gilbert (later a winner of the Nobel Prize in Chemistry) wrote a paper arguing that Anderson and Nambu's ideas for generating mass for a vector boson could not work in a relativistic theory. This was Higgs's cue: a few weeks later he wrote a first paper pointing out a potential loophole in Gilbert's argument (though not a specific model). He sent his paper to the journal *Physics Letters*, which quickly accepted it for publication. A few days later, he wrote a second paper, which contained an explicit model for mass generation, but was taken aback when the same journal rejected this paper as not being of practical interest. Undeterred, Higgs tweaked his paper to make his message more explicit, and submitted it to *Physical Review Letters*, where it was accepted.

Higgs pointed out explicitly that his model predicted the existence of a massive scalar boson

Unknown to Higgs, François Englert and Robert Brout had already sent a paper describing a similar model to the same journal, where it was published ahead of Higgs's paper. Both papers postulated a scalar field with a non-zero vacuum expectation value that gave mass to a vector boson. However, there was a key difference: Higgs pointed out explicitly that his model predicted the existence of a massive scalar boson, whereas this was not mentioned in the Englert–Brout paper. For this reason, the particle he predicted became known as the Higgs boson. Shortly after the publication of the Higgs and Englert–Brout papers, Gerry Guralnik, Carl Hagen and Tom Kibble published an article referring to their papers and filling in some aspects of the theory, but also not mentioning the existence of the massive scalar boson.

In 1965 Higgs went for a sabbatical to the University of North Carolina, where he continued working on his theory. Remarkably prescient, he wrote a third paper discussing how his boson could decay into a pair of massive gauge bosons as well as calculating associated scattering processes. However, he encountered scepticism about the validity of his theory, and neither his nor the other pioneering mass-generation papers garnered significant attention for several years.

This started to change in 1967 and 1968 when Steven Weinberg and Abdus Salam incorporated the mass-generation mechanism into their formulation of the electroweak sector of the Standard Model. But interest only really took off a few years later, after Gerard 't Hooft and Martinus Veltman showed that spontaneously broken gauge theories are renormalisable and hence could be used to make accurate and reliable predictions for comparison with experiment, and when neutral weak interactions were discovered in the Gargamelle bubble chamber at CERN in 1973.

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The search begins

During the 1970s interest in the experimental community moved towards searches for the massive intermediate vector bosons, the W and Z. However, it seemed to Mary Gaillard, Dimitri Nanopoulos and myself that the key long-term target should be the Higgs boson, the capstone of the structure of the Standard Model, and in 1975 we wrote a paper describing its phenomenology. At the time the existence of the Higgs boson was still regarded with some scepticism, and we ended our paper by writing that "We do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up." I met Peter Higgs for the first time around 1980, and he was clearly flattered by our interest in his boson, but unprepared for the subsequent interest in the big experimental searches that followed.

Searching for the Higgs boson moved to the top of the agenda following the discovery of the W and Z at CERN in 1983, when the Superconducting Super Collider project was launched in the US, followed by the first LHC workshop in 1984. Being a profoundly modest man, Higgs followed these developments from a distance as a somewhat bemused spectator. In the 1990s, precision experiments at LEP and elsewhere confirmed predictions of the Standard Model with high accuracy – if and only if the Higgs boson (or something very like it) was included in the theoretical calculations. Higgs became quietly confident in the reality of his boson. By the time the LHC started accumulating collisions at an energy of 7 and 8 TeV, anticipation of its possible discovery was growing.

Following early hints at the end of 2011, the word went around that on 4 July 2012 the ATLAS and CMS experiments would give a joint seminar presenting their latest results. I was tasked with locating Higgs and persuading him that he might find the results interesting. Somewhat reluctantly, he decided to come to CERN for the seminar, and he had no cause to regret it. He wiped tears from his eyes when the discovery of a new particle resembling his boson was announced, and confessed that he had never expected to see it in his lifetime.

Famously, in October 2013 as the Nobel Prize was being announced, Higgs went missing, in order to avoid being thronged by the media. Some months previously, in a pub in Edinburgh, he had told me that the existence of the Higgs boson was not a "big deal", but I assured him that it was. Without his theory, electrons would fly away from nuclei at the speed of light and atoms would not exist, and radioactivity would be a force as strong as electricity and magnetism. His prediction of the existence of the particle that bears his name was a deep insight, and its discovery was the crowning moment that confirmed his understanding of the way the universe works.

Peter Higgs is survived by his two sons, a daughter-in-law and two grandchildren.

John Ellis *King's College London/CERN.*

Giuseppe Fidecaro 1926–2024

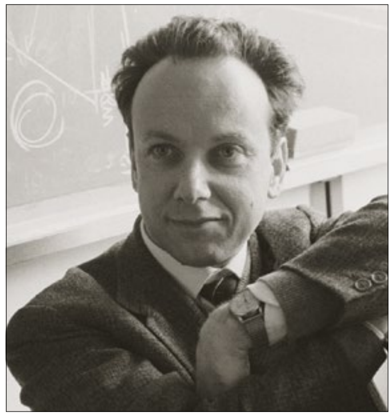
Superior intelligence and unwavering will

Experimental physicist Giuseppe Fidecaro, who joined CERN in 1956 and continued there long into his retirement, passed away on 28 March.

Born in Messina, Italy in 1926, Giuseppe studied physics at the University of Rome, graduating in 1947 under the supervision of Edoardo Amaldi. Amaldi had become interested in cosmic rays and asked young "Pippo" to help him build a large detector to study the scattering of mesons on an iron target to explore the nuclear force. Between 1952 and 1954, Giuseppe continued to work on cosmic rays at the Tête Grise laboratory, 3500 m above Cervinia, where Maria Cervasi, whom he had met during his studies at Rome, also worked.

In 1953 Amaldi, who had become secretary general of the provisional CERN, suggested that Giuseppe spend time at the University of Liverpool to learn from the new synchrocyclotron being built there. He went to CERN with Maria, by then his wife, in 1956 and began preparing experiments for the 600 MeV Synchrocyclotron (SC), which came into operation in August 1957.

In January 1958, during a conference in New York, Giuseppe attended a presentation by Feynman describing the universal "V–A" theory of weak interactions. He heard that the theory lacked a key experimental ingredient: the decay of a pion into an electron and neutrino, predicted to occur 10 000 times less frequently than to a muon and a neutrino, which had not been observed in two experiments performed by well-known physicists. Upon his return to CERN, Pippo decided with the other members of the SC group that this would be the target of the next experiment. A device was immediately designed and built, and 40 events in perfect agreement with the V–A prediction were presented by Pippo in September 1958. The news put the newly born CERN on the map of the world of particle physics and laid the groundwork for the future discoveries of neutral currents, the W and Z bosons, and the Higgs field.


Giuseppe Fidecaro at CERN in 1964.

CERN 221-11-64

In 1960, with the start-up of the PS, Giuseppe led his group to measure – using a system of precision scintillators – the antiproton–proton cross section. The following year, he became professor at the University of Trieste and established a group that carried out a series of important scattering measurements at the PS and the SPS, in particular using polarised targets, during the 1970s. Following the proposal and execution of an experiment at the ILL in Grenoble searching for possible neutron–antineutron oscillations, in 1990 he presented an article "Fixed target B-physics at the Large Hadron Collider" at the LHC workshop in Aachen, which proposed, among other things, the use of a very intense proton beam extracted from the accelerator with a crystal, similar to what had been envisaged for the Superconducting Super Collider. This, and discussions with Giovanni Carboni and Walter Scandale, were at the origin of the RD22 collaboration, which for the first time proved the possibility of high-efficiency proton extraction from an accelerator using a bent crystal – a technique that is now used in LHC beam collimation.

Outside physics, Giuseppe made numerous contributions to CERN. In the early 1960s he was a member of the founding committee of the International Center for Theoretical Physics. In 1975 he was appointed as co-chair of a joint scientific committee set up under a collaboration agreement between CERN and the former USSR concerning the use of atomic energy, a responsibility he held until 1986. He was also tasked with coordinating cooperation with JINR in Dubna.

Giuseppe officially retired in 1991 but, together with Maria, continued his work at CERN as an honorary member of the personnel until as recently as 2020, during which time he devoted himself to research in the history of physics. He produced reports of rare beauty and precision, notably three well-documented articles on the contributions of Bruno Pontecorvo, whose friend he became in Dubna in 1989. Giuseppe was also known to CERN visitors, featuring prominently in the film shown in the Synchrocyclotron exhibition. Maria Fidecaro, with whom his rich human and scientific journey was deeply entwined, passed away in September 2023.

His friends and colleagues.

Marcello Ciafaloni 1940–2023

A master of QCD and gravitational scattering

Internationally known theorist Marcello Ciafaloni passed away in Florence, Italy on 8 September 2023. Born in 1940 in the small town of Teramo in southern Italy, he was admitted for his higher education to the selective Scuola Normale Superiore in Pisa where he graduated in 1965. Since 1980 he was a full professor in theoretical physics at the University of Florence.

As a research associate at Berkeley (1969–1970) and a fellow at CERN (1972–1974), Ciafaloni initially focused his research on high-energy soft hadronic physics and produced important results in the context of Reggeon field theory. Towards the end of the seventies, he shifted his attention to perturbative QCD, in particular to hard processes and small-x physics where sophisticated re-summation techniques are needed. Since then, and throughout his career, he produced many fundamental results in perturbative QCD, including his single-author contribution to the celebrated CCFM equation (where the first C stands for his name), an important ingredient for QCD-based event generators.


Marcello Ciafaloni's work underpinned QCD-based event generators.

Family photo

Since 1987, Ciafaloni added a second dimension to his research spectrum by devoting part of his activity to the gravitational scattering of strings, a thought-experiment for understanding string theory's version of quantum gravity. This work originated from one of his periodic visits to the CERN TH division and involved, besides Marcello, Daniele Amati and myself.

The so-called ACV collaboration carried on until 2007 (with long visits by Marcello at CERN in 1995 and 2001), but my own collaboration with Marcello continued until 2018, when his health started deteriorating. More recently, the techniques used for this "academic" problem turned out to be relevant for describing real black-hole mergers and the ensuing gravitational radiation.

I had the great privilege of working with Marcello on many occasions throughout his career. His deep knowledge of physics and his passion were only matched by his amazing technical skills. He had set very demanding standards for himself and pursued them with great intellectual honesty and much generosity towards his students and collaborators. His passing is a big loss for our community.

Gabriele Veneziano *CERN.*

Dieter Proch 1943–2024

A super force for accelerators

Dieter Proch, who made significant contributions to accelerator science, passed away unexpectedly on 27 February 2024 at the age of 80.

Dieter studied physics at the University of Bonn, where he joined the group of Helmut Piel, which had just started working on superconducting accelerator resonators. He then followed Piel, who had accepted an appointment as professor at the newly founded University of Wuppertal, and completed his doctorate on measurements of superconducting accelerator resonators. Soon after, he analysed the serious problem of so-called one-point multipacting in superconducting resonators prevalent at the time. Together with Wuppertal colleagues, he proposed changing the shape of resonators to have a spherical profile, which solved the multipacting problem. Subsequently, Dieter completed research stays at Cornell and CERN, where in 1981 he contributed to the development of spherical superconducting resonators for LEP II to double the energy of LEP. He then took up a permanent position at DESY, where he remained for almost 27 years until June 2009.


Dieter Proch significantly enhanced DESY's scientific reputation.

DESY

During his first years at DESY, Dieter's focus was on the development of superconducting accelerator structures for the HERA accelerator that was being planned. He was head of the "Superconducting acceleration sections" experimental programme, where he demonstrated organisational talent as well as scientific and technical skills. Within a few years he pushed superconducting resonators from theoretical considerations to preliminary technological studies, and the operation of experimental resonators in the PETRA accelerator.

In the mid-1980s, Dieter took over a group focusing on superconducting accelerator technology. The group was responsible for the design, manufacturing, testing, installation and operation of the superconducting resonators in HERA.

In addition, Dieter was one of the founders of the international TESLA collaboration. Under his leadership, a groundbreaking infrastructure for the treatment, assembly and testing of superconducting accelerator resonators was built at DESY. This development work made it possible to increase the originally targeted field gradients from 25 to 35 MV/m. He organised close collaborations with many laboratories in Germany, Europe, Asia and the US. Particularly noteworthy here are Peking University and Tsinghua University, both of which appointed Dieter as a visiting professor.

As a globally recognised expert and deputy chair of the TESLA technology collaboration, Dieter served on important committees for many years, such as the advisory board for SNS at Oak Ridge. At DESY, the FLASH and European XFEL user systems are based on his fundamental work. The SRF Workshop, which later became a recognised international conference, was always particularly close to his heart. The scientific reputation that DESY enjoys worldwide was significantly influenced by Dieter. He also collaborated on several articles for the *Handbook of Accelerator Physics and Engineering*.

Dieter's contributions continue to shape our understanding and advancement of accelerator technology. We thank him very much and will always remember him fondly.

His friends and colleagues *at DESY, Cornell and CERN.*

IGOR GOLUTVIN 1934–2023

A pioneer of the CMS experiment

Igor Anatolievich Golutvin, an outstanding scientist who founded new directions and research techniques in particle physics, died on 13 September 2023.

Born on 8 August 1934 in Moscow, Golutvin graduated from MIPT in 1957 and started his work at JINR in 1958. Several generations of detectors for large-scale physics facilities were developed under his supervision at the JINR Synchrophasotron, the IHEP accelerator in Serpukhov, and at the Proton Synchrotron and the LHC at CERN.

Golutvin became one of the pioneers of the CMS experiment, driving the cooperation of Russia and other JINR member states via the Russia and Dubna Member States (RDMS) CMS collaboration. Over the past 30 years, under his supervision, RDMS physicists have completed the development of unique detectors for CMS. Igor was also instrumental in initiating Grid computing for CMS in Russia. He was awarded the 2014 Cherenkov Prize of the Russian Academy of Sciences for his outstanding contribution to the development of CMS. In recent years, he played an important role in the preparation of upgrades for CMS, in particular concerning the calorimeters.

During his work at JINR, Golutvin established a scientific school and trained a team of active, qualified physicists and engineers. Within the framework of cooperation between CMS Russia and other JINR member states, he brought together like-minded people with the aim of preserving Russian scientific schools, built unique teams of engineers and physicists, and developed favourable conditions for attracting gifted young physicists, which he saw as extremely important for the implementation of long-term scientific projects.

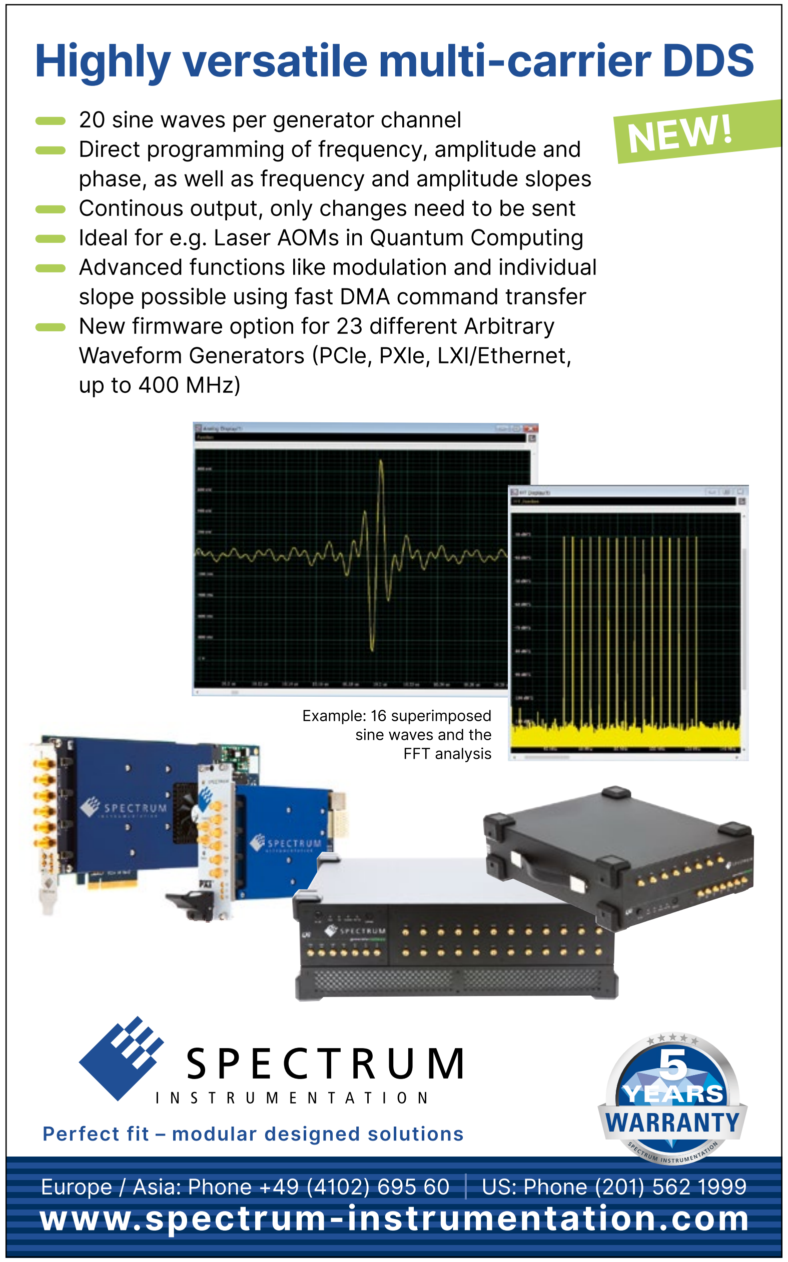

JINR

Igor Golutvin drove the cooperation of JINR member states with CMS.

Igor was a member of the equipment committee of the International Committee for Future Accelerators, an editorial board member of the journal *Nuclear Instruments and Methods*, a directorate member of the CMS collaboration at CERN, head of the collaboration of the institutes of Russia and JINR in CMS, and the organiser and head of numerous international and Russian scientific conferences and symposia.

He was also a professor/full member of the Russian Academy of Engineering Sciences, Russian Academy of Natural Sciences, International Academy of Sciences, Honoured Scientist of the Russian Federation and chief researcher for CMS at VBLHEP. For many years of fruitful work, Golutvin was awarded numerous state and scientific awards and prizes.

His friends and colleagues *at JINR.*



BACKGROUND

Notes and observations from the high-energy physics community

Instrumental X-rays

ESRF/P Jayet

"Il Cannone", crafted in 1743 and reputed to be virtuoso Niccolò Paganini's favourite violin, ranks among the most important instruments in the history of Western music. To help understand and preserve it, the Municipality of Genoa and the Premio Paganini in Italy teamed up with researchers at the ESRF in Grenoble to place the precious artefact in the path of an ultra-bright X-ray beam. Multi-resolution propagation phase-contrast X-ray microtomography, a non-destructive technique widely used for palaeontology, produced a 3D image of the violin at the level of its cellular structure, enabling deeper study of the structural status of the wood and the secrets behind Il Cannone's acoustic prowess.

3.2 billion

Number of pixels in the LSST digital camera, the largest ever built for astronomy, for which construction at SLAC has been completed ahead of installation at the Vera Rubin observatory in Chile later this year.

Media corner

"How the story of these anomalies will end is unclear. But the wealth of emerging evidence does suggest that physics may be on the brink of something big."

LHCb physicist **Harry Cliff** trails his new book *Space Oddities* in *The Guardian* (15 April).

"One of the things I predict – but it's something we may have to fight for – is you will have an AI assistant, which you can trust, and it works for you, like a doctor."

Tim Berners-Lee reflects on the future of the web following his publication of an open letter marking its 35th anniversary (*CNBC*, 12 March).

"We are explorers, and we believe that we can see something interesting in this new terrain. So, we have to take a look."

Mitesh Patel of Imperial College talking to *BBC Online* (25 March) about the newly approved SHiP experiment at CERN (see p7).

"It is also a way to guarantee the fixation and even return of 'brains' to Brazil. Furthermore, we are entering a promising market for metals and minerals."

Luciana Santos, Brazilian minister of science, technology and innovation, on the country's formal ascension to CERN as an associate member state (*GZH*, 28 March) (translated).

"Le CERN s'honorerait donc d'organiser en toute transparence un grand débat démocratique sur le sujet et de se doter à cette fin d'un comité d'éthique, de même que c'est le cas dans d'autres grandes institutions scientifiques comme le CEA ou le CNRS."

An op-ed in *Le Mond* (21 March) signed by nine associates and political delegates of green parties in France and Switzerland in the context of the proposed Future Circular Collider.

From the archive: April/May 1984

Multitasking, CERN-style

JET

On 17 April 1984, JET, the Joint European Torus nuclear fusion project, was formally opened at Culham, UK, by Britain's Queen Elizabeth II and France's President Francois Mitterrand. The guests of honour are seen escorted by JET Council President Jean Teillac, formerly President of CERN Council. Two rows behind the Queen is Hans-Otto Wüster, JET Director and a former member of the CERN Directorate.

DESY

CERN Director General (and former DESY Director) Herwig Schopper (left on image) visited the DESY Laboratory in Hamburg early in March 1984 for a colloquium marking his 60th birthday. He was greeted by Alexander Hocker (right), who played an important role in the creation of CERN and DESY, watched by a smiling Hans-Otto Wüster.

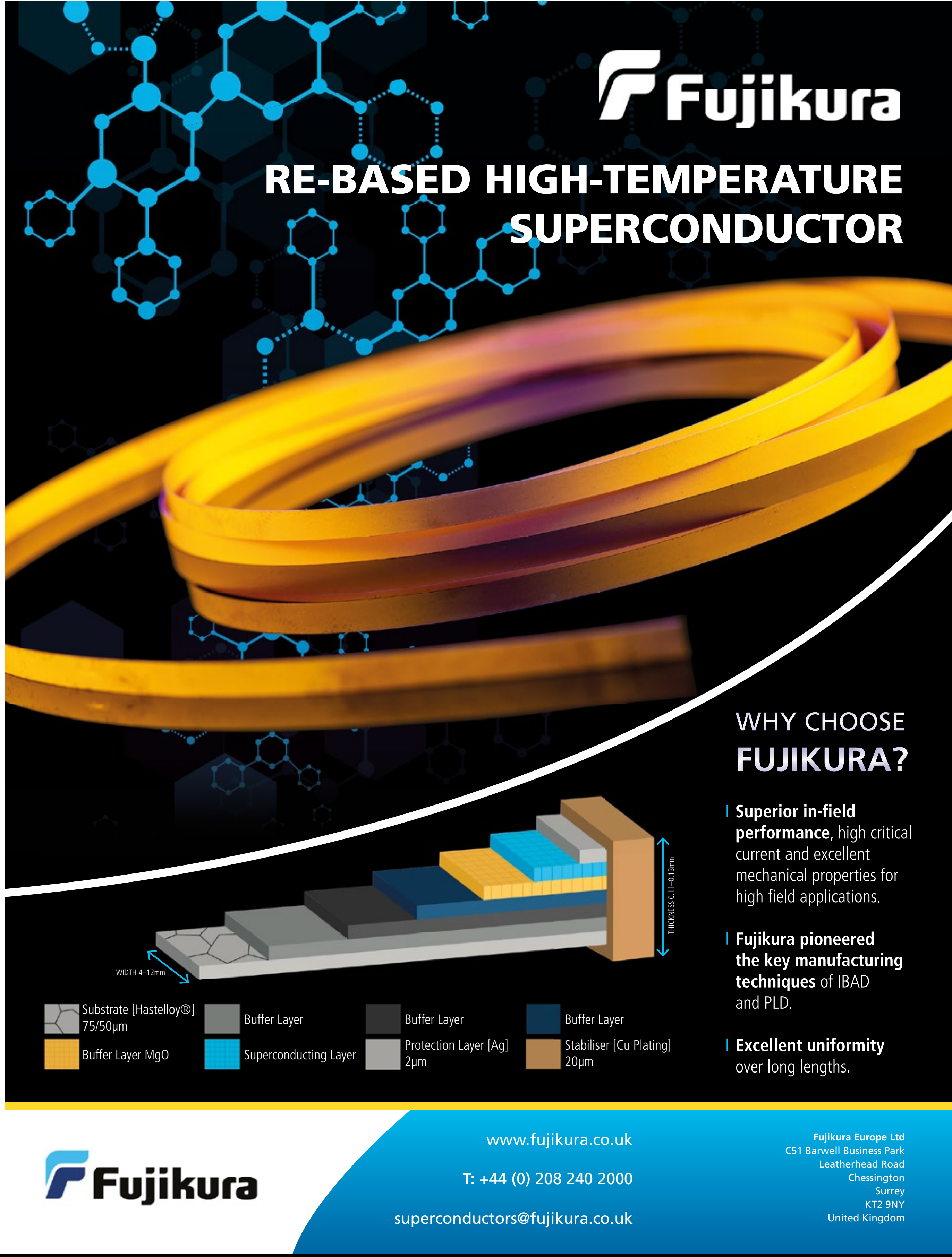
- Text adapted from *CERN Courier April 1984 (p157) and May 1984 (p199).*

Compiler's note

Erstwhile members of CERN's directorate often feature eminently in other international physics projects. Centenarian Herwig Schopper, CERN DG from 1981 to 1988, played a pivotal role in getting SESAME, the Synchrotron-light for Experimental Science and Applications in the Middle East centre, established in Jordan in 2017. Hans-Otto Wüster, deputy DG of CERN Lab II from 1971 to 1975, was JET director from its inception in 1978 until his sudden death in 1985. In a swansong run of September 2023, JET broke the world record for sustained nuclear fusion, generating 69 megajoules of energy over a period of 6 seconds from 0.2 mg of fuel. That's only enough for four or five hot baths, but the achievement instills confidence in projects such as ITER, the International Thermonuclear Experimental Reactor, scheduled to start up this decade in southern France. Chris Llewellyn Smith, CERN DG from 1994 to 1998, served as chairman of the ITER Council from 2007 to 2009.

Know your footprint

The Young High-Energy Physicists association encourages you to evaluate your carbon footprint using a new online tool published in March: limesurvey.web.cern.ch/863499. The Know Your Footprint Calculator estimates the equivalent tonnes of CO$_2$ (tCO2e) released into the atmosphere annually as a result of professional activities. The team's calculations suggest that the footprint of a benchmark doctoral researcher in high-energy physics is roughly 31 tCO2e – far in excess of the remaining carbon budget of 1.7 tCO2e (4.8 tCO2e) per person per year for a maximum temperature increases of 1.5°C (2.0°C) (arXiv:2403.03308). Of this footprint, 21 tCO2e are due to professional activities, including participation in an experiment, affiliation to an institute, moderate usage of computing resources, and travel to shifts, meetings and conferences. "Reducing the footprint of high-energy physics is part of our responsibility as researchers," says corresponding author Valerie Lang (Freiburg). "Every gram of CO$_2$ counts."



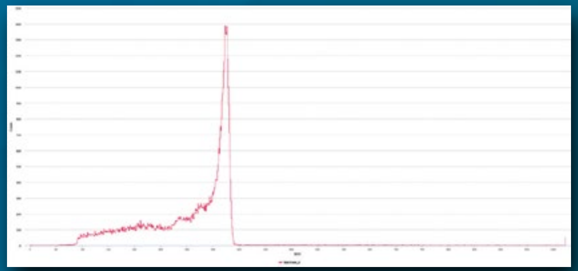
CAEN Electronic Instrumentation

NBrick Neutron Position Sensing System

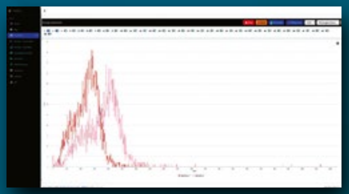
^{3}He Tubes · Control Software and Libraries · 10/100 MbE · ALL in ONE system

CAEN introduces its latest innovation for neutron physics, streamlining research at spallation sources, SANS instruments, and nuclear security domains.

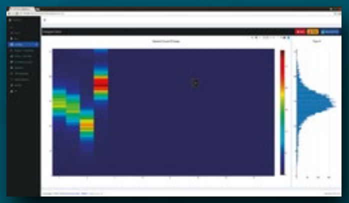
- Bias and read out up to 16 position-sensitive gas detectors for neutrons
- Independent channels high voltage up to +4 kV, 3mA
- 32 ch. charge sensitive preamplifier built on expertise from ILL, France
- 32 ch. digital signal processor, with FPGA-based Resistive Charge Division algorithm
- Thanos DAQ included: position reconstruction, neutron counting and spectroscopy, ToF



Typical thermal neutron spectrum acquired with the Thanos DAQ, collecting charge from just one end of a ^{3}He tube.



Energy spectrum measured at the two ends of one ^{3}He tube – x-axis is not-calibrated energy.



Position heatmap (counts over position) corresponding to four different ^{3}He tubes and 2D-projection of counts onto the y-axis of a single tube.

The **CAEN** Brick is a rackmount system composed of three boards:

R1443C: Charge Sensitive Preamplifier specifically designed for ^{3}He/BF$_3$ tubes (32-ch independent HV).

R5560C: 32 channels 14-bit 125 MS/s Pulse Processor.

R8033: High Voltage board (Mod. R8033DP: 16-ch +4kV/3mA).

www.caen.it
*Small details… **Great differences***