WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2022 issue of *CERN Courier*.

As LHC Run 3 gets into its stride and the first results at a new energy frontier roll in (p5), all eyes are on what's next: the High-Luminosity LHC (HL-LHC), scheduled to start operations in 2029. Civil engineering for the major upgrade is complete (p7) and new crystal collimators for HL-LHC operations are to be put to the test during the current run (p35). Looking beyond the LHC, how best to deal with the millions of cubic metres of excavation materials from a future circular collider? (p9), and a new project to explore the use of high-temperature superconductors for FCC-ee (p8). The HL-LHC and proposed future colliders also feature large in the recent US Snowmass community planning exercise (p23).

Diving into a different experimental arena, the vast neutrino telescope KM3NeT is taking shape beneath the Mediterranean Sea, reports our cover feature (p30). In the US, newly founded firm TAU Systems aims to be the first to commercialise plasma-wakefield accelerators (p51). In the theory world, a new international society unites researchers in the quest for quantum gravity (p45). And in Switzerland, a new study confirms the impact of physics on society (p9). Plus: news digest (p13), energy frontiers (p15), field notes (p19), reviews (p49) and more.

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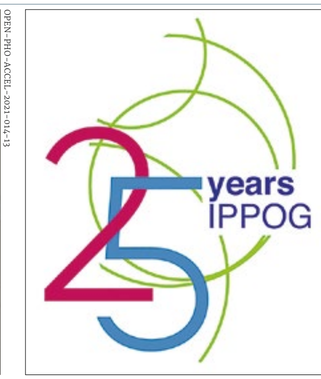
EDITOR: MATTHEW CHALMERS, CERN
DIGITAL EDITION CREATED BY IOP PUBLISHING

IN THIS ISSUE

Volume 62 Number 6 November/December 2022

Closing in *Civil engineering for the High-Luminosity LHC completed.* **7**



For the love of physics *IPPOG marks 25 years of particle-physics outreach.* **41**

Riding the wave *New firm seeks to commercialise laser–plasma wakefield accelerators.* **51**

FROM THE EDITOR

Back to business as *unusual*

Matthew Chalmers
Editor

As 2022 draws to a close, the pace at CERN is picking up. Restaurant 1 is back to its bustling best, parking spaces are at a premium, and the corridors are alive with users and visitors, thanks to the lifting of COVID-19 restrictions. The start of LHC Run 3 on 5 July, one day after celebrations surrounding the 10th anniversary of the Higgs boson's discovery, injected energy at CERN and generated huge interest beyond. Almost five million people connected live on CERN's social media and through other broadcasting services, and the hashtags #Higgs10 and #LHCRun3 were trending in Switzerland, France, the UK, Germany and the US.

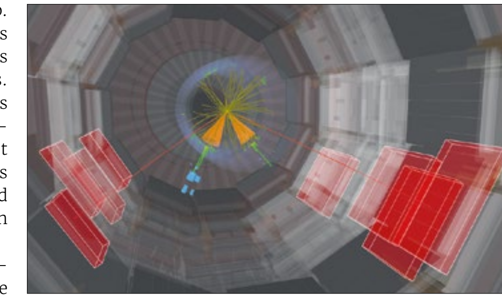
So accustomed have we become to the exceptional performance of the LHC and its experiments, already unique in scale and complexity, that it is easy to take a new run for granted. After three years of significant upgrades and maintenance to the machine and detectors, and apart from a three-week outage beginning on 23 August due to an issue with cavity pressure-release discs, data-taking has been running smoothly at a new centre-of-mass energy of 13.6 TeV. The intensity ramp-up also proceeded smoothly. Larger datasets and novel analysis methods will soon allow the energy frontier to be scrutinised at unprecedented levels.

New frontiers

The first Run 3 physics result is already in: a measurement of the top-quark pair production cross-section in proton–proton collisions at 13.6 TeV, presented by the CMS collaboration at the TOP 2022 workshop in Durham on 6 September (see image). ALICE, ATLAS and LHCb too were completing commissioning and first analyses at the new collision energy as the *Courier* went to press. Meanwhile, in September, a dedicated run for the LHCf experiment located 140 m either side of ATLAS saw the LHC set a new record for the longest fill: 57.4 hrs (p58).

So accustomed have we become to the exceptional performance of the LHC that it is easy to take a new run for granted

In light of the current energy crisis, CERN decided to start the 2022 year-end technical stop on 28 November, two weeks earlier than initially planned and postponing this year's heavy-ion run. The operation of the accelerator complex will also be reduced by four weeks in 2023, as part of a significant ongoing energy-saving programme being implemented across the organisation.



Top notch *A $t\bar{t}$ event candidate containing two high-energy muons and two b-quark jets recorded by CMS on 27 July.*

As LHC physicists begin four years of high-energy data-taking and analysis, all eyes are on Run 4 – the High-Luminosity LHC (HL-LHC), starting in 2029. Civil engineering for the upgrade is complete (p7), and new crystal collimators for HL-LHC operations are to be put to the test during the current run (p35). Looking further ahead: how best to deal with the millions of cubic metres of excavation materials from a future circular collider? (p9), and exploring the use of high-temperature superconductors for future accelerator magnets (p8). The HL-LHC and proposed future colliders feature large in the recent US Snowmass community planning exercise, a full report on which can be read on p23.

Diving into a completely different experimental arena, the vast neutrino telescope KM3NeT is taking shape beneath the Mediterranean Sea (p30). In the US, newly-founded firm TAU Systems aims to be the first to commercialise plasma-wakefield accelerators (p51). In the theory world, a new international society unites researchers in the quest for quantum gravity (p45). And in Switzerland, a new study confirms the impact of physics on society (p9).

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

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

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

ISSN 0304-288X

NEWS ANALYSIS

HIGH-LUMINOSITY LHC

HL-LHC civil engineering reaches completion

After five years of arduous and continuous activity, the main civil-engineering works for the High-Luminosity LHC project (HL-LHC) are on track to be completed by the end of the year. Approved in June 2016 and due to enter operation in 2029, the HL-LHC is a major upgrade that will extend the LHC's discovery potential significantly. It relies on several innovative and challenging technologies, including new superconducting quadrupole magnets, compact crab cavities to rotate the beams at the collision points, and 80 m-long high-power superconducting links, among many others.

These new LHC accelerator components will be mostly integrated at Point 1 and Point 5 of the ring, where the two general-purpose detectors ATLAS and CMS are located, respectively. As such, the HL-LHC requires new, large civil-engineering structures at each site to house the services, technical infrastructure and accelerator equipment required to power, control and cool the machine's new long-straight sections.

Connections

At each Point, the underground structures consist of a vertical shaft (80 m deep and 10 m in diameter) leading to a service cavern (16 m in diameter and 46 m long). A power-converter gallery (5.6 m in diameter and 300 m long), two service galleries (3.1 m in diameter and 54 m long), two radio-frequency galleries (5.8 m in diameter and 68 m long), as well as two short safety galleries, complete the underground layout. The connection to the LHC tunnel will be made via 12 vertical cores (1 m in diameter and 7 m deep), which will be drilled later and completed during long-shutdown 3 after the removal of the existing LHC long-straight sections.

The surface structures consist of five buildings. Three are constructed from reinforced concrete to house noisy equipment such as helium compressors, cooling towers, water pumps, chillers and ventilation units. The other two buildings have steel-frame structures to house electrical distribution cabinets, a helium refrigerator cold-box and the shaft access system. The buildings are interconnected via buried technical galleries.

In sight *Top: the new HL-LHC surface structures at Point 1 and (bottom) a power-converter gallery at Point 5.*

The HL-LHC civil-engineering project is based on four main contracts. Two consultancy service contracts are dedicated to the design and construction administration: Setectpi-CSD-Rocksoil (ORIGIN) at Point 1 and Lombardi-Artelia-Pini (LAP) at Point 5. Two supply contracts are dedicated to the construction of both the underground and surface structures: Marti Tunnelbau – Marti Österreich – Marti Deutschland (JVMM) at Point 1 and Implenia Schweiz – Baresel – Implenia Construction (CIB) at Point 5.

In total, 92,000 m^3 of spoil has been excavated from the underground structures, while 30,000 m^3 of concrete and 5000 tonnes of reinforcement-steel were used to construct the underground structures. At Point 5, based on the experience of civil engineering for the CMS shaft, groundwater infiltration was envisaged to make HL-LHC shaft excavation difficult. A different execution methodology and a dry summer in 2018 made the task easier, although the discovery of unexpected hydrocarbon layers (not seen during the CMS works) added some additional difficulties in the management of the polluted spoil. At Point 1, the expected quantity of spoil polluted by hydrocarbon was managed accordingly. The construction of the surface structures, meanwhile, required 6 km of anchor piles, 15,000 m^3 of concrete, 1400 tonnes of reinforcement-steel and 700 tonnes of steel frames.

Opportunities

"The two sites generated 120 jobs on average from 2018 to 2021, solely for companies in charge of civil-engineering construction," says Luz Anastasia Lopez-Hernandez, head of the project-portfolio management group of the site and civil-engineering department.

Special care was taken to limit worksite nuisance with respect to CERN's neighbours. Truck wheels were systematically washed before leaving the worksites, and temporary buildings were erected on top of the shaft heads to limit the noise impact of the excavation work. The only complaint received during the construction period was related to light pollution at Point 5, after which it was decided to limit worksite lighting during nightfall to the minimum compatible with worker safety. As the excavation of the two shafts started in 2018 in parallel with LHC operation, special care was taken to limit the vibration level by using electrically driven road-header excavators.

The COVID-19 pandemic, which, among other things, required the two worksites to be closed for several weeks in 2020, caused a delay of one-to-two months with respect to the initial construction schedule. The Russian Federation's invasion of Ukraine also impacted activities this year by delaying some deliveries.

"The next step is to equip these new structures with their technical infrastructures before the next long shutdown, which will be dedicated to the installation of the accelerator equipment," says Laurent Tavian, work-package leader of the HL-LHC infrastructure, logistics and civil engineering.

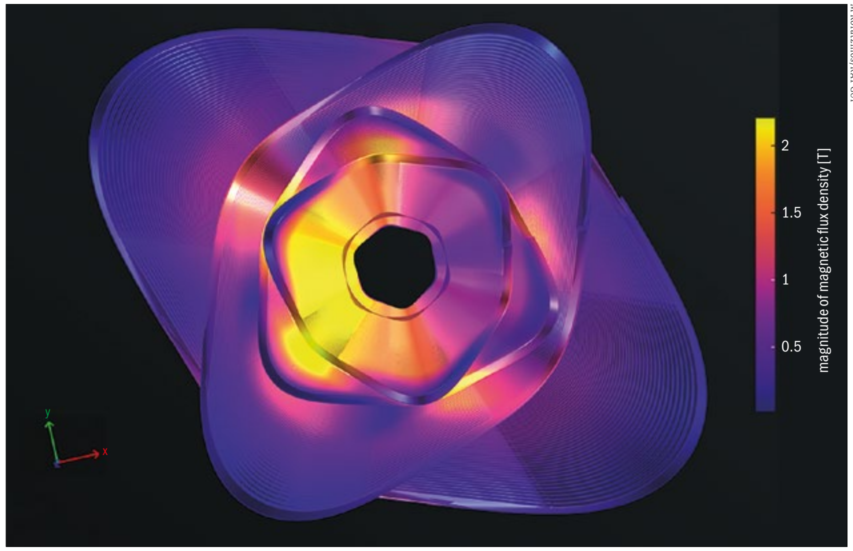
FUTURE CIRCULAR COLLIDER

FCC-ee designers turn up the heat

The proposed electron–positron Higgs and electroweak factory FCC-ee, a major pillar of the Future Circular Collider (FCC) study, is a leading contender for a flagship project at CERN to follow the LHC. Envisaged to be housed in a 91 km-long tunnel in the Geneva region, and to be followed by a high-energy hadron collider utilising the same infrastructure, it is currently the subject of a technical and financial feasibility study, as recommended by the 2020 update of the European strategy for particle physics.

Maximising energy efficiency is a major factor in the FCC design. Two new projects backed by the Swiss Accelerator Research and Technology collaboration (CHART) seek to reduce the environmental impact of FCC-ee by exploring the use of high-temperature superconductors in core accelerator technologies.

Much like its predecessor, LEP, and indeed every lepton collider to date, the main magnet systems in the FCC-ee design are based on normal-conducting technology. While perfectly adequate from a magnetic-field point of view, normal-conducting magnets consume electricity through Ohmic heating. The FCC-ee focusing and defocusing elements, comprising about 3000 quadrupole magnets and 6000 sextupole magnets, are estimated to consume in excess of 50 MW when operating at the highest energies. This can be reduced if the magnetic systems are made superconducting, and if high-temperature superconductors (HTS) were to be used. Whereas conventional superconductors such as the niobium-titanium used in the LHC must be cooled to extremely low temperatures (1.9–4.5 K), state-of-the-art HTS materials can operate up to 90 K, significantly reducing the cryogenic power needed to keep them superconducting. The question remains if high-performing HTS accelerator magnets, with all their advantages on paper, can be built in practice.



Innovative *The magnetic flux density of a nested main sextupole–quadrupole system for FCC-ee, looking along the direction of the electron beam.*

In April 2022, the CHART executive board gave the green light to two projects investigating the feasibility of superconducting technology for the main magnet systems of FCC-ee. CHART was founded in 2016 as an umbrella collaboration for R&D activities in Switzerland, with CERN, PSI, EPFL, ETH-Zurich and the University of Geneva as present partners. The larger HTS4 project, involving CERN and PSI, will focus on superconducting magnets, while CPES (Cryogenic Power Electronic Supply) will focus on cryogenic power supplies, with partners ETHZ and PSI.

The use of HTS-based magnets could dramatically reduce the power drawn by the main quadrupole and sextupole systems for FCC-ee when operating at the highest centre-of-mass energies, explains HTS4 principal investigator Michael Koratzinos of PSI. Furthermore, he says, since HTS magnets do not need iron to shape the magnetic field, they can be made much lighter and can be nested inside one another to increase performance and flexibility in the optics design. "Turning FCC-ee superconducting not only helps with the reduction in operational costs and the environmental credentials of the accelerator, but it also helps society develop this new and exciting HTS technology with potential applications in everyday life."

> **Turning FCC-ee superconducting not only helps with operational costs and environmental credentials, but the new HTS technology has potential applications in everyday life**

High demand

HTS conductors are currently in high demand, mainly from a multitude of privately-funded fusion projects, such as the SPARC project at MIT. Their main disadvantage is their high cost, but this is expected to come down as demand picks up. SPARC needs about 10,000 km of HTS conductor during the next few years, compared to an estimated 20,000 km for FCC-ee, although on a later time scale.

The ultimate aim of HTS4 is the production of a full-size prototype of one of the FCC-ee short-straight sections based on HTS technology. Four work packages will address: integration with the rest of the FCC-ee accelerator systems; enabling technologies on peripheral issues such as impregnation; the conceptual and technical design of a short demonstrator and a prototype; and the design, construction and testing of the full prototype module.

"Any future project at CERN and elsewhere relies on innovative R&D to minimise its electricity consumption," says project leader of the FCC study Michael Benedikt of CERN. "We are doing our utmost at FCC to increase our energy efficiency."

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NEWS ANALYSIS

FUTURE CIRCULAR COLLIDER

Sustainable mining wins awards

At a ceremony in the CERN Globe on 27 September, the winners of "Mining the Future" – a competition co-organised by CERN and the University of Leoben to identify the best way to handle excavated materials from the proposed Future Circular Collider (FCC) project – were announced. Launched in June 2021 in the frame of the European Union co-funded FCC Innovation Study, Mining the Future invited experts beyond the physics community to seek sustainable ways of reusing the heterogeneous sedimentary rock that would need to be excavated for the FCC infrastructure, which is centered on a 91 km-circumference tunnel in the Geneva basin. Twelve proposals, submitted by consortia of universities, major companies and start-ups, were reviewed based on their technological readiness, innovative potential and socioeconomic impact.

Following final pitches in the Globe by the four shortlisted entrants, a consortium led by Swiss firm BG Ingenieurs Conseils was awarded first prize – including support to the value of €40,000 to bring the technology to maturity – for their proposal "Molasse is the New Ore". Using a near real-time flow analysis that has been demonstrated in cement plants, the proposal would see excavated materials immediately identified and separated for further processing on-site, treating them not as waste that needs to be managed and thereby serving environmental objectives and efficiency targets.

Standing up for sustainability *Participants of the "Mining the Future" award ceremony on 27 September.*

The runners-up were proposals led by: Amberg (to sort, characterise and redistribute the molasse into fractions of known compositions and recycle each material on a large scale locally); Briques Technique Concept (to produce bricks from the excavated material for the construction of nearby buildings); and Edaphos (to process the molasses into topsoil-like material in a process known as soil conditioning). Although only one winner was chosen, it emerged during the ceremony that an integrated approach of all four shortlisted scenarios would be a valid scenario for managing the estimated 7–8 million m^3 of molasse materials required for the FCC construction project.

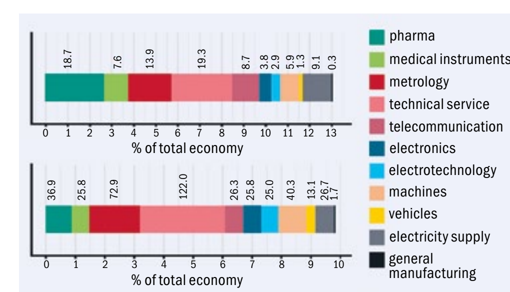
"This is a key ingredient for the FCC feasibility study while also creating business opportunities for applying these technologies in different markets," said competition creator Johannes Gutleber of CERN. "The proposals submitted in the course of the contest show that designing a new research infrastructure acts as an amplifier of ideas for society at large."

POLICY

Swiss study demonstrates physics impact

Physics-based industries are as important to the Swiss economy as production or trade, concludes a new report by the Swiss Physical Society (SPS). Seeking to determine the impact of physics on Swiss society, and motivated by a similar Europe-wide study completed in 2019 by the European Physical Society (*CERN Courier* January/February 2020 p9), the SPS team, with support from the Swiss Academy of Natural Sciences and Swiss service-provider IMSD, carried out a statistical analysis revealing key indicators of the national value of physics.

Currently, states the report, the turnover of physics-based industries (PBI) in Switzerland is estimated to exceed CHF 274 billion in revenue, and is expected to grow further. PBI, defined as those industries that are strongly reliant on modern technologies developed by physicists, were divided into 11 categories ranging from pharmaceuticals and medical instruments to electricity supply and general manufacturing. The share of PBI in Switzerland's gross value added (GVA) was found to be CHF 91.5 billion, or 13% of the total for 2019, while the number of full-time equivalent jobs was 417,000 (9.8%). Furthermore, the specific GVA for PBI increased by 6.3% from 2015 to 2019 – almost three times higher than the average increase among all economic-activity sectors during the same period.



Return on investment *Gross value added (top; in billion CHF) and full-time equivalent jobs (bottom; in thousands) for Switzerland in 2019 for 11 physics-based industries.*

Not included in these figures are the contributions of physicists who are employed in other industries, nor additional economic impact due to downstream effects such as household spending associated with economic activity in PBI. Estimating the GVA multiplier associated with the impact of PBI to be between 2.31 and 2.49, the report concludes that every CHF 1.00 of direct physics-related output contributes CHF 2.31 to 2.49 to the economy-wide output. Beyond economic impact, the report also evaluated the contribution of education and innovation to Swiss society, and highlighted ways in which to address the shortage of skilled workers and the gender gap.

"The impact physics has on society has been studied multiple times in a variety of countries and all arrive at the same conclusion: economic success in a modern, technology-driven society is the fruit of long-term support for physics in education and research," says former SPS president Hans Peter Beck. "Innovative ideas that come out of fundamental, curiosity-driven research are at the source of what leads to success in society."

Further reading

https://scnat.ch/en/id/PjB5e.

CERNCOURIER
VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022

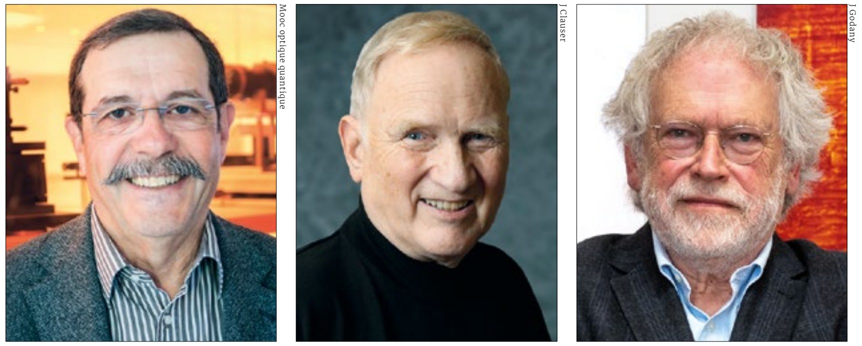
Quantum information

Nobel recognition for quantum pioneers

Announced on 4 October, the 2022 Nobel Prize in Physics has been awarded to Alain Aspect, John Clauser and Anton Zeilinger for groundbreaking experiments with entangled photons that open a path to advanced quantum technologies. Working independently in the 1970s and 1980s, their work established the violation of Bell inequalities – as formulated by the late CERN theorist John Bell – and pioneered the field of quantum information science.

First elucidated by Schrödinger in 1935, entanglement sparked a long debate about the physical interpretation of quantum mechanics. Was it a complete theory, or was the paradoxical correlation between entangled particles due to hidden variables that dictate in which state an experiment will find them? In 1964 John Bell proposed a theorem, known as Bell's inequalities, that allowed this question to be put to the test. It states that if hidden variables are in play, the correlation between the results of a large number of measurements will never exceed a certain value; conversely, if quantum mechanics is complete, this value can be exceeded, as measured experimentally.

John Clauser (J F Clauser & Associates, US) was the first to investigate Bell's theorem experimentally, obtaining measurements that clearly violated a Bell inequality and thus supported quantum mechanics. Alain Aspect (Université Paris-Saclay and École Polytechnique, France) put the findings on even more solid ground by devising ways to perform measurements of entangled pairs of photons after they had left their source, thus ruling out the effects of the setting in which they were emitted. Using refined tools and a long series of experiments, Anton Zeilinger (University of Vienna, Austria) used entangled states to demonstrate, among other things, quantum teleportation.



Foundational *From left: Nobel winners Alain Aspect, John Clauser and Anton Zeilinger.*

These delicate, pioneering experiments not only confirmed quantum theory, but established the basis for a new field of science and technology that has applications in computing, communication, sensing and simulation. In 2020 CERN joined this rapidly growing global endeavour with the launch of the CERN Quantum Technology Initiative.

Foundational work in quantum-information science was also the subject of the 2023 Breakthrough Prize in Fundamental Physics, announced in September, for which Charles H Bennett (IBM), Gilles Brassard (Montréal), David Deutsch (Oxford) and Peter Shor (MIT) will receive $3 million each (see p52).

Open science

CERN opens new era in knowledge sharing

In September, CERN approved a new policy for open science, with immediate effect. Developed by the Open Science Strategy Working Group (OSWG), which includes members from CERN departments and experiments, the policy aims to make all CERN research fully accessible, reproducible, inclusive, democratic and transparent for both researchers and wider society.

Open science has always been one of CERN's key values, dating back to the signing of the CERN Convention at UNESCO in 1952. The new policy follows the 2020 update of the European Strategy for Particle Physics, which highlighted the importance of open science, and UNESCO's Recommendation on Open Science, published in 2021. It encompasses the existing policies for open access and open data, which make all research papers and experimental data publicly available. It also brings together other existing elements of open science – open-source software and hardware, research integrity, open infrastructure and research assessment (which make research reliable and reproducible) and training, outreach and citizen science, which aim to educate and create dialogue with the next generation of researchers and the public.

"The publication of the Open Science Policy gives a solid framework in which the popular suite of open-source tools and services provided by CERN, including Zenodo, Invenio and REANA, can continue to grow and support the adoption of open-science practices, not only within physics but also across the globe's research communities," said Enrica Porcari, head of CERN's IT department.

The OSWG will continue to assess how open science evolves at CERN, developing the policy in accordance with new best practices. Alongside this, a new open-science report will be published each year, showing CERN's continued commitment to the initiative.

● https://openscience.cern.

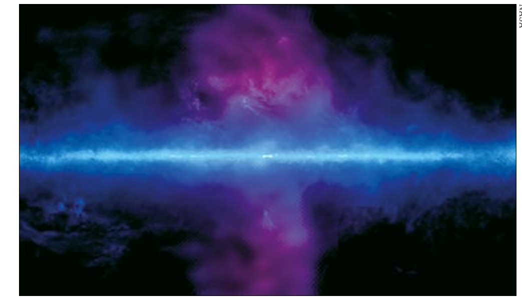
Astrowatch

Probing the Milky Way's violent history

Active galactic nuclei (AGN) are one of the most studied astrophysical objects. Known to be the brightest persistent sources of photons in the radio to gamma-ray spectrum, they are also thought to be responsible for high-energy cosmic rays and neutrinos. As such, they play an important role in the universe and its evolution.

AGNs are galaxies in which the supermassive black hole at their centre is accreting matter, thereby producing violent jets responsible for the observed emissions. While our galaxy has a supermassive black hole at its centre, it is currently not accreting matter and therefore the nucleus of the Milky Way is not active. Strong hints of past activity were, however, discovered using the Fermi-LAT satellite in 2010. In particular, the data showed two giant gamma-ray emitting bubbles – now known as the Fermi bubbles – extending from the galactic centre and covering almost-half of the sky (see image). The exact origin of the giant plasma lobes remains to be understood. However, their position and bipolar nature point towards an origin in the Milky Way's centre several million years ago, likely during a period of high activity in the galactic nucleus.

A new study led by Trisha Ashley from the Space Telescope Science Institute, Baltimore, brings a fresh perspective on the origin of these structures. Her team focused on the chemical composition of gas clouds inside the bubbles using UV absorption data collected by the Hubble Space Telescope and Green Bank Telescope. Based on their location and movement, these high-velocity clouds had been assumed to originate in the disk of the Milky Way before being swept up as the bubbles were emitted from the galactic centre. However, measurements of the clouds' elemental makeup cast doubt on this assumption.



Mysterious *Discovered in 2010, the "Fermi bubbles" (magenta) are giant plumes of gamma rays emerging above and below the galactic plane.*

UV surprise

Gas clouds from the galactic disk should have a similar chemical composition (referred to as metallicity by astronomers) to those that once collapsed into stars like the Sun. In the galactic disk, the abundance of elements heavier than hydrogen (high metallicity) is expected to be higher thanks to several generations of stars responsible for the production of such elements, whereas in the galactic halo the metallicity is expected to be lower due to a lack of stellar evolution. To measure the chemical composition of the gas clouds, Ashley and her team looked at the UV spectra from sources behind them to see the induced absorption lines. To their surprise, they found not only clouds with high metallicity but also those with a lower metallicity, matching that of galactic halo gas, thereby implying a different origin for these clouds. Suggestions that the second class of clouds is a result of heavy clouds accumulating low-metallicity gases are unlikely to hold, as the time it would take to absorb these gases is significantly longer than the age of the Fermi bubbles. Instead, it appears that while the bubbles did drag along gas clouds from the galactic plane, they also swept up existing halo gas clouds as they expanded outwards.

These results imply that events such as those which produced the Fermi bubbles play an important role in gas accumulation in a galactic plane. They remove gas from the galactic disk, while in parallel, push back gas flowing into the galactic disk from the halo. As less gas reaches the disk, star formation gets suppressed, and as such, these events play an important role in galaxy evolution. Since studying small-scale details such as gas clouds in other galaxies is impossible, these results provide a unique insight into our own galaxy as well as into galaxy evolution in general.

Further reading

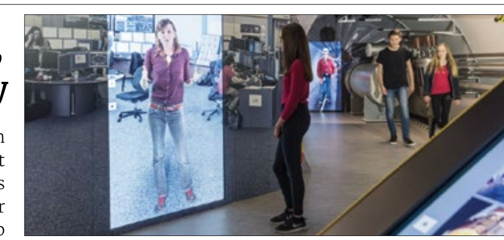
T Ashley *et al.* 2022 *Nat. Astron.* **6** 895.

Education and Outreach

Farewell Microcosm, hello Science Gateway

Having engaged innumerable visitors in the world of particle physics for the past 32 years, the CERN Microcosm closed its doors for the last time on 18 September in preparation for CERN's new flagship Science Gateway project, opening in 2023. The well-loved exhibition space opened to the public in 1990 to help CERN share its research openly, offering a glimpse behind the scenes to both tourists and schools alike.

Over the years, the exhibitions have evolved considerably. The first version of Microcosm included an exhibition by the European Space Agency, highlighting the strong ties between CERN and other European research organisations, which continue today through the EIROforum network. In 1997 CERN Director-General Chris Llewellyn Smith inaugurated a revamped exhibition with content in four languages and stories of new projects such as the LHC. Two years later, a new exhibition was added to Microcosm's portfolio, telling the story of research on the weak force, with large pieces of the Antiproton Accumulator and the UA1 and UA2 detectors. The 2000s brought hands-on experimentation for the first time and a demo area for science shows.



Bringing physics to life *The most recent Microcosm exhibitions featured realistic audiovisual content of scientists and engineers.*

In 2014 S'Cool LAB arrived, home to the expanding programme of experimentation for high-school students and teachers. And in 2015 the latest version of Microcosm opened, with new exhibitions offering a behind-the-scenes tour of the lab, together with realistic audiovisual content of scientists and engineers.

In recent years, Microcosm has also made great strides towards improving accessibility, with wheelchair-accessible design, signing and subtitling for the deaf and hard of hearing, and tactile content for the visually impaired – an effort that will be continued and strengthened at Science Gateway. "Microcosm has been strongly supported by many at CERN over the years," says Emma Sanders, head of exhibitions at CERN. "I suspect I won't be the only one to feel a little emotional on its closure, but we all look forward to the next step, with the opening of Science Gateway next June."

CERNCOURIER
Volume 62 Number 6 November/December 2022
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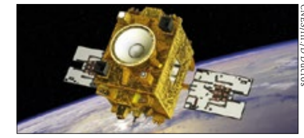
NEWS DIGEST


CNES/ill./D Ducros

Free falling *An artist's impression of the MICROSCOPE satellite.*

Gravity under the microscope

The MICROSCOPE collaboration has reported the most precise test of the weak equivalence principle (WEP), a cornerstone of general relativity which states that all bodies fall at the same rate in a gravitational field regardless of their composition or mass. Operated by the French space agency CNES, MICROSCOPE uses electrostatic forces to keep two cylinders made of platinum and titanium in equilibrium as they free-fall in Earth's orbit. After carefully monitoring the forces on the test masses for 2.5 years, the collaboration found no violation of the WEP, expressing the result in terms of the so-called Eötvös parameter: $[-1.52 \pm 2.3(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-15}$. The result, which places new constraints on possible violations of Lorentz invariance, bodes well for a next-generation mission aiming at sensitivities of 10^{-17}, says the team (*Phys. Rev. Lett.* **129** 121102).

Testing QED to the max

The world's most precise measurement of the electron magnetic moment has been claimed by Gerald Gabrielse and co-workers at Northwestern University. Via quantum-jump spectroscopy of one electron suspended in a Penning trap, the group determined g/2 in terms of the Bohr magneton, $-\mu/\mu_B$, to 1.001 159 652 180 59 (13), improving on their previous result by a factor of 2.2. This most precisely measured property of an elementary particle agrees with the Standard Model at the level of one part in 10^{12} – a test that will improve further when discrepant measurements of the fine-structure constant are resolved, reports the team (arXiv: 2209.13084).

Shining light on axions

Searching for solar axions in ^{76}Ge-enriched high-purity germanium detectors at Sanford Underground Laboratory in South Dakota, researchers working on the Majorana Demonstrator experiment have placed new constraints on the properties of these hypothetical particles. Due to the strong time–energy dependence of axion–photon conversion between the position of the solar axion's entry angle in the crystalline detector plane and the produced photon, solid-state detectors may enhance axion–photon conversion via the inverse Primakoff effect. Using data collected from January 2017 to November 2019, the collaboration placed a new limit at 95% confidence on the axion–photon coupling: $g_{a\gamma} < 1.45 \times 10^{-9}\,\text{GeV}^{-1}$. The result improves the limit from laboratory searches for axion masses between 1.2 to 100 eV (*Phys. Rev. Lett.* **129** 081803).


N Hubbard

Sensitive *The Majorana Demonstrator cryostat.*

FLASH therapy with ^{12}C ions

A team at the GSI Helmholtz Center in Darmstadt has reported the first *in vivo* application of "FLASH" radiotherapy using ^{12}C ions. The FLASH effect delivers an ultra-high dose of radiation for a very short time, destroying cancerous tissue but leaving healthy tissue undamaged. Marco Durante and co-workers divided mice that had a metastatic tumour implanted into a limb into three groups. Each group was treated either via FLASH, conventional, or "sham" radiotherapy at GSI's FAIR facility. FLASH irradiation was able to control the primary tumour in the limb and reduced the lung metastases significantly. Both effects were more pronounced than with conventional irradiation (*Radiother Oncol.* doi:10.1016/j.radonc.2022.05.003). In 2020, a collaboration between CERN and CHUV (Lausanne) was established to develop FLASH radiotherapy based on high-energy electrons (*CERN Courier* November/December 2020 p7).


BNL

Colourful *The STAR detector.*

QCD gets hotter

The STAR collaboration at Brookhaven's Relativistic Heavy Ion Collider has reported evidence of gluon saturation – a prediction of QCD whereby gluons at low transverse momenta recombine. If the rate of two gluons recombining into one balances out the rate of single gluons splitting, the gluon density reaches a steady state, or plateau. A smoking gun of such nonlinear gluon dynamics is a suppression in the yield of back-to-back decays of two neutral pions. By colliding protons with other protons as well as with aluminium and gold ions, the STAR team found the suppression to be proportional to the ion's mass number, as predicted by models of gluon recombination at low transverse momenta (*Phys. Rev. Lett.* **129** 092501).

CUPID-0 on neutrino's nature

Detecting neutrinoless double-beta decay ($0\nu\beta\beta$) would be a direct sign of lepton-number violation and thus of physics beyond the Standard Model, demonstrating that the neutrino is a Majorana particle. The first phase of CUPID (CUORE Upgrade with Particle Identification), a medium-scale $0\nu\beta\beta$ detector based on scintillating bolometric technology located in Gran Sasso, has produced its final results. Searching for $0\nu\beta\beta$ of ^{82}Se with a total exposure of 8.82 kg yr, the CUPID collaboration set a limit on the half-life of ^{82}Se to the ground state of ^{82}Kr of $> 4.6 \times 10^{24}$ yr at 90% credible interval, corresponding to an effective Majorana neutrino mass $m_{\beta\beta} < (263–545)$ meV. According to the team, this is the most competitive result based on ^{82}Se (*Phys. Rev. Lett.* **129** 111801).

FCC-ee least disruptive

In terms of carbon footprint versus physics output, FCC-ee is the least disruptive of the proposed Higgs factories in terms of environmental impact, estimate Patrick Janot and Alain Blondel of the FCC Feasibility Study coordination group. While noting that their numbers "are not devoid of uncertainty", they found that the projected footprints per Higgs boson produced, evaluated using the 2021 carbon emission of available electricity, vary by a factor of 100 depending on the considered project (*Eur. Phys. J. Plus* **137** 1122).

Quantifying the thing called swing

Delayed beats can cause a breakdown in a piece of music – except in jazz, and especially in Swing jazz, which emerged at the end of the 1920s. Yet, the essence of why tunes "swing" has remained mysterious. In a new study, physicists and psychologists from the University of Göttingen analysed 456 jazz piano solos with downbeat-offbeat pairs from the Weimar Jazz Database, concluding that an occasional delay of as little as 30 ms is a key component of swing. The findings were supported by an experiment in which professional jazz musicians were asked if four prepared tunes, each with different downbeat-offbeat pairs, swing (*Commun. Phys.* **5** 237).

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Probing QCD beyond LHC energies

The study of elastic hadron scattering is a cornerstone in understanding the non-perturbative properties of strong interactions. A key role is played by experiments at the LHC, where it is possible to precisely measure proton–proton (pp) interactions at a very high centre-of-mass energy. The goal is to detect the process $pp \rightarrow pp$, in which the interacting protons remain intact and are scattered at angles of a few microradians with respect to the beamline. The importance of such measurements follows from their relation to the total hadronic pp cross section via the optical theorem, and to properties of proton interactions at asymptotically high energies via dispersion relations.

In ATLAS, elastic scattering is studied using a dedicated experimental setup – the ALFA detectors, which allow measurements of scattered-proton trajectories inside the beam pipe, just a few millimetres from the LHC beam. They are installed inside so-called Roman pots located at distances of 237 and 245 m on either side of the ATLAS interaction point.

Recently, ATLAS reported a measurement of elastic scattering at a centre-of-mass energy of 13 TeV. The data were collected with a special setting of the LHC magnets characterised by a high β^* of 2500 m, which results in a large beam-spot size and a very small beam divergence. The latter allows precise measurements of small scattering angles. With these optics, the ALFA system detected events characterised by very small values of the Mandelstam t variable, which is proportional to the scattering angle squared. Measurements of small |t| values give access to the Coulomb–nuclear interference (CNI) kinematic region, where the contribution from electromagnetic and strong interactions are of similar magnitude.

The ALFA detectors use scintillating-fibre technology to measure the position of the passing proton. The t value for each event is reconstructed from the measured positions using knowledge of the magnetic fields of the LHC magnets between the interaction point and the detectors. The selection of candidate events is based on the strong correlations between the elastically scattered protons, resulting

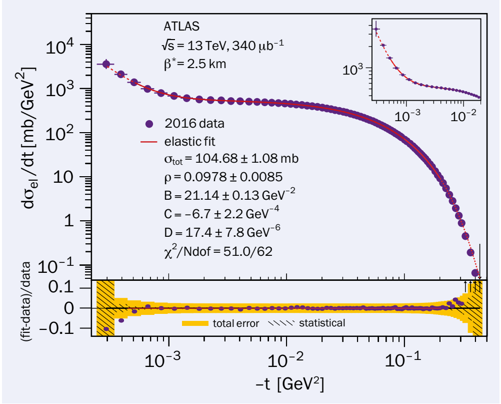


Fig. 1. *The measured differential elastic proton–proton cross section as a function of the Mandelstam t variable together with a fit function used to extract the physics parameters.*

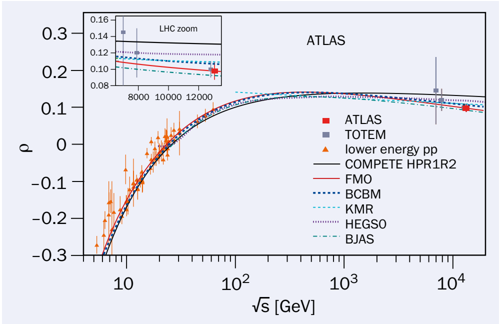


Fig. 2. *The centre-of-mass energy evolution of the* ρ *parameter together with predictions of various theoretical models.*

from energy and momentum conservation. The analysis is heavily based on data-driven techniques, which are used for the alignment of the detectors, background estimation, evaluation of reconstruction efficiency and optics tuning.

Figure 1 presents the measured differential elastic cross section as a function of t. The shape of the distribution is sensitive to important physics parameters, such as the total cross section (σ_{tot}) and the ρ parameter, defined as the ratio of real to imaginary parts of the forward scattering amplitude. The smallest |t| values, and thus the smallest scattering angles, are dominated by the electromagnetic interaction between the protons. The CNI effects are strongest for |t| around 10^{-3} GeV² and provide the sensitivity to the ρ parameter. For larger |t| values, the strong interaction dominates, and the spectrum depends on the value of σ_{tot}. The physics parameters are extracted from a fit to the t distribution.

The ρ parameter is related, through dispersion relations, to the energy dependence of σ_{tot}, with a certain sensitivity also to energies above those at the LHC. In addition, ρ is sensitive to possible differences between pp and $p\bar{p}$ scattering amplitudes at asymptotic energies. ATLAS measured $\rho = 0.098 \pm 0.011$, in agreement with a previous TOTEM measurement. The result is in conflict with pre-LHC theoretical expectations (see the COMPETE line in figure 2), which assumed that no pp/$p\bar{p}$ difference is present asymptotically and that σ_{tot} increases proportionally to the squared logarithm of the centre-of-mass energy, similarly to the evolution observed at accessible energies back then. This suggests that one of the above assumptions is incorrect: either the increase of σ_{tot} slows down above LHC energies, or protons and antiprotons interact differently at asymptotic energies. The second statement is often associated with the so-called odderon exchange. Both possibilities affect our understanding of the high-energy behaviour of strong interactions.

ATLAS also measured the total pp hadronic cross section σ_{tot} = (104.7 ± 1.1) mb. This is the most precise measurement to date at this energy, due to a dedicated luminosity measurement that contributed less than 1 mb to the total systematic uncertainty. However, the long-standing tension between the ATLAS and TOTEM σ_{tot} measurements, with the latter being about 5% higher than ATLAS, persists.

ATLAS has collected more elastic scattering data in LHC Run 2, which are currently being analysed. New data taking is planned during Run 3, where a special run is foreseen at a centre-of-mass energy of 13.6 TeV.

Further reading

ATLAS Collab. 2022 arXiv:2207.12246.

CMS

Rare B-meson decays to two muons

Studies of rare B-meson decays at the LHC provide a sensitive probe of physics beyond the Standard Model (SM) and allow us to explore energy scales much higher than those directly accessible. A key factor in the success of these studies is the availability of precise theoretical predictions that can be compared with experimentally accessible processes. The dimuon decays $B_s^0\to\mu^+\mu^-$ and $B^0\to\mu^+\mu^-$ are a case in point. In particular, studies of these decays could help researchers to understand the nature of several anomalies seen in other rare B-meson decays.

The CMS collaboration recently reported a new measurement of the $B_s^0\to\mu^+\mu^-$ branching fraction and effective lifetime, as well as the result of a search for the $B^0\to\mu^+\mu^-$ decay, using data recorded during LHC Run 2. This new study benefits not only from a large event sample but also from advanced machine-learning algorithms, which are used to uncover the rare signal events out of the overwhelming background. The $B_s^0\to\mu^+\mu^-$ signal is very clearly seen (see figure 1), leading to more precise measurements than previously achieved. The $B_s^0\to\mu^+\mu^-$ branching fraction is measured to be $(3.8\pm0.4)\times10^{-9}$, the relative uncertainty of 11% being a remarkable improvement with respect to that of the previous CMS result, 23%.

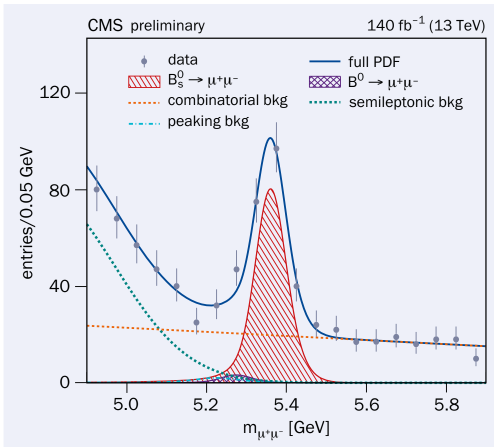


Fig. 1. *Dimuon mass distribution for high signal purity events collected during LHC Run 2. The blue curve represents the result of a fit that includes the two signal contributions and multiple backgrounds.*

This measured value is consistent with the SM prediction of $(3.7\pm0.1)\times10^{-9}$, and reduces a previous tension between theory and experiment, which was based on the combination of the previous CMS result with the ATLAS and LHCb values. The variation in the central value of the CMS measurements is mostly driven by the use of a larger data sample and by the change of the B-hadron fragmentation fraction ratio (by about 8%). The measured effective lifetime of the $B_s^0\to\mu^+\mu^-$ decay, 1.8 ± 0.2 ps, is also consistent with the SM prediction. The precision of this measurement is approaching the level necessary to probe the CP properties of $B_s^0\to\mu^+\mu^-$, which could differ from the SM prediction. Finally, the $B^0\to\mu^+\mu^-$ decay remains unseen.

CMS physicists are looking forward to continuing these rare-decay studies with the large data samples to be collected during LHC Run 3. Besides the improved precision expected for $B_s^0\to\mu^+\mu^-$ measurements, seeing the first evidence of $B^0\to\mu^+\mu^-$ is high on their wish list.

Further reading

CMS Collab. 2022 CMS-PAS-BPH-21-006.

ALICE

Hypertriton characterised with unprecedented precision

At the LHC, light nuclei and antinuclei are produced both in proton–proton and in heavy-ion collisions. Unstable nuclei, called hypernuclei, are also produced. First observed in cosmic rays in 1953, hypernuclei are formed by a mix of protons, neutrons and hyperons containing one or more strange quarks and undergo weak decays. Almost 70 years since their discovery, hypernuclei are still a source of fascination for nuclear physicists since their production is very rare and the measurement of their properties is extremely challenging.

The only hypernucleus observed so far at the LHC is the hypertriton ($^3_\Lambda$H), composed of a Lambda baryon (Λ), a proton and a neutron. While, traditionally, hypernuclei are studied in low-energy nuclear experiments, the hundreds of hypertritons and antihypertritons produced in each lead–lead run at the LHC provide one of the largest data samples for their study. The hypertritons fly for a few centimetres in the experimental apparatus before decaying into a ^{3}He nucleus and a charged pion, which are then identified by the detectors.

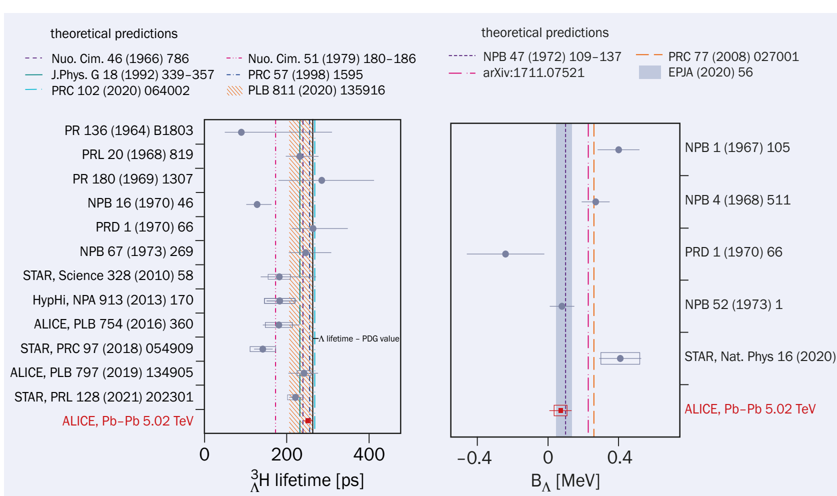


Fig. 1. *Measurements of the $^3_\Lambda$H lifetime (left) and Λ-separation energy (right) obtained with different experimental techniques, with the latest ALICE results shown in red. The horizontal lines and boxes show the statistical and systematic uncertainties, respectively, while the dashed–dotted lines are the corresponding theoretical predictions.*

The ALICE collaboration recently completed a new analysis of the largest Run 2 data sample, achieving the most precise measurements to date of the hypertriton lifetime and its Λ-separation energy (the energy required to separate the Λ from the rest of the hypertriton). The lifetime, measured from the distribution of reconstructed two-body decay lengths, was found to be 253 ± 11 (stat.) $\pm$ 6 (syst.) ps, while the separation energy, obtained from the hypertriton invariant-mass distribution, was measured to be 72 ± 63 (stat.) $\pm$ 36 (syst.) keV.

These two quantities are fundamental to understand the structure of this hypernucleus and therefore the nature of the strong interaction. While the strong force binding neutrons and protons inside atomic nuclei is well understood, the characteristics of the strong force binding nucleons and hyperons are not precisely known.

The study of this interaction is not only interesting per se, but it is also an input for modelling of the dense core of neutron stars. Indeed, the creation of hyperons is energetically favoured compared to ordinary nucleonic matter in the inner core of neutron stars. Therefore, detailed knowledge of the interactions between nucleons and hyperons is required to understand these compact astrophysical objects.

The interaction between the hyperon inside the hypertriton and the other two nucleons is extremely feeble

The new ALICE measurements indicate that the interaction between the hyperon inside the hypertriton and the other two nucleons is extremely feeble (see figure 1). This is also confirmed by the lifetime of the hypertriton, which is compatible with the free Λ-baryon lifetime. Finally, since at the LHC matter and antimatter are produced in the same amount, the ALICE collaboration could compare the lifetimes of the antihypertriton and the hypertriton. Within the experimental uncertainty, the lifetimes were found to be compatible, as expected from CPT invariance.

During LHC Run 3, ALICE will extend its studies to heavier hypernuclei, putting tighter constraints on the interaction models among hyperons and nucleons.

Further reading

ALICE Collab. 2022 arXiv:2209.07360.

LHCb

Spotting kaon decays into four muons

The LHCb experiment is designed to study heavy-flavour particles containing beauty and charm quarks. Nevertheless, thanks to the large strangeness production cross-sections at the LHC as well as the excellent reconstruction performance of LHCb at low momenta, the experiment is also able to produce precise results in strange decays, complementary to those from dedicated experiments such as NA62 and KOTO. The collaboration has recently released a "trillio-scale" upper limit on the branching fraction of the decay $K_S^0\to\mu^+\mu^-\mu^+\mu^-$, being the first at this scale at the LHC. The same dataset was used to search for $K_L^0\to\mu^+\mu^-\mu^+\mu^-$, yielding the world best upper limit f and the first LHC result on a K_L^0 decay.

According to the Standard Model (SM), K_S^0 (K_L^0) mesons decay into four muons at a very small rate of a few 10^{-14} (10^{-13}). The decay rates of these processes are very sensitive to possible contributions from new, yet-to-be discovered particles such as dark photons, which could significantly enhance or suppress the decay rate via quantum interference with the SM amplitude. Despite the unprecedented K^0-meson production rate at the LHC, performing this search is challenging due to the low transverse momentum (typically a few hundred MeV) of the muons. LHCb exploits its unique capability to select, in real time, low transverse-momentum muons – a capability that has improved in recent years thanks to the versatility of its online trigger system. The analysis used machine learning to discriminate long-lived particles from combinatorial background, as well as a data-driven and detailed map of the detector material around the interaction point. The invariant mass of the four-muon system is used as a control variable to statistically separate the potential signal from the remaining combinatorial background.

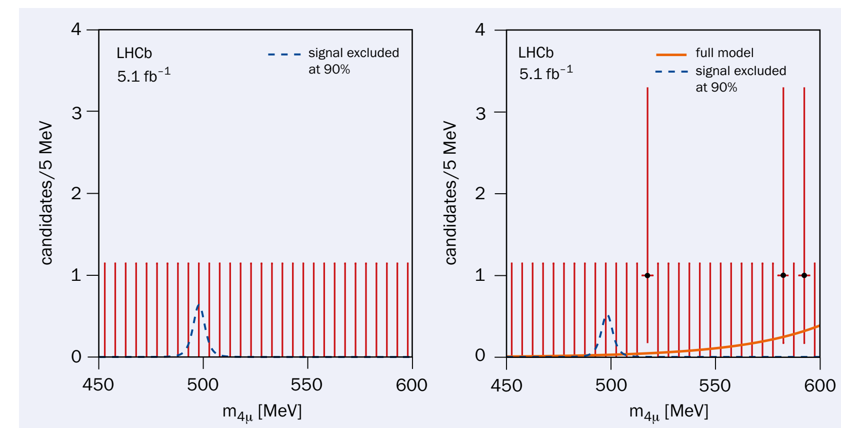


Fig. 1. *Invariant-mass distribution of the observed $K^0\to\mu^+\mu^-\mu^+\mu^-$ candidates using two different trigger categories (left: xTOS, right: TIS). The expected $K^0\to\mu^+\mu^-\mu^+\mu^-$ signal for the branching fraction excluded at 90% CL is shown in blue. The orange line represents the fit of the surviving events to an exponential function.*

No selected event consistent with the decay of K_S^0 into four muons, which should appear in the region around the K_S^0 mass of 498 MeV, was observed (see figure 1). In the absence of a signal, upper limits on the respective branching fractions are set to 5.1×10^{-12} for the K_S^0 decay mode and 2.3×10^{-9} for the K_L^0 mode at 90% CL. These results represent the world's most precise searches for these decays, and the branching fraction in $K_S^0\to\mu^+\mu^-\mu^+\mu^-$ is the most stringent upper limit on a K_S^0 decay mode.

The upgraded LHCb detector, which started data-taking this year, offers excellent opportunities to further improve the search precision and eventually find evidence of this decay. In addition to the increased luminosity, the LHCb upgrade has a fully software trigger, which is expected to significantly improve the efficiency for K^0 decays into four muons and other decays with very soft final-state particles.

Further reading

LHCb Collab. 2022 LHCb-PAPER-2022-035.

FIELD NOTES

Reports from events, conferences and meetings

JENAS 2022

JENAS picks up the pace in Spain

Intersection *Members of the particle, nuclear and astroparticle-physics communities meet at the CSIC auditorium in Madrid for the JENAS 2022 symposium.*

The second joint ECFA (European Committee for Future Accelerators), NuPECC (Nuclear Physics European Collaboration Committee) and APPEC (AstroParticle Physics European Consortium) symposium, JENAS, was held from 3 to 6 May in Madrid, Spain. Senior and junior members of the astroparticle, nuclear and particle-physics communities presented their challenges and discussed common issues with the goal of achieving a more comprehensive assessment of overlapping research topics. For many of the more than 160 participants, it was their first in-person attendance at a conference after more than two years due to the COVID-19 pandemic.

Focal point

The symposium began with the research highlights and strategies of the three research fields. A major part of this concerned the progress and plans of the six joint projects that have emerged since the first JENAS event in 2019: dark matter (iDMEu initiative); gravitational waves for fundamental physics; machine-learning optimised design of experiments; nuclear physics at the LHC; storage rings to search for charged-particle electric dipole moments; and synergies between the LHC and future electron–ion collider experiments. The discussions on the joint projects were complemented by a poster session where young scientists presented the details of many of these activities.

Detector R&D, software and computing, as well as the application of artificial intelligence, are important examples where large synergies between the three fields can be exploited. On detector R&D there is interest in collaborating on important research topics such as those identified in the 2021 ECFA roadmap on detector R&D. In this roadmap, colleagues from the astroparticle and nuclear-physics communities were involved. Likewise, the challenges of processing and handling large datasets, distributed computing, as well as developing modern analysis methods for complex data analyses involving machine learning, can be addressed together.

Overview talks and round-table discussions related to education, outreach, open science and knowledge transfer allowed participants to emphasise and exchange best practices. In addition, the first results of surveys on diversity and the recognition of individual achievements in large collaborations were presented and discussed. For the latter, a joint APPEC–ECFA–NuPECC working group has presented an aggregation of best practices already in place. A major finding is that many collaborations have already addressed this topic thoroughly. However, they are encouraged to further monitor progress and consider introducing more of the best practices that were identified.

> **The goal was achieving a more comprehensive assessment of overlapping research topics**

Synergy

One day was dedicated to presentations and closed-session discussions with representatives from both European funding agencies and the European Commission. The aim was to evaluate whether appropriate funding schemes and organisational structures can be established to better exploit the synergies between astroparticle, nuclear and particle physics, and thus enable a more efficient use of resources. The positive and constructive feedback will be taken into account when carrying out the common projects and towards the preparation of the third JENAS event, which is planned to take place in about three years' time.

Andreas Haungs *APPEC chair,*
Karl Jakobs *ECFA chair and*
Marek Lewitowicz *NuPECC chair.*

IDM 2022

Identifying dark matter

The international conference series on the identification of dark matter (IDM) was brought to life in 1996 with the motto that "it is of critical importance now not just to pursue further evidence for its existence but rather to identify what the dark matter is." Despite earnest attempts to identify what dark matter comprises, the answer to this question remains elusive. Today, the evidence for dark matter is overwhelming; its amount is known to be around 27% of the universe's energy-density budget. IDM2022 illuminated the dark-matter mystery from all angles, ranging from cosmological evidence via astrophysics to possible dark-matter particle candidates and their detection via indirect searches, direct searches and colliders.

The 14th edition of IDM took place in Vienna, Austria, from 18 to 22 July, attracting about 250 physicists and more than 200 contributions. The conference was initially scheduled for 2020 but changed to an online format due to the pandemic, while the in-person IDM was delayed until 2022. Many young scientists were able to meet the dark-matter community for the first time "in real life". The Strings 2022 conference took place in Vienna simultaneously, with complementary presentations.

One focus of IDM2022 was the direct detection of dark matter. Tremendous progress in the sensitivity of direct detection experiments has been achieved in the past few decades over a wide dark-matter particle mass range. All major experiments presented their latest results. While in the past, direct searches focused on the classical WIMP region in a mass between a few GeV and several TeV, the search region is now enlarged towards even lighter dark-matter particles down to the keV region. Different mass regions require different technologies and new ideas were presented to increase the sensitivities towards these unexplored mass regions. For GeV WIMP dark-matter searches, the XENON collaboration displayed the first results from their latest setup, XENONnT, which has a significantly lower background level and recently eliminated a previously seen excess in XENON1T (*CERN Courier* September/October 2022 p13). The XENON, Darwin and LZ collaborations recently formed the XLZD collaboration with the aim of building a next-generation liquid-xenon experiment.

Greetings from Vienna *Many IDM participants met in person for the first time to discuss and exchange the latest dark-matter results.*

While the XENON1T excess is gone, direct-detection experiments exploring the sub-GeV mass regime still face unknown background contributions, especially in solid-state detectors. This is currently one of the biggest obstacles to increasing the sensitivity to even smaller cross-sections. No complete understanding has been achieved so far, but combining the results, knowledge and expertise of the experiments points to stress relaxations in crystals as one primary underlying source. To tackle this tricky problem, a subset of the IDM2022 participants held a dedicated satellite meeting. This EXCESS workshop was the third event of its kind, and the first to take place in person.

The direct detection experiment DAMA has observed a statistically significant signal of an annual modulated event rate for several years. This observation is consistent with Earth moving through the dark-matter halo, but has not been confirmed by any other experiment. DAMA recently reduced the energy threshold to 0.5 keV electron equivalent by upgrading their readout electronics to further increase sensitivity. Several new dark-matter experiments based on the same target material – NaI – are running or being commissioned to provide more information on the long-standing DAMA observation: ANAIS, COSINE, COSINUS and SABRE. Even lighter forms of dark matter, such as axions and axion-like particles, were discussed, as well as the possibility that dark matter comprises bound states.

Primordial black holes are also attractive potential dark-matter candidates. Astronomical data from, for example, microlensing, structure formation and gravitational waves hint at their existence. However, current data gives no handle on whether primordial black holes could be responsible for all the universe's dark-matter content, or only correspond to part of the overall dark-matter density. Besides black-hole mergers, gravitational-wave signals can provide additional information to understand the origin of dark matter. In particular, processes in the early universe detected via gravitational waves could provide new insights into the particle nature of dark matter. With the increased sensitivity of operating and future gravitational-wave detectors, new players will provide additional data to unravel the dark-matter problem.

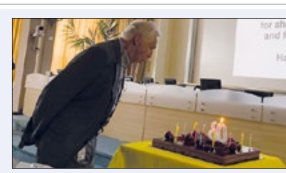
With a plethora of new ideas and experiments presented at this year's IDM, the path is prepared for the next edition in L'Aquila, Italy, in 2024.

Florian Reindl *and* **Jochen Schieck** *Austrian Academy of Sciences and TU Wien.*

VENEZIANO@80

A celebration for Gabriele Veneziano

On 7 September colleagues and friends of Gabriele Veneziano gathered at CERN for an informal celebration of the renowned theorist's 80th birthday. While a visitor in the CERN theory division (TH) in 1968, Veneziano wrote a paper "Construction of a crossing-simmetric, Regge-behaved amplitude for linearly rising trajectories". It was an attempt to explain the strong interaction, but ended up marking the beginning of string theory. During the special TH colloquium, talks by Paolo Di Vecchia (NBI&Nordita), Thibault Damour (IHES) and others explored this and numerous other aspects of Veneziano's work, much of which was undertaken during his 30 year-long career at CERN.



Buon compleanno *Veneziano blows out his candles in the Council chamber.*

Concluding the day's proceedings, Veneziano thanked his mentors, CERN TH and chance – "the chance of having lived through one of most interesting periods in the history of physics… during which, through a wonderful cooperation between theory and experiment, enormous progress has been made in our understanding of nature at its deepest level."

NUFACT 2022

Catching neutrinos in Utah

Neutrinos are the least understood of all elementary particles, and the fact that they have mass is a firm indication of physics beyond the Standard Model. Decades of effort have been devoted to exploring the properties of neutrinos. However, there are still many important questions to address. For example, little is known about the absolute mass scale and neutrino-mass ordering. Also, we have not achieved a decent measurement of the CP phase in the neutrino mixing "PMNS" matrix. Furthermore, the nature of neutrino masses, i.e. whether they are Dirac or Majorana, remains unknown.

Connections *Now in-person, the members of the NuFact 2022 workshop explored synergies to shed light on the neutrino's nature.*

From 30 July to 6 August the 23rd NuFACT workshop hosted by the University of Utah reviewed recent developments in neutrino physics, particle physics and astroparticle physics. The workshop brought together experts from all leading neutrino experiments and discussed theoretical aspects, with the aim of facilitating new connections between different disciplines and theorists and experimentalists.

Talking points

NuFACT2022 topics were spread into seven working groups: neutrino oscillations; neutrino scattering physics; accelerator physics; muon physics; neutrinos beyond PMNS; detectors; and inclusion, diversity, equity, education and outreach. The latter was newly established at this year's workshop to become an integral part of the series.

Three mini-workshops took place. One explored plans for the second phase of the European Spallation Source neutrino Super Beam (ESSνSB) project, for which the European Union has recently decided to continue its support for another four years. This second phase will study new components that open additional physics opportunities including muon studies, precise neutrino cross-section measurements and sterile-neutrino searches.

The two-day mini-workshop "Multi-messenger Tomography of the Earth", involving 22 talks, saw leading neutrino physicists and geoscientists exchange ideas on how Earth's interior models may impact high-precision measurements of neutrino oscillation parameters. Participants also addressed the potential of using neutrino absorption at high energies (PeV–TeV) and neutrino oscillation at low energies (~GeV) inside Earth to locate the core–mantle boundary, determine the density of the core and mantle, and measure the chemical composition of the core. A third workshop targeted career development, with the aim of improving communication and negotiation skills among early-career scientists.

Progress in using neutrino-oscillation measurements to search for hints of new physics and symmetries in nature was discussed extensively. Central questions to be addressed include: is the neutrino-mixing angle θ_{23} exactly 45°, which might hint at a new symmetry in nature? Is the PMNS matrix unitary or could it indicate there are additional neutrinos or something fundamentally wrong with our understanding of the neutrino sector? Are there more than the three active neutrinos? Do we see indications for CP violation in the neutrino sector or is it even maximal? Do neutrino-mass eigenstates follow the same "normal" ordering as observed for quarks, for which there is currently a slight preference in the global fit data ?

The latest results from leading experiments including IceCube, KM3NeT/ORCA, NOvA,Super-K and T2K were presented. T2K presented a new analysis using the same data runs as last year, but using more data from the near and far detector samples combined with upgraded cross-section and flux models. T2K and NOvA data preferences on δ_{CP} and $\sin^2\theta_{23}$ are broadly compatible and joint fit results can be expected for late 2022. For the normal-mass ordering case, the most probable regions are distinct, and the significant contour overlap of 1σ, while no preference on CP violation can be inferred. For the inverted mass ordering case, T2K and NOvA contours overlap and are consistent with maximal CP violation in the neutrino sector.

Particularly competitive results of neutrino oscillation-parameter measurements with neutrino telescopes are available from IceCube-DeepCore and ORCA, and are now approaching the precision of accelerator-based neutrino experiments.

Various theoretical aspects of neutrino physics were covered. The nature of the neutrino mass, either Dirac or Majorana, remains a key focus. Different see-saw mechanism types and their experimental consequences were intensively discussed. In particular, recent progress in Majorana neutrino tests using both neutrinoless double-beta decay experiments as well as LHC measurements by the new FASER experiment were reported. Connecting neutrino and muon experiments, such as charged-lepton-flavour violation and the application of a possible muon collider to neutrino physics, were extensively addressed. The existence of sterile neutrinos and their properties remain of high importance to the field and future experimental results are highly anticipated, such as the short-baseline program at Fermilab and JSNS² at J-PARC. Alternative explanations for various neutrino anomalies were also discussed, including more general dark-sector searches using neutrino experiments. The electron low-energy excess at MicroBooNE in particular draws attention. The focus is on improved event reconstructions, which may unveil the nature of this anomalous excess. Assuming the existence of one species of sterile neutrino, 3+1 oscillation analyses have been carried out to interpret the anomaly and compare with results from other experiments. Although inconclusive, this anomaly triggers many interesting ideas that will motivate follow-up studies.

Taking place shortly after the Snowmass Summer Meeting in Seattle (see p23), NuFACT2022 also offered an opportunity to summarise the scientific vision for the future of neutrino physics in the US. The neutrino frontier in Snowmass has 10 topical groups, with physics beyond the Standard Model and neutrinos as messengers emerging as major focuses. Many possible synergies between neutrino physics and other branches of physics were also highlighted.

Carsten Rott *and* **Yue Zhao** *University of Utah.*

CERNCOURIER

VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022

IOP Publishing

IUPAP CENTENNIAL

100 years of international collaboration in physics

The International Union of Pure and Applied Physics (IUPAP) is an offspring of the International Research Council, a temporary body created after the First World War to rebuild and promote research across the sciences. IUPAP was established in 1922 with 13 member countries and held its first general assembly in Paris the following year. Originally, neither the International Research Council nor IUPAP included any of the countries of the Central Powers (Germany, Austria–Hungary, Bulgaria and the Ottoman Empire). Many lessons in science diplomacy had to be learned before IUPAP and the other scientific unions became truly international and physicists from all countries could apply to join. Today, with 60 member countries, the union strongly advocates that no scientist shall be excluded from the scientific community as long as their work is based on ethics and the principles of science in its highest ideals – an aspect that certainly will be further elaborated by the working group on ethics established by IUPAP in October last year.

IUPAP

Preservation *Current and future generations of physicists commemorated the centennial of IUPAP.*

Information exchange

Among IUPAP's commissions covering all the different disciplines of physics is the Commission on Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants (C2), formed in 1931. The task of this commission is to promote the exchange of information and views among the members of the international scientific community in the general field of fundamental constants. As an example, the international system of units (SI) was originally recommended by IUPAP in 1960, and C2 has maintained its role in recommending further improvements, including resolutions supporting the choice of constants to define the new SI as well as the decision to proceed with the redefinition of four of the seven units made in May 2019.

From 11 to 13 July, around 250 physicists from some 70 countries gathered to celebrate the 100th birthday of IUPAP at a symposium held at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy. The symposium was one of the official events of the International Year of Basic Sciences for Sustainable Development, which was officially inaugurated only a few days earlier at the UNESCO headquarters in Paris (*CERN Courier* March/April 2022 p51). About 40% of the participants were physically present, while the rest connected online.

IUPAP continues to promote physics as an essential tool for development and sustainability in the next century

Various panels composed of international experts discussed important issues in alignment with the IUPAP's core aims, including: how to support and encourage early-career physicists, how to improve diversity in physics, how to strengthen the ties to physicists working in industry, how to improve the quality of physics education, and how to promote physics in less developed countries.

A number of influential scientists, including Giorgio Parisi (La Sapienza) and Laura Greene (Florida State University), described their roles in providing evidence-based advice to their respective governments on science and shared best practices that could be useful across borders. Other prominent speakers included William Phillips (Maryland), who covered the quantum reform of modern metric systems; Donna Strickland (Waterloo), who discussed the physics of high-intensity lasers; and Takaaki Kajita (Tokyo), who presented 100 years of neutrino physics via an online connection with the International Conference on High Energy Physics (ICHEP) in Bologna. Climate scientist Tim Palmer (Oxford) argued that a supercomputing facility modelled on the organisation of CERN would enable a step-change in quantifying climate change (*CERN Courier* July/August 2021 p49), while Stewart Prager (Princeton) outlined a new project sponsored by the American Physical Society to engage physicists in reducing nuclear threat. Dedicated panels discussed the development of physics in Africa and the Middle East, Asia and the Pacific, and Latin America. It is clear that in these regions IUPAP has a large potential to foster further international collaboration.

IUPAP enhances the vital role of young physicists, among others, through the award of early-career scientist prizes. In Trieste, several recent recipients of the prize were invited to present their research. The talks were all striking and left the audience with high hopes for the future of physics. Furthermore, the logistics in the auditorium and the handling of all the questions that came in from online participants were smoothly taken care of by members of the International Association of Physics Students.

The centennial symposium was an opportunity to reflect on IUPAP's role in promoting international cooperation and to welcome Ukraine as a new member. The decision to admit Ukraine was expedited to send a strong signal of support for the war-torn country – a war that has not spared its scientific institutions and the people who work there, as expressed by the president of the Ukrainian Academy of Sciences Anatoly Zagorodny in a powerful online presentation. IUPAP has issued a statement strongly condemning the Russian aggression in Ukraine, while also expressing the principle that no scientist should be excluded from union-sponsored conferences, as long as he or she carries out work not contributing to weapons development. To overcome difficulties related to conferences, IUPAP has put in place that excluded scientists can participate using the Union as their affiliation – similar to the model applied for the Olympic Games.

IUPAP has served the physics community for 100 years and has strong ambitions to continue to assist in the worldwide development of physics and to promote physics as an essential tool for development and sustainability in the next century.

Monica Pepe Altarelli *IUPAP vice-president and* **Jens Vigen** *IUPAP secretary general and CERN.*

CHARTING THE FUTURE OF US PARTICLE PHYSICS

The most recent 'Snowmass' community planning exercise revealed the great opportunities present in high-energy physics in the coming decades, write Joel Butler, R Sekhar Chivukula, Priscilla Cushman, André de Gouvêa, Tao Han and Young-Kee Kim.

Future physics *The buildings that will house the new PIP-II accelerator at Fermilab, extensions to which were discussed in the Snowmass neutrino and accelerator frontiers. (Credit: Fermilab)*

During the past several decades of intense experimental and theoretical research, particle physicists have come to rely on the Standard Model to describe phenomena at the smallest scales and highest energies. This highly predictive, relativistic spontaneously-broken gauge theory has pointed the way to a sequence of discoveries, including that of the W and Z bosons, the gluons, and the charm and top quarks. At each point, it gave us an approximate mass scale or energy range to explore, which told us what kind of facilities we needed to build to observe predicted phenomena. Finally, in 2012, its most remarkable prediction – the existence of a Higgs particle associated with an apparently fundamental scalar field responsible for electroweak symmetry breaking – was confirmed. There are, however, big questions in particle physics to which we don't know the answers.

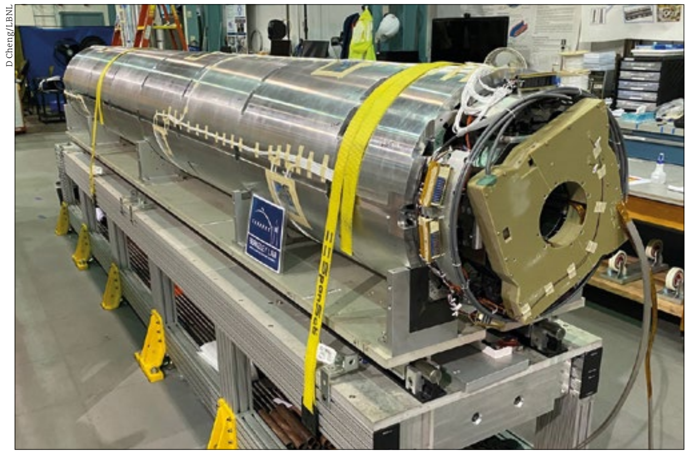
Every seven to 10 years since 1982, high-energy physicists in the US have undertaken a community planning exercise to identify the most important questions for the following two decades and the facilities, infrastructure and R&D needed to pursue them. For many years these efforts, which are sponsored by the Division of Particles and Fields (DPF) of the American Physical Society (APS) and include scientists from other countries and related fields, concluded with a summer workshop in Snowmass, Colorado. The planning exercise focuses on scientific issues, whereas establishing project priorities is the task of a Particle Physics Project Prioritization Panel "P5", charged by the US Department of Energy (DOE) and the National Science Foundation (NSF).

The latest study, "Snowmass 2021" (*CERN Courier* January/February 2022 p43) was meant to conclude in July 2021, but had to be delayed due to the COVID-19 pandemic. Despite the challenges, our community accomplished an amazing amount of work. The final discussions and synthesis of all the white papers, seminars, workshops and other materials took place at the University of Washington in Seattle from 17–26 July 2022. At the end of the meeting, Hitoshi Murayama (UC Berkeley and the University of Tokyo) was named chairperson of the new P5 subpanel, which will take input from Snowmass 2021.

Snowmass in context

The last US community planning exercise was held in 2013. The subsequent P5 report synthesised the questions identified into five physics drivers: use the Higgs boson as a tool for discovery; pursue the physics associated with neutrino mass; identify the new physics of dark matter; understand cosmic acceleration; and explore the unknown. It also made 29 project-oriented recommendations. The two projects assigned the highest priority were participation in the High-Luminosity LHC and the ATLAS and CMS experiments; and the construction of the LBNF/DUNE long-baseline neutrino experiment, which will detect neutrinos produced at Fermilab interacting in massive underground detectors

CERNCOURIER
VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022



D Cheng/LBNL

High priority *A niobium-tin quadrupole magnet for the HL-LHC upgrade project (a high priority of the Snowmass energy frontier) built and tested at Lawrence Berkeley National Laboratory.*

1300 km away in the Homestake mine in South Dakota.

Nearly a decade since the last Snowmass/P5 exercise, some elements of the recommended experimental programme have taken data and have succeeded in pushing the boundaries of our knowledge. But despite some hints, they have not yet produced a result that points us in a specific direction. Snowmass 2021 reconfirmed the relevance of the physics drivers, and added a proposal for a sixth: flavour physics as a tool for discovery. Specifically, we don't understand why three generations of matter particles exist nor the origin of the mass patterns that they exhibit. We do not know why the quark and the lepton mixing matrices are so different, or whether CP violation exists in the neutrino sector and how it relates to the observed matter–antimatter asymmetry of the universe. There are, currently, several tantalising hints of new particles and interactions that could explain various anomalies in the weak decays of B mesons and the anomalous magnetic moment of the muon. Depending on what the near-future brings, dedicated next-generation flavour experiments are likely to be required and could play a key role in the quest for physics beyond the Standard Model.

Snowmass 2021 was organised into 10 working groups or "frontiers": accelerator, cosmic, community engagement, computational, energy, instrumentation, neutrinos, rare processes and precision measurements, theory, and underground facilities and infrastructure. Each frontier divided its work into several topical groups, taking into account input from the 2020 update of the European strategy for particle physics and other international studies. More than 500 new white papers were produced. An early-career organisation assisted young physicists in contributing to the Snowmass process and international participation was encouraged, with leaders of international institutes and laboratories including Fabiola Gianotti (CERN), Masanori Yamauchi (KEK) and Yifang Wang (IHEP) giving presentations during special plenary sessions at the Seattle workshop. In describing the US programme, Fermilab director Lia Merminga emphasised the importance of international collaboration, citing the close relationship between the US and CERN.

Nearly a decade since the last Snowmass exercise, the recommended experimental programme has succeeded in pushing the boundaries of our knowledge

There was broad agreement that a successful future programme should include a healthy breadth and balance of physics topics, experiment sizes and timescales, supported via a dedicated, robust and ongoing funding process. Completion of existing experiments and execution of DUNE and the HL-LHC programmes are critical for addressing the science drivers in the near-term. Strong and continued support for formal theory, phenomenology and computational theory is needed, as are stronger, targeted efforts connecting theory to experiment. Both R&D directed to specific future projects and generic research needs to be supported in critical enabling technologies such as accelerators, instrumentation/detectors and computation, and in new ones such as quantum science and machine learning. Finally, a cohesive, strategic approach to promoting diversity, equity and inclusion, and to improving outreach and engagement, is required.

Snowmass 2021: a preview of the outcomes

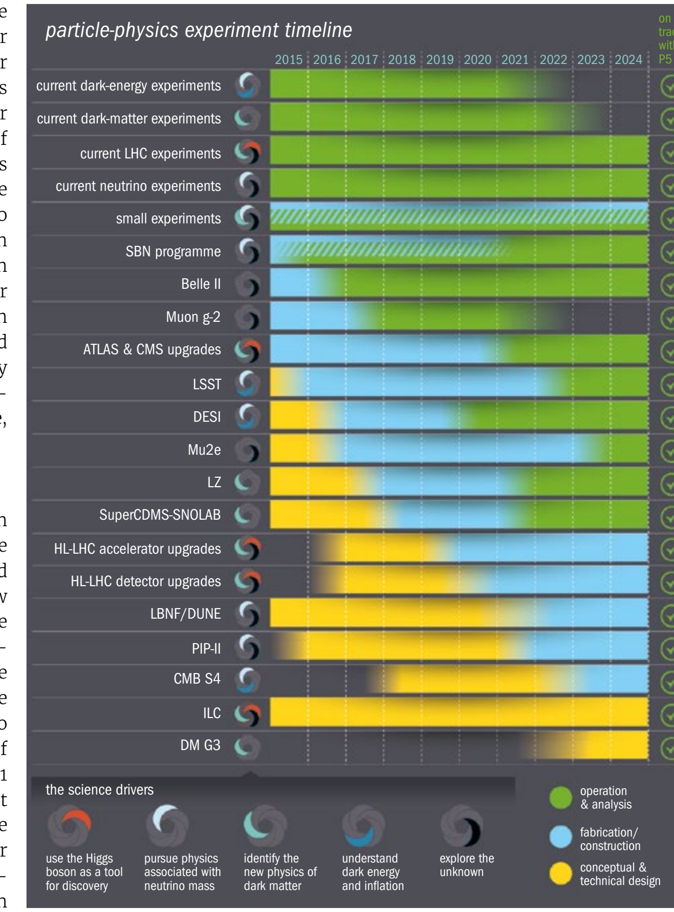
A panoply of ideas were discussed at Snowmass 2021. Here, in the context of the 10 frontiers, we list some of the larger projects and programmes that are proposed to be carried out, or at least started, in the next two decades, and some important conclusions concerning enabling technologies and infrastructure, with the disclaimer that these may change as the final Snowmass frontier reports are written.

The cosmic frontier

The cosmic frontier is focused on understanding how fundamental physics shapes the behaviour of the universe, in particular concerning the nature of dark matter (DM) and dark energy. The space of DM models encompasses a dizzying array of possibilities representing many orders of magnitude in mass and couplings, making the DM programme one of the most interdisciplinary investigations in high-energy and particle physics. The cosmic frontier DM programme will "delve deep, search wide" by employing a range of direct searches for WIMPs interacting with targets on Earth or produced at accelerators, indirect searches for the products of DM annihilation and probes based on analyses of cosmic structure. A complementary thrust is building the next generation of cosmological probes. The next big project in this arena is CMB-S4, a system of telescopes to study the cosmic microwave background and address the mystery of cosmic inflation, which is expected to operate through to at least 2036 (*CERN Courier* March/April 2022 p36). Additional projects that would start after 2029 are Spec-S5 (the follow-on spectroscopic device to DESI), a project to carry out line intensity mapping (LIM), and planning efforts to increase the sensitivity of gravity wave detection by at least a factor of 10 (10^3 in sensitive volume) beyond what will be achieved by LIGO/Virgo.

The energy frontier

The immediate goal for the energy frontier is to carry out the 2014 P5 recommendations to complete the HL-LHC upgrade and execute its physics programme. A new aspect of the proposed programme is the emergence of a variety of auxiliary experiments, examples of which are FASER (operational) and MATHULSA (proposed), that can use the existing LHC interaction regions to explore parts of discovery space in the far-forward regions. These are mid-scale detectors in cost and complexity, and provide room for additional innovation at the HL-LHC. The energy frontier supports the construction of a global e^+e^- Higgs factory as soon as possible. Either a linear collider or a circular collider can provide the necessary sensitivity, and a programme of directed detector and accelerator R&D for a Higgs factory is needed immediately to enable US participation. To ensure the long-term viability of the field, the energy frontier wants to begin accelerator and detector R&D towards a 10 TeV muon collider or a 100 TeV-scale hadron collider, in collaboration with partners worldwide. Finally, the US energy-frontier community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the US, specifically either an e^+e^- Higgs factory or a muon collider, while maintaining its international collaborative partnerships and obligations with, for example, CERN future-collider R&D projects.



usparticlephysics.org

Project status *Projects in operation (green), under construction or in production (blue) or still under design and project definition (yellow).*

The neutrino frontier

What are the neutrino masses? Are neutrinos their own antiparticles? How are the masses ordered? What is the origin of neutrino mass and flavour? Do neutrinos and antineutrinos oscillate differently? And are there new particles and interactions that can be discovered? These are among the fascinating questions elaborated by the neutrino frontier. The DUNE R&D programme, propelled by the development of large-scale liquid-argon detectors in the US and Europe, in particular through the CERN Neutrino Platform, has demonstrated the power and feasibility of this technique. Following the completion of DUNE Phase 1 by 2030, DUNE Phase 2 is the neutrino community's highest priority project for 2030–2040. The Phase 2 project has three components: a replacement of the Fermilab 8 GeV Booster to deliver 2.4 MW to the DUNE target and possibly to provide beam for other experiments; the construction of an additional 20 kT (fiducial) of far-detectors at Homestake; and a fully capable near-detector complex at Fermilab to provide very precise control of the systematic uncertainties for the far-detector measurements, besides carrying out a rich physics programme of their own. DUNE will perform definitive studies of neutrino oscillations, test the three-flavour paradigm, search for new neutrino interactions, and will resolve the mass hierarchy question and hopefully observe CP violation. There are many other aspects of neutrino physics that merit study, including the absolute mass, the search for neutrinoless double beta decay (which bears on the issue of whether the neutrino is a Dirac or a Majorana fermion), the measurement of cross sections, and the search for sterile neutrinos. Several of these will be part of the US neutrino programme, either based in the US or through collaboration abroad.

Rare processes and precision measurements

The rare processes and precision measurements frontier is currently working on two mid-sized US projects at Fermilab endorsed by P5 in 2014: the Muon g-2 experiment, which has produced exciting results and will continue to take data for at least a few more years; and the Mu2e experiment, which is under construction. The programme also has important investments in flavour physics through support of the Belle II experiment in Japan and LHCb at CERN. Priorities for the next few years are to complete g-2, begin taking data with Mu2e, and continue collaboration at Belle II and LHCb, including participation in future upgrades. Looking ahead, the central themes are to understand quark and lepton flavour and its violation measurements, and the search for dark-matter production in the mass range from sub-MeV to a few GeV in fixed-target proton and electron experiments. There is a proposal to study muon science in an advanced muon facility at Fermilab that would greatly improve the search for lepton-flavour violation in $\mu \to e\gamma$, $\mu N \to eN$ and $\mu \to 3e$ decays. This would require an intense proton beam with unique characteristics and accumulator rings to manage the production of muon beams with different energies and time profiles.

Theory frontier

Theoretical particle physics seeks to provide a predictive mathematical description of matter, energy, space and time that synthesises our knowledge of the universe, analyses and interprets existing experimental results and motivates future experimental investigation. Theory connects parti-

seattlesnowmass2021.net

Better together *Around 700 people attended the Snowmass Community Summer Study and Workshop at the University of Washington in Seattle from 17–26 July, with a further 650 connecting remotely.*

A global effort will be required, and much thought is being applied to ensuring that the US can play an appropriate role

cle physics to other areas (e.g. gravity and cosmology) and extends the boundaries of our understanding (e.g. quantum information). Together, fundamental, phenomenological and computational theory form a vibrant ecosystem whose health is essential to all aspects of the US high-energy physics programme. The theory frontier recommends, among others, invigorated support for a broad programme of research as part of a balanced portfolio and an emphasis on targeted initiatives to connect theory to experiment.

Accelerator frontier

The accelerator frontier, which has many crossovers with the energy frontier, aims to prepare for the next generations of major accelerator-based particle physics projects to explore the energy, neutrino and rare-process-and-precision frontiers. In the near term, a multi-MW beam-power upgrade of the Fermilab proton accelerator complex is required for DUNE phase 2. Studies are required to understand what other requirements the Fermilab accelerator complex needs to meet if the same upgrade is to be used for related rare-decay and precision experiments. In the energy frontier, a global consensus for an e^+e^- Higgs factory as the next collider has been reaffirmed. While some options (e.g. the International Linear Collider) have mature designs, other options (such as FCC-ee, C^3, HELEN and CLIC) require further R&D to understand if they are viable. In order to further explore the energy frontier, a very high-energy circular hadron collider or a multi-TeV muon collider will be needed, both of which require substantial study to see if construction is feasible in the decade starting 2040 or beyond. It is proposed that the US establish a national integrated R&D programme on future colliders to carry out technology R&D and accelerator design studies for future collider concepts. Since machines of this magnitude will require international collaboration, the US R&D programme must be well-aligned and consistent with international efforts. Also under consideration are new acceleration techniques, such as wakefield acceleration, and ERLs, along with proposed R&D programmes that could indicate how they would contribute to the design of future colliders.

Computational frontier

Software and computing are essential to all high-energy physics experiments and many theoretical studies. However, computing has entered a new "post-Moore's law" phase. Speed-ups in processing now come from the use of heterogeneous resources such as GPUs and FPGAs developed in the commercial sector, with significant implications for the way we develop and maintain software. We are also beginning to rely on community hardware resources such as high-performance computing centres and the cloud rather than dedicated experiment resources. Finally, new machine-learning approaches are changing the way we work. This new computing environment requires new approaches to address the long-term development, maintenance and user support of essential software packages and cross-cutting R&D efforts. Additionally, strong investment in career development for software and computing researchers is needed to ensure future success. The computational frontier therefore recommends the creation of a standing coordinating panel for software and computing under the auspices of the APS DPF, mirroring the Coordinating Panel for Advanced Detectors established in 2012.

Instrumentation frontier

Improved instrumentation is the key to progress in neutrino physics, collider physics and the physics of the cosmic and rare-processes frontiers. Many aspects now at the cutting-edge of detector development were hardly present 10 years ago, including quantum sensors, machine-learning and precision timing. Funding for instrumentation in the US, however, is actually declining. Key elements of a rejuvenated instrumentation effort include programmes to develop and maintain a sufficiently large and diverse workforce, including physicists, engineers and technicians at universities and national laboratories; double the US detector R&D budget over the next five years and modify funding models to enable R&D consortia; expand and sustain support for innovative detector R&D and establish a separate review process for such pathfinding endeavours; and develop and maintain critical facilities, centres and capabilities for sharing knowledge and tools.

The underground frontier

Underground experiments address some of the most important areas of particle physics, including the search for dark matter, neutrino physics (including neutrinoless double beta decay and atmospheric neutrinos), cosmic-ray physics and searches for proton decay. The underground frontier concluded that future experiments and their enabling R&D require more space than is currently planned. They proposed a possible addition of the underground space at a depth of 4850 feet at SURF/Homestake and possible additional space at a depth of 7400 feet. These would open up space to develop new experiments and would provide the opportunity for SURF to host next-generation dark-matter or neutrinoless double beta decay experiments.

Community engagement

The community engagement frontier concentrated on seven areas: interaction with industry; career pipeline and development; diversity, equity and inclusion; physics education; public education and outreach; public policy and government engagement; and environmental and societal impacts. The inclusion of this broad array of issues as a "frontier" was a novel aspect of Snowmass 2021 and led to the formulation of many proposals for consideration and implementation by the community as a whole. These issues impact the ability of all frontiers to successfully complete their work, and some, such as the need to broaden representation, are highlighted by other frontiers too. While many recommendations apply directly to the DOE and NSF programmes and could be considered by P5, many others are directed to the HEP community as a whole. We in DPF are considering how best to pursue these issues with government agencies, APS and other groups.

The exciting road ahead

Almost three months since the Seattle workshop, the individual frontier reports are now nearly all complete and the process of synthesising the results has begun. One important theme is to stay the course on the programme approved by the last P5 in the hopes that the hints and anomalies that have shown up since then will provide some guidance for physics beyond the Standard Model. The second theme is that, in the absence of a specific target, we will have to plan a very diverse programme of experiments, theoretical studies and machine and detector R&D in which we broadly explore the large space of possibilities. In all cases, a global effort will be required, and much thought is being applied to ensuring that the US can play an appropriate role.

We believe that members of the US high-energy physics community left the Seattle workshop with an appreciation of the great opportunities present in each frontier, the interconnections between the frontiers and the connections to programmes in the rest of the world. We hope that our report will help P5 produce recommendations that we can unite behind, as we did in 2014. That has proven to be an effective step in convincing the public and policy makers that we have conducted a rigorous process and achieved a consensus that is worthy of their support. ●

THE AUTHORS

APS–DPF chair line: **Joel Butler** *chair,* **R Sekhar Chivukula** *chair-elect,* **Priscilla Cushman** *chair 2019,* **André de Gouvêa** *vice-chair,* **Tao Han** *chair 2021 and* **Young-Kee Kim** *chair 2020.*

NEUTRINOS OUT OF THE BLUE

More than 17,000 photomultipliers for KM3NeT are already transmitting data from the Mediterranean seabed, opening a new vista on the neutrino's properties. Paschal Coyle, Antoine Kouchner and Gwenhaël De Wasseige take a deep dive.

In the dark abysses of the Mediterranean Sea, what promises to be the world's largest neutrino telescope, KM3NeT, is rapidly taking shape. Using transparent seawater as the detection medium, its large three-dimensional arrays of photosensors will instrument a volume of more than one cubic kilometre and detect the faint Cherenkov light induced by the passage of charged particles produced in nearby neutrino interactions. The main physics goals of KM3NeT are to detect high-energy cosmic neutrinos and identify their astrophysical origins, as well as to study the fundamental properties of the neutrino itself.

KM3NeT (the Cubic Kilometre Neutrino Telescope) is the successor to the ANTARES neutrino telescope, which operated continuously from 2008 and has recently been decommissioned (see "The ANTARES legacy" panel, p32). KM3NeT comprises two detectors: ARCA (Astroparticle Research with Cosmics in the Abyss), located at a depth of 3500 m offshore from Sicily, and ORCA (Oscillation Research with Cosmics in the Abyss), located at a depth of 2450 m offshore from southern France. ARCA is a sparse detector of about 1 km^3 that is optimised for the detection of TeV–PeV neutrinos, while ORCA is a 7 Mt-dense detector optimised for sub-TeV neutrinos. The KM3NeT collaboration comprises more than 250 scientists from 16 countries.

The key technology is the digital optical module (DOM) – a pressure-resistant glass sphere hosting 31 three-inch photomultiplier tubes, various calibration devices and the readout electronics (see "Modular" image). A total of 18 DOMs are hosted on a single detection line, and the lines are anchored to the seafloor and held taut by a submerged buoy. The ORCA detector will comprise around 100 lines and the ARCA detector will have twice as many. The bases of the lines are connected via cables on the seafloor to junction boxes, from which electro-optical cables many tens of kilometres long bring the data to shore along optical fibres. Information on every single photon is transmitted to the shore stations, where trigger algorithms are applied to select interesting events for offline analysis.

From the light pattern recorded by the DOMs, the energy and the direction of a neutrino can be estimated. Furthermore, the neutrino flavour can also be distinguished; muon neutrino charged-current (CC) interactions produce an extended track-like signature (see "Subsea shower" image) whereas electron- and tau-neutrino CC interactions, as well as neutral-current interactions, produce more compact shower-like events. By selecting up-going neutrinos, i.e. those that have travelled from the other side of Earth, the large background from down-going

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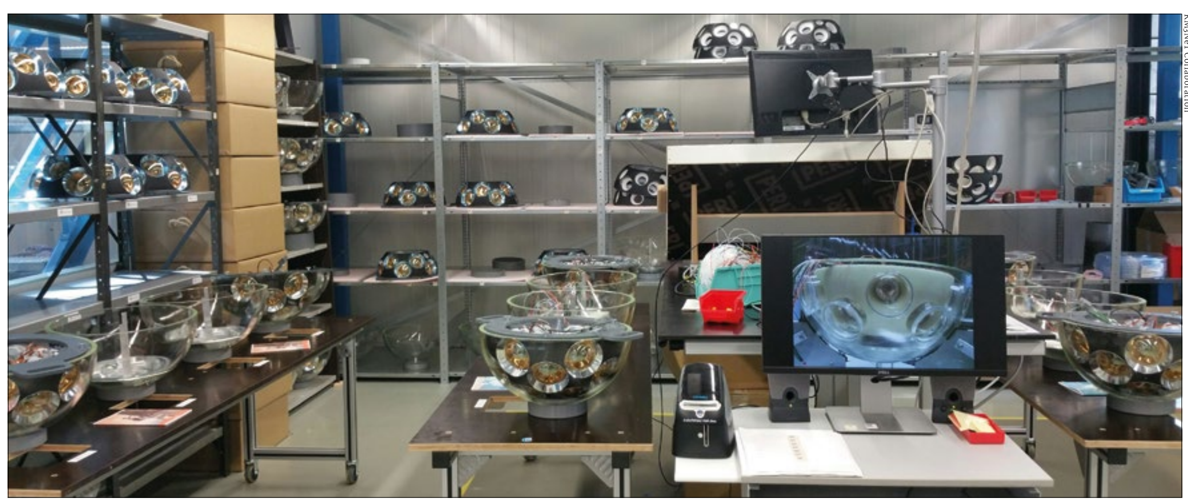
KM3NeT Collaboration

First descent *One of the KM3NeT lines bundled up before being unwound and lowered into position.*



KM3NeT Collaboration

Modular *The assembly room for the KM3NeT optical modules, with a photo of the first prototype module visible as a screen saver.*

atmospheric muons can be rejected and a clean sample of neutrinos obtained.

The first KM3NeT detection line was connected in 2016 and currently a total of 32 lines are operating at the two sites. The first science results with these partial detectors have already been obtained.

Fundamental neutrino properties

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions. As they whiz through the universe, barely interacting with any other particles, they have the unique ability to oscillate between their three different types or flavours (electron, muon and tau). The observation of neutrino oscillations in the late 1990s implies that neutrinos have a non-zero mass, contrary to the Standard Model expectation. Understanding the origin and order of the neutrino masses could therefore unlock a path to new physics. Numerous neutrino experiments around the world are closing in on the neutrino's properties, using both artificial (accelerator and reactor) and natural (atmospheric and extraterrestrial) neutrino sources.

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions

The KM3NeT/ORCA array is optimised for the detection of atmospheric neutrinos, produced when cosmic rays strike atomic nuclei at an altitude of around 15 km. Such interactions produce a cascade of particles on Earth's surface, mostly pions and kaons, which decay to neutrinos capable of traversing the entire planet. About two thirds of these are muon neutrinos and antineutrinos, and the remainder are electron neutrinos and antineutrinos.

Measuring the directions and energies of the detected atmospheric neutrinos allows the oscillatory behaviour of neutrinos to be studied, and thus elements of the leptonic "PMNS" mixing matrix to be determined. The measured direction is used as a proxy for the distance the atmospheric neutrino has travelled through Earth between its points of production and detection. First preliminary results with six ORCA lines and one year of data clearly show the expected disappearance of muon neutrinos with increasing baseline/energy. The corresponding constraints on θ_{23} (the mixing angle between the m_2 and m_3 states) and Δm^2_{32} (the mass difference of the squared masses) already start to be competitive with multi-year results from the current long-baseline accelerator experiments (see "Physics debut" figure, p33).

A longer-term physics goal of KM3NeT is to determine the neutrino mass ordering, i.e. whether the third neutrino

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VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022

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The ANTARES legacy

Building a telescope anchored deep at the bottom of the sea requires skill, patience and expertise. KM3NeT would not be on its way without the invaluable experience gained from its older sibling, the ANTARES telescope. ANTARES operated continuously for more than 15 years, and pioneered solutions to construct and operate a neutrino detector in the challenging environment of the deep sea. Despite ANTARES containing only 12 detector lines compared to 86 in IceCube, its superior angular resolution (due to the intrinsic water properties) and its Northern Hemisphere location provided competitive results and valuable insights and constraints in various domains.

Following IceCube's discovery of a diffuse flux of cosmic neutrinos, the ANTARES all-flavour neutrino data sample revealed a mild (1.8σ) excess of high-energy events consistent with the neutrino signal detected by IceCube. ANTARES also contributed strongly to the multi-messenger endeavour,


ANTARES Collaboration

Stepping stone *A prototype of the KM3NeT DOM was tested on an ANTARES line in 2013 and recovered in June 2022.*

participating in the search for a neutrino counterpart to major alerts from the LIGO/Virgo gravitational-wave interferometers, IceCube, ground-based imaging air Cherenkov telescopes, as well as X- and gamma-ray satellites. For instance, the TXS0506+056 blazar is the second most significant point source, with a local significance of 2.8σ, strengthening its case as the first high-energy neutrino source. ANTARES also distributed its own neutrino alerts with an unprecedented low latency for a neutrino telescope.

Its energy threshold of a few tens of GeV allowed the study of atmospheric muon neutrino disappearance due to neutrino oscillations and to constrain the "3+1" neutrino model. In this domain, results consistent with world best-fit values were obtained, as well as competitive limits on non-standard interactions. The data were also used to search for dark-matter particles that would have accumulated in astrophysical bodies like the Sun or the galactic centre before annihilating or decaying into neutrinos. Since no excesses were found, competitive limits were set that reduce the parameter space to be explored by direct, indirect (including KM3NeT) and collider dark-matter experiments.

Recently superseded in sensitivity by KM3NeT, ANTARES was finally decommissioned in February 2022.

mass eigenstate is heavier or lighter than the first two. This is important to help constrain the plethora of theoretical models proposed to explain the neutrino masses. Due to the large distances travelled by atmospheric neutrinos as they pass through Earth's mantle and core, subtle matter effects come into play and distort the expected oscillation pattern in the zenith angle/energy plane. By comparing the observed distortions to those expected for either "normal" or "inverted" mass ordering, and thanks to the large neutrino sample collected, the neutrino mass ordering can be determined.

A 115-line configuration of ORCA operating for three years is expected to provide a three-sigma sensitivity for most θ_{23} values. KM3NeT could therefore be the first detector to unambiguously determine the neutrino mass ordering, on a time scale in advance of the planned long-baseline accelerator experiments. New-physics scenarios (for example, non-standard interactions, neutrino decays and sterile neutrinos) that modify the oscillation patterns recorded in both ORCA and ARCA have already been explored. While no significant deviations from the Standard Model have been observed, the enhanced sensitivity as the detectors grow will push the existing limits and probe uncharted territories.

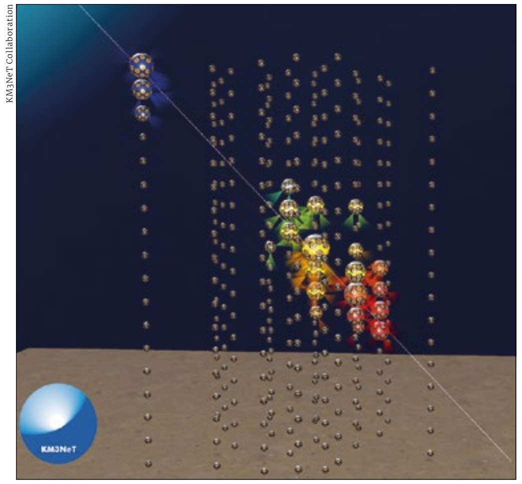
KM3NeT could be the first detector to unambiguously determine the neutrino mass ordering

Neutrino astronomy

At the beginning of the 1960s, it was realised that the neutrino could play a special role in the study of the universe at large. Weakly interacting with matter and electrically neutral, it enables exploration at greater distances and higher energies than is possible with conventional electromagnetic probes. In addition, neutrinos are the unambiguous smoking gun of hadronic acceleration processes occurring at their source.

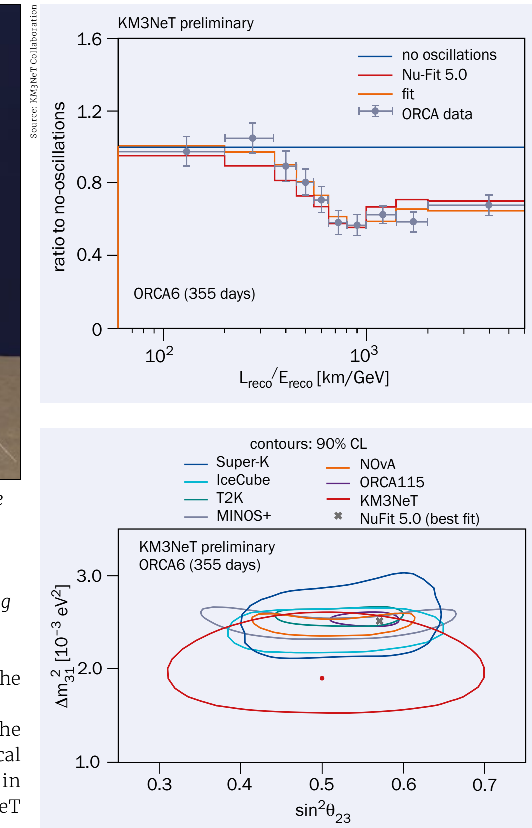
Since the observation of a significant flux of cosmic high-energy neutrinos in the TeV–PeV range by the IceCube Neutrino Observatory at the South Pole in 2013, the focus of neutrino astronomers has been to identify the astrophysical origins of these neutrinos. Amongst the diverse possible sources, a multi-messenger approach has identified the first: the flaring blazar TXS0506+056. While other source candidates have appeared, such as tidal disruption events and radio-bright blazars, the currently identified source population(s) cannot fully explain the detected flux. Having a neutrino telescope with a sensitivity similar to that of IceCube and with a complementary field of view allows the full neutrino sky to be continuously monitored. KM3NeT's location in the Northern Hemisphere provides an optimal view of the galactic plane and makes it the ideal instrument to detect, characterise and resolve sources that may emit galactic neutrinos.

Soon, KM3NeT will start sending alerts to its multi-messenger partners – including conventional electromagnetic telescopes but also other neutrino telescopes such as IceCube and Baikal/GVD – when a neutrino candidate with a high probability of astrophysical origin is detected. This is right on time for the fourth observing run of the LIGO, Virgo and KAGRA gravitational-wave interferometers. While so far no neutrinos have been observed from binary compact systems detected through gravitational waves, a joint detection would reveal unique information on the high-energy processes in the environment of the mergers. Furthermore, the exceptional pointing resolution of KM3NeT would significantly reduce the region of interest where electromagnetic partners should search for a counterpart. The ARCA detector, for example, will benefit from the low optical scattering of deep seawater to reconstruct the direction of muon-neutrino events to



KM3NeT Collaboration

Subsea shower *A muon neutrino candidate recorded by the new ARCA21 configuration. When a neutrino interacts with seawater nuclei, it causes a recoil that generates a burst of light due to the Cherenkov effect. The size and colour of the spheres represent the number of detected photons and timing relative to the first detected photon, respectively.*



Source: KM3NeT Collaboration

The acquisition of long-term oceanographic data helps researchers understand and eventually mitigate the harmful effects of global processes

Physics debut *First measurements of neutrino oscillation parameters with KM3NeT/ORCA6, showing the expected disappearance of muon neutrinos with increasing baseline/energy (top) and corresponding constraints on the mixing angle θ_{23}, and squared mass difference Δm^2_{31} between the second and third neutrino-mass eigenstates (bottom).*

less than 0.1 degrees at 100 TeV and around 1 degree for the electron/tau neutrino flavours.

Last but not least, KM3NeT is already waiting for the next close-by core-collapse supernova. Such astrophysical events are rare: the first and only one ever detected in neutrinos, SN1987a, occurred 35 years ago. The KM3NeT DOMs are continuously monitoring for a short-duration increase in counting rates on many DOMs simultaneously – the signature of a flash of MeV supernova neutrinos passing through the detectors – and the detector is networked with other neutrino telescopes via the SuperNova Early Warning System (SNEWS). If a galactic supernova would happen today, the number of neutrinos detected by SNEWS would be four orders of magnitude more than for SN1987a!

Whether the cosmic-neutrino sources are point-like, extended, transient or variable, the KM3NeT collaboration has developed reconstruction techniques, event selections and statistical frameworks to identify them and determine their characteristics. Disentangling the galactic from the extragalactic components, the steady from the transient and the electromagnetically bright from the obscure are on KM3NeT's to-do list for the coming decade.

Marine science

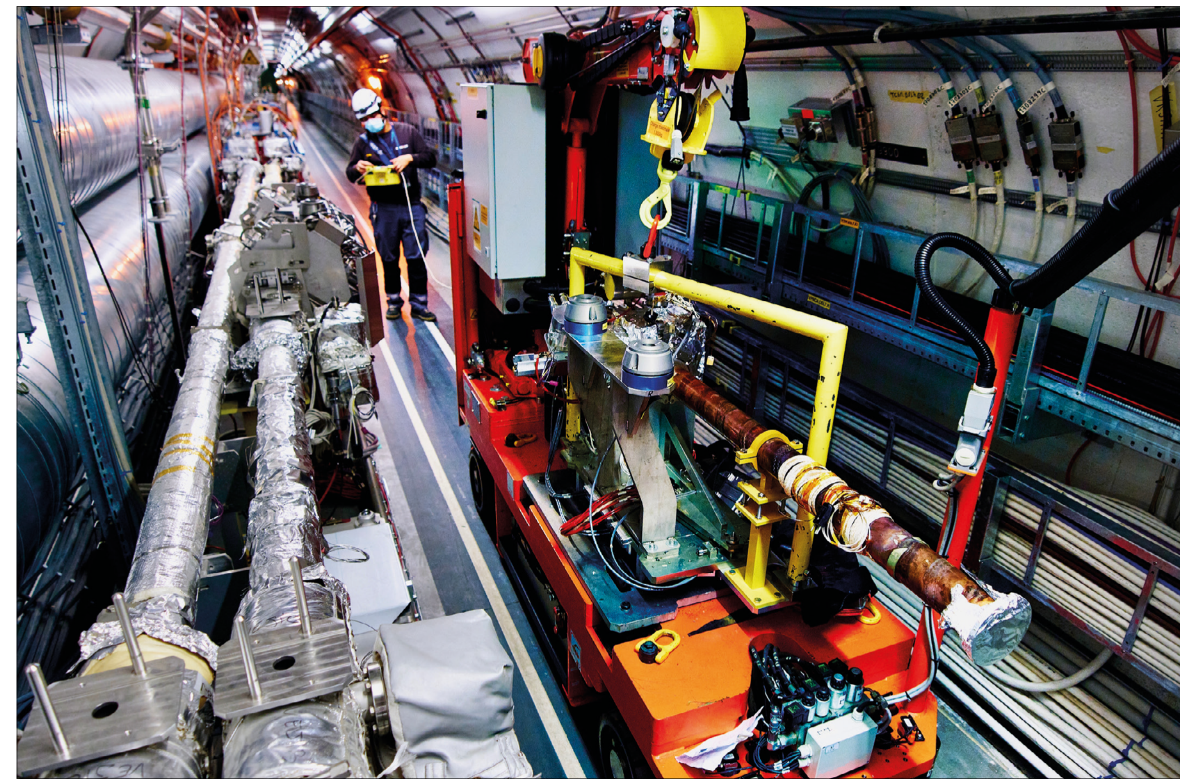
KM3NeT is important not only for particle physics, but is also a powerful tool for marine sciences. The acquisition of long-term oceanographic data helps researchers understand and eventually mitigate the harmful effects of global processes, such as climate change and anthropogenic impact, as well as study episodic events such as earthquakes, tsunamis, biodiversity changes and pollution – all of which are difficult to study with short-term conventional marine expeditions. To this end, the sea-floor infrastructures of first the ANTARES and now the KM3NeT sites are unique cabled marine observatories. They are open to all scientific communities, and as such are important nodes of the European Multidisciplinary Seafloor and water-column Observatory, EMSO.

Furthermore, the KM3NeT optical sensors and the acoustics sensors (used for the positioning of the DOMs) themselves provide unique information on deep-sea bioluminescence and bioacoustics. The ANTARES collaboration has several publications studying deep-sea bioluminescence and acoustic detection of cetaceans, and recently KM3NeT invited citizen scientists to analyse its optical and acoustic data via the Zooniverse platform in the context of the EU project REINFORCE.

The KM3NeT detectors will continue to grow in size and sensitivity as additional new lines are installed over the next five years. With three major neutrino telescope facilities now online – Baikal/GVD, IceCube and KM3NeT – neutrino astronomy is truly entering its golden era. ●

CRYSTAL COLLIMATION BRINGS HL-LHC INTO FOCUS

A crucial upgrade of the LHC collimation system to cope with the challenges of High-Luminosity LHC operation is being put to the test during LHC Run 3, write Stefano Redaelli, Mario Di Castro and Roderik Bruce.



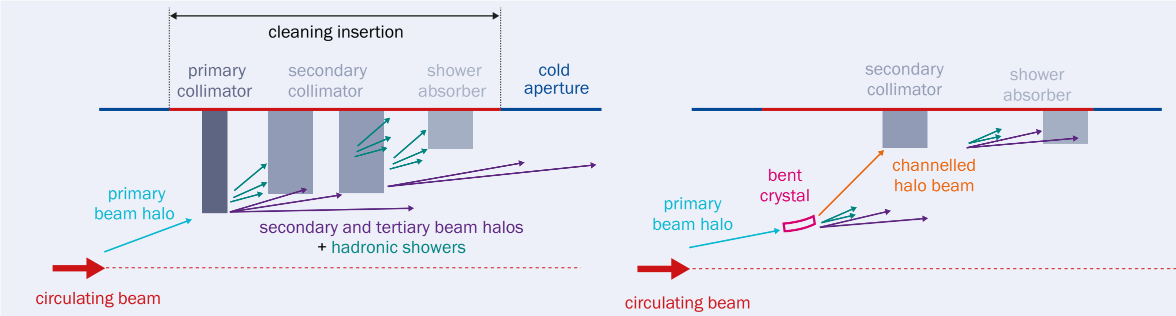
CERN SY/STI

On target *The installation in November 2021 of crystal primary collimators, which allow the crystal to be moved to the desired distance from the circulating beam.*

The start of LHC Run 3 in 2022 marked an important milestone for CERN: the first step into the High-Luminosity LHC (HL-LHC) era. Thanks to a significant upgrade of the LHC injectors, the Run 3 proton beams are more intense than ever. Together with the raised centre-of-mass collision energy from 13 to 13.6 TeV, Run 3 offers a rich physics programme involving the collisions of both proton and heavy-ion beams. This is made possible thanks to several important upgrades involving HL-LHC hardware that were carried out during Long Shutdown 2 (LS2), ahead of the full deployment of the HL-LHC project during LS3, around four years from now.

The HL-LHC aims to operate with 2.3×10^{11} protons per bunch (compared to the goal of 1.8×10^{11} protons per bunch at the end of Run 3), producing a stored beam energy of about 710 MJ (compared to 540 MJ in Run 3). Lead-ion beams, on the other hand, will already reach their HL-LHC target intensity upgrade in Run 3. This is thanks to the "slip stacking" technique currently implemented at the Super Proton Synchrotron, which uses complex radio-frequency manipulations to shorten the bunch spacing of LHC beam trains from 75 to 50 ns. Equating to a stored beam energy of up to 20.5 MJ at 6.8 TeV (compared to a maximum of 12.9 MJ achieved in 2018 at 6.37 TeV), the full HL-LHC upgrade needed to handle these more intense ion beams must be available throughout Run 3.

When the LHC works as a heavy-ion collider, many specific challenges need to be faced. Magnetically, the machine behaves in a similar way as during proton–proton operation. However, since the lead-ion bunch charge is about



Multi-stage collimation *An optimised arrangement of primary, secondary and absorber collimators, located in the LHC's ~500 m-long warm betatron cleaning insertion region (left), is needed to intercept primary beam losses and safely dispose of the higher order halos and energy that they produce following the interaction with the collimator materials. In an ideal crystal-based collimation scheme (right), the channelling process suppresses the nuclear interaction of halo particles compared to that of the standard primary collimators.*

15 times lower than for protons, a number of typical machine challenges – such as beam–beam interactions, impedance, electron-cloud effects, injection and beam-dump protection – are relaxed. Mitigating the nuisance of beam halos, however, is certainly not one of the tasks that gets easier.

These halos are formed by particles that stray from the ideal beam orbit. More than 100 collimators are located at specific locations in the LHC to ensure that errant particles are cleaned or absorbed, thus protecting sensitive superconducting and other accelerator components. Although the total stored beam energy with ions is more than 30 times lower than it is for protons, the conventional multi-stage collimation system at the LHC (see "Multi-stage collimation" figure) is about two orders of magnitude less efficient for ion beams. Nuclear fragmentation processes occurring when ions interact with conventional collimator materials produce ion fragments with different magnetic rigidities without producing transverse kicks sufficient to steer these fragments onto the secondary collimators. Instead, they travel nearly unperturbed through the "betatron" collimation system in interaction region 7 (IR7) responsible for disposing safely of transverse beam losses. This creates clusters of losses in the high-dispersion regions, where the first superconducting dipole magnets of the cold arcs act as powerful spectrometers, increasing the risk of quenches whereby the magnets cease to become superconducting.

The ion-collimation limitation is a well-known concern for the LHC. Nevertheless, the standard system has performed quite well so far and provided adequate cleaning efficiency for the nominal LHC ion-beam parameters. But the HL-LHC targets pose additional challenges. In particular, the upgrade does not allow sufficient operational margins without improving the betatron collimation cleaning. Lead-ion beam losses in the cold dipole magnets downstream of IR7 might reach a level three times higher than their quench limits, estimated at their 7 TeV current equivalent.

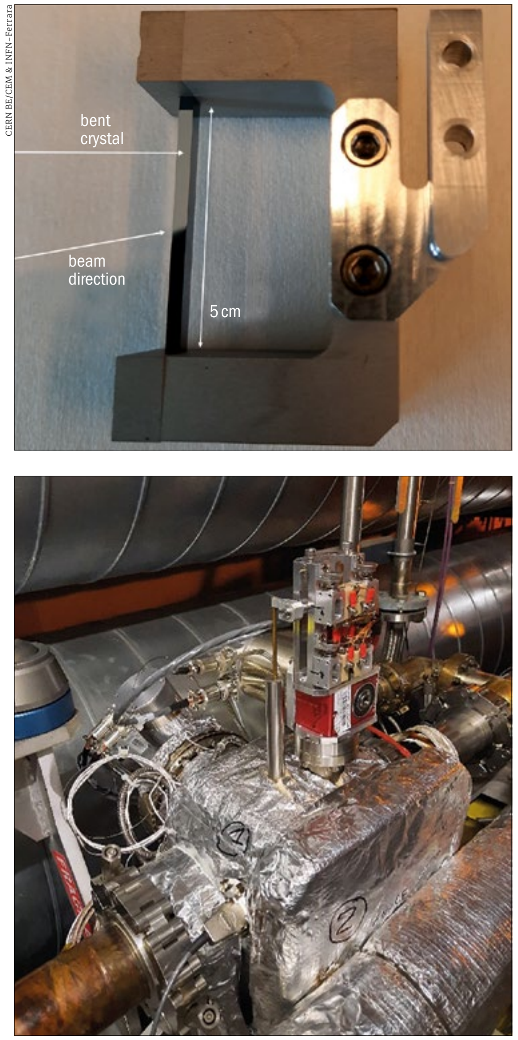
Improved ion-collimation cleaning has paved the way to adopt crystal collimation as the baseline of the HL-LHC

Various paths have been followed within the HL-LHC project to address this limitation. The baseline solution was to improve the collimation cleaning by adding standard collimators in the dispersion-suppressor regions that would locally dispose of the off-momentum halo particles before they impact the cold magnets. To create the necessary space, two shorter dipoles with a stronger (11 T) field would replace a standard, 15 m-long 8.3 T LHC dipole. This robust upgrade, which works equally well for proton beams, was planned to be used in Run 3. However, due to technical issues with the availability of the new dipoles, which are based on a niobium-tin rather than niobium-titanium conductor, the decision was taken to defer their installation. The HL-LHC project now relies on an alternative solution based on a crystal collimation scheme that was studied in parallel.

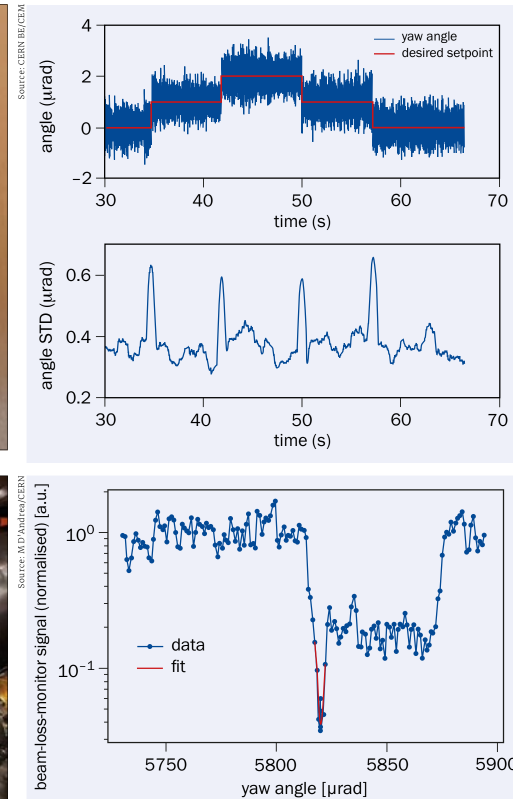
Crystals in the LHC

The development of crystal applications with hadron beams at CERN dates back to the activities carried out by the UA9 collaboration at the CERN SPS. Crystal collimation makes use of a phenomenon called planar channelling: charged particles impinging on a pure crystal with well-defined impact conditions can remain trapped in the electromagnetic potential well generated by the regular planes of atoms. If the crystal is bent, particles follow its geometrical shape and experience a net kick that can steer them with high efficiency to a downstream absorber. Crystal collimation was tested at the Tevatron, and in 2018 a prototype system was used for protons at the LHC in a special run at injection energy. The scheme is particularly attractive for ion beams as it was demonstrated that the existing secondary collimators can serve as a halo absorber without risking damage.

At the LHC, a total of four bent crystals are needed for the horizontal and vertical collimation of both beams. During Run 2, a test stand for crystal-collimation tests was installed in the LHC betatron cleaning region of IR7 with the aim of demonstrating the feasibility of this advanced collimation technique at LHC energies. Silicon crystals with a length of just 4 mm were bent to a curvature radius of 80 m to produce a 50 µrad deflection – much larger than the few-µrad angles typically experienced by proton interaction with the 60 cm-long primary collimators (see "Silicon swerve" image). Indeed, to produce such a kick with conventional dipole magnets would require a field of around 300 T in the same volume of the crystal. The crystals were mounted on an assembly (see "On target" image, p35) that is a jewel of accelerator technology and control: the target collimator primary crystal (TCPC). This device allows the crystal to be



Silicon swerve *Top: a silicon-strip crystal (built by INFN Ferrara) used for LHC beam collimation, which is bent to an 80 m-curvature radius to produce a 50 µrad kick. Bottom: the vacuum tank in the LHC housing the bent crystal and interferometer head used during beam tests to control the crystal's orientation.*



High precision *Top: small angular adjustments of the crystal achieved with the high-performance interferometer, demonstrating that steps as small as 1 µrad can be achieved. Bottom: local beam losses at the crystal as a function of the crystal angular orientation measured during an "angular scan" at 6.8 TeV in May 2022. The onset of channelling is revealed in the small range of minimum losses around 5820 µrad, corresponding to a condition whereby nuclear interactions with matter are suppressed.*

moved to the desired distance from the circulating beam – typically just a few millimetres at 7 TeV – and its angular orientation to be adjusted to better than 1 µrad. While the former is no more demanding than the control system of other LHC collimators, the angular control demands a customised technology that is the heart of LHC crystal collimation.

Crystal channelling can only occur for particles impinging on the crystal surface with well-defined impact conditions. For a 6.8 TeV proton beam, they must have an angle of 90° with angular deviations of at most 0.0001° (around 2 µrad) – which is similar to aiming at a 10 cm-wide snooker pocket from a shooting distance of 5 km! If this tiny angular acceptance is not respected, the transverse momentum is sufficient to send particles out of the potential well produced between the planes of the crystal lattice, thus losing the channelling condition. Both the beam-impact conditions and the accuracy of the crystal's angle must therefore be kept under excellent control.

The crystal collimators are steered remotely using a technology that is unique to the CERN accelerator complex. It relies on a high-precision interferometer that provides suitable feedback to the advanced controller, and a precise piezo-actuation device that drives the crystal orientation with respect to impinging halo particles with unprecedented precision. During Run 2, the system demonstrated the sub-microradian accuracy required to maintain crystal channelling at high beam energy (see "High precision" figure, top). A recent feature of the newly installed devices is that the interferometer heads (which enable the precise control of the angle) are located outside the vacuum with the laser light coupled to the angular stage by means of viewports. This means that any fibre degradation due to motion or radiation, which was observed on the prototype system, can be corrected during routine maintenance. Using this setup in 2018, an improvement in ion-collimation cleaning by up to a factor of eight was demonstrated experimentally with the best crystal, paving the way for crystal collimation to become the baseline solution for the HL-LHC.

The test devices used during Run 2 served their purpose

CERNCOURIER
VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022
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well, but they do not meet the standards required for regular, high-efficiency operation. An upgrade plan was therefore put in place to replace them with a higher performing new design. This has been developed in a crash programme at CERN that started in November 2020, when the decision to postpone the installation of the 11 T dipoles was taken. Two units were built and installed in the LHC in 2021 (see "On target" image, p35) and another four are nearing completion: two for installation in the LHC at the end of 2022 and the others serving as operational spares. The first two installed units replaced the two prototype vertical crystals that showed the lowest performance. The horizontal prototype devices remain in place for 2022, since they performed well and were tested with a pilot beam in October 2021.

The start of Run 3 in April this year provided a unique opportunity to test the new devices with proton beams, ahead of the next operational ion run. One of the first challenges is to establish the optimal alignment of the crystals, to make sure stray particles are channelled as required. While channelled, the impinging particles interact with the crystal with the lowest nuclear-interaction rate: halo particles travel preferentially in the "empty" channel relatively far from the lattice nuclei. Optimum channelling is therefore revealed by the orientation that has the lowest losses, as measured by beam-loss monitors located immediately downstream of the crystal (see "High precision" figure, bottom, p37). Considering the large angular range possible (more than 50 μrad, compared with the full angular range of 20 mrad), establishing this optimum condition is a bit like finding a needle in a haystack. However, following a successful campaign in dedicated operational beam tests in August 2022, channelling was efficiently established for both the new and old crystals, allowing the commissioning phase to continue.

Looking forward

The LHC collimation system is the most complex beam-cleaning system built to date for particle accelerators. However, it must be further improved to successfully face the upcoming challenges from the HL-LHC upgrade which, for heavy-ion beams, begins during Run 3. Crystal collimation is a crucial upgrade that is now being put into operation to improve the betatron cleaning in preparation for the upgraded ion-beam parameters, mitigating the risks of machine downtime from ion-beam losses. The collimation cleaning performance will be established experimentally as soon as Run 3 ion operation begins. Initial beam tests with protons indicate that the newly installed bent crystals perform well. The first measurements demonstrated that the crystals can be put into operation as expected and showed the specified channelling property. We are therefore confident that this advanced technology can be used successfully for the heavy-ion challenges of the HL-LHC programme. ●

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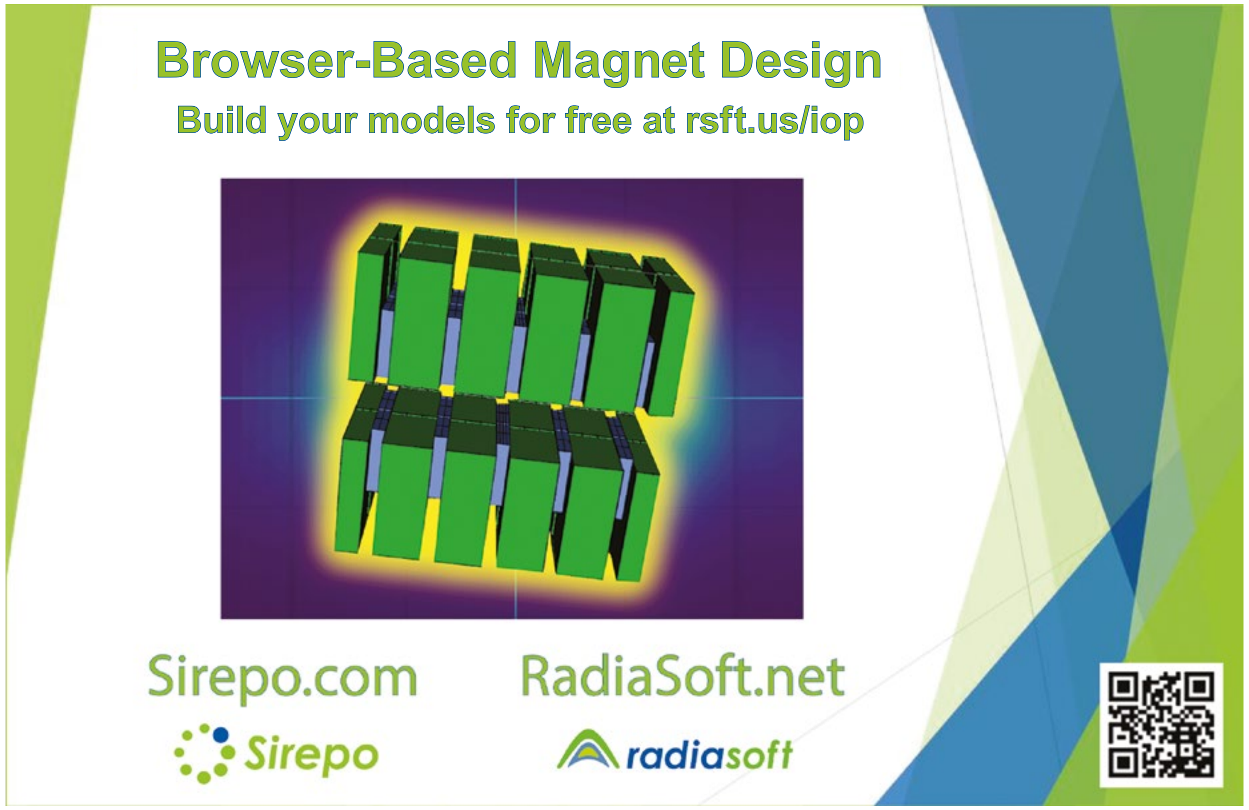

IPPOG CELEBRATES 25 YEARS OF ENGAGEMENT

Outreach is as essential as hardware, computing and analysis, says co-chair of the International Particle Physics Outreach Group, Steve Goldfarb. Without it, we won't have the support we need to build future facilities.

Global reach *Undergraduate students at Kathmandu University show off their results while taking an ATLAS Masterclass run by the author and local researchers.*

This year, the International Particle Physics Outreach Group (IPPOG) celebrates its 25th anniversary. Our group is an international collaboration of active particle physicists, communication experts and educators dedicated to disseminating the goals and accomplishments of fundamental scientific research to the public. Our audiences range from young schoolchildren to college graduates and teachers, from the visiting public to heads of state, and we engage them in classrooms, laboratories, experimental halls, music festivals, art exhibitions, office buildings and government offices across the planet. The activities we use to reach these diverse audiences include public lectures, visits, games, exhibits, books, online apps, and pretty much anything that can be used to demonstrate scientific methodology and instil appreciation for fundamental research.

What drives us to commit so much effort to outreach and public engagement when we are already deeply invested in a field that is both time and labour intensive? First of all, we love doing it. Particle physics is an active and exciting field that lies at the forefront of human understanding of the universe. The analysis methods and tools we employ are innovative, our machines and detectors are jaw-dropping in their size and complexity, and our international collaborations are the largest, most diverse ever assembled. It is a privilege to be part of this community and we love sharing that with those around us.

Secondly, we've learned that public engagement improves us as scientists. Learning how to distil complex scientific concepts into understandable descriptions, captivating stories and relatable analogies helps us to better comprehend the topics ourselves. It gives us a clearer picture in our own minds of where our work fits into the larger frame of society. It also significantly improves our communication skills, yielding capabilities that help us down the road as we apply for grants and propose new projects or analyses.

Thirdly, we also understand our moral obligation to share the results of our research with society. The endeavour to improve our understanding of the world around us is rooted in millennia of human evolution and culture. It is how we not only improve our own lives, but also how we provide the tools future generations need to survive. In more practical terms, we realise the importance of engaging those who support our research. That includes funding bodies, as well as the voters who select those bodies and prioritise the deployment of resources.

Finally, but equally as important, we realise the value to both our own field and society at large of encouraging our youth to pursue careers in science and technology. The next generation of experiments will include machines, detectors and collaborations that are even larger than the ones we have today. Given their projected lifetimes, the grandchildren of today's students will be among those analysing the data. And we need to train that workforce today.

Birth and evolution

Dedicating time and resources to outreach efforts is not easy. As researchers, our days (and often nights) are taken up by analysis meetings, detector shifts, conference deadlines and institutional obligations. So, when we do make the effort it needs to be done in an effective manner, reaching as large and diverse an audience as possible, with messages that are clear and coherent.

Former CERN Director-General Chris Llewellyn Smith certainly had this in mind when he first proposed the establishment of the European particle physics outreach group (EPOG) in 1997. The group held its first meeting on 19 September that year, under the chairmanship of Frank Close. Its primary objectives were to exchange ideas and best practices in particle-physics education and outreach,

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CERNCOURIER
VOLUME 62 NUMBER 6 NOVEMBER/DECEMBER 2022
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IPPOG Collaboration

Science interlude *Participants of the Colours of Ostrava music festival in the Czech Republic learn to build cloud chambers on the Big Bang stage organised by students and researchers from local universities and supported in part by IPPOG.*

to define common goals and activities, and to develop and share materials supporting the efforts.

The original members of EPOG were delegates from the CERN Member States, one each from the four major LHC experiments, one each from the CERN and DESY laboratories, and a chair and deputy chair assigned by the European Committee for Future Accelerators (ECFA) and the high-energy physics branch of the European Physical Society. Over the course of the following 25 years, EPOG has expanded beyond Europe (becoming IPPOG), developed major worldwide programmes, including International Masterclasses in Particle Physics and Global Cosmics, and established itself as an international collaboration, defined and supported by a memorandum of understanding (MoU).

Today, the IPPOG collaboration comprises 39 members (32 countries, six experiments and one international lab) and two associate members (national labs). Each member, by signing the MoU, commits to supporting particle-physics outreach worldwide. Members also provide modest funding, which is used to support IPPOG's core team, its administration and communication platforms, thus facilitating the development and expansion of its global programmes and activities.

The Masterclasses programme now reaches tens of thousands of students in countries spread around the globe, and is engaging new students and training new physics mentors every year. The Global Cosmics portal, hosted on the IPPOG website, provides access to a wide variety of projects distributing cosmic-ray detectors and/or data into remote classrooms that would not normally have access to particle-physics research. And a modest project budget has helped the IPPOG collaboration to establish a presence at science, music and art festivals around the globe by supporting the efforts of local researchers.

Most recently, IPPOG launched a new website, featuring information about the collaboration, its programmes and activities, and giving access to a growing database of educational resources. The resource database serves teachers and students, as well as our own community, and includes searchable, high-quality materials, project descriptions and references to related resources procured and contributed by our colleagues.

Our projects and activities are reviewed and refined periodically during twice-annual collaboration meetings hosted by member countries and laboratories. They feature hands-on activities and presentations by working groups, members, partners and panels of world-renowned topical experts. We present and publish the progress of our activities each year during major physics and science-education conferences. Presentations are made in parallel and poster sessions, and plenary talks, to share developments with the greater community and offer opportunities for their own contributions.

The challenging road ahead

While these accomplishments are noteworthy and lay a strong basis for the development of particle-physics outreach, they are not enough to face the challenges of tomorrow. Or even today. The world has changed dramatically since the days we first advocated for the construction of our current accelerators and detectors. And we are partly to blame. The invention of the web at CERN more than 30 years ago greatly facilitated access to and propagation of scientific facts and publications. Unfortunately, it also became a tool for the development and even faster dissemination of lies and conspiracy theories.

Effective science education is crucial to stem the tide of disinformation. A student in a Masterclass, for example, learns quickly that truth is found in data: only by selecting events and plotting measurements is she/he able to discover what nature has in store. And it might not agree with her/his original hypothesis. It is what it is. This simple lesson teaches students how to extract signal from background, truth from fiction. Other important lessons include the value of international collaboration, the symmetries and beauty of nature and the applications of our technology to society.

How do we, as scientists, make such opportunities available to a broader audience? First and foremost, we need more of us doing outreach. Many physicists do not make the effort because they perceive it as costly to their career. Taking time away from analysis and publication can be detrimental to our advancement, especially for students and junior faculty, unless there is sufficient support and recognition. Our community needs to recognise that outreach has become a key component of scientific research. It is as essential as hardware, computing and analysis. Without it, we won't have the support we need to build future facilities. That means senior faculty must value experience in outreach on a par with other qualities when selecting new hires, and their institutions need to support outreach activities.

We also need to increase the diversity of our audience. While particle physics can boast of its international reach, our membership is still quite limited in social, economic and cultural scope. We are sorely missing women, people of diverse ethnicities and minorities. Communication strategies and educational methods can be adopted to address this, but they require resources and dedicated personnel.

That's what IPPOG is striving for. Our expertise and capabilities increase with membership, which is continually on the rise. This past year we have been in discussion with Mexico, Nepal, Canada and the Baltic States, and more are planned for the near future. Some will sign up, others may need more time, but all are committed to maintaining and improving their investment in science education and public engagement. We invite *Courier* readers to join us in committing to build a brighter future for our field and our world. ●

Further reading

http://ippog.org.

OPINION VIEWPOINT

Joining forces for quantum gravity

Increasing cross-talk between different communities will be of great advantage to the endeavour of quantum gravity, even if there is no explicit convergence in fundamental perspectives, argue Bianca Dittrich and Daniele Oriti.

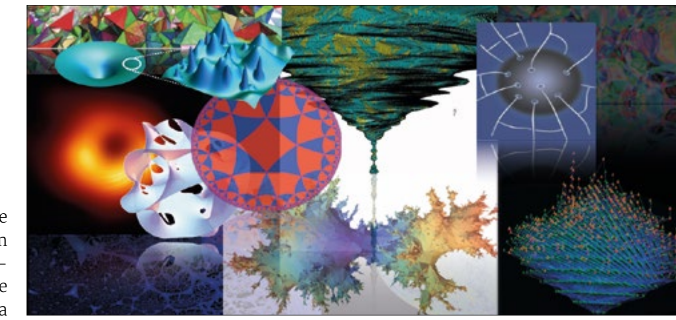
Bianca Dittrich *(Perimeter Institute) and* **Daniele Oriti** *(Ludwig Maximilian University) are co-chair and chair of the International Society for Quantum Gravity.*

The challenge of casting space–time and gravity in the language of quantum mechanics and unravelling their fundamental structure has occupied some of the best minds in physics for almost a century. Not only is it one of the hardest problems out there – requiring mastery of general relativity, quantum field theory, high-level mathematics and deep conceptual issues – but distinct sub-communities of researchers have developed around different and apparently mutually exclusive approaches.

Historically, this reflected to a large extent the existing subdivision of theoretical physics between the particle-physics community and the much smaller gravitational physics one, with condensed-matter theorists entirely alien, at the time, to the quantum gravity (QG) problem. Until 30 years ago, the QG landscape roughly featured two main camps, often identified simply with string theory and canonical loop quantum gravity, even if a few more hybrid formalisms already existed. Much progress has been achieved in this divided landscape, somehow maintaining each camp in the belief that one only had to push forward its own strategies to succeed. At a more sociological level, intertwined with serious scientific disagreements, this even led, in the early 2000s, to what the popular press dubbed the "String Wars".

Today there is a growing conviction that if we are going to make progress towards this "holy grail" of physics, we need to adopt a more open attitude. We need to pay serious attention to available tools, results and ideas wherever they originated, pursuing unified perspectives when suitable and contrasting them in a constructive manner otherwise. In fact, the past 30 years has seen the development of several QG approaches, the birth of new (hybrid) ones, fresh directions and many results. A new generation has grown up in a diverse, if conflicting, scientific landscape. Today there is much more emphasis on QG phenomenology and physical aspects, thanks to parallel advances in observational cosmology and astrophysics, alongside the recognition that some mathematical developments naturally cut across specific QG formalisms. There is also much more contact with "outside" communities such as particle physics, cosmology, condensed matter and quantum information, which are not interested in internal QG divisions but only in QG deliverables. Furthermore, several scientific overlaps between QG formalisms exist and are often so strong that they make the definition of sharp boundaries between them look artificial.

A new generation has grown up in a diverse, if conflicting, scientific landscape



Unifying *Established last year, the International Society for Quantum Gravity recognises that many open issues are shared across different approaches and formalisms.*

Introducing the ISQG

The time is ripe to move away from the String Wars towards a "multipolar QG pax", in which diversity does not mean irreducible conflict and disagreement is turned into a call for better understanding. To this end, last year we created the International Society for Quantum Gravity (ISQG) with a founding committee representing different QG approaches and more than 400 members who do not necessarily agree scientifically, but value intelligent disagreement.

ISQG's scientific goals are to: promote top-quality research on each QG formalism and each open issue (mathematical, physical and in particular conceptual); stimulate cross-fertilisation across formalisms (e.g. by focusing on shared mathematical ingredients/ideas or on shared physical issues); be prepared for QG observations and tests (develop a common language to interpret experiments with QG implications, and a better understanding of how different approaches would differ in predictions); and push for new ideas and directions. Its sociological goals are equally important. It aims to help recognise that we are a single community with shared interests and goals, overcome barriers and diffidence among sub-communities, support young researchers and promote QG outside the community. A number of initiatives, as well as new funding schemes, are being planned to help achieve these goals.

We envision the main role of the ISQG as sponsoring and supporting the initiatives proposed by its members, in addition to organising its own. This includes a bi-annual conference series to be announced soon, focused workshops and schools, seminar series, career support for young researchers and the preparation of outreach and educational material on quantum gravity.

So far, the ISQG has been well received, with more than 100 participants attending its inaugural workshop in October 2021. Researchers in quantum gravity and related fields are welcome to join the society, contribute to its initiatives and help to create a community that transcends outdated boundaries between different approaches, which only hinder scientific progress. We need all of you!
• www.isqg.org.

CERNCOURIER
Volume 62 Number 6 November/December 2022
IOP Publishing

OPINION
INTERVIEW

A view from Fermilab

Accelerator physicist Lia Merminga describes her career and priorities as new Fermilab director.

In control *Lia Merminga became Fermilab's seventh director on 18 April 2022.*

What first drew you to physics, and to accelerators in particular?
In school I liked and did well in science and math. I liked the feeling of certainty of math. There is an objective truth in math. And I was fascinated by the fact that I could use math to describe physical phenomena, to capture the complexity of the world in elegant mathematical equations. I also had an excellent, rigorous high-school physics teacher, whom I admired.

Accelerators offered the possibility of addressing fundamental challenges in (accelerator) physics and technology, and getting verifiable results in a reasonable amount of time to have a material impact. In addition, particle accelerators enable research and discovery in a vast range of scientific fields (such as particle and nuclear physics, X-ray and neutron science) and societal applications such as cancer treatment and radioisotope production.

What was your thesis topic?
My PhD thesis tackled experimentally, theoretically and via computer simulations the nonlinear dynamics of transverse particle oscillations in the former Tevatron collider at Fermilab, motivated by planning for the Superconducting Super Collider. Nonlinearities were introduced in the Tevatron by special sextupole magnets. In a series of experiments, we obtained accurate measurements of various phase-space features with sextupoles switched on. One of the features was the experimental demonstration of "nonlinear resonance islands" – protons captured on fixed points in phase space.

What have been the most rewarding and challenging aspects of your career so far?
There are many rewarding aspects of what I do. Seeing an audience, especially young people, who light up when I explain a fascinating concept. Pointing to something tangible that I contributed towards that will enable scientists to make discoveries in accelerator, particle or nuclear physics. Having conceived, worked on and advocated certain types of accelerators and seeing them realised. Predicting a behaviour of the particle beam, and verifying it in experiments. Also, troubleshooting a serious problem, and after days and nights of toil, finding the origin of or solution to the problem.

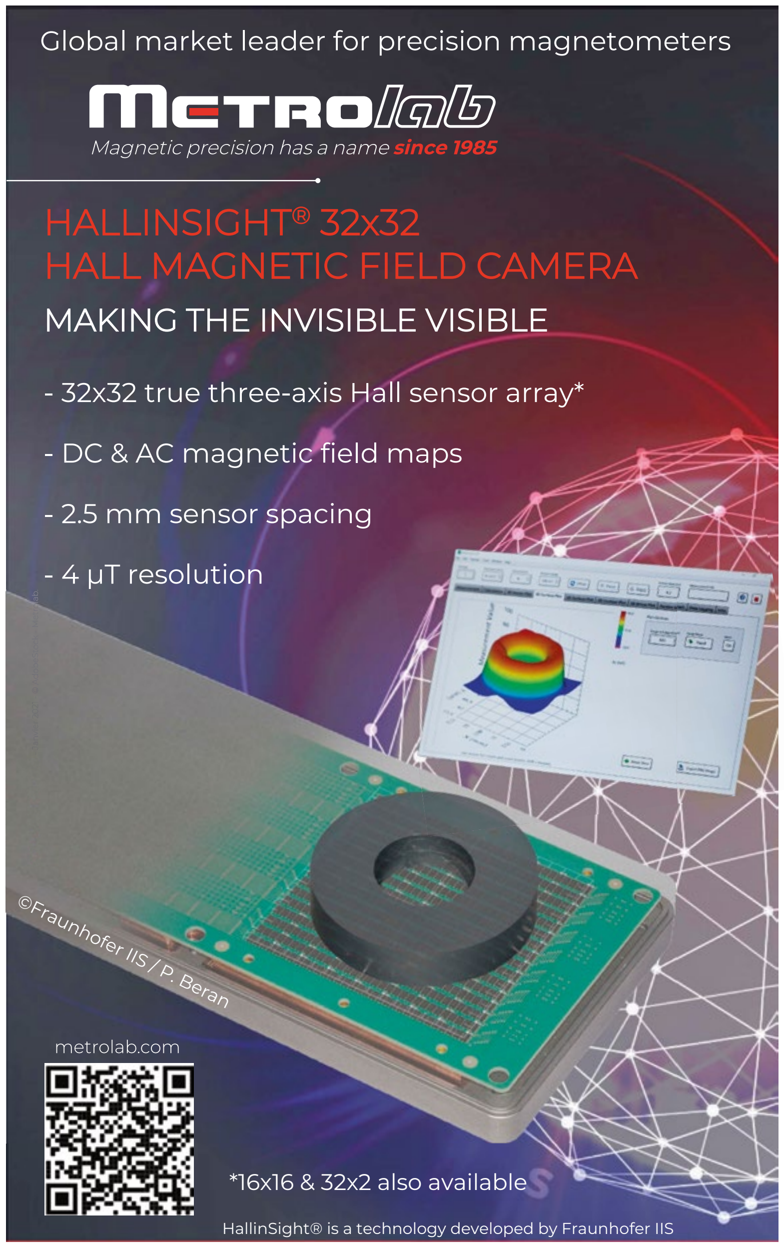
In terms of challenges, at Fermilab right now we are working on very complex and challenging projects like LBNF/DUNE. It involves more than 1400 international collaborators preparing and building a technically complex endeavour almost one mile underground. The mere scale of the operation is enormous but the pay-off is completing something unprecedented and enabling groundbreaking discoveries.

What are your goals as Fermilab director?
First and foremost, the completion of LBNF/DUNE to advance neutrino physics. Also, the completion of the remainder of the 2014 "P5" programmes, including the HL-LHC upgrades of the accelerator and CMS detector, and a new experiment at Fermilab called Mu2e. Looking to the future, when the next P5 report is completed, we will launch the next series of projects. Quantum technology is also a growing focus. Fermilab hosts one of five national quantum centres in addition to being a partner in a second one. We utilise our world-leading expertise in superconducting radiofrequency technology and instrumentation/control to advance quantum information technologies, as well as conducting unique dark-matter searches using this expertise.

Is being director different to what you imaged?
It takes a lot of hard work to build an excellent team, exceeding my initial projection. But equally our staff's commitment, good will and dedication have also exceeded my expectations.

Which collider should follow the LHC, and what is the role of the US/Fermilab in realising such a project?
No matter which collider is chosen, there is still a lot of R&D required for any path concerning magnets, radiofrequency cavities and detectors. This R&D is crucial to multiple applications. I would advocate the development of these capabilities to push the state of the art for accelerators and detectors in the near future. Future colliders are an important component of the current Snowmass/P5 community planning exercise. Here, Fermilab is aligned with the previous P5 and is committed to following the next P5 recommendations.

The upcoming century promises a fascinating array of ground-breaking discoveries



How would you describe high-energy physics today compared to when you entered the field?
In the 1980s, the major building blocks of the Standard Model were largely in place, and the focus of the field was to experimentally verify many of its predictions. Today, the Standard Model is much more thoroughly tested, but there is evidence that it does not completely describe the whole picture.

A lot of present-day research is about physics beyond the Standard Model, including dark matter, dark energy and the question of matter–antimatter asymmetry in the universe. In parallel, technologies have advanced tremendously since the 1980s, enabling unprecedented precision, parameter reach and new discoveries. This applies to accelerators, telescopes, detectors and computing. The upcoming century promises a fascinating array of groundbreaking discoveries, all of which will fundamentally further our understanding of the universe.

What can be done to ensure that there are more female laboratory directors worldwide?
I think it is important to increase the pipeline, starting with efforts to attract young people in elementary and high school. We need to look at changing the cultural perspective that women can't do STEM and get to the point where the entire culture is open-minded. We also need to change the make-up of the committees.

It is important to encourage females to take on leadership positions and then support and empower them with enlightened mentors. Once they develop their careers, we will have a much bigger pool for future lab directors. We must inspire and empower young girls and women to follow their dreams, and help them stay focused to succeed.

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

OPINION REVIEWS

Connecting the dots with neural networks

Deep Learning for Physics Research
By Martin Erdmann, Jonas Glombitza, Gregor Kasieczka and Uwe Klemradt
World Scientific

The use of deep learning in particle physics has exploded in recent years. Based on INSPIRE HEP's database, the number of papers in high-energy physics and related fields referring to deep learning and similar topics has grown 10-fold over the last decade. A textbook introducing these concepts to physics students is therefore timely and valuable.


Placidplace/Pixabay

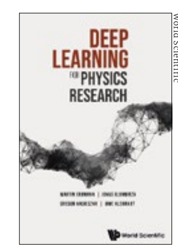
Going deep *A timely and valuable look at this fast-evolving field.*

When teaching deep learning to physicists, it can be difficult to strike a balance between theory and practice, physics and programming, and foundations and state-of-the-art. Born out of a lecture series at RWTH Aachen and Hamburg universities, *Deep Learning for Physics Research* by Martin Erdmann, Jonas Glombitza, Gregor Kasieczka and Uwe Klemradt does an admiral job of striking this balance.

The book contains 21 chapters split across four parts: deep-learning basics, standard deep neural-networks, interpretability and uncertainty quantification, and advanced concepts.

In part one, the authors cover introductory topics including physics data, neural-network building blocks, training and model building. Part two surveys and applies different neural-network structures, including fully connected, convolutional, recurrent and graph neural-networks, while also reviewing multi-task learning. Part three covers introspection, interpretability, uncertainty quantification, and revisits different objective functions for a variety of learning tasks. Finally, part four touches on weakly supervised and unsupervised learning methods, generative models, domain adaptation and anomaly detection. Helping to lower the barrier to entry for physics students to use deep learning in their work, the authors contextualise these methods in real physics-research studies, which is an added benefit compared to similar textbooks.

Deep learning borrows many concepts from physics, which can provide a way of connecting similar ideas in the two fields. A nice example explained in the book is the cross-entropy loss function, which has its origins in the definition of entropy according to Gibbs and Boltzmann. Another example that crops up, although rather late in part three, is the connection between the mean-squared-error loss function and the log-likelihood function for a Gaussian probability distribution, which may be more familiar to physics students accustomed to performing maximum likelihood fits.



World Scientific

Hands-on

Accompanying the textbook is a breadth of free, online Jupyter notebooks (executable Python code in an interactive format), which are available at http://deeplearningphysics.org. These curated notebooks are paired with different chapters and immerse students in hands-on exercises. Both the problem and corresponding solution notebooks are available online, and are accessible to students even without expensive computing hardware as they can be launched on free cloud services such as Google Colab or Binder. In addition, students who have a CERN account can launch the notebooks on CERN's service for web-based analysis (SWAN) platform.

Advanced exercises include the training and evaluation of a denoising autoencoder for speckle removal in X-ray images and a Wasserstein generative adversarial network for the generation of cosmic-ray-induced air-shower footprints. What is truly exciting about these exercises is their use of physics research examples, many taken from recent publications. Students can see how close their homework exercises and solutions are to cutting-edge research, which can be highly motivating.

In a book spanning less than 300 pages (excluding references), it is impossible to cover everything, especially as new deep-learning methods are developed almost daily. For a more theoretical understanding of the fundamentals of deep learning, readers are advised to consult the classic *Deep Learning* by Ian Goodfellow, Yoshua Bengio and Aaron Courville, while for more recent deep-learning developments in particle physics they are directed to the article "A Living Review of Machine Learning for Particle Physics" by Matthew Feickert and Benjamin Nachman.

With continued interest in deep learning, coverage of a variety of real physics-research examples and a breadth of accessible, online exercises, *Deep Learning in Physics Research* is poised to be a standard textbook on the bookshelf of physics students for years to come.

Javier Duarte *UC San Diego.*

An Infinity of Worlds
By Will Kinney
MIT Press

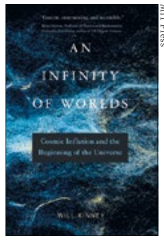
Cosmology, along with quantum mechanics, is probably among the most misunderstood physics topics for the layperson. Many misconceptions exist, for instance whether the universe had a beginning or not, what the cosmic expansion is, or even what exactly is meant by the term "Big Bang". Will Kinney's book *An Infinity of Worlds: Cosmic Inflation and the Beginning of the Universe* clarifies and corrects these misconceptions in the most accessible way.

A valuable contribution to both science education and dissemination

Kinney's main aim is to introduce cosmic inflation – a period of exponential expansion conjectured to have taken place in the very early universe – to a general audience. He starts by discussing the Standard Model of cosmology and how we know that it is correct. ▷

This is done most successfully and in a very succinct way. In only 24 pages, the book clarifies all the relevant concepts about what it means for the universe to expand, its thermal history and what a modern cosmologist means by the term Big Bang.

The book continues with an accessible discussion about the motivation for inflation. There are plenty of comments about the current evidence for the theory, its testability and future directions, along with discussions about the multiverse, quantum gravity, the anthropic principle and how all these combine together.



MIT Press

A clear understanding

There are two main points that the author manages to successfully induce the reader to reflect on. The first is the extreme success of the cosmic microwave background (CMB) as a tool to understand cosmology: its black-body spectrum established the Big Bang; its analysis demonstrated the flatness of the universe and its dark contents and motivated inflation; its fluctuations play a large part in our understanding of structure formation in the universe; and, along with the polarisation of the CMB, photons provide a window into the dynamics of inflation. Kinney notes that there are also plenty of features that have not been measured, which are especially important for inflation, such as the B-modes of the CMB and primordial gravitational waves, meaning that CMB-related observations have a long way to go.

The second main point is the importance of a clear understanding of what we know and what we do not know in cosmology. The Big Bang, which is essentially the statement that the universe started as a hot plasma of particles and cooled as it expanded, is a fact. The evidence, which goes well beyond the observation of cosmic expansion, is explained very well in Kinney's book. Beyond that there are many unknowns. Despite the excellent motivation for and the significant observational successes of inflationary models, they are yet to be experimentally verified. It is probably safe to assume, along with the author, that we will know in the future whether inflation happened or not. Even if we establish that it did and understand its mechanism, it is not clear what we can learn beyond that. Most inflationary models make statements about elements, such as the inflationary multiverse, that in principle cannot be observed.

Steven Weinberg once commented that we did not have to wait to see the dark side of the moon to conclude that it exists. Whether this analogy can be extended successfully to include inflation or string theory is definitely debatable. What is certain, however, is that there will be no shortage of interesting topics and discussions in the years to come about cosmology and fundamental physics in general. Kinney's book can serve as a useful introduction for the general public, but also for physics students and even physicists working in different fields. As such, this book is a valuable contribution to both science education and dissemination.

Nikolaos Rompotis *University of Liverpool.*

Taking plasma accelerators to market

Newly established US firm TAU Systems aims to commercialise laser-plasma wakefield accelerators for applications ranging from medical imaging to advanced light sources, finds Matthew Chalmers.

TAU Systems

Eyes down *TAU Systems CEO Björn Manuel Hegelich (left) and COO Jerome Paye in the lab at Texas.*

In 1997, physics undergraduate Manuel Hegelich attended a lecture by a visiting professor that would change the course of his career. A new generation of ultra-short-pulse lasers had opened the possibility to accelerate particles to high energies using high-power lasers, a concept first developed in the late 1970s. "It completely captured my passion," says Hegelich. "I understood the incredible promise for research and industrial advancement if we could make this technology accessible to the masses."

Twenty-five years later, Hegelich founded TAU Systems to do just that. In September the US-based firm secured a $15 million investment to build a commercial laser-driven particle accelerator. The target application is X-ray free-electron lasers (XFELs), only a handful of which exist worldwide due to the need for large radio-frequency linacs to accelerate electrons. Laser-driven acceleration could drastically reduce the size and cost of XFELs, says Hegelich, and offers many other applications such as medical imaging.

Beam time

"As a commercial customer it is difficult to get time on the European XFEL at DESY or the LCLS at SLAC, but these are absolutely fantastic machines that show you biological and chemical interactions that you can't see in any other way," he explains. "TAU Systems' business model is two-pronged: we will offer beam time, data acquisition and analysis as a full-service supplier as well as complete laser-driven accelerators and XFEL systems for sale to, among others, pharma and biotech, battery and solar technology, and other material-science-driven markets."

Laser-driven accelerators begin by firing an intense laser pulse at a gas target to excite plasma waves, upon which charged particles can "surf" and gain energy. Researchers worldwide have been pursuing the idea for more than two decades, demonstrating impressive accelerating gradients. CERN's AWAKE experiment, meanwhile, is exploring the use of proton-driven plasmas that would enable even greater gradients. The challenge is to be able to extract a stable and reliable beam that is useful for applications.

Hegelich began studying the interaction between ultra-intense electromagnetic fields and matter during his PhD at Ludwig Maximilian University in Munich. In 2002 he went to Los Alamos National Laboratory where he ended up leading their laser-acceleration group. A decade later, the University of Texas at Austin invited him to head up a group there. Hegelich has been on unpaid leave of absence since last year to focus on his company, which currently numbers 14 employees and rising. "We have got to a point where we think we can make a product rather than an experiment," he explains.

The breakthrough was to inject the gas target with nanoparticles with the right properties at the right time, so as to seed the wakefield sooner and thus enable a larger portion of the wave to be exploited. The resulting electron beam contains so much charge that it drives its own wave, capable of accelerating electrons to 10 GeV over a distance of just 10 cm, explains Hegelich. "The whole community has been chasing 10 GeV for a very long time, because if you ever wanted to build a big collider, or drive an XFEL, you'd need to put together 10 GeV acceleration stages. While gains were theorised, we saw something that was so much more powerful than what we were hoping for. Sometimes it's better to be lucky than to be good!"

Hegelich says he was also lucky to attract an investor, German internet entrepreneur Lukasz Gadowski, so soon after he started looking last summer. "This is hardware development: it takes a lot of capital just to get going. Lukasz and I met by accident when I was consulting on a totally different topic. He has invested $15 million and is very interested in the technical side."

TAU Systems (the name comes from the symbol used for the laser pulse duration) aims to offer its first products for sale in 2024, have an XFEL service centre operational by 2026 and start selling full XFEL systems by 2027. Improving beam stability will remain the short-term focus, says Hegelich. "At Texas we have a laser system that shoots once per hour or so, with no feedback loop, so sometimes you get a great shot and most of the time you don't. But we have done some experiments in other regimes with smaller lasers, and other groups have done remarkable work here and shown that it is possible to run for three days straight. Now that we have this company, I can hire actual engineers and programmers – a luxury I simply didn't have as a university professor."

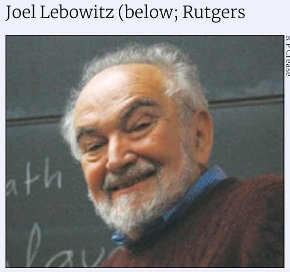
He also doesn't rule out more fundamental applications such as high-energy physics. "I am not going to say that we will replace a collider with a laser, although if things take off and if there is a multibillion-dollar project, then you never know."

Matthew Chalmers *editor.*

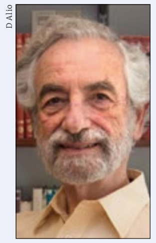
Appointments and awards

2023 Breakthrough Prizes
For their foundational contributions to quantum information science, which have found applications ranging from quantum gravity to metrology, Charles H Bennett (IBM), Gilles Brassard (Montréal), David Deutsch (Oxford) and Peter Shor (MIT) have been awarded the 2023 Breakthrough Prize in Fundamental Physics, each receiving $3 million. The Breakthrough Prize Foundation also awarded Anna Grassellino (Fermilab), above, one of six 2023 New Horizons prizes for early-career achievements in physics, each worth $100,000, for the discovery of major performance enhancements to niobium superconducting radio-frequency cavities, with applications ranging from accelerator physics to quantum devices.

2022 Dirac medallists
The Dirac Medal of the International Centre for Theoretical Physics in Trieste for 2022 has been awarded to Joel Lebowitz (below; Rutgers



University), Elliot Lieb (top left; Princeton) and David Ruelle (top right; Institut des Hautes Études Scientifiques) "for groundbreaking and mathematically rigorous contributions to the understanding of the statistical mechanics of classical and quantum physical systems". The trio's contributions include, among others: the study of non-equilibrium physics and



large deviations; the proof of the stability of matter; the analytic solution of two-dimensional models; seminal results in quantum information theory; the definition of Gibbs states for infinite systems; and the analysis of chaos and turbulence.

Falling Walls for precise physics
Stefan Ulmer (RIKEN) has been awarded a Falling Walls prize in the category of physical sciences

for his research in testing fundamental symmetries with antiprotons. Ulmer is founding spokesperson of the BASE experiment at CERN, which has achieved several record measurements of the properties of antiprotons and invented new trapping technologies to further improve them. The annual award is announced on 9 November in Berlin as part of the Falling Walls science summit to commemorate the fall of the Berlin Wall.

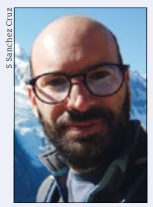
Lise Meitner Prize
The European Physical Society has awarded Philip Walker (University of Surrey) the Lise Meitner Prize for seminal contributions to the understanding of long-lived nuclear excited states, called

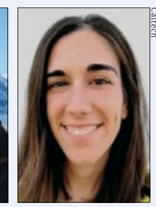
isomers, and the factors that determine their half-lives, which range from nanoseconds to years. Walker's work brings a "fabled" gamma-ray laser, which could have applications in medical treatments, closer to reality, says the citation. The Lise Meitner Prize, granted every two years for outstanding work in experimental, theoretical or applied nuclear science, is named after the Austrian-born physicist who is best known for the understanding of nuclear fission, but also did important work on isomers.

Odderon recognition
Christophe Royon (University of Kansas) from the TOTEM, CMS and DØ collaborations has received the gold medal of the Mexican Physics Society's division of particles and fields "for his leadership in the discovery of odd-gluon state odderon from elastic proton–proton and proton–antiproton collisions at the TOTEM and DØ detectors, his contributions to QCD and

physics beyond the Standard Model, and for his support to the Mexican high-energy physics community". Overwhelming evidence for the existence of the odderon, theorised 50 years ago, was reported last year (*CERN Courier* May/June 2021 p8).

Best theses in Spain
Particle physicists Sergio Sanchez Cruz (below left; University of Zurich) and Clara Murgui Gálvez (below right; Caltech) have been recognised by the Royal Spanish Physics Society for the best doctoral thesis presented in a Spanish university. Sanchez Cruz (who did his PhD at the University of Oviedo) won in the category of experimental physics with his thesis "Search for new physics in events with high transverse momentum leptons with the CMS detector at the LHC", while





Murgui (PhD at the University of Valencia) was rewarded in the category of theoretical physics for her thesis "Phenomenological and cosmological aspects of electroweak models beyond the Standard Model".

Alumni Network wins gold
The CERN Office for Alumni Relations has received a CASE (Council for the Advancement and Support of Education) Gold Circle of Excellence Award for 2022 for its "Second Collisions" virtual reunion held in October 2021. Judges described the event as highly innovative, with the virtual recreation of the CERN site giving alumni the opportunity to revisit and explore iconic buildings and take part in a variety of activities from keynote speeches to networking. The use of in-house resources to deliver the virtual environment and increase internal buy-in was also noted, as was the creative use of the virtual booths featuring CERN spin-off and start-up companies. Established five years ago, the Alumni Network has grown to more than 8000 members.

RECRUITMENT

PEOPLE OBITUARIES

Harald Fritzsch 1943–2022

A lasting and profound impact

On 16 August 2022, pioneering theorist Harald Fritzsch unexpectedly died at the age of 79. His essential contributions to the development of quantum chromodynamics and the grand unification of the fundamental forces made a lasting and profound impact on the field of theoretical physics.

Harald Fritzsch was born on 10 February 1943 in Zwickau, Germany. He studied physics and completed his diploma thesis at Leipzig University in June 1968. At this time, he had already contemplated leaving the German Democratic Republic (GDR) and so sent his diploma thesis to Werner Heisenberg in Munich. In 1968, in an adventurous and dramatic escape by boat across the Black Sea from the Eastern Block to Turkey, Fritzsch and a friend fled the GDR and relocated to the Federal Republic of Germany. Fritzsch went straight to Munich, where Heisenberg accepted him as a doctoral student in his research group at the Max Planck Institute for Physics. His thesis, supervised by Heinrich Mitter and completed in 1971, dealt with light-cone algebra and the quantisation of the strong interaction. In 1970 Fritzsch received a DAAD scholarship for a six-month stay at SLAC and met Murray Gell-Mann for the first time, in Aspen.

After receiving his doctorate, Fritzsch spent a year as a research fellow at CERN, followed by four years as a senior research associate at Caltech. The collaboration between Fritzsch and Gell-Mann continued and led to groundbreaking work on the strong interaction. In 1977 Fritzsch followed a call as professor at the University of Wuppertal, which changed to become the University of Bern. Then, in 1979, he became Ordinarius at Ludwig Maximilian University in Munich.

H Fritzsch

Harald Fritzsch made fundamental contributions to quantum chromodynamics.

In 1971 Fritzsch and Gell-Mann introduced the colour quantum number as the exact symmetry underlying the strong interactions, thereby solving the long-standing problem of preserving the exclusion principle as discussed, for example, by Han and Nambu in 1965. A year later, Fritzsch and Gell-Mann proposed a Yang–Mills gauge theory with local colour symmetry, which is now called quantum chromodynamics (QCD). This new idea was first presented by Gell-Mann in the fall of 1972 at a conference in Chicago, and then in a joint conference paper by Fritzsch and Gell-Mann. In 1973 their famous paper on the colour-octet model of QCD, now also with Heinrich Leutwyler, appeared in *Physics Letters*. This publication, together with the papers by Gross, Politzer and Wilczek about asymptotic freedom in non-Abelian gauge theories, all published in the same year, is regarded as the beginning of QCD.

Fritzsch wrote many other scientific papers that are of great importance for theoretical particle physics, for example on SO(10) grand-unification, weak interactions, the famous Fritzsch mass matrices and composite models. For his significant scientific achievements, he was awarded the Dirac Medal of the University of New South Wales in Australia in 2008. He was a member of the Society of German Natural Scientists and Physicians, and of the Berlin-Brandenburg Academy of Sciences. In 2013 he was awarded an honorary doctorate from Leipzig University.

Fritzsch is also widely known as an author of popular scientific books. His book *Quarks*, published in 1980, was translated into more than 20 languages, and in 1994 he was awarded the Medal for Scientific Journalism of the German Physical Society.

In addition to his outstanding scientific achievements, we also admired Harald for his strong, determined, honest and straightforward mind, and for his courage to express his sound opinions and to tackle problems and disputes, even if inconvenient to some.

Until the very end, Harald was seen in his university office almost every day. He will be sadly missed, but never forgotten.

Siegfried Bethke *and* **Dieter Lüst** *Max Planck Institute for Physics, Munich.*

Alain Magnon 1944–2022

Instrumental in COMPASS

Alain Magnon, a well-known French nuclear physicist and long-serving spokesperson of the COMPASS collaboration at CERN (2003–2010), passed away on 18 March 2022. Retired from IRFU CEA Saclay for more than 10 years, he remained an enthusiastic COMPASS member, valuably participating in the activities of the Illinois and Matrivani groups. In recent years he was an active contributor to the Physics Beyond Colliders working group and to the MUonE project at CERN.

Alain had a rigorous and resolute approach to instrumentation

After graduating as an engineer from the École centrale des arts et manufactures in Paris in the late 1960s, Alain joined the nuclear physics division at Saclay where he worked on the first prototypes of multi-wire proportional chambers. Interested in continuing his career as a nuclear physicist, he later moved to the University of Chicago to carry out his PhD thesis work on the hyperfine structure of muonium, under the supervision of Val Telegdi.

Returning to Saclay, Alain played a leading role in measurements of the muon lifetime and capture rates, resulting in one of the most precise determinations of the Fermi weak-coupling constant. These measurements were ▷

CERNCOURIER
Volume 62 Number 6 November/December 2022
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later extended to both positive and negatively charged muons using an ultra-pure liquid hydrogen target. Mastering advanced cryogenic and vacuum technologies, Alain worked hard to reduce the impurity level of the target to negligible values. He also participated in one of the earliest measurements of the pion electromagnetic radius in coincidence (e, e′π) experiments. Later, Alain contributed to one of the first experiments on parity-violation at the MIT–Bates accelerator under the direction of Vernon Hughes. As a member of the (e, e′p) group at Saclay, he devoted great efforts to measuring the proton form factor within the ^{40}Ca nucleus, providing evidence that the bound nucleon form factor has the same Q^2 dependence as that of the free nucleon.

At the beginning of the 1990s, Alain switched to high-energy muon scattering. He made important contributions to the SMC polarised target and served as the contact for the collaboration. Later, he became one of the founding members of the COMPASS experiment. As head of the Saclay group, he proposed and led the project for the construction of large-sized drift chambers. He also coordinated the crucial Saclay–CERN work to repair and test the COMPASS large-acceptance superconducting magnet. Project and group leader, accomplished detector expert and tenacious spokesperson, Alain Magnon played an essential role in the success of COMPASS as a unique experiment and as a renowned international collaboration.

Alain Magnon was an accomplished detector expert and tenacious spokesperson.

All of his colleagues and friends will miss Alain and his rigorous and resolute approach to instrumentation and scientific research.

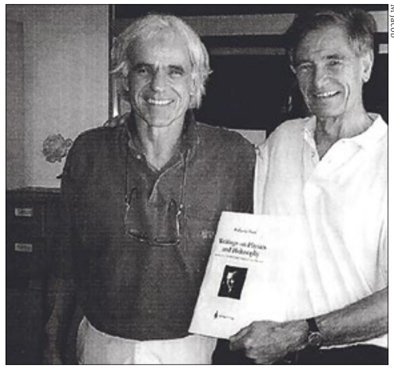
Bakur Parsamyan *INFN Torino,* **Stephane Platchkov** *IRFU Saclay and* **Fulvio Tessarotto** *INFN Trieste, for the COMPASS collaboration.*

Karl von Meyenn 1937–2022

Physicist and science historian

Physicist and historian of science Karl von Meyenn passed away on 18 June 2022 in his hometown of Neuburg an der Donau. Karl was a CERN associate for many years, often to be found in Salle Pauli amongst the archive and library of Wolfgang Pauli, on whom he was one of the world's leading experts.

Karl was born in Potsdam in 1937 and began studying physics in Chile, where his parents emigrated. He completed his doctorate in 1971 with Siegfried Flügge in Freiburg im Breisgau, then returned with his wife to Chile and taught at the Pontificia Universidad Católica until the military coup of 1973. Back in Germany, he worked first as a senior assistant to Helmut Reik at the faculty of physics in Freiburg, before specialising in the history of science with Armin Hermann at the Historical Institute of the University of Stuttgart in 1975. From 1985 to 1990 he was a professor of history of science at the Universitat Autònoma in Barcelona, after which he joined Hans-Peter Dürr at the Max Planck Institute for Physics in Munich. He also carried out research at the Institute of Theoretical Physics (with Frank Steiner) at the University of Ulm, and at CERN, where he devoted himself to Pauli's scientific legacy.



Karl Von Meyenn (left) with theorist Charles Enz, who is holding a copy of Pauli's Writings on Physics and Philosophy, *published under the auspices of the Pauli Committee at CERN, of which they were both members.*

Franca Pauli donated her husband's scientific writings, library and other items to CERN during the 1960s and 1970s, and CERN took responsibility for safeguarding and making this valuable collection available. The Pauli Committee turned to Karl von Meyenn, who tracked down copies of other letters in public or private ownership, then collated this wealth of material into publishable form. Besides the monumental eight volumes of Pauli correspondence, Karl published a biographical anthology on the great physicists (*Die großen Physiker*) in 1997–1999, a two-volume selection of Erwin Schrödinger's correspondence in 2011, and numerous essays, lectures and collaborative books on individual scientists and their interactions in developing new concepts in physics. In 2000 he was awarded the Marc-Auguste Pictet Medal of the Société de Physique et d'Histoire Naturelle de Genève for his work on the history of modern physics. Karl was a member of the Pauli Committee from 1994 and an honorary councillor at ETH Zurich since 2006. The library he leaves in Neuburg is a testimony to his great love of classical culture and broad cultural life. Combining great learning and rigorous scholarship with an engaging curiosity and enthusiasm, Karl was a stimulating and extremely likeable colleague. He will be sadly missed.

His colleagues and friends.

François Piuz 1937–2022

A unique expertise in detectors

François Piuz, a talented and passionate CERN physicist since 1968 who was leader of several projects, passed away on 21 July 2022 aged 85. Throughout his distinguished career, François worked at the forefront of particle detectors. With his many talents, he made significant contributions to topics ranging from the fundamental principles of detector operation to the innovative technologies required to deploy detectors in large experiments.

François began his scientific journey in the early 1970s as a notable member of the team that transformed the invention of the Nobel Prize-winning multi-wire proportional chamber (MWPC) into the system of 50,000 wires for the Split-Field Magnet facility at the CERN Intersecting Storage Rings. At this time, he wanted to understand the functioning of these new detectors at the fundamental, microscopic level. His work on the concept of "ionisation clusters" in the MWPC became a classic and ▷

was crucial to the development of particle identification based on multiple measurements of ionisation. One spectacular use of this approach is the X-ray photon detection system of the ALICE experiment's Transition Radiation Detector at the LHC. Cluster counting is also a candidate technique for high-granularity dE/dx measurements at future colliders.

Another highlight that came from his insightful understanding was the development of a novel drift chamber topology capable of measuring particles with exceptional spatial resolution and multi-track separation, as required for the SPS experiments in the 1980s. During this time, he renewed his interest in particle identification and contributed to pioneering studies demonstrating the outstanding potential of solid cesium iodide (CsI) photocathodes for the detection of Cherenkov photons, which would prove so fruitful in the ALICE experiment's HMPID (High Momentum Particle Identification Detector) RICH detector.

In 1992 François was one of the main proponents, and the co-spokesperson, of the RD26 project, which, in six years, had successfully developed the technology to produce large-area (up to 0.3 m²) CsI-based gaseous photon detectors for use in RICH systems operated in heavy-ion collision experiments. This project represented the summit of his outstanding scientific career, in which he coupled his unique expertise in gaseous detectors, developed while working with Charpak, with a passion for photography and, therefore, photon detection. Such technology allowed the construction of the largest CsI-RICH detector ever built and rapidly found applications in other experiments, including NA44 and COMPASS at CERN, HADES at GSI and the Hall A experiment at JLab.

François Piuz made significant contributions to the many detector projects he worked on.

François was a member of the ALICE collaboration from its first days and led the HMPID project until 2000. After his retirement in 2002, he continued to actively participate in the construction, installation and operation of the HMPID, which, nearly two decades after its construction, continues to operate at higher rates for LHC Run 3. François was also involved in coordinating test-beam activities, which were instrumental to the R&D for all ALICE detectors.

François's remarkable knowledge and ability to envision solutions to complex problems were key to the success of the many detector projects that he worked on. He was always interested in new ideas and ready to provide help and support to colleagues. These qualities, combined with a playful sense of humour, made François a very friendly and charismatic personality. He will be missed by many, but will always be remembered for his great qualities, both as a physicist and as a person, by those who were fortunate enough to have worked closely with him.

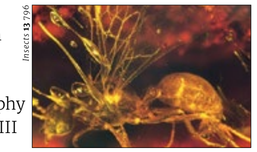
His friends and colleagues.

CERNCOURIER
Volume 62 Number 6 November/December 2022
IOP Publishing

BACKGROUND

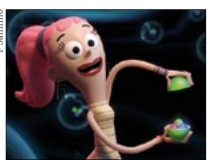
Notes and observations from the high-energy physics community

An ant called DESY


Insects 13 796

The long list of eponyms for animals has a new entry: *Desyopone hereon*. More than 20 million years after being captured in a drop of amber, an extinct ant species has been discovered using 3D X-ray tomography at the Hereon beamline at DESY's PETRA III light source. Examining the remains of 13 animals, researchers from the universities of Jena (Germany), Rennes (France) and Gdansk (Poland) were able to prove that the ant belongs to a hitherto unknown species. Honouring the laboratory and beamline that contributed to the discovery, the new genus was named after DESY and the new species after Hereon (*Insects* **13** 796).

Meet Quantum Kate


F Sannino

Seeking to break stereotypes that fundamental science is geeky, nerdy and reserved for boys, theorist Francesco Sannino (University of Southern Denmark) has created a series of animated videos around Quantum Kate – a YouTuber who looks and acts like a typical teenager, but with a vast knowledge of quantum mechanics. "The most challenging aspects were to find the right balance between science and entertainment, rigour and fun," he says. "I believe that fundamental physics can be as exciting as *Harry Potter* if communicated well." (Source: *Symmetry Magazine*)

57.4 hours

The LHC's longest ever proton fill, started on 23 September, providing "low burn-off" collisions for the LHCf experiment

Media corner

"This prize is an encouragement to young people – the prize would not be possible without the more than 100 young people who worked with me over the years."

Anton Zeilinger during the press conference for this year's Nobel Prize in Physics on 4 October (see p10).

"L'univers est une symphonie inachevée de processus enchevêtrés, et la connaissance scientifique vise à déchiffrer cette symphonie avec curiosité, émerveillement et joie."

Michel Spiro, talking to Radio France (5 October).

"This is something we do not do primarily to save money, but as a sign of social responsibility."

Joachim Mnich, CERN director for research and computing, discussing energy-saving measures in response to rising global electricity costs (*Nature*, 12 October).

"A surprise at Snowmass was the grassroots support for a collider on US soil."

Priscilla Cushman, University of Minnesota, quoted in *Physics Today* (October) on the Snowmass community planning exercise (see p23).

From the archive: November/December 1982

Nobels and neutrinos


Cornell

Cornell theoretician Kenneth Wilson (centre) is jubilant on winning the 1982 Nobel prize for physics, with 1965 laureate Hans Bethe (right) and Laboratory Director Boyce McDaniel holding the celebratory bottle.

The most prestigious award in physics goes this year (1982) to Kenneth Wilson, in recognition of his work on critical phenomena and phase transitions. The techniques he used have shown their worth in many other fields, including elementary particle physics. Also to his credit, Wilson has run a mile in 4 minutes 17 seconds.

A team from Caltech, SIN and Munich Technical University has produced new results on neutrino oscillations. The energy spectrum of neutrinos from beta decays of fission products from the Swiss Goesgen light water reactor is known to an accuracy of a few percent. During a six month period, the experimenters recorded 11,000 neutrino events, 37.9 m from the reactor core. The ratio of observed to predicted event rates was consistent with there being no oscillations. The measurement is being continued at 46 m to improve the sensitivity. These results have wide implications, from theories of solar evolution to the possible gravitational closure of the entire universe – an impressive contribution from a modest experiment at a power station in a small country on a minor planet of a typical star in an average galaxy!

● Based on text from *CERN Courier* November 1982 p371 and December 1982 pp403–404.

Compiler's note

First postulated by Bruno Pontecorvo in 1959, flavour-changing neutrino oscillations were detected by Super-K and SNO 40 years later, winning the 2015 Nobel Prize in Physics. This solved the solar neutrino problem and implied that neutrinos have non-zero mass, albeit at least a million times smaller than the electron mass. Evidence that the three flavours have different masses, and that right-handed neutrinos are not seen, have led to further speculations: neutrinos may be compound particles, right-handed neutrinos may be so massive as to be undetectable with present experimental facilities, and left- and right-handed neutrinos may share a see-saw, getting mass from each other without interacting with the Brout–Englert–Higgs field. In fact, neutrinos may hold the key to the very existence of the universe – a large weight for small shoulders!

Correction

The 1975 Nobel Prize in Physics was shared by Aage Bohr, Ben Mottelson and James Rainwater, not David Pines as stated due to an editing error in the September/October obituaries section (p59).

CERNCOURIER
Volume 62 Number 6 November/December 2022
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DT5550W Weeroc ASICs Development system
R5560 128 Ch. 14-bit @125 MS/s Digitizer with differential inputs
R5560SE 128 Ch. 14-bit @125 MS/s Digitizer with single-ended inputs
DT5560SE 32 Ch. 14-bit @125 MS/s Digitizer
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