WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2021 issue of *CERN Courier*.

The 2020 update of the European strategy for particle physics (ESPP) concluded that an electron–positron Higgs factory is the highest priority collider after the LHC. The ability to produce copious quantities of Higgs bosons in a very clean environment would help tame the “wild west” scalar sector of the Standard Model Lagrangian, and impact many others, as physicists seek to venture beyond the well signposted environs of the Standard Model.

This issue looks at the physics capabilities of the various Higgs-factory proposals, in terms of their reach on the Higgs boson (p23) and beyond (p29, 35, 39). We also look at the role of CERN in implementing the broader ESPP recommendations (p43), a priority being a technical and financial feasibility study for a 100 km future circular hadron collider at CERN with a Higgs and electroweak factory as a possible first stage (p20). Meanwhile, efforts are under way to identify R&D synergies between the Higgs factories (p44), and mechanisms are being strengthened to take on board the views of early-career researchers about the future of their field (p50).

Elsewhere in this issue: counting down to LHC Run 3 (p7); anomalies and new multi-quark states at LHCb (p12); CMS targets Higgs-boson pair production (p15); the latest on long-lived particles (p19); CERN’s new director for research and computing (p45); and, last but not least, the solution to the *Courier*’s end-of-year crossword (p62).

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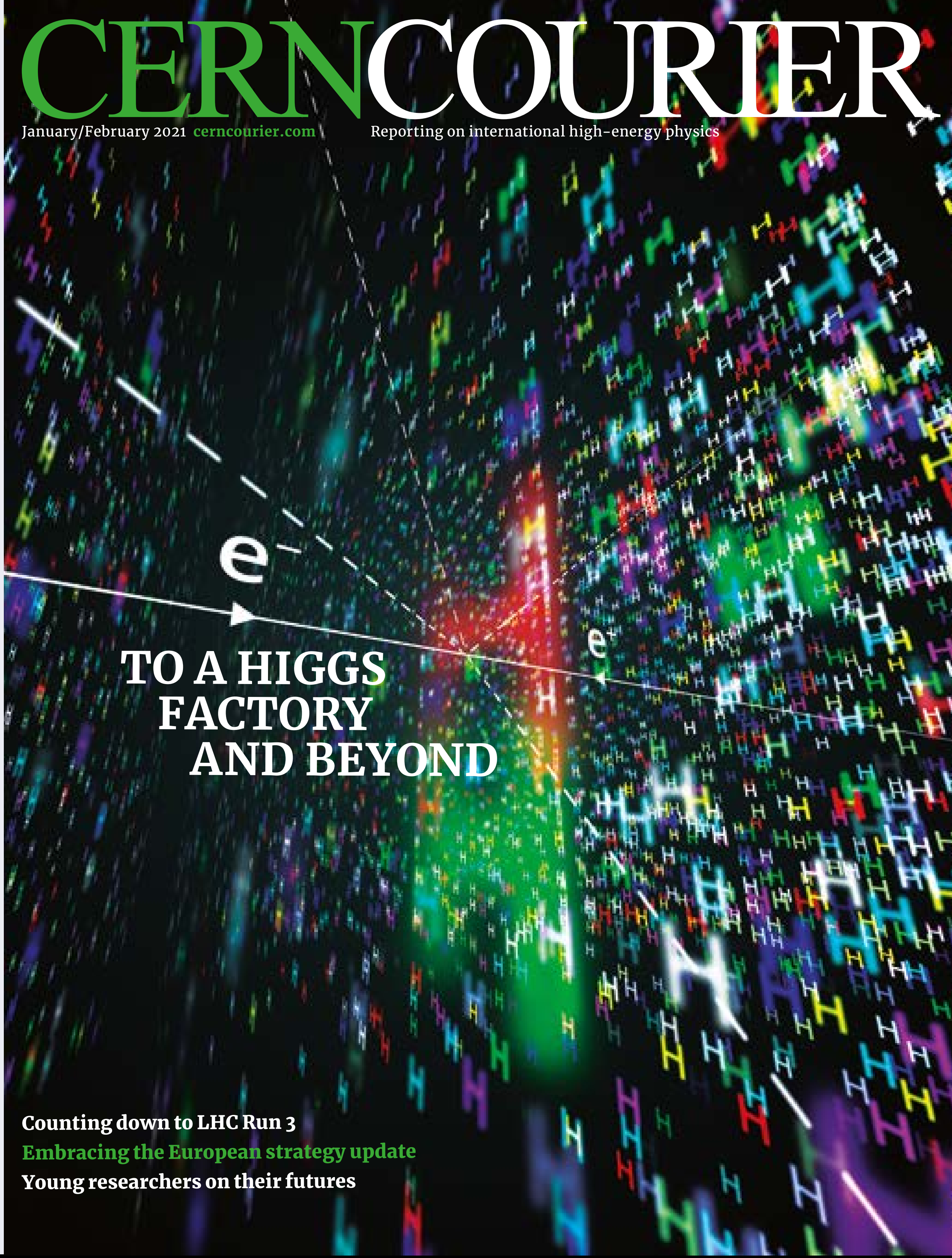
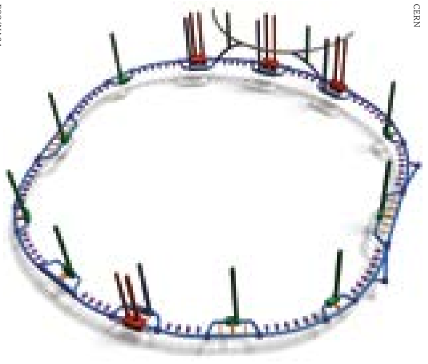


IN THIS ISSUE

VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021

Cosmic accelerators *Could plasma-wakefield acceleration explain ultra-high-energy cosmic rays?* **11**



Lift off *Feasibility study for a future circular collider gets under way.* **20**

Meet Mnich *CERN's new director for research and computing.* **45**

NEWS

ANALYSIS
Countdown to Run 3 • HL-LHC magnets • CERN medical technology • HEP-based ventilator • Cosmic plasma-wakefield acceleration. **7**

ENERGY FRONTIERS
Higgs-boson pair production • Higgs gets the SMEFT treatment • Heavy flavours probe QGP geometry • LHCb sheds light on V_{ub} puzzle. **15**

FIELD NOTES
A long-lasting paradigm shift • Horizon event for FCC innovators • Targeting tumours with electrons. **19**

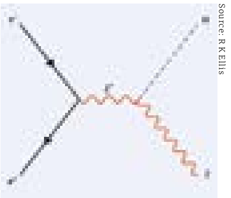
PEOPLE

CAREERS
A wake-up call from the next generation
Early-career researchers voice their hopes and concerns about the future of particle physics. **50**

OBITUARIES
• Yuri Orlov
• Glen Lambertson
• Jacques Séguinot
• Willem de Boer
• Richard Roberts
• Yuri Alexahin
• Paul Murphy. **58**

FEATURES

HIGGS PHYSICS
Targeting a Higgs factory
An electron–positron collider following the LHC would yield precise knowledge of the Higgs boson. **23**



BEYOND A HIGGS FACTORY
FCC-ee
A 100 km circular electron–positron collider would be the first stage towards a 100 TeV proton–proton collider. **29**

ILC
High-luminosity, polarised beams and the triggerless operation of detectors offer rich physics opportunities. **35**

CLIC
The precision of a lepton collider and the high-energy reach of multi-TeV collisions has great discovery potential. **39**

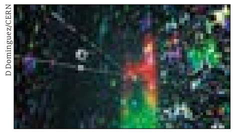
OPINION

VIEWPOINT
Implementing a vision for CERN
The European strategy update forms the basis of CERN's objectives for the next five years, explains Fabiola Gianotti. **43**

COMMENT
Together towards new facilities
We need to pursue synergies between Higgs factories, says Jorgen D'Hondt. **44**

REVIEWS
To Russia with love
The most dangerous spy in history
• Scientific journeys
• The mirror trap. **48**

DEPARTMENTS



On the cover: *Artistic interpretation of a precision Higgs factory.* **23**

FROM THE EDITOR	5
NEWS DIGEST	12
INTERVIEW	45
APPOINTMENTS & AWARDS	52
RECRUITMENT	53
BACKGROUND	62

FROM THE EDITOR

Follow the physics

Matthew Chalmers
Editor

The 2020 update of the European strategy for particle physics (ESPP) showed particle physicists to be united in their opinion that an electron–positron Higgs factory should follow the LHC. The ability to produce copious quantities of Higgs bosons in a very clean environment would help tame the "wild west" scalar sector of the Standard Model Lagrangian, and impact many others (p23). Which of the four proposed Higgs factories should be built is not yet decided.

Before the discovery of the Higgs boson in 2012, linear e^+e^- colliders were intensively studied. Two proposals – the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) – vied to make detailed measurements of the Higgs boson and be neatly stepped up in energy to study other particles the LHC might find. But when the Higgs turned out to be relatively light, and with no heavier particles in sight, circular e^+e^- colliders came back into vogue – first a proposal to return a modern-day LEP to the LHC tunnel. In 2014 CERN launched the Future Circular Collider study to explore a 100 km-circumference facility offering e^+e^- (FCC-ee) and proton–proton (FCC-hh) modes. China chimed in with a similar proposal. Both projects recently completed conceptual design reports.

The 2020 ESPP update recommended a technical and financial feasibility study (p20) be undertaken for FCC-hh with FCC-ee as a possible first stage. It noted that the timely realisation of an ILC in Japan would be compatible with the strategy, and, while considering FCC-hh the most promising machine to explore the energy frontier, CLIC remains an alternative for the Higgs factory in case FCC is found to be unfeasible.

While particle physicists arguing about colliders is nothing new, rarely have they faced so many well-advanced options

While particle physicists arguing about colliders is nothing new, rarely have they faced so many well-advanced options. Large communities have built up around projects and careers invested in them. Some young researchers are wondering which horse to back (p50).

While the Higgs-factory proposals are reasonably well matched in terms of Higgs measurements, the ESPP process also drew attention to their broader physics programmes (p29, 35, 39), especially if potential upgrades go ahead. The integrated FCC programme offers the furthest scientific reach, but requires a large early investment in the tunnel and, for its hadron mode, new high-field magnet technology. The ILC is technically ready for construction, but is awaiting a decision by the Japanese government whether it will be hosted there; neither Japan nor China placed a Higgs factory on their latest scientific priority lists, while Europe will conclude on the FCC's feasibility by the next strategy update towards the middle of the decade.

CERN's recently approved medium-term plan provides a first implementation of the ESPP vision (p43). Meanwhile, community efforts are under way to identify R&D synergies between the Higgs factories (p44). The ESPP update urged vigorous R&D on advanced accelerator technologies across the board, including a design study for a muon collider, and supports a diverse range of non-collider efforts in areas such as neutrino and hidden-sector physics. Ever-strengthening links between particle physics, astrophysics and cosmology show that colliders are not the only tool to address fundamental questions about the universe. But they are an irreplaceable one, offering the most systematic way to explore a wide range of phenomena.

novost-design/FCC study

Aiming high *A FCC-ee event (p29).*

In pursuing FCC to the next level, Europe has chosen the most ambitious path available. By keeping other options open in the meantime, it's also a cautious approach, fitting of the perplexing situation the field finds itself in after 10 years of LHC results. Whatever the shape of the future, implementing the ESPP vision requires the support of the full community as it seeks to venture beyond the well signposted environs of the Standard Model, into unknown territory.

Reporting on international high-energy physics

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NEWS ANALYSIS

CERN

Final stretch for LHC upgrades

The second long shutdown of the LHC and its injector complex began two years ago, at the start of 2019. Since then, sweeping upgrades and key maintenance work have resulted in a rejuvenated accelerator complex with injectors fit for a decade or more of high-brightness beam production. With major detector upgrades proceeding in parallel, physicists are eyeing the final stretch of the road to Run 3 – which promises to deliver to the experiments an integrated luminosity twice that of Run 1 and Run 2 combined in less than three years of operations.

The ceremonial key to the Super Proton Synchrotron (SPS) was handed over to SPS operations on 4 December, signalling the successful completion of the LHC Injectors Upgrade (LIU) programme. "The amazing accomplishment of delivering the machine keys with only a small delay is thanks to the hard work, dedication and flexibility of many," says head of the operations group Rende Steerenberg, who emphasised the thoroughness with which special measures to ensure the safety of personnel during the COVID-19 pandemic were observed. "A large number of physicists, engineers and technicians strived day-in day-out to complete the upgrade and consolidation of the accelerator complex safely and efficiently following the spring lockdown."

P De Brabander/CERN-PHOTO-202011-145-7

Tiny TIM *The Train Inspection Monorail robot (top) monitors a worker in the LHC tunnel during LS2.*

Major changes to the SPS include the dismantling and remounting of its radio-frequency cavities, the installation of new power amplifiers, and the installation of state-of-the-art beam-control and beam-dump systems. First beam from the new Linac 4 was injected into the upgraded Proton Synchrotron Booster (PSB) on 7 December. The PSB will undergo a commissioning period before injecting beam into the Proton Synchrotron (PS) on 1 March. It will then be the turn of the PS to be commissioned, before sending beam to the SPS on 12 April.

Among many changes to the LHC, all 1232 dipole-magnet interconnections were opened and their electrical insulation consolidated, removing the limitation that prevented the LHC from reaching 7 TeV per beam during Run 2. The cryogenics team cooled the first of the LHC's eight sectors to its 1.9 K operational temperature on 15 November, with five other sectors being cooled in parallel and the full machine set to be cold by spring. After handing over to the electrical quality-assurance team for the final electrical tests, powering tests and a long campaign of quench training will take place to enable the LHC magnets to support fields in excess of those required during Run 2, when the beam energy was 6.5 TeV. Test beams are due to circulate at the end of September 2021, just four months later than planned before the COVID-19 pandemic.

Detector work

In parallel to work on CERN's accelerator infrastructure, experimental physicists are working hard to complete major upgrades to the detectors which anticipate the stringent requirements of triggering and reconstructing events at the upgraded LHC. The refurbishment of trigger electronics for the ATLAS detector's liquid-argon calorimeter is progressing quickly and the construction of the muon detector's two new "small wheels" is set to be completed by October 2021. With a complex upgrade of the CMS detector's muon system now complete, a newly built beam pipe will soon be fitted in the cavern, followed by the refurbished pixel detector with a new inner layer; magnet upgrades and shielding consolidation will then follow. With ALICE's time-projection chamber now reinstalled, work is underway to install the detector's new muon forward tracker, and a new 10 GPixel inner-tracking system will be installed in the first quarter of 2021. Meanwhile, the next steps for a significant revamp to the LHCb detector are the mounting of new vertex-locator modules and the first sensitive detector parts of the new ring-imaging Cherenkov detector during the first months of 2021. Following the completion of the upgrade programmes, Run 3 of the LHC will begin in March 2022.

Following the completion of the upgrade programmes, Run 3 of the LHC will begin in March 2022

Accelerator infrastructure relating to earlier stages in the lives of LHC protons is already beginning to be recommissioned. Hydrogen ions from a local source have been transferred to the ELENA ring to commission the newly installed transfer lines to CERN's antimatter experiments. A newly developed source has fed lead ions into Linac 3, which provides ions to the LHC's physics experiments, while pre-irradiated targets have provided stable isotopes to the ISOLDE nuclear-physics facility. Many experiments at ISOLDE and the PS–SPS complex will be able to start taking data in summer 2021.

No changes have been made to the LHC schedule beyond 2022. Following the completion of Run 3, the third long shutdown will begin at the start of 2025 for the LHC, and in early 2026 for the injector chain, and will end in mid-2027. During this time the installation of the High-Luminosity LHC (HL-LHC) will be completed, adding major high-technology upgrades to CERN's flagship machine. In concert with the programme of injector upgrades completed in LS2, these will allow the HL-LHC to deliver an order-of-magnitude greater integrated luminosity to the experiments than its predecessor.

MAGNET TECHNOLOGY

HL-LHC magnets enter production in the US

The significant increase in luminosity targeted by the high-luminosity LHC (HL-LHC) demands large-aperture quadrupole magnets that are able to focus the proton beams more tightly as they collide. A total of 24 such magnets are to be installed on either side of the ATLAS and CMS experiments in time for HL-LHC operations in 2027, marking the first time niobium-tin (Nb_3Sn) magnet technology is used in an accelerator.

Nb_3Sn is a superconducting material with a critical magnetic field that far exceeds that of the niobium-titanium presently used in the LHC magnets, but once formed it becomes brittle and strain-sensitive, which makes it much more challenging to process and use.

Following the first successful test of a US-built HL-LHC quadrupole magnet at Brookhaven National Laboratory (BNL) in January last year (*CERN Courier* May/June 2020 p7) – attaining a conductor peak field of 11.4 T and exceeding the required integrated gradient of 556 T in a 150 mm-aperture bore – a second quadrupole magnet has now been tested at BNL at nominal performance. Since the US-built quadrupole magnets must be connected in pairs before they can constitute fully operational accelerator magnets, the milestone signals the end of the prototyping phase for the HL-LHC quadrupoles, explains Giorgio Apollinari of Fermilab, who is head of the US Accelerator Upgrade Projects (AUP). "The primary importance is that we have entered the 'production' period that will make installation viable in early 2025. It also means we have satisfied the requirements from our funding agency and now the US Department of Energy is poised to authorise the full construction for the US contribution to HL-LHC."

The design and production of the HL-LHC quadrupole magnets are the result of a joint venture between CERN, BNL, Fermilab and Lawrence Berkeley National Laboratory, preceded by the 15 year-long US LHC Accelerator Research Program (LARP). The US labs are to provide a total of ten 9 m-long helium-tight vessels (eight for installation and two as spares) for the HL-LHC, each containing two 4.2 m-long magnets. CERN is also producing ten 9 m-long vessels, each containing a 7.5 m-long magnet. The six magnets to be placed on each side of ATLAS and CMS – four from the US and two from CERN – will be powered in series on the same electrical circuit.

Next generation *BNL technicians Ray Ceruti, Frank Teich, Pete Galioto, Pat Doutney and Dan Sullivan with the second US quadrupole magnet for the HL-LHC to have reached design performance.*

"The synergy between CERN and the US laboratories allowed us to considerably reduce the risks, have a faster schedule and a better optimisation of resources," says Ezio Todesco of CERN's superconductors and cryostats group. The quadrupole magnet programme at CERN is also making significant progress, he adds, with a short-model quadrupole having recently reached a record 13.4 T peak field in the coil, which is 2 T more than the project requirements. "The full series of magnets, sharing the same design and built on three sites, will also give very relevant information about the viability of future hadron colliders, which are expected to rely on massive, industrial production of Nb_3Sn magnets with fields up to 16 T."

Since the second US quadrupole magnet was tested in October, the AUP teams have completed the assembly of a third magnet and are close to completing the assembly of a fourth. Next, the first two magnets will be assembled in a single cold mass before being tested in a horizontal configuration and then shipped to CERN in time for the "string test" planned in 2023.

"In all activities at the forefront of technology, like in the case for these focusing Nb_3Sn quadrupoles, the major challenge is probably the transition from an 'R&D mentality', where minor improvements can be a daily business, to a 'production mentality', where there is a need to build to specific procedures and criteria, with all deviations being formally treated and corrected or addressed," says Apollinari. "And let's not forget that the success of this second magnet test came with a pandemic raging across the world."

MEDICAL TECHNOLOGY

European projects boost CERN's medical applications

A CERN-based effort to bring about the next generation of hadron-therapy facilities has obtained new funding from the European Commission (EC) to pursue technology R&D. CERN's Next Ion Medical Machine Study (NIMMS) aims to drive a new European effort for ion-beam therapy based on smaller, cheaper accelerators that allow faster treatments, operation with multiple ions, and patient irradiation from different angles using a compact gantry system. Its predecessor the Proton-Ion Medical Machine Study (PIMMS), which was undertaken at CERN during the late 1990s, underpinned the CNAO (Italy) and MedAustron (Austria) treatment centres that helped propel Europe to the forefront of hadron therapy.

These results demonstrate CERN's outstanding success rate in research-infrastructure projects

Covering the period 2021–2024, two recently approved EC Horizon 2020 Research Infrastructure projects will support NIMMS while also connecting its activities to collaborating institutes throughout Europe. The multidisciplinary HITRIplus project (Heavy Ion Therapy Research Integration) includes work packages dedicated to accelerator, gantry and superconducting magnet design. The IFAST project (Innovation Fostering in Accelerator Science and Technology) will include activities on prototyping superconducting magnets for ion therapy with industry, together with many other actions related to advanced accelerator R&D.

"Over the past three years we have collected about €4 million of EC contributions, directed to a collaboration of more than 15 partners, representing about a factor of eight leverage on the original CERN funding," says NIMMS project leader Maurizio Vretenar. "A key achievement was the simultaneous approval of HITRIplus and IFAST because they contain three strong work packages built around the NIMMS work-plan and associate our work with a wide collaboration of institutes."

A major NIMMS partner is the new South East European International Institute for Sustainable Technologies (SEEIIST), an initiative started by former CERN Director-General Herwig Schopper and former minister of science for Montenegro Sanja Damjanovic, which aims to build a pan-European facility for cancer research and therapy with ions in South East Europe (*CERN Courier* March 2018 p5). CNAO and MedAustron are closely involved in the superconducting gantry design, CIEMAT in Spain will build a high-frequency linac section, and INFN is developing new superconducting magnets, with the TERA Foundation continuing to underpin medical-accelerator R&D.

Leverage *CERN's radioisotope facility MEDICIS (pictured in 2018), and a project called NIMMS, developing next-generation accelerators for cancer therapy, have attracted Horizon 2020 funding.*

MEDICIS success

Also successful in securing new Horizon 2020 funding is a project built around CERN's MEDICIS facility, which is devoted to the production of novel radioisotopes for medical research together with institutes in life and medical sciences. The PRISMAP project (the European medical isotope programme) will bring together key facilities in the provision of high-purity-grade new radionuclides to advance early-phase research into radiopharmaceuticals, targeted drugs for cancer, "theranostics" and personalised medicine in Europe.

A successful programme towards this goal was developed by MEDICIS during the past two years, with partner institutes providing sources that were purified on a MEDICIS beamline using mass separation, explains Thierry Stora of CERN. "Our programme was particularly impressive this year, with record separation efficiencies of more than 50% met for ^{167}Tm, the first medical isotope produced at CERN 40 years ago with somewhat lower efficiencies," he says. "It also allowed the translation of ^{153}Sm, already used in low specific activity grades for palliative treatments, to R&D for new therapeutic applications." MEDICIS is now concluding its programme with the separation of ^{225}Ac, a fast-emerging radionuclide for the rising field of targeted alpha therapy. "Isotope mass separation at MEDICIS acted as a catalyst for the creation of the European medical isotope programme," says Stora, who leads the MEDICIS facility.

Together with other project consortia, the MEDICIS and HITRIplus teams are also working to identify the relevance of their research for the EC's future cancer mission, which is part of its next framework programme, Horizon Europe, beginning this year.

Two further EC Horizon 2020 projects launched by CERN – AIDAinnova, which will enable collaboration on common detector projects, and RADNEXT, which will provide a network of irradiation facilities to test state-of-the-art microelectronics – were approved in November. "These results demonstrate CERN's outstanding success rate in research-infrastructure projects," says Svet Stavrev, head of CERN's EU projects management and operational support section. "Since the beginning of the programme, Horizon 2020 has provided valuable support to major projects, studies and initiatives for accelerator and detector R&D in the particle-physics community."

HEP-based ventilator to be adapted for clinical use

A versatile ventilator to help combat COVID-19 developed by members of the LHCb collaboration is to be re-engineered for manufacture and clinical use. The High Performance Low-cost Ventilator (HPLV) is designed to assist patients in low- and middle-income countries suffering from severe respiratory problems as a result of COVID-19. Following the award of £760,000 by UK Research and Innovation, announced in December, Ian Lazarus of the Science and Technology Facilities Council's Daresbury Laboratory and co-workers aim to produce and test plans for the creation of an affordable, reliable and easy to operate ventilator that does not rely so heavily on compressed gases and mains electricity supply.

"I am proud to be leading the HPLV team in which we have brought together experts from medicine, science, engineering and knowledge transfer with a shared goal to make resilient high-quality ventilators available in areas of the world that currently don't have enough of them," said Lazarus in a press release.

Our goal is to make resilient high-quality ventilators available in areas of the world that don't have enough of them

While the majority of people who contract COVID-19 suffer mild symptoms, in some cases the disease can cause severe breathing difficulties and pneumonia. For such patients, the availability of ventilators that deliver oxygen to the lungs while removing carbon dioxide is critical. Commercially available ventilators are typically costly, require considerable experience to use, and often rely on the provision of high-flow ▷

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oxygen and medically pure compressed air, which are not readily available in many countries.

The HPLV takes as its starting point the High Energy physics Ventilator (HEV), which was inspired by an initiative at the University of Liverpool and developed at CERN in March 2019 during the first COVID-19 lockdown. The idea emerged when physicists and engineers in LHCb's vertex locator (VELO) group realised that the systems which are routinely used to supply and control gas at desired temperatures and pressures in particle-physics detectors are well matched to the techniques required to build and operate a ventilator (*CERN Courier* May/June 2020 p8). HPLV will see the hardware and software of HEV adapted to make it ready for regulatory approval and manufacture. Project partners at the Federal Institute of Rio de Janeiro in Brazil – in collaboration with CERN, the University of Birmingham, the University of Liverpool and the UK's Medical Devices Testing and Evaluation Centre – will now identify difficulties encountered when ventilating patients and pass that information to the design team to ensure that the HPLV is fit for purpose.

CERN-PHOTO-202008-107-1

Breathe easy *The CERN-based High Energy physics Ventilator is to be reengineered for clinical use by a UK-led team.*

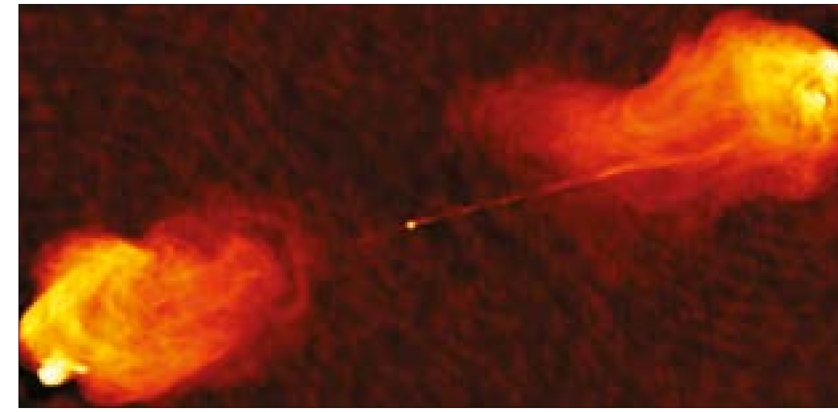
"We warmly welcome the HPLV initiative, and look forward to working together with the outstanding HPLV team for our common humanitarian goal," says Paula Collins, who co-leads the HEV project with CERN and LHCb colleague Jan Buytaert. The HPLV is one of several HEV offshoots involving 25 academic partners, she explains. "In December we also saw the first HEV prototypes to be constructed outside CERN, at the Swiss company Jean Gallay SA, which specialises in engineering for aerospace and energy. We have continued our outreach worldwide, and in particular wish to highlight an agreement being built up with a company in India that plans to modify the HEV design for local needs. None of this would have been possible without the incredible support and advice received from the medical community."

ASTROWATCH

Cosmic plasma-wakefield acceleration

The ability to accelerate charged particles using the "wakefields" of plasma density waves offers the promise of high-energy particle accelerators that are more compact than those based on radio-frequency cavities. Proposed in 1979, the idea is to create a wave inside a plasma upon which electrons can "surf" and gain energy over short distances. Although highly complex, laser-driven wakefield acceleration (WFA) has been successfully used to accelerate electron beams to tens of GeV within distances of less than a metre, and the AWAKE experiment at CERN is attempting to achieve higher accelerating gradients by using protons as drive beams. Recent studies suggest that WFA may also occur naturally, potentially offering an explanation for some of the highest energy cosmic rays ever observed.

NRAO/AUI



No lasers here Radio waves produced by electrons that have been propelled to relativistic speeds through a long, thin jet at the core of the galaxy Cygnus A.

So-called Fermi acceleration, first conceived by the eponymous Italian in 1949, is considered to be the main mechanism responsible for high-energy cosmic rays. In this process, charged particles are accelerated due to relativistic shockwaves occurring within jets emitted by black-hole binaries, active galactic nuclei or gamma-ray bursts, to name just a few sources. As a charged particle travels within the jet it gets accelerated each time it passes through the shock wave, allowing it to gain energy until the magnetic field in the environment can no longer contain it. This process predicts the observed power-law spectrum of cosmic rays quite well, at least up to energies of around 10^{19} eV. Beyond this energy, however, Fermi acceleration becomes less efficient as the particles start to lose energy due to collisions and/or synchrotron radiation. The existence of ultra-high-energy cosmic rays (UHECRs), which have been observed up to energies of 10^{21} eV, indicates that a different acceleration mechanism could be at play in that energy domain. Thanks to its very high efficiency, WFA could provide such a mechanism.

Although there are clearly no laser beams in astrophysical objects, plasma fields that can support waves can be found in many astrophysical settings. For example, in theories developed by Toshiki Tajima of the University of California at Irvine (UCI), one of the inventors of WFA technology, waves could be produced by instabilities in the accretion disks around compact objects such as black holes. These accretion disks can periodically transition from a highly magnetised to a little magnetised state, emitting electromagnetic waves that can propagate into the disk's jets in the form of Alfven waves. As these waves continue to propagate along the jets they transform back into electromagnetic waves that can accelerate electrons on the front of the plasma's "bow wake" and protons on the back of it.

Plasma fields that can support waves can be found in many astrophysical settings

Clear predictions

The energies that are theoretically achievable in cosmic-ray WFA depend on the mass of the compact object, as do the periodicities with which such waves can be produced. This allows clear predictions to be made for a range of different objects, which can be tested against observational data.

Groups based at UCI and at RIKEN in Japan recently tested these predictions on a range of astrophysical objects, spanning from 1 to 10^9 solar masses. Although not conclusive, these first comparisons between theory and observations indicate several interesting features that require further investigation. For example, WFA models predict periodic emission of both UHECRs – the protons on the back of the bow wake – in coincidence with electromagnetic radiation produced by the electrons from the front of the bow wake. Due to interactions with the intergalactic medium, UHECRs are also expected to produce secondary particles, including neutrinos. WFA could thereby also explain periodic outbursts of neutrinos in coincidence with gamma-rays from, for example, blazars, for which evidence was recently found by the IceCube experiment in collaboration with a range of electromagnetic instruments. Additionally, WFA could explain the non-uniformity of the UHECR sky such as that recently reported by the Pierre Auger Observatory (see *CERN Courier* December 2017 p15), as it allows for cosmic rays with energies up to 10^{24} eV to be produced within objects that lie within the location of the observed hot-spot.

In concert with future space-based UHECR detectors such as JEM-EUSO and POEMMA, further analysis of existing data should definitively answer the question of whether WFA does indeed occur in space. The clear predictions relating to periodicity, and the coincident emission of neutrinos, gamma-rays and other electromagnetic radiation, make it an ideal subject to study within the multi- messenger frameworks that are currently being set up.

Further reading

T Tajima *et al.* 2020 *Rev. Mod. Plasma Phys.* **4** 7.
G Huxtable *et al.* 2020 arXiv.org:2009.12333.
T Ebisuzaki and T Tajima 2019 arXiv.org:1905.04506.

CERNCOURIER

VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021

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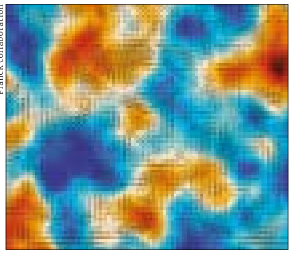
NEWS DIGEST



Polarisation (rods) and temperature anisotropy (colour) for 2.5° of CMB sky.

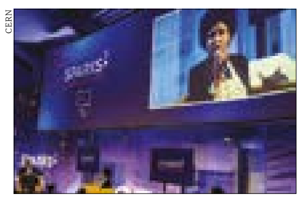
A polarising measurement
Researchers at Japan's KEK laboratory have reported the most precise analysis yet of the polarisation of the cosmic microwave background (CMB), finding hints of a rotation. The polarisation of the CMB is sensitive to parity-violating physics whereby new scalar fields or dark-matter particles imbue CMB photons with a rotation via "cosmic birefringence". Precise measurements of the polarisation angle therefore offer a way to search for new physics. The KEK team applied a new technique to 2018 Planck data, wherein they compare it with galactic foreground emission from within the Milky Way. This approach permits an error cancellation that doubles precision compared to previous measurements, claims the team (*Phys. Rev. Lett.* **125** 221301). Their initial measurement is consistent with the Standard Model within 2.4 standard deviations.

No carbon chauvinism at MIT
MIT's new Institute for Artificial Intelligence and Fundamental Interactions (IAIFI) opened its doors in November. Devoted to the use of neural networks in physics, IAIFI is one of five new US institutes set up to galvanise research into AI, each of which will receive $20 million over five years. Directed by MIT theorist Jesse Thaler, the centre will foster dialogue between researchers across physics and computer science, with the goal of creating machines that can interact with physicists on a comparable intellectual footing. A lesser ambition would amount to "carbon chauvinism", according to the institute's community-building coordinator, Max Tegmark.

New P_5' anomaly
Data presented at the Implications of LHCb Measurements workshop, held online from 28 to 30 October, compound previously seen flavour anomalies in B-meson decays. In 2013 the collaboration observed an anomaly in measurements of P_5' – an angular observable in the decay $B^0 \to K^{*0}\mu^+\mu^-$ constructed to be as independent as possible of poorly constrained hadronic physics. The latest analysis shows that data favour a minimal extension to the Standard Model at 3.3σ significance (*CERN Courier* May/June 2020 p10). The collaboration now reports a comparable 3.1σ effect in $B^+ \to K^{*+}\mu^+\mu^-$ decays, which feature the same $b \to s$ transition (LHCb-PAPER-2020-041). The decays could be sensitive to virtual contributions from new particles with masses that are inaccessible to direct searches at the LHC, and could be related to lepton-universality anomalies also seen by LHCb, say theorists.

New multi-quark states
The LHCb collaboration also reported measurements of two new multi-quark states at its October Implications workshop. An X(4740) structure of unknown nature was observed with 5.2σ significance in the invariant mass of $J/\psi\phi$ in $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decays (LHCb-PAPER-2020-035). The collaboration also reported 3.1σ evidence for the predicted $uds c\bar{c}$ pentaquark $P_{cs}(4459)$ in a six-dimensional amplitude analysis of $\Xi_b^- \to J/\psi K^- \Lambda$ decays (LHCb-PAPER-2020-039). Meanwhile, in China, the BESIII collaboration reports a 5.3σ resonance with a mass of 3983 MeV in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ events – the first candidate for a charged hidden-charm tetraquark with strangeness, says the collaboration (arXiv:2011.07855).

Interdisciplinary engagement
On 26 November CERN launched a new public forum designed to inspire innovation in issues in science and technology related to its mission of science for peace. The "Sparks! Serendipity Forum" will convene leading scientists from diverse fields alongside policymakers, industry leaders, philanthropists and ethicists. The first two-day event, which will begin on 18 September, will focus on artificial intelligence.



CMS's Jennifer Ngadiuba at the launch of CERN's Sparks! Serendipity Forum.

Confirmed participants include Nobel laureate in economics Daniel Kahneman, Berkeley professor of computer science Stuart Russell, AI ethics global leader at IBM Francesca Rossi, and DeepMind vice-president of research Koray Kavukcuoglu.

First cosmic tau neutrinos spotted
The IceCube collaboration has reported the first sightings of PeV-scale tau neutrinos – a smoking gun for neutrinos from astrophysical sources (arXiv:2011.03561). The events exhibit two distinct energy depositions separated by tens of metres in the South-Pole Cherenkov detector: one from the initial hadronic interaction, and one from the decay of the resulting tau lepton. Though few tau neutrinos are expected to be created by sources such as active galactic nuclei, gamma-ray bursts or microquasars, neutrino oscillations should cause them to arrive on Earth with roughly the same flux as the other neutrino flavours. The flavour composition of astrophysical neutrinos probes both the nature of cosmic accelerators and physics beyond the Standard Model, which could affect neutrino propagation.

Fifth force squeezed by SQUID
A team pioneering searches for macroscopic "fifth forces" using a SQUID magnetometer at INFN-LNL has pushed down limits on spin-mass interactions by roughly two orders of magnitude for interaction ranges from 1 cm to 10 m and 10 to 300 km (arXiv:2011.07100, submitted to *Phys. Rev. X*). Neighbouring world-best "pure laboratory" constraints are set by experiments with torsion balances, and astrophysical bounds are currently at least two orders of magnitude stricter across the board. Precision magnetometry may be further leveraged to explore a vast region of the fifth force's parameter space by increasing the size of the apparatus to suppress noise, claims the team.

Neutrons aid pollution detection
A team of scientists from the University of Lisbon have used neutrons to detect air pollution in the region of Ponte de Sor, an area known for its charcoal industry. The study took place after complaints of smells, clouds of smoke in winter and reports of asthma and other respiratory diseases in the area. Collaborating with scientists from the Technical University of Munich (TUM), the team took samples of lichens from the immediate vicinity of charcoal kilns in the region and irradiated them using an intense neutron beam at TUM, causing nuclei to capture the neutrons and emit prompt gamma rays upon de-excitation. A Compton-suppressed spectrometer detected a higher concentration of sulphur and twice the amount of phosphorus, both of which are produced in the combustion process, compared to samples located further away.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

CMS targets Higgs-boson pair production

The Higgs boson discovered in 2012 by the ATLAS and CMS experiments is the pinnacle of the scientific results so far at the LHC. Measurements of its couplings to W and Z bosons and to heavy fermions have provided a strong indication that the mechanism of electroweak symmetry breaking is similar to that proposed by Brout, Englert and Higgs (BEH) more than 50 years ago. In this model, the BEH field exists throughout space with a non-zero field strength corresponding to the minimum of the BEH potential. The measurement of the shape of the BEH potential has become one of the main goals of experimental particle physics. It governs not only the nature of the electroweak phase transition in the early universe, when the BEH field gained its non-zero "vacuum expectation value" (VEV), but also the question of whether deeper minima than the present vacuum exist.

Interactions with the BEH VEV give mass not only to the W and Z bosons and the fermions, but also to the Higgs boson itself. If the mass of the Higgs boson is well known, the Standard Model (SM) can therefore predict the Higgs self-coupling, λ – the key unknown parameter in the shape of the BEH potential of the SM. The measurement of the production of Higgs-boson pairs (HH) gives a direct way to measure λ. Higgs-boson pair production is not yet established experimentally, as it is a thousand times less frequent than the production of a single Higgs boson. However, the presence of physics beyond the SM can substantially enhance the HH production rate. The search for HH production at the LHC is therefore an important test of the SM.

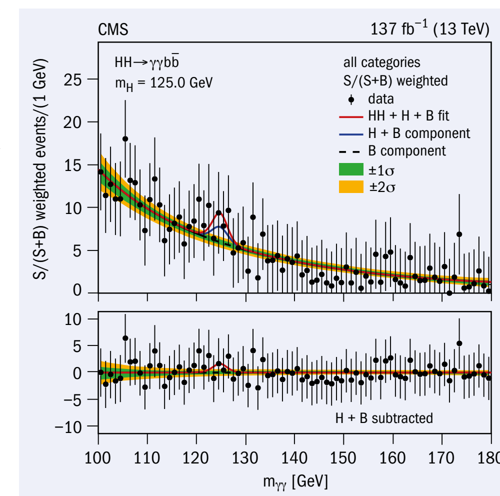


Fig. 1. *The weighted diphoton invariant mass distribution for the selected $\gamma\gamma b\bar{b}$ events. The red line includes the observed HH signal contribution, while the blue line represents the contribution from background processes only.*

A recent result by the CMS collaboration describes a search for HH production in final states with two photons and two b-jets (figure 1). The large data sample collected during LHC Run 2 excludes a HH production rate larger than 7.7 times that predicted by the SM. CMS has set the best constraint to date on the ratio of the measured λ parameter to the SM prediction, $\kappa_\lambda = 0.6^{+6.3}_{-1.8}$.

The sensitivity of the analysis has been improved by about a factor four over the previous result that used the data collected in 2016, benefitting equally from the increase in luminosity and from a wealth of innovative analysis techniques. The electromagnetic calorimeter of the CMS experiment allows the measurement of $H \to \gamma\gamma$ candidates with excellent resolution (about 1–2%). Advanced machine-learning techniques, including deep neural networks, were introduced to significantly improve the mass resolution of $H \to b\bar{b}$, from 15% down to 11%. The analysis combines information from the invariant mass of the HH system, reflecting the underlying physics processes, and a multivariate classifier exploring the kinematic properties as well as the identification of photons and b-jets.

Events were categorised to enhance the sensitivity to Higgs production via gluon fusion as well as, for the first time, vector-boson fusion. The latter constrains the quartic coupling between two vector bosons and two Higgs bosons, such as WWHH, which is an extremely rare interaction in the SM. In addition, dedicated categories from a previous analysis were added to account for the associated production of top quarks and a single Higgs boson, and to provide a simultaneous constraint on the top-quark Yukawa coupling and λ. Several hypotheses predicting new physics were also constrained. The results are an encouraging step forwards in the quest to measure the BEH potential and to further interrogate the SM.

Further reading

CMS Collab. 2020 arXiv:2011.12373.

ATLAS

Higgs boson gets SMEFT treatment

The growing LHC dataset eight years after the discovery of the Higgs boson allows the experiments to study its properties more and more precisely, searching for hints of physics beyond the Standard Model (SM). New phenomena might occur at energy scales beyond the reach of the LHC, pointing to the existence of so-far undiscovered particles with masses too heavy to be directly produced in 13 TeV proton–proton collisions. Without knowing the exact nature of the new physics, LHC data can be analysed to systematically constrain new types of interactions in the framework of an effective field theory (EFT). One historical EFT example is Fermi's effective interaction model for nuclear beta decay, which is valid as long as the probed energy scale is well below the mass of the W boson. The move to constrain EFTs rather than signal strengths for couplings marks a new, more comprehensive phase in SM tests at the LHC.

LHC data can constrain new types of interactions in the framework of an effective field theory

Almost all types of new physics would give rise to new interactions with SM particles, with different models leaving different EFT footprints. As the underlying dynamics is not known and effects can be subtle, it is important to combine as many measurements as possible across the full spectrum of the LHC research programme.

A new ATLAS analysis presented at the Higgs 2020 conference, held online from 26 to 30 October, takes a first step in this direction. The analysis combines measurements of production cross-sections and kinematic variables of Higgs-boson events in several decay channels ▷

CERNCOURIER
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(diphoton, four-lepton and di-b-quark decays) to constrain new phenomena within the so-called SMEFT framework. The combination of measurements allows multiple new interactions involving the Higgs boson to be constrained simultaneously. This approach requires fewer hypotheses on the other unconstrained interactions than studying the EFT terms one measurement at a time. The results are therefore more generic and easier to interpret in a broader context.

Figure 1 shows the allowed ranges for the coupling coefficients of new EFT interactions to which the ATLAS combined Higgs analysis is sensitive. The coefficient $c^{(3)}_{Hq}$, for example, describes the strength of an effective four-particle interaction between two quarks, a gauge boson and the Higgs boson. The SM predicts all these coefficients to vanish, as their corresponding interactions are not present. Significant positive or negative deviations would indicate new physics. For instance, a non-vanishing value of $c^{(3)}_{Hq}$ would cause deviations from the SM in the ZH and WH cross-sections at high transverse momentum of the Higgs boson, which are not observed in the measured channels.

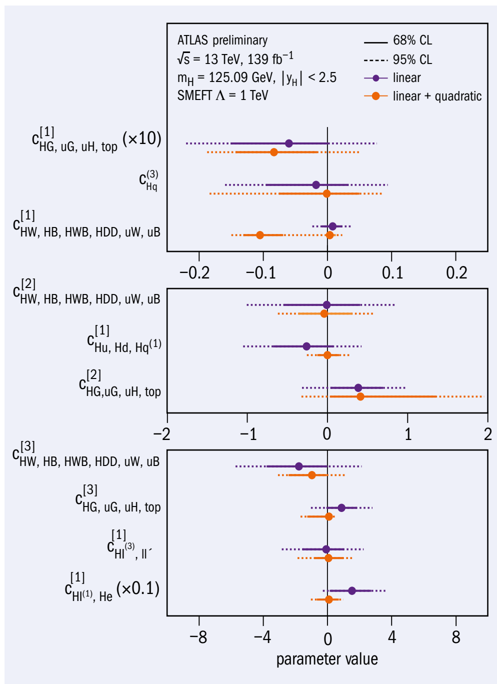


Fig. 1. *Allowed ranges for the coupling coefficients of new EFT interactions in a so-called rotated Warsaw basis, including only contributions from the interference between SM and new-physics diagrams (purple), or also including pure new-physics terms that appear at higher order (orange). The SM prediction for all these coefficients is zero.*

All measurements are compatible with the SM, indicating that if new physics is present it either has a mass scale larger than 1 TeV (the reference scale for which these results are reported) – or it manifests itself in interactions to which the available measurements are not yet sensitive. In the meantime, thanks to the design of the analysis, the results can be added to wider EFT interpretations that combine measurements from different physics processes (e.g. electroweak-boson or top-quark production) studied by ATLAS and other experiments, providing a consistent and increasingly detailed mapping of the allowed new physics extensions of the SM.

Further reading

ATLAS Collab. 2020 ATLAS-CONF-2020-027.
ATLAS Collab. 2020 ATLAS-CONF-2020-053.

ALICE

Heavy flavours probe QGP geometry

Charm and beauty quarks are excellent probes of the hot and dense state of deconfined quarks and gluons (quark–gluon plasma, QGP) which is created in high-energy heavy-ion collisions. These heavy quarks are produced in hard-scattering processes at the early stages of the collisions, and interact with the constituents of the newly created QGP through both elastic and inelastic processes. These quarks, which can be studied through their decays into leptons, lose energy while propagating through the QGP medium. Consequently, different production yields are observed at large momenta in nucleus–nucleus collisions compared to proton–proton collisions. This effect can be quantified using the nuclear modification factor, R_{AA}, which is the ratio of nucleus–nucleus and proton–proton particle yields, scaled by the average number of binary nucleon–nucleon collisions. Comparing measurements in different collision systems sheds light on heavy-quark energy-loss mechanisms, and provides high-precision tomography of the QGP.

A new analysis by the ALICE collaboration compares the production of leptons from heavy-flavour hadron decays in Pb–Pb and Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.02 and 5.44 TeV, respectively. The measurements use the muon and electron decay channels at forward rapidity and mid-rapidity. The results show that collision geometry plays an important role in heavy-quark energy loss.

A remarkable agreement is observed between the muon yields in head-on Xe–Xe collisions and slightly offset Pb–Pb collisions (figure 1, left). Given the larger size of the lead nucleus, these collision centrality classes – 0–10% and 10–20%, respectively – give rise to similar ▷ charged-particle multiplicities, and thus suggest the creation of similar QGP densities and sizes in the colliding systems.

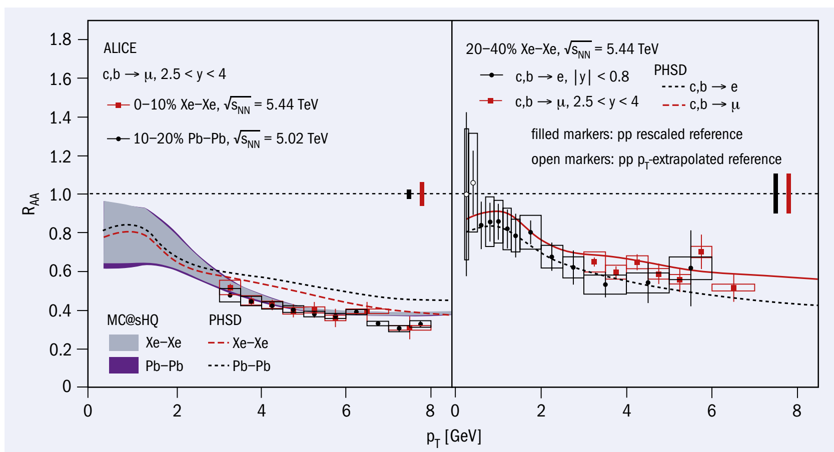


Fig. 1. *Left: the p_T-differential R_{AA} of muons from heavy-flavour hadron decays at forward rapidity in Xe–Xe (centrality class 0–10%) and Pb–Pb (centrality class 10–20%) collisions. Right: the p_T-differential R_{AA} of muons and electrons from heavy-flavour hadron decays in semi-central (20–40%) Xe–Xe collisions. Comparisons with transport-model calculations are displayed.*

In both cases, the production of muons from heavy-flavour hadron decays is suppressed up to a factor of about 2.5 for 5 GeV < p_T < 6 GeV. This suppression is successfully reproduced by the MC@sHQ+EPOS2 model, which considers both elastic and inelastic energy-loss processes of the heavy quarks in the QGP, but is underestimated by the PHSD model, which only includes elastic processes. The analysis also saw ALICE's first sensitivity down to p_T = 0.2 GeV using a lower magnetic field (0.2 T) in the solenoid magnet (figure 1, right). The suppression pattern for muons and electrons from heavy-flavour hadron decays is similar at both forward and mid-rapidity, indicating that heavy quarks strongly interact with the medium over a wide rapidity interval. The suppression is smaller in these "glancing" semi-central collisions than in the previously discussed head-on collisions. This is compatible with the hypothesis that the in-medium energy loss depends on the energy density and on the size of the system created in the collision.

The precision of the measurements brings new insights into the nature of parton energy loss

The precision of the measurements brings new insights into the nature of parton energy loss and new constraints to the modelling of its dependence on the size of the QGP medium in transport-model calculations. Further constraints will be set by future high precision measurements during Run 3, when ALICE will measure leptons from charm and beauty decays separately, at both central and forward rapidity. A short run with the much smaller oxygen–oxygen system may also be scheduled and contribute to a deeper understanding of the dependence of system size on in-medium energy loss for heavy quarks.

Further reading

ALICE Collab. 2020 arXiv:2011.05718.
ALICE Collab. 2020 arXiv:2011.06970.

LHCb

LHCb sheds light on V_{ub} puzzle

The Cabibbo–Kobayashi–Maskawa (CKM) matrix element V_{ub} describes the coupling between u and b quarks in the weak interaction, and is one of the fundamental parameters of the Standard Model (SM). Though it was first observed to be non-zero 30 years ago, its value is still debated. $|V_{ub}|$ determines the length of the least well-known side of the corresponding unitarity triangle, and is therefore a key ingredient for testing the consistency of the SM in the flavour sector. LHCb has recently published a new result on $|V_{ub}|$ using the first ever measurement of the $B^0_s \to K^-\mu^+\nu_\mu$ decay.

$|V_{ub}|$ and $|V_{cb}|$ are the focus of a long-standing puzzle. When comparing the world-average values derived from inclusive and exclusive B-meson decays, respectively, the inclusive and exclusive measurements disagree by more than three standard deviations, for measurements of both $|V_{ub}|$ and $|V_{cb}|$. Traditionally, the exclusive $|V_{ub}|$ determination requires the reconstruction of the semi-leptonic $b \to u$ decay $B^0 \to \pi^-\mu^+\nu_\mu$. LHCb also has access to B^0_s meson and b-baryon decays, but the missing neutrino makes it difficult to isolate the signal from the copious background. Defying expectations, however, in 2015 LHCb managed to observe the $\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$ decay, and used the normalisation channel $\Lambda^0_b \to \Lambda^+_c\mu^-\bar{\nu}_\mu$ to determine $|V_{ub}|/|V_{cb}|$. The main difficulty in this type of analysis resides in the fact that only two charged particles are reconstructed in decays such as $B^0_s \to K^-\mu^+\nu_\mu$ and $\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$. A huge background arising from other sources dominates the selected data sample. Machine-learning algorithms are therefore used to isolate the signal from the various background categories consisting of decays with additional charged and/or neutral particles in the final state. The remaining irreducible background is modelled by using both simulation and control samples extracted from data.

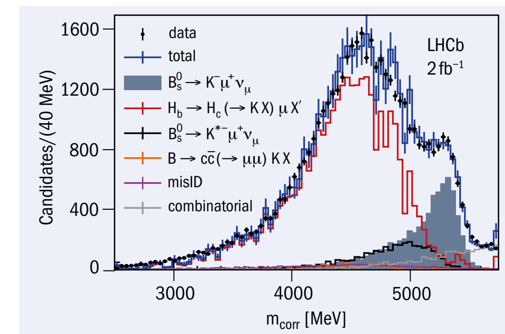


Fig. 1. *Distribution of the corrected mass m_{corr} for candidates that passed all the selection criteria, in the low q^2 region. The corrected mass makes use of the flight direction of the B^0_s candidate to account for the missing neutrino. Fit projections are overlaid as histograms.*

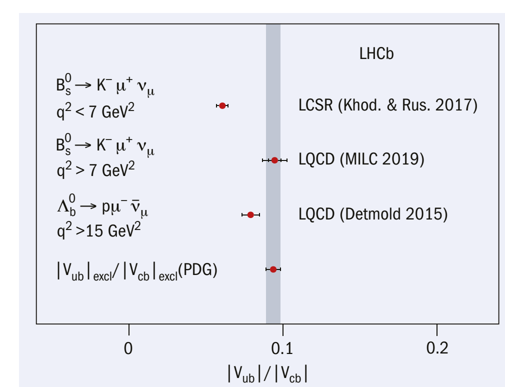


Fig. 2. *Measurements of $|V_{ub}|/|V_{cb}|$ by the LHCb collaboration and from the ratio of the PDG averages of exclusive $|V_{ub}|$ and $|V_{cb}|$ measurements. The form-factor calculations used in different q^2 regions of the new $|V_{ub}|$ determination are noted.*

In a recent paper, the LHCb collaboration presented the first observation of the decay $B^0_s \to K^-\mu^+\nu_\mu$. The decay $B^0_s \to D^-_s\mu^+\nu_\mu$ is used as a normalisation channel to minimise experimental systematic uncertainties. The study was performed in two regions of the squared invariant mass (or momentum transfer) q^2 of the muon and the neutrino below and above 7 GeV^2. The observed total yield was about 13,000 events, corresponding to a branching fraction of $(1.06 \pm 0.10) \times 10^{-4}$, of which about one third stemmed from the low q^2 range (figure 1).

The extraction of the ratio $|V_{ub}|/|V_{cb}|$ requires external knowledge of the form factors describing the strong $B^0_s \to K^-$ and $B^0_s \to D^-_s$ transitions, to account for the interactions of the quarks bound in mesons. These vary with the momentum transfer and are calculated using non-perturbative techniques, such as lattice QCD (LQCD) and light-cone sum rules (LCSR). As LQCD and LCSR calculations are more accurate at high and low q^2, respectively, they are used in the corresponding q^2 regions. The obtained value of $|V_{ub}|/|V_{cb}| = 0.095 \pm 0.008$ in the high q^2 interval shows agreement with the world average of exclusive measurements, and with the LHCb result using $\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$ decays, while in the low q^2 region, $|V_{ub}|/|V_{cb}| = 0.061 \pm 0.004$ is significantly lower (figure 2). This is the first experimental test of the form-factor calculations, and new results are expected in the near future. These will help settle the exclusive versus inclusive debate surrounding the values of $|V_{ub}|$ and $|V_{cb}|$, and provide further constraints on the unitarity triangle.

Further reading

LHCb Collab. 2020 arXiv:2012.05143.

FIELD NOTES

Reports from events, conferences and meetings

Long-Lived Particles workshop

A long-lasting paradigm shift

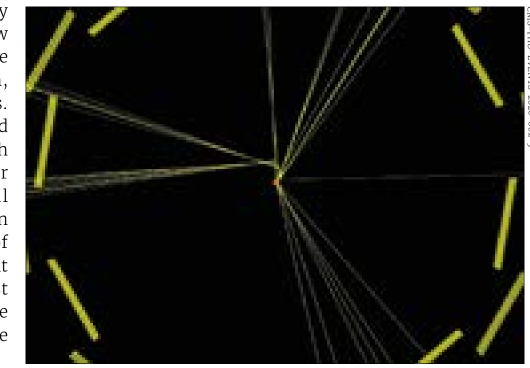
Searches for new physics at high-energy colliders traditionally target heavy new particles with short lifetimes. These searches determine detector design, data acquisition and analysis methods. However, there could be new long-lived particles (LLPs) that travel through the detectors without decaying, either because they are light or have small couplings. Searches for LLPs have been going on at the LHC since the start of data taking, and at previous colliders, but they are attracting increasing interest in recent times, more so in light of the lack of new particles discovered in more mainstream searches.

Detecting LLPs at the LHC experiments requires a paradigm shift with respect to the usual data-analysis and trigger strategies. To that end, more than 200 experimentalists and theorists met online from 16 to 19 November for the eighth workshop of the LHC LLP community.

Dark showers

Strong theoretical motivations underpin searches for LLPs. For example, dark matter could be part of a larger dark sector, parallel to the Standard Model (SM), with new particles and interactions. If dark quarks could be produced at the LHC, they would undergo fragmentation and hadronisation in the dark sector, resulting in characteristic "dark showers" – one of the focuses of the workshop. Collider signatures for dark showers depend on the fraction of unstable particles they contain and their lifetime, with a range of categories presenting their own analysis challenges: QCD-like jets, semi-visible jets, emerging jets and displaced vertices with missing transverse energy. Delegates agreed on the importance of connecting collider-level searches for dark showers with astrophysical and cosmological scales. In a similar spirit of collaboration across communities, a joint session with the HEP Software Foundation focused on triggering and reconstruction software for dedicated LLP detectors.

The discovery of heavy neutral leptons (HNLs) could address different open questions of the SM. For example, neutrinos are expected to be left-handed and massless in the SM, but oscillate between flavours as their wavefunction evolves, providing evidence for as-yet immeasurably small masses. One way to fix this problem is to complete the field pattern of the SM with right-handed HNLs. The number and other characteristics of HNLs depend on the model considered, but in many cases HNLs are long-lived and connect to other important questions of the SM, such as dark matter and the baryon asymmetry of the universe. There are many ongoing searches for HNLs at the LHC and many more proposed elsewhere. During the November workshop the discussion touched on different models and simulations, reviewing what is available and what is needed for the different signal benchmarks.



CMS-PHO-EVENTS-2020-002-5

Displaced vertex *A simulated CMS collision where a long-lived particle travels a short distance before it decays.*

Another focus was the reinterpretation of previous LLP searches. Recasting public results is common practice at the LHC and a good way to increase physics impact, but reinterpreting LLP searches is more difficult than prompt searches due to the use of non-standard selections and analysis-specific objects.

The latest results from CERN experiments were presented. ATLAS reported the first LHC search for sleptons using displaced-lepton final states, greatly improving sensitivity compared to LEP. CMS presented a search for strongly interacting massive particles with trackless jets, and a search for long-lived particles decaying to jets with displaced vertices. LHCb reported searches for low-mass di-muon resonances and a search for heavy neutrinos in the decay of a W boson into two muons and a jet, and the NA62 experiment at CERN's SPS presented a search for π^0 decays to invisible particles. These results bring important new constraints on the properties and parameters of LLP models.

A series of dedicated LLP detectors at CERN – including the Forward Physics Facility for the HL-LHC, the CMS forward detector, FASER, Codex-b and Codex-ß, MilliQan, MoEDAL-MAPP, MATHUSLA, ANUBIS, SND@LHC and FORMOSA – are in different stages between proposal and operation. These additional detectors, located at various distances from the LHC experiments, have diverse strengths: some, like MilliQan, look for specific particles (milli-charged particles, in that case), whereas others, like Mathusla, offer a very low background environment in which to search for neutral LLPs. These complementary efforts will, in the near future, provide all the different pieces needed to build the most complete picture possible of a variety of LLP searches, from axion-like particles to exotic Higgs decays, potentially opening the door to a dark sector.

Into the future

The workshop featured a dedicated session on future colliders for the first time. Designing these experiments with LLPs in mind would radically boost discovery chances. Key considerations will be tracking and the tracking volume, timing information, trigger and DAQ, as well as potential additional instrumentation in tunnels or using the experimental caverns.

Together with the range of new results presented and many more in the pipeline, the 2020 LLP workshop was representative of a vibrant research community, constantly pushing the "lifetime frontier".

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Volume 61 Number 1 January/February 2021
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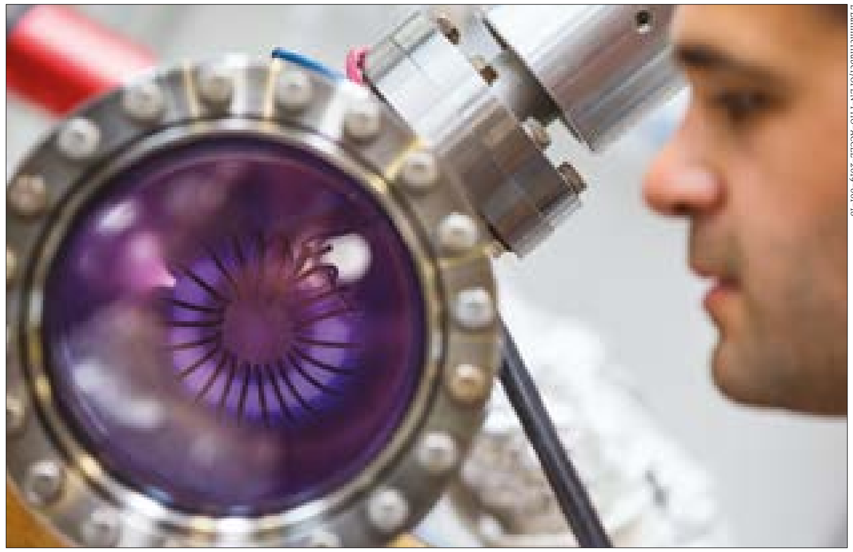
Future Circular Collider workshop

Horizon event for FCC innovators



L Lammerhuber/OPEN-PHO-ACCEL-2019-001-18

Magneto-spattering *A researcher experiments with a technique for applying a thin superconducting film to radio-frequency (RF) cavities. Superconducting RF is a key technology for the sustainable operation of the FCC as a Higgs and electroweak factory.*

The recent Future Circular Collider (FCC) workshop, held online from 9 to 13 November, brought together roughly 500 scientists, engineers and stakeholders to prepare a circular-collider-oriented roadmap towards the realisation of the vision of the European strategy for particle physics: to prepare a Higgs factory followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than at the LHC.

The meeting combined the fourth FCC physics week with the kick-off event for the EU-funded Horizon 2020 FCC Innovation Study (FCCIS). A successor to the previous EuroCirCol project, which was completed in 2019 and supported the preparation of the FCC conceptual design report (CDR), it will support the preparation of a feasibility study of a 100 km-circumference collider that could host an intensity-frontier electron–positron Higgs and electroweak factory (FCC-ee), followed by a 100 TeV energy-frontier hadron collider (FCC-hh) – an integrated scheme that EuroCirCol showed to be doable "in principle". Key advantages of the FCC design are the multiple interaction points, high beam luminosities and long-term science mission covering both precision and energy frontiers over several decades (see p29). The design must now be validated. "The feasibility study of FCC is particularly challenging and will require the hard work, dedication and enthusiasm of the full FCC community," noted CERN Director-General Fabiola Gianotti.

Unprecedented capabilities

The main goal of the study, said FCC-study project-leader Michael Benedikt, is to demonstrate the practical feasibility of delivering the unprecedented luminosities and precise energy-calibration capabilities of the proposed electroweak factory in a modular fashion. The study will also incorporate a socio-economic impact analysis and an implementation plan for an infrastructure that could fit in the global research landscape, he said. The feasibility study – a "CDR++" – will be prepared by 2025/2026, in time for the next strategy update.

A key consideration for FCC-ee that was discussed at the meeting is the development of a complete collider design with full beam-dynamic simulations and a complete injector. Continuous top-up injection, from a full-energy booster ring installed next to the collider, will lead to stable operation and maximum integrated luminosity, offering availability for physics runs of more than 80%. A series of tests in research facilities around Europe, including at PETRA-III (DESY), KARA (KIT), DAΦNE (Frascati), and potentially other facilities such as VEPP-4M (BINP), will provide the opportunity to validate the concepts. Developing a staged superconducting radio-frequency system is another major challenge. Multi-cell 400 MHz Nb/Cu cavities required for the Higgs-factory operation mode will be available within five years, alongside a full cryomodule. A mock-up of a 25 m-long full-arc half-cell of the FCC-ee is expected for 2025. Such cells will cover about 80 km of FCC-ee's 100 km circumference.

BLEED/FCC collaboration

Physics-analysis questions were also at the forefront of participants' minds. "We are confronted with three deep and pressing questions when we observe our universe," noted ECFA chair Jorgen D'Hondt. "What is the mechanism responsible for the transition from massless to massive particles? What are the processes that lead to the breaking of symmetry between particles and antiparticles? And how is the observed universe connected to what remains invisible to us?" Theorist Christopher Grojean (DESY) showed that electroweak, Higgs and flavour data from FCC-ee, in conjunction with astrophysical and cosmological observations, have the potential to break through the armour of the Standard Model and begin to tackle these questions. Discussions explored the need to halve theoretical uncertainties and hone detector designs to match the high statistical precision offered by the FCC-ee, and the possibility of complementing FCC-ee with a linear collider such as the proposed International Linear Collider, which could access higher energies.

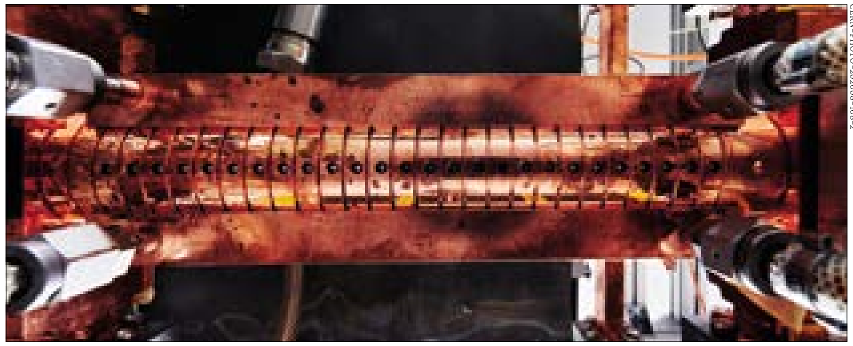
Strong message

The November FCC workshop paved the way for progress beyond the state-of-the-art in a variety of areas that could ensure the sustainable and efficient realisation of a post-LHC collider. A strong message from the workshop was that the FCC feasibility study must be a global endeavour that attracts industrial partners to co-develop key technologies, and inspires the next generation of particle physicists.

Panos Charitos *CERN.*

Very High Energy Electron Radiotherapy Workshop

Targeting tumours with electrons



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Belly of the beast *A CLIC X-band RF cavity prototype in CERN's CLEAR user facility.*

More than 10,000 electron linear accelerators are in use in radiotherapy (RT) worldwide. Most operate at energies from 5 to 15 MeV, using secondary bremsstrahlung radiation generated from interactions with high-density targets to kill tumours. Recently, however, the feasibility of compact and cost-effective high-gradient (~100 MV/m) linacs has led to a resurgence of interest in directly targeting cancer cells with very-high-energy electron (VHEE) beams, from 50 to 250 MeV. The VHEE 2020 International Workshop saw more than 400 scientists gather virtually, from 5 to 7 October, to explore the technology's potential. Attendees ranged from clinicians to biologists, and from accelerator physicists to dosimetry experts.

VHEE beams offer several benefits. Small-diameter VHEE beams can be scanned and focused easily, enabling finer resolution for intensity-modulated treatments than is possible with photon beams. Electron accelerators are more compact and significantly cheaper than current installations required for proton therapy. And VHEE beams can operate at high dose rates compatible with the "FLASH" effect – a paradigm-shifting method for delivering ultra-high doses within tenths of a second. The technique has recently been shown to preserve normal tissue in various species and organs while still maintaining anti-tumour efficacy equivalent to conventional RT at the same dose level, in part due to decreased production of toxic reactive oxygen species. The FLASH effect has been shown to take place with electron, photon and, most recently, proton beams. However, electron beams promise to deliver an intrinsically higher dose, especially over large areas as would be needed for large tumours.

Many challenges, both technological and biological, have to be addressed and overcome for the ultimate goal of using VHEE and VHEE-FLASH as an innovative modality for effective cancer treatment with minimal damage to healthy tissues. All of these were extensively covered and thoroughly discussed in the different sessions of VHEE 2020. Most of the preclinical data demonstrating the increased therapeutic index of FLASH uses a single fraction and hypo-fractionated regimen of RT and 4 to 6 MeV beams, which do not allow treatments of deep-seated tumours and trigger large lateral penumbra – a problem that can be solved by increasing the electron energy to values higher than 50 MeV.

The major challenge for VHEE-FLASH, however, is the delivery of very high dose-rate, possibly over a large area, providing a uniform dose distribution throughout the target. Of particular importance, as was repeatedly pointed out during the workshop, is the development of reliable online dosimetry for very high dose rates – a regime not adapted to the current standard dosimetry techniques for RT, as ionisation chambers, which are routinely used in medical linacs, suffer from nonlinear effects at very high dose rates. R&D is needed to develop novel ion chambers, or alternatives such as solid-state detectors or calibrated beam diagnostics.

Continued advances

The longstanding synergies with accelerators developed for high-energy physics continue to bear fruit. Since the 1980s, when pioneering preliminary work on FLASH was being carried out by researchers at Lausanne University Hospital (CHUV) in Switzerland and the Curie Institute in France, high-gradient linac technology advances for VHEE have been made at CERN for the proposed Compact Linear Collider (CLIC). An extensive R&D programme on normal-conducting radio-frequency accelerating structures is being carried out to obtain the demanding performances of the CLIC linac: an accelerating gradient of 100 MV/m, low breakdown rate, micron-tolerance alignment and a high RF-to-beam efficiency (around 30%). All this is now being applied in the conceptual designs of new RT facilities, such as one jointly being developed by CHUV and CERN (*CERN Courier* November/December 2020 p7).

The use of novel accelerator techniques such as laser-plasma accelerators is also starting to be applied in the VHEE field.

Establishing innovative treatment modalities for cancer is a major 21st century health challenge

It is important to compare the properties of the electron beams depending on the way they are produced (radio-frequency or laser-plasma-accelerator technologies). A number of experimental test facilities are already available to perform these ambitious objectives: the CERN Linear Electron Accelerator for Research (CLEAR), so far rather unique in being able to provide both high-energy (50–250 MeV) and high-charge beams; VELA–CLARA at Daresbury Laboratory; PITZ at DESY and finally ELBE–HZDR using the superconducting radio-frequency technology at Dresden. Further radiobiology studies with laser-plasma accelerated electron beams are currently being performed at the DRACO PetaWatt laser facility in ELBE Center at HZDR-Dresden and at the Laboratoire d'Optique Appliqué in the Institute Polytechnique de Paris. Future facilities, as exemplified by the CERN–CHUV facility previously mentioned or the PHASER proposal at SLAC, are also on the horizon.

Establishing innovative treatment modalities for cancer is a major 21st century health challenge. By 2040, cancer is predicted to be the leading cause of death, with approximately 27.5 million newly diagnosed patients and 16.3 million related deaths per year. The October VHEE workshop demonstrated the continuing potential of accelerator physics to drive new RT treatments, and also included a lively session dedicated to industrial partners. The large increase in attendance since the first workshop in 2017 in Daresbury shows the vitality and increasing interest in this field.

Manjit Dosanjh *CERN and the University of Oxford*, **Roberto Corsini** *CERN*, **Angeles Faus-Golfe** *IJClab–IN2P3 and* **Marie-Catherine Vozenin** *CHUV.*

TARGETING A HIGGS FACTORY

An electron–positron collider to follow the LHC will produce copious Higgs bosons, yielding precise knowledge of this unique particle, explain Keith Ellis and Beate Heinemann.

Looking back on the great discoveries in particle physics, one can see two classes. The discovery of the Ω^- in 1964 and of the top quark in 1995 were the final pieces of a puzzle – they completed an existing mathematical structure. In contrast, the discovery of CP violation in 1964 and of the J/ψ in 1974 opened up new vistas on the microscopic world. Paradoxically, although the Higgs boson was slated for discovery for almost half a century following the papers of Brout, Englert, Higgs, Weinberg and others, its discovery belongs in the second class. It constitutes a novel departure in the same way as the J/ψ and the discovery of CP violation, rather than the completion of a paradigm as represented by the discoveries of the Ω^- and the top quark.

The novelty of the Higgs boson derives largely from its apparently scalar nature. It is the only fundamental particle without spin. Additionally, it is the only fundamental particle with a self-coupling (gluons also couple to other gluons, but only to those with different colour combinations). Measurements of the couplings of the Higgs boson to the W and Z bosons at the LHC have confirmed its role in the generation of their masses, likewise for the charged third-generation fermions. Despite this great success, the Higgs boson is connected to many of the most troublesome aspects of the Standard Model (see "Connecting the Higgs to Standard Model enigmas" panel). It is for this reason that the recently concluded update of the European strategy for particle physics advocated an electron–positron Higgs factory as the highest priority collider after the LHC, to allow detailed study of this novel and unique particle.

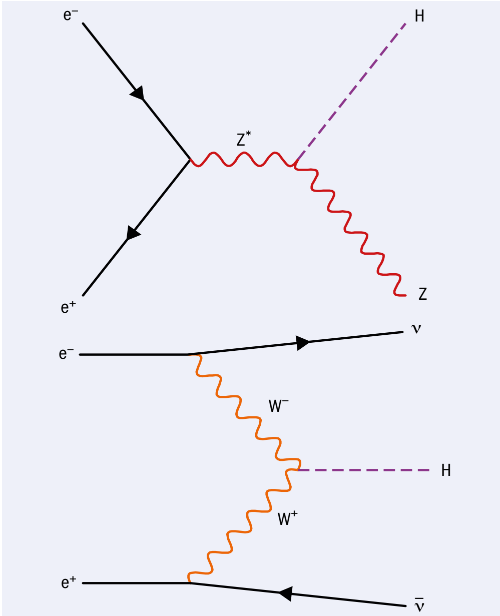
Circular vs linear

The discovery of the Higgs boson at the relatively light mass of 125 GeV, announced by the ATLAS and CMS collaborations in 2012, had two important consequences for experiment. The first was the large number of potentially observable branching fractions available. The second was that circular, as well as linear, e^+e^- machines could serve as Higgs factories. The two basic mechanisms for Higgs-boson production at such colliders are associated production, $e^+e^- \to ZH$, and vector-boson fusion. The former process is dominant at the low-energy first stage of the various Higgs factories under consideration, with vector-boson fusion becoming more important with increasing energy (see "Channeling the

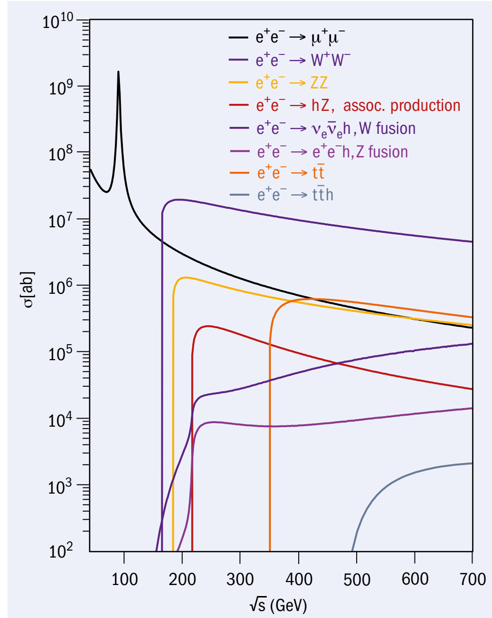
THE AUTHORS

Keith Ellis *Durham University and* **Beate Heinemann** *DESY and Albert-Ludwigs-Universitaet Freiburg.*

Channeling the Higgs *Feynman diagrams for Higgs-boson production at an electron–positron collider (left) and their cross sections together with other cross sections of interest (right).*



Source: R K Ellis



R K Ellis/Durham

Higgs" figure). About a quarter of a million Higgs bosons would be produced per inverse attobarn of data, leading to substantial numbers of recorded events even after the branching ratios to observable modes are taken into account.

Four Higgs-factory designs are presently being considered. Two are linear accelerators, namely the International Linear Collider (ILC) under consideration in Japan and the Compact Linear Collider (CLIC) at CERN, while the other two are circular: the Future Circular Collider (FCC-ee) at CERN and the Circular Electron Positron Collider (CEPC) in China.

The beams in circular colliders continuously lose energy due to synchrotron radiation, causing the luminosity at circular colliders to decrease with beam energy roughly as $E_b^{-3.5}$. The advantage of circular colliders is their high instantaneous luminosity, in particular at the centre-of-mass energy relevant for the Higgs-physics programme (250 GeV), but even more so at lower energies such as those corresponding to the Z-boson mass (91 GeV). Electron and positron beams in a circular machine naturally achieve transverse polarisation, which can be exploited to make precise measurements of the beam energy via the electron and positron spin-precession frequencies.

In contrast, for linear colliders the luminosity increases roughly linearly with the beam energy. The advantages of linear accelerators are that they can be extended to higher energies, and the beams can be polarised longitudinally. The ZH associated cross section can be increased by 40% with longitudinal polarisations of –80% and 30% for electrons and positrons, respectively. This increase, coupled with the ability to isolate certain components of Higgs-boson production by tuning the polarisation, enables a linear machine to achieve similar precisions on Higgs-boson measurements with half the integrated luminosity of a circular machine.

About a quarter of a million Higgs bosons could be produced per inverse attobarn of data

FCC-ee, CEPC and ILC are foreseen to run for several years at a centre-of-mass energy of around 250 GeV, where the ZH production cross section is largest. Instead, CLIC plans to run its first stage at 380 GeV where both WW fusion and ZH production contribute, and $t\bar{t}$ production is possible. The circular colliders FCC-ee and CEPC envisage running at the Z-pole and at the WW production threshold for long enough to collect of the order 10^{12} Z bosons and 10^8 WW pairs, enabling powerful electroweak and flavour-physics programmes (see "Compare and contrast" table). To achieve design luminosity, all proposed e^+e^- colliders need beams focused to a very small size in one direction (30–70 nm for FCC-ee, 3–8 nm for ILC and 1–3 nm for CLIC), which are all below the values so far achieved at existing facilities.

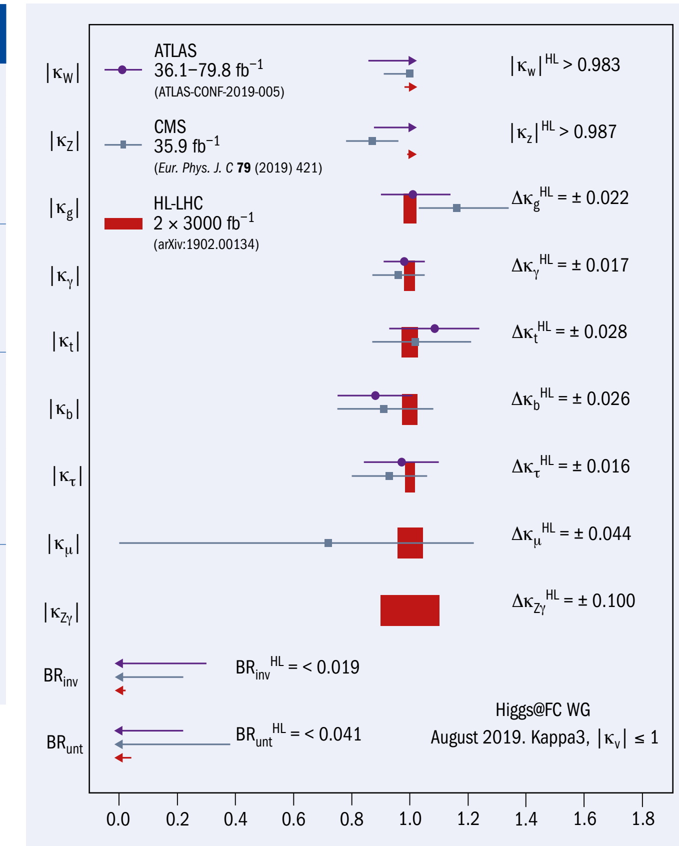
Evolving designs

The proposed circular colliders are based on a combination of concepts that have been proven and used in previous and present colliders (LEP, SLC, PEP-II, KEKB, SuperKEKB, DAFNE). In Higgs-production mode the beam lifetime is limited by Bhabha scattering to about 30 minutes and therefore requires quasi-continuous injection or "top-up" as used by the B-factories. Each of the circular collider main concepts and parameters has been demonstrated in a previous machine, and thus the designs are considered mature. The total FCC-ee construction cost is estimated to be 10.5 billion CHF for energies up to 240 GeV, with an additional 1.1 billion CHF to go to the $t\bar{t}$ threshold. This includes 5.4 billion CHF for the tunnel, which could be reused later for a hadron collider. The CEPC cost has been estimated at \$5 billion, including \$1.3 billion for the tunnel. With the present design, the FCC-ee power consumption is 260–340 MW for the various energy stages (compared to 150 MW for the LHC).

Source: arXiv:1905.03764

Collider	√s	$\mathscr{L}_{inst}$ [10^{34}] $cm^{-2}s^{-1}$	$\mathscr{L}$ [ab^{-1}]	Time [years]
FCC-ee				15
	M_Z	100–200	150	4
	$2M_W$	25	10	1–2
FCC-ee$_{240}$	240 GeV	7	5	3
FCC-ee$_{365}$	$2m_{top}$	0.8–1.4	1.5	5
CEPC				10
	M_Z	17–32	16	2
	$2M_W$	10	2.6	1
	240 GeV	3	5.6	7
ILC				>20
(∗)	M_Z	0.8	0.1	1–2
ILC$_{250}$	250 GeV	1.35–2.7	2.0	11.5
ILC$_{350}$	350 GeV	1.6	0.2	1
ILC$_{500}$	500 GeV	1.8–3.6	4.0	8.5
ILC$_{1000}^{(*)}$	1000 GeV	3.6–7.2	8.0	8.5
CLIC				27
(∗)	M_Z	0.8	0.1	1–2
CLIC$_{380}$	380 GeV	1.5	1.0	8
CLIC$_{1500}$	1.5 TeV	3.7	2.5	7
CLIC$_{3000}$	3.0 TeV	6.0	5.0	8

Compare and contrast *Summary of the different stages of future Higgs factories. Luminosity values assume two collider detectors running concurrently at CEPC and FCC, and one at ILC and CLIC (when two values for the instantaneous luminosity are given these are before and after a planned upgrade). The total time shown for each collider includes shutdowns needed to perform energy upgrades. Alternative scenarios where FCC-ee has four interaction points are also under consideration. Programmes labelled with (∗) are not part of the core proposal for these colliders.*



Source: arXiv.org:1910.11775

Kappa couplings *Relative precision on Higgs coupling modifiers, κ, determined by ATLAS and CMS with the LHC data at present, and as expected for HL-LHC with the constraint $\kappa_V \leq 1$ for V = W, Z. Also shown are the constraints on invisible and untagged decay branching ratios, BR_{inv} and BR_{unt}.*

The ILC was proposed in the late 1990s and a technical design report published in 2012. It uses superconducting RF cavities for the acceleration, as used in the currently operating European XFEL facility in Germany, to aim for gradients of 35 MV/m. The cost of the first energy stage (250 GeV) was estimated as \$4.8–5.3 billion, with a power consumption of 130–200 MW, and an expression of interest to host the ILC as a global project is being considered in Japan. The CLIC accelerator uses a second beam, termed a drive-beam, to accelerate the primary beam, aiming for gradients in excess of 100 MV/m. This concept has been demonstrated with electron beams at the CLIC test facility, CTF3. The cost of the first energy stage of CLIC is estimated as 5.9 billion CHF with a power consumption of 170 MW, rising to 590 MW for final-stage operation at 3 TeV.

Another important difference between the proposed linear and circular colliders concerns the number of detectors they can host. Collisions at linear machines only occur at one interaction point, while in circular colliders at least two interaction points are proposed, doubling the luminosity available for analyses. Two detectors also offer the dual benefits of scientific competition and the cross-checking of results. At the ILC two detectors are proposed but they cannot run concurrently since they use the same interaction point.

FCC-ee and CLIC have both been proposed as CERN-hosted international projects, similar to the LHC or high-luminosity LHC (HL-LHC). At present, as recommended by the 2020 update of the European strategy for particle physics, a feasibility study for the FCC (including its post-FCC-ee hadron-collider stage, FCC-hh) is ongoing, with the goal of presenting an updated conceptual design report by the next strategy update in 2026. Among the e^+e^- colliders, CLIC has the greatest capacity to be extended to the multi-TeV energy range. In its low-energy incarnation it could be realised either with the drive-beam or conventional technology. CEPC is conceptually and technologically similar to FCC-ee and has also presented a conceptual design report. Nearly all statements about FCC-ee also hold for CEPC except that CEPC's design luminosity is about a factor of two lower, and thus it takes longer to acquire the same integrated luminosity. At circular colliders, the multi-TeV regime (at least 100 TeV in the case of FCC-hh) would be reached by using proton

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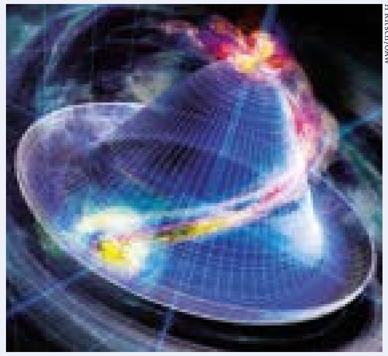
Connecting the Higgs to Standard Model enigmas

In addition to the vacuum expectation value of the Higgs field and the mass of the Higgs boson, the discovery of the Higgs boson introduces a large number of parameters into the Standard Model. Among them are the Yukawa couplings of the nine charged fermions (in contrast, the gauge sector of the SM has only three free parameters). The Yukawa forces, of which only three have been discovered corresponding to the couplings to the charged third-generation fermions, are completely new. They are of disparate strengths and, unlike the other forces, are not subject to the constraint of local gauge invariance. They provide a parameterisation of the theory of flavour, rather than an explanation. It is of primary importance to discover, bound and characterise the Yukawa forces. In particular, the discovery of CP violation in the Yukawa couplings would go beyond the confines of the Standard Model.

Famously, because of its scalar nature, the quantum corrections to the Higgs boson mass are only bounded by the cut-off on the theory, demanding large renormalisations to maintain the mass at 125 GeV as measured.



H Ritsch/DAW

Shaping the vacuum *An artistic impression of the Brout–Englert–Higgs potential.*

This issue is not so much a problem for the Standard Model per se. However, in the context of a more complete theory that aims to supersede and encompass the Standard Model, it becomes much more troubling. In effect, the degree of cancellation necessary to maintain the Higgs mass at 125 GeV effectively sabotages the predictive power of any more complete theory. This sabotage becomes deadly as the scale of the new physics is pushed to higher and higher energies.

The electroweak potential is another area of importance in which our current knowledge is fragmentary. Within the confines of the Standard Model the potential is completely specified by the position of its minimum – the vacuum expectation value and the second derivative of the potential at the minimum, the mass of the Higgs boson (or equivalently its self-coupling). We have no direct knowledge of the behaviour of the potential at larger field values further from the minimum. In addition, extrapolation of the currently understood Higgs potential to higher energy reveals a world teetering between stability and instability. Further information about the behaviour of the potential could help us to interpret the meaning of this result. A modified electroweak potential might also give rise to a first-order phase transition at high temperature, rather than the smooth crossover expected for the Standard Model Higgs potential. This would fulfil one of the three Sakharov conditions necessary to generate an asymmetry between matter and antimatter in our universe.

beams, similar to what was done with LHC following LEP.

To quantify the scientific reach of the proposed colliders compared to current knowledge or the expectations for the HL-LHC, it is necessary to define figures-of-merit for the observables that will be measured. For the Higgs boson the focus is on the coupling strengths to the Standard Model bosons and fermions, as well as the couplings to any new particles. The strength with which the Higgs boson couples to the various particles, i, is denoted by κ_i, defined such that $\kappa_i = 1$ corresponds to the Standard Model. Non-standard phenomena are included in this "kappa" framework by introducing two new quantities: the branching ratio into invisible particles (determined by measuring the missing energy in identified Higgs events), and the branching ratio to untagged particles (determined by measuring the contributions to the total width accounted for by the observed modes, or by directly searching for anomalous decays).

To assess the potential impact of the e^+e^- Higgs factories it is important to examine the point of departure provided by the LHC and HL-LHC

Higgs-boson observables

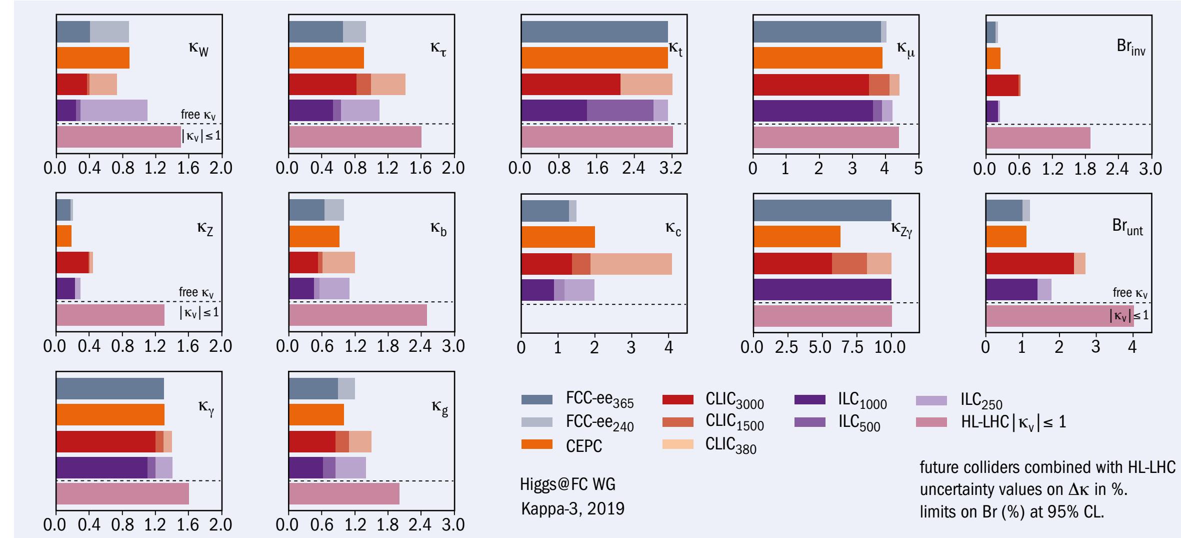
At hadron colliders, only ratios of κ_i parameters can be measured, since a precise measurement of the total width of the Higgs boson is lacking (the expected total width of the Higgs boson in the Standard Model is 4.2 MeV, which is far too small to be resolved experimentally). To determine the absolute κ_i values at a hadron collider a further assumption needs to be made, either on decay rates of the Higgs boson to new particles or on one of the κ_i values. An assumption that is often made, and valid in many beyond-the-Standard-Model theories, is that $\kappa_Z \leq 1$.

The kappa framework, however, by construction, does not parameterise possible effects coming from different Lorentz structures and/or the energy dependence of the Higgs couplings. Such effects could generically arise from the existence of new physics at higher scales and could lead not only to changes in the predicted rates, but also in distributions. Deviations of κ_i from 1 indicate a departure from the Standard Model, but do not provide a tool to diagnose its cause. This shortcoming is remedied in so-called effective-operator formalisms by including operators of mass dimension greater than four.

At e^+e^- colliders a Higgs boson produced via $e^+e^- \to ZH$ can be identified without observing its decay products. This measurement, of primary importance, is unique to e^+e^- colliders. By measuring the Z decay products and with the precise knowledge of the momenta of the incoming e^- and e^+ beams, the presence of the Higgs boson in ZH events can be inferred based on energy and momentum conservation alone, without actually tagging the Higgs boson. In this way one directly measures the coupling between the Higgs and Z bosons. In combination with the Higgs branching ratio to Z pairs it can be interpreted as a measurement of the Higgs-boson width. The first-stage e^+e^- Higgs factories all constrain the total width at about the 2% level.

LHC and HL-LHC

To assess the potential impact of the e^+e^- Higgs factories it is important to examine the point of departure provided by the LHC and HL-LHC. Since its startup in 2010 the LHC has made a monumental impact on our understanding of the Higgs sector. After the Higgs discovery in 2012, a measurement programme started and now, with nearly 150 fb^{-1} of data analysed by ATLAS and CMS, much has



Relative precision *The expected relative precision of the Higgs coupling parameters and the upper limits on the decay ratios to invisible and untagged particles for the various colliders. All values are given in %. For the HL-LHC, a constraint $|\kappa_V| \leq 1$ is applied for V = W, Z. For all the future colliders the results are combined with HL-LHC.*

been learned. The Higgs-boson mass has been measured with a precision of < 0.2%, its spin and parity confirmed as expected in the Standard Model, and its coupling to bosons and to third-generation charged fermions established with a precision of 5–10%.

With the HL-LHC and its experiments planned to operate from 2027, the precision on the coupling parameters and the branching ratios to new particles will be increased by a factor of 5–10 in all cases, typically resulting in a sensitivity of a few % (see "Kappa couplings" figure). The HL-LHC will also enable measurements of the very rare $\mu^+\mu^-$ decay, the first evidence for which was recently reported by CMS and ATLAS, and thus show whether the Higgs boson also generates the mass of a second-generation fermion. With the full HL-LHC dataset, corresponding to 3000 fb^{-1} for each of ATLAS and CMS, it is expected that di-Higgs production will be established with a significance of four standard deviations. This will allow a determination of the Higgs-boson's coupling to itself with a precision of 50%.

The LHC has also made enormous progress in the direct searches for new particles at high energies. With more than 1000 papers published on this topic, hunting down particles predicted by dozens of theoretical ideas, and no firm sign of a new particle anywhere, it is clear that the new physics is either heavier, or more weakly coupled or has other features that hides it in the LHC data. The LHC is also a precision machine for electroweak physics, having measured the W-boson mass and the top-quark mass with uncertainties of 0.02% and 0.3%, respectively. In addition, a large number of relevant cross-section measurements of multi-boson production have been made, probing the trilinear and quartic interactions of the gauge bosons with each other.

Higgs-factory impact

In terms of the measurement precision on the Higgs-boson couplings, the proposed Higgs factories are expected to bring a major improvement with respect to HL-LHC in most cases (see "Relative precision" figure). Only for the rare decays to muons, photons and Zγ, and for the very massive top quark, is this not the case. The highest precision (0.2% in the case of FCC-ee) is achieved on κ_Z since the main Higgs production mode, ZH, depends directly on it, regardless of the decay mode. For other Standard Model particles, improvement factors of two to four are typical. For the invisible and untagged decays, the constraints are improved to around 0.2% and 1%, respectively, for some of the Higgs factories. A new measurement, not possible at the LHC, is that of the charm-quark coupling, κ_c.

None of the initial stages of the proposed Higgs factories will be able to directly probe the self-coupling of the Higgs boson beyond the 50% expected from the HL-LHC, since the cross-sections for the relevant processes ($e^+e^- \to ZHH$ and $e^+e^- \to HH\nu\bar{\nu}$) are negligible at centre-of-mass energies below 400 GeV. The Higgs self-coupling, however, enters through loops also in single-Higgs production and indirect effects might therefore be observable, for instance as a small (< 1%) deviation in measurements of the inclusive ZH cross section. Measurements of the Higgs self-coupling exploiting the di-Higgs production process can only be performed at higher energy colliders. The ILC and CLIC project uncertainties of around 30% at their intermediate energies and around 10% at their ultimate energies, while FCC-hh projects a precision of around 5%. Similarly, for the Higgs coupling to the top quark, the HL-LHC precision of 3.2% will not be improved by the initial stages of any of the Higgs factories.

The proposed Higgs factories also have a rich physics programme at lower energies, particularly at the Z pole. FCC-ee, for instance, plans to run for four years at the Z pole to accumulate a total of more than 10^{12} Z bosons – 100,000 times more than at LEP. This will enable a rich and unprecedented electroweak physics programme, constraining so-called oblique parameters (which are sensitive to violations of weak isospin) at the per-mille level, 100 times better than today. It will also enable a B-physics programme, complementary to that at Belle II and LHCb. At CEPC, a similar programme is possible, while at ILC and CLIC the luminosity when running at the Z pole is much lower: the typical number of Z-bosons that can be accumulated here is 10^9, 100 times more than LEP but not at the same level as the circular colliders. FCC-ee's electroweak programme also foresees a run at the WW threshold to enable a high-precision measurement of the W mass.

Concerning the large top-quark mass, measurements at the LHC suffer from uncertainties associated with renormalisation schemes and it is unlikely to improve the precision significantly at the HL-LHC beyond the currently achieved value of 400 MeV. At an e^+e^- collider operating at the $t\bar{t}$ threshold (~350 GeV), a measurement of the top mass with total uncertainty of around 50 MeV and with full control of the issues associated with the renormalisation scheme is possible. In addition to its importance as a fundamental parameter of the Standard Model, the top mass is the dominant term in the evolution of the Higgs potential with energy to determine vacuum stability (see "Connecting the Higgs to Standard Model enigmas" panel).

The Higgs boson has not exhausted its ability to surprise

In short, a Higgs factory promises to expand our knowledge of nature at the smallest scales. The ZH cross-section measurement alone will probe fine tuning at a level of a few permille, about 30 times better than what we know today. This provides indirect sensitivity to new particles with masses up to 10–30 TeV, depending on their coupling strength, and could point to a new energy scale in nature.

But most of all the Higgs boson has not exhausted its ability to surprise. The rest of the Standard Model is a compact structure, exquisitely tested, and ruled by local gauge invariance and other symmetries. Compared to this, the Lagrangian of the Higgs sector is the wild west, where the final laws have yet to be written. Does the Higgs boson have a significant rate of invisible decays, which could be a key component in understanding the nature of dark matter in our universe? Does the Higgs boson act as a portal to other scalar degrees of freedom? Does the Higgs boson provide a source of CP violation? An electron–positron Higgs factory provides a tool to address these questions with unique clarity, when deviations between the measured and predicted values of observables are detected. Building on the data from the HL-LHC, it will be the perfect tool to elucidate the underlying laws of physics. ●

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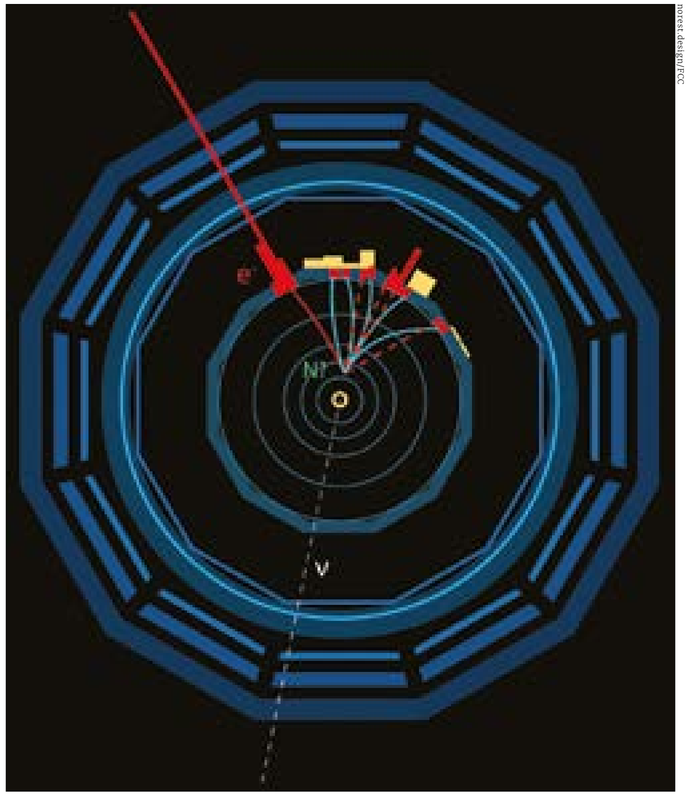
FCC-ee: BEYOND A HIGGS FACTORY

A 100 km tunnel hosting a circular electron–positron collider as a first stage towards a 100 TeV proton–proton collider would probe new phenomena coupled to the Higgs and electroweak sectors with unparalleled precision.



norest.design/FCC

Discovery potential *An artistic rendering of the production and decay of a long-lived heavy neutral lepton at FCC-ee.*

The proposed 100 km-circumference Future Circular Collider (FCC) at CERN features, as a first stage, an electron–positron Higgs and electroweak factory (FCC-ee) operating at centre-of-mass energies from 91 GeV (the Z mass) to a maximum of 365 GeV (above the $t\bar{t}$ production threshold). The same tunnel is then planned to host a hadron collider (FCC-hh) operating at the highest possible energies, at least 100 TeV. The complete FCC programme, whose financial and technical feasibility is currently under study, offers unprecedented potential in terms of the reach on phenomena beyond the Standard Model (SM). The proposed Circular Electron Positron Collider project in China adopts the scheme envisioned for the FCC-ee, with a somewhat less ambitious overall physics programme.

While the original goal of a future lepton collider is the precise study of the interactions of the scalar boson discovered in 2012 at the LHC, seeking answers to open questions in particle physics requires many high-precision measurements of the other three heaviest SM particles: the W and Z electroweak bosons and the top quark. Beyond the exploration of the Higgs sector, FCC-ee offers a rich range of opportunities to indirectly and directly discover new phenomena.

Studies of Higgs-boson interactions are prime tests of the dynamics of electroweak symmetry breaking and of the generation of elementary-particle masses. At FCC-ee, the Higgs boson will dominantly be produced by radiation off a Z boson. With around one million such $e^+e^- \rightarrow ZH$ events recorded in three years of operation, a per-mil precision is targeted on the cross-section measurement. This corresponds to probing phenomena coupled to the scalar SM sector at energy scales approaching 10 TeV. The Higgsstrahlung process is, however, sensitive to gauge interactions beyond those of the Higgs boson (see "Higgs production" figure), which can themselves be affected by new physics. A robust test of the SM's consistency will require independent experimental determination of these interactions. The precision available today is insufficient, however, and calls for new electroweak measurements to be performed.

Electroweak and top-quark precision

FCC-ee will provide these missing pieces, and much more. An unprecedented number (5×10^{12}) of Z bosons will be produced with an exquisite knowledge of the centre-of-mass energy (100 keV or lower, thanks to the availability of transverse polarisation of the beams), thereby surpassing the precision of all previous measurements at LEP and SLC by several orders of magnitude. Uncertainties of the order of 100 keV on the Z-boson's mass and 25 keV on its width can be achieved, as well as precisions of around 10^{-5} on the

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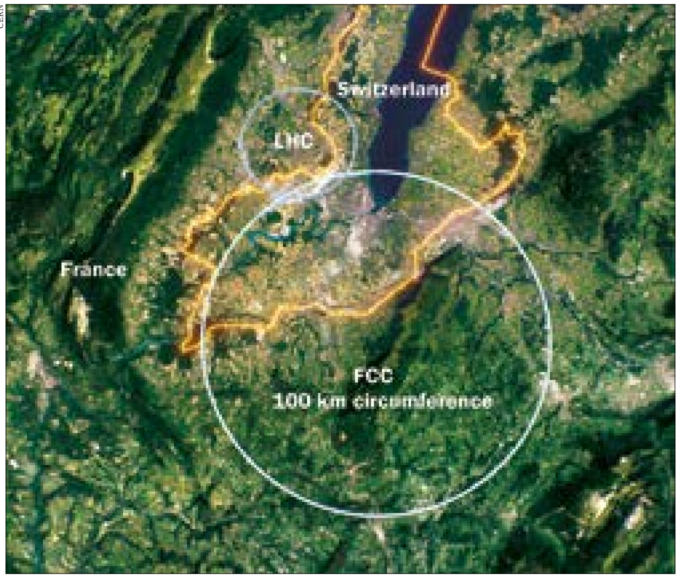
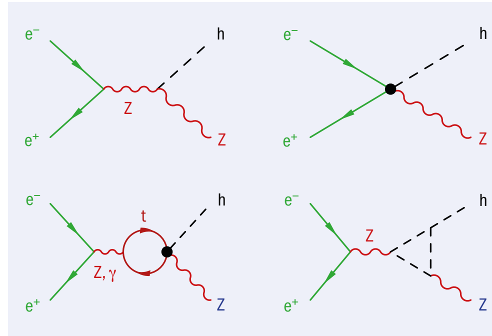


Going large *The proposed layout of the Future Circular Collider.*



Higgs production *Representative tree- and loop-level contributions to Higgsstrahlung, the main Higgs production process at FCC-ee. Couplings marked with a black dot vanish in the Standard Model, while all others may also receive new-physics contributions. Uncertainties in interactions not involving a Higgs boson could limit the precision to which Higgs interactions can be extracted. Gauge invariance also relates Higgs interactions to others that are better probed in processes involving only gauge bosons and fermions.*

various charged fermion couplings, and of 3×10^{-5} on the QED coupling strength $\alpha_{QED}(m_Z)$. Impressive numbers of pairs of tau leptons (1.7×10^{11}) and 10^{12} each of c and b quarks will be produced in Z decays, allowing order-of-magnitude improvements on tau and heavy-flavour observables compared to other planned facilities.

At the WW threshold, with 10^8 W bosons collected at a centre-of-mass energy of 161 GeV and threshold scans with an energy uncertainty of about 300 keV, a unique W-boson mass precision of 0.5 MeV will be reached. Meticulous measurements of di-boson production will be essential for the Higgs programme, given the gauge-symmetry relations between triple-gauge-boson and Higgs-gauge-boson interactions. Hadronic W and Z decays will also provide measurements of the QCD coupling strength with per-mil uncertainties – a factor of 10 better than the current world average.

Stepping up to a centre-of-mass energy of 350 GeV, $e^+e^-\rightarrow t\bar{t}$ measurements would deliver an impressive determination of the top-quark mass with 10 MeV statistical uncertainty, thanks to energy scans with a 4 MeV precision. At the highest FCC-ee energies, the determination of the top quark's electroweak couplings, which affect Higgs processes, can be performed to sub-percent precision.

These high-precision FCC-ee measurements in the Higgs, electroweak and top-quark sectors will be sensitive to a large variety of new-physics scenarios. High-mass physics with SM couplings, for example, can be tested up to scales of the order of 50 TeV. Regardless of mass scale, mixing of new particles with known ones at the level of a few tens of ppm will also produce visible effects.

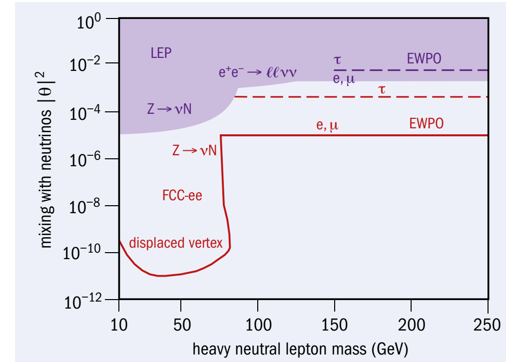
Stepping up to an energy of 350 GeV would deliver an impressive determination of the top-quark mass

Probing new physics at the Z pole

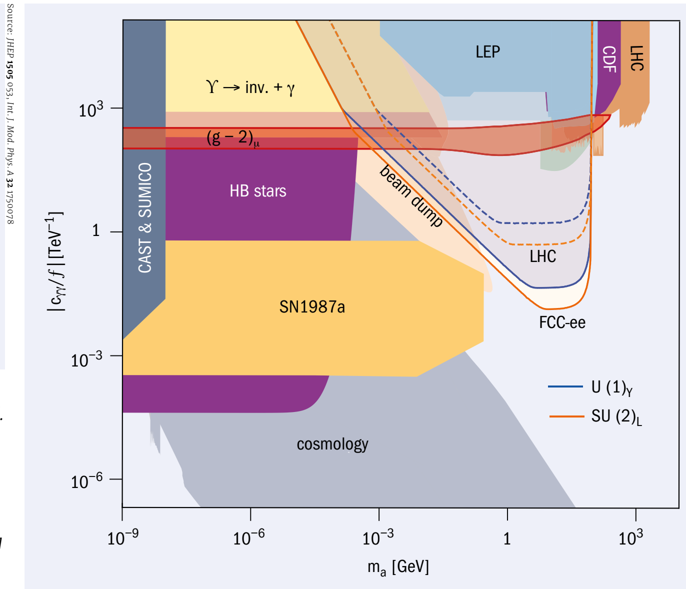
Given that new light particles are constrained to be feebly coupled to the SM, large e^+e^- luminosities are needed to search for them. By examining an astounding number of Z-boson decays, FCC-ee will explore uncharted territories in direct searches for feebly coupled light states, such as heavy neutral leptons and axion-like particles. If not directly produced, the former are also probed indirectly through precision electroweak measurements.

Heavy neutral leptons (N) are sterile particles, such as those invoked in neutrino mass-generation mechanisms. The mixing of these states with neutrinos would induce interactions with electroweak bosons and charged leptons, for example $N\ell W$, $N\nu Z$ or $N\nu H$. Heavy neutral leptons can have a wide range of masses and be searched for at FCC-ee, both directly and indirectly, with unparalleled reach. When heavier than the muon and mixing with either the e or μ flavours, they lower the $\mu\rightarrow e\nu_e\nu_\mu$ decay rate and affect the extraction of the Fermi constant, leading to deviations from the SM in many precision electroweak observables. When lighter than the Z boson, they could be produced in $Z\rightarrow\nu N$ decays. FCC-ee will bring order-of-magnitude improvements over LEP bounds in both regimes (see "Heavy neutral leptons" figure). The direct sensitivity improves even more dramatically than the indirect one: in the parameter space where N have sizeable lifetimes, displaced vertices provide a spectacular, background-free, signature (see "Discovery potential" image). This region of great interest corresponds to weak-scale leptogenesis, in which right-handed neutrinos participate in the generation of the baryon asymmetry of the universe.

Axion-like particles (ALPs) are pseudoscalar singlets with derivative couplings to the SM, which may be generated in the breaking of global symmetries at high scales. They could contribute to the dark-matter relic abundance and, in a specific range of parameter space, provide a dynamical explanation for the absence of CP violation in the strong interaction. Having symmetry-protected masses, ALPs can be naturally light. For masses smaller than twice that of the electron, they can only visibly decay to photons. Suppressed by a potentially large scale, their couplings



Heavy neutral leptons *Present and prospective 95% C.L. limits on the mass and mixing of new heavy neutral leptons, N. The dominant bounds in the displayed mass range arise from direct $Z\rightarrow N\nu$ searches and, indirectly, from the measurement of electroweak precision observables (preliminary dashed line for a mixing to the τ flavour). FCC-ee would improve constraints by orders of magnitude in both regimes, extending to masses way beyond those pictured.*



Axion-like particles *Producing 5×10^{12} Z bosons, FCC-ee would be particularly sensitive to their decay to a photon and an axion-like particle, when the latter couples to either $U(1)_Y$ hypercharge (blue lines) or $SU(2)_L$ weak isospin (orange lines). Dashed lines delimit the parameter space accessible at the LHC with an integrated luminosity of 300 fb^{-1}. The reach of FCC-ee on the coupling to photons requires four decays within 1.5 m of the beam axis compared to 100 at the LHC and assumes all axion-like particles decay to photon pairs.*

to the SM may be tiny. ALPs lifetimes could thus be large. A coupling to either hypercharge or weak isospin would allow them to be produced in Z-boson decays together with a photon and to decay to photon pairs. Searching for this signature, FCC-ee will probe couplings more than an order of magnitude smaller than those accessible at the LHC (see "Axion-like particles" figure). Pairs of ALPs could possibly also be produced in the decay of the Higgs boson, whose small width enhances branching fractions and allows small couplings to be probed. Producing Higgs bosons in larger numbers, hadron colliders are, however, more efficient at probing such interactions.

Towards a new frontier

The physics potential of FCC-ee clearly extends much beyond its original purpose as a Higgs and electroweak factory. Upgrading the facility to FCC-hh will require a new machine based on high-field superconducting magnets, although key parts of FCC-ee infrastructure would be usable at both colliders. Compared to the LHC, FCC-hh will collect about 10 times more integrated luminosity and increase the direct discovery reach for high-mass particles – such as Z′ or W′ gauge bosons, gluinos and squarks, and even WIMP dark matter – by a factor of around 10, up to scales of about 50 TeV. It would also serve as a giga Higgs factory, producing more than 10^{10} Higgs bosons during its planned 25 years of data taking, albeit not in the ultraclean collision environment of FCC-ee.

Beyond exquisite precision on Higgs-boson couplings to other SM particles, a 100 TeV proton–proton collider comes to the fore in revealing how the Higgs boson couples to itself, which is connected to the electroweak phase transition in the early universe and ultimately to the stability of the vacuum. The rate of Higgs pair-production events, which in some part occur through the Higgs self-interaction, would grow by a factor of 40 at FCC-hh with respect to the LHC and enable this unique property of the Higgs boson to be measured with a statistical accuracy reaching ±2%. Such a measurement would comprehensively explore classes of models that rely on modifying the Higgs potential to drive a strong first-order phase transition at the time of electroweak symmetry breaking, a necessary condition to induce baryogenesis.

Following the highly successful model of LEP and its successor, the LHC, the integrated FCC programme offers a far-reaching particle-physics programme at the limits of known technology to significantly push the frontier of our knowledge of the fundamental particles and interactions. A conceptual design report was published in 2019, estimating that operations could begin as soon as 2040 for FCC-ee and 2065 for FCC-hh. Exploring the financial and technical feasibility of this visionary project is one of the highest priority recommendations of the 2020 update of the European strategy for particle physics, with a decision on whether or not to proceed expected by the next strategy update towards the middle of the decade. ●

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Shiny linac *How an International Linear Collider in Japan might look. (credit: Rey.Hori/KEK)*

ILC: BEYOND THE HIGGS

The high-luminosity, polarised beams of the proposed International Linear Collider and the triggerless operation of its detectors offer rich physics opportunities beyond its Higgs-factory programme.

The International Linear Collider (ILC) is a proposed electron–positron linear collider with a Higgs factory operating at a centre-of-mass energy of 250 GeV (ILC250) as a first stage. Its electron and positron beams can be longitudinally polarised, and the accelerator may be extended to operate at 500 GeV up to 1 TeV, and possibly beyond. In addition, the unique time structure of the ILC beams (which would collide at short bursts of 1312 bunches with 0.554 ms spacing at a frequency of 5 Hz) places much less stringent requirements on readout speed and radiation hardness than conditions at the LHC detectors. This allows the use of low-mass tracking and high-granularity sensors in the ILC detectors, giving unprecedented resolution in jet-energy measurements. It also results in an expected data rate of just a few GB/s, allowing collisions to be recorded without a trigger.

ILC250 primarily targets precision measurements of the Higgs boson (see p23). However, fully exploiting these measurements demands substantial improvement in our knowledge about many other Standard Model (SM) observables. Here, ILC250 opens three avenues: the study of gauge-boson pair-production and fermion pair-production at 250 GeV; fermion-pair production at effective centre-of-mass energies lowered to about

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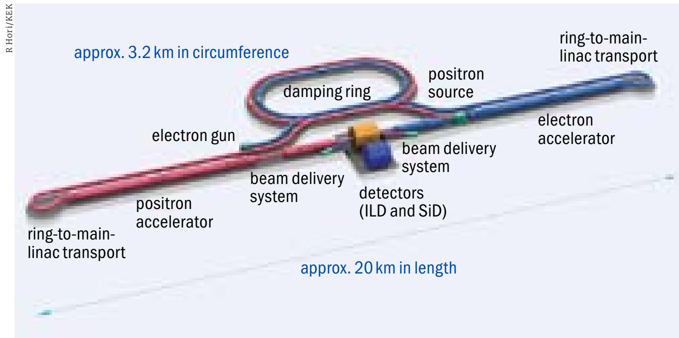
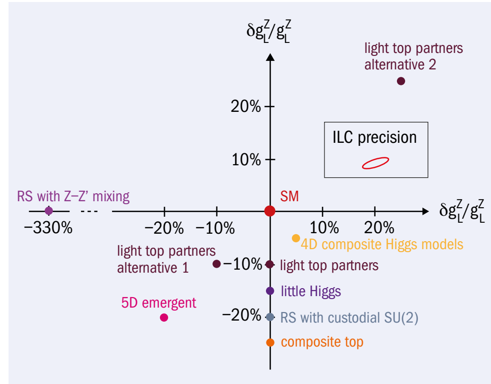


Loop the loop *Schematic of the ILC250 layout, with a total length of 21 km.*



Model sensitivity *Deviations of the left- and right-handed couplings of the top quark to the Z boson as predicted by several Randall–Sundrum (RS) and/or compositeness or little-Higgs models. The red ellipse indicates the precision that can be expected at ILC500 with 500 fb^{-1} of integrated luminosity shared equally between the beam polarisations.*

91.2 GeV by prior emission of photons (radiative returns to the Z pole); and operation of the collider at both the Z pole and the WW threshold. In all of these cases, the polarisation of the electron and positron beams (at polarisations up to 80% and 30%–60%, respectively) boosts the statistical power of many measurements by factors between 2.5 (for Higgs measurements) and 10 (at the Z pole), thanks to the ability to exploit observables such as left–right asymmetries of production cross-sections. These additional polarisation-dependent observables are also essential to disentangle the unavoidable interference between Z and γ exchange in fermion pair-production at energies above the Z pole, enabling access to the chiral couplings of fermions to the Z and the photon. Broadly speaking, the polarised beams and the high luminosity of ILC250 will lead to at least one order of magnitude improvement over the current knowledge for many SM precision observables.

Other important inputs when interpreting Higgs measurements are charged triple-gauge couplings (TGCs), which are also probes of physics beyond the SM. ILC250 will measure these 100 times more precisely than LEP, with a further factor-of-two improvement possible at the higher-energy stage ILC500. These numbers refer to the case of extracting simultaneously all three TGCs relevant in SM effective field theory, which is currently the most favoured framework for the interpretation of precision Higgs-boson data, whereas TGC results from the LHC assume that only one of these couplings deviates from its SM value at a time. With both beams polarised and with full control over the orientation of the polarisation vectors, all 28 TGC parameters that exist in the most general case can potentially be determined simultaneously at the ILC.

ILC250 primarily targets precision measurements of the Higgs boson

Z-pole physics

Classic electroweak precision observables refer to the Z pole. ILC250 will produce about 90 million visible Z events via radiative return, which is about five times more than at LEP and 100 times more than SLC. Thanks to the polarised beams, these data will allow a direct measurement of the asymmetry A_e between the left- and right-handed electron's coupling to the Z boson with 10 times better accuracy than today, and enable the asymmetries A_f of the final-state fermions to the Z to be directly extracted. This is quite different from the case of unpolarised beams, where only the product A_e A_f can be accessed. Compared to LEP/SLC results, the Z-pole asymmetries can be improved by typically a factor of 20 using only the radiative returns to the Z at ILC250. This would settle beyond doubt the long-standing question of whether the 3σ tension between the weak mixing-angle extractions from SLC and LEP originates from physics beyond the SM. With a few minor modifications, the ILC can also directly operate at the Z pole, improving fermion asymmetries by another factor 6 to 25 with respect to the radiative-return results.

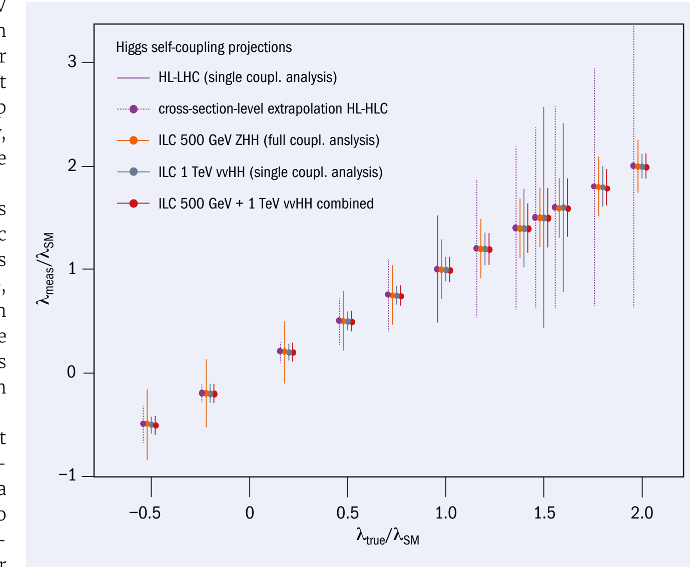
At energies above the Z pole, di-fermion production is sensitive to hypothetical, heavy siblings of the Z boson (so-called Z′ bosons) and to four-fermion operators, i.e. contact-interaction-like parametrisations of yet unknown interactions. ILC250 could indirectly discover Z′ particles with masses up to 6 TeV, while ILC1000 could extend the reach to 18 TeV. For contact interactions, depending on the details of the assumed model, compositeness scales of up to 160 TeV can be probed at ILC250, and up to nearly 400 TeV at ILC1000.

Direct searches for new physics

At first glance, it might seem that direct searches at ILC250 offer only a marginal improvement over LEP, which attained a collision energy of 209 GeV. Nevertheless, the higher integrated luminosity of the ILC (about 2000 times higher than LEP's above the WW threshold), its polarised beams, much-improved detectors, and triggerless readout will provide new opportunities to search for physics beyond the SM. For example, ILC250 will improve on LEP searches for a new scalar particle produced in association with the Z boson by over an order of magnitude. Another example of a rate-limited search at LEP is the supersymmetric partner of the tau lepton, the tau slepton. In the most general case, tau-slepton masses above 26.3 GeV are not excluded, and in this case no improvement from HL-LHC is expected. The ILC, with its highly-granular detectors covering angles down to 6 mrad with respect to the collision axis, has the ability to cover masses up to nearly the kinematic limit of half the collision energy, also in the experimentally most difficult parts of the parameter space.

The absence of discoveries of new high-mass states at the LHC has led to increased interest in fermionic "Z-portal" models, with masses of dark-matter particles below the electroweak scale. A dark photon, for example, could be detected via its mixing with SM photons. In searching for such phenomena, ILC250 could cover the region between the reach of the B-factories, which is limited to below 10 GeV, and the LHC experiments, which start searching in a range above 150 GeV.

The ILC's Higgs-factory stage will require only about 40% of the tunnel length available at the Kitakami Mountains in northern Japan, which is capable of housing a linear collider at least 50 km long. This is sufficient to reach a centre-of-mass energy of 1 TeV with current technology by extending the linacs and augmenting power and cryogenics. The upgrade to ILC500 is expected to cost approximately 60% of the ILC250 cost, while going to 1 TeV would require an estimated 100% of the ILC250 cost, assuming a modest increase of the accelerating gradient over what has been achieved (*CERN Courier* November/December 2020 p35). These upgrades offer the opportunity to optimise the exact energies of the post-Higgs-factory stages according to physics needs and technological advances.



Higgs self-coupling *Projected precisions on the Higgs self-coupling λ at different ILC energy stages. Only the combination of double Higgsstrahlung and VBF-based measurements can guarantee a precision of at least 10–20% for any value of λ.*

ILC at higher energies

ILC500 targets the energy range 500–600 GeV, which would improve the precision on Higgs-boson couplings typically by a factor of two compared to ILC250 and on charged triple-gauge couplings by a factor of three to four. It would also offer optimal sensitivity in three important measurements. The first is the electroweak couplings of the top quark, for which a variety of new-physics models predict deviations for instance in its coupling to the Z (see "Model sensitivity" figure). The second is the Higgs self-coupling λ from double Higgs-strahlung ($e^+e^- \rightarrow ZHH$): while ILC500 could reach a precision of 27% on λ, at 1 TeV a measurement based on vector-boson fusion (VBF) reaches 10%. These numbers assume that λ takes the value predicted by the SM. However, the situation can be quite different if λ is larger, as is typically required by models of baryogenesis, and only the combination of double Higgs-strahlung and VBF-based measurements can guarantee a precision of at least 10–20% for any value of λ (see "Higgs self-coupling" figure). A third physics target is the top-quark Yukawa coupling, for which a precision of 6.3% is projected at ILC500, 3.2% at 550 GeV and 1.6% at 1 TeV.

While ILC250 has interesting discovery potential in various rate-limited searches, ILC500 extends the kinematic reach significantly beyond LEP. For instance, in models of supersymmetry that adhere to naturalness, the supersymmetric partners of the Higgs boson (the higgsinos) must have masses that are not too far from the Z or Higgs bosons, typically around 100 to 300 GeV. While the lower range of these particles is already accessible at ILC250, the higher energy stages of the ILC will be able to cover the remainder of this search space. The ILC is also able to reconstruct decay chains when the mass differences among higgsinos are small, which is a challenging signature for the HL-LHC.

The higher integrated luminosity of the ILC will provide new opportunities to search for physics beyond the SM

The ILC is the only future collider that is currently being discussed at the government level, by Japan, the US and various countries in Europe. It is also the most technologically established proposal, its cutting edge radio-frequency cavities already in operation at the European XFEL. The 2020 update of the European strategy for particle physics also noted that, should an ILC in Japan go ahead, the European particle-physics community would wish to collaborate. Recently, an ILC international development team was established to prepare for the creation of the ILC pre-laboratory, which will make all necessary technical preparations before construction can begin. If intergovernmental negotiations are successful, the ILC could undergo commissioning as early as the mid-2030s. ●

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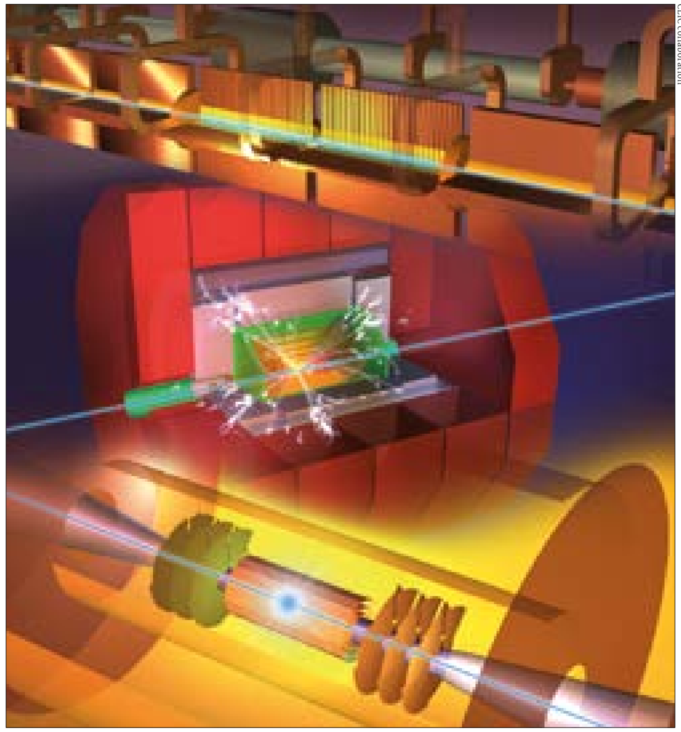
CLIC: BEYOND A HIGGS FACTORY


CLIC collaboration

CLIC here *Impressions of the CLIC accelerator and its detectors.*

With top-quark production at the initial stage and the potential for multi-TeV collisions, CLIC has unique aspects beyond a Higgs factory.

The Compact Linear Collider (CLIC) is conceived in its first stage to be an 11 km-long electron–positron collider operating at a centre-of-mass energy of 380 GeV. Unlike other Higgs-factory proposals that start around 240 GeV, CLIC benefits at the initial stage not only from top-quark production, but also from two Higgs-boson production modes – Higgsstrahlung ($e^+e^- \rightarrow HZ$) and WW fusion – giving extra complementary input for global interpretations of the data.

A defining feature of a linear collider is that its collision energy can be raised by extending its length. While the European strategy update recommended a circular hadron collider at the energy frontier as a long-term ambition, CLIC represents a compelling alternative were a circular machine found not to be feasible. CLIC has the potential to be extended in several stages up to 50 km and a maximum energy of 3 TeV, giving access to a wide range of physics processes (see "Multichannel" figure). Some important processes such as Higgsstrahlung production fall with energy, while others such as double-Higgs production require higher energies, and processes occurring through vector-boson fusion grow with energy. In general, the beyond-Standard-Model (BSM) sensitivity of scattering processes such as ZH, WW and two-fermion (including top-pair) production rises strongly with energy, so the higher-energy stages bring further sensitivity to potential new physics both indirectly and directly.

In contrast to the ILC (see p35), CLIC operates via a novel two-beam scheme, whereby radio-frequency power extracted from a high-current, low-energy drive beam is used to accelerate the colliding beams. Were a decision to be made to upgrade CLIC from 380 GeV to 1.5 TeV, the length of the main linacs would have to be extended to 29 km, as well as moving and adding accelerator modules. Going from an energy of 1.5 to 3 TeV, as well as further lengthening of the main linacs, a second drive-beam complex must be added. CLIC's combination of Higgs- and top-factory running, and multi-TeV extension potential, makes it illuminating to study the physics prospects of the initial stage in parallel with those of the ultimate energy.

Higgs physics

At 380 GeV, with 1 ab^{-1} of integrated luminosity CLIC would produce around 160,000 Higgs bosons. This stage would enable precision determinations well beyond the HL-LHC, for example in the single-Higgs couplings to WW, ZZ, $b\bar{b}$, and $c\bar{c}$. Due to the known kinematic constraints in the collision environment, it also allows an absolute determination of the Higgs couplings, as opposed to the ratios accessible at the LHC. The corresponding precision on Higgs-coupling measurements is increased considerably by the enhanced statistics at 1.5 TeV, where CLIC could produce 1 million Higgs bosons with an integrated luminosity of 2.5 ab^{-1} as well as opening sensitivity to other processes. A linear collider like CLIC provides considerable flexibility, for example: collecting at 380 GeV 1 ab^{-1} in 8 years or 4 ab^{-1} in 13 years, as studied recently, before a possible jump to 1.5 TeV.

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CERNCOURIER
VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021
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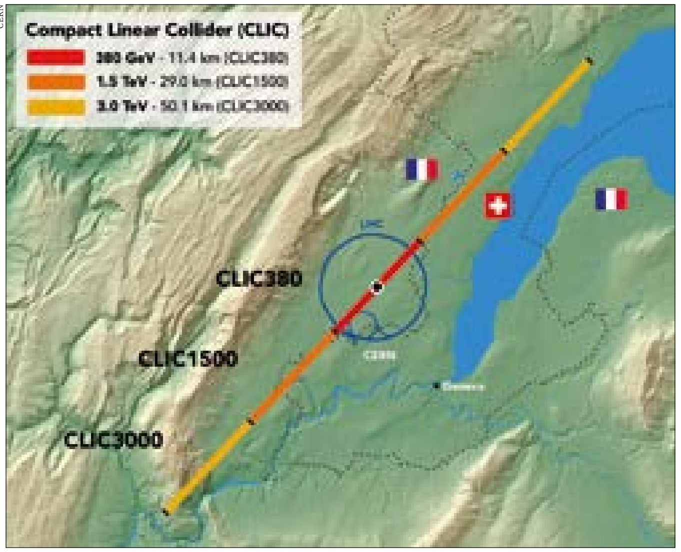
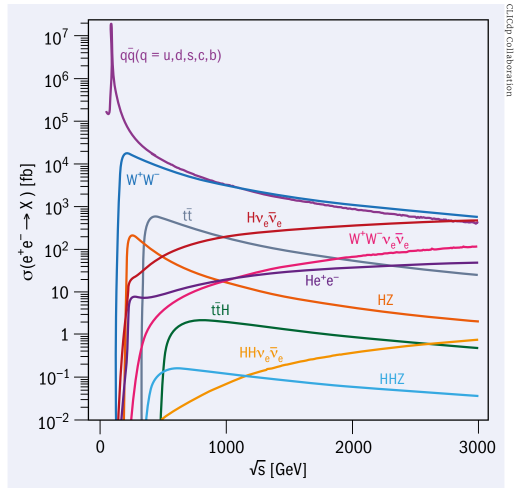


Physics by extension *The three stages of CLIC's baseline design.*



Multichannel *Important physics processes across CLIC's full staged energy programme.*

The 1.5 TeV energy stage gives access to two double-Higgs production mechanisms: double-Higgsstrahlung ($e^+e^- \to ZHH$) and vector-boson fusion ($e^+e^- \to HH\nu_e\bar{\nu}_e$). Such production of Higgs-boson pairs allows the Higgs self-coupling to be probed directly. While the 1.5 TeV stage could reach a precision of −29%/+67% using a rate-only analysis, at 3 TeV an ultimate Higgs self-coupling precision of −8%/+11% is expected, also exploiting differential information. Furthermore, the ability to measure both the ZHH and $HH\nu_e\bar{\nu}_e$ processes allows for an unambiguous determination of the Higgs self-coupling even if it is far from its Standard Model value. Unlike indirect determinations from ZH measurements at lower Higgs-factory energies, the precision of CLIC's direct Higgs-self-coupling measurement is largely preserved in global fits. CLIC could thus robustly verify that the Higgs self-coupling assumes the value predicted by the Standard Model, or uniquely identify the new-physics effects responsible for potential tensions with the Standard Model in Higgs observables.

Top-quark physics

CLIC is unique among the proposed electron–positron colliders in producing top-quark pairs at its initial energy stage. Electroweak couplings to third-generation fermions such as the top are particularly relevant in many BSM scenarios. Operating at the top-quark pair-production threshold of around 350 GeV would allow precise measurements of the top-quark mass and width, while cross-section and asymmetry measurements would probe the top-quark interactions. However, comprehensive exploration of top-quark couplings requires several energy stages, and spacing them widely as the CLIC baseline envisages enhances energy-dependent effects.

A linear collider like CLIC provides considerable flexibility

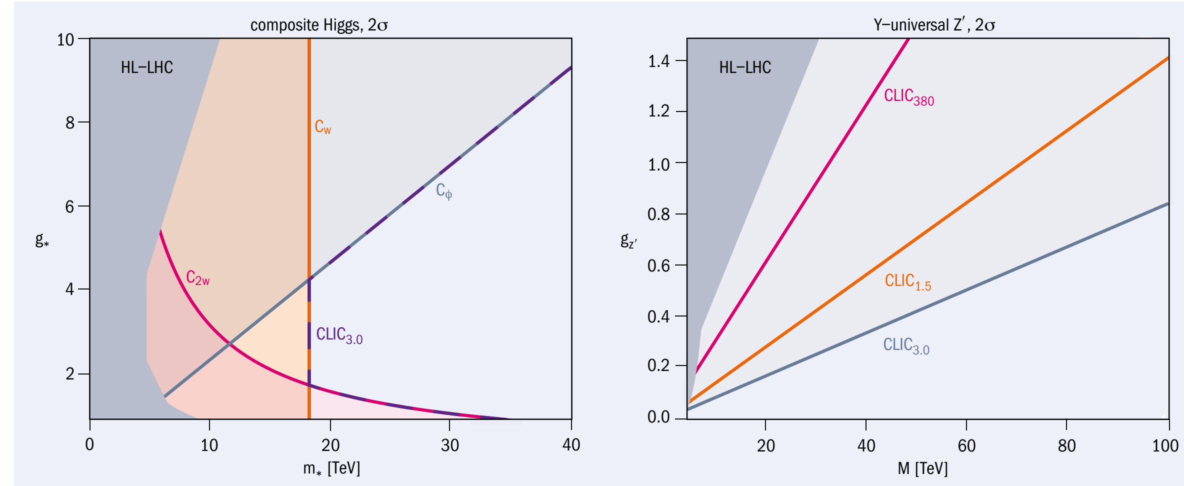
Electron-beam longitudinal polarisation at ±80% plays an important role in the precision programme at CLIC. Generally the polarisation significantly enhances WW-fusion processes, for example single- and double-Higgs production at higher energies; we make use of this in the baseline scenario by taking more data with left-handed electrons at the later stages. In the interpretation of Standard Model measurements, polarisation also helps to disentangle different contributions. The coupling of the top quark to the Z boson and the photon is one such example.

Indirect searches

Many observables such as cross-sections and differential distributions for WW and two-fermion production, in addition to measurements from the Higgs-boson and top-quark sectors, can be used to constrain potential new physics in the framework of effective field theory. Here, the Standard Model Lagrangian is supplemented by interaction operators of higher dimension that describe the effects of new particles. These particles could be too heavy to be produced at CLIC, but can still be probed through the effects they induce, indirectly, on CLIC observables.

For many new-physics operators, CLIC is projected to bring an order of magnitude increase in sensitivity over the HL-LHC. The 380 GeV stage already significantly enhances our knowledge of operators relating to modifications of the Higgs couplings, as well as electroweak observables such as triple-gauge couplings. The higher-energy stages are then particularly effective in probing operators that induce corrections to Standard Model predictions which grow with energy. Sensitivity to these operators allows a wide range of new-physics scenarios to be probed without reference to particular models. Comparisons performed for the 2020 update of the European strategy for particle physics show, for example, that sensitivities derived in this way to four-fermion, or two-fermion two-boson contact interactions rise very steeply with the centre-of-mass energy of a lepton collider, allowing CLIC to probe scales up to 100 TeV and beyond.

Precision measurements of Standard Model processes can also be interpreted in the context of particular BSM models, such as the broad classes of composite Higgs and top, or extra-dimension models. At CLIC this represents strong new-physics reach. For example, a 3 TeV CLIC has sensitivity to Higgs compositeness up to a scale of around 18 TeV for all values of the compositeness sector coupling strength (see "Sensitivity" figure, left), and can reach beyond 40 TeV in particularly favourable scenarios; in all cases well beyond what the HL-LHC can exclude. At high masses, a multi-TeV lepton collider such as CLIC also provides the best possible sensitivity to search for new vector bosons such as the Y-universal Z′, which has couplings to quarks and leptons that are comparable (see figure, right).



Sensitivity *CLIC's 2σ sensitivity in coupling and scale/mass parameters to composite Higgs bosons, combining different measurements (left) and to a new vector boson, comparing different energy stages (right).*

As a further example, the very high energy of CLIC, and therefore the high propagator virtuality in two-fermion production, means that high-precision differential cross-sections could reveal deviations from Standard Model predictions owing to the presence of new particles in loops. This would allow discovery or exclusion of new states, for example dark-matter candidates, with a variety of possible quantum numbers and masses in the range of several TeV.

Direct searches

Direct searches for new physics at CLIC benefit from the relatively clean collision environment and from triggerless detector readout, both of which allow searches for elusive signatures that are difficult at a hadron collider. Mono-photon final states are an example of such a signature. In simplified dark-matter models containing a dark-matter particle and a mediator, dark-matter particles can be pair-produced in association with a photon, which is observed in the detector. In the case of a scalar mediator, lepton colliders are particularly sensitive and CLIC's reach for the mediator can exceed its centre-of-mass energy significantly. In the case where the couplings to electrons and quarks are different, e^+e^- and proton colliders provide complementary sensitivities.

Lepton colliders can in general explore much closer to kinematic limits than hadron colliders, and this was recently verified in several examples of pair production, including simplified supersymmetric models and doubly charged Higgs production. Supersymmetric models where the higgsino multiplet is decoupled from all other supersymmetric states can lead to charginos decaying to slightly lighter neutralinos and leaving a "disappearing track stub" signature in the detector. CLIC at 3 TeV would be sensitive to such a higgsino to masses beyond 1.1 TeV, which is what would be required for the higgsino to account for the dark-matter relic mass density.

All the above approaches can be combined to illuminate the electroweak phase transition in the early universe. Models of electroweak baryogenesis can contain new scalar particles to facilitate a strong first-order phase transition, during which the electroweak symmetry is broken. Such scalar singlet extensions of the Higgs sector can be searched for directly; and indirectly from a universal scaling of all Higgs couplings.

Lepton colliders can in general explore much closer to kinematic limits than hadron colliders

Having both the precision capacity of a lepton collider and also the high-energy reach of multi-TeV collisions, CLIC has strong potential beyond a Higgs factory as a discovery machine. Over the next five years CERN will maintain a level of R&D in key CLIC technologies, which are also being adapted for medical applications (*CERN Courier* November/December 2020 p7), such that the project could be realised in a timely way after the HL-LHC if the international community decides to take this route. ●

Further reading

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CERNCOURIER
VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021
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OPINION VIEWPOINT

Implementing a vision for CERN's future

The 2020 update of the European strategy for particle physics forms the basis of CERN's objectives for the next five years, explains Fabiola Gianotti.

CERN-PHOTO-201512-261-6

Fabiola Gianotti *is Director-General of CERN. Her second term of office began in January 2021.*

The European strategy for particle physics (ESPP), updated by the CERN Council in June 2020, lays the foundations for a bright future for accelerator-based particle physics. Its 20 recommendations – covering the components of a compelling scientific programme for the short, medium and long terms, as well as the societal and environmental impact of the field, public engagement and support for early-career scientists – set out an ambitious but prudent approach to realise the post-LHC future in Europe within the worldwide context.

Full exploitation of the LHC and its high-luminosity upgrade is a major priority, both in terms of its physics potential and its role as a springboard to a future energy-frontier machine. The ESPP identified an electron–positron Higgs factory as the highest priority next collider. It also recommended that Europe, together with its international partners, investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, with an electron–positron Higgs and electroweak factory as a possible first stage. Reinforced R&D on a range of accelerator technologies is another ESPP priority, as is continued support for a diverse scientific programme.

Implementation starts now

It is CERN's role, in strong collaboration with other laboratories and institutions in Europe and beyond, to help translate the visionary scientific objectives of the ESPP update into reality. CERN's recently approved medium-term plan (MTP), which covers the period 2021–2025, provides a first implementation of the ESPP vision.

Continued progress requires a courageous, global experimental venture involving all the tools at our disposal

Starting this year, CERN will deploy efforts on the feasibility study for a Future Circular Collider (FCC) as recommended by the ESPP update. One of the first goals is to verify that there are no showstoppers to building a 100 km tunnel in the Geneva region, and to gather pledges for the necessary funds to build it. The estimated FCC cost cannot be met only from CERN's budget, and special contributions from non-Member States as well as new funding mechanisms will be required. Concerning the enabling technologies, the first priority is to demonstrate that the superconducting high-field magnets needed for 100 TeV (or more) proton–proton collisions in a 100 km tunnel can be made available on the mid-century time scale. To this end CERN is implementing a reinforced magnet R&D programme in partnership with industry and other institutions in Europe and beyond. Fresh resources will be used to explore low- and high-temperature superconducting materials, to develop magnet models towards industrialisation and cost reduction, and to build the needed test infrastructure. These studies will also have vast applications outside the field. Minimising the environmental impact of the tunnel, the colliders and detectors will be another major focus, as well as maximising the benefits to society from the transfer of FCC-related technologies.

Great shape Wandering the immeasurable, *a 15 tonne sculpture tracing 4000 years of scientific knowledge, welcomes visitors to CERN.*

The 2020 MTP includes resources to continue R&D on key technologies for the Compact Linear Collider and for the establishment of an international design study for a muon collider. Further advanced accelerator technologies will be pursued, as well as detector R&D and a new initiative on quantum technologies.

Scientific diversity is an important pillar of CERN's programme and will continue to be supported. Resources for the CERN-hosted Physics Beyond Colliders study have been increased in the 2020 MTP and developments for long-baseline neutrino experiments in the US and Japan will continue at an intense pace via the CERN Neutrino Platform.

Immense impact

The discovery of the Higgs boson, a particle with unprecedented characteristics, has contributed to turning the focus of particle physics towards deep structural questions. Furthermore, many of the open questions in the microscopic world are increasingly intertwined with the universe at large. Continued progress on this rich and ambitious path of fundamental exploration requires a courageous, global experimental venture involving all the tools at our disposal: high-energy colliders, low-energy precision tests, observational cosmology, cosmic rays, dark-matter searches, gravitational waves, neutrinos, and many more. High-energy colliders, in particular, will continue to be an indispensable and irreplaceable tool to scrutinise nature at the smallest scales. If the FCC can be realised, its impact will be immense, not only on CERN's future, but also on humanity's knowledge.

CERNCOURIER

VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021

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OPINION COMMENT

Together towards new facilities

With the strategy discussion behind us, we need to focus on getting things done together by pursuing technical and scientific synergies between Higgs factories, says Jorgen D'Hondt.

Vrije Universiteit Brussel

Jorgen D'Hondt, *Vrije Universiteit Brussel, completed his three-year term as ECFA chair in December 2020.*

The recently completed European strategy for particle physics (ESPP) outlines a coherent and fascinating vision for an effective and efficient exploration of the most fundamental laws of physics. Scientific recommendations for the field provide concrete guidance and priorities on future research facilities and efforts to expand our current knowledge. The depth with which we can address open mysteries about the universe depends heavily on our ability to innovate instrumentation and research infrastructures.

CERN-PHOTO-201904-099-14

Well-oiled machine *Collaborative R&D already underpins the instrumentation challenges of the LHC detectors, such as the testing of silicon sensors for the CMS high-granularity calorimeter under development for the high-luminosity LHC.*

The ESPP calls upon the European Committee for Future Accelerators (ECFA) to develop a global detector R&D roadmap to support proposals at European and national levels. That roadmap will define the backbone of the detector R&D needed to implement the community's vision for both the short and long term. At its plenary meeting in November, ECFA initiated a roadmap panel to develop and organise the process to realise the ESPP goals in a timely fashion. In addition to listing the targeted R&D projects required, the roadmap will also consider transformational, blue-sky R&D relevant to the ESPP.

Six technology-oriented task forces will capture each of the major components in detector instrumentation: gaseous and liquid detectors; solid-state detectors; photon detection and particle-identification; calorimetry; and quantum and emerging technologies. Along with three cross-cutting task forces devoted to electronics, integration and training, these efforts will proceed via in-depth consultation with the research community. An open symposium for each task force, due to be held in March or April 2021, will inform discussions that will eventually culminate in a roadmap document in the summer. To identify synergies and opportunities with adjacent research fields, an advisory panel – comprising representatives from the nuclear and astrophysics fields, the photon- and neutron-physics communities, as well as those working in fusion and space research – will also be established.

The roadmap will also consider transformational, blue-sky R&D relevant to the ESPP

In parallel, with a view to stepping up accelerator R&D, the European Laboratory Directors Group is developing an accelerator R&D roadmap as a work-plan for this decade. Technologies under consideration include high-field magnets, high-temperature superconductors, plasma-wakefield acceleration and other high-gradient accelerating structures, bright muon beams, and energy-recovery linacs. The roadmap, to be completed on a similar timeline as that for detectors, will set the course for R&D and technology demonstrators to enable future facilities that support the scientific objectives of the ESPP.

Gathering for a Higgs factory

The global ambition for the next-generation accelerator beyond the HL-LHC is an electron–positron Higgs factory, which can include an electroweak and top-quark factory in its programme. Pending the outcome of the technical and financial feasibility study for a future FCC-like hadron collider at CERN, the community has at this stage not concluded on the type of Higgs factory that is to emerge with priority. The International Linear Collider (ILC) in Japan and the Future Circular Collider (FCC-ee) at CERN are listed, with the Compact Linear Collider (CLIC) as a possible backup.

It goes without saying, and for ECFA within its mandate to explore, that the duplication of similar accelerators should be avoided and international cooperation for creating these facilities should be encouraged if it is essential and efficient for achieving the ESPP goal. At this point, coordination of R&D activities is crucial to maximise scientific results and to make the most efficient use of resources.

Recognising the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather, ECFA supports a series of workshops from 2021 to share challenges and expertise, and to respond coherently to this ESPP priority. An international advisory committee will soon be formed to further identify synergies both in detector R&D and physics-analysis methods to make efforts applicable or transferable across Higgs factories. Concrete collaborative research programmes are to emerge to pursue these synergies. With the strategy discussion behind us, we now need to focus on getting things done together.

OPINION INTERVIEW

Seeking consensus

Joachim Mnich discusses the opportunities and challenges he faces as CERN's new director for research and computing, and how the best of particle physics is yet to come.

You started out studying electrical engineering. Why the switch to physics, and what have been your main research interests?

Actually, I studied them both in parallel, having started out in electrical engineering and then attending physics courses after I found myself getting a bit bored. I graduated with a Masters in electrical engineering, and then pursued a PhD in particle physics, working on the MARK-J experiment at DESY studying muon pairs, which allowed us to make estimates of the Z mass and $\sin^2\theta$. To some level at MARK-J we could already test electroweak theory. Afterwards, I did a postdoc at CERN for two years on the L3 experiment, and ended up staying on L3 for 12 years. My background in engineering has helped several times during my career. For example, I acted as an interface between the physicists at CERN and the engineers in Aachen who designed and built the complicated L3 readout electronics, as they couldn't always speak the same language.

DESY

Moving south *Joachim Mnich, former DESY director of particle physics, joined the CERN directorate on 1 January.*

How do you remember your LEP days?

It was a marvellous time, certainly some of the best years of my life. For the firsts few years at L3 I didn't do any physics analysis – I was down in the tunnel dealing with the readout electronics. After a few years I was able to pick up physics again, going back to electroweak physics, and becoming the coordinator of the line-shape group that was in charge of measurements of Z parameters. I later became L3 analysis coordinator. I was there for essentially the whole duration of LEP, leaving CERN at the end of 1999 and joining the CMS group at Aachen University.

What are your key achievements since becoming DESY's director for particle and astroparticle physics in 2009?

I came to DESY shortly before the experiments at HERA stopped and became director as the analyses were ramping down and LHC activities were ramping up. Certainly, one of the biggest achievements during this time was helping DESY transition from having local experiments onsite to a laboratory that now plays a key role in the CMS and ATLAS experiments. DESY became one of the largest Tier-2 data centres of the worldwide LHC computing grid, plus it had a lot of experts on proton structure and in detector operation who were highly welcomed by the LHC experiments. DESY joined the LHC relatively late, in 2008, but now has a very strong involvement in the ATLAS and CMS trackers, for example, and has set up a large infrastructure to build one end-cap tracker for ATLAS and one for CMS. DESY also joined the Belle experiment at KEK, and continues to be one of the leading labs in the development of detector R&D for future colliders. Smaller scale experiments at DESY also picked up speed, in particular axion searches. Recently the 24th dipole for the ALPS-II experiment was installed, which is really impressive. The motivation for astroparticle physics was always more concentrated at DESY's Zeuthen site, and two years ago it was decided to create an independent division for astroparticle physics to give it more visibility.

How has the transition from collider physics to X-ray science changed life at DESY?

Well, there is no longer the burden at DESY to operate large accelerators and other facilities for particle physics, so those resources are now all directed towards photon science, such as the operation of the PETRA light source, the FLASH facility and the European XFEL. On the other hand, the laboratory has also grown

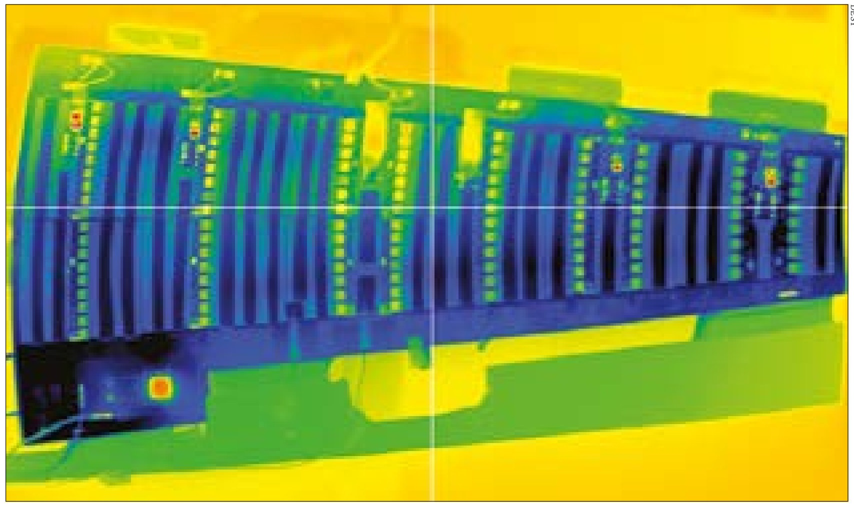
CERNCOURIER
VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021

over the last decade, to the benefit of photon science. However, if you count the number of DESY authors in ATLAS and CMS, it is still the second or third largest laboratory, so DESY is still very significant in particle physics.

How would you sum-up the state of high-energy physics today?
I'm optimistic, otherwise I wouldn't be here! Often when I talk to students, I tell them that the best is yet to come in particle physics. Yes it's true, we do not have at the moment a scenario like we had for the LHC, or for the Sp$\bar{p}$S, which had clear targets to discover new particles, but if you look back in history, this hasn't been the case very often. We would not have built several machines, including LEP, if that was the case. Discovery doesn't have to necessarily mean new particles. So that's why I am optimistic for the future of the field, because we have the Higgs boson now, which is a very special particle. It's the first of its kind – not another quark or lepton. Studying the Higgs in detail might be the key to new insights into fundamental physics. This is also the central theme of the recent European strategy update.

What do you see as your main opportunities and challenges during the next five years?
CERN is a very complicated thing. I have been away for 20 years now, so I am still in a learning phase. It is very clear what our challenges are though. We have to make the next LHC run a success, and we also need to prepare for the HL-LHC. The world is looking on us for that. The second most important thing is the implementation of the European strategy update, and in particular, the preparation for the longer-term future of CERN. We have to prepare a convincing plan for the post-LHC collider, to be ready for decision at the next strategy update at the latest.

What is in store for computing?
Computing will remain a major challenge. LHC Run 3 will start soon and we have to prepare for it now, including securing the necessary funds. On the horizon there is the high-luminosity LHC, with an enormous increase in data volumes that would by far exceed the available capacities in a flat-budget scenario. We will have to work in close collaboration with the experiments and our international partners to address this challenge and be open to new ideas and emerging technologies. I believe that the new Prévessin Computing Centre will be instrumental and enhance collaboration among the experiments and the IT department.


DESY

LHC at DESY *Infrared imaging at DESY of an ATLAS tracker end-cap petal to check a new cooling system for HL-LHC operations. Similar work is also taking place at DESY for the CMS upgrade.*

What involvement did you have in the European strategy update?
I was a member of the European strategy group in my capacity as research director for particle physics at DESY. The strategy group contained the scientific delegates to council, plus about a dozen people from the national laboratories. I was in Bad Honnef in January 2020 for the final drafting session – it was an interesting time. If you had asked me on the Monday of that week what the result at the end would be, I would have said there was no way that we could reach consensus on a strategy. But we did, even if deciding on the specific facility to be built was beyond the ESPP mandate.

Should a post-LHC electron–positron Higgs factory be linear or circular?
Its shape is not my principal concern – I want one to be built, preferably at CERN. However, if we can get additional resources from outside the field to have one built in Japan or China, then we should grab the opportunity and try a global collaboration. I think even for the next project at CERN, we also need support from outside Europe. I don't think the question of linear vs circular is a technology one – I think we have already mastered both technologies. We have pros and cons for both types of machine, but for me it is important that we get support for one of them, and the feasibility study that has been requested for a large circular tunnel in the Geneva area is an important step.

I don't think the question of linear vs circular is a technology one

Young people ask me which horse will win the race – I don't know. I consider it as my task as CERN's director for research and computing to unite the community behind the next collider because that will be vital for our success. The next collider will be a Higgs factory and there are so many things in common between the various proposals if you consider the detectors or the physics. People should come together and try to push the idea of a Higgs factory in whatever topology. Look, I am a scientist. At DESY I have been working on linear colliders. And in the European XFEL we essentially already have a prototype for the International Linear Collider. But if CERN or China build a circular collider, I will be the first one who signs up for an experiment! I think many others think like me.

What are the main challenges in getting the next collider off the ground?
We have competition now – very severe competition. I see that in Germany everybody is now speaking about life science and biology because of the pandemic, plus there are other key societal challenges such as climate and energy. These are topics

that also have an interesting story to tell, and one which might be easier to understand. If someone asks me what the applications of the Higgs boson are, I reply that I don't know. However, I am convinced that in 50 or 100 years from now, people will know. As particle physicists we have to continue to point out our role in society to motivate the investments and resources for our future plans, not just in science, but in technology and impact on society. If you look at the first accelerators, they were not built with other applications in mind – they were built to understand what the core of matter is. But look at the applications of accelerators, detectors and computing that have spun-off from this. X-ray science is one very strong, unforeseen example.

I consider it as my task as CERN director for research to unite the community

Would a lack of consensus for the next collider risk making physicists appear unsure about their ambitions?
Of course, there will be people who think that. However, there are also politicians, who I know in the US for instance, who are very supportive of the field. If you compare us to the synchrotron field for instance, there are dozens of light-source facilities around the world. This discipline has the benefit of not having to converge on only one – each country can essentially build its own facility. We have the challenge that we have to get a global consensus. I think many politicians understand this. While it is true that particle physics is not a decisive topic in elections, we have a duty to share our scientific adventure and results with the public. We are very fortunate in Germany that we have had a scientist as chancellor for the past 15 years, which I think this is one of the main reasons Germany is flourishing.

What would be the implication for European particle physics were Japan or China to proceed with a Higgs factory?
I do not have a "gold-plated" answer for this. It really depends on things that are beyond our direct control as physicists. It could be an opportunity for CERN. One of the things that the strategy update confirms is that Europe is the leader of the field scientifically and also technologically, thanks mainly to the LHC. One of the arguments that CERN could profit from is the fact that Europe should want to remain the leader, or at least "a leader" in the field. That might be very helpful for CERN to also get a future project on track. Being the leader in the field is something that CERN, and Europe, can build upon.

What is your philosophy for successful scientific management?
I believe in flat hierarchies. Science is about competition for the best ideas, and the capital of research laboratories like CERN are the people, their motivation and their creativity. Therefore, I intend to foster the CERN spirit of fruitful collaboration in our laboratory but also with all our partners in Europe and the rest of the world.

Interview by **Matthew Chalmers**.

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OPINION REVIEWS

To Russia with love

Trinity: The Treachery and Pursuit of the Most Dangerous Spy in History

By Frank Close

Penguin

LANL/M Rayner

Trinity test *Klaus Fuchs' Los Alamos ID badge overlaid on a photograph of the first detonation of a nuclear device, on 16 July 1945.*

"Why do you give all those secrets to the Russians?" So teases an inebriated Mary Bunemann, confidante to the leading nuclear physicists at the UK's Atomic Energy Research Establishment, at the emotional climax of Frank Close's new book *Trinity: The Treachery and Pursuit of the Most Dangerous Spy in History*. The scene is a party on New Year's Eve in 1949, in the cloistered laboratory at Harwell, in the Berkshire countryside. With her voice audible across a room populated by his close colleagues and friends, Bunemann unwittingly confronted the theoretical physicist Klaus Fuchs with the truth of his double life. As Close's text suspensefully unfolds, the biggest brain working on Britain's effort to build a nuclear arsenal had been faced with the very same allegation by an MI5 interrogator just 10 days earlier.

Klaus Fuchs began working on nuclear weapons in 1941, when he was recruited by Rudolf Peierls – the "midwife to the atomic age", in Close's estimation. Both men were refugees from Nazi Germany. A few years older, and better established in Britain, Peierls would become a friend and mentor to Fuchs. A quarter of a century later, Peierls would also establish a relationship with a young Frank Close, when he arrived at Oxford's theoretical physics department. Close has now been able to make a poignant contribution to the literature of the bomb by sharing the witness of his connection to the Peierls family, who felt Fuchs' betrayal bitterly, and were personally affected by the suspicion engendered by his espionage.

Close's story expands dramatically in scope when Peierls and Fuchs are recruited to the Manhattan Project. Though Peierls was among the first to glimpse the power of atomic weapons, Fuchs began to exceed him in significance to the project during this period. In one of the strongest portions of the book, Close balances physics, politics and the intrigue of shady meetings with Fuchs' handlers at a time when he passed to the Soviet Union a complete set of instructions for building the first stage of a uranium bomb, a full description of the plutonium bomb used in the Trinity test in the New Mexico desert, and detailed notes on Enrico Fermi's lectures on the hydrogen bomb.

The story becomes intensely claustrophobic when Fuchs returns to England to head the theoretical physics department at Harwell. Here, Close evokes the contradictions in Fuchs' character: his conviction that nuclear knowledge should be shared between great powers to avert war; his principled but tested faith in communism, awakened while protesting the rise of Nazism; his devoted pastoral care for members of his inner circle at Harwell, even as the net closed around him; and his willingness to share not only nuclear secrets but also the bed of his colleague's wife. Close has a particular obsession with the question of whether Fuchs' eventual confession was induced by unrealistic suggestions that he could be forgiven and continue his work. But inducement did not jeopardise Fuchs' ultimate conviction and imprisonment, despite MI5's fears, and Close judges his 14-year sentence, later reduced, to be just. Even here, however, the Soviets had the last laugh, with Fuchs' apprehension not only depriving the British nuclear programme of its greatest intellectual asset, but also precipitating the defection of Bruno Pontecorvo.


Penguin

Close chose an ideal moment to research his history, writing with the benefit of newly released MI5 records, and before several others were withdrawn without notice. He applies forensic attention to the agency's pursuit of the nuclear spy. Occasionally, however, this is to the detriment of the reader, with events seemingly diffracted onto the pages – both prefigured and returned to as the story progresses and new evidence comes to light. We step through time in Fuchs' shoes, for example only learning at the end of the book that two other spies at the Manhattan Project were also passing information to the Russians. While Close's inclination to let the evidence speak for itself is surely the mark of a good physicist, readers in search of a more analytical history may wish to also consult Mike Rossiter's 2014 biography *The Spy Who Changed the World: Klaus Fuchs and the secrets of the nuclear bomb*, which offers a more rounded presentation of the Russian and American perspectives.

Intimate portrait

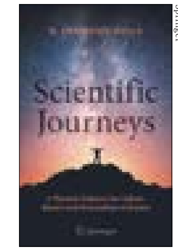
By bringing physics expertise, personal connections and impressive attention to detail to bear, Frank Close's latest book has much to offer readers seeking insights into a formative time for the field, when the most talented minds in nuclear physics also bore the weight of world politics on their shoulders. He eloquently tells the tragedy of "the most dangerous spy in history", as it played out between the trinity of Fuchs, his mentor Peierls and a shadowy network of spooks. Above all, the text is an intimate portrait of the inner struggles of a principled man who betrayed his adopted homeland, even as he grew to love it, and by doing so helped to shape the latter half of the 20th century.

Mark Rayner *associate editor.*

Scientific Journeys: A Physicist Explores the Culture, History and Personalities of Science

By H Frederick Dylla

Springer



Springer

H Frederick Dylla is a "Sputnik kid", whose curiosity and ingenuity led him on a successful 50-year career in physics, from plasma to accelerators and leading the American Institute of Physics. His debut book, *Scientific Journeys: A Physicist Explores the Culture, History and Personalities of Science*, is a collection of essays that puts a multidisciplinary historical perspective on the actors and events that shaped the world of science and scholarly publishing. Through geopolitical and economic context and a rich record of key events, he highlights innovations that have found their use in social and business applications. Those cited as having contributed to global technological progress range from the web and smartphones to medical imaging and renewable energy.

The book is divided in five chapters: "signposts" (in the form of key people and events in scientific history); mentors and milestones in his life; science policy; communicating science; and finally a brief insight into the relationship between science and art. He begins with the story of medieval German abbess, mystic, composer and medicinal botanist Hildegard of Bingen: "a bright signpost of scholarship". Dylla goes on to explore the idea that a single individual at the right time and place can change the course of history. Bounding through the centuries, he highlights the importance of science policy and science communication, the funding of big and small science alike, and the contemporary challenges linked to research, teaching science and scholarly publishing. Examples among these, says Dylla, are the protection of scientific integrity, new practices of distance learning and the weaknesses of the open-access model. The book ends bang up to date with a thought on the coronavirus pandemic and science's key role in overcoming it.

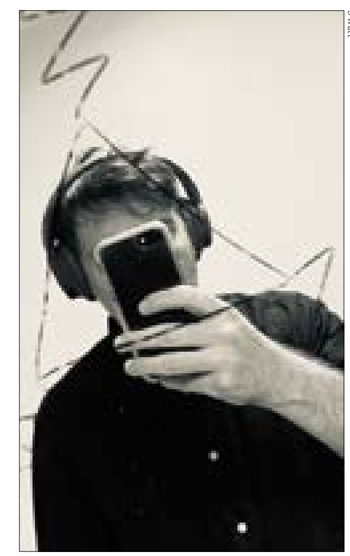
Intended for teachers, science historians and students from high school to graduate school, Dylla's book puts a face on scientific inventions. The weightiest chapter, mentors and milestones, focuses on personalities who have played an important role in his scientific voyage. Among the many named, however, Mildred Dresselhaus – the "queen of carbon" – is the only female scientist featured in the book besides Hildegard. Though by beginning the book with a brilliant but at best scientifically adjacent abbess who preceded Galileo by four centuries Dylla tacitly acknowledges the importance of representing diversity, the book unintentionally makes it discomfortingly clear how scarce role models for women can be in the white-male dominated world of science. The lack of a discussion on diversity is a missed opportunity in an otherwise excellent book.

Cristina Agrigoroae *CERN.*

The Mirror Trap

By Simon Watt

The Bloomsbury Festival, 17 October 2020


S Watt

Mirror, mirror *Simon Watt performs The Mirror Trap.*

A quantum physicist has mysteriously disappeared, leaving behind two mirrors, a strange machine, hallucinogenic drugs and a diary filled with ramblings and Feynman diagrams. His last thoughts reveal his views on the many-worlds interpretation – the controversial idea that there are as many worlds as there are possible outcomes in quantum measurements.

The Mirror Trap is an online performance where the audience has the chance to experiment with the psychology of self-identity and explore the interpretations of quantum mechanics. The public is asked to draw Feynman diagrams on a mirror, plonk themselves down in front of it and listen to the play using headphones, thereby transforming a dimly lit room into a private theatrical space.

The experience is hypnotic, eerie and introspective. Ideas at the intersection between physics and psychology are described in a beautifully written monologue. The protagonist believes that he has devised a new way to access a parallel universe and replicate Schrödinger's thought experiment; however, he must play the role of the cat, and be observed. Under severe emotional pressure, he begs the audience to witness his desperate attempt to reach a universe where he did not make the biggest mistake of his life.

While the physicist is digging deep into his psyche and preparing for a leap into the unknown, visual and auditory illusions play tricks with the participants' brains. From *Snow White* to *Alice Through the Looking-Glass*, mirrors have been linked to mysterious portals, superstition and fairy tales. In this play, they are portals to other worlds, and also tools to reflect about life, self and perception. Many people feel subjective sensations of otherness and report dissociative identity effects when looking at themselves in a mirror. This strange-face-in-the-mirror illusion is more pronounced in dim light and is associated with Troxler's fading and neural adaptation: when we look at an unchanging image some features disappear temporarily from our perception and our brain fills this missing information with other elements. This effect is particularly spooky when applied to one's own face.

A chance to experiment with the psychology of self-identity and explore the interpretations of quantum mechanics

The performance was written, created and played by biologist and science communicator Simon Watt, with assistance from playwright Alexandra Wood. The 20-minute piece was followed by a discussion and question-and-answer session with Watt, psychologist Julia Shaw, and physicist Harry Cliff of LHCb and the University of Cambridge, who was scientific consultant for this work and guest physicist at the Bloomsbury Festival, under the auspices of which the piece was performed. Watt is now looking for other researchers and festivals interested in collaborating.

As arts and science festivals have moved online because of Covid-19 restrictions, this show found a creative way to engage the public while sitting at home. A well-thought-out merging of drama and science engagement, *The Mirror Trap* is an intense and intriguing experience for physicists and non-physicists alike.

Letizia Diamante *University of Cambridge.*

CERNCOURIER

VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021

IOP Publishing

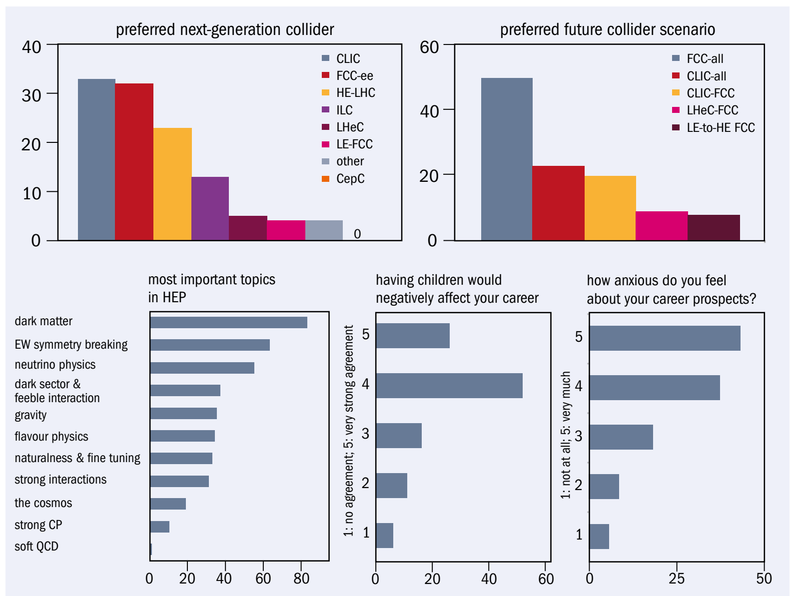
PEOPLE CAREERS

A wake-up call from the next generation

Early-career researchers voice their hopes and concerns about the future of particle physics.

The recent update of the European strategy for particle physics (ESPP) offered a unique opportunity for early-career researchers (ECRs) to shape the future of our field. Mandated by the European Committee for Future Accelerators (ECFA) to provide input to the ESPP process, a diverse group of about 180 ECRs were nominated to debate topics including the physics prospects at future colliders and the associated implications for their careers. A steering board comprising around 25 ECRs organised working groups devoted to topics including detector and accelerator physics, and key areas of high-energy physics research. Furthermore, working groups were dedicated to the environment and sustainability, and to human and social factors – aspects that have been overlooked in previous ESPP exercises. A debate took place in November 2019 and a survey was launched to obtain a quantitative understanding of the views raised.

The feedback from these activities was combined into a report reflecting the opinions of almost 120 signed authors. The survey suggests that more than half of the respondents are postdocs, around two-fifths PhD students and approximately a tenth staff members. Moreover, roughly one-third were female and two-thirds male. Several areas, such as which collider should follow the LHC and environmental and sustainability considerations, were highlighted by the participating ECRs. Among the many topics discussed, we highlight here a handful of aspects that we feel are key to the future of our field.



Fresh perspectives *Selected results from the early-career researchers survey.*

Building a sustainable future

A widespread concern is that the attractiveness of our field is at risk, and that dedicated actions need to be taken to safeguard its future. Certain areas of work are vital to the field, but are undervalued, resulting in shortages of key skills. Due to significant job insecurity many ECRs struggle to maintain a healthy work–life balance. Moreover, the lack of attractive career paths in science, compared to the flexible working hours and family-friendly policies offered by many companies these days, potentially compromises the ability of our field to attract and retain the brightest minds in the short- and long-term future. With the funding for the proposed Future Circular Collider (a key pillar of the ESPP recommendations) not yet clear, and despite it receiving the largest support among future-collider scenarios in CERN's latest medium-term financial plan, an additional risk arises for ECRs to back the wrong horse.

It is imperative to holistically include social and human factors when planning for a sustainable future of our field. Therefore, we strongly recommend that long-term project evaluations and strategy updates assess and include the impact of their implementation on the situation of young academics. Specifically, equal recognition and career paths for domains such as computing and detector development have to be established to maintain expertise in the field.

Next-generation colliders beyond the LHC will need to overcome major technical challenges in detector physics, software and computing to meet their ambitious physics goals. Our survey and debate showed that young researchers are concerned about a shortage of experts in these domains, where very few staff positions and even less professorships are open for particle physicists specialised in detector development and software and computing. In particular in the light of ever increasing project time scales, a sizable fraction of funding for non-permanent positions must be converted to funding for permanent positions in order to establish a sustainable ratio between fixed-term postdocs and staff scientists.

The possibility for a healthy work–life balance and the reconciliation of family and a scientific career is a must: currently, most of the ECRs consulted think that having children could damage their future and that moving between countries is generally a requirement to pursue a career in particle physics. These might constitute two reasons why only 20% of the polled ECRs have children. Put in a broader perspective, the future of the field will depend on the success of reaching a diverse community, with viable career paths for a wide spectrum of schemes of life. In order to reach this diverse community, it is not enough to simply offer more day-care places to parents. Similarly, the #BlackInTheIvory movement in 2020 shone a spotlight on the significant barriers faced by the Black community in academia – an issue also shared by many other minority groups. Discrimination in academia has to be counteracted systematically, including the filling of positions or grant-approval processes, where societal and diversity aspects must be taken into account with high priority.

The environmental sustainability of future projects is a clear concern for young researchers, and particle-physics institutes should use their prominent position in the public eye to set an example to other fields and society at large. The energy efficiency of equipment and the power consumption of future collider scenarios are considered only partially in the ESPP update, and we support the idea of preparing a more comprehensive analysis that includes the environmental impact of the construction as well as the disposal of large infrastructures. There should be further discussion of nuclear versus renewable energy usage and a concrete plan on how to achieve a higher renewable energy fraction. The ECRs were also of the view that much travel within our field is unnecessary, and that ways to reduce this should be brought to the fore. Since the survey was conducted, due to the ongoing COVID-19 pandemic, various conferences have already moved online, proving that progress can be made on this front.

Collider preference

In the context of the still-open questions in particle physics and potential challenges of future research programmes, the ECRs find dark matter, electroweak symmetry breaking and neutrino physics to be the three most important topics of our field. They also underline the importance of a European collider project soon after the completion of the HL-LHC. Postponing the choice of the next collider project at CERN to the 2030s, for example, would potentially negatively impact the future of the field: there could be fewer permanent jobs in detector physics, computing and software if preparations for future experiments cannot begin after the current upgrades. Additionally, it could be difficult to attract new, young bright minds into the field if there is a gap in data-taking after the LHC. While physics topics were already discussed in great detail during the broader ESPP process, many ECRs stated their discomfort about the way the next-generation scenarios were compared, especially by how the different states of maturity of the projects were not sufficiently taken into account.

About 90% of ECRs believe that the next collider should be an electron–positron machine, concurring with the ESPP recommendations, although there is not a strong preference if this machine is linear or circular. While there was equal preference for CLIC and FCC-ee as the next-generation collider, a clear preference was expressed for the full FCC programme over the full CLIC programme. Given the diverse interest in future collider scenarios, and keeping in mind the unclear situation of the ILC, we strongly believe that a robust and diverse R&D programme on both accelerators and detectors must be a high priority for the future of our field.

In conclusion, both the debate and the report were widely viewed as a success, with extremely positive feedback from ECFA and the ECRs. Young researchers were able to share their views and concerns for the future of the field, while familiarising themselves with and influencing the outcome of the ESPP. ECFA has now established a permanent panel of ECRs, which is a major milestone to make such discussions among early-career researchers more regular and effective in the future.

Further reading

N Andari *et al.* 2020 arXiv.org:2002.02837.

Erica Brondolin *CERN*, **Elena Graverini** *EPFL*, **Hendrik Jansen** *DESY*, **Josh McFayden** *University of Sussex*, **Elliot Reynolds** *University of Birmingham* and **Sarah Williams** *University of Cambridge*.

CERNCOURIER
VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021
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Appointments and awards

Bagger leads APS

Theoretical particle physicist Jonathan Bagger took up the role of CEO of the American Physical Society (APS) in January, succeeding Kate Kirby. Bagger has been director of the TRIUMF laboratory in Vancouver, British Columbia, since 2014, during which he reshaped the lab's hiring practices and established the laboratory's committee on equity, diversity and inclusion. He completed his PhD under the supervision of Edward Witten with research interests in supersymmetry and string theory, and is known for the Bagger–Lambert–Gustavsson action. "This is a critical moment for physics," he said. "I look forward to working with the board and council to ensure that APS faithfully represents the interests of its members while continuing to build a broad and inclusive community to address the world's most pressing challenges."

New ECFA chair

At the 107th plenary meeting of the European Committee for Future Accelerators (ECFA), Karl Jakobs (University of Freiburg) was announced as the new ECFA chairperson. He took over from Jorgen D'Hondt (Vrije Universiteit Brussel) on 1 January for a mandate of three years. ECFA carries out long-range planning for European high-energy accelerators, large-scale facilities and equipment, and plays an important role in building communities to address the vision formulated by the European strategy for particle physics. Jakobs has been spokesperson at ATLAS since 2017, having been part of the collaboration since its beginnings in 1992.

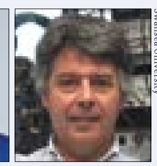
Nuclear win for ISOLDE

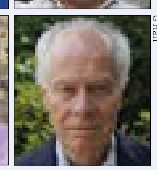
The nuclear-physics board of the European Physical Society has awarded the 2020 Lise Meitner Prize to three physicists who have played a decisive role in turning ISOLDE at CERN into a world-leading facility for the investigation of nuclear structure:

Klaus Blaum of Max Planck Institute for Nuclear Physics (top left), Björn Jonson of Chalmers University of Technology (top right) and Piet Van Duppen of KU Leuven (bottom). Blaum was recognised for high-precision determinations of nuclear ground-state properties using laser and mass-spectroscopy, Johnson for his studies of the lightest exotic nuclei, and Van Duppen for the production and investigation of post-accelerated radioactive beams with REX-ISOLDE. The awards were handed out during an online event on 26 November during the ISOLDE users meeting and workshop.

IOP awards for HEP

In late October, the UK Institute of Physics (IOP) announced its 2020 awards, categorised into gold, silver and bronze. The gold-medal Paul Dirac Prize was awarded to Carlos Frenk (upper left) of the University of Cambridge for "outstanding contributions to establishing the current standard model for the formation of all cosmic structure, and for leading computational cosmology within the UK for more than three decades". Michael Charlton of Swansea University (upper right) was awarded the Joseph Thomson Prize, a silver medal, for "scientific leadership in antimatter science, particularly within the ATHENA and ALPHA collaborations, and the formation and study of antihydrogen, including precision two-photon spectroscopy of the 1S–2S transition". Also, a silver medal, the Cecilia Payne-Gaposchkin Prize was given to Simon Hooker (middle left) of the University of Oxford for pioneering contributions to the development of high-power plasma waveguides and their application to laser-driven plasma accelerators. The two other silver medals in high-energy physics were granted to CMS collaborator Geoffrey Hall (middle right) of Imperial College London, who





received the James Chadwick Prize for his pioneering work in developing silicon detectors and front-end electronics for particle physics experiments, and to theorist Kellogg Stelle (lower), also at Imperial, who was presented with the John William Strutt, Lord Rayleigh Prize for his seminal contributions to fundamental physics including supersymmetric field theories and supergravity.

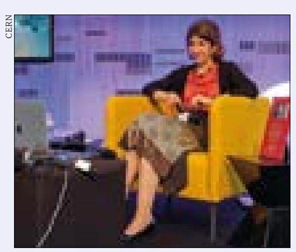
Simetría winners announced

Chilean artist Patricia Domínguez (left) and Swiss artist Chloé Delarue (right) have been announced as the two winners

of the Simetría arts residency at CERN and ALMA–ESO. The pair will complete a joint three-week residency at CERN and the Chilean facilities of the European Southern Observatory (ESO), "to discover new expressions in their artistic practices". Simetría is organised by Arts at CERN in Geneva and by Corporación Chilena de Video y Artes Electrónicas in Chile to foster dialogue between art and fundamental science, as well as interdisciplinary exchange between artists and scientists working or living in Switzerland and Chile.

Innovator's award for CERN

The Arthur C Clarke 2020 Innovator's Award has been presented to CERN for innovation and continuing work to enhance our understanding of fundamental physics. The award, which was first given out in 2002, recognises "initiatives or new inventions that had recent impact or hold particular promise for satellite communications and society". Usually granted to a single person, it is only the second time that a large organisation has won the award, with Skybox Imaging winning in 2014. Other



previous winners include Elon Musk, Jeff Bezos and astronomer Jill Tarter. CERN Director-General Fabiola Gianotti accepted the award on behalf of CERN at the Unleash Imagination 2020 event in November (above).

RECRUITMENT

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PhD Opportunities at the Cockcroft Institute

Fully-funded PhD studentships in physics and engineering, starting October 2021 at the Cockcroft Institute of Accelerator Science & Technology

The Cockcroft Institute of Accelerator Science and Technology

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More details and application forms may be found at:
www.cockcroft.ac.uk/join-us/
Queries may be made to Laura Corner: email: laura.corner@liverpool.ac.uk

PhD projects in physics and engineering are currently available within the following topics for an October 2021 start:

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Addressing Global Challenges: using accelerator technology to benefit society, in radiotherapy, industrial/environmental processing, or security.

Prospective students should send a CV and completed application form to Janis Davidson: email: janis.davidson@stfc.ac.uk

PhD positions are available until filled.

Lancaster University | University of Liverpool | Manchester 1824 The University of Manchester | Science & Technology Facilities Council | University of Strathclyde Glasgow

ELI Beamlines research centre in Dolní Břežany is a part of pan-European infrastructure ELI (Extreme Light Infrastructure) representing a unique tool of support of scientific excellence in Europe by making available its capacities to the best scientific teams across the world. One of the aims of ELI Beamlines is to create the highest power kJ class laser system in the world and to operate it on a long-term basis. Due to ultra-high performances of 10 PW and concentrated intensities of up to 1024 W/cm2, we can offer our users a unique source of radiation and beams of accelerated particles. These beamlines are enabling ground-breaking research in the areas of physics and science dealing with materials, but also in biomedicine or laboratory astrophysics and many other fields. ELI Beamlines is part of the Institute of Physics of the Czech Academy of Sciences, and it was open in 2015.

ELI Beamlines facility is building a new laboratory for coating of very large high-power laser optics with sizes >1 m. The laboratory will be equipped with new machines, metrology and optics handling systems. We are seeking a motivated candidate for the position of

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Applications, containing CV, cover letter, contacts of references, and any other material the candidate considers relevant, should be sent to
Mrs Jana Ženíšková, HR specialist (jana.zeniskova@eli-beams.eu, +420 601560322)

Information regarding the personal data processing and access to the personal data at the Institute of Physics of the Czech Academy of Sciences can be found on:
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ess EUROPEAN SPALLATION SOURCE

Associate Director ESH&Q

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For more information about the role and the ESS recruitment process, please look at https://europeanspallationsource.se/careers/vacancies. Submit your application as soon as possible, as we will review applications continuously, latest by **February 18th 2021**.

CERNCOURIER
VOLUME 61 NUMBER 1 JANUARY/FEBRUARY 2021
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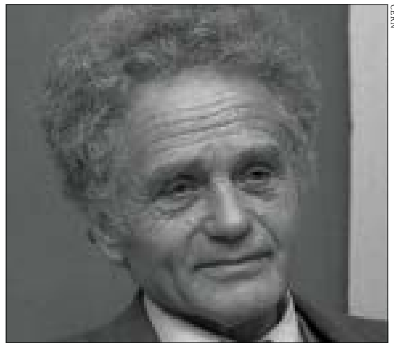
PEOPLE OBITUARIES

Yuri Orlov 1924–2020

A defender of scientific freedom

Yuri Orlov, a world-renowned accelerator physicist and a leading figure in the worldwide campaign for human rights in Soviet Russia, passed away at the end of September at the age of 96.

Yuri was born in Moscow in 1924. He studied and worked there until 1956, when a critical pro-democracy speech he gave at the Institute for Theoretical and Experimental Physics resulted in him being fired and banned from scientific work. He then moved to the Yerevan Physics Institute in Armenia where he earned his first doctorate ("Nonlinear theory of betatron oscillations in the strong-focusing synchrotron") in 1958, followed by the award of a second doctorate in 1963. While in Yerevan, he designed the 6 GeV electron synchrotron, became head of the electromagnetic interaction laboratory, and was elected to the Armenian Academy of Sciences.



CERN

Yuri was a world-renowned accelerator physicist and a campaigner for human rights.

In 1972 Yuri returned to Moscow and joined the influential dissident movement that included Andrei Sakharov and Aleksandr Solzhenitsyn. When the final documents of the Helsinki Conference on Security and Co-operation in Europe were signed in 1975, Yuri founded the Moscow Helsinki Group with the aim of having all human rights guaranteed in the Helsinki documents accorded to all citizens of the Soviet Union. As was to be expected, Yuri was arrested in 1977, tried in a political mock trial in 1978 and convicted to seven years in a labour camp in Perm.

As soon as Yuri Orlov's ordeal became known in Europe and North America, physicists began to protest against the treatment of their colleague. At CERN, where several physicists had had personal contacts with Yuri, the Yuri Orlov Committee was founded with Georges Charpak as one of its founding members. The long-standing fruitful scientific collaboration with the Soviet Union was challenged and the support of eminent political leaders of the CERN member states was solicited.

Surviving a total of seven years of labour camp under extreme conditions, Yuri was deported to Siberia for a period of five years. Because of continuing international pressure, he was then deported to the US in 1986, where he was offered a position at Cornell University. Soon after his forced emigration, Yuri visited CERN and he spent a sabbatical there in 1988/1989 working in the accelerator division to develop the idea of ion "shaking". He joined the muon g-2 experiment at Brookhaven National Laboratory and worked on Brookhaven proposals to measure the electric dipole moments of protons, electrons and deuterons. At Cornell he pursued this work as well as an alternative design for the proposed B-factory, and wrote on the foundations of quantum mechanics. In 2008 he was named a professor of physics and professor of government, and taught physics and human rights until his retirement in 2015.

Yuri authored or co-authored more than 240 scientific papers and technical reports, and wrote a memoir, *Dangerous Thoughts: Memoirs of a Russian Life* (William Morrow & Co, 1991). Among the many honours Yuri received are the American Physical Society's 2006 Sakharov prize "For his distinction as a creative physicist and as a lifelong, ardent leader in the defence and development of international human rights, justice and the freedom of expression for scientists", and the APS 2021 Wilson Prize for outstanding achievements in the physics of particle accelerators, of which he was notified shortly before his death.

Yuri's example as a scientist committed to the freedom of science, its cultural dimension in world affairs and his defence of the human right of expression of one's convictions is an example and inspiration to all of us.

Members of the former Yuri Orlov Committee.

Glen Lambertson 1926–2020

An early giant of US accelerator physics

Glen Lambertson, one of the early giants of US accelerator physics, passed away on 30 August aged 94. Glen is best known for the injection/extraction magnet that bears his name. His greatest achievements, however, were, to quote from the American Physical Society (APS) 2006 Wilson Prize citation, "... fundamental contributions ... in the area of beam electrodynamics including the development of beam instrumentation for the feedback systems that are essential for the operation of high luminosity electron and hadron colliders".

Glen's studies at the University of Colorado were interrupted by World War II, during which he saw action serving in the legendary 10th Mountain Division. Severely wounded in Northern Italy, his life was saved by the newly discovered wonder drug "penicillin". (Incidentally, he remained an avid skier well into his 80s.) After the war he completed his degree at Colorado in engineering physics and did graduate work at the University of California, quickly becoming involved with accelerators. His first contact was as an operator of the 184-Inch Synchrocyclotron, where he commented that Ernest Lawrence would often reach over his shoulder to "tweak a knob".

Lambertson family

Glen is best known for the injection/extraction magnet that bears his name.

Glen played a large part in the design of the magnet system for the Bevatron at Lawrence Berkeley National Laboratory, and in 1960 was instrumental in the retrofitting of a resonant extraction system for this machine, vastly improving its performance and effectiveness as a discovery tool for the newly established field of particle physics. His patent for the "Lambertson magnet" is dated 1965, and this concept is still widely used for the injection and extraction of beams in synchrotrons and storage rings.

In the mid-1970s Glen was a major contributor to the ESCAR project – a first attempt to build a small (4 GeV) superconducting accelerator to provide data and experience for future large superconducting machines. While funds were not available to complete the project, two quadrants of dipoles were built and successfully tested, along with the necessary cryogenic and control-system infrastructures. Later in the 1970s, following the developments in stochastic cooling by Simon Van der Meer, Glen led the successful experiment to demonstrate stochastic cooling at the Fermilab 200 MeV cooling test ring. His techniques were transferred to rings at Fermilab and Brookhaven.

His most productive studies were in beam instabilities, in particular the instrumentation to detect and control electron-cloud instabilities. He was a key figure in the successful commissioning of both the PEP-II B-factory at SLAC, and the Advanced Light Source at Berkeley. He also had close contacts with CERN, serving as a visiting scientist in 1993 and later playing an important role in calculating the impedance of injection-line components for the LHC.

Glen's work was widely recognised. In addition to the APS Wilson prize, he was an APS fellow and also won the US Particle Accelerator School Prize for Achievement in Accelerator Science and Technology.

His always relaxed demeanour and sage advice were a constant inspiration to us, and we forgave him his incredibly awful puns. Rest in peace, Glen!

Jose Alonso *LBNL.*

Jacques Séguinot 1932–2020

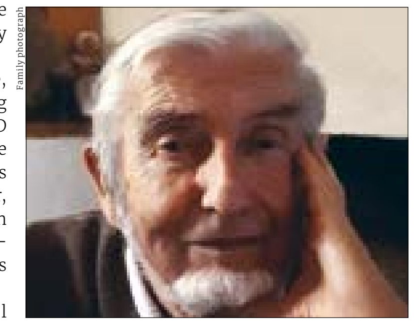
A great detector physicist

Jacques Séguinot, a founding father of the ring-imaging Cherenkov detector, passed away on 12 October.

Born in 1932 in a small village in Vendée, Jacques studied electromechanical engineering at the University of Caen and received his PhD in physics in 1954. His solid engineering base was visible in every experiment that Jacques designed and built throughout his long career, which followed a classic French academic path – from a *stagiaire de recherche* in 1954 to a *directeur de recherche* in 1981, which he held until his official retirement in 1990.

His first studies saw him spend several months at the French cosmic-ray laboratory on the Col du Midi near Mont Blanc, after which he worked on accelerator-based experiments: first at Saturne (CEA Saclay), and from 1964 onwards at CERN's Proton Synchrotron studying strong interactions with pion and kaon beams. At the end of the 1960s, Jacques began a long and fruitful collaboration with Tom Ypsilantis, leading to a seminal 1977 paper establishing a new particle identification technology that became known as the RICH (Ring Imaging Cherenkov Counter).

The idea was to use the recently introduced multiwire proportional chamber, filled with a photosensitive gas, to detect and localise ultraviolet photons emitted by fast charged particles in a radiating medium, and to use a suitable optical arrangement to create a ring pattern whose radius depends on the particle speed.



Family photograph

Jacques Séguinot had a solid engineering base.

Combined with magnetic analysis, the RICH made it possible to identify a particle's mass in a wide range of energies. In further work, Séguinot and Ypsilantis developed algorithms to optimise the momentum resolution of the detectors, as well as adapting radiators to cover different momentum ranges where other technologies were ineffective.

The early RICH devices were successfully deployed at the fixed-target experiments OMEGA at CERN and E605 at Fermilab. The ability of the detector to extend over most of the solid angle around the target or colliding-beam intersections also made it particularly relevant for experiments at the newly commissioned LEP and SLD accelerators. The RICH detector at LEP's DELPHI experiment came close to the original design, with nearly 4π angular coverage, and Jacques' contribution to this detector was key.

In view of the growing interest in meson factories, Jacques and Tom worked on faster RICH devices with shorter photo-conversion lengths, and also on CsI solid photo-converters. This led to applications in the RICH for CLEO at the CESR storage ring, the CsI-based RICH detectors in CERN's ALICE, COMPASS and other experiments. Another very ambitious R&D programme, which started in the mid-1990s, aimed at developing highly segmented photodetectors sensitive to visible light. Jacques saw the potential of such hybrid photo detectors (HPD) for applications in medical imaging, and proposed an innovative PET device in which matrices of long scintillation crystals are read from both sides by HPDs. In the meantime, SiPM photodetectors had become available, with a number of practical advantages over HPDs. In the AX-PET collaboration, Jacques and several others built a fully operational axial PET with SiPM readout.

The high-energy physics community has lost an excellent detector physicist with an extraordinary sense of engineering. His groundbreaking ideas live on, including in the most recent detectors such as Belle II in Japan. But we will also remember Jacques' fine personality, patience and decency.

Christian Joram and Fabio Sauli *CERN.*

Willem de Boer 1948–2020

Creativity and relentless drive

Willem ("Wim") de Boer passed away on 13 October, aged 72. Wim studied physics at the University of Delft and graduated in 1974 with a thesis on the dynamic orientation of nuclei at low temperatures, which laid the foundation of polarised targets in high-energy physics. Following a CERN fellowship, he joined the University of Michigan, Ann Arbor and worked on polarised proton–proton scattering at the ANL synchrotron, where he found an unexplained difference in the cross sections for parallel and antiparallel spins.

In 1975 Wim took up a position at the Max Planck Institute for Physics in Munich where he stayed, interrupted by a sabbatical at SLAC in 1987, for 14 years. In Munich he joined the team working on the CELLO experiment at DESY, where he took responsibility for the ▷

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Volume 61 Number 1 January/February 2021
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data-acquisition system. The CELLO years were instrumental for precision studies of QCD, out of which the triple-gluon coupling and the running of the strong coupling constant emerged – a subject Wim pursued ever after.

Following his appointment to a professorship at the University of Karlsruhe in 1989, Wim created research groups at LEP's DELPHI experiment, the AMS-02 experiment on the International Space Station, and he coordinated a group at the LHC's CMS experiment. Having studied the running of the coupling constants of the weak, electromagnetic and strong interactions, Wim found, together with Ugo Amaldi and Hermann Fürstenau, that these could only meet in a unified way at high energies if phenomena beyond the Standard Model, such as supersymmetry, existed. This was published in their seminal 1991 paper "Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP", which led to the expectation that a new energy domain would open up at the TeV scale with the lightest supersymmetric particle constituting dark matter. The paper has been cited almost 2000 times.

Wim contributed a multitude of ideas, studies and publications to each of the experiments he worked on, driven by the single question: where is supersymmetry? He looked for dark-matter signals at the lowest energies in our galaxy using earth-bound observatories, balloon experiments and satellites, at signals from direct production at LEP and the LHC, and in anomalous decay modes of bottom mesons using data from the Belle and BaBar experiments, among others.

M Balzer, KIT

Wim de Boer was an enthusiastic all-round physicist.

It is our belief that Wim was most fascinated by AMS-02. Not only did he and his group contribute an electronic readout system to the detector, he also saw it take off from Cape Canaveral with the penultimate Space Shuttle flight in 2011, celebrated by the visit of the whole crew of astronauts to Karlsruhe later that year.

Wim's career saw him work across detectors using gases, liquids, silicon and diamonds, and study their performance in magnetic fields and high-radiation backgrounds. He also investigated the use of detectors for medical and technical applications. His last R&D effort began only a few weeks before his death: the development of a novel cooling system for high-density batteries.

Our field has lost a great all-round physicist with unparalleled creativity and diligence, a warm collegiality and a very characteristic dry humour. Well aware of his rapid illness, his last words to his family were: "*Hij gaat nog niet, want hij heeft nog zoveel ideeën!*" (roughly "He's not going yet, because he still has so many ideas!). He will be missed deeply.

Guido Drexlin and Thomas Müller *KIT.*

Richard Roberts 1940–2020

Specialising in strong interactions

When theorist Richard "Dick" Roberts began his career in the 1960s, the strong force was largely mysterious. Today, with the advent of quantum chromodynamics (QCD), we understand the detailed quark and gluon sub-structure of protons and even atomic nuclei. This development is due in no small part to the work that Roberts performed with his collaborators Alan Martin, James Stirling and, latterly, Robert Thorne.

The eponymous MRS and MRST collaborations analysed inelastic data on hadrons for more than three decades, extracting with ever higher precision the structure functions and thereby the momentum distributions of quarks and gluons in the proton. The MRS(T) distribution functions became a staple of particle physics and key to much of the planning for experiments at the LHC, and the subsequent analyses that led to the discovery of the Higgs boson.

Dick Roberts was born in North Wales, UK in 1940. He studied mathematics at King's College, London, and won the Drew medal for achieving the highest mathematics degree in the whole of the University of London. He went on to complete a PhD at Imperial College, followed by research at Durham, CERN and UC San Diego, and then, in 1971, the Rutherford High Energy Laboratory (today the Rutherford Appleton Laboratory) near Oxford, where he remained until his retirement in 2000.

Throughout his career, he specialised in the theory and phenomenology of the strong interaction. The 1960s were the days of Regge theory and, while at CERN, he started working on the related Veneziano model and ideas about duality, which he subsequently developed, mainly with Hong-Mo Chan and D P Roy. Towards the end of the 1970s, with the discovery of the J/ψ, he became one of the first to apply the then novel ideas of QCD to the analysis of structure functions. With increasing precision, the MRS team extracted the parton distributions, which soon became a standard tool for experimental analysis and interpretation of data. He also made important contributions to understanding the EMC effect – where the distributions of quarks in atomic nuclei are subtly evolved in momentum space relative to what is found for quarks in free nucleons – and to the proton spin puzzle of the 1980s. His pedagogic understanding of QCD was to shine in his 1990 textbook *Structure of the Proton* (Cambridge University Press).

G Ross

Roberts was the "R" in the MRST collaboration, famous for calculating hadronic structure functions.

During the 1990s Dick was quick to develop the phenomenological implications of supersymmetric grand-unified theories that might be tested by the LHC. He also tackled the mystery of the origin of quark mass structure in work that has stimulated much of the ongoing activity in this area.

His retirement from research after 2000 soon led to another career, which revealed his talent for teaching. For the past 15 years he tutored first-year students at Oxford University's Exeter College, and continued teaching until the university was closed by the COVID-19 pandemic in March 2020.

Quiet, unassuming but extremely effective, he was the powerhouse behind the scenes in many of his collaborations. Dick loved opera, piano playing, poetry, teaching, reading, sport, gardening and physics. He had a spark of good humour, a gentleness of spirit, and a warmth without parallel.

Frank Close and Graham Ross *University of Oxford.*

Yuri Alexahin 1948–2020

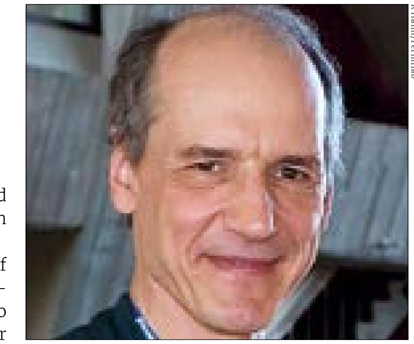
Driving novel accelerator concepts

On 8 September, Fermilab senior scientist and world-leading beam physicist Yuri I Alexahin died from a sudden stroke.

Yuri was born in 1948 in the Russian town of Vorkuta. After studying physics and graduating from Moscow State University, from 1971 to 1988 he worked at the Joint Institute for Nuclear Research in Dubna and, in 1980, received his PhD in physics from the Institute of High Temperatures of the USSR Academy of Sciences. In Dubna, Yuri developed an interest in the physics of accelerators and beams and, especially, of charged-particle colliders, which remained the focus of his work throughout his career. He generated brilliant ideas and made critical contributions to a number of facilities and projects. He proposed a new scheme for a tau-charm factory based on monochromatisation to reduce the collision energy spread, addressed a problem of limited dynamic aperture at high energies faced by CERN's LEP collider, and recommended the low-emittance option for LEP operation at the W^+ production energies.

Yuri published pioneering works on the theory of coherent beam–beam oscillations and their stabilisation with Landau damping, laying the foundation for a parameter optimisation of the LHC. Among many other highlights, Yuri ingeniously predicted the loss of Landau damping for the two beams colliding in the LHC, derived analytical formulae describing the emittance growth in collision with transverse feedback and noise, and produced some of the most thought-provoking articles related to the LHC design.

R Hahn/Fermilab



Yuri played a critical role in the luminosity increases at the Tevatron.

In 2000, Yuri joined Fermilab's accelerator division, where he made seminal contributions to the theory of nonlinear beam–beam compensation by electron lenses and was deeply engaged in Run II of the Tevatron, playing a critical role in the luminosity increases of what was then the world's most powerful accelerator. Widely recognised is Yuri's leading role in the design and implementation of optimal helical orbits to minimise Tevatron beam–beam effects at injection, acceleration and squeeze, and his optimisation of the beam lifetime at injection energy via reduction of the differential chromaticity.

From 2007 to 2018 Yuri led the accelerator theory group at Fermilab. These years were another extremely productive period, as he steered the interaction-region lattice development for an energy-frontier muon collider within the US Muon Accelerator Program. He also invented the so-called "helical FOFO-snake" muon ionisation cooling channel concept. Yuri was closely involved in the operation and upgrade of the existing Fermilab accelerator complex and in other intensity-frontier accelerators worldwide. Not only was he actively taking part in many experimental beam studies, but he also proposed new theoretical and numerical algorithms for space-charge dominated beams, for the Landau damping of beam instabilities provided by electron lenses and for novel space-charge compensation techniques.

Yuri will be remembered by his colleagues, friends and family as a highly intelligent, kind and soft-spoken person. An excellent mentor, he generously shared his knowledge with students and younger colleagues, and many world-renowned physicists are happy to call him their teacher. While being a workaholic, in his leisure time he loved to ski and was an avid sports fan.

Vladimir Shiltsev and Alexander Valishev *Fermilab,* **Frank Schmidt and Frank Zimmermann** *CERN.*

Paul Murphy 1930–2020

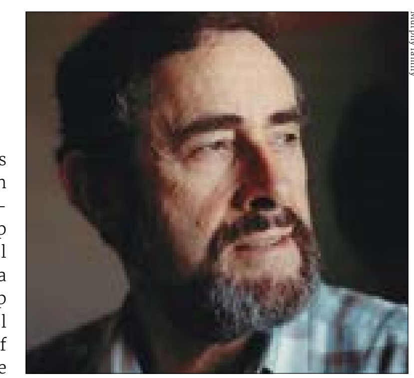
A sharp physics mind

Leading member of the UK particle-physics community, Paul Murphy, passed away on 26 August. Paul was a keen and brilliant physicist who was head of the particle-physics group at the University of Manchester from 1965 until his retirement in 1990. He started his PhD as a Fulbright Scholar theoretician in Fermi's group in Chicago, but later discovered that his real talent lay in experimentation. Styling himself as a "gas and glue" man, Paul was one of the few physicists at the time who could design and make spark chambers that worked.

He then went to Liverpool to work on the 400 MeV cyclotron before joining the Rutherford Laboratory and going to UC Berkeley to study hyperons at the 6 GeV Bevatron. On returning in the early 1960s, he and John Thresher carried out a series of experiments to determine the spin-parity of pion–nucleon resonances, for which they were awarded the Rutherford medal and prize by the UK Institute of Physics.

Aged only 34, Paul moved to Manchester to become a professor, heading up the newly formed high-energy physics group. As well as leading the group into two experiments at the new electron synchrotron, NINA, at the Daresbury Laboratory, he spearheaded the development of particle detectors at Manchester and built the group's strong reputation in this area. First were the wire spark chambers with digital instead of photographic readout, a version of which was then used in the CERN, Holland, Lancaster, Manchester (CHLM) experiment that concentrated on proton–proton diffraction scattering at the CERN ISR facility. Paul then led the group developing (quieter) large-area drift chambers that were used to detect muons, first at the JADE experiment at DESY, which helped to discover the gluon, and then at LEP's OPAL experiment at CERN. His sharp physics mind led him to be a pioneer at the start of each new accelerator facility, for instance realising the potential for NINA to produce a useable beam of neutral kaons.

Murphy family



Murphy was a long-time leader of particle physics at the University of Manchester.

Paul was a firm believer in making the most of wherever he found himself. He played a major role in national and international particle physics, chairing and contributing to many strategic decision-making bodies. He was also an engaging educator at all levels, often livening up his lectures with many anecdotes.

Paul was a passionate humanitarian and loved people; he wanted to show everyone he met that he valued them, for example, by learning how to welcome them in their own language. His insight into people and physics alike was extraordinary, and his penchant for making a little friendly mischief never far from the surface.

His family, friends and colleagues.

CERNCOURIER
Volume 61 Number 1 January/February 2021
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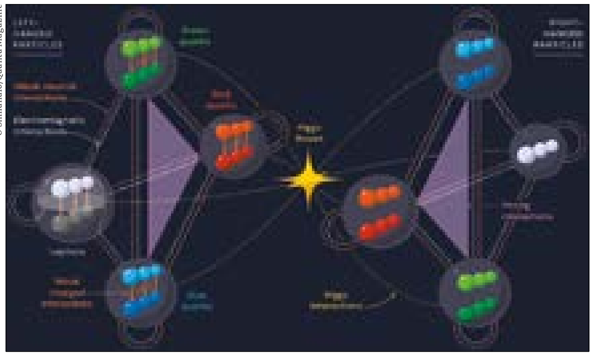
BACKGROUND

Notes and observations from the high-energy physics community

Return of the double simplex


© Shmahalo/Quanta Magazine

It's the Standard Model, Jim, but not as we know it.

Popular representations of the Standard Model (SM) often hide its beautiful weirdness, for example slotting quarks and leptons into boxes and arranging them like a low-grade Mendeleev, or contriving a dartboard arrangement. The "double simplex" scheme invented in 2005 by US theorist Chris Quigg, which was recently given a flashy makeover by *Quanta* magazine (above), is much richer (arXiv:hep-ph/0509037).

Jogesh Pati and Abdus Salam's suggestion, in their 1974 shot at a grand unified theory, that lepton number be regarded as a fourth colour, inspired Quigg to place the leptons at the fourth point of an SU(4) tetrahedron. The additional edges therefore represent possible leptoquark transitions. Left-handed fermion doublets (left) are reflected in the broken mirror of parity to reveal right-handed fermion singlets (right), though *Quanta*, unlike Quigg perhaps favouring a purely left-handed Majorana mass term, omit possible right-handed neutrinos.

A final distinction is that Quigg chooses to superimpose the left and right simplexes – a term for a generalised triangle or tetrahedron in an arbitrary number of dimensions – while *Quanta* elects to separate the tetrahedra, and label couplings to the Higgs boson with sweeping loops. This obscures a beautiful feature of Quigg's design, whereby the Yukawa couplings hypothesised by the SM, which couple the left- and right-handed incarnations of massive fermions in interactions with the Higgs field, link opposite corners of the superimposed double simplex, placing the Higgs boson at the centre of the picture. Quigg, who intended that the double simplex precipitate questions, also points out that the corners of the superimposed tetrahedra define a cube, whose edges suggest a possible new category of feeble interactions yet to be discovered.

Crossword solution

Congratulations to Holly Pacey of the University of Cambridge and ATLAS, who wins a *Courier* mug for submitting the first correct solution to the brainteaser on p58 of the November/December edition.

Across: 1 drop in the bucket, 8 muon, 9 EPICS, 10 ket, 13 RA, 14 Luca Parmitano, 15 Xe, 16 Sv, 17 toast, 19 Hubble, 20 horn, 22 naive, 23 Ar, 25 KOTO, 26 IR, 27 Brookhaven, 28 Aa, 29 Xi, 30 ET, 32 gadolinium, 33 CERN

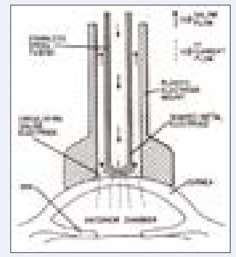
Down: 1 Dr, 2 proscribe, 3 Ne, 4 Hyper Kamiokande, 5 back in the saddle, 6 KEK, 7 Tata, 8 molecular, 11 Eros, 12 RAM, 17 ten, 18 anyon, 21 niobium, 24 bra, 25 KE, 26 ITER, 27 BaBar, 31 CNO

From the archive: January/February 1981

Medicine and merrymaking

At the Los Alamos Meson Physics Facility LAMPF Users meeting in November 1980, Applications Group leader James Bradbury reported work on cancer therapy, radioisotope production, proton tomography and special instrumentation.

One rewarding innovation is a circulating saline electrode (CSE) for vision correction. Often extreme cases of refractive error in the eye cannot be treated with external lenses. Thermal modification of corneal shape has been an alternative to corneal transplant, but surface damage caused by the heating limits the technique. The CSE permits RF heating of the cornea plus epithelial cooling with a saline solution to achieve a more favourable temperature profile.



LAMPF's circulating saline electrode allows r.f. heating of the cornea to correct the error under much more favourable conditions.

● Compiled from text on pp17, 18 and 27 of *CERN Courier* Jan/Feb 1981.

Compiler's note

The contribution of physics R&D to nuclear medicine, radiotherapy and medical imaging is fairly well known, but Los Alamos is rarely associated with delicate surgical instrumentation. However, irrigated-tip electrodes, like those developed at LAMPF, are now commonly used in RF-assisted resection procedures such as cardiac ablation and the treatment of surface tissue tumours.

During these difficult days of lockdown, what better than to recall some cheerful CERN celebrations from 1980, when masks were theatrical and interpersonal distances a matter of choice. The top image shows the traditional children's Christmas party and below the Theory Division's Christmas Show.


CERN 216.12.80


CERN 539.12.80

137.035999206(11)

The latest measurement of $1/\alpha$ using rubidium atoms more than doubles the precision on this key parameter, and differs by more than 5σ from a 2018 measurement with caesium, modifying constraints on dark-matter particles such as those proposed to explain the Atomki anomaly (*Nature* 588 61).

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