WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2024 issue of *CERN Courier*.

The mid-term report of the Future Circular Collider (FCC) feasibility study demonstrates significant progress across all project deliverables, including physics opportunities, the placement and implementation of the ring, civil engineering, technical infrastructure, accelerators, detectors and cost (pp25–38). While further work is to be done, no technical showstoppers have been found. From the perspective of the technical schedule alone, operations of the Higgs, electroweak and top factory FCC-ee could start in the early 2040s.

In China, a technical design report for the Circular Electron–Positron Collider demonstrates significant progress towards a facility that could operate in the second half of the 2030s, along with excellent prospects for approval and funding (p39). Meanwhile in the US, there is renewed interest in colliding muons, for which major technology challenges remain (p45).

All proposed future colliders have a rich physics case rooted in deeper investigation of the Higgs sector, and Europe needs to move fast to minimise the gap between the LHC and the next collider at CERN (p43). If the feasibility study shows that the FCC can be afforded, then it represents the best available option for the future of CERN and particle physics.

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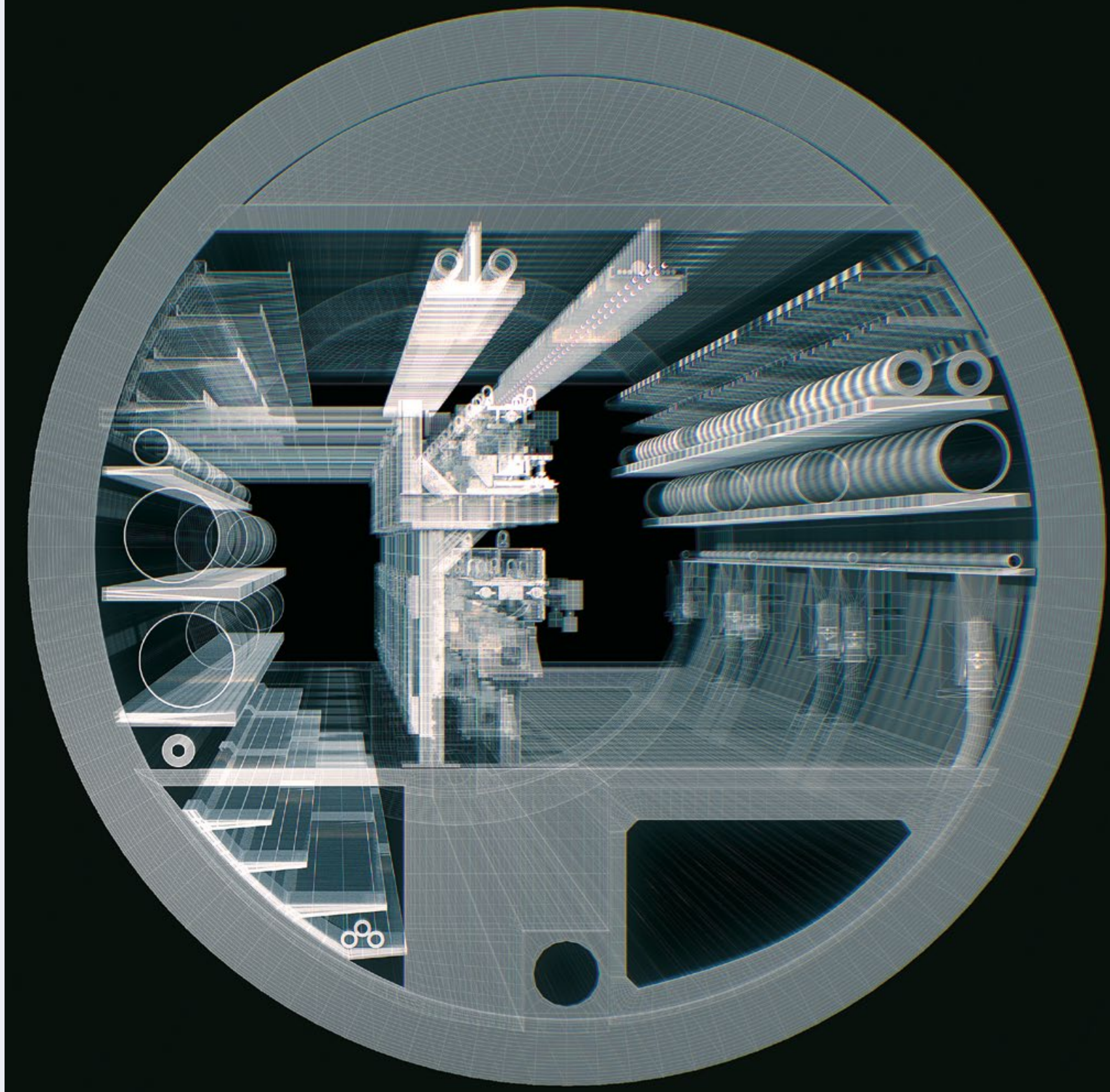
DIGITAL EDITION CREATED BY IOP PUBLISHING

CERNCOURIER
March/April 2024 cerncourier.com
Reporting on international high-energy physics

DESIGNS ON THE FUTURE



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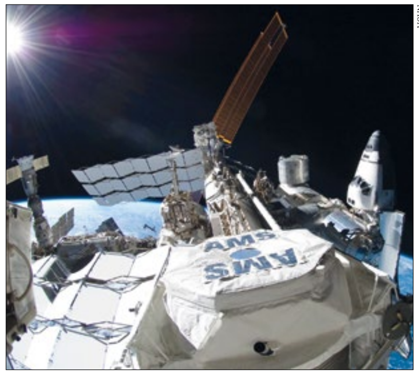
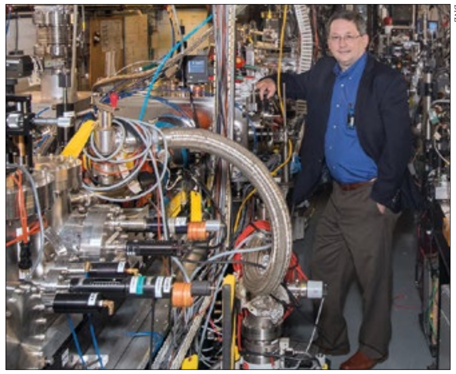

NASA

Space odyssey *AMS prepares for a major upgrade to its tracking system.* **7**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Muon shot *Mark Palmer addresses the challenges in building a muon collider.* **45**


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A year at the pole *Tales from an IceCube winterover.* **50**

FROM THE EDITOR

Towards a future collider

Matthew Chalmers
Editor

The LHC has found the Higgs boson and nothing else, leaving particle physicists with no clue as to where to go next. Really? It's time to break this tired and inaccurate narrative.

Based on a small fraction of their final expected datasets, the LHC experiments have published more than 3000 papers reporting fresh insights into the fundamental laws and constituents of the universe. That's "new physics" in a real sense. Moreover, the LHC has transformed decades of thinking about the nature of physics beyond the Standard Model. The path ahead is challenging but clear: build the most versatile and powerful exploration tool possible.

All proposed future colliders have a rich physics case rooted in deeper investigation of the Higgs sector. The lightness of the Higgs boson and the no-show so far of other new elementary particles at TeV energies make circular e^+e^- colliders an appealing alternative to linear machines. They enable significantly higher luminosity and up to four experiments, while also offering the infrastructure for a subsequent hadron collider.

This issue (pp25–38) digests the mid-term report of the Future Circular Collider (FCC) feasibility study, a review of which was completed in February. While further work is to be done, no technical showstoppers have been found. The technology pathways for the future hadron collider, FCC-hh, are being defined. For the lepton stage, FCC-ee, the design is advancing quickly. From the perspective of the technical schedule alone, operations could start in the early 2040s.

In China, a technical design report for the Circular Electron–Positron Collider demonstrates significant progress towards a facility that could operate in the second half of the 2030s, along with excellent prospects for approval and funding (p39). Meanwhile in the US, there is renewed interest in colliding muons, for which major technology challenges remain. If they can be mastered, a muon collider offers an interesting path towards high-energy lepton colliders (p45).

Europe needs to move fast to minimise the gap between the LHC and the next collider at CERN

Europe needs to move fast to minimise the gap between the LHC and the next collider at CERN. It is therefore hoped that the FCC feasibility study can be completed as soon as possible, to be considered in full during the next European strategy update (p43). Beyond resources, the project's success requires strong support and boldness within the community. The cost of FCC-ee, estimated at CHF 15 billion, would be spread out over a period of at least 15 years, while independent analyses show that the socio-economic returns of the FCC would far outweigh its cost.

Work in progress *An artist's impression of a future hadron collider.*

As for timescales and approvals, colliders are once-in-a-generation efforts and few had an easy ride. It was 1977 when then-DG John Adams insisted that the LEP tunnel be made large enough to host a possible future hadron collider. The physics case for the nascent LHC was made in 1984, after which it took some 10 years to be approved and 25 years for the magnets to be developed and installed. The first proposal for LEP was refused by the CERN Council on account of its size and cost. The SPS had an even trickier birth. Making the case for the future SPS in these pages in August 1964, Mervyn Hine of the directorate for applied physics wrote: "The scientific case for Europe's continuing forcefully in high-energy physics is overwhelming; the equipment needed is technically feasible; the scientific manpower needed will be available; the money is trivial. Only conservatism or timidity will stop it."

Financing the next flagship collider at CERN might no longer be considered trivial, but if the feasibility study shows that the FCC can be afforded then it represents the best available option for the future of CERN and particle physics.

Reporting on international high-energy physics

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

IOP Publishing

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Produced for CERN by IOP Publishing Ltd No.2 The Distillery, Glassfields, Avon Street Bristol BS2 0GR Tel +44 (0)117 929 7481

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Advertising Tel +44 (0)117 930 1026 (for UK/Europe display advertising) or +44 (0)117 930 1164 (for recruitment advertising); e-mail sales@cerncourier.com

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

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

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

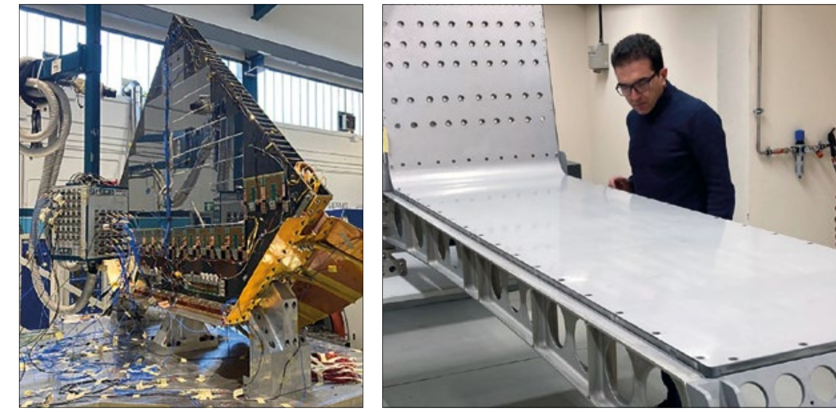
ISSN 0304-288X

NEWS ANALYSIS

Cosmic rays

AMS upgrade seeks to solve cosmic conundrum

Since being delivered to the International Space Station (ISS) by Space Shuttle *Endeavour* in 2011, the Alpha Magnetic Spectrometer (AMS-02) has recorded more than 200 billion cosmic-ray events with energies extending into the multi-TeV range. Although never designed to be serviceable, a major intervention to the 7.5 tonne detector in 2019/2020, during which astronauts replaced a failing cooling system, extended the lifetime of AMS significantly (*CERN Courier* March/April 2020 p7). Now, the international collaboration is preparing a new mission to upgrade the detector itself, by adding an additional tracker layer and associated thermal radiators. If all goes to plan, the upgrade will allow physicists to gather key data relating to a mysterious excess of cosmic rays at high energies.

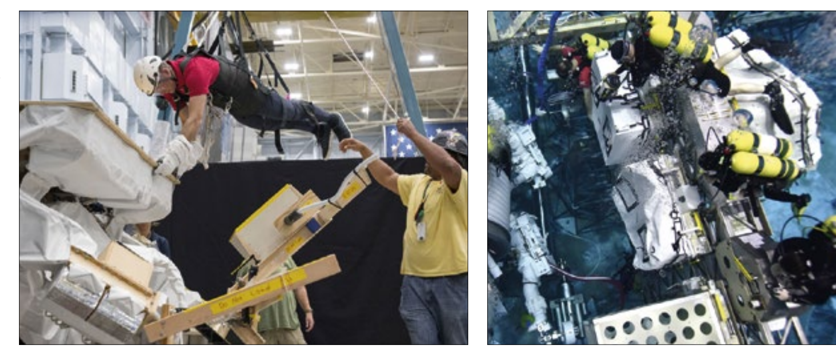


D Perez

On schedule *Vibration tests of a quarter of the new tracker layer taking place at INFN PG/SERMS Terni in Italy (left), and AMS chief engineer Corrado Gargiulo inspecting the prototype PDS radiator at CERN.*

Precise dataset

The increasingly precise AMS-02 dataset reveals numerous unexplained features in cosmic-ray spectra (*CERN Courier* December 2016 p26). In particular, a high-energy excess in the relative positron flux does not follow the single power-law behaviour expected from standard cosmic-ray interactions with the interstellar medium. While known astrophysical sources such as pulsars cannot yet be ruled out, the spectrum fits well to dark-matter models. If the excess events are indeed due to the annihilation of dark-matter particles, a smoking gun would be a high-energy cut-off in the spectrum. By increasing the AMS acceptance by 300%, the addition of a new tracker layer is the only way that the experiment can gather the necessary data to test this hypothesis before the scheduled decommissioning of the ISS in 2030.



C Gargiulo/NASA

Space choreography *AMS access-verification and extravehicular activities training taking place at NASA's Johnson Space Center (left) and Neutral Buoyancy Lab (right).*

"By 2030 AMS will extend the energy range of the positron flux measurement from 1.4 to 2 TeV and reduce the error by a factor of two compared to current data," says AMS spokesperson Sam Ting of MIT. "This will allow us to measure the anisotropy accurately to permit a separation between dark matter and pulsars at 99.93% confidence."

> **By 2030 AMS will extend the energy range of the positron flux measurement from 1.4 to 2 TeV and reduce the error by a factor of two**

Led by MIT, and assembled and tested at CERN/ESA with NASA support, AMS is a unique particle-physics experiment in space. It consists of a transition radiation detector to identify electrons and positrons, a permanent magnet together with nine silicon-tracker layers to measure momentum and identify different particle species, two banks of time-of-flight counters, veto counters, a ring-image Cherenkov counter and an electromagnetic calorimeter.

The additional tracker layer, 2.6 m in diameter, 30 cm thick and weighing 250 kg, will be installed on the top-most part of the detector. The tracking sensors will populate the opposite faces of an ultralight carbon plane specifically developed for AMS to fulfil thermoelastic stability requirements, surrounded by an octagonal carbon frame that also provides the main structural interface during launch. The powering and readout ▷

electronics for the new layer will generate additional heat that is rejected to space by radiators at its periphery. Two new radiators will therefore be integrated into the detector prior to the installation of the layer, while a third, much larger power-distribution radiator (PDS) will also be installed to recuperate the performance of one of the AMS main radiators, which has suffered degradation and radiation damage after 13 years in low-Earth orbit. In January, a prototype of the PDS, manufactured and supported by aerospace company AIDC in Taiwan, was delivered to CERN for tests.

First steps for the upgrade took place in 2021, and the US Department of Energy together with NASA approved the mission in March 2023. The testing of components and construction of prototypes at institutes around the world is proceeding quickly in view of a planned launch in February 2026. The silicon strips, 8 m^2 of which will cover both faces of the layer, were produced by Hamamatsu and are being assembled into "ladders" of different lengths at IHEP in Beijing. These are then shipped to INFN Perugia in Italy, where they are joined together to form a quarter plane. Once fully characterised, the eight quarters will be installed at CERN on both faces of the mechanical plane and integrated with electronics, thermal hardware and the necessary brackets. Crucial for the new tracker layer to survive the harsh launch environment and to maintain, once in orbit, the sensor within five microns relative to ground measurements, are the large carbon plane and the shielding cupolas, developed at CERN, as well as the NASA brackets that will attach the layer module to AMS. This hardware represents a major R&D programme in its own right.

The testing of components and the construction of prototypes at institutes around the world is proceeding quickly

Following the first qualification model in late 2023, consisting of a quarter of the entire assembled layer, AMS engineers are now working towards a full-size model that will take the system closer to flight. The main tests to simulate the environment that the layer will experience during launch and once in orbit are vibrational and thermal-vacuum, to be performed in Italy (INFN PG) and in Germany (IABG), while the sensors' position in the layer will be fully mapped at CERN and then tested with beams from the SPS, explains AMS chief engineer Corrado Gargiulo of CERN: "Everything is going very, very fast. This is a requirement, otherwise we arrive too late at the ISS for the upgrade to make sense."

The new module is being designed to fit snuggly into the nose of a SpaceX Dragon rocket. Once safely delivered to the ISS, a robotic arm will dispatch the module to AMS where astronauts will, through a series of extravehicular activities (EVAs), perform the final mounting. Training for the delicate EVAs is well underway at NASA's Johnson Space Center. Nearby, at the Neutral Buoyancy Laboratory, the astronauts are trained in a large swimming pool on how to attach the different components under the watchful eyes of safety and NASA divers, among them Gargiulo (see "Space choreography" images). As with the EVAs required to replace the cooling system, a number of custom-built tools and detailed procedures have to be developed and tested.

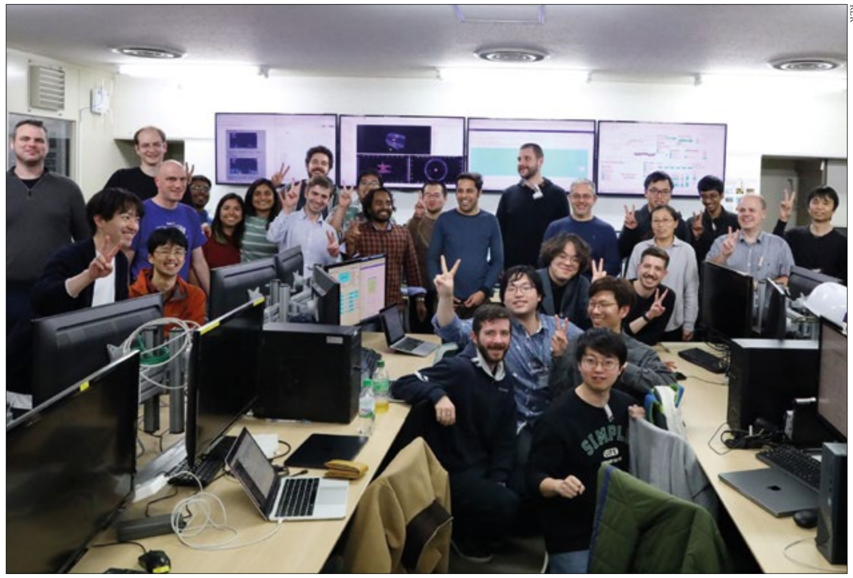
"If the previous ones were considered high-risk surgery, the EVAs for the new upgrade are unprecedented for the several different locations where astronauts will be required to work in much tighter and less accessible spaces," explains Ken Bollweg, NASA manager of AMS, who is leading the operations aspect.

KEK

Belle II is back in business

On 20 February the Belle II detector at SuperKEKB in Japan recorded its first e^+e^- collisions since summer 2022, when the facility entered a scheduled long shutdown. During the shutdown, a new vertex detector incorporating a fully implemented pixel detector, together with an improved beam pipe at the collision point, was installed to better handle the expected increases in luminosity and backgrounds originating from the beams. Furthermore, the radiation shielding around the detector was enhanced, and other measures to improve the data-collection performance were implemented.

Belle II, for which first collisions were recorded in the fully instrumented detector in March 2019, aims to uncover new phenomena through precise analysis of the properties of B mesons and other particles produced by the SuperKEKB accelerator. Its long-term goal is to accumulate a dataset 50 times larger than that of the former Belle experiment.



KEK

All smiles *Run 2 gets under way in the Belle II control room on 20 February.*

CERN

Beams back for a bumper year

As winter bids farewell, the recommissioning of the CERN accelerator complex is gathering pace, with diverse communities eagerly awaiting particle beams in their experiments. Following the year-end technical stop, beam entered Linac4 on 5 February, two days ahead of schedule. It was then sent to the PS Booster and reached the PS on 21 February. Following SPS beam commissioning beginning in March, the first particle beams are scheduled to enter the LHC on 11 March, initially with one to a few bunches at most.

The expectations for 2024 are high. For the LHC, the focus is on proton–proton luminosity production, aiming at an unprecedented accumulation of up to 90 fb^{-1}. This, together with the luminosity forecast for the 2025 run, should provide a sizeable analysis dataset to keep physicists busy during Long Shutdown 3. The 2024 LHC run will conclude with lead–lead collisions, scheduled from 6 to 28 October.

CERN

And they're off *Linac4's fixed display showing the beam's electrical current.*

The injector chain also has an ambitious year ahead, serving a busy fixed-target programme. Physics is set to start in the PS East Area on 22 March, followed by the PS n_TOF facility on 25 March. Physics in ISOLDE, downstream of the PS Booster, will start on 8 April, followed by the SPS North Area on 10 April. The antimatter factory is set to start delivering antiprotons to its experiments on 22 April, while the AWAKE facility will run for 10 weeks and the SPS HiRadMat facility for four one-week runs.

Beyond this busy physics programme, many machine development studies and tests are planned in all the machines. One of these tests will take place between mid-March and early June to configure the Linac3 source to produce magnesium ions, which will be accelerated in Linac3, injected into LEIR, and possibly even into the PS. This test will help assess the feasibility and performance of magnesium beams in the accelerator complex, for potential future applications in the LHC and the SPS North Area.

As the countdown to 11 March continues, the operations and expert teams are working diligently to prepare the machines and the beams for another successful physics run.

CLOUD

Iodine vapours impact climate modelling

Climate models are missing an important source of aerosol particles in polar and marine regions, according to new results from the CLOUD experiment at CERN. Atmospheric aerosol particles exert a strong net cooling effect on the climate by making clouds brighter and more extensive, thereby reflecting more sunlight back out to space. However, how aerosol particles form in the atmosphere remains poorly understood, especially in polar and marine regions.

The CLOUD experiment, located in CERN's East Area, maintains ultra-low contaminant levels and precisely controls all experimental parameters affecting aerosol formation growth under realistic atmospheric conditions. During the past 15 years, the collaboration has uncovered new processes through which aerosol particles form from mixtures of vapours and grow to sizes where they can seed cloud droplets. A beam from the Proton Synchrotron simulates, in the CLOUD chamber, the ionisation from galactic cosmic rays at any altitude in the troposphere.

CERN-PHOTO-202303-068-2

Enhancement *A new quartz flow-tube system called FLOTUS was added to the CLOUD experiment in 2023 to allow pre-ageing of organic vapours before injection into the chamber.*

Globally, the main vapour driving particle formation is thought to be sulphuric acid, stabilised by ammonia. However, ammonia is frequently lacking in polar and marine regions, and models generally underpredict the observed particle-formation rates. The latest CLOUD study challenges this view, by showing that iodine oxoacids can replace the role of ammonia and act synergistically with sulphuric acid to greatly enhance particle-formation rates.

"Our results show that climate models need to include iodine oxoacids along with sulphuric acid and other vapours," says CLOUD spokesperson Jasper Kirkby. "This is particularly important in polar regions, which are highly sensitive to small changes in aerosol particles and clouds. Here, increased aerosol and clouds actually have a warming effect by absorbing infrared radiation otherwise lost to space, and then re-radiating it back down to the surface."

The new findings build on earlier CLOUD studies which showed that iodine oxoacids rapidly form particles even in the complete absence of sulphuric acid. At iodine oxoacid concentrations that are typical of marine and polar regions (between 0.1 and 5 relative to those of sulphuric acid), the CLOUD data show that the formation rates of sulphuric acid particles are between 10 and 10,000 times faster than previous estimates.

"Global marine iodine emissions have tripled in the past 70 years due to thinning sea ice and rising ozone concentrations, and this trend is likely to continue," adds Kirkby. "The resultant increase of marine aerosol particles and clouds, suggested by our findings, will have created a positive feedback that accelerates the loss of sea ice in polar regions, while simultaneously introducing a cooling effect at lower latitudes. The next generation of climate models will need to take iodine vapours and their synergy with sulphuric acid into account."

Further reading

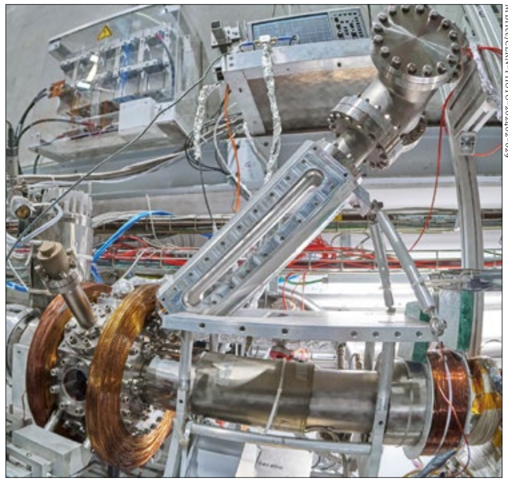
X-C He *et al.* 2023 *Science* **382** 1308.

ANTIMATTER

The promise of laser-cooled positronium

Consisting only of an electron and a positron, positronium (Ps) offers unique exploration of a purely leptonic matter–antimatter system. Traditionally, experiments have relied on formation processes that produce clouds of Ps with a large velocity distribution, limiting the precision of spectroscopic studies due to the large Doppler broadening of the Ps transition lines. Now, after almost 10 years of effort, the AEgIS collaboration at CERN's Antiproton Decelerator has experimentally demonstrated laser-cooling of Ps for the first time, opening new possibilities for antimatter research.

"This is a breakthrough for the antimatter community that has been awaited for almost 30 years, and which has both a broad physics and technological impact," says AEgIS physics coordinator Benjamin Rienacker of the University of Liverpool. "Precise Ps spectroscopy experiments could reach the sensitivity to probe the gravitational interaction in a two-body system (with 50% on-shell antimatter mass and made of point-like particles) in a cleaner way than with antihydrogen. Cold ensembles of Ps could also enable Bose–Einstein condensation of an antimatter compound system that provides a path to a coherent gamma-ray source, while allowing precise measurements of the positron mass and fine structure constant, among other applications."


M Brice/CERN-PHOTO-202402-029

Opening doors *The primary goal of the Antimatter Experiment: gravity, Interferometry, Spectroscopy (AEgIS) is to directly measure the effect of Earth's gravitational field on antiatoms.*

Laser cooling, which was applied to antihydrogen atoms for the first time by the ALPHA experiment in 2021 (*CERN Courier* May/June 2021 p9), slows atoms gradually during the course of many cycles of photon absorption and emission. This is normally done using a narrowband laser, which emits light with a small frequency range. By contrast, the AEgIS team uses a pulsed alexandrite-based laser with high intensity, large bandwidth and long pulse duration to meet the cooling requirements. The system enabled the AEgIS team to decrease the temperature of the Ps atoms from 380 K to 170 K, corresponding to a decrease in the transversal component of the Ps velocity from 54 to 37 km s^{-1}.

The feat presents a major technical challenge since, unlike antihydrogen, Ps is unstable and annihilates with a lifetime of only 142 ns. The use of a large bandwidth laser has the advantage of cooling a large fraction of the Ps cloud while increasing the effective lifetime, resulting in a higher amount of Ps after cooling for further experimentation.

"Our results can be further improved, starting from a cryogenic Ps source, which we also know how to build in AEgIS, to reach our dream temperature of 10 K or lower," says AEgIS spokesperson Ruggero Caravita of INFN–TIFPA. "Other ideas are to add a second cooling stage with a narrower spectral bandwidth set to a detuning level closer to resonance, or by coherent laser cooling."

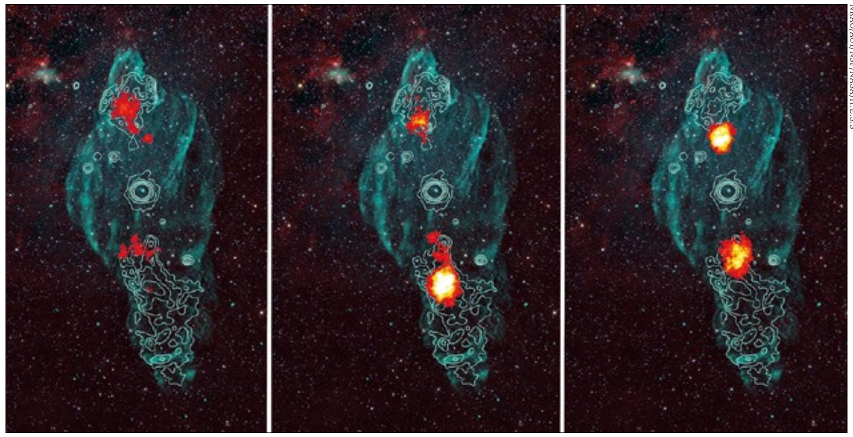
Further reading

AEgIS Collab. 2024 *Phys. Rev. Lett.* **132** 083402.

ASTROWATCH

Potent accelerators in microquasar jets

Supernova remnants (SNRs) are excellent candidates for the production of galactic cosmic rays. Still, as we approach the "knee" region in the cosmic-ray spectrum (in the few-PeV regime), other astrophysical sources may contribute. A recent study by the High Energy Stereoscopic System (H.E.S.S.) observatory in Namibia sheds light on one such source, called SS 433, a microquasar located nearly 18,000 light-years away. It is a binary system formed by a compact object, such as a neutron star or a stellar-mass black hole, and a companion star, where the former is continuously accreting matter from the latter and emitting relativistic jets perpendicular to the accretion plane.


NRAO/AUI/NSF/NASA/H.E.S.S

High energy *Composite images showing gamma-ray emission (red) from SS 433 in low (left), intermediate (middle) and high (right) energy ranges. Radio observations (green) display the Manatee Nebula, with the microquasar visible as a bright dot near the centre of the image.*

The jets of SS 433 are oriented perpendicular to our line of sight and constantly distort the SNR shell (called W50, or the Manatee Nebula) that ▷

was created during the black-hole formation. Radio observations reveal the precessing motion of the jets up to 0.3 light-years from the black hole, disappearing thereafter. At approximately 81 light-years from the black hole, they reappear as collimated large-scale structures in the X- and gamma-ray bands, termed "outer jets". These jets are a fascinating probe into particle-acceleration sites, as interactions between jets and their environments can lead to the acceleration of particles that produce gamma rays.

Excellent resolution

The H.E.S.S. collaboration collected and analysed more than 200 hours of data from SS 433 to investigate the acceleration and propagation of electrons in its outer jets. Being an imaging air-shower Cherenkov telescope, H.E.S.S. offers excellent energy and angular resolutions. The gamma-ray image showed two emission regions along the outer jets, which overlap with previously observed X-ray sources. To study the energy dependence of the emission, the full energy range was split into three parts, indicating that the highest energy emission is concentrated closer to the central source, i.e. at the base of the outer jets. A proposed explanation for the observations is that electrons are accelerated to TeV energies, generate high-energy gamma rays via inverse Compton scattering, and subsequently lose energy as they propagate outwards to generate the observed X-rays.

Monte Carlo simulations modelled the morphology of the gamma-ray emission and revealed a significant deceleration in the velocity of the outer jets at their bases, indicating a possible shock region. With a lower limit on the cut-off energy for electron injection into this region, the acceleration energies were found to be > 200 TeV at 68% confidence level. Additionally, protons and heavier nuclei can also be accelerated in these regions and reach much higher energies as they are affected by weaker energy losses and carry higher total energy than electrons.

These jets are a fascinating probe into particle-acceleration sites

SS 433 is, unfortunately, ruled out as a contributor to the observed cosmic-ray flux on Earth. Considering the age of the system to be 30,000 years and proton energies of 1 PeV, the distance traversed by a cosmic-ray particle is much smaller than even the lowest estimates for the distance to SS 433. Even with a significantly larger galactic diffusion coefficient or an age 40 times older, it remains incompatible with other measurements and the highest estimate on the age of the nebula. While proton acceleration does occur in the outer jets of SS 433, these particles don't play a part in the cosmic-ray flux measured on Earth.

This study, by revealing the energy-dependent morphology of a galactic microquasar and constraining jet velocities at large distances, firmly establishes shocks in microquasar jets as potent particle-acceleration sites and offers valuable insights for future modelling of these astrophysical structures. It opens up exciting possibilities in the search for galactic cosmic-ray sources at PeV energies and extragalactic ones at EeV energies.

Further reading

H.E.S.S Collab. 2024 *Science* **383** 402.

NEWS DIGEST

M Kapust, Sanford Underground Research Facility

The excavated DUNE cavern.

DUNE caverns complete

In February, excavation workers at SURF, South Dakota finished carving out the future home of the gigantic DUNE detectors, which are scheduled to operate in 2028. Since construction began in 2021, roughly 800,000 tonnes of rock have been removed and transported 1.5 km to the surface. Overall, four large liquid-argon detectors will be placed in the caverns, where they will measure neutrino beams sent 1300 km through Earth from Fermilab. In January the LBNF/DUNE project passed another milestone with the delivery of steel components for the detector cryostats, which were manufactured and tested in Spain on behalf of CERN.

South Africa digs deep

Africa's first deep-underground science laboratory could become a reality in the next five to 10 years, following the launch of a feasibility study for the Paarl Africa Underground Laboratory (PAUL) in South Africa's Western Cape. After almost a decade of consideration, in December the South Africa department of science allocated funding to explore the viability of an underground laboratory with a volume of about 10,000 m^3. PAUL would take advantage of a planned expansion of the Huguenot road tunnel through Du Toits Kloof Mountain and complement existing astronomy facilities in South Africa such as MeerKAT, SKA and HERA. Constituting only the second underground lab in the Southern hemisphere, it could also host dark-matter experiments complementary to those in the Northern hemisphere (arXiv:2306.12083).

LHCb opens up

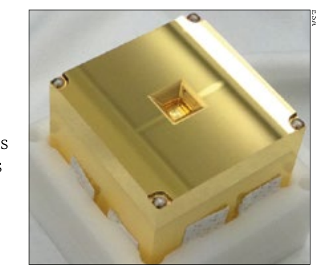
In line with CERN's open-data policy, the LHCb collaboration has released its full Run 1 dataset to the world. While all scientific results were already publicly available via open-access papers, the full release includes the data (collected in 2011 and 2012) that was used to produce many of them. The approximately 800 TB dataset encompasses raw data as well as processed event displays, a glossary, documentation and metadata. With dedicated LHCb algorithms, including the provision of pre-filtered data suitable for a wide range of physics studies, the beauty of LHC physics can now be explored by anyone.

Dark Energy Survey

Having scanned more than 300 million distant galaxies from 2013 to 2019, the Dark Energy Survey (DES) has released its final results (arXiv:2401.02929). Among them are new measurements of the accelerating expansion of the universe based on the observation of 1499 type 1a supernovae – the largest supernova sample compiled by a single telescope. The measurements, which employed novel photometry and machine-learning techniques, agree with the standard cosmological model. But further data, for example from the upcoming Vera C. Rubin Observatory, are needed to rule out more complex models. The 570-megapixel DES camera was built by Fermilab and mounted on the Víctor M. Blanco Telescope in Chile, from where it scanned almost an eighth of the sky.

LISA construction launched

On 25 January, the European Space Agency gave the go-ahead to build the instruments and spacecraft for the Laser Interferometer Space Antenna (LISA). Work will start in January 2025 once a European industrial contractor has been chosen, with a planned launch date of 2035 on an Ariane 6 rocket. LISA is a triangular constellation of three spacecraft spaced 2.5 million km apart that will trail Earth in its orbit around the Sun. Each contains a pair of solid gold-platinum cubes in free-fall, the relative separation of which changes due to passing gravitational waves. The vast length of the interferometer arms will enable LISA to detect signals beyond the reach of ground-based observatories allowing, for example, the study of lower-mass supernovae, mergers of hyper-dense stars and stellar-mass black holes.



ESA

A LISA test mass.

FAIRness at HORIZON-ZEN

Established at CERN a decade ago, the Zenodo data repository has stored scientific data for ever more research communities (notably providing a platform to efficiently share results, datasets and software during the COVID-19 pandemic) and today is used by more than 8000 research organisations. A new European project launched last year aims to take Zenodo to the next level and make it a prime repository for European Union (EU) research data. HORIZON-ZEN is the latest in a series of projects funded by the EU to make the data collected by European research more findable, accessible, interoperable and reusable (FAIR), in compliance with Horizon Europe requirements. The project aims to make FAIR simpler and more streamlined for researchers, and to establish best practices of FAIR data principles.

Extreme QED test

Quantum electrodynamics (QED) is one of the best-tested theories in physics, but most tests so far have been performed at relatively low field strengths and with light atoms and ions. In the realm of very strong electromagnetic fields such as in the heaviest highly charged ions, QED calculations enter a qualitatively different, non-perturbative regime where the predictions are only partially tested. Using the Experimental Storage Ring at GSI Darmstadt, researchers have now performed a measurement on relativistic uranium ions with different charge states that is sensitive to such higher-order QED effects. The experimental result can discriminate between several state-of-the-art theoretical approaches and provides an important benchmark for calculations in the strong-field domain (*Nature* **625** 673).

Fixed lines in the SPS

Resonances are frequent in nature when an external force perturbs an oscillatory dynamical system. In particle accelerators resonances can cause particles to go off track, resulting in beam loss and off-target hits. Accelerator physicists at GSI and CERN have now obtained first experimental evidence for a special kind of accelerator resonance structure called fixed lines. After many years of experimental investigations, they observed a second order coupled resonance by inducing transverse oscillations of proton beams in CERN's SPS and studying how third-order resonances affected beam particles. A deeper understanding of resonance structures in phase space could enable physicists to achieve more intense and brighter beams for both current and future accelerator projects (doi:10.21203/rs.3.rs-2371173/v1).

CERNCOURIER
Volume 64 Number 2 March/April 2024
IOP Publishing

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Electroweak SUSY after LHC Run 2

Supersymmetry (SUSY) provides elegant solutions to many of the problems of the Standard Model (SM) by introducing new boson/fermion partners for each SM fermion/boson, and by extending the Higgs sector. If SUSY is realised in nature at the TeV scale, it would accommodate a light Higgs boson without excessive fine-tuning. It could furthermore provide a viable dark-matter candidate, and be a key ingredient to the unification of the electroweak and strong forces at high energy. The SUSY partners of the SM bosons can mix to form what are called charginos and neutralinos, collectively referred to as electroweakinos.

Electroweakinos would be produced only through the electroweak interaction, where their production cross sections in proton–proton collisions are orders of magnitude smaller than strongly produced squarks and gluinos (the supersymmetric partners of quarks and gluons). Therefore, while extensive searches using the Run 1 (7–8 TeV) and Run 2 (13 TeV) LHC datasets have turned up null results, the corresponding chargino/neutralino exclusion limits remain substantially weaker than those for strongly interacting SUSY particles.

The ATLAS collaboration has recently released a comprehensive analysis of the electroweak SUSY landscape based on its Run 2 searches. Each individual search targeted specific chargino/neutralino production mechanisms and subsequent decay modes. The analyses were originally interpreted in so-called "simplified models", where only one production mechanism is considered, and only one possible decay. However, if SUSY is realised in nature, its particles will have many possible production and decay modes, with rates depending on the SUSY parameters. The new ATLAS analysis brings these pieces together by reinterpreting 10 searches in the phenomenological Minimal Supersymmetric Standard Model (pMSSM), which includes a range of SUSY particles, production mechanisms and decay modes governed by 19 SUSY parameters. The results provide a global picture of ATLAS's sensitivity to electroweak SUSY and, importantly, reveals the gaps that remain to be explored.

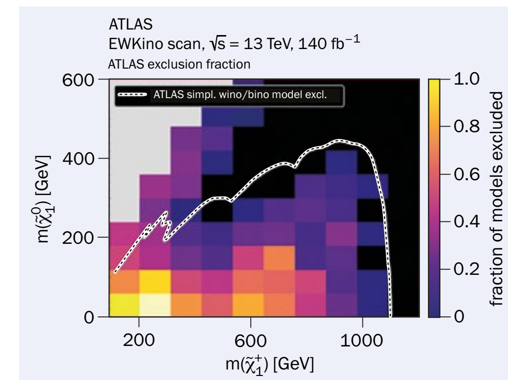


Fig. 1. *The fraction of pMSSM models excluded by ATLAS in the plane of the lightest chargino mass (x-axis) versus the lightest neutralino mass (y-axis). The dashed line shows the exclusion of simplified SUSY models reported by individual searches in this mass plane.*

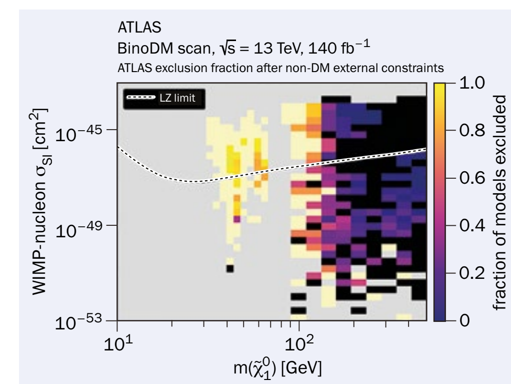


Fig. 2. *The fraction of pMSSM models excluded by ATLAS in the plane of the lightest neutralino (i.e. the dark-matter candidate) mass (x-axis) versus the spin-independent WIMP–nucleon scattering cross-section (y-axis). The dashed line shows the upper limits from the LZ experiment.*

The 19-dimensional pMSSM parameter space was randomly sampled to produce a set of 20,000 SUSY model points. The 10 selected ATLAS searches were then performed on each model point to determine whether it is excluded with at least 95% confidence level. This involved simulating datasets for each SUSY model, and re-running the corresponding analyses and statistical fits. An extensive suite of reinterpretation tools was employed to achieve this, including preserved likelihoods and RECAST – a framework for preserving analysis workflows and re-applying them to new signal models.

The results show that, while electroweakino masses have been excluded up to 1 TeV in simplified models, the coverage with regard to the pMSSM is not exhaustive. Numerous scenarios remain viable, including mass regions nominally covered by previous searches (inside the dashed line in figure 1). The pMSSM models may evade detection due to smaller production cross-sections and decay probabilities compared to simplified models. Scenarios with small mass-splittings between the lightest and next-to-lightest neutralino can reproduce the dark-matter relic density, but are particularly elusive at the LHC. The decays in these models produce challenging event features with low-momentum particles that are difficult to reconstruct and separate from SM events.

Beyond ATLAS, experiments such as LZ aim at detecting relic dark-matter particles through their scattering by target nuclei. This provides a complementary probe to ATLAS searches for dark matter produced in the LHC collisions. Figure 2 shows the LZ sensitivity to the pMSSM models considered by ATLAS, compared to the sensitivity of its SUSY searches. ATLAS is particularly sensitive to the region where the dark-matter candidate is around half the Z/Higgs-boson mass, causing enhanced dark-matter annihilation that could have reduced the otherwise overabundant dark-matter relic density to the observed value.

The new ATLAS results demonstrate the breadth and depth of its search programme for supersymmetry, while uncovering its gaps. Supersymmetry may still be hiding in the data, and several scenarios have been identified that will be targeted, benefiting from the incoming Run 3 data.

Further reading

ATLAS Collab. 2024 arXiv:2402.01392.

CMS

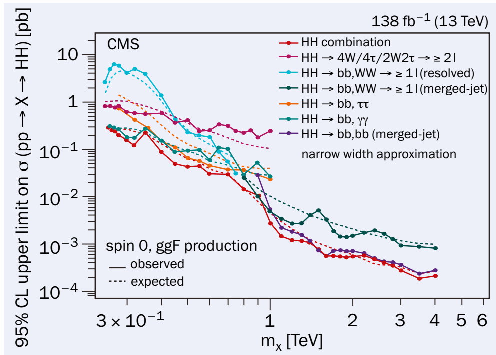
Probing resonant production of Higgs bosons

Besides being a cornerstone of the Standard Model (SM), the Higgs boson (H) opens a very powerful path to search for physics beyond the SM. In particular, in the SM there are no particles that are sufficiently heavy to decay into two Higgs bosons. Therefore, if we observe the resonant production of HH pairs, for example, we have clear evidence for the existence of new physics, as predicted by models with an extended Higgs sector.

The CMS collaboration recently conducted a search for the resonant production of Higgs-boson pairs. The analysis combines six different analyses and five HH final states, targeting H decays into b quarks, photons, τ leptons and W bosons. As figure 1 shows for a spin-0 resonance (denoted X), the combination of the decay modes covers a wide mass range, from 280 GeV to 4 TeV. While no resonant signal is observed, stringent upper limits on the $pp \to X \to HH$ cross section are obtained, which reach values of about 0.2 fb at the highest masses. These are the strongest observed limits to date for a scalar mass below 320 GeV or above 800 GeV.

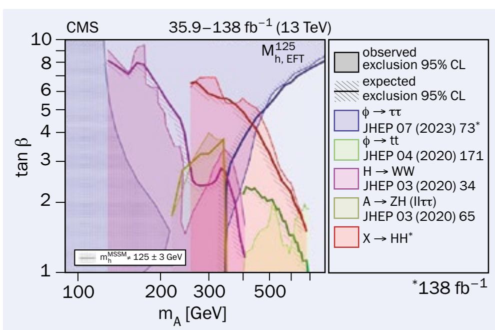
One possible candidate for such a resonance is a heavy scalar from an extended Higgs sector, as predicted in the Minimal Supersymmetric Standard Model (MSSM), which features three neutral and two charged Higgs bosons. Figure 2 shows the excluded region of the model parameter tanβ (the ratio of vacuum expectation values of the two underlying Higgs doublets) as a function of the mass of the CP-odd Higgs boson, m_A. The HH combination is sensitive up to well beyond $\tan\beta = 6$, just above the HH threshold, and its exclusion extends up to beyond 600 GeV, outperforming the lower limits from the (also shown) searches of single heavy Higgs-boson production in this mass range. Compared to other direct searches, there is unique sensitivity for $m_A > 450$ GeV and $\tan\beta < 5$.

This result is part of a recent comprehensive review article on resonant Higgs-boson production searches by the CMS collaboration, covering the VH, HH and YH final states, with V denoting a W or Z boson and Y representing an additional new boson.



Source: CMS collab.

Fig. 1. *Observed (solid lines) and expected (dotted lines) upper limits on the cross section of a spin-0 resonance times its branching fraction into a pair of Higgs bosons, as a function of its mass, for six analysis signatures and their combination (red).*



Source: CMS collab.

Fig. 2. *Interpretation of the HH combination measurement in a MSSM benchmark model, showing exclusion limits in the tanβ versus m_A plane and comparisons to other CMS results.*

Further reading

CMS Collab. 2024 (to be submitted).
E A Bagnaschi *et al.* 2021 LHCHWG-2021-001.

ALICE

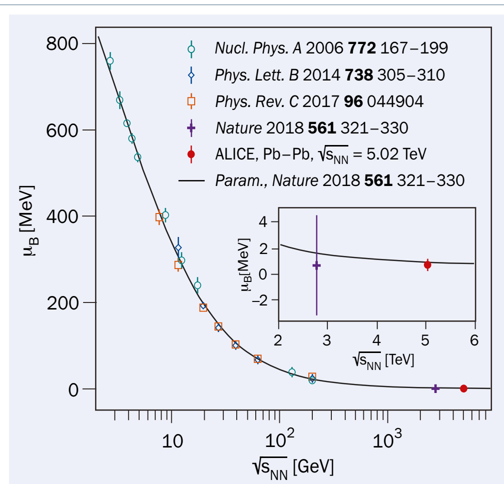
Balancing matter and antimatter in Pb–Pb collisions

When lead ions collide head-on at the LHC they deposit most of their kinetic energy in the collision zone, forming new matter at extremely high temperatures and energy densities. The hot and dense zone quickly expands and cools down, leading to the production of approximately equal numbers of particles and antiparticles at mid-rapidity. However, in reality the balance between matter and antimatter can be slightly distorted.

The collision starts with matter only, i.e. protons and neutrons from the incoming beam. During the collision process, incoming lead nuclei interact while penetrating each other, and most of their quantum numbers are carried away by particles travelling close to the beam direction. Due to strong interactions among the quarks and gluons, quantum numbers of the colliding ions are transported to mid-rapidity rather than to the ions themselves. This leads to an imbalance of baryons originating from the initial state, which has more baryons than antibaryons.

This matter–antimatter imbalance can be quantified by determining two global system properties: the chemical potentials associated with the electric charge and baryon number (denoted μ_Q and μ_B, respectively). In a thermodynamic description, the chemical potentials determine the net electric-charge and baryon-number densities of the system. Thus, μ_B measures the imbalance between matter and antimatter, with a vanishing value indicating a perfect balance.

In a new, high-precision measurement, the ALICE collaboration reports the most precise characterisation so far of the imbalance between matter and antimatter in collisions between lead nuclei at a centre-of-mass energy per nucleon pair of 5.02 TeV. The study was carried out by measuring the antiparticle-to-particle yield ratios of light-flavour hadrons, which make up the bulk of particles produced in heavy-ion collisions. The measurement using the ALICE central barrel detectors included identified charged pions, protons and multi-strange Ω^- baryons, in addition to light nuclei, ^{3}He, triton and the hypertriton (a bound state of a proton, a neutron and a Λ-baryon). The larger baryon content of these light nuclei makes them more sensitive to baryon-asymmetry effects.



Source: arXiv:2311.13332

Fig. 1. *Baryon chemical potential, μ_B, extracted from experimental data as a function of the centre-of-mass energy per nucleon pair. Data points are compared with a phenomenological parametrisation of μ_B. The inset shows μ_B extracted at two LHC energies.*

The analysis reveals that in head-on lead–ion collisions, for every 1000 produced protons, approximately 986 ± 6 antiprotons are produced. The chemical potentials extracted from the experimental data are $\mu_Q = -0.18 \pm 0.90$ MeV and $\mu_B = 0.71 \pm 0.45$ MeV. These values are compatible with zero, showing that the medium created in lead–lead collisions at the LHC is nearly electrically neutral and baryon-number-free at mid-rapidity. This observation holds for the full centrality range, from collisions where the incoming ions peripherally interact with each other up to the most violent head-on processes, indicating that quantum-number transport at the LHC is independent of the size of the system formed.

The values of μ_B are shown in figure 1 as a function of the centre-of-mass energy of the colliding nuclei, along with lower-energy measurements at other facilities. The recent ALICE result is indicated by the red solid circle, along with a phenomenological parametrisation of μ_B. The decreasing trend of μ_B observed as a function of increasing collision energy indicates that different net-baryon-number density conditions can be explored by varying the beam energy, reaching almost vanishing net-baryon content at the LHC. The inset gives the μ_B values extracted at two LHC energies. It shows that the new ALICE result is almost one order of magnitude more precise than the previous estimate (violet), thanks to a more refined study of systematic uncertainties.

The new ALICE result is almost one order of magnitude more precise than the previous estimate

The present study with improved precision characterises the vanishing baryon-asymmetry at the LHC, posing stringent limits to models describing baryon-number transport effects. Using the data samples collected in LHC Run 3, these studies will be extended to the strangeness sectors, enabling a full characterisation of quantum-number transport at the LHC.

Further reading

ALICE Collab. 2023 arXiv:2311.13332.

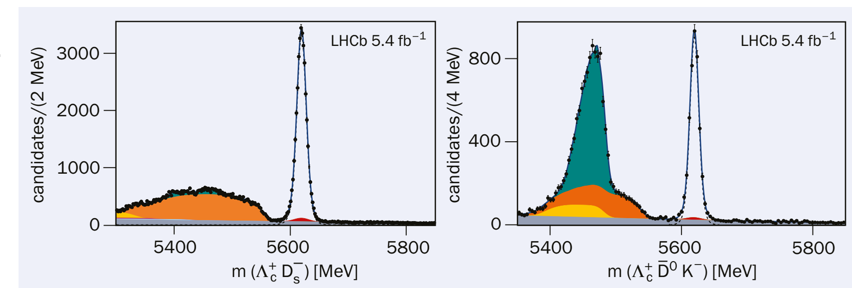
LHCb

New pentaquark searches in beauty decays

Pentaquarks, bound states of five quarks predicted in the first formulation of the quark model in 1964, have had a troubled history. Following disputed claims of the discovery of light-flavour species over 20 years ago, pentaquarks with hidden charm are now well-established members of the hadronic spectrum. The breakthrough was achieved by the LHCb experiment in 2015 with the observation of P_c^+ states in the J/ψ p system.

The P_c^+ quark content ($uudc\bar{c}$) implies that decays to two open-charm hadrons, such as $\Lambda_c^+ \bar{D}^0$ or $\Lambda_c^+ \bar{D}^{*0}$, are possible. The rates of such decays are important for understanding more about the nature of the P_c^+ states, as different models predict rates that differ by orders of magnitude. Distinguishing between the proposed mechanisms by which pentaquarks, and excited hadrons in general, are produced and bound allows a better understanding of the dynamics of the strong interaction in the non-perturbative regime.

A new analysis by LHCb of the open-charm hadrons in Λ_b decays was presented at the International Conference on Meson–Nucleon Physics and the Structure of the Nucleon, held in Mainz in October. It concerns the first observation and measurement of the branching fractions of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays using proton–proton collision data collected during LHC Run 2.



Source: LHCb-PAPER-2023-034

Fig. 1. *Invariant-mass distributions of (left) $\Lambda_c^+ D_s^-$ and (right) $\Lambda_c^+ \bar{D}^0 K^-$ candidates with the results of the fit overlaid. The exclusive Λ_b^0 decays to $\Lambda_c^+ D_s^-$ and $\Lambda_c^+ \bar{D}^0 K^-$ peak around the nominal Λ_b^0 mass of 5620 MeV. The partially reconstructed decays $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ and $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$ are shown in orange and green, while nuisance components are shown in different colours.*

All branching fractions are measured relative to the known $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ decay mode, which is reconstructed with the same set of six final-state hadrons: $p K^- \pi^+ K^+ \pi^- K^-$. Many systematic uncertainties in the measured ratios therefore cancel out, making the precision on the relative branching fraction of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$ statistically limited. For $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ the resulting branching fractions are systematically limited. This is because either a photon or neutral pion is not reconstructed, so their shape in the invariant mass spectrum of the reconstructed particles is more difficult to describe and more affected by the backgrounds (see figure 1, where the components with a missing photon for which a branching fraction is calculated are shown in orange and those with a missing neutral pion in green).

The partially reconstructed $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decay cannot be used directly to search for pentaquarks, but it is an important input to model calculations. In addition, as a two-body decay, it is a powerful test of factorisation assumptions in heavy-quark effective theory.

In the $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ decay, the production process of the P_c^+ pentaquarks is the same as in the discovery channel, $\Lambda_b^0 \to J/\psi\, p K^-$. A comparison between the measured branching fractions and observed signal yields can thus be used to estimate the expected sensitivity for observing P_c^+ signals in the open-charm channels. In particular, the rate of a Λ_b^0 decay to $\Lambda_c^+ \bar{D}^0 K^-$ is about six times greater than to $J/\psi\, p K^-$; however, more than 60 times as much data would be needed to match the currently available $\Lambda_b^0 \to J/\psi\, p K^-$ signal yield.

A factor of about 24 in this calculation comes from the branching fractions ratio of J/ψ and open-charm hadrons, given their reconstructed decay modes. The rest is from reconstruction and selection inefficiencies, which favour the four-prong $\mu^+\mu^- p K^-$ over the fully hadronic six-body final state. With the upgraded Run 3 detector and now triggerless detector readout, a large part of the inefficiency for fully hadronic final states is recoverable, making pentaquark searches in double open-charm final states more favourable compared to the situation in Run 2.

Further reading

LHCb Collab. 2023 LHCb-PAPER-2023-034.

CERNCOURIER
Volume 64 Number 2 March/April 2024
IOP Publishing

FIELD NOTES

Reports from events, conferences and meetings

CHAMONIX WORKSHOP 2024

Building on success, planning for the future

From 29 January to 1 February, the Chamonix Workshop 2024 upheld its long tradition of fostering open and collaborative discussions within CERN's accelerator and physics communities. This year marked a significant shift with more explicit inclusion of the injector complex, acknowledging its crucial role in shaping future research endeavours. Chamonix discussions focused on three main areas: maximising the remaining years of Run 3; the High-Luminosity LHC (HL-LHC), preparations for Long Shutdown 3 and operations in Run 4; and a look to the further future and the proposed Future Circular Collider (FCC).

A Valenza

Machine talk *Participants of the 2024 Chamonix Workshop.*

Immense effort

Analysing the performance of CERN's accelerator complex, speakers noted the impressive progress to date, examined limitations in the LHC and injectors and discussed improvements for optimal performance in upcoming runs. It's difficult to do justice to the immense technical effort made by all systems, operations and technical infrastructure teams that underpins the exploitation of the complex. Machine availability emerged as a crucial theme, recognised as critical for both maximising the potential of existing facilities and ensuring the success of the HL-LHC. Fault tracking, dedicated maintenance efforts and targeted infrastructure improvements across the complex were highlighted as key contributors to achieving and maintaining optimal uptime.

As the HL-LHC project moves into full series production, the technical challenges associated with magnets, cold powering and crab cavities are being addressed (*CERN Courier* January/February 2024 p37). Looking beyond Long Shutdown 3 (LS3), potential limitations are already being targeted now, with, for example, electron-cloud mitigation measures planned to be deployed in LS3. The transition to the high-luminosity era will involve a huge programme of work that requires meticulous preparation and a well-coordinated effort across the complex during LS3, which will see the deployment of the HL-LHC, a widespread consolidation effort, and other upgrades such as that planned for the ECN3 cavern at CERN's North Area.

The vision for the next decades of these facilities is diverse, imaginative and well-motivated from a physics perspective

The breadth and depth of the physics being performed at CERN facilities is quite remarkable, and the Chamonix workshop reconfirmed the high demand from experimentalists across the board. The unique capabilities of ISOLDE, n_TOF, AD-ELENA, and the East and North Areas were recognised. The North Area, for example, provides protons, hadrons, electrons and ion beams for detector R&D, experiments, the CERN neutrino platform, irradiation facilities and counts more than 2000 users. The vision for the next decades of these facilities is diverse, imaginative and well-motivated from a physics perspective. The potential for long-term exploitation and leveraging fully the capabilities of the LHC and other facilities is considerable, demanding continued support and development.

In the longer term, CERN is exploring the potential construction of the FCC via a dedicated feasibility study that has just delivered a mid-term report – a summary of which was presented at Chamonix. The initiative is accompanied by R&D on key accelerator technologies. The physics case for FCC-ee was well made for an audience of mostly non-particle physicists, concluding that the FCC is the only proposed collider that covers each key area in the field – electroweak, QCD, flavour, Higgs and searches for phenomena beyond the Standard Model – in paradigm-shifting depth.

Environmental consciousness

Sustainability was another focus of the Chamonix workshop. Building and operating future facilities with environmental consciousness is a top priority, and full life-cycle analyses will be performed for any options to help ensure a low-carbon future.

Interesting times, lots to do. To quote former CERN Director-General Herwig Schopper from 1983: "It is therefore clear that, for some time to come, there will be interesting work to do and I doubt whether accelerator experts will find themselves without a job."

Mike Lamont *CERN.*

Workshop on Sustainability for Future Accelerators

Accelerator sustainability in focus

The world is facing a crisis of anthropogenic climate change, driven by excessive CO_2 emissions during the past 150 years. In response, the United Nations has defined goals in a race towards zero net-carbon emission. One of these goals is to ensure that all projects due to be completed by 2030 or after have a net-zero carbon operation, with a reduction in embodied carbon by at least 40% compared to current practice. At the same time, the European Union (EU), Japan and other nations have decided to become carbon neutral by around 2050.

These boundary conditions put large-scale science projects under pressure to reduce CO_2 emissions during construction, operation and potentially decommissioning. For context: given the current French energy mix, CERN's annual 1.3 TWh electricity consumption (which is mostly used for accelerator operation) corresponds to roughly 50 kt CO_2e global warming potential (GWP), while recent estimates for the construction of tunnels for future colliders are in the multi-100 kt CO_2e GWP range.

Green realisation

To discuss potential ways forward, a Workshop on Sustainability for Future Accelerators (WSFA2023) took place on 25–27 September in Morioka, Japan within the framework of the recently started EU project EAJADE (Europe–America–Japan Accelerator Development and Exchange). Around 50 international experts discussed a slew of topics ranging from life-cycle assessments (LCAs) of accelerator technologies with carbon-reduction potential to funding initiatives towards sustainable accelerator R&D, and local initiatives aimed at the "green" realisation of future colliders. With the workshop being held in Japan, the proposed International Linear Collider (ILC) figured prominently as a reference project – attracting considerable attention from local media.

M Titov

In the field *The workshop offered the opportunity to visit a geothermal power plant in Hachimantai city.*

The general context of discussions was set by Beate Heinemann, DESY director for particle physics, on behalf of the European Laboratory Directors Group (LDG). The LDG recently created a working group to assess the sustainability of accelerators, with a mandate to develop guidelines and a minimum set of key indicators pertaining to the methodology and scope of reporting of sustainability aspects for future high-energy physics projects. Since LCAs are becoming the main tool to estimate GWP, a number of project representatives discussed their take on sustainability and steps towards performing LCAs. Starting with the much-cited ARUP study on linear colliders published in 2023 (edms.cern.ch/document/2917948/1), there were presentations on the ESS in Sweden, the ISIS-II neutron and muon source in the UK, the CERN sustainability forum, the Future Circular Collider, the Cool Copper Collider and other proposed colliders. Also discussed were R&D items for sustainable technologies, including CERN's High Efficiency Klystron Project, the ZEPTO permanent-magnet project, thin film-coated SRF cavities and others.

A second big block in the workshop agenda was devoted to the "greening" of future accelerators and potential local and general construction measures towards achieving this goal. The focus was on Japanese efforts around the ILC, but numerous results can be re-interpreted in a more general way. Presentations were given on the potential of concrete to turn from a massive carbon source into a carbon sink with net negative CO_2e balance (a topic with huge industrial interest), on large-scale wooden construction (e.g. for experimental halls), and on the ILC connection with the agriculture, forestry and fisheries industries to reduce CO_2 emissions and offset them by increasing CO_2 absorption. The focus was on building an energy recycling society by the time the ILC would become operational.

What have we learnt on our way towards sustainable large-scale research infrastructures? First, that time might be our friend: energy mixes will include increasingly larger carbon-free components, making construction projects and operations more eco-friendly. Also, new and more sustainable technologies will be developed that help achieve global climate goals. Second, we as a community must consider the imprint our research leaves on the globe, along with as many indicators as possible. The GWP can be a beginning, but there are many other factors relating, for example, to rare-earth elements, toxicity and acidity. The LCA methodology provides the accelerator community with guidelines for the planning of more sustainable large-scale projects and needs to be further developed – including end-of-life, decommissioning and recycling steps – in an appropriate manner. Last but not least, it is clear that we need to be proactive in anticipating the changes happening in the energy markets and society with respect to sustainability-driven challenges at all levels.

Thomas Schörner *DESY,* **Steinar Stapnes** *CERN and* **Maxim Titov** *CEA Saclay.*

Implications of LHCb measurements and future prospects

Tango for two: LHCb and theory

The 13th annual "Implications of LHCb measurements and future prospects" workshop, held at CERN on 25–27 October 2023, drew substantial interest with 231 participants. This collaborative event between LHCb and the theoretical community showcased the mutual enthusiasm for LHCb's physics advances. The workshop featured five streams highlighting the latest experimental and theoretical developments in mixing and CP violation, heavy ions and fixed-target results, flavour-changing charged currents, QCD spectroscopy and exotics, and flavour-changing neutral currents.

The opening talk by Monica Pepe Altarelli underscored LHCb's diverse physics programme, solidifying its role as a highly versatile forward detector. While celebrating successes, her talk candidly addressed setbacks, notably the new results in tests of lepton-flavour universality. LHCb detector and computing upgrades for Run 3 include a fully software-based trigger using graphics processing units. The collaboration is also working towards an Upgrade II programme for Long Shutdown 4 (2033–2034) that would position LHCb as a potentially unique global flavour facility.

On mixing and CP violation, the October workshop unveiled intriguing insights ▷

in both the beauty and charm sectors. In the beauty sector, notable highlights encompass measurements of the mixing parameter $\Delta\Gamma_s$ and of CP-violating phases such as $\varphi_{s,d}$, $\varphi_s^{s\bar{s}s}$ and γ. CP asymmetries were further scrutinised in $B \to DD$ decays, accounting for SU(3) breaking and re-scattering effects. In the charm sector, the estimated CP asymmetries considering final-state interactions were found to be small compared to the experimental values related to $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ decays. Novel measurements of CP violation in three-body charm hadron decays were also presented.

Y Amhis

Grand vision *Monica Pepe Altarelli underscored LHCb's diverse physics programme, which has seen the publication of around 700 physics papers and the discovery of 64 out of 72 new hadrons at the LHC.*

Unique capabilities

On the theoretical front, discussions delved into the current status of bottom-baryon lifetimes. Recent lattice predictions on the ε_K parameter were also showcased, offering refined constraints on the unitarity triangle. The LHCb experiment's unique capabilities were discussed in the heavy ions and fixed-target session. Operating in fixed-target mode, LHCb collected data pertaining to proton–ion and lead–ion interactions during LHC Run 2 using the SMOG system. Key highlights included measurements impacting theoretical models of charm hadronisation, global analyses of nuclear parton density functions, and the identification of helium nuclei and deuterons. The first Run 3 data with the SMOG2 upgrade showed promising results in proton–argon and proton–hydrogen collisions, opening a path to measurements with implications for heavy-ion physics and astrophysics.

The session on flavour-changing charged currents unveiled a recent measurement concerning the longitudinal polarisation of D^{*-} mesons in $B^0 \to D^{*-}\tau^-\bar{\nu}_\tau$ decays, aligning with Standard Model (SM) expectations. Discussions delved into lepton-flavour-universality tests that showed a 3.3σ tension with predictions in the combined $R(D^{(*)})$ measurement. Noteworthy were new lattice-QCD predictions for charged current decays, especially $R(D^{(*)})$, showcasing disparities in the SM prediction across different lattice groups. Updates on the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ lead to a reduced tension between inclusive and exclusive determinations. The session also discussed the impact of high-energy constraints of Wilson coefficients on charged-current decays and Bayesian inference of form-factor parameters, regulated by unitarity and analyticity. The QCD spectroscopy and exotics session also featured important findings, including the discovery of novel baryon states, notably $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$. Pentaquark exploration involved diverse charm–hadron combinations, alongside precision measurements of the Ω_c^0 mass and first observations of b-hadron decays with potential exotic-state contributions. Charmonia-associated production provided fresh insights for testing QCD predictions, and an approach based on effective field theory (EFT) interpreting pentaquarks as hadronic molecules was presented. A new model-independent Born–Oppenheimer EFT framework for the interpretation of doubly heavy tetraquarks, utilising lattice QCD predictions, was introduced. Scrutinising charm-tetraquark decays and the interpretation of newly discovered hadron states at the LHC were also discussed.

During the flavour-changing neutral-current session a new analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays was presented, showing consistency with SM expectations. Stringent limits on branching fractions of rare charm decays and precise differential branching fraction measurements of b-baryon decays were also highlighted. Challenges in SM predictions for $b \to s\ell\ell$ and rare charm decays were discussed, underscoring the imperative for a deeper comprehension of underlying hadronic processes, particularly leveraging LHCb data. Global analyses of $b \to d\ell\ell$ and $b \to s\ell\ell$ decays were presented, alongside future prospects for these decays in Run 3 and beyond. The session also explored strategies to enhance sensitivity to new physics in $B^\pm \to \pi^\pm\mu^+\mu^-$ decays.

The keynote talk, delivered by Svjetlana Fajfer, offered a comprehensive summary and highlighted existing anomalies that demand further consideration. Tackling these challenges necessitates precise measurements at both low and high energies, with the collaborative efforts of LHCb, Belle II, CMS and ATLAS. Additionally, advancements in lattice QCD and other novel theoretical approaches are needed for precise theoretical predictions in tandem with experimental efforts.

Eleftheria Malami *University of Siegen/Nikhef and* **Abhijit Mathad** *University of Zurich/CERN.*

Gigahertz Rate and Rapid Muon Acceleration

Pushing accelerator frontiers in Bern

Novel accelerator concepts will play an important role in future accelerators for high-energy physics. Two relevant scenarios being explored in the framework of the European Union I.FAST project are the generation of relativistic single electrons with gigahertz repetition rate for dark-matter searches, and the rapid acceleration of muons with GV/m accelerating fields for experiments at the energy frontier. The topical workshop "Gigahertz Rate and Rapid Muon Acceleration", held in Bern from 10 to 13 December 2023, addressed the latest developments in these and related topics.

CERN-PHOTO-202307-176-29

Future concepts *The AWAKE facility could conceivably be used to test the plasma-wakefield acceleration of muons.*

The first part of the workshop was devoted to dark-matter searches and dielectric laser acceleration (DLA). For dark-matter searches, multiple experiments are proposed across different classes (muons vs electrons and positrons, appearance vs disappearance experiments, etc), and an adequate background rejection is important. Promising advanced accelerator technologies are DLA for single electrons – perhaps also ▷

muons – and plasma-wakefield accelerators for muons and pions.

Some dark matter-experiments look for an appearance that requires a high flux of incoming particles. For electrons, the standard is set by BDX at JLab, for protons by the proposed SHiP experiment at CERN, and for photons by the proposed Gamma Factory at CERN. In addition, appearances could be seen at existing collider experiments such as the LHC. Other dark-matter experiments search for disappearance. They rely on DC-like electron beams, with prominent examples being LDMX at SLAC and the newly proposed DLA–DMX at PSI. A DC-like muon beam could be explored by the M3 experiment at Fermilab.

Paolo Crivelli (ETH Zürich) described the NA64 experiment as one of the most prominent examples of ongoing accelerator-based dark-matter searches, and presented the first results using a high-energy muon beam. The proposed LDMX experiment at SLAC, presented by Silke Möbius (University of Bern), may set a new standard for indirect dark-matter searches, while advanced concepts employing dielectric laser acceleration, in particular when integrating the accelerating structure with laser oscillator, could achieve many orders of magnitude higher rates of single high-energy electrons entering into an LDMX-type detector.

Uwe Niedermayer (TU Darmstadt), Stefanie Kraus (University Erlangen-Nürnberg) and Raziyeh Dadashi (PSI/EPFL) reviewed the state of the art in DLA plus future plans. Yves Bellouard (EPFL) discussed advances in high-repetition-rate lasers and micro/nano-structures, which suggests that the proposed combined laser-accelerator structures are within reach. Of course, the detector time resolution would also need to be improved tremendously to keep pace with the higher rate of the accelerator.

The workshop showed how advanced accelerator concepts can jump-start dark-sector searches

Acceleration and decay

The second part of the workshop was devoted to the plasma acceleration of non-ultra relativistic and rapidly decaying particles, such as muons and pions. Vladimir Shiltsev (Fermilab) and Daniel Schulte (CERN) presented tentative parameters and ongoing R&D efforts towards a muon collider. Shiltsev also discussed the intriguing possibility of low-emittance muon sources based on plasma-wakefield accelerators, while Alexander Pukhov (Heinrich Heine University Düsseldorf) and Chiara Badiali (IST Lisbon) discussed how plasma acceleration could bring slow particles, such as muons, to relativistic velocities.

The workshop fostered numerous heated discussions and uncovered unresolved issues, which included the "Bern controversy" regarding the ultimate limits of luminosity for PeV energies. Muons are considered particles of choice for future accelerators at the energy frontier. Both low- and high-energy muons have useful applications. Is there an Angstrom limit to the beam diameter? Are tiny beta functions possible? Can plasmas help to overcome such limitations? Understanding and modelling non-point-like particle luminosity is another important topic, also relevant for the Gamma Factory.

The final part of the workshop assembled a roadmap and perspective. DLA studies are to be maintained and, if possible, accelerated. A reasonable target is achieving a gradient of 500 MeV/m and an energy gain of 0.05 GeV in five years on a single wafer, while an integrated DLA laser oscillator could be foreseen five to seven years from now. Plasma-wakefield acceleration of muons could conceivably be tested either at CERN–AWAKE or PSI. It was proposed, as a first step, to put a solid target or tape into the AWAKE set up.

The gamma factory, presented by Witek Krasny (LPNHE), was recognised as an intense source of polarised muons and positrons. For muon-acceleration studies, the dephasing issue, linked to the muons' non-ultrarelativistic energy, seems to be resolved. A demonstrator experiment for muon plasma acceleration is called for. Open questions include when and where?

Overall, the Bern workshop showed how advanced accelerator concepts can jump start dark-sector searches and muon/pion acceleration. High-repetition-rate acceleration of single electrons for dark-matter searches, using dielectric laser accelerators, and applying high-gradient plasma acceleration to muon and/or pion beams, are intriguing and far-forward looking topics.

Giuliano Franchetti *GSI*, **Rasmus Ischebeck** *PSI and* **Frank Zimmermann** *CERN*.

13TH ICFA SEMINAR

A global forum for high-energy physics

The International Committee for Future Accelerators (ICFA) was formally founded in 1977 as a working group in IUPAP's commission 11 (C11, Particles and Fields). Today it remains the place for discussions on all aspects of particle physics, in particular on the large accelerators that are at the heart of the field, and on the strategic deliberations in the various regions of the world. Although ICFA has no means of ensuring that any of its resolutions are carried out, it can act as the "conscience" of the field, and its recommendations can also influence national or regional activities. Among the currently 16 members, which include directors of CERN, Fermilab, IHEP, KEK and DESY, three are from Europe, three from the US, two from Russia, two from Japan, and one each from China and Canada. Three further members collectively represent smaller countries and regions, and the functions of chair and secretary rotate through the Americas, Europe and Asia, usually every three years.

T Schörner / DESY

High level *Shoji Asai (KEK), Ursula Bassler (IJCLab), Fabiola Gianotti (CERN), Lia Merminga (Fermilab), Nigel Smith (TRIUMF) and Yifang Wang (IHEP) during the panel discussion at the ICFA seminar.*

A significant fraction of ICFA's work is carried out within a set of seven panels, which meet regularly and assemble expertise on more technical or detailed ▷ aspects of particular importance to the field. One is devoted to the International Linear Collider (ILC). For more than two decades, ICFA has promoted the realisation of the ILC, for which a global design effort was put in place in 2005. In parallel, an international collaboration under CERN's leadership had been working on the Compact Linear Collider (CLIC). Recognising the synergies between the two concepts, ICFA established a single coordinating structure, the Linear Collider Collaboration (LCC), in 2012. Also that year, the Japanese high-energy physics community proposed to host the ILC in Japan as a global project.

The LCC mandate came to an end in 2020, when ICFA put in place the ILC International Development Team (IDT) and its working groups. In June 2021 the IDT developed a proposal for the "preparatory laboratory" as a first step towards the realisation of the ILC in Japan.

For more than two decades, ICFA has promoted the realisation of the ILC

Evolving landscape

While the IDT is continuing its work, the global Higgs-factory landscape has evolved since the early days of the ILC: more – linear and circular – studies and proposals are on the table, not least as demonstrated by the P5 report in the US. ICFA will soon discuss in what way its discussions and structures need to be adapted to better reflect this evolving landscape.

In November 2023 ICFA established a new panel devoted to the "data lifecycle", which involves everything from data acquisition, processing, distribution, storage, access, analysis, simulation and preservation, to management, software, workflows, computing and networking. The panel, which replaces two previous ones on related topics, was created in response to the growing importance of data management and open science in recent years. Its membership is currently being put together with the aim to develop ideas and strategies for workforce development and professional recognition mechanisms.

ICFA's farthest-reaching and most visible activity is the ICFA Seminar. The 13th ICFA seminar on "Future Perspectives in High-Energy Physics" took place at DESY from 28 November to 1 December 2023. For the first time in six years (the prior ICFA seminar had taken place in 2017 in Ottawa, Canada), this select crowd of scientists, lab directors and funding agency representatives could come together in person for updates and discussions. One highlight was the panel discussion between the directors of KEK, CERN, Fermilab and IHEP, in which views on a future global strategy were discussed. The seminar concluded on a festive note with the formal passing of the ICFA chair baton from Stuart Henderson (JLAB) to Pierluigi Campana (INFN), who will lead ICFA for the next three years.

ICFA is the only global representation of the particle-physics community, and the ideal discussion forum for global strategic developments, especially large international collider projects. In view of the current situation with numerous opportunities for future facilities – not least a future Higgs factory, but also smaller and more diverse projects – the committee and its panels look forward to serving the field of particle physics through continued advocacy, exploration, discussion and facilitation.

Stuart Henderson *JLab*, **Pierluigi Campana** *INFN*, **Thomas Schörner** *DESY*.

MACHINE MATTERS

From the latest accelerator designs to their estimated cost and long-term societal returns, the *Courier* gathers the key takeaways so far from the Future Circular Collider feasibility study.

Scalar adventure *A sketch of the FCC-ee accelerator in its tunnel. (Credit: Polar Media)*

It's exactly 10 years since 350 physicists and engineers met at the University of Geneva to kick-off the Future Circular Collider (FCC) study. A response to the 2013 European strategy for particle physics, the study initially examined options for an energy-frontier collider in a new 80–100 km-circumference tunnel. By late 2018 a conceptual design report (CDR) integrating the physics, detector, accelerator and infrastructure of a staged lepton (FCC-ee) and hadron (FCC-hh) collider was published. Two years of lengthy deliberations later, the 2020 European strategy recommended that the community investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an e^+e^- Higgs and electroweak factory as a possible first stage.

After three years of work, mobilising the expertise of physicists and engineers from around the world, a mid-term report of the FCC feasibility study was completed in December 2023. Numerous technical documents and a 700-page overview of the results demonstrate significant progress across all project deliverables, including physics opportunities, the placement and implementation of the ring, civil engineering, technical infrastructure, accelerators, detectors and cost. No technical showstoppers have been identified, and the results were received positively by the CERN Council during a special session on 2 February. Here and in the following pages, the *Courier* gathers the key take-aways.

A collider for the times

The scientific backdrop to the FCC is the existence of a 125 GeV Higgs boson together with no sign yet of new elementary particles at the TeV scale – transformational discoveries by the LHC that call for a broad and versatile exploration tool with unprecedented precision, sensitivity and energy reach (p30). An unfathomable amount of work has led to an optimal placement of the FCC ring, surface sites and project implementation with CERN's host states (p27). The 90.7 km FCC tunnel, constituting a major global civil-engineering project in its own right, is well understood (p35). Assuming a decision to advance to the next

THE AUTHOR

Matthew Chalmers *editor.*

CERNCOURIER
Volume 64 Number 2 March/April 2024
IOP Publishing

Studies show that the FCC would deliver benefits that outweigh its costs

stage is taken by the CERN Council after the next European strategy process, a preparatory phase (involving project authorisation, preparation of civil-engineering works, technical design for the collider, injectors and the detectors, further consolidation of physics cases and detector development) would take place from 2026 to 2032. Construction could then take place in 2033–2040, with the installation phase and transition to operation between 2038 and the mid-2040s.

The multi-energy lepton collider FCC-ee, which would produce huge quantities of Z, W and Higgs bosons, and ultimately top-quark pairs, over a period of about 15 years, builds on the remarkable success of LEP, which was instrumental in confirming the Standard Model and in guiding physicists to the discoveries of the top quark and the Higgs boson. Once thought to be the final word on circular e^+e^- colliders, advances in accelerator technology since LEP (such as top-up injection at B factories and synchrotron-radiation light sources, developments in superconducting RF, and novel beam-focusing techniques) offer collision rates more than two orders of magnitude larger. Boosting the FCC-ee luminosity further, a key outcome of the mid-term report is a new ring-layout that enables four interaction points.

Ideal springboard

The mid-term report confirms that FCC-ee is both a mature design for a Higgs, electroweak and top factory, and an ideal springboard for an energy-frontier collider, FCC-hh, for which it would provide a significant part of the infrastructure. Since the revised FCC-ee placement studies, the overall layout of FCC-hh has changed radically compared to the initial concept phase, with three key benefits: an optimal size of the experiment caverns, with the option of sharing detector components between the lepton and the hadron machines; a reduction in the number of surface sites; and a shorter tunnel for the transfer lines from the injector to the collider ring. The new layout is compatible with an injection scheme that delivers beams to the FCC-hh ring from the LHC or from an upgrade of the SPS.

The mid-term report addresses the challenging R&D for the high-field FCC-hh magnets. A key deliverable of the feasibility study is a summary of R&D plans based on Nb_3Sn, high-temperature superconductors (HTS) and hybrid technologies. While Nb_3Sn magnets are considered relatively low-risk, HTS technology would enable the most aspirational goals to be reached. Due to the sizable gap in technology readiness between the two options, however, the study team advises against an early decision. Instead, an adapted "phase-gate" process is proposed with regular review, steering and decision points every five years, and coordinated with the CERN high-field magnet programme.

Taking into account the time needed to construct and operate FCC-ee and, in parallel, to develop the high-field dipole magnet technology, it is estimated that FCC-hh could begin physics operations in the early 2070s.

The cost of an FCC-ee with four interaction points is estimated to be CHF 15 billion, around a third of which is taken up by the tunnel. The reliability of the FCC-ee cost estimate will be improved following further development of the various accelerator systems and equipment required, along with the subsurface investigations starting in 2024. The final feasibility-study report will also address risk-management and the personnel resources required from project development to construction.

Power consumption is another topic of interest. The FCC-ee will be the largest particle accelerator ever built, with its RF, magnet and cryogenic systems drawing the main loads. The total CERN energy consumption throughout the FCC-ee scientific programme is estimated to vary between 2.0 and 2.8 TWh/year depending on the energy mode, to be compared with about 1.6 TWh/year during the High-Luminosity LHC era. The figures are hoped to be lowered as R&D (for example, to improve the performance of superconducting cavities and the efficiency of power sources) advances. The FCC study team is also working with regional authorities to identify ways in which part of this energy may be re-used for heating in local industries and public infrastructures.

Electrical power would be provided from the French electricity grid, and the system is designed such that no new sub-stations will need to be constructed between the different FCC-ee energy stages. Studies carried out in conjunction with McKinsey and Accenture indicate that by the time the FCC comes into operation, a low carbon footprint can be achieved with an energy mix that contains a large fraction of energy from renewable sources.

Return on investment

Beyond the creation of new knowledge, studies undertaken within the European Union co-funded FCC Innovation Study show that the FCC would deliver benefits that outweigh its cost. Impacts on industry from high-tech developments, the sustained training of early-stage researchers and engineers, the development of open and free software, the creation of spin-off companies, cultural goods and other factors lead to an estimated benefit/cost ratio of 1.66. The FCC project is linked to the creation of around 800,000 person-years of jobs, states the mid-term report, and the FCC-ee scientific programme is estimated to generate an overall local economic impact of more than €4 billion.

The digested mid-term report in summary: the FCC integrated programme is an ideal match for the uncharted physics territory ahead; its placement at CERN is geologically and territorially feasible; no technical showstoppers have been identified; the FCC would return more to society than it costs. Accelerator, detector, engineering and physics studies by the global FCC collaboration are continuing across more than 150 institutes in more than 30 countries, while new partners are sought to work on various R&D (p37). The final report of the FCC feasibility study is due in early 2025. ●

WHERE AND HOW?

An update on the latest progress in optimising the placement of the FCC ring, taking into account scientific output, territorial compatibility and implementation risks.

Designing a next-generation collider with a performance that meets the scientific demands of the particle-physics community is one thing. Ensuring its territorial compatibility, technical feasibility and cost control is quite another. A core element of the FCC feasibility study is therefore the placement of the ring and the necessary surface sites, for which an iterative approach in collaboration with CERN's host states, France and Switzerland, has been adopted from the outset.

Territorial compatibility requires numerous natural, technical, urban and cultural constraints to be identified and considered. The goal is to limit the consumption of land, keep the quantity of excavated materials to a minimum and re-use as much as possible, minimise the consumption of resources such as electricity and water, avoid visibility, noise and dust nuisances, and create synergies with future neighbours where possible. Following eight years of intense study, one configuration was identified out of some 100 variants as being particularly suitable. This scenario has a circumference of about 90.7 km, eight surface sites and permits the installation of up to four experiments.

During 2023 this reference scenario was reviewed with different regional stakeholders and now serves as the baseline for further design and optimisation activities. These include geophysical and geotechnical investigations to set the optimum depth of the tunnel, links to high voltage grids, access to water for cooling purposes, connections to major rail and road infrastructures, landscape integration and the development of sustainable mitigation measures.

Drill down

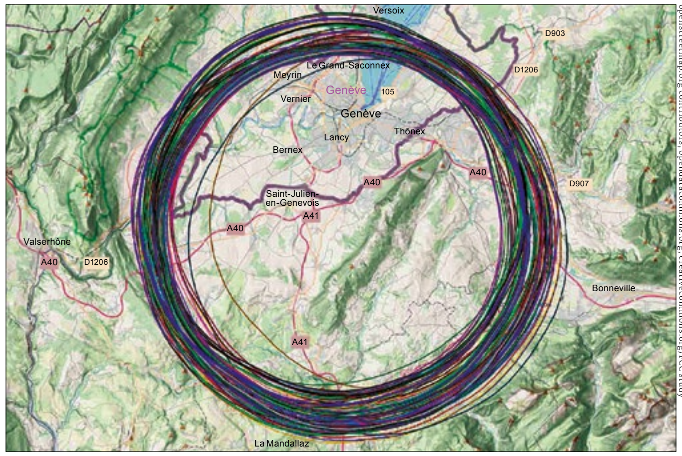
Working out how to place a 90.7 km-circumference research infrastructure in a densely populated region requires several dozens of criteria to be met. While initial investigations concerned observations at the square-kilometre level, the focus gradually moved to thousands of square metres and individual land-plot levels. Initial cartographic and database research has progressively been replaced with analysis in the field, working meetings with public administration services and eventually individuals with expert local knowledge. In addition to the scientific and technical requirements, the FCC implementation scenario takes into account the project-implementation risks, cost impacts, access to resources (electricity, water, land), transport requirements, and estimates of the urban and demographic evolution. The study also analyses socio-economic benefits for the region.

The reference layout with only eight surface sites requires less than 50 ha of land use on the surface and constitutes a significant reduction in footprint with respect to the initial scenario drawn up in 2014. All sites are situated close to road infrastructure, with less than 5 km of new roads required, and several of the eight sites are located in the vicinity of 400 kV grid lines. The layout of the FCC is integrated geographically with the existing CERN accelerator complex, with beam transfer possible from either the LHC or via the SPS tunnel.

The feasibility study, carried out with relevant consultancy companies, confirms the technical feasibility of all eight surface sites and the underground works. Working meetings with all the municipalities affected in France and Switzerland have not revealed any showstoppers so far, even if decisions by municipalities and the host states are yet to be taken. Next steps include the detailed integration of the surface sites in the environment.

Timescales are critical to be able to continue with such studies. By the end of the feasibility study in 2025, all land plots that are required by the project need to be communicated to the host states. In addition, a formal environmental evaluation phase in both France and Switzerland is necessary for the authorisation procedures. These activities rely on an agreement between CERN and the host states on the steps to be made by each stakeholder, including the associated legal and regulatory conditions.

Throughout all studies, CERN has been accompanied by the services of the Swiss and French authorities at different levels. This dialogue concerns the more detailed expression of the needs and constraints of the local actors and the identification of potential co-development topics and compensatory measures. The findings are gradually being integrated into a process of project optimisation of the reference scenario to further improve its added value for the territory while keeping the science value high and the project implementation risks low. ●



openstreetmap.org contributors, opendatacommons.org, creativecommons.org/FCC study

In the zone *More than 100 placement scenarios with different layout geometries and surface sites have been analysed.*

THE AUTHOR

Johannes Gutleber *CERN.*

CERNCOURIER

Volume 64 Number 2 March/April 2024

FCC: THE PHYSICS CASE

From understanding the structure of the elementary blocks of matter and the forces acting between them, to exhaustively probing the existence of new phenomena at low and high energies, the Future Circular Collider offers unique exploration of space, time and matter.

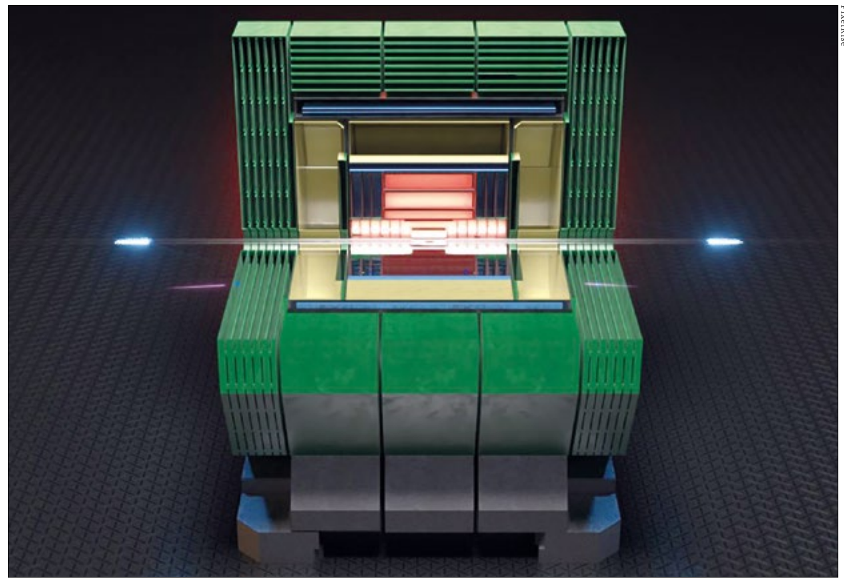
THE AUTHORS
Patrick Janot *CERN and* **Christophe Grojean** *DESY.*

Results from the LHC so far have transformed the particle-physics landscape. The discovery of the Higgs boson with a mass of 125 GeV – in agreement with the prediction from earlier precision measurements at LEP and other colliders – has completed the long-predicted matrix of particles and interactions of the Standard Model (SM) and cleared the decks for a new phase of exploration. On the other hand, the lack of evidence for an anticipated supporting cast of particles beyond the SM (BSM) gives no clear guidance as to what form this exploration may take. For the first time since the Fermi theory almost a century ago, particle physicists are voyaging into completely uncharted territory, where our only compass is the certitude that the SM in isolation cannot account for all observations. This absence of theoretical guidance calls for a powerful experimental programme to push the frontiers of the unknown as far as possible.

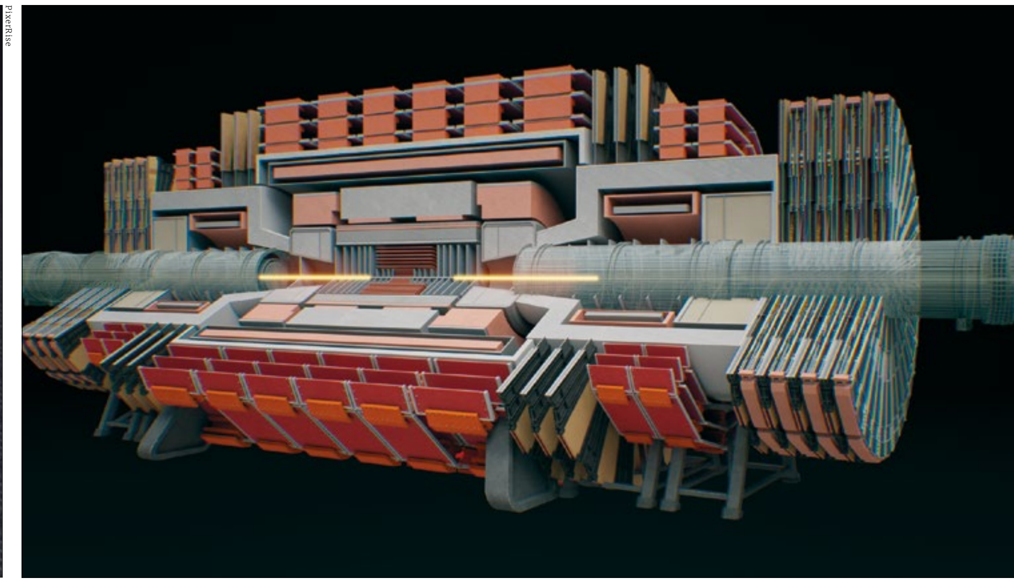
The absence of LHC signals for new phenomena in the TeV range requires physicists to think differently about the open questions in fundamental physics. These include the abundance of matter over antimatter, the nature of dark matter, the quark and lepton flavour puzzle in general, and the non-zero nature of neutrino masses in particular. Solutions could be at even higher energies, at the price of either an unnatural value of the electroweak scale or an ingenious but still elusive structure. Radically new physics scenarios have been devised, often involving light and very-weakly coupled structures. Neither the mass scale (from meV to ZeV) of this new physics nor the intensity of its couplings (from 1 to 10^{-12} or less) to the SM are known, calling for a versatile exploration tool.

For the first time since the Fermi theory almost a century ago, particle physicists are voyaging into completely uncharted territory

By providing considerable advances in sensitivity, precision and, eventually, energy far above the TeV scale, the integrated Future Circular Collider (FCC) programme is the perfect vehicle with which to navigate this new landscape. Its first stage FCC-ee, an e^+e^- collider operating at centre-of-mass energies ranging from below the Z pole (90 GeV) to beyond the top-quark pair-production threshold (365 GeV), would map the properties of the Higgs and electroweak gauge bosons and the top quark with precisions that are orders of magnitude better than today, acquiring sensitivity to the processes that led to the formation of the Brout–Englert–Higgs field a fraction of a nanosecond after the Big Bang.



On point *A detector concept for FCC-ee, a collider operating at energies from 90 to 365 GeV.*



Final frontier *An illustration of a detector for FCC-hh, which could improve the direct discovery reach for new particles.*

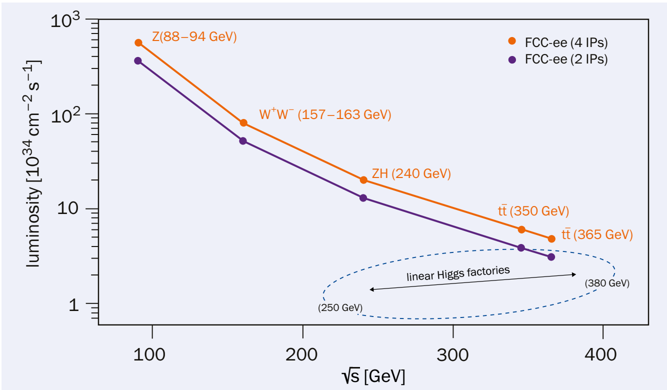
A comprehensive campaign of precision electroweak, QCD, flavour, tau, Higgs and top-quark measurements sensitive to tiny deviations from the predicted SM behaviour would probe energy scales far beyond the direct kinematic reach, while a subsequent pp collider (FCC-hh) would improve – by about an order of magnitude – the direct discovery reach for new particles. Both machines are strongly motivated in their own rights. Together, they offer the furthest physics reach of all proposed future colliders, and put the fundamental scalar sector of the universe centre-stage.

A scalar odyssey

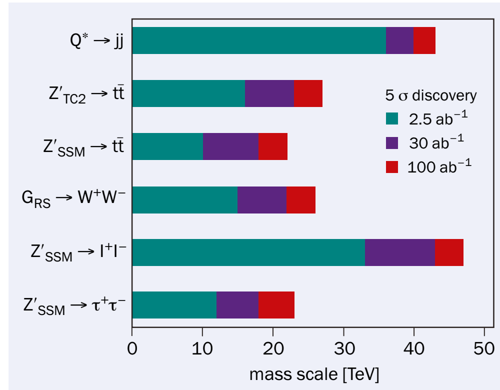
The power of FCC-ee to probe the Higgs boson and other SM particles at much higher resolution would allow physicists to peer further into the cloud of quantum fluctuations surrounding them. The combination of results from previous lepton and hadron colliders at CERN and elsewhere has shown that electroweak symmetry breaking is consistent with its SM parameterisation, but its origin (and the origin of the Higgs boson itself) demands a deeper explanation. The FCC is uniquely placed to address this mystery via a combination of per-mil-level Higgs-boson and parts-per-millon gauge-boson measurements, along with direct high-energy exploration, to comprehensively probe symmetry-based explanations for an electroweak hierarchy. In particular, measurements of the Higgs boson's self-coupling at the FCC would test whether the electroweak phase transition was first- or second-order, revealing whether it could have potentially played a role in setting the out-of-equilibrium condition necessary for creating the matter–antimatter asymmetry.

While the Brout–Englert–Higgs mechanism nicely explains the pattern of gauge-boson masses, the peculiar structure of quark and lepton masses (as well as the quark mixing angles) is ad hoc within the SM and could be the low-energy imprint of some new dynamics. The FCC will probe such potential new symmetries and forces, in particular via detailed studies of b and τ decays and of $b \to \tau$ transitions, and significantly extend knowledge of flavour physics. A deeper understanding of approximate conservation laws such as baryon- and lepton-number conservation (or the absence thereof in the case of Majorana neutrinos) would test the limits of lepton-flavour universality and violation, for example, and could reveal new selection rules governing the fundamental laws. Measuring the first- and second-generation Yukawa couplings will also be crucial to complete our understanding, with a potential FCC-ee run at the s-channel Higgs resonance offering the best sensitivity to the electron Yukawa coupling. Stepping back, the FCC would sharpen understanding of the SM as a low-energy effective field theory approximation of a deeper, richer theory by extending the reach of direct and indirect exploration by about one order of magnitude.

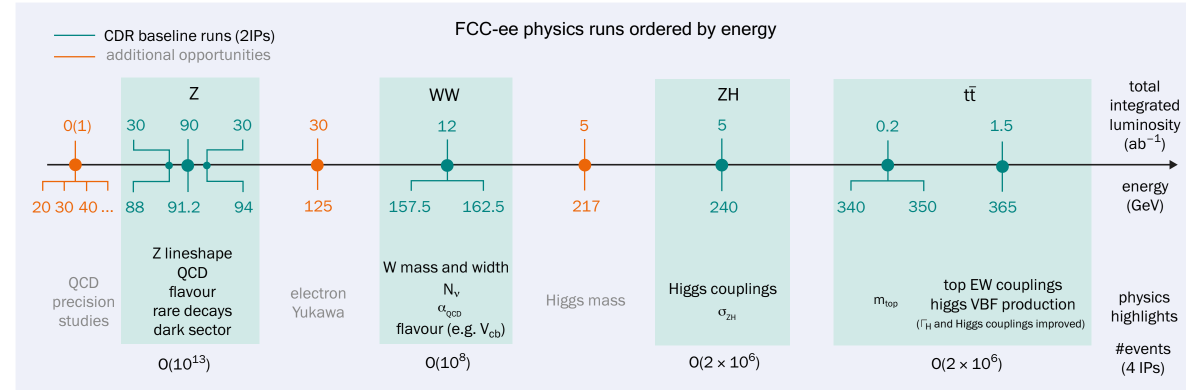
The unprecedented statistics from FCC-ee also make it uniquely sensitive to exploring weakly coupled dark sectors and other candidates for new physics beyond the SM (such as heavy axions, dark photons and long-lived particles). Decades of searches across different experiments have pushed the mass of the initially favoured dark-matter candidate (weakly interacting massive particles, WIMPs) progressively beyond the reach of the highest energy e^+e^- colliders. As a consequence, hidden sectors consisting of new particles that interact almost imperceptibly with the SM are rapidly gaining popularity as an alternative that could hold the answer not only to this problem but to a variety of others, such as the origin of neutrino masses. If dark matter is a doublet or a triplet WIMP, FCC-hh would cover the entire parameter space up to the upper mass limit for thermal relic. The FCC could also host a range of com-



Luminosity bonanza *The FCC-ee baseline design luminosity summed over four (orange) interaction points as a function of centre-of-mass energy, also showing the luminosity typically achievable by linear colliders with a single interaction point.*



Direct exploration *The FCC-hh discovery reach as a function of mass for various resonances expected in new-physics scenarios.*



FCC-ee physics *The minimal potential physics programme (green) for FCC-ee with two interaction points and 15 years of running ordered by increasing centre-of-mass energy. Also indicated are the approximate numbers of Z, WW, ZH and $t\bar{t}$ events with four interaction points and the physics opportunities with possible additional centre-of-mass energies (orange).*

plementary detector facilities to extend its capabilities for neutrino physics, long-lived particles and forward physics.

Completing this brief, high-level summary of the FCC physics reach are the origins of exotic astrophysical and cosmological signals, such as stochastic gravitational waves from cosmological phase transitions or astrophysical signatures of high-energy gamma rays. These phenomena, which include a modified electroweak phase transition, confining new physics in a dark sector, or annihilating TeV-scale WIMPs, could arise due to new physics which is directly accessible only to an energy-frontier facility.

Precision rules

Back in 2011, the original incarnation of a circular e^+e^- collider to follow the LHC (dubbed LEP3) was to create a high-luminosity Higgs factory operating at 240 GeV in the LEP/LHC tunnel, providing similar precision to that at a linear collider running at the same centre-of-mass energy for a much smaller price tag. Choosing to build a larger 80–100 km version not only allows the tunnel and infrastructure to be reused for a 100 TeV hadron collider, but extends the FCC-ee scientific reach significantly beyond the study of the Higgs boson alone. The unparalleled control of the centre-of-mass energy via the use of resonant depolarisation and the unrivalled luminosity of an FCC-ee with four interaction points would produce around 6×10^{12} Z bosons, 2.4×10^{8} W pairs (offering ppm precision on the Z and W masses and widths), 2×10^{6} Higgs bosons and 2×10^{6} top-quark pairs (impossible to produce with e^+e^- collisions in the LEP/LHC tunnel) in as little as 16 years.

From the Fermi interaction to the discovery of the W and Z, and from electroweak measurements to the discovery of the top quark and the Higgs boson, greater precision has operated as a route to discoveries. Any deviation from the SM predictions, interpreted as the manifestation of new contact interactions, will point to a new energy scale that will be explored directly in a later stage. One of the findings of the FCC feasibility study is the richness of the FCC-ee Z-pole run, which promises comprehensive measurements of the Z lineshape and many electroweak observables with a 50-fold increase in precision, as well as direct and uniquely precise determinations of the electromagnetic and strong coupling constants. The comparison between these data and commensurately precise SM predictions would severely constrain the existence of new physics via virtual loops or mixing, corresponding to a factor-of-seven increase in energy scale – a jump similar to that from the LHC to FCC-hh. The Z-pole run also enables otherwise unreachable flavour (b, τ) physics, studies of QCD and hadronisation, searches for rare or forbidden decays, and exploration of the dark sector.

After the Z-pole run, the W boson provides a further precision tool at FCC-ee. Its mass is one of the most precisely measured parameters that can be calculated in the SM and is thus of utmost importance. In the planned WW-threshold run, current knowledge can be improved by more than an order of magnitude to test the SM as well as a plethora of new-physics models at a higher quantum level. Together, the very-high-luminosity Z and W runs will determine the gauge-boson sector with the sharpest precision ever.

Going to its highest energy, FCC-ee would explore physics associated with the heaviest known particle, the top quark, whose mass plays a fundamental role in the prediction of SM processes and for the cosmological fate of the vacuum. An improvement in precision by more than an order of magnitude will go hand in hand with a significant improvement in the strong coupling constant, and is crucial for precision exploration beyond the SM.

High-energy synergies

A later FCC-hh stage would complement and substantially extend the FCC-ee physics reach in nearly all areas. Compared to the LHC, it would increase the energy for direct exploration by a factor of seven, with the potential to observe new particles with masses up to 40 TeV (see "Direct exploration" figure). The day FCC-hh directly finds a signal for beyond-SM physics, the precision measurements from FCC-ee will be essential to pinpoint its microscopic origin. Indirectly, FCC-hh will be sensitive to energies of around 100 TeV, for example in the tails of Drell–Yan distributions. The large production of SM particles, including the Higgs boson, at large transverse momentum allows measurements to be performed in kinematic regions with optimal signal-to-background ratio and reduced experimental systematic uncertainties, testing the existence of effective contact interactions in ways that are complementary to what is accessible at lepton colliders. Dedicated FCC-hh experiments, for instance with forward detectors, would enrich further the new-physics opportunities and hunt for long-lived and millicharged particles.

Further increasing the synergies between FCC-ee and FCC-hh is the importance of operating four detectors (instead of two as in the conceptual design study), which has led to an optimised ring layout with a new four-fold periodicity. With four interaction points, FCC-ee provides a net gain in integrated luminosity for a given physics outcome. It also allows for a range of detector solutions to cover all physics opportunities, strengthens the robustness of systematic-uncertainty estimates and discovery claims, and opens several key physics targets that are tantalisingly close (but missed) with only two detectors. The latter include the first 5σ observation of the Higgs-boson self-coupling, and the opportunity to access the Higgs-boson coupling to electrons – one of FCC-ee's toughest physics challenges.

No physics case for FCC would be complete without a thorough assessment of the corresponding detector challenges. A key deliverable of the feasibility study is a complete set of specifications ensuring that calorimeters, tracking and vertex detectors, muon detectors, luminometers and particle-identification devices meet the physics requirements. In the context of a Higgs factory operating at the ZH production threshold and above, these requirements have already been studied extensively for proposed linear colliders. However, the different experimental environment and the huge statistics of FCC-ee demand that they are revisited. The exquisite statistical uncertainties anticipated on key electroweak measurements at the Z peak and at the WW threshold call for a superb control of the systematic uncertainties, which will put considerable demands on the acceptance, construction quality and stability of the detectors. In addition, the specific discovery potential for very weakly coupled particles must be kept in mind.

The software and computing demands of FCC are an integral element of the feasibility study. From the outset, the driving consideration has been to develop a single software "ecosystem" adaptable to any future collider and usable by any future experiment, based on the best software available. Some tools, such as flavour tagging, significantly exceed the performance of algorithms previously used for linear-collider studies, but there is still much work needed to bring the software to the level required by the FCC-ee. This includes the need for more accurate simulations of beam-related quantities, the machine–detector interface and the detectors themselves. In addition, various reconstruction and analysis tools for use by all collaborators need to be developed and implemented, reaping the benefits from the LHC experience and past linear-collider studies, and computing resources for regular simulated data production need to be evaluated.

Powerful plan

The alignment of stars – that from the initial concept in 2011/2012 of a 100 km-class electron–positron collider in the same tunnel as a future 100 TeV proton–proton collider led to the 2020 update of the European strategy for particle physics endorsing the FCC feasibility study as a top priority for CERN and its international partners – provides the global high-energy physics community with the most powerful exploration tool. FCC-ee offers ideal conditions (luminosity, centre-of-mass energy calibration, multiple experiments and possibly monochromatisation) for the study of the four heaviest particles of the SM with a flurry of opportunities for precision measurements, searches for rare or forbidden processes, and the possible discovery of feebly coupled particles. It is also the perfect springboard for a 100 TeV hadron collider, for which it provides a great part of the infrastructure. Strongly motivated in their own rights, together these two machines offer a uniquely powerful long-term plan for 21st-century particle physics. ●

FCC-ee offers ideal conditions for the study of the four heaviest particles of the SM

CERNCOURIER
VOLUME 64 NUMBER 2 MARCH/APRIL 2024
IOP Publishing

TUNNELLING TO THE FUTURE

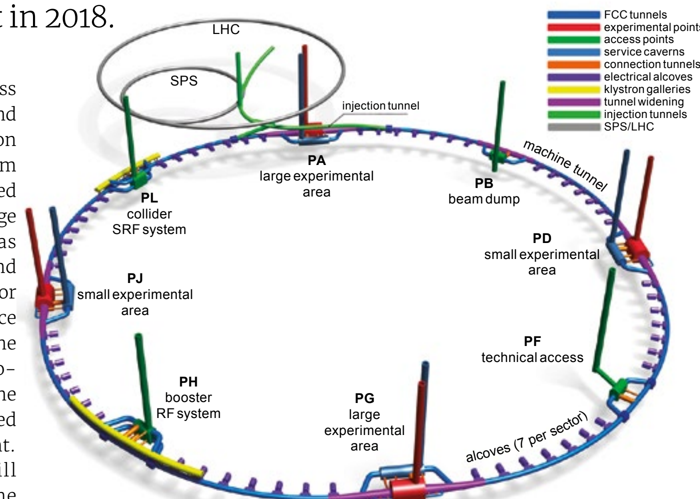
The Future Circular Collider would constitute one of the largest tunnelling projects ever undertaken, with several significant changes in civil engineering since the conceptual design report in 2018.

CERN has been burrowing beneath the French–Swiss border for half a century. Its first major underground project was the 7 km-circumference Super Proton Synchrotron (SPS), constructed at a depth of around 40 m by a single tunnel boring machine (TBM). This was followed by the Large Electron–Positron (LEP) collider at an average depth of around 100 m, for which the 27 km tunnel was constructed between 1983 and 1989 using three TBMs and a more traditional "drill and blast" method for the sector closest to the Jura mountain range. With a circumference of 90.7 km, weaving through the molasse and limestone beneath Lake Geneva and around Mont Salève, the proposed Future Circular Collider (FCC) would constitute the largest tunnel ever constructed at CERN and be considered a major global civil-engineering project in its own right.

Should the FCC be approved, civil engineering will be the first major on-site activity to take place. The mid-term review of the FCC feasibility study schedules ground-breaking for the first shafts to begin in 2033, after which it would take between six and eight years for each underground sector to be made available for the installation of the technical infrastructure, the machine and the experiments.

Evolving engineering

Since the completion of the FCC conceptual design report in 2018, several significant changes have been made to the civil engineering. These include a 7 km reduction in the overall circumference of the main tunnel, a reduction in the number of surface sites from 12 to eight, and a reduction in the number of permanent shafts from 18 to 12 (two at each of the four experiment sites, one at each of the four technical sites). A temporary shaft will also be required for the construction of the transfer tunnel connecting the injection system to the FCC tunnel, although it may be possible to re-use an existing but unused shaft for this purpose. Additional underground civil engineering for the RF systems will also be required. The diameter of the main tunnel (5.5 m) and its inclination (0.5%) remain unchanged, resulting in a tunnel depth that varies between approximately 50 m – where it passes under the Rhône River – and 500 m – where it passes beneath the Borne plateau on the eastern side of the study site.



One of a kind *A schematic layout (not to scale) of the underground civil engineering for the FCC-ee machine and infrastructure. (Credit: FCC study)*

The tunnel would be constructed using up to eight TBMs, which are able to excavate and install the tunnel lining in a single-pass operation. Desktop studies show that the geology that would be encountered during most of the underground construction would be favourable, since the molasse rock is usually watertight and can be easily supported using a range of standard rock-support measures. The main beam tunnel will, however, need to pass through about 4.4 km of limestone, which may require the drill-and-blast method to be utilised. These geological assumptions need to be confirmed via a major *in situ* site investigation campaign planned for 2024–2025.

Two sizes of experiment cavern complexes are envisaged, serving both the lepton and hadron FCC stages. One includes a cavern to house the largest planned FCC-hh detector with dimensions of 35 × 35 × 66 m (similar to the existing ATLAS cavern) and the other a 25 × 25 × 66 m cavern to house the smaller FCC-ee detectors (similar to the CMS cavern). A second cavern 25 m wide and up to 100 m long would be required at each experiment area to house various technical infrastructure, while a 50 m-thick rock pillar between the detector and the service caverns would provide electromagnetic shielding from the detector as well as the overall structural stability of the cavern complex. Numerous smaller caverns and interconnecting tunnels

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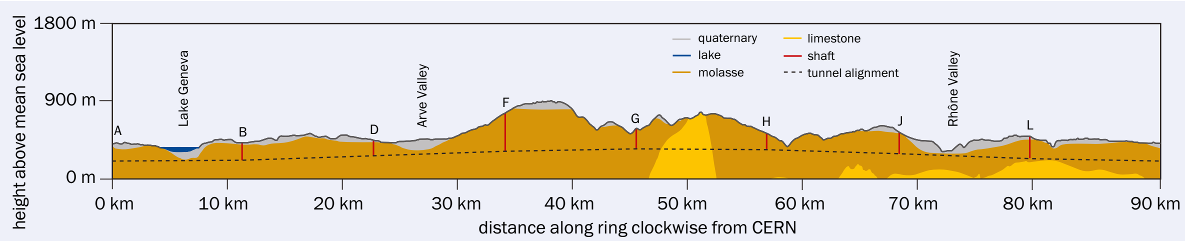
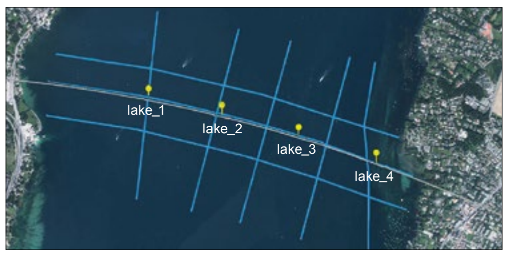
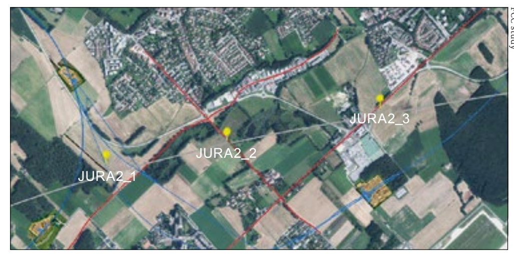
John Osborne *CERN.*



Geological profile *The FCC tunnel would encounter the two main geological units of the Geneva basin: molasse and limestone.*





Site studies *The locations of the boreholes that will be used to sample the geology beneath the lake (left) and Jura (right) sectors of the FCC ring during 2024 and 2025.*

and galleries will be required to link the main structures, and these are expected to be excavated using road-header machines or rock breakers.

Conceptual layouts for two of the eight new surface sites have been prepared under a collaboration agreement with Fermilab, and studies of the experiment site at Ferney-Voltaire in France and the technical site at Choulex/Presinge in Switzerland have been undertaken. The requirements for other surface sites will be developed into preliminary designs in the second half of the feasibility study. In addition, several locations have been investigated for a new high-energy linac, which has been proposed as an alternative to using the SPS as a pre-injector for the FCC, with the most promising site located close to the existing CERN Prévessin site.

Feasibility campaign

As an essential step in demonstrating the feasibility of underground civil-engineering works for the FCC, CERN has been working with international consultants and the University of Geneva to develop a 3D geological model using information gathered from previous borehole and geophysical investigations. To improve this understanding, a targeted campaign of subsurface investigations using a combination of geophysical analyses and deep-borehole drilling has been planned in the areas of highest geological uncertainty. The campaign, which is currently being tendered with specialist companies, will commence in 2024 and continue into 2025 to ensure that the results are available before the end of the feasibility study. About 30 boreholes will be drilled and used in conjunction with 80 km of seismic lines to investigate the location of the molasse rock, in particular under Lake Geneva, the Rhône river and in those areas where limestone formations may be close to the planned tunnel horizon.

With a total of around 15 million tonnes of rock and soil to be excavated, sustainability is a major focus of the FCC civil-engineering studies

On the surface, there is scope for staging the construction of buildings. All the buildings that are only required for the FCC-hh phase would be postponed, but the land areas needed for them would be reserved and included in the overall site perimeter. Buried networks, roads and technical galleries would be designed and constructed such that they can be extended later to accommodate the FCC-hh structures.

With a total of around 15 million tonnes of rock and soil to be excavated, sustainability is a major focus of the FCC civil-engineering studies. To this end, in the framework of the European Union co-funded FCC Innovation Study, CERN and the University of Leoben launched an international challenge-based competition, "Mining the Future", in 2021 to identify credible and innovative ways to reuse the molasse. The results of the competition include the use of limestone for concrete production and stabilisation of constructions within the project, the re-use of excavated materials to back-fill quarries and mines, the transformation of sterile molasse into fertile soil for agriculture and forestry, the production of bricks from compressed molasse, and the development of novel construction materials with molasse ingredients for use in the project as far as technically suitable. The next step is the implementation of a pilot "Open Sky Laboratory" permitting the demonstration of the separation techniques of the winning consortium (led by BG engineering), and collaboration with CERN's host states and other stakeholders to identify suitable locations for its use. In addition, the FCC feasibility study is working towards a full assessment to minimise the carbon footprint during construction.

The civil-engineering plans for the FCC project have been presented several times to the global tunnelling community, most recently at the 2023 World Tunnel Congress in Athens. The scale and technical complexity of the project is creating a great deal of interest from designers and contractors, and has even triggered a dedicated visit to CERN from the executive committee of the International Tunnelling Association, which reinforces the significant progress that has been made. ●

THE PEOPLE FACTOR

The FCC collaboration is a dynamic amalgamation of individuals, institutes and countries working to push technologies and develop new instruments to enable the next leap in particle physics. It is imperative to recognise the dedication of existing members while inviting new partners to bring their unique skills and perspectives.

Forward looking *The 7th FCC physics workshop, held in Annecy in early 2024.*

Since its inception a decade ago, the Future Circular Collider (FCC) collaboration has evolved in scope and scale – especially since the completion of the conceptual design report in 2018, when directed efforts were made to broaden the project's reach and attract new partners. Such endeavours are crucial considering the ambitious nature of the FCC project and the immense global collaboration required to bring it to fruition.

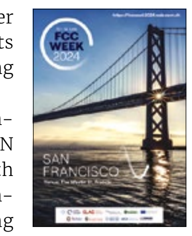
Today, the collaboration brings together more than 130 institutes from 31 countries. Contributions from members span a broad spectrum encompassing theoretical and experimental particle physics, applied science, engineering, computing and technology. Ongoing collaborations with research centres internationally are pushing the performance of key technologies such as superconducting radio-frequency cavities and klystrons, as well as magnets based on novel high-temperature superconductors (see p38). Increased global collaboration is a prerequisite for success, and links with high-tech industry will be essential to further advance the implementation of the FCC.

The proposed four-interaction point layout for the FCC is not only designed to offer the broadest physics coverage, but makes it a future collider commensurate with the size and aspirations of the current high-energy physics community. The attractiveness of the FCC is also reflected in the composition of participants at annual conferences, which shows a good balance between early-career and more senior researchers, geographical diversity, and gender. The latter currently stands at a 70:30 male-to-female ratio, which has been increasing during the course of the feasibility study.

Global working group

The FCC feasibility study has established a global working group with a mandate to engage countries with mature communities, a long-standing participation in CERN's programmes, and the potential to contribute substantially to the project's long-term scientific objectives. In addition, an informal forum of national contacts allows exchanges between physicists from different countries and the development of collaborations inside FCC. Each interested country has one or two national contacts who have the opportunity to report regularly on the development of their FCC activities.

Drawing parallels with the LHC and HL-LHC successes, CERN's unique experience with large-scale scientific collaborations has been invaluable in shaping the cohesive and productive environment of the FCC collaboration. It is imperative to recognise the dedication of existing members while addressing the need for new contributors to bolster the collaboration. As the FCC considers the next stage of its scientific journey, potential partners are invited to bring their unique skills and perspectives.



Go west *The 10th FCC conference will take place in San Francisco on 10–14 June.*

First discussions on the governance and financial considerations for the FCC project are taking place in the CERN Council. The models aim to provide a structure for both the construction and operation phases, and assume compatibility with the CERN Convention, while also taking into account the United Nations' sustainable development goals. In parallel, the organisational structure of the FCC experiment collaborations is being discussed. Given the inherently cooperative and distributed nature of these collaborations, a relatively lightweight structure will be put forth, based on openness, equality at the level of participating institutes and a wide consultation within the collaboration for key decisions.

Since 2021, the FCC has implemented a robust organisational structure, acting under the authority of the CERN Council, that facilitates efficient communication and coordination among its members. Looking ahead, the path to the governance model required for the FCC project and operation phases is both exciting and challenging. Importantly, it requires the long-term engagement and support of participants from CERN's member and associate member states, and from the non-member states, whose community at CERN has been growing with the LHC, particularly from institutes located in North America and the Asia-Pacific regions. As the project evolves further, it is crucial to refine and adapt the collaboration model to ensure the efficient allocation of resources and sustained momentum.

The FCC offers a multitude of R&D opportunities, and the collaborative spirit that defines it promises to shape the future of particle physics. As we go forward, the FCC collaboration beckons individuals and institutions to contribute to the next chapter in our exploration of the fundamental laws and building blocks of the universe. ●

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CERNCOURIER
Volume 64 Number 2 March/April 2024
IOP Publishing

ADVANCING HARDWARE

Vacuum, radio-frequency, magnet and alignment experts offer a snapshot of some of the latest progress towards key FCC-ee components.

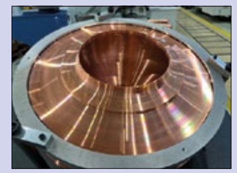
Vacuum system

CERN

The CERN vacuum group has been actively designing components for the FCC-ee vacuum system. Among them are 3D-printed synchrotron-radiation absorbers (SRAs), cold-sprayed copper "bosses", which could be machined to obtain weld- and flange-free beam position monitor button electrodes (pictured), and plasma-sprayed thin titanium tracks to be used as a radiation-hard bake-out heating system. In parallel, a collaboration with a spin-off company from the University of Calabria is dealing with the implementation of shape-memory alloy flanges. The design of a 2 m-long vacuum chamber extrusion with one SRA is almost finalised, and a soon-to-be-built prototype will be tested at the KARA light source at KIT. We have also begun studying a vacuum chamber with a smaller inner diameter compared to the FCC-ee baseline, including its impact on the machine-detector interface and the booster. The length of the vacuum sectors has been optimised, and their integration in the overall tunnel design is under study. The vacuum group is also looking forward to prototyping the required NEG-coating set-up, as the vacuum chambers could be up to 12 m long and coating them in a vertical position, as is usually done, would be difficult, especially for industry when moving to mass production.

Robert Kersevan *CERN.*

Superconducting cavities



CERN

A key goal of R&D for the FCC superconducting radio-frequency (SRF) system, conducted by the CERN SY-RF, TE-VSC and EN-MME groups, is to optimise Nb/Cu technology for the fabrication of the cavities. Achieving high SRF performance in thin-film-coated cavities requires minimising substrate defects. Previous experiences show that imperfections located around electron beam welds in areas subjected to high magnetic field areas can constrain the quality factor of Nb/Cu cavities. To surpass the current limitations of Nb-coated cavities, a seamless configuration along with higher substrate quality and shape conformity is a promising alternative. Instead of traditional shaping methods such as deep-drawing or spinning, the ongoing use of techniques such as hydroforming and machining directly from the bulk material shows high potential for valuable results without altering the substrate. Moreover, it ensures effectiveness, repeatability and precision in the final shape of the cavity. Based on the impressive RF performance obtained from seamless Nb-coated 1.3 GHz cavities manufactured at CERN from bulk copper, the CERN teams are confident that such spectacular results will be repeated with a 400 MHz cavity (pictured) that is being machined as a preliminary prototype for the FCC RF study.

Said Atieh *CERN.*

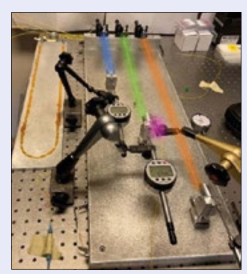
HTS main arc magnets

M Koratzinos

At the end of 2023, the first demonstrator of a high-temperature superconductor (HTS) sextupole designed for the FCC-ee arcs was fabricated at CERN (pictured). Built using novel technology from a CERN spin-off company, the magnet adopts a "canted cosine theta" design and is the first such device to use HTS rare-earth barium copper oxide (ReBCO) tape as its conductor – something that was long considered technically challenging. The main advantage of such a magnet is that ohmic losses (a significant source of electric power consumption for a normal-conducting accelerator) are reduced to zero, whereas refrigeration losses are much reduced compared to low-temperature-superconductor devices. Other advantages include increased performance due to the possibility of "nesting" magnets together, which is not possible for normal-conducting magnets that use iron to shape their magnetic fields. The increase in performance is such that up to 40% of the cost of the system can be recovered from the lower required RF voltage and therefore a smaller number of accelerating RF cavities. The magnet is the fruit of a CERN–PSI collaboration called FCCee-HTS4, funded through the CHART consortium in Switzerland. Future plans include the winding of the magnet at CERN, followed by tests for magnetic performance and quality.

Mike Koratzinos *PSI.*

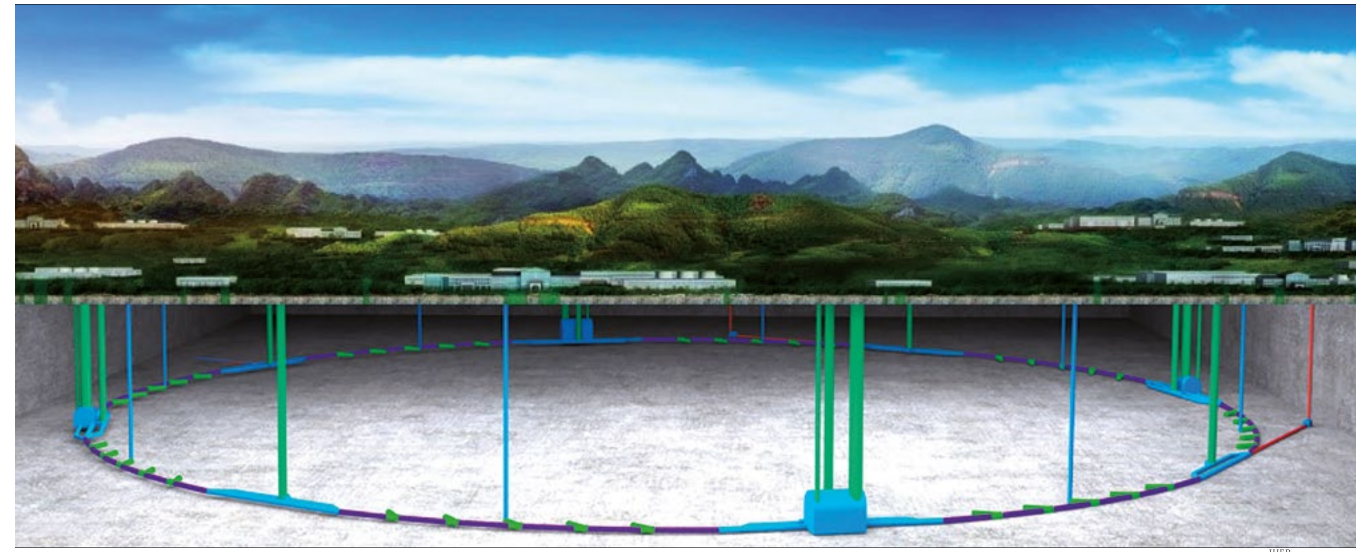
Machine-detector interface alignment



L Watrelot

Designed to meet strict alignment requirements in the FCC-ee interaction points, the Machine Detector Interface (MDI) alignment system is a key element of the feasibility study. Challenging conditions – including extremely low temperatures, elevated radiation levels and limited space – hinder the deployment of standard survey equipment and sensors in this important region. New and exotic techniques and sensing systems have therefore been studied. The main solution, called in-lined multiplexed and distributed frequency scanning interferometry (IMD-FSI), uses an interferometer with a wavelength-sweeping laser source to measure multiple lengths along a single optical fibre, simultaneously and independently. A network of fibres can then be installed in a helical pattern to monitor the shape of components inside the MDI, such as the support of the screening solenoid. A prototype IMD-FSI system (pictured) has proved extremely promising, and the next step is a full fibre network implementation on a cylinder. This system could also be implemented in other regions of the collider, for example to monitor sensitive tunnel sections or other civil-engineering structures such as towers, dams and bridges.

Léonard Watrelot *CERN.*



IHEP

CHINA'S DESIGNS FOR A FUTURE CIRCULAR COLLIDER

The completion of the accelerator technical design report for the proposed Circular Electron–Positron Collider in China marks a milestone towards construction, write Jie Gao, Yuhui Li and Chenghui Yu.

To uncover the fundamental laws of the universe and its evolution is a great human endeavour. The most effective way to achieve this goal in particle physics is via powerful, high-energy accelerators. The July 2012 discovery at CERN of the Higgs boson with a mass of 125 GeV opened a door to an unknown part of the universe. The Higgs boson is not only at the heart of the Standard Model (SM) but is also at the centre of many mysteries. These include the large hierarchy between the weak and the Planck scales, the nature of the electroweak phase transition, the origin of mass, the naturalness problem, the stability of the vacuum, and many other related fundamental questions about nature beyond the SM, such as the origin of the matter–antimatter asymmetry and the nature of dark matter.

Precise measurements of the Higgs boson's properties serve as probes into the underlying fundamental physics principles of the SM and beyond. For this reason, in September 2012 Chinese scientists proposed the Circular Electron–Positron Collider (CEPC) and the Super proton–proton Collider (SppC) as an international, large science project hosted in China to match the grand goals of particle physics, complementary to linear and muon colliders. Around the same time, physicists at CERN proposed the Future Circular Collider (FCC) staged across electron–positron (e^+e^-) and hadron–hadron operations.

Since then, the global high-energy physics community has reached consensus on the importance of an e^+e^- Higgs factory as the next collider after the LHC. In Europe, the 2020 update of the European strategy for particle physics concluded that a Higgs factory is the highest priority, while the US Snowmass 2021 community study and subsequent

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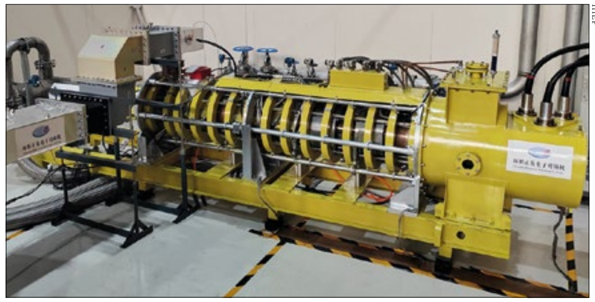
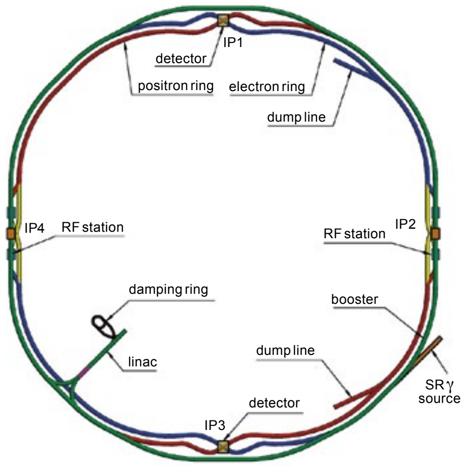
CERNCOURIER

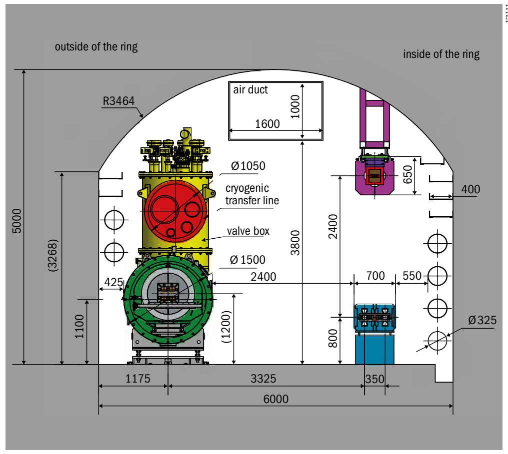
Volume 64 Number 2 March/April 2024

IOP Publishing



CEPC technologies *A 1.3 GHz 8×9-cell cavity cryomodule (left) and a 650 MHz 800 kW continuous-wavelength, high-efficiency klystron (right) developed and tested at IHEP in Beijing.*





Going underground *The CEPC layout (left) and a cross section of the tunnel if drill-and-blast methods are used (right) showing the SppC ring and cryogenic modules (green and red) on the outer side and the CEPC booster (purple) and collider rings (blue) on the inner side.*

P5 report released in December 2023 also stressed the importance of overseas Higgs factories. CEPC scientists have actively contributed to both exercises. Meanwhile in Japan, which proposed to host an International Linear Collider (ILC) Higgs factory in 2012, a new baseline design to start at a collision energy of 250 GeV instead of 500 GeV was presented in 2017.

In China, both the 464th and 572th Xiangshan Science Conferences in 2013 and 2016 concluded that "CEPC is the best approach and a major historical opportunity for the national development of an accelerator-based high-energy physics programme". In 2023, CEPC was identified as the top future particle accelerator in the planning study conducted by the Chinese Academy of Sciences (CAS). This followed an April 2022 statement by the International Committee for Future Accelerators (ICFA) that "reconfirms the international consensus on the importance of a Higgs Factory as the highest priority for realising the scientific goals of particle physics" and expressed support for Higgs-factory proposals worldwide. Five years after the publication of a conceptual design report in November 2018, a technical design report (TDR) for the CEPC accelerator – numbering more than 1000 pages and representing the first such report for a Higgs factory based on a circular collider – has now been completed.

CEPC is a circular Higgs factory comprising four accelerators: a 30 GeV linac, a 1.1 GeV damping ring, a booster with an energy up to 180 GeV, and a collider operating at four different energy modes corresponding to ZH production (240 GeV), the Z-pole (91 GeV), the W^+W^- threshold (160 GeV) and the $t\bar{t}$ threshold (360 GeV). The machines are connected by 10 transport lines. While the linac and damping ring would be constructed on the surface, the booster and collider would be situated in an underground ring with a circumference of 100 km, reserving space for a later hadron collider, SppC.

CEPC in focus

The CEPC collider features a double-ring structure, with electron and positron beams circulating in opposite directions in separate beam pipes and colliding at two interaction points where large detectors will be installed. The 100 km-circumference full-energy CEPC booster, positioned atop the collider in the same tunnel, functions as a synchrotron featuring a 30 GeV injection energy and an extraction energy equal to the beam collision energy. To maintain constant luminosity, top-up injection will be employed. The 1.8 km-long linac, which serves as an injector to the booster, accelerates both electrons and positrons using S- and C-band radio-frequency systems, equipped with a damping ring to reduce positron emittance. As an alternative option, polarisation schemes are also under study.

CEPC is the best approach and a major historical opportunity for the national development of an accelerator-based high-energy physics programme

A follow-up to CEPC is SppC, a proton–proton collider with a centre-of-mass energy of up to 125 TeV. The tunnel, primarily consisting of hard rock that will be excavated using either a tunnel boring machine or drill-and-blast methods, allows the SppC to be installed without removing the CEPC. This unique layout opens exciting long-term possibilities for electron–proton and electron–ion physics in addition to the CEPC's e^+e^- and the SppC's proton–proton and ion–ion physics operations. Furthermore, the CEPC would be configured to operate as a high-energy synchrotron-radiation light source with two gamma-ray beamlines, extending the usable synchrotron-radiation spectrum to unprecedented energy (from 100 keV to more than 100 MeV) and brightness ranges. The 30 GeV injection linac can also produce a high-energy X-ray free electron laser by adding an undulator.

Dedicated goals

The CEPC operation plan and physics goals follow a "10-2-1-5" scheme, dedicating 10 years as a Higgs factory, two years as a Z factory, one year as a W factory and possibly an additional five years' operation at the $t\bar{t}$ threshold. The four collision modes (corresponding to H, Z, WW and $t\bar{t}$ production) have a baseline synchrotron radiation power of 30 MW per beam. Luminosity upgrades are also considered by increasing the synchrotron-radiation power per beam up to 50 MW, reaching a luminosity of 8×10^{34} at 240 GeV. With the upgraded luminosity plan, 4.3 million Higgs bosons, 4.1 trillion Z bosons, 210 million W bosons and 0.6 million $t\bar{t}$ pairs would be produced in the two CEPC detectors.

After the completion of the CEPC conceptual design report, the accelerator entered a five-year-long TDR study during which the design was further optimised. The resulting report, released on 25 December 2023, emphasises the optimal luminosity, coverage of H, Z, W and $t\bar{t}$ energies, and the full spectrum of technology R&D, civil-engineering designs, industrial and international collaborations and participation.

Smaller emittances at the interaction points have been adopted to increase the luminosities, dynamic apertures including various errors for four energies match the design goals, beam–beam and collective effects have been verified, and the machine–detector interface has been optimized with a 20 cm-diameter central beryllium pipe at the interaction points. The booster has adopted a theoretical minimum emittance-like lattice design with an injection energy raised to 30 GeV and output energy of up to 180 GeV.

Boosting R&D *A full-size prototype dipole magnet for the CEPC booster.*

CEPC accelerator R&D has been conducted in synergy with the fourth-generation 6 GeV High Energy Photon Source project at IHEP in Beijing. These R&D activities cover the collider and booster magnets, superconducting quadrupoles for the insertion regions, NEG-coated vacuum chambers, superconducting cryomodules, cryogenic systems, continuous-wavelength high-efficiency klystrons, magnet power supplies, mechanics, S-band and C-band linac and positron source, damping ring, instrumentation and feedbacks, control system, survey and alignment, radiation protection and environmental aspects.

As three examples, firstly the CEPC booster 1.3 GHz 8×9-cell cavity cryomodule has been shown to reach a quality factor/accelerating gradient of 3.4×10^{10}/23 MVm^{-1}, surpassing the booster specification (see "CEPC technologies", left image). Secondly, the CEPC 650 MHz one-cell cavity reached 2.3×10^{10}/41.6 MVm^{-1} at 2 K with electrical-polishing treatment and 6.3×10^{10}/31 MVm^{-1} with medium-temperature treatment. Thirdly, three collider-ring 650 MHz, 800 kW continuous-wavelength high-efficiency klystrons have been developed at IHEP, where the second klystron (see "CEPC technologies", right image) has reached an efficiency of 77.2% at 849 kW in pulsed mode compared with the design value of 77% at 800 kW in CW mode. The third klystron is a multibeam klystron with a design goal of 80.5%, and its electron source is currently undergoing tests. The achievements of the CEPC accelerator TDR are also a result of strong industrial participation and contributions, via the CEPC industrial promotion consortium.

High-energy ambitions

As part of future strategic technology R&D in high-energy physics and beyond, the CEPC team has proposed an alternative beam-driven plasma injector with beam energies from 10 to 30 GeV. To develop and demonstrate the necessary plasma technologies, such as positron acceleration, staged acceleration and high beam qualities for future linear colliders, IHEP initiated a plasma acceleration experimental programme in September 2023 using the injector

IHEP

Merry Christmas *The formal release of the CEPC accelerator technical design report on 25 December 2023.*

linac of BEPCII (a 1.89 GeV e^+e^- collider with a luminosity of 10^{33} cm^{-2}s^{-1}) and experimental facilities funded by CAS to the tune of RMB 0.12 billion ($17 million).

The SppC, in conjunction with the CEPC, would not only provide unprecedented precision on Higgs-boson measurements but explore a significantly larger region of the new-physics landscape, propelling our understanding of the physical world to new heights. A future hadron collider is both more costly than a Higgs factory and more technically challenging. Critical issues such as high-field (20 T or higher) superconducting magnets, synchrotron radiation in a cryogenic environment and a sophisticated beam-collimation system for quench protection must be adequately addressed before construction can begin.

High-field magnets based on high-temperature iron-based superconductors are proposed as the key development path for the SppC. This technology has a much higher magnetic field potential (>30 T) and lower cost than the NbTi/Nb_3Sn technologies used nowadays, and significant progress has been made, together with industry, during the past eight years. In 2016 more than 100 m of iron-based "7-core" tape was fabricated, reaching a current density of 450 A/mm^2 at 10 T and 4.2 K in 2022.

The SppC is expected to achieve a peak luminosity of 10^{35} cm^{-2}s^{-1} per interaction point and an integrated luminosity of approximately 30 ab^{-1}, assuming two interaction points and a runtime of 20–30 years. To further reduce the energy consumption of SppC and CEPC (which has a total power consumption of 262 MW at the ZH energy with a synchrotron-radiation power of 30 MW per beam), various countermeasures are under study.

From 2019 to 2022, CEPC accelerator activities were guided by an International Accelerator Review Committee. In June and September 2023, the CEPC accelerator international TDR and cost review were carried out at Hong Kong University of Science and Technology, while the civil-engineering cost was reviewed by a domestic committee in June 2023. The total CEPC cost is estimated at RMB 36.4 billion ($5.15 billion), with accelerator, infrastructure and experiments taking up RMB 19 billion, 10.1 billion and 4 billion, respectively. Among all the CEPC candidate sites, three – Qinhuangdao, Huzhou and Changsha – have been studied in the TDR.

The SppC, in conjunction with the CEPC, would propel our understanding of the physical world to new heights

At the end of October 2023, the CEPC international advisory committee supported the conclusion of the TDR review that the accelerator team is well prepared to enter an engineering design report (EDR) phase. The following month, CEPC–SppC proposals were presented at the ICFA Seminar at DESY, declaring the completion of the CEPC accelerator TDR.

Concerning the technology and status of the CEPC detectors, a full spectrum R&D programme has been carried out, spanning the pixel vertex detector, silicon tracker, time projection chamber and drift chamber, time-of-flight detector, calorimeters, high-temperature superconducting solenoid and mechanical design, among others. This R&D also benefits from past experiences with BESIII (in particular concerning the drift chamber and superconducting magnet) and from the High-Luminosity LHC upgrades for ATLAS and CMS (such as the silicon-strip detector and high-granularity calorimeter). The CEPC detector TDR reference design began in January 2024 and will be completed in mid-2025 within the EDR phase (2024–2027).

EDR and schedule

The aim is to present the CEPC proposal (including accelerator, detector and engineering) for selection by the Chinese government around 2025, with construction to start in around 2027 and to be completed around 2035. A preliminary accelerator EDR plan has been established and is to be reviewed by the International Accelerator Review Committee in 2024.

Concerning CEPC development towards construction, CAS is planning for China's 15th "five-year plan" for large science projects, for which a steering committee chaired by the CAS president was established in 2022. High-energy physics and nuclear physics, one of eight fields in the plan, has selected nine proposals that have been reviewed in an open and international way. CEPC is ranked first, with the smallest uncertainties by every committee (including domestic committees and an international advisory committee). A final report has been submitted to CAS for consideration.

CEPC has always been envisioned as an international big-science project, and participation is warmly welcomed both in scientific and industrial ways. The CEPC accelerator TDR represents the efforts of thousands of domestic and overseas scientists and engineers. Such a facility would play an important role in future plans of the worldwide high-energy physics community, deepening our understanding of matter, energy and the universe to an unprecedented degree while facilitating extensive research and collaboration to explore the frontiers of technology. ●

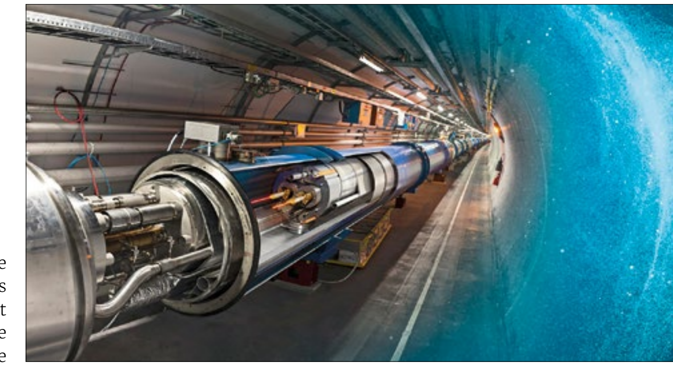
Further reading

CEPC Study Group 2018 arXiv:1809.00285 and 1811.10545.
CEPC Accelerator Study Group 2019 arXiv:1901.03169 and 1901.03170.
CEPC Accelerator Study Group 2022 arXiv:2203.09451 and 2205.08553.
CEPC Study Group 2023 arXiv:2312.14363.

Quo vadis, European particle physics?

With accelerator and detector R&D for a future e^+e^- collider advancing quickly and physics studies being consolidated, what remains, says Paris Sphicas, is for the community to converge on the next machine in the context of the next European strategy update.

CERN



Into the unknown *All eyes are on how CERN will pursue the advancement of the field in the post-LHC era.*

P Sphicas

Paris Sphicas, *National and Kapodistrian University of Athens and CERN, started his three-year term as ECFA chair in January 2024.*

The 2020 European strategy for particle physics justifiably singled out the Higgs boson as the most mysterious element of the Standard Model. Uncovering the particle's true nature and answering the numerous questions raised by its interactions with other particles is set forth as the highest priority of the field. And this, the strategy concluded, requires the next dream machines: an e^+e^- Higgs factory and, in the longer term, a 100 TeV hadron collider. Getting there will be no easy feat, and thus several intermediate steps, necessary for bringing this programme to fruition, have been set in motion.

Firstly, the European Committee for Future Accelerators (ECFA) was called upon by the CERN Council to formulate a global detector R&D roadmap for both short- and long-term experimental endeavours. A painstaking consultation process across the entire range of detector technologies – from gas, liquid and solid-state detectors to particle-identification systems, calorimetry and blue-sky R&D – culminated in a 250-page document and the creation of detector R&D collaborations to focus on the most relevant topics. In parallel, the European Laboratory Directors Group has compiled an accelerator R&D roadmap spanning activities such as high-field magnets, high-gradient accelerating elements, plasma-wakefield acceleration, energy-recovery linacs, and more.

The entire field, and especially the younger generations, are most eagerly awaiting this decision

With the accelerator and detector development in the best of hands, what remains is to converge on the next machine: namely the e^+e^- collider that takes us as close as we can to a full understanding of the Higgs boson and the electroweak and top-quark sectors. Thankfully, we already know a lot about the reach of such "HET" factories from previous studies, in particular those carried out during the previous strategy update. To encourage further work en route to the next strategy update, ECFA has put together a HET-factory study group that brings together both the linear and circular e^+e^- detector communities. The goal is to solidify our understanding of the requirements that the physics places on the experiments and on the associated beams. A common software framework with more realistic detector simulation and a parallel study of detector structures are the other working areas in the study group. Good progress is visible, and the third and last major workshop on the HET-factory study will take place in October 2024.

Major players

The other major players in the global high-energy physics scene completed their corresponding strategy processes either several years ago (Japan with the ILC and China with the CEPC) or recently (US with the P5 process). All eyes are now turned to Europe as we enter the final stretch towards the next update of the European strategy. With the Future Circular Collider feasibility study due to be completed next year, all the elements needed for a fully informed decision on the future of European – and global – particle physics will soon be in place.

The next strategy process will build on the excellent work that took place in the context of the previous one, which culminated with a large community gathering in Granada. Taking into account the updated information, it is both expected and highly desirable that the process converges quickly, with a definitive recommendation on both the next e^+e^- collider and the longer-term prospects. The entire field, and especially the younger generations, are most eagerly awaiting this decision. Today, in parallel with maximally exploiting the physics potential of the LHC, our most important duty is to ensure that current PhD candidates find themselves at the centre of future discoveries a few decades from now.

Is all this possible for Europe? Absolutely! CERN has an unparalleled track record on the world stage with the ISR, Sp$\bar{p}$S and LEP legacies, as well as the tremendous success of the LHC. These have not only provided some of the greatest advances in our understanding of the fundamental elements of nature, but also serve as guarantors of CERN's ability to continue advancing the energy frontier, keeping Europe at the leading edge of scientific knowledge. All that is currently needed is the final direction – and the start signal. *Quo vadis* European particle physics? Towards the next discovery frontier, to further unravel the mysteries of the fascinating universe we have come to inhabit.

CERN COURIER
VOLUME 64 NUMBER 2 MARCH/APRIL 2024
IOP Publishing

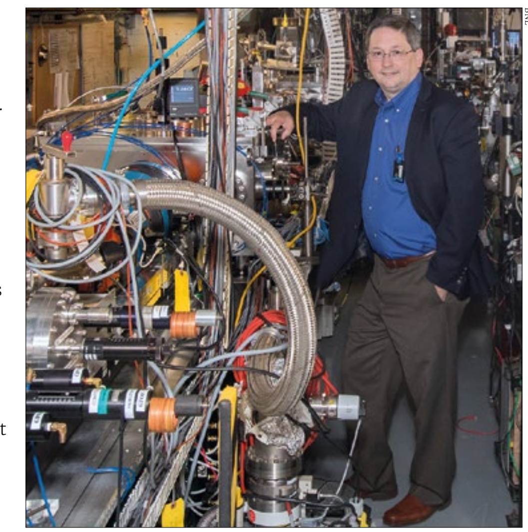
OPINION
INTERVIEW

Shooting for a muon collider

Significant technology development is required to establish the feasibility of a muon collider. Mastering it, says Mark Palmer, offers an alternative path to the next energy frontier.

Why is everyone talking about the muon collider?

The physics landscape has changed. We have not seen signs of new particles above the Higgs-boson mass. Typical limits are now well above 1 TeV based on LHC data, which means we need to look for the new physics that we anticipate at higher energies. The consensus during the recent US Snowmass process was that we should aim for 10 TeV in the centre-of-mass. A muon collider has the feature that its expected wall-plug power scales very favourably as you go to the multi-TeV scale. While significant technology development is required to establish the overall feasibility, performance and cost of such a machine, our current performance estimates make it a very interesting candidate. This motivates an active R&D and design programme to validate this approach.



Complex paths *Mark Palmer is director of accelerator science and technology at Brookhaven National Laboratory.*

Why was the US Muon Accelerator Program (MAP) discontinued a decade ago?

MAP was approved in early 2011 to assess the feasibility of the technologies required. By 2014, the community had just discovered the Higgs boson and was focused on pursuing a Higgs factory. Mature concepts based on superconducting (ILC) and normal-conducting (CLIC) linear-collider technologies were at hand, and these approaches envisioned subsequent energy upgrades that would enable the exploration of a new-particle spectrum extending into the TeV scale. Because of the relatively low mass of the Higgs, work was also going into a large circular collider design that would represent minimal technical risk. A muon collider, a concept with much lower overall maturity level and with significantly different operating characteristics, did not appear to provide a timely path to realising the Higgs factory.

The other application of interest involving muon-accelerator technologies was the neutrino factory. However, the field concluded that a long-baseline neutrino experiment based on the "superbeam source" represented the best path forward. In a constrained budget environment, the concepts being pursued by MAP didn't have sufficient priority and support to continue.

What do we know so far about the feasibility of a muon collider?

As the MAP effort concluded, several key R&D and design efforts were nearing completion and were subsequently published. These included demonstrations of normal-conducting RF cavities in multi-Tesla magnetic fields operating with >50 MV/m accelerating gradients, simulated 6D cooling-channel designs capable of achieving the necessary emittance cooling for collider applications, and a measurement of the cooling process at the international Muon Ionization Cooling Experiment (MICE).

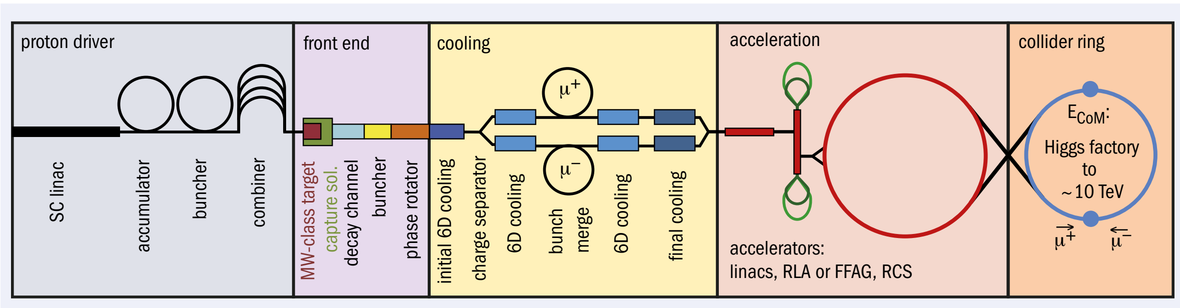
While MICE only characterised the performance of a partial cooling cell, the precise measurements provided by its tracking detector system confirmed that the muons behaved consistently with the cooling process as described in the simulation codes that were employed to design the cooling channel for a high-brightness muon source.

Another key advance was detailed simulations of the performance of a muon-collider detector in the lead-up to the last European strategy update. These efforts, utilising the beam-induced background samples prepared by MAP, demonstrated that useful physics results could be obtained with reasonable assumptions about the performance of the individual elements of the detector.

How are things going with the International Muon Collider Collaboration (IMCC)?

The IMCC, led by CERN with European funding support from the MuCol project, presently coordinates global activities towards R&D and design. The collaboration's input has been crucial in developing the technically limited timeline towards a multi-TeV muon collider as outlined in the accelerator R&D roadmap commissioned by the European Laboratory Directors Group. The IMCC is making excellent progress towards a reference design for the muon-collider complex as well as defining a cooling demonstrator. An interim report is currently being prepared. However, current funding levels for the effort correspond to roughly half of the estimated levels required to achieve the technically limited timeline. With the strong support for pursuing an energy-frontier muon collider in the US, it is hoped that a fully global effort will be able to support the effort at levels that much more closely match the requirements of a technically limited timeline.

CERNCOURIER
Volume 64 Number 2 March/April 2024
IOP Publishing



Dream machine *The famous diagram, produced by Mark Palmer, showing the main components of a high-energy muon collider.*

How does the IMCC relate to the P5 recommendations for reinvigorated muon collider R&D at Fermilab?
Any future collider operating at the energy frontier will have to be supported by a global development team, and the issue of where such a machine can be sited will depend on a complex set of circumstances that we certainly can't predict now. The fundamental goal is to identify the technology and one or more sites where it can be deployed so that we are able to continue our exploration of the fundamental building blocks and processes in the universe for all humankind. Thus, the current IMCC activities are fully aligned with the aspiration expressed by P5 to explore the option for conducting muon collider R&D in the US and exploring the possibility of Fermilab as a host site for a future machine.

What are the key accelerator challenges to be overcome?
While there are a number of challenging subsystems to engineer, the most novel aspect of the machine remains the ionisation cooling channel. Demonstration of the beam operations of a cooling module at high beam intensity will be necessary to give us confidence that the technology is robust enough for high-energy physics applications. In addition to this absolutely unique subsystem of the muon collider, we require detailed end-to-end simulations of the overall machine performance, detailed engineering conceptual designs for all key components, and successful engineering demonstrations of suitable-scale prototypes for several critical systems. These include the target, the fast-ramping magnet system for the high-energy accelerator stages, the large-aperture collider ring magnets that must be adequately shielded against the decay products of the muon beams, and detector subsystems that can robustly operate in an environment with the beam-induced backgrounds from the muon decays.

And the detector challenges?
Tremendous progress in detector technology has resulted from the design and operation of the LHC detectors. Further progress in obtaining precision physics measurements in very high-occupancy environments as we prepare for the HL-LHC provides confidence for the detector requirements of a muon collider, which will have to deal with similar hit rates. While the details of the occupancy in the detectors for these two types of machine are not identical, the concepts being implemented for better time and spatial segmentation appear quite effective for both.

A particular feature of the muon collider detector is the "shielding nozzle" that was first introduced in MAP to protect the innermost detector elements. These nozzles impact the overall physics performance by limiting the near-axis coverage. However, with detailed detector performance studies underway, we are now in a position to carry out detailed detector and shielding studies to optimise these elements for overall physics performance.

How is the vast neutrino flux being addressed?
The very high-energy muon beams in a collider result in a narrow cone of neutrinos being produced in the forward direction as they circulate around the collider ring. When the beams are moving through dipoles, the constant change in transverse direction helps to dilute this flux, but any straight sections in the ring effectively act as a high-energy neutrino source that shines in a specific direction.

Any future collider operating at the energy frontier will have to be supported by a global development team

The tremendous flux of neutrinos from a straight section of a TeV-scale collider are expected to create ionising radiation wherever they exit Earth's surface. Thus, there are a set of mitigation strategies incorporated into the design effort to make sure that there are absolutely no risks. This includes minimising the number of straight sections, incorporating magnet-movers that allow the vertical trajectories of the beams to be changed slowly throughout the collider, and ensuring that the beams do not exit in populated areas.

What does the timeline for a 10 TeV muon collider look like?
We need to deliver a complete end-to-end reference design in time for the next European strategy update and for the US interim panel review that was recommended in the P5 report. A conceptual design report (CDR) for a demonstrator facility then has to be completed such that construction could begin by around 2030. Over the course of the next decade, the engineering design concepts for each subsystem have to be prepared and prototyping R&D has to be carried out, while also producing a CDR for the high-energy facility, including detailed performance simulations. By the late 2030s, the demonstrator facility and prototyping programme would enable detailed technical specifications for all key systems. Upgrades to the demonstrator facility could be necessary to further clarify performance and technical specifications. The final steps would be to complete a technical design that incorporates results from the demonstrator programme and to develop site-specific plans for the labs that would like to be considered as potential hosts for the facility. The start of 10 TeV collider operations would then be guided by a physics-driven plan, including potential intermediate stages, but likely at least a decade after construction approval.

The current schedule puts physics operations of a high-energy muon collider about five years earlier than an FCC-ee. Is this realistic?
I would characterise these two timelines as being of different types. The FCC-ee timeline is based on an integrated plan for CERN, while the 3 TeV muon collider is explicitly a technically limited plan which assumes that a sufficient funding profile can be provided, and that there are no external constraints that could impact deployment. In other words, the muon-collider timeline remains an aspiration, whereas the FCC-ee timeline attempts to build-in actual deployment constraints.

What is the estimated cost of a 10 TeV muon collider?
At present, the cost estimates rely on broad extrapolations from existing collider systems. While these extrapolations suggest that a multi-TeV muon collider may well be one of the most cost-effective routes to the energy frontier, the uncertainties remain large. To deliver a "realistic" cost estimate, we will require a complete end-to-end reference design, engineering conceptual designs for all of the unique systems required, detailed cost estimates for the engineering conceptual designs and extrapolated cost estimates for the remaining "standard" accelerator systems. With the present technically limited schedule as prepared by the IMCC, this would suggest that a detailed and realistic cost estimate could be available around the end of this decade.

A detailed and realistic cost estimate could be available around the end of this decade

How does a high-energy muon collider fit into the global picture?
There are multiple ways this can fit. At present, we need to acknowledge that the R&D for the magnets for a high-energy proton–proton machine, such as those being pursued in Europe and China, still require an extensive R&D programme. This is likely a multi-decade effort in and of itself, and is commensurate with the timescales needed to carry out muon-collider R&D and design work. Having more than one technology option on the table to achieve our ultimate physics goals is a necessity. Furthermore, the complementarity between lepton- and hadron-collider paths may be needed to support our overarching scientific goals.

From a somewhat different point of view, the potential applications of a high-intensity muon source extend beyond colliders. The technology offers improved performance and new opportunities for other scientific goals such as a high-performance source for future neutrino and charged lepton flavour violation experiments, materials science and active interrogation of complex structures, among others. Clarifying the broader context for the technology is currently being pursued within the IMCC effort.

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

OPINION REVIEWS

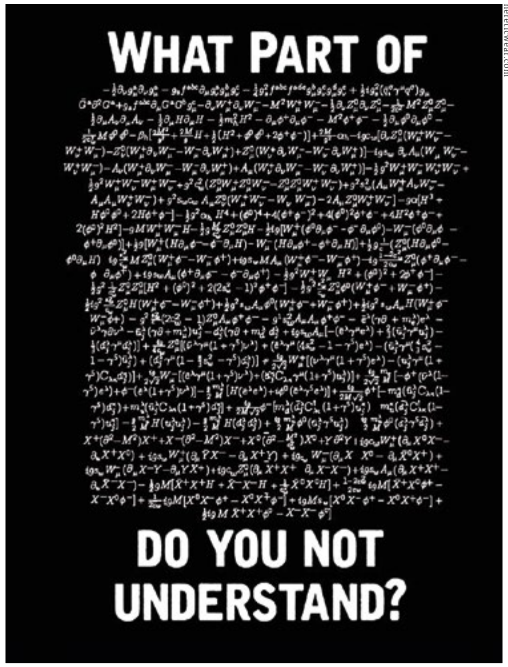
The full spectra of particle physics

Fundamentals of Particle Physics: Understanding the Standard Model

By Pascal Paganini

Cambridge University Press

This textbook for advanced undergraduate and graduate students, written by experimental particle-physicist Pascal Paganini of Ecole Polytechnique, aims to teach Standard Model calculations of quantities that are relevant for modern experimental research. Each chapter ends with a collection of unsolved problems to help the student practice the discussed calculations. The level is similar to the well-known textbook *Quarks and Leptons* by F Halzen and A D Martin (Wiley, 1984), but with a broader introduction and including more up-to-date material. The notation is also similar, and shared with several other popular textbooks at the same level, making it easy for students to use it along with other resources.

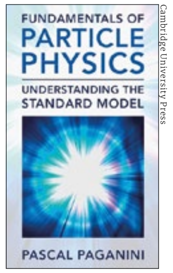


Clear instructions *Paganini introduces all aspects of particle physics, from calculations to experimental applications.*

Comprehensive

Fundamentals of Particle Physics starts with a general introduction that is around 50 pages long and includes information on detectors and statistics. It continues with a recap of relativistic kinematics, quantum mechanics of angular momentum and spin, phase-space calculations for cross sections and decays as well as symmetries. The main part of the book begins with a discussion of relativistic quantum mechanics, covering the equations of motion of spin 0, 1 and ½ particles along with a detailed description of Dirac spinors and their properties. Then, it addresses quantum electrodynamics (QED), including the QED Lagrangian, standard QED cross-section calculations and a section dedicated to magnetic moments (g–2). About 100 pages are devoted to hadronic physics: deep inelastic scattering, parton model, parton-distribution functions and quantum chromodynamics (QCD). Calculations in perturbative QCD are discussed in some detail and there is also an accessible section in non-perturbative QCD that can serve as a very nice introduction to beginner graduate students.

The book continues with weak interactions, covering the Fermi theory, W-boson exchange, CKM matrix, neutrinos, neutrino mixing and CP-violation. The following chapter presents the electroweak theory and introduces gauge-boson interactions. A dedicated chapter is reserved for the Higgs boson. This includes a nice section about the discovery of the particle and the measurements that are performed at the LHC, as well as some comments about the pre-history (LEP and Tevatron) and the future (HL-LHC and FCC). A clear discussion about naturalness and several other conceptual issues offers a light and useful read for students of any level. The final chapter goes through the Standard Model as a whole, including a very useful evaluation of its successes and weaknesses.



> ***Fundamentals* looks to teach Standard Model calculations of quantities that are relevant for modern experimental research**

In terms of beyond-Standard Model physics, only dark matter and neutrino masses are covered.

Although this is not a quantum field-theory textbook, some of its elements are introduced; in particular second quantisation, S-matrix, Dyson's expansion and a few words about renormalisation are included. These are very useful in bridging the gap between practical calculations and their theoretical background, also serving as a quick reference.

There are several useful appendices, most notably a 30-page introduction to group theory that can serve as a guide for a short standalone course in the subject or as a quick reference. The book also includes elements of the Lagrangian formalism, which could have been a bit more expanded to include a more detailed presentation of Noether's theorem, probably in an additional appendix.

Overall the book achieves a good balance between calculations and more conceptual discussions. All students in the field can benefit from the sections on the Higgs-boson discovery and the Standard Model. Being concise and not too long, *Fundamentals of Particle Physics* can easily be used as a primary or secondary textbook for a particle-physics course that introduces calculations using Feynman diagrams in the Standard Model to students.

Nikolaos Rompotis *University of Liverpool.*

Advances in Cosmology

Edited by M Streit-Bianchi, P Catapano, C Galbiati and E Magnani

Springer-Verlag

On the 30th anniversary of the discovery of weak neutral currents, the architects of the Standard Model of strong and electroweak interactions met in the CERN main auditorium on 16 September 2003 to debate the future of high-energy physics. During the panel discussion, Steven Weinberg repeatedly propounded the idea that cosmology is part of the future of high-energy physics, since cosmology "is now a science" as opposed to a mere theoretical framework characterised by diverging schools of thought. Twenty years later, this viewpoint may serve as a summary of the collection of articles in *Advances in Cosmology*.

The papers assembled in this volume encompass the themes that are today associated with the broad domain of cosmology. After a swift theoretical section, the contributions range from dark-matter searches (both at the LHC and in space) to gravitational waves and optical astronomy. The last two sections even explore the boundaries between cosmology, philosophy and artistic intuition. Indeed, as former CERN Director-General Rolf Heuer correctly puts it in his thoughtful foreword, the birth of quantum mechanics was also a philosophical enterprise: both Wolfgang Pauli and Werner Heisenberg never denied their Platonic inspiration and reading *Timaeus* (the famous Plato dialogue dealing with the origin and purpose of the universe) was essential for physicists of that generation to develop their notion of symmetry (see, for instance, Heisenberg's 1969 book *Physics and Beyond*).

In around 370 pages, the editors of *Advances in Cosmology* manage to squeeze in more than two millennia of developments ranging from Pythagoras to the LHC, and for this reason the various contributions clearly follow different registers. Interested readers will not only find specific technical accounts but also the wisdom of science communicators and even artists. This is why the complementary parts of the monograph share the same common goals, even if they are not part of the same logical line of thinking.

Advances in Cosmology appeals to those who cherish an inclusive and eclectic approach to cosmology and, more generally, to modern science. While in the mid 1930s Edwin Hubble qualified the frontier of astronomy as the "realm of the nebulae", modern cosmology combines the microscopic phenomena of quantum mechanics with the macroscopic effects of general relativity. As this monograph concretely demonstrates, the boundaries between particle phenomenology and the universe's sciences are progressively fading away. Will the next 20 years witness only major theoretical and experimental breakthroughs, or more radical changes of paradigm? From the diverse contributions collected in this book, we could say, *a posteriori*, that scientific revolutions are never isolated as they need environmental selection rules that come from cultural, technological and even religious boundary conditions that cannot be artificially manufactured. This is why paradigm shifts are often difficult to predict and only recognised well after their appearance.

Massimo Giovannini *CERN and INFN Milan-Bicocca, Italy.*

CERNCOURIER
VOLUME 64 NUMBER 2 MARCH/APRIL 2024
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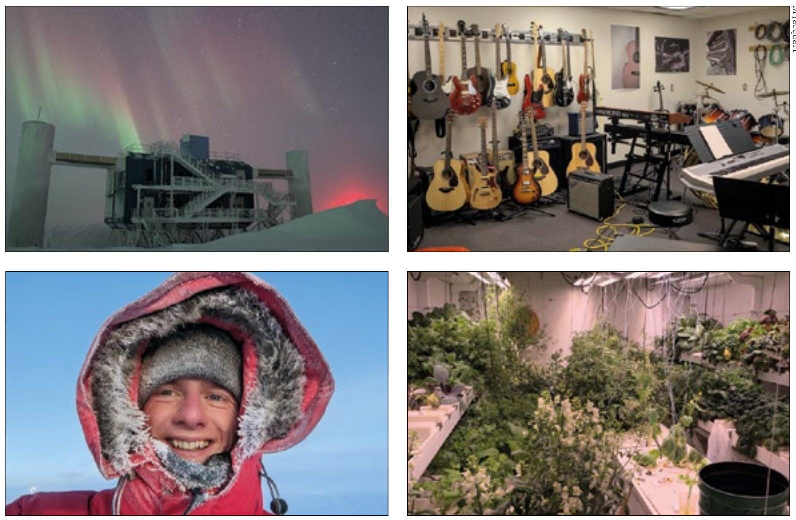
PEOPLE CAREERS

The coolest job in physics

Embedded in 3 km-thick ice, the IceCube Neutrino Observatory at the South Pole needs permanent human company to keep it operational. Recent IceCube "winterover" Marc Jacquart shares his experience of working in a cool but hostile environment.



M Jacquart

Light in the dark *(clockwise from top left) The Aurora Australis, a music room and a greenhouse help IceCube winterovers such as Marc Jacquart survive long polar nights.*

IceCube's 5160 optical sensors positioned deep within the Antarctic ice detect around 100,000 neutrinos per year, some of which are the most energetic events ever recorded. To make sure that the detector is operational throughout the year, people are required to spend extended periods at the South Pole, where temperatures are on average around –60°C during the winter.

Marc Jacquart was one of two "winterovers" for IceCube during the season November 2022 to November 2023. Having completed his master's degree, during which he analysed IceCube data, he saw an internal email about the position and applied: "It was a long-time dream-come-true. I had wanted to go to the South Pole since I heard about IceCube six years earlier." First he had to pass medical tests, a routine requirement for winterovers because it is difficult to evacuate people during the winter. His next stop was the University of Wisconsin–Madison, the lead institution for the IceCube collaboration, where he and his colleague Hrvoje Dujmović received three months' training on how to operate, troubleshoot, calibrate and repair IceCube's hardware and software components using a small replica of the data centre. "Our job is to ensure the highest detector uptime, so we need to know how to fix a problem immediately if something breaks."

The pair made their way to McMurdo Station on the shores of Antarctica closest to New Zealand in early November 2022. From there, a plane took them 1350 km to the Amundsen–Scott station, located 2835 m above sea level and only 150 m from the geographic South Pole. During the summer, up to 150 people stay at the station to make major repairs and upgrades to the research facilities, which also include the South Pole Telescope, BICEP and an atmospheric research observatory. By mid-February, most people leave. "We were only 43 winterovers left, and that's when you can help each other and busy yourself with all kinds of things," says Marc.

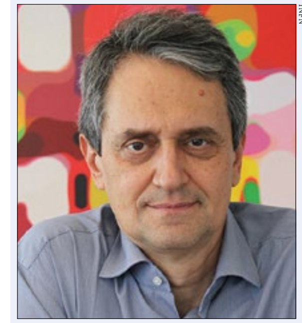
Part of station life is volunteering for teams, which in Marc's case included the fire fighters, amongst others. To bide their time during a nearly six-month-long night, the inhabitants can go to the library, music room or grow vegetables in a repurposed biology experiment to freshen up the preserved foods. While winter in the Antarctic Circle is harsh outside, says Marc, it has one major highlight: the southern lights. "I remember one time, they were just dancing, moving and very bright. We stayed outside for a full hour packed in layers and layers of clothes!"

As a winterover, Marc ensured that the IceCube detector worked 24/7 and recorded every incoming neutrino. "Usually, we have 99.9% uptime. If there is something wrong, we have a pager that pings us, even in the middle of the night." To ensure that the rarest high-energy neutrinos are recorded, the only real downtime for the detector, he says, is when operators perform a full restart every 32 hours. For such events, which could point to high-energy phenomena in the universe, IceCube sends a real-time alert to other experiments. About 200 machines are located in the data centre and collect 1 TB of data per day, only 10% of which are sent north to a data centre in the US due to satellite-bandwidth limitations. The remaining data gets stored on hard drives, which must be swapped manually by the winterovers every two weeks. During the summer, when aircraft can reach the South Pole on a regular basis, boxes stashed with hard drives are taken back for thorough data analysis and archiving.

Since returning home to Switzerland, Marc is considering his next steps. "I have the opportunity to work on a radio observatory in the US next year. After a year operating the IceCube detector, I'm interested to work with hardware more. And I am definitely considering a PhD with IceCube afterwards, as there is a lot coming up." Currently, the IceCube collaboration is working towards IceCube-Gen2, with the first step being to add seven strings with improved optical modules to the existing underground complex. In a second step, 120 further cables with refined light sensors will optimise the detector, and two radio detectors as well as an extended array will be placed on the surface. The upgrades will enlarge IceCube's coverage from one to eight cubic kilometres, offering more than enough tasks for future winterovers during the decade. "Maybe in a few years I would be keen to return to the South Pole. It's a very special place."

Sanje Fenkart *editorial assistant.*

Appointments and awards



New chairs for ICFA...

Experimental particle physicist Pierluigi Campana (INFN Frascati) took over from Stuart Henderson as chair of the 16-member International Committee for Future Accelerators (ICFA) on 1 January. Campana started out on the ALEPH and KLOE experiments, and since 2002 he has been a member of the LHCb collaboration, serving as spokesperson from 2011–2014. He was director at Frascati between 2011 and 2015.

...and ECFA

January also saw the ECFA (European Committee for Future Accelerators) chair pass from Karl Jacobs to Paris Sphicas (pictured; NKU Athens). After working on heavy flavours at the UA1 and CDF experiments, he joined the CMS collaboration in

the mid-1990s. His current focus is on searches for new physics and the trigger for the HL-LHC upgrade. Of utmost importance during his three-year mandate as ECFA chair is the next European strategy process (see p43).

New head at ESRF

The European Synchrotron Radiation Facility (ESRF) has appointed Jean Daillant as its next director general, succeeding Francesco Sette who has led the Grenoble-based light source for nearly 16 years. A soft-matter physicist by training, Daillant has been director general of the SOLEIL synchrotron since 2011, before which he was joint director of LURE at Orsay. He will take up the new position in September 2024.

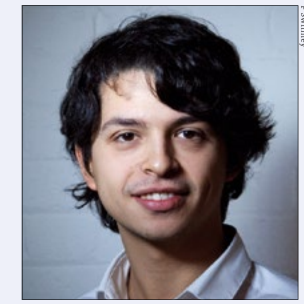
All change at Auger

In November, Antonella Castellina (pictured; INAF) was appointed spokesperson for the Pierre Auger Observatory in Argentina, which is devoted to the study of high-energy

cosmic rays. Her former role as co-spokesperson has been taken up by Markus Roth (KIT). Before moving to astroparticle physics, Castellina worked on diffractive physics using forward multi-particle spectrometers and on calorimeters for the study of proton decay via positions at UCLA and CERN. She then studied neutrinos from stellar collapses at the underground laboratories of Mont Blanc and Gran Sasso, and extensive air showers at the EAS-TOP observatory, where she led the analysis of data from the hadronic calorimeter.

GEO award for FCC paper

Building a new collider doesn't just involve cutting-edge accelerator and particle physics, but also requires a deep understanding of the proposed location. At the 2024 Geography of Innovation (GEOINNO) conference held at the University of Manchester from 10–12 January, Gabriele Piazza (LSE), whose research is co-funded by CERN in the



framework of the FCC feasibility study, won the Best PhD Paper Award for his paper "Where the God particle touches the ground: the local impact of research infrastructure procurement".

Cosmological win for QCD

A neat proposal to use QCD predictions to test a potential early-universe contribution to the stochastic gravitational-wave background (arXiv:2306.17136) has earned Gabriele Franciolini (pictured; CERN), Davide Racco (ETH Zurich) and Fabrizio Rompineve (Universitat Autònoma de Barcelona) third place in the 2023 Buchalter Cosmology Prize. Second place went to CNRS trio Denis Werth, Lucas Pinol and Sébastien Renaux-Petel for a novel

method to compute primordial correlation functions that can be used to test inflationary models (arXiv:2302.00655), while the first prize recognised Kyle Boone and Matthew McQuinn of the University of Washington for a new method to constrain cosmological parameters including the Hubble constant (arXiv:2210.07159).

New-physics group

DESY theorist Johannes Braathen has received €1.59 million from the German Research Foundation to set up the Emmy Noether research group. Due to run for six years and to support researchers in achieving independence at an early stage of their careers, the group aims to make extremely precise and generic theoretical predictions for beyond-Standard

Model phenomena that can be investigated by experiments ranging from the LHC to cosmological probes.

Comstock for circuit QED

The 2024 Comstock Prize in Physics goes to Yale researchers Michel Devoret and Robert Schoelkopf for their ground-breaking work in quantum information processing – specifically "circuit quantum electrodynamics", which allows quantum information to be distributed by microwave signals on wires and paved the way for applications in quantum computing and sensing. Awarded every five years to one or more North American physicists for work related to electricity, magnetism or radiant energy, the Comstock prize comes with a $50,000 sum and an additional $50,000 to support recipients' research.

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PEOPLE OBITUARIES

Bruce Marsh 1980–2023

A specialist in laser technology at CERN

Bruce Marsh, a recognised international leader in laser technologies for radioactive ion-beam production, tragically passed away on 30 December 2023 at the age of 43. Bruce was an invaluable member of the sources, targets and interactions group at CERN, where he was leader of the lasers and photocathodes section. Across CERN, he contributed to shared endeavours with his vast expertise, knowledge, attention to detail and kindness towards those around him. Outside CERN, he was an outstanding figure in the scientific and technical domains of laser ion-source technology, revolutionising its application across various fields.

Bruce completed his PhD at the University of Manchester, and his thesis research included work at the ISOLDE facility at CERN, which he later joined as a fellow in 2006 before taking up a staff position in 2010. In his different roles, Bruce contributed greatly to the development of the resonance ionisation laser ion source (RILIS) techniques dedicated to the production of radioisotopes for fundamental research and medicine at ISOLDE. The ISOLDE RILIS system has become a reference for all radioactive ion-beam facilities worldwide. Furthermore, Bruce worked closely with his team to contribute to the advancement of future accelerators and colliders at CERN, with a particular focus on CLIC, AWAKE and the Gamma Factory.

Bruce Marsh also contributed to the advancement of future accelerators and colliders at CERN.

His work extended beyond CERN, influencing the global landscape of nuclear-structure and laser-physics research. He was a leading expert in the development and applications of RILIS-based in-source resonance ionisation spectroscopy. The technique allowed studies of nuclear ground- and isomer-state properties of radioactive isotopes, including recent investigations in mercury and bismuth isotopes that gained wide attention outside nuclear physics. Bruce authored articles in many high-impact journals and was invited to present his work at numerous international conferences, workshops and schools, many of which he helped to organise.

Bruce also achieved international recognition through his role as the coordinator of the European Union-funded Marie Skłodowska-Curie training network Laser Ionisation and Spectroscopy of Actinides (LISA), which comprises a dozen laboratories in Europe, several other international partners and 15 doctoral students, who explore the structure of the actinide elements.

Bruce will be fondly remembered for his warm and welcoming spirit – always ready with a smile for everyone – and for his strong sense of justice. An unwavering champion of diversity in the workplace, Bruce fostered an inclusive environment where every voice was valued, and every individual felt empowered to contribute to shared goals with their unique perspectives. He provided invaluable opportunities for integration, learning and professional growth for his colleagues and was always available for advice on professional and private matters. Despite his wealth of knowledge and accomplishments, he remained humble in all situations, leaving a lasting impact on all who knew him.

His friends and colleagues, *including the ISOLDE Collaboration.*

Fritz Nolden 1953–2023

An expert in stochastic cooling

Our long-time colleague Fritz Nolden passed away on 28 December 2023 at the age of 70.

After studying physics at the Technical University of Munich and completing his diploma thesis under the supervision of Paul Kienle, Fritz Nolden began working at GSI Darmstadt in July 1985. His work focused on aspects of the planned Experimental Storage Ring (ESR) in Bernhard Franzke's group. Initially he dealt with general questions regarding the interpretation and design of the storage ring and related beam-dynamics aspects. Here he benefited from his ability to work on theoretical problems, which played a major role in his further career and which, as he always liked to emphasise, was the greatest motivation and basis for his work.

Fritz Nolden's work focused on the Experimental Storage Ring at GSI.

After working intensively in the construction and commissioning of the ESR, Nolden increasingly found time to deal with the theory and structure of stochastic cooling. This led to the completion of his doctoral thesis at the Technical University of Munich in 1995 on theoretical aspects of a stochastic cooling system at the ESR. He was responsible for the commissioning of this system at the ESR in the same year, and worked on a variety of problems that arose during the operation of the ESR facility, both theoretically and experimentally. Colleagues from the research departments also appreciated his support, in both words and actions, ▷

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when planning and carrying out experiments at the ESR.

In addition to his ongoing willingness to ensure the operation of the ESR in a jointly responsible position, he also increasingly took on tasks in planning the storage rings for FAIR and in particular their stochastic-cooling systems. Many criteria and specifications of these systems go back to his theoretical work and planning activities.

Until his retirement in 2017, Nolden continued to support the operation of the ESR with all his expertise and commitment. After his retirement, he still visited GSI regularly to discuss current issues with colleagues and share his wealth

Nolden was an open and competent partner in scientific exchange

of experience with them. He was a sought-after conversation partner because he not only brought his expertise to the discussions, but also liked to season his comments with subtle humour.

Fritz's professional contributions were also valued by many international colleagues, for whom he was an open and competent partner in scientific exchange. Worth mentioning here are his many years of exchange with colleagues at CERN and his consulting work at the IMP Lanzhou.

We mourn the loss of a colleague with excellent specialist knowledge, great interest and commitment in his tasks for GSI and FAIR, who always showed a friendly manner and a great openness to all the problems that were brought to his attention.

Markus Steck *GSI,* **Fritz Caspers** *CERN and* **Wolfgang Höfle** *CERN.*

Kishori Mohan Pathak 1930–2023

A brilliant physicist who returned to his roots

Kishori Mohan Pathak, the first doctor of physics at Gauhati University (Assam, India) and founding vice-chancellor of Central Tezpur University, passed away in June 2023 at the age of 93.

Pathak completed his master's degree in physics from the University of Calcutta in 1956, with a specialisation in nuclear physics and cosmic radiation. The following year, he started as a lecturer in physics at Cotton College, Guwahati. With his zeal to scale new heights, he left for England and started research at Durham University under the guidance of Astronomer Royal Arnold W Wolfendale. He received his PhD in 1967 for his work on high-energy cosmic rays.

It is praiseworthy that instead of continuing research abroad in highly sophisticated labs, Kishori returned to his native land with a strong determination to motivate the talented young people of the region towards higher studies in the upcoming field of cosmic-ray physics. Soon after returning to Assam in 1969, he successfully established a research group in the physics department of Gauhati University, which was dedicated to studies of the electromagnetic radiation at radio and optical Cherenkov frequencies from ultra-high-energy ($>10^{16}$ eV) cosmic-ray showers. His research activities saw him visit and interact with cosmic-ray

Central Tezpur University

In addition to cosmic-ray physics, Kishori Pathak collaborated with geologists and promoted higher education in northeast India.

physicists at CERN and Munich University, and in 1995 he was recognised by his election as a fellow of the UK Institute of Physics.

As well as cosmic-ray physics, Kishori Pathak collaborated with geologists at Gauhati University. Using the technique of fission track dating, he successfully dated rocks and minerals of the Meghalaya Plateau in the northeastern region of India for the first-time, providing data of great importance in determining the geological formation of the plateau as well as the natural resources for the economic development of the region. He also extensively studied the probable effect of uranium content in water from various sources of the whole of the northeastern region of India, which had a high incidence of cancer, and in the 1980s made extensive futurological studies on the problems of higher education in the region. This experience helped Pathak while setting up the Central University of Tezpur, which is now one of the most sought-after institutions of higher education in India, with a national and international reputation. In recognition of his contributions towards society, he received the Outstanding Service Gold Medal from the Governor of Assam in 1991 and was selected for the Lifetime Achievement Award in the 2023 State Science Awards.

Kishori Pathak will be remembered as a brilliant cosmic-ray physicist and a great academician who worked wholeheartedly throughout his entire life to uplift the people around him.

Biren Das *Central Tezpur University and* **Pranayee Datta** *Gauhati University.*

Igor Savin 1930–2023

A strong force for JINR–CERN collaboration

Igor Savin, honorary director of the Veksler and Baldin Laboratory of High Energy Physics (VBLHEP) at JINR, Dubna died on 8 July 2023 after a long illness. Born in Bryansk region, Russia in 1930, he graduated from Lomonosov Moscow State University and started his work in Dubna in 1955. He gained international prestige by studying interference in K-meson decays in experiments at CERN, which confirmed the violation of CP invariance. In 1967 he defended his PhD thesis based on the results of his work, and in 1974 his DSc thesis. The latter included classic results on kaon regeneration that were obtained by an international collaboration including physicists from Bulgaria, Hungary, Czechoslovakia and East Germany formed under Savin's leadership. The collaboration conducted a series of experiments at the U-70 accelerator in Protvino, showing that the regeneration cross section decreases as a function of the kaon momentum in line with the Pomeranchuk theorem on the asymptotic equality of total cross sections for particles and antiparticles.

In 1974 Igor Savin led a small group of physicists from Dubna to visit CERN to identify an experiment where JINR's participation would be significant. Thanks to his enthusiasm and organisational talent, this led to the first large-scale joint CERN–JINR project, NA4 at the SPS, which was approved in 1975 and finished in 1995. He led the JINR team participating in the study of deep inelastic scattering of ▷

muons from nucleons and nuclei. This research established γ/Z interference in the electroweak interactions of muons on nuclei, indicating the existence of an intermediate Z-boson discovered at CERN a year and a half later, and enabled the structure functions of protons and deuterons to be measured at percent levels. The latter were shown to be in agreement with the new theory of strong interactions, QCD, and proved that the structure functions of free and bound nucleons in the nucleus differ. This first equal cooperation between JINR and CERN contributed to the development at Dubna of the most advanced technologies and promoted strong collaboration with the global scientific community.

Igor Savin founded a new scientific direction at JINR: the experimental and theoretical study of the spin structure of nucleons and nuclei, which has gone from strength to strength. Igor headed the JINR group in the SMC experiment at CERN, in which the spin-dependent structure functions of protons and deuterons were measured and a small contribution of the valence quarks to the nucleon spin was found. He also led the JINR team in the COMPASS

JINR

Igor Savin made major contributions to the study of the spin structure of nucleons and nuclei.

experiment at CERN and actively participated in the HERMES experiment at DESY to further study the nucleon spin structure in electron scattering reactions on longitudinally and transversely polarised nucleons.

As director of VBLHEP JINR, Igor Savin paid great attention to the development of international scientific cooperation, which is the backbone of the laboratory. The main task was to perform research at external accelerators at IHEP, CERN, DESY, Brookhaven and other world centres. His work has been recognised with numerous awards, including the gold medal of the Czech Academy of Sciences and the medals of the Hungarian People's Republic and the German Democratic Republic. He was a scientist with a worldwide reputation, who helped create the glorious history of JINR. On the occasion of his 90th birthday, Carlo Rubbia said: "Igor, your anniversary celebration represents for all of us a unique result to which we have been involved over many decades and of which we are extremely proud".

Igor Savin leaves a deep mark on science and a bright memory to everyone who had the honour and privilege to call him their friend, colleague or mentor. A wonderful man and a true scientist will be missed by all who knew and loved him.

Alexander Cheplakov *and* **Victor Kukhtin** *JINR.*

Mykola Shulga 1947–2024

Exceptional diligence and capacity

Mykola Shulga, an outstanding Ukrainian theoretical high-energy physicist, passed away on 23 January 2024. Born on 15 September 1947 in Kharkiv, Ukraine, he graduated with honours from Kharkiv State University in 1971. In 1973 he joined the Kharkiv Institute of Physics and Technology (KIPT) where he worked for the rest of his life. He held many leadership positions at KIPT and became its director general in 2016.

A significant role in Shulga's formation as a scientist was played by his PhD advisor and prominent KIPT theorist Oleksandr Akhiezer. Together they developed the quasi-classical theory of coherent radiation of channelled and over-barrier electrons and positrons in crystals. This theory provided an understanding of the basic emission mechanisms in oriented crystals, which is crucial for creating an intense gamma-ray source as well as a crystal-based positron source for future electron–positron colliders.

Mykola Shulga always worked to ensure that his theoretical predictions were tested experimentally. Many of them were confirmed recently at CERN. In 2005–2010 the NA63 collaboration confirmed the Ternovsky–Shulga–Fomin effect – a suppression of bremsstrahlung radiation from ultrarelativistic electrons in thin layers of matter. In 2009–2017 the UA9 collaboration confirmed his prediction of a stochastic Grinenko–Shulga mechanism of high-energy particle-beam deflection by a

NSC KIPT

Mykola Shulga always worked to ensure that his predictions were tested experimentally.

bent crystal. This mechanism allows the deflection of both positively and negatively charged particles, and is planned to be implemented at the PETRA IV synchrotron at DESY and future electron–positron colliders.

Shulga was a laureate of the State Prize of Ukraine in the field of science and technology (2002), won prizes of the National Academy of Sciences of Ukraine (NASU) named after O S Davydov (2000) and O I Akhiezer (2018), and received many other awards. In 2009 he was elected an academician of NASU and in 2015 became head of its department of nuclear physics and power engineering. From 2004 to 2013 he was vice-president of the Ukrainian Physical Society.

Shulga paid great attention to working with young physicists, whom he taught for many years at V N Karazin Kharkiv National University. He trained eight PhD students and eight doctors of science, and among his students are eight laureates of the State Prize of Ukraine in the field of science and technology.

Thanks to his high human qualities, exceptional diligence and amazing capacity for work, Mykola Shulga gained great authority and respect in the scientific community. He led National Science Center KIPT (NSC KIPT) through two years of the full-scale invasion of Ukraine by the Russian Federation, working to eliminate the consequences of more than 100 missile strikes on the NSC KIPT territory, which left not a single building undamaged. Undeterred by the war, until his last days he continued to promote the creation of a new international centre for nuclear physics and medicine on the NSC KIPT site (*CERN Courier* January/February 2024 p30).

His bright memory will forever remain in the hearts of his colleagues, friends, relatives and loved ones.

His friends and colleagues.

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BACKGROUND

Notes and observations from the high-energy physics community

Neutrinos out of the woods


Oyso/Pixabay

Leaf it out *EeV neutrinos could be detected by instrumenting hillside forests.*

The idea of using trees as radio antennas dates back to the 1900s. Hillside forests of radio antennas could also pick up electromagnetic radiation from in-air decays of tau leptons from Earth-skimming tau neutrinos. Steven Prohira (University of Kansas) now proposes to reduce the ecological footprint of such observatories by simply wiring trees to readout electronics. Foliage should cause minimal propagation losses, he estimates, noting that trees are intrinsically broadband detectors (arXiv:2401.14454). Offering a very large detector volume, the technique could push the neutrino energy reach into EeV territory – as is also being explored by projects such as the Giant Radio Array for Neutrino Detection, among others.

0.241 The squared speed of sound (in units of the squared speed of light) in quark–gluon plasma measured by the CMS collaboration, in precise agreement with predictions from lattice quantum chromodynamics

Media corner

"The reason to invest in the FCC is to gain fundamental knowledge about the way the universe works. This will be rewarding in a cultural or philosophical sense. It may also pay off practically in the far future through applications we cannot foresee today."

The Financial Times (9 February) hits the nail on the head.

"CERN's rationale for favouring such an approach (other than for Europe to retain its prominent position in the field) includes the fact that alternative technologies – such as muon colliders and the acceleration of protons using waves of plasma – are as yet unproven."

Nature (17 January) seeks to weigh up the prospects of muon-versus-hadron colliders.

"Of course we will work with our US colleagues if they plan to build a new collider in the US, but it's on a timescale which is totally different from the timescale of the FCC."

CERN DG **Fabiola Gianotti** quoted in *Scientific American* (7 February).

"This is about extending the frontier of human knowledge into the heart of matter and the fundamental forces, in part to see how fundamental they really are."

Jon Butterworth of UCL on the FCC (*The Guardian*, 5 February).

"The scientific case for such an experimental prospectus could hardly be stronger. Critics, however, have pointed to the projects's hefty price tag, uncertain outcome and far-off results, some of which would not be in until the 2070s, as reasons against pursuing it. But no scientific project, especially one on this scale, is free of cost and risk. The effort to advance the frontier of human knowledge should be allowed to accelerate apace."

The Times of London speaking out for fundamental exploration (6 February).

From the archive: April 1984

Physics without borders


CERN 295.10.83

The final scene at ISR intersection 8. This assembly was used by a Brookhaven/Cambridge/CERN/Copenhagen/London (Queen Mary College)/Lund/Pittsburgh/Pennsylvania/Rutherford/Tel Aviv team. The apparatus was gradually extended to its final configuration with four walls of uranium/scintillator hadron calorimeter surrounding the central solenoid and detectors. On these walls, additional arrays of sodium iodide from the USSR were used by an Athens/Bonn/Moscow/Brookhaven/Novosibirsk team. The composition of these teams reflects the success of the ISR in attracting international users.

In the early 1960s, a formal CERN proposal was put forward for twin rings to store two 25 GeV proton beams from the PS. The proposal gathered momentum, benefiting from the French Government's offer of additional land to extend the CERN site and provide a home for the machine. On 27 January 1971, two proton beams collided for the first time in the newly completed Intersecting Storage Rings (ISR). Hadron colliders had arrived. The last meeting of the ISR Experiments Committee was on the same date in 1984. The premature closure of the ISR came as a result of the restrictions imposed to build the LEP electron–positron ring at CERN within a constant budget. Something had to go.

● Text adapted from *CERN Courier* April 1984 pp 92–97 and 101–102.

Compiler's note

In 1971 CERN Council approved the construction of Laboratory II in Prévessin, France, adjoining the Swiss site. In 1972 the first particles to cross the Franco–Swiss border were from the Proton Synchrotron Booster. Now most of the 27 km LEP/LHC ring is on the French side of the border, reaching the Jura foothills. If the Future Circular Collider is built at CERN it will additionally pass under Lake Geneva, the Saléve and the Vuache.

In its 70th year, the CERN "family" now includes almost half the countries in the world. These range from 23 full member states, who pay the operational budget and vote at Council, 10 associate members, six observers and more than 60 non-member states and countries with formal collaborations. The lab has about 2600 staff members who organise and run its facilities, and around 12,500 researchers from more than 600 institutes and universities who use them.

Nature says no to AI

Generative AI tools such as ChatGPT, which turn simple prompts into text, videos and images, have thrown a spanner into many walks of life – science included. The journal *Nature* has now declared that no AI-generated images or videos will be allowed in its publications, apart from in articles that are specifically about AI. Transparency, attribution and consent are an integral part of scientific practice, state the editors, and generative AI fails to meet these criteria. For now, *Nature* continues to allow the inclusion of text that has been produced with AI assistance, providing this is fully documented with appropriate sources.

DALL-E/OpenAI

Get real *An AI creation from the prompt "nature scientific journal".*