WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2022 issue of *CERN Courier*.

A new ground-based observatory, CMB-S4, will study the anisotropies in the cosmic microwave background in unprecedented detail (p34). Among its science goals are to constrain models of inflation (the theme of this issue's cryptic cover) and other fundamental phenomena such as the possible existence of light-relic particles beyond the Standard Model (p27). Along with missions such as the recently launched James Webb Space Telescope (p7), CMB-S4 shows the increasingly fruitful interaction between fundamental physics, cosmology, astrophysics and astronomy to address open questions linking the largest and smallest scales.

In the collider world, the restart of Linac4 on 9 February lights the fuse for the start of LHC Run 3 in June (p8). The rich physics programme ahead owes thanks in part to extensive works completed during Long Shutdown 2, including a major programme by the CERN vacuum group (p39). Progress also continues apace for the superconducting RF "crab" cavities for the High-Luminosity LHC (p45). Meanwhile, in the US, Run 22 of the Relativistic Heavy-Ion Collider is stress-testing technologies for the future Electron–Ion Collider (p9).

Also in the issue: ATLAS and CMS close in on the Higgs' self-coupling (p17); basic science for sustainable development (p51); a teaching career (p59); the latest meeting reports (p21); news in brief (p15); reviews (p57); and bison (p66).

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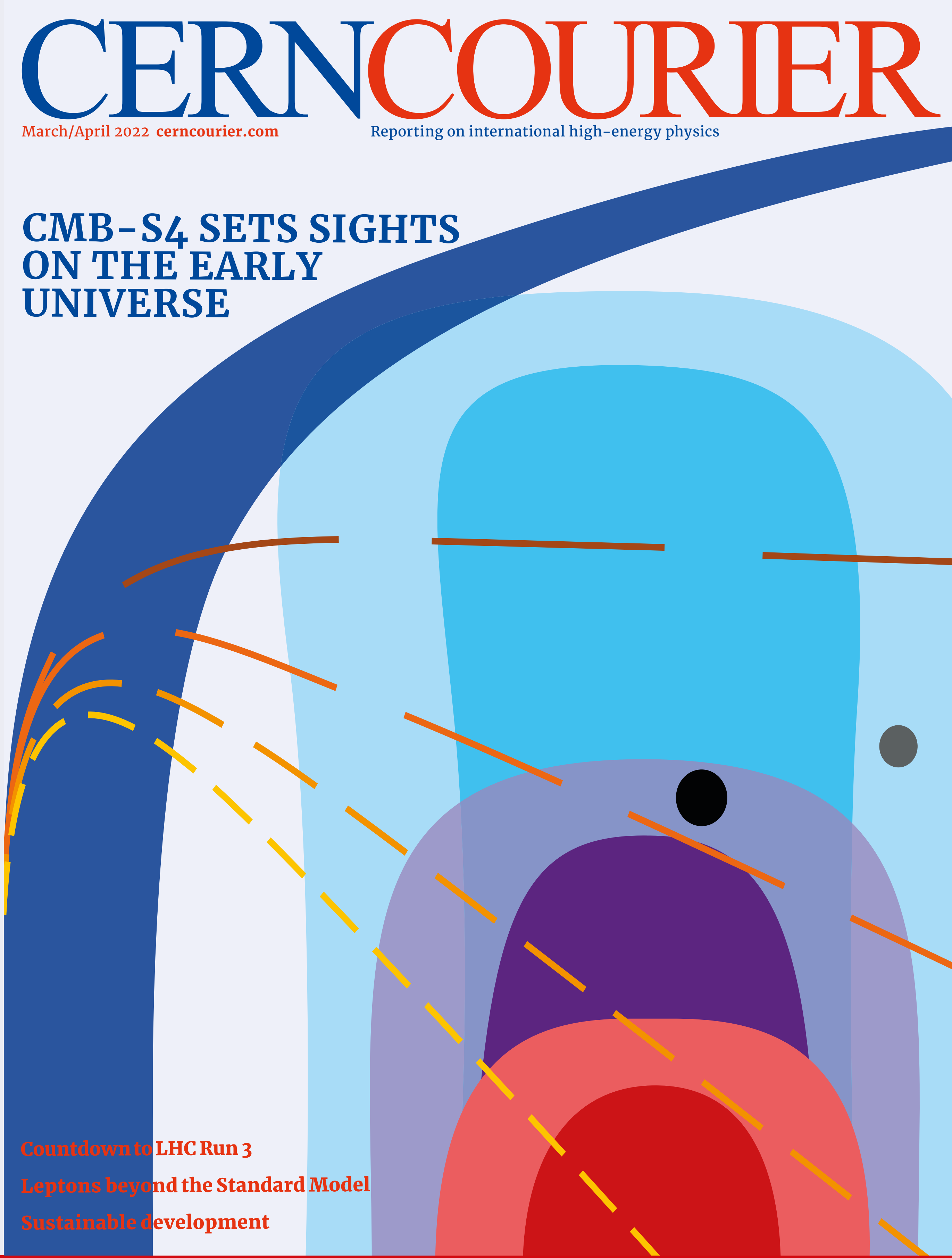
DIGITAL EDITION CREATED BY IOP PUBLISHING



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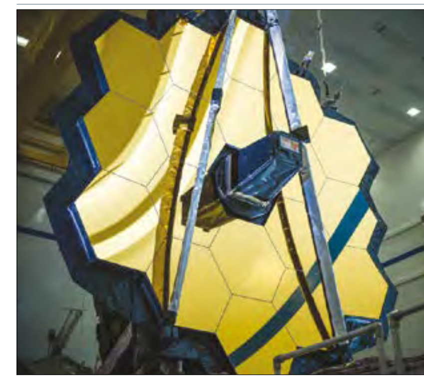

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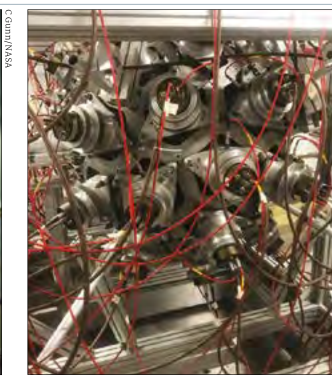

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FROM THE EDITOR

Connecting the dots

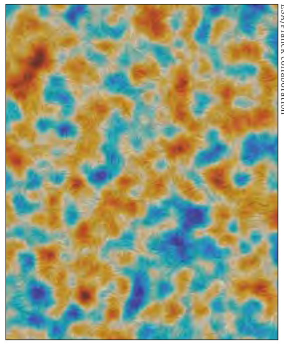
Matthew Chalmers
Editor

When Bell Labs astronomers Arno Penzias and Robert Wilson detected a persistent source of noise in a radio-communications antenna in 1964, they had no idea that it would lead to the birth of modern cosmology, not to mention the award of a Nobel prize. Having exhausted all the explanations that they could think of (at one point famously leading to the extermination of pigeons found roosting in the large horn-shaped device), the mystery was finally solved when Robert Dicke and co-workers at Princeton linked the faint isotropic signal to the cosmic black-body radiation that they had hypothesised should exist if the universe started in a hot Big Bang. The two groups published back-to-back letters in *Astrophysical Journal* in July 1965, setting cosmology on an ever converging path with particle physics.

Produced when radiation and matter decoupled around 375,000 years after the Big Bang, the cosmic microwave background (CMB) contains the imprints of high-energy processes that took place in the early universe. The creation of the lightest elements and the masses of neutrinos left their marks, while the tiny anisotropies in the CMB temperature reflect primordial density fluctuations that seeded all the structure we see today – and don't see, given that dark energy and dark matter are crucial to fit the CMB data. Following half a century of continuously improving ground-based and balloon-borne measurements, punctuated by the COBE, WMAP and Planck satellite missions, the CMB anisotropies have been revealed in stunning detail.

The CMB-S4 observatory will open a completely new window onto the physics of the early universe

A newly approved ground-based observatory, CMB-S4, will exceed these capabilities by more than an order of magnitude (p34). One of its goals is to constrain models of inflation, perhaps the most striking alliance between particle physics and cosmology (and the theme of this issue's cryptic cover). By amplifying random quantum fluctuations to cosmological scales, this short period of exponential expansion is the leading paradigm to explain the origin of the initial density perturbations. It is also predicted to generate primordial gravitational waves that introduce a characteristic polarisation pattern to the CMB. If this picture is correct, CMB-S4 will open a completely new window onto the physics of the early universe, possibly providing insights into the quantum nature of gravity.


ESA/Planck collaboration

Primordial *CMB temperature anisotropies and polarisation.*

Another CMB-S4 goal is to detect the influence of any additional light-relic particles such as axions or sterile neutrinos. As a second in-depth physics article in this issue explores, extending the Standard Model with additional neutrinos is a compelling way to solve its observational shortcomings (p27). The imminent operation of the James Webb Space Telescope (p7) further testifies to the increasingly fruitful interaction between fundamental physics, cosmology, astrophysics and astronomy to address open questions linking the largest and smallest scales.

Counting down to Run 3

In the collider world, the successful restart of Linac4 on 9 February lights the fuse for the start of LHC Run 3 in June (p8). The rich physics programme ahead owes thanks in part to extensive works completed during Long Shutdown 2, including a major programme by the CERN vacuum group (p39). For the longer term, progress continues apace for the High-Luminosity LHC crab cavities (p45). Meanwhile, in the US, Run 22 of the Relativistic Heavy-Ion Collider is stress-testing the accelerator and detector technologies for the future Electron-Ion Collider (p9).

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Reporting on international high-energy physics

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

IOP Publishing

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

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

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

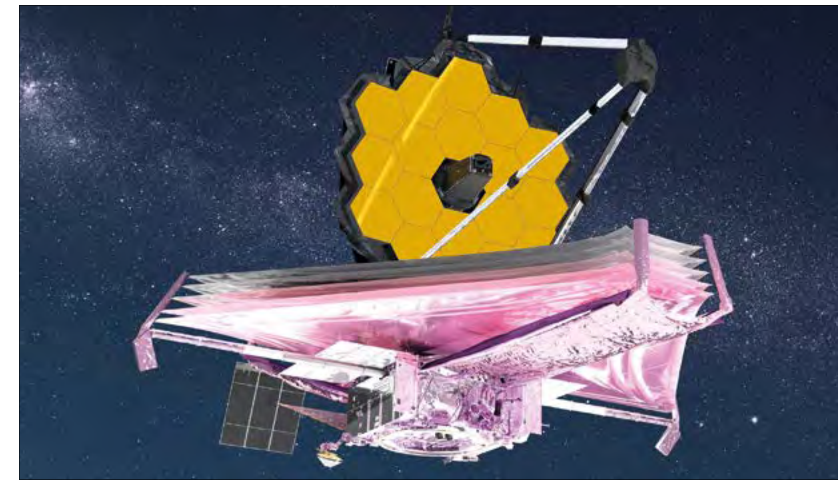
ISSN 0304-288X

NEWS ANALYSIS

Cosmology

Webb prepares to eye dark universe

After 25 years of development, the James Webb Space Telescope (JWST) successfully launched from Europe's spaceport in French Guiana on the morning of 25 December. Nerves were on edge as the Ariane 5 rocket blasted its $10 billion cargo through the atmosphere, aided by a velocity kick from its equatorial launch site. An equally nail-biting moment came 27 minutes later, when the telescope separated from the launch vehicle and deployed its solar array. In scenes reminiscent of those at CERN on 10 September 2008 when the first protons made their way around the LHC, the JWST command centre erupted in applause. "Go Webb, go!" cheered the ground team as the craft drifted into the darkness.



Golden view *An illustration of the James Webb Space Telescope, showing its 6.5 m-diameter gold-coated primary mirror and five-layer Kapton sunshield.*

Shedding new light

The result of an international partnership between NASA, ESA and the Canadian Space Agency, Webb took a similar time to design and build as the LHC and cost almost twice as much. Its science goals are also complementary to particle physics. The 6.2 tonne probe's primary mirror – the largest ever flown in space, with a diameter of 6.5 m compared to 2.4 m for its predecessor, Hubble – will detect light, stretched to the infrared by the expansion of the universe, from the very first galaxies. In addition to shedding new light on the formation of galaxies and planets, Webb will deepen our understanding of dark matter and dark energy. "The promise of Webb is not what we know we will discover," said NASA administrator Bill Nelson after the launch. "It's what we don't yet understand or can't yet fathom about our universe. I can't wait to see what it uncovers!"

Five days after launch, Webb successfully unfurled and tensioned its 300 m^2 sunshield. Although the craft's final position at Earth–Sun Lagrange point 2 (L2) ensures that it is sheltered by Earth's shadow, further protection from sunlight is necessary to keep its four science instruments operating at 34 K. The delicate deployment procedure involved 139 release mechanisms, 70 hinge assemblies, some 400 pulleys and 90 individual cables – each of which was a potential single-point failure. Just over one week later, on 7 and 8 January, the two wings of the primary mirror, which had to be folded in for launch, were opened, involving the final four of a total of 178 release mechanisms. The ground team then began the long procedure of aligning the telescope optics via 126 actuators on the backside of the primary mirror's 18 hexagonal segments. On 24 January, having completed a 1.51 million-km journey, the observatory successfully inserted itself into its orbit at L2, marking the end of the complex deployment process and the beginning of commissioning activities. The process will take months, with Webb scheduled to return its first science images in the summer.

Into the dark

The 1998 discovery of the accelerating expansion of the universe, which implies that around 70% of the universe is made up of an unknown dark energy, stemmed from observations of distant type-Ia supernovae that appeared fainter than expected. While the primary evidence came from ground-based observations, Hubble helped confirm the existence of dark energy via optical and near-infrared observations of supernovae at earlier times. Uniquely, Webb will allow cosmologists to see even farther, from as early as 200 million years after the Big Bang, while also extending the observation and cross-calibration of other standard candles, such as Cepheid variables and red giants, beyond what is currently possible with Hubble. Operating in the infrared rather than optical regime also means less scattering of light from interstellar gas.

With these capabilities, the JWST should enable the local rate of expansion to be determined to a precision of 1%. This will bring important information to the current tension between the measured expansion rate at early and late times, as quantified by the Hubble constant, and possibly shed light on the nature of dark energy (*CERN Courier* July/August 2021 p51).

By measuring the motion and gravitational lensing of early objects, Webb will also survey the distribution of dark matter, and might even hint at what it's made of. "In order to make progress in the identification of dark matter, we need observations that clearly discriminate among the tens of possible explanations that theorists have put forward in the past four decades," explains Gianfranco Bertone, director of the European Consortium for Astroparticle Theory. "If dark matter is 'warm' for example – ▷

meaning that it is composed of particles moving at mildly relativistic speeds when first structures are assembled – we should be able to detect its imprint on the number density of small dark-matter halos probed by the JWST. Or, if dark matter is made of primordial black holes, as suggested in the early 1970s by Stephen Hawking, the JWST could detect the faint emission produced by the accretion of gas onto these objects in early epochs."

Next generation

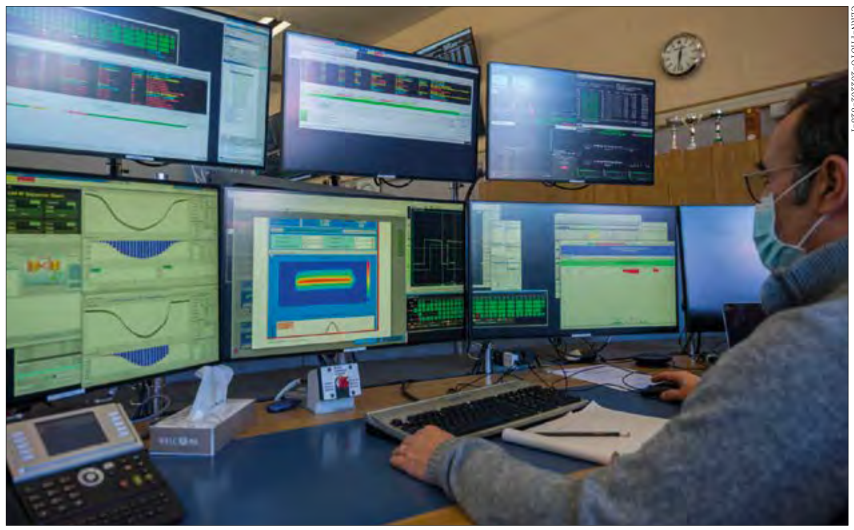
On 11 February, Webb returned images of its first star in the form of 18 blurry white dots, the product of the unaligned primary-mirror segments all reflecting light from the same star back at the secondary mirror and into its near-infrared camera. Though underwhelming at first sight, this and similar images are crucial to allow operators to gradually align and focus the hexagonal mirror segments until 18 images become one. After that, Webb will start downlinking science data at a rate of about 60 GB per day.

Launching Webb is a huge celebration of the international collaboration that made this mission possible

"Launching Webb is a huge celebration of the international collaboration that made this next-generation mission possible," said ESA director-general Josef Aschbacher. "We are close to receiving Webb's new view of the universe and the exciting scientific discoveries that it will make."

CERN

LHC Run 3: the final countdown



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All systems go *Shift-leader Jose-Luis Sanchez Alvarez commissioning the Linac4 beam on 8 February.*

The successful restart of Linac4 on 9 February marked the start of the final countdown to LHC Run 3. Inaugurated in May 2017 after two decades of design and construction, Linac4 was connected to the next link in the accelerator chain, the Proton Synchrotron Booster (PSB), in 2019 at the beginning of Long Shutdown 2 (LS2) and operated for physics last year. The 86 m-long accelerator now replaces the long-serving Linac2 as the source of all proton beams for CERN experiments.

On 14 February, H^- ions accelerated to 160 MeV in Linac4 were sent to the PSB, with beam commissioning and physics expected to start in ISOLDE on 7 and 28 March. Beams will be sent to the PS on 28 February, to serve, following set-up, experiments in the East Area, the Antiproton Decelerator and n_TOF. The SPS will be commissioned with beam during the week beginning 7 March, after which protons will be supplied to the AWAKE facility and to the North Area experiments, where physics operations are due to begin on 25 April.

Meanwhile, preparations for some of the protons' final destination, the LHC, are under way. Powering tests and magnet training in the last of the LHC's eight sectors are scheduled to start in the week of 28 February and to last for four weeks, after which the TI12 and TI18 transfer tunnels and the LHC experiments will be closed and the machine checkout will begin. LHC beam commissioning is scheduled to start on 11 April, with collisions at 450 GeV per beam expected around 10 May. Stable beams with collisions at 6.8 TeV per beam and nominal bunch population are scheduled for 15 June. An intensity ramp up will follow, producing collisions with 1200 bunches per beam in the week beginning 18 July on the way to more than double this number of bunches. High-energy proton–proton operations will continue for three to four months, before the start of a month-long run with heavy ions on 14 November. All dates are subject to change as the teams grapple with LHC operations at higher luminosities and energies than those during Run 2, following significant upgrade and consolidation work completed during LS2.

Among the novelties of Run 3 are the first runs of the neutrino experiments FASERν and SND@LHC, as well as the greater integrated luminosities and physics capabilities resulting from upgrades of the four main LHC experiments. A special request was made by LHCb for a SMOG2 proton–helium run in 2023 to measure the antiproton production rate and thus improve understanding of the cosmic antiproton excess reported by AMS-02. Ion runs with oxygen, including proton–oxygen and oxygen–oxygen, will commence in 2023 or 2024. The former is long-awaited by the cosmic-ray community to help improve models of high-energy air showers, while high-energy oxygen–oxygen collisions allow studies of the emergence of collective effects in small systems. High β* runs to maximise the interaction rate will be available for the forward experiments TOTEM and LHCf in late 2022 and early 2023.

On 28 January, CERN announced a change to the LHC schedule to allow necessary work for the High-Luminosity LHC (HL-LHC) both in the machine and in the ATLAS and CMS experiments. The new schedule foresees Long Shutdown 3 to start in 2026, one year later than in the previous schedule, and to last for three instead of 2.5 years. "Although the HL-LHC upgrade is not yet completed, a gradual intensity increase from 1.2×10^{11} to 1.8×10^{11} protons per bunch is foreseen for 2023," says Rende Steerenberg, head of the operations group. "This promises exciting times and a huge amount of data for the experiments."

BROOKHAVEN

RHIC stress-tests the future EIC

Brookhaven National Laboratory

Stellar innards *STAR collaborator Zhenyu Ye inspects the readout cables of the upgraded silicon tracker, which now operates closer to the interaction point.*

The world's longest-serving hadron collider, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, started its latest run in December. In addition to further probing the quark-gluon plasma, the focus of RHIC Run 22 (the 3.8 km-circumference collider's 22nd run in as many years) is on testing innovative accelerator techniques and detector technologies for the Electron-Ion Collider (EIC) due to enter operation at Brookhaven in the early 2030s.

The EIC, which will add an electron storage ring to RHIC, will collide 5–18 GeV electrons (and possibly positrons) with ion beams of up to 275 GeV per nucleon, targeting luminosities of 10^{34} cm^{-2} s^{-1} and a beam polarisation of up to 85%. This will enable researchers to go beyond the present one-dimensional picture of nuclei and nucleons: by correlating the longitudinal components of the quark and gluon momenta with their transverse momenta and spatial distribution inside the nucleon, the EIC will enable 3D "nuclear femtography" (*CERN Courier* October 2018 p31).

Unique ability

Preparations for the EIC rely on RHIC's unique ability to collide polarised proton beams via the use of helical dipole magnets, which offers a directional frame of reference to study hadron collisions. The last time polarised protons were collided at RHIC was 2017. For Run 22, the accelerator team aims to accumulate proton–proton collisions at the highest possible polarisation, and also at the highest energies (255 GeV per beam). To ensure the EIC hadron beams are as tightly packed as possible, thus maximising the luminosity, the accelerator team will try a technique previously used at RHIC to accelerate larger particles, but which has never been used with protons before.

"We are going to split each proton bunch into two when they're still at low energy in the Booster, and accelerate those as two separate bunches," explains Run-22 coordinator Vincent Schoefer. "That splitting will alleviate some of the stress during low energy, and then we can merge the bunches back together to put very dense bunches into RHIC." Such merging is challenging, he adds, because it takes around 300,000 turns in the Alternating Gradient Synchrotron (the link between the Booster and RHIC), during which the protons must be handled "very gently".

To further reduce the spread of high-energy hadron beams, the team will explore several cooling strategies (a major challenge for high-energy hadron beams) for possible use at the EIC. One is coherent electron cooling, whereby electrons from a high-gain free-electron laser are used to attract the protons closer to a central position. In addition, the team plans to ramp up beams of helium-3 ions to develop methods for measuring the polarisation of particles other than protons. Measuring how particles in the beam scatter off a gas target is the established method, but ions such as helium-3 can complicate matters by breaking up when they strike the target. To accurately measure the polarisation of helium-3 and other beams at the EIC, it is necessary to identify when this breakup occurs. During Run 22 the RHIC team will test its ability to accurately characterise scattering products using unpolarised helium-3 beams to develop new polarimetry methods.

The team will explore several cooling strategies for possible use at the EIC

During the run, RHIC's recently upgraded STAR detector will track particles emerging from collisions at a wider range of angles than ever before (covering a rapidity of –1.5–4.2). The upgrades include finer granulated sensors for the inner part of the time projection chamber, and two new forward-tracking detectors and electromagnetic and hadronic calorimetery at one end of the detector, which will allow better reconstruction of jets.

Detector technologies

In addition to increasing the dataset for exploring colour-charge interactions, these upgrades will give physicists crucial information about the detector technologies and the behaviour of nucleon structure relevant to the EIC. RHIC's other main detector, the upgraded sPHENIX, is under construction and scheduled to enter operation during Run 23 next year.

"Our goal this run is basically doing EIC physics with proton–proton collisions," says Elke-Caroline Aschenauer, who led the STAR upgrade project. "We have to verify that what you measure in electron–proton collisions at the EIC and in proton–proton events at RHIC is universal – meaning it doesn't depend on which probe you use to measure it."

CERNCOURIER

VOLUME 62 NUMBER 2 MARCH/APRIL 2022

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NEWS ANALYSIS

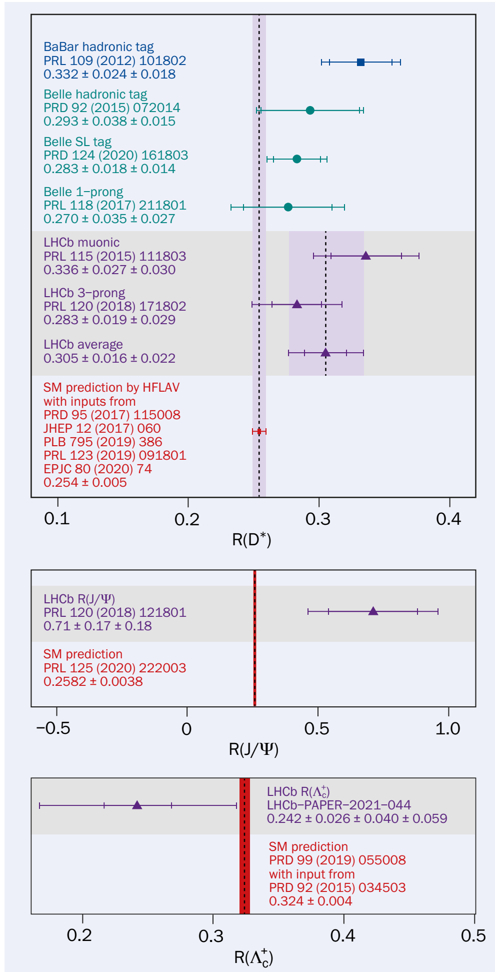
FLAVOUR PHYSICS

LHCb probes lepton universality with taus

The LHCb collaboration has made the first observation of the semileptonic baryon decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$, and used it to carry out a new test of lepton-flavour universality. Presented on 10 January at the 30th Lepton Photon conference organised by the University of Manchester (see p21), the result brings a further tool to understand the flavour anomalies reported by LHCb and other experiments in recent years.

Lepton-flavour universality (LFU) is the principle that the weak interaction couples to electrons, muons and tau leptons equally. Decays of hadrons to electrons, muons and tau leptons are therefore predicted to occur at the same rate, once differences in the lepton masses are taken into account. During the past few years, physicists have seen hints that some processes might not respect LFU. One of the strongest comes from $b \to c\ell^-\bar{\nu}_\ell$ ($\ell = e, \mu$) transitions in B-meson decays, as quantified by the parameter R(D*), which measures the ratio of the branching fractions of $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^*\ell^-\bar{\nu}_\ell$.

The combined deviation from precise Standard Model predictions of R(D*) and R(D) as measured by the BaBar, Belle and LHCb collaborations amounts to around 3.4σ. R(J/ψ), which concerns the branching ratios of $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$, was also found by LHCb to be larger than expected, but only at the level of around 2σ (*CERN Courier* November 2017 p11). Another key test of LFU involves the flavour-changing neutral current (FCNC) quark transition $b \to s\ell^+\ell^-$, for which several channels suggest that electrons are produced at a greater rate than muons. The largest effect comes from the decay $B^+ \to K^+e^+e^-$, for which LHCb finds R(K) to lie 3.1σ from the Standard Model expectation (*CERN Courier* May/June 2021 p17). Taken individually, none of the measurements are significant. But together they present an intriguing pattern. New-physics models based on leptoquarks have been proposed as possible explanations for the anomalies observed in semileptonic B-meson decays and in FCNC reactions (*CERN Courier* May/June 2019 p33).



LHCb

In line *Lepton-universality measurements using tau leptons via the branching-fraction ratios R(D*), R(J/ψ) and, most recently, R(Λ_c^+).*

Baryons entered the fray in late 2019, when LHCb compared the rates of $\Lambda_b^0 \to pK^-e^+e^-$ and $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays (*CERN Courier* January/February 2020 p13). Although R(pK) also erred on the side of fewer muons than electrons, it was found to be in agreement with the Standard Model within the limited statistics. The latest LHCb analysis, which compared the branching ratio of $\Lambda_b^0 \to \Lambda_c^+\tau^-\bar{\nu}_\tau$ from a sample of around 350 events selected from LHC Run 1 to that of $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ measured by the former DELPHI experiment at LEP, found R(Λ_c^+) = 0.242 ± 0.026(stat) ± 0.040(syst) ± 0.059(ext), in good agreement (approximately 1σ) with the Standard Model prediction of 0.324 ± 0.004.

Baryon decays provide complementary constraints on potential violations of LFU to those from meson decays due to the different spin of the initial state. This allows constraints to be placed on possible new-physics scenarios, explains Guy Wormser of IJCLab, who led the LHCb analysis: "R(D*) can be large and R(Λ_c^+) small in one new-physics scenario or R(D*) large and R(Λ_c^+) even larger in another. The spin of the accompanying hadron changes the way new-physics couples into the reaction, and it also depends on the spin of the particle present in the new-physics model, usually a leptoquark that can be a scalar, pseudoscalar, vector, axial vector or tensor. Our result excludes phase-space regions in some of these scenarios. In the future, a combined measurement of LFU violation – if it is confirmed – in mesons and baryons can therefore help to pin down the characteristics of the new-physics mediator."

The latest LHCb result concerning R(Λ_c^+) is likely to trigger intensive discussions among theorists, says the collaboration, with future measurements of this and other "R" measurements using Run 2 and Run 3 data keenly anticipated.

Further reading

LHCb Collab. 2022 arXiv:2201.03497.

ANTIMATTER

BASE breaks new ground in matter–antimatter tests

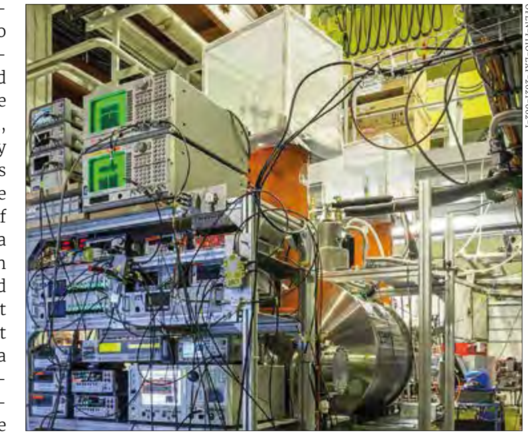
The BASE collaboration at the CERN Antiproton Decelerator (AD) has made the most precise comparison yet between the properties of matter and antimatter. Reporting in *Nature* in January, following a 1.5 year-long measurement campaign, the collaboration finds the charge-to-mass ratios of protons and antiprotons to be identical within an experimental uncertainty of just 16 parts per trillion. The result is four times more precise than the previous BASE comparison in 2015 and places strong constraints on possible violations of CPT invariance in the Standard Model.

The charge-to-mass ratio is now the most precisely measured property of the antiproton

Invariance under the simultaneous operations of charge conjugation, parity transformation and time reversal is a pillar of quantum field theories such as the Standard Model. Direct, high-precision tests of CPT invariance are therefore powerful probes of new physics, and of the possible mechanisms through which the universe came to be matter-dominated.

"The charge-to-mass ratio is now the most precisely measured property of the antiproton," says BASE spokesperson Stefan Ulmer of RIKEN in Japan. "To reach this precision, we made considerable upgrades to the experiment and carried out the measurements when the antimatter factory was closed down, so that they would not be affected by disturbances from the experiment's magnetic field." The upgrades include a rigorous re-design of the cryostage of the experiment and the development of a multi-layer shielding-coil system, which considerably reduced magnetic-field fluctuations in the central measurement trap, explains Ulmer. "Another important ingredient is the implementation of a superconducting image-current detection system with tunable resonance frequency and ultra-high non-destructive detection efficiency, which eliminates the dominant systematic shift of the previous charge-to-mass ratio comparison."

The BASE team confined antiprotons and negatively charged hydrogen ions in a state-of-the-art Penning trap, in which charged particles follow a cyclical trajectory with a frequency that scales with the trap's magnetic-field strength and the particle's charge-to-mass ratio. By alternately feeding antiprotons and hydrogen ions one at a time into the trap, the team was able to measure their cyclotron frequencies under the same conditions. Performed over four campaigns between December 2017 and May 2019, the measurements involved more than 24,000 cyclotron-frequency comparisons, each lasting 260 seconds. Within the experimental uncertainty, the result, $-(q/m)_p/(q/m)_{\bar{p}} = 1.000000000003(16)$, demonstrates that the Standard Model respects CPT invariance at an energy scale of 1.96×10^{-27} GeV at 68% confidence. It also improves knowledge of 10 coefficients in the Standard Model extension – a generalised, observer-independent effective field theory used for investigations of Lorentz violation.



OPEN-PHO-EXP-2021-002-1

Sensitive *The BASE electronics rack, also showing the experiment's horizontal Penning-trap magnet and orange cryostats.*

Weak equivalence principle

The BASE team also used their data to test the weak equivalence principle, which states that different bodies in the same gravitational field undergo the same acceleration. Any difference between the gravitational interaction of protons and antiprotons, for example due to anomalous gravitational scalar or tensor couplings to antimatter, would result in a difference in the proton and antiproton cyclotron frequencies. Sampling the varying gravitational field of Earth as it orbits the Sun, BASE found no such difference, constraining the strength of anomalous antimatter/gravitational interactions to less than 1.8×10^{-7} and enabling the first differential test of the weak equivalence principle (WEP) using antiprotons.

"From this interpretation we constrain the differential matter–antimatter WEP-violating coefficient to less than 0.03, which is comparable to the initial precision goals of other AD experiments that aim to drop antihydrogen in the Earth's gravitational field," explains Ulmer. "BASE did not directly drop antimatter, but our measurement of the influence of gravity on a baryonic antimatter particle is, according to our understanding, conceptually very similar, indicating no anomalous interaction between antimatter and gravity at the achieved level of uncertainty."

The collaboration expects to reach even higher sensitivities on both the WEP test and the proton–antiproton charge-to-mass ratio comparison by increasing the experiment's magnetic-field strength, stability and homogeneity. Further improvements are anticipated from the use of transportable antiproton traps, such as BASE-STEP, which allow precision antiproton experiments to be moved from the fluctuating accelerator environment to a calm laboratory space.

Further reading

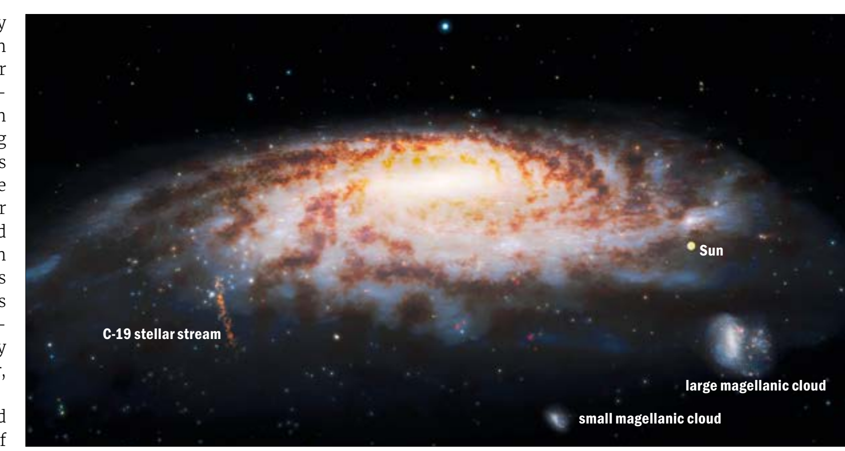
BASE Collab. 2022 *Nature* **601** 53.

ASTROWATCH

Ruins of ancient star system found within our galaxy

Despite it being our galactic home, many open questions remain about the origin and evolution of the Milky Way. To answer such questions, astronomers study individual stars and clusters of stars within our galaxy as well as those in others. Using data from the European Space Agency's Gaia satellite, which is undertaking the largest and most precise 3D map of our galaxy by surveying an unprecedented one per cent of the Milky Way's 100 billion or so stars, an international group has discovered a stream of stars spread across the night sky with peculiar characteristics. The stars appear not only to be very old, but also very similar to one another, indicating a common origin.

The discovered stream of stars, called C-19, are spread over tens of thousands of light years, and appear to be the remnant of a globular cluster. A globular cluster ▷



Gemini Observatory/NOIRLab/NSF/AURA/J da Silva/Spaceengine/M Zamani

Cosmic fossil *C-19 (lower left) is a grouping of stars in the Milky Way halo that share a common orbital motion around the galaxy.*

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is a very dense clump of stars with a total typical mass of 10^4 or 10^5 solar masses, the centre of which can be so dense that stable planetary systems cannot form due to gravitational disruptions from neighbouring stars. Additionally, the clusters are typically very old. Estimates based on the luminosity of dead cooling remnants (white dwarfs) reveal some to be up to 12.8 billion years old, in stark contrast to neighbouring stars in their host galaxies. The origin, formation and reason for clusters to end up in these galaxies remains poorly understood.

The newly discovered stream has metallicities lower than 0.05% that of the Sun

One way to discern the age of globular clusters is to study the elemental composition of the stars within them. This is often expressed as the metallicity, which is the ratio of all elements heavier than hydrogen and helium (confusingly referred to as metals in the astronomical community) to these two light elements. Hydrogen and helium were produced during the Big Bang, while anything heavier was produced in the first generation of stars, implying that the first generation of stars had zero metallicity and that the metallicity increases with each generation. Until recently the lowest metallicities of stars in globular clusters were 0.2% that of the Sun. This "lower floor" in metallicity was thought to put constraints on their maximum age and size, with lower-metallicity clusters thought to be unable to survive to this day. The newly discovered stream, however, has metallicities lower than 0.05% that of the Sun, changing this perception.

Captured clusters

The stars in the recently observed C-19 stream are no longer a dense cluster. Rather, they all appear to follow the same orbit within our galaxy, the plane of which is almost perpendicular to the galactic disk in which we orbit its centre. This similarity in orbit, as well as their very similar metallicity and general chemical content, indicate that they once formed a globular cluster which was absorbed by the Milky Way. The orbit dynamics further indicate it was captured at a time when the potential well of the Milky Way was significantly smaller than it is now, implying that the capture of this cluster by our galaxy occurred long ago. Since then, the once dense cluster heated up and got smeared out as it orbited the galactic centre through interactions with the disk, as well as with the potential dark-matter halo.

The discovery, published in *Nature*, does not directly answer the question of where and how globular clusters were formed. It does however provide us with a nearby laboratory to study issues like cluster and galaxy formation, the merging of such objects and the subsequent destruction of the cluster through interactions with both baryonic as well as potential dark matter. This particular cluster furthermore consists of some of the oldest stars found, and could have been formed before the reionisation of the universe, which is thought to have taken place between 150 million and a billion years after the Big Bang. Further information about such ancient objects can be expected soon thanks to the recently launched James Webb Space Telescope (see p7). This instrument will be able to see some of the earliest formed galaxies, and can thereby provide additional clues on the origin of the fossils now found within our own galaxy.

Further reading
N Martin *et al.* 2022 *Nature* **601** 45.

NEWS DIGEST

Mitigating COVID-19

Airborne transmission of COVID-19 can be mitigated in existing infrastructures without major modifications or costly consolidation plans, concludes a study based on the COVID Airborne Risk Assessment (CARA) tool. Developed at CERN, CARA allows quick and accurate assessments of the risk of airborne transmission by simulating the long-range airborne spread of SARS-CoV-2 viruses in an indoor setting (cara.web.cern.ch). The methodology is highly dependent on the viral load at the time of transmission, confirming findings that 20% of infected hosts can emit approximately two orders of magnitude more viral-containing particles. In their study, Andre Henriques and co-workers found that the viral-emission risk is reduced by a factor of five by wearing surgical masks, and that natural ventilation strategies are very effective in reducing the chances of indoor transmission, although opening windows only periodically might not be ideal in certain settings (*Interface Focus* **12** 20210076).

Sliding naturalness

Theorists Raffaele D'Agnolo and Daniele Teresi have proposed a new framework to simultaneously solve the electroweak-hierarchy and strong-CP problems. The idea rests on the existence of two new scalar particles with axion-like couplings to gluons after the QCD phase transition in the early universe, in which an approximate symmetry exists between them. One of the scalars is similar to the postulated Peccei–Quinn QCD axion and provides a dark-matter candidate, while the other is assumed to be heavier. Since the scalars' potential is directly related to the Higgs vacuum expectation value (vev), only universes that possess the observed values for the Higgs vev and the QCD angle $\theta \ll 1$ exist. The theory can be tested by experiments searching for electric dipole moments and axion-like dark matter, say the authors (*Phys. Rev. Lett.* **128** 021803).

DESY Innovation Factory

DESY has selected architects for its new Innovation Factory, comprising two buildings located on the DESY campus and at the nearby Altona Innovation Park. Opening in 2025, the facility aims to provide a link between science, start-ups and industry in the fields of life science and new materials. The project follows other incubators to foster knowledge transfer, such as IdeaSquare at CERN and the Higgs Centre for Innovation at the University of Edinburgh.


DESY, ARGE TRAPEZ/Blanck + Morgen

The Altona Innovation Park building.

Ripples in the neutron form factor

Precise measurements of the neutron effective form factor by the BESIII collaboration bring new insights into the fundamental structure of the neutron, which, as for the proton, is still not fully understood. By determining the Born cross section of $e^+e^- \to n\bar{n}$ events in a 647.9 pb^{-1} data sample recorded at a centre-of-mass energy of 2–3.08 GeV, the team found oscillations in the neutron effective form factor that are similar to those observed for the proton. The finding, which improves the statistics on the neutron form factor by more than a factor of 60 compared to previous measurements, hints at a more complicated structure of nucleons and aligns with theoretical predictions, although disagrees with earlier measurements at the former FENICE experiment at ADONE (*Nat. Phys.* **17** 1200).

Testing the Cherenkov water

CERN has conditionally approved a 45 tonne Water Cherenkov Test Experiment (WCTE) to help develop new detector technologies for neutrino experiments in Japan and elsewhere. Such detectors have long been used to measure or search for low-rate processes such as neutrino interactions or proton decay on account of their scalability to large masses. The Super-K and future Hyper-K detectors, as well as the proposed THEIA and ESSnuSB experiments, will add new detection capabilities, such as loading gadolinium into Super-K, to increase their reach and precision. Due to operate in the CERN T9 test beam in 2023, the WCTE, based on a similar design to the proposed Hyper-K Intermediate Water Cherenkov Detector, will allow prototype detector technologies to be tested with known particle fluxes, energies and types (CERN-SPSC-2019-042).

Heavy lifting for the X(3872)

The CMS collaboration has found the first evidence for the production of the exotic meson X(3872) in relativistic heavy-ion collisions. Discovered by the Belle collaboration in 2003, the X(3872)'s quantum numbers were narrowed down by CDF and later determined to be $J^{PC} = 1^{++}$ by LHCb. But its true nature is still not understood, with proposals including a conventional charm–anticharm bound state, a D-meson molecule or a tetraquark. Using a 1.7 nb^{-1} sample of lead–lead collisions recorded in 2018 at an energy of 5.02 TeV per nucleon pair, CMS revealed the X(3872) via the decay chain $J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$ at a significance of 4.2σ. Combined with previous measurements in e^+e^- and pp collisions, the result provides unique insights into the nature and production mechanism of the exotic state (*Phys. Rev. Lett.* **128** 032001).

Lizards on the lattice

Researchers from the University of Geneva have used the Ising model, routinely used by physicists to understand phase transitions, to describe the colour change of the ocellated lizard's scales from green to black, which occurs throughout the creature's life. By arranging the scales on a honeycomb lattice and assigning black and green to the different spin states, the preference between each colour is analogous to the choice of the spin state forced by an external magnetic field, resulting in a labyrinthine pattern of green and black. While providing few insights into the underlying microscopic cell-biology, says the team, the work poses unconventional questions about possible relationships between genetic variability, Darwinian selection and the principle of maximum entropy (*Phys. Rev. Lett.* **128** 048102).


M Milinkovitch

An ocellated lizard and its scales.

CERNCOURIER
Volume 62 Number 2 March/April 2022
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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Extending the reach on Higgs' self-coupling

The discovery of the Higgs boson and the comprehensive measurements of its properties provide a strong indication that the mechanism of electroweak symmetry breaking (EWSB) is compatible with the one predicted by Brout, Englert and Higgs (BEH) in 1964. But there remain unprobed features of EWSB, chiefly whether the form of the BEH potential follows the predicted "Mexican hat" shape. One of the parameters that determines the form of the BEH potential is the Higgs boson's trilinear self-coupling, λ. Experimentally, this fundamental parameter can be measured via Higgs-boson pair (HH) production, where a single virtual Higgs boson splits into two Higgs bosons. However, such a measurement is very challenging as the Standard Model (SM) HH production cross-section is more than 1000 times lower than that of single Higgs-boson production.

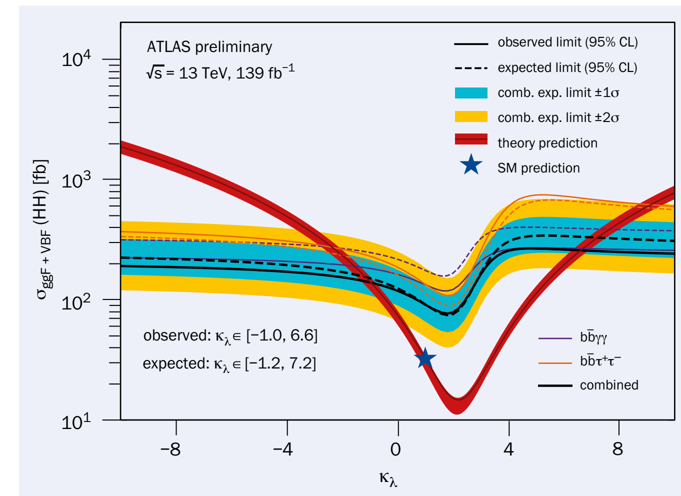


Fig. 1. *Observed (solid) and expected (dashed) upper limits at 95% CL on the non-resonant HH production cross section as a function of the coupling strength of the Higgs boson trilinear-self-coupling κ_λ. The lower and upper limits on κ_λ are determined by the crossing points of the upper limits on the HH cross section with the theory prediction.*

Beyond the SM (BSM) physics with modified or new Higgs-boson couplings could lead to significantly enhanced HH production. Some BSM scenarios predict new heavy particles that may lead to resonant HH production, contrary to the non-resonant production featured by the triple-Higgs-boson coupling. New ATLAS results set tight constraints on both the non-resonant and resonant scenarios, showing that the boundaries of what can be achieved with the current and future LHC datasets can be significantly pushed.

The ATLAS collaboration recently released results of searches for HH production in three final states – $bb\gamma\gamma$, $bb\tau\tau$ and 4b (where one Higgs boson decays into two b-quarks and the other into two photons, two tau-leptons or two b-quarks) and their combination, exploiting the full LHC Run-2 dataset. The first two analyses target both resonant and non-resonant HH production, while the 4b analysis targets only resonant HH production. These three channels are the most sensitive final states in each scenario. The three decay modes of the second Higgs boson provide good sensitivity in different kinematic regions, so that the analyses are highly complementary. The HH → $bb\gamma\gamma$ process has the lowest branching ratio but high efficiency to trigger and reconstruct photons, as well as an excellent diphoton mass resolution, leading to the best sensitivity at low HH invariant masses. The HH → 4b final state has the highest branching ratio but suffers from the requirement to impose high transverse momentum b-jet trigger thresholds, the ambiguity in the Higgs boson reconstruction and the large multijet background. However, it provides the best sensitivity at high HH invariant masses. Finally, the HH → $bb\tau\tau$ decay has a moderate branching ratio as well as a moderate background contamination, giving the best sensitivity in the intermediate HH mass range.

BSM physics with new Higgs-boson couplings could lead to significantly enhanced HH production

With the latest analyses, a remarkably stringent observed (expected) upper limit of 3.1 (3.1) times the SM prediction on non-resonant HH production was obtained at 95% confidence level (CL). The coupling strength of the Higgs boson trilinear self-coupling in units of the SM value κ_λ is observed (expected) to be constrained between −1.0 and 6.6 (−1.2 and 7.2) at 95% CL (see figure 1). These are the world's tightest constraints obtained on this process. The observed (expected) exclusion limits at 95% CL on the resonant HH production cross-section range between 1.1 and 595 fb (1.2 and 392 fb) for resonance masses between 250 and 5000 GeV.

The sensitivity of the current analyses is still limited by statistical uncertainties and is expected to improve significantly with the future luminosity increase during LHC Run 3 and the HL-LHC programme. A comparison between the current results and previous partial Run-2 dataset results has shown that an improvement by more than a factor of three on the limits is achieved. A factor of two was expected from the larger dataset, and the remaining improvements arise from better object reconstruction and identification techniques, and new analysis methods.

These latest results inspire confidence that the observation of the SM HH production and a precise measurement of the Higgs-boson trilinear self-coupling may be possible at the HL-LHC.

Further reading

ATLAS Collab. 2021 arXiv:2112.11876.
ATLAS Collab. 2021 ATLAS-CONF-2021-030.
ATLAS Collab. 2022 arXiv:2202.07288.
ATLAS Collab. 2021 ATLAS-CONF-2021-052.

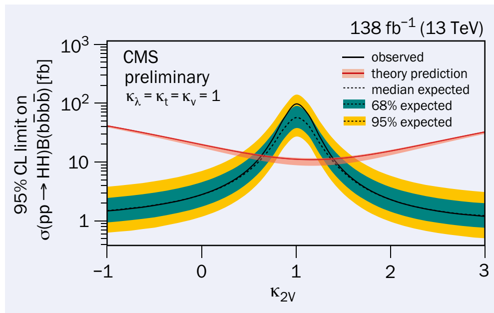
CMS

Graph neural networks boost di-Higgs search

Two fundamental characteristics of the Higgs boson (H) that have yet to be measured precisely are its self-coupling λ, which indicates how strongly it interacts with itself, and its quartic coupling to the vector bosons, which mediate the weak force. These couplings can be directly accessed at the LHC by studying the production of Higgs-boson pairs, which is an extremely rare process occurring about 1000 times less frequently than single-H production. However, several new-physics models predict a significant enhancement in the HH production rate compared to the Standard Model (SM) prediction, especially when the H pairs are very energetic, or boosted. Recently, the CMS collaboration developed a new strategy employing graph neural networks to search for boosted HH production in the four-bottom-quark final state, which is one of the most sensitive modes currently under examination.

H pairs are produced primarily via gluon and vector-boson fusion. The former production mode is sensitive to the self-coupling, while the latter probes the quartic coupling involving a pair of weak vector bosons and two Higgs bosons. The extracted modifiers of the coupling-strength parameters, κ_λ and κ_{2V}, quantify their strengths relative to the SM expectation.

This latest CMS search targets both production modes and selects two Higgs bosons with a high Lorentz boost. When each Higgs boson decays to a pair of



Source: CMS-PAS-B2G-22-003

Fig. 1. *Observed (solid) and expected (dashed) exclusion limit on the HH production cross section times the branching fraction into four bottom quarks as a function of κ_{2V} with other couplings fixed to the SM values. The crossings of the observed limit and the theoretical cross section (red line) indicate the allowed range of the coupling values: $0.6 < \kappa_{2V} < 1.4$.*

bottom quarks, the two quarks are reconstructed as a single large-radius jet. The main challenge is thus to identify the specific H jet while rejecting the background from light-flavour quarks and gluons. Graph neural networks, such as the ParticleNet algorithm, have been shown to distinguish successfully between real H jets and background jets. Using measured properties of the particles and secondary vertices within the jet cone, this algorithm treats each jet as an unordered set of its constituents, considers potential correlations between them, and assigns each jet a probability to originate from a Higgs-boson decay. At an H-jet selection efficiency of 60%, ParticleNet rejects background jets twice as efficiently as the previous best algorithm (known as DeepAK8). A modified version of this algorithm is also used to improve the H-jet mass resolution by nearly 40%.

Using the full LHC Run-2 dataset, the new result excludes an HH production rate larger than 9 times the SM cross-section at 95% confidence level, versus an expected limit of 5. This represents an improvement by a factor of 30 compared to the previous best result for boosted HH production. The analysis yields a strong constraint on the HH production rate and κ_λ, and the most stringent constraint on κ_{2V} to date, assuming all other H couplings to be at their SM values (see figure 1). For the first time, and with the assumption that the other couplings are consistent with the SM, the result excludes the $\kappa_{2V} = 0$ scenario at over five standard deviations, confirming the existence of a quartic coupling between two vector bosons and two Higgs bosons. This search paves the way for a more extensive use of advanced machine-learning techniques, the exploration of the boosted HH production regime, and further investigation into the potentially anomalous character of the Higgs boson in Run 3 and beyond.

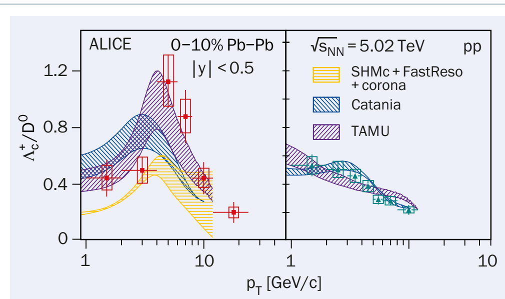
Further reading

CMS Collab. 2021 CMS-PAS-B2G-22-003.
CMS Collab. 2021 CMS-DP-2020-002.
CMS Collab. 2020 *JINST* **15** P06005.

ALICE

Charm baryons constrain hadronisation

Understanding the mechanisms of hadron formation represents one of the most interesting open questions in particle physics. Hadronisation is a non-perturbative process that is not calculable in quantum chromodynamics and is typically described with phenomenological models, such as the Lund string model. Ultrarelativistic nuclear collisions, where a high-density plasma of deconfined quarks and gluons, the quark–gluon plasma (QGP), is created, provide an ideal setup to test the limits of this description. In these conditions,



Source: arXiv:2112.08156

Fig. 1. *The Λ_c^+/D^0 production ratio as a function of p_T in central Pb–Pb (left) and pp (right) collisions at 5.02 TeV, compared with theoretical predictions of the SHMc, Catania and TAMU models.*

hadrons may be formed via a combination of deconfined quarks close in phase space. This process can lead, for example, to increased production of baryons with respect to mesons in momentum ranges up to 10 GeV/c. The ALICE and CMS experiments at the LHC, and PHENIX and STAR at RHIC, have indeed observed substantial modifications of the event hadro-chemistry in heavy-ion collisions compared to proton–proton and e^+e^- collisions. In particular, the total abundances of light and strange hadrons were found to follow, quite remarkably, the "thermal" expectations for a deconfined medium close to equilibrium.

Measurements of heavy-flavour hadron production play a unique role in such studies. Heavy quarks are mostly produced in hard scatterings at the early stages of the collisions, well before the QGP is formed. Furthermore, their thermal production is negligible since their masses are larger than the typical QGP temperature. Due to the much better theoretical control on their production and propagation in the medium, heavy ▷

quarks provide unique constraints on the QGP properties and the nature of hadronisation mechanisms, compared to light quarks. Heavy-flavour measurements in heavy-ion collisions also test whether the transverse momenta (p_T) integrated yields of charm hadrons are consistent with the hypothesis of statistical models, for which charm quarks are expected to reach an almost complete thermalisation in the QGP, despite being initially very far from equilibrium.

The ALICE experiment has recently made an improvement towards a quantitative understanding of hadron formation from a QGP by performing the first measurement of the charm baryon-to-meson ratio Λ_c^+/D^0 in central (head-on) Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. By exploiting its unique tracking and particle-identification capabilities, and using machine-learning techniques, ALICE has measured the ratio down to very low p_T (less than 1 GeV/c), where hadronisation mechanisms via a combination of quarks are expected to dominate (figure 1, left). The measured production ratio of Λ_c^+/D^0 in central Pb–Pb collisions is found to be larger than in pp collisions at p_T of 4–8 GeV/c (figure 1, right). On the other hand, the p_T-integrated ratio was found to be compatible with the result of pp collisions within one standard deviation.

ALICE has recently made an improvement towards a quantitative understanding of hadron formation from a QGP

A comparison with theoretical calculations confirms the discrimination power of this measurement. The experimental data are well described by transport models that include mechanisms of the combination of quarks from the deconfined medium (TAMU and Catania). Given the current uncertainties, a conclusive answer on the agreement with statistical models (SHMc) cannot yet be reached. This motivates future high-precision and more differential measurements with the upgraded ALICE detector during the upcoming LHC Run-3 Pb–Pb runs. Thanks to the increased rate-capabilities of the new readout systems of the time projection chamber and the new inner tracking system, ALICE will increase its acquisition rate by up to a factor of about 50 in Pb–Pb collisions and will benefit from a much higher tracking resolution (by a factor 3–6 for low-p_T tracks). High-accuracy measurements performed in Runs 3 and 4 will therefore provide significant discrimination power on theoretical calculations and strong constraints on the mechanisms underlying the hadronisation of charm quarks from the QGP.

Further reading

ALICE Collab. 2021 arXiv:2112.08156.

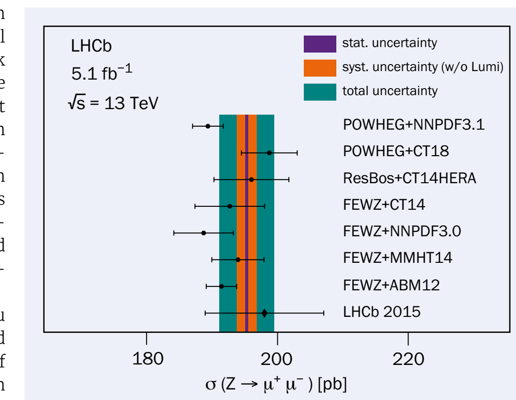
LHCb

Precision Z-boson production measurements

The precise determination of the Z-boson parameters at e^+e^- colliders was crucial for the establishment of the electroweak theory of the Standard Model. Today, the Z boson has become an essential object of experimental study at the LHC. In particular, measurements of the Z boson's production and decay properties in high-energy proton–proton collisions provide insights into the parton distribution functions (PDFs) of the proton and are an implicit test of quantum chromodynamics (QCD).

Recently, using a sample of $Z \to \mu^+\mu^-$ events, the LHCb collaboration reported the most precise measurement to date of the Z-boson production cross section in the forward region at a centre-of-mass energy of 13 TeV (see figure 1). The collaboration also reported the first measurements of the angular coefficients in $Z \to \mu^+\mu^-$ decays in the forward region, which encode key information about the QCD mechanisms underlying the Z-boson production mechanism. In addition to improving knowledge of the proton PDFs, these two analyses contribute to the study of spin-momentum correlations in the proton, complementing ATLAS and CMS measurements in the central region.

In addition to the up and down valence quarks, a proton comprises a sea of quark–antiquark pairs primarily produced via gluon splitting. Given their similar masses, one would expect that the nucleon sea is flavour-symmetric for up and down quarks. However, in the early 1990s, the New Muon



Source: arXiv:2112.07458

Fig. 1. *Comparison between data (coloured bands) and predictions (black circles) of the integrated cross-section $\sigma(pp \to Z \to \mu^+\mu^-)$. The purple band corresponds to the statistical uncertainty, and orange and green bands correspond to the systematic uncertainty and total uncertainty, respectively. The diamond point corresponds to the previous LHCb measurement.*

Collaboration at CERN found that this symmetry is violated. Later, the ratio of down antiquarks to up antiquarks in the proton was directly measured by the NA51 experiment at CERN and the NuSea/E866 experiment at Fermilab, revealing a significant asymmetry in the sea-quark PDF distributions. Recently, the SeaQuest/E906 experiment at Fermilab reported a new result on this ratio, showing different trends in the larger Bjorken-x range (x > 0.2) compared to the previous results and raising the tension with the NuSea measurement.

With a detector instrumented in the forward region, LHCb is ideally placed to study decays of highly boosted Z bosons produced by interactions between one parton with large-x and another with small-x. Considering that both the NuSea and SeaQuest results have large contributions from nuclear effects, the current LHCb measurement of the Z production cross section based on a data sample of 5.1 fb^{-1} provides important complementary constraints in the large-x region.

The measurement of the angular coefficient "A_2," in $Z \to \mu^+\mu^-$ decays is sensitive to the transverse-momentum-dependent (TMD) PDFs, as it is proportional to the convolution of the two so-called Boer–Mulders functions of the two initial partons. A measurement of A_2 can thus provide stringent constraints on the non-perturbative partonic spin-momentum correlation within unpolarised protons. By comparing the measured A_2 in different dimuon mass ranges, the LHCb measurement provides an important input for the determination of the proton TMD PDFs, which are crucial to properly describe the production of electroweak bosons at the LHC. Together with the production cross section, these results from LHCb reinforce the importance of a forward detector to complement other measurements at the LHC.

Further reading

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LHCb Collab. 2021 LHCb-PAPER-2021-048.

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FIELD NOTES

Reports from events, conferences and meetings

30th International Symposium on Lepton Photon Interactions at High Energies

Shining light on the precision frontier

The 30th International Symposium on Lepton Photon Interactions at High Energies, hosted online by the University of Manchester from 10 to 14 January, saw more than 500 physicists from around the world engaged in a broad science programme. The Lepton Photon series dates to the 1960s and takes place every two years. This was the first time the conference was meant to return to the UK in more than 50 years, with its original August time slot moved to January due to COVID-19 restrictions. The agenda was stretched to improve accessibility in different time zones. Posters were presented via pre-recorded videos and three prizes were awarded following a public vote.

M Gersabeck

Faces and places *More than 500 attendees participated in lively discussions on physics, diversity and outreach.*

With 2022 marking the 10-year anniversary of the Higgs-boson discovery, it was appropriate that the conference kicked-off with an experimental Higgs-summary talk. Both the ATLAS and CMS collaborations showcased their latest high-precision measurements of Higgs-boson properties and searches for physics beyond the Standard Model using the Higgs boson as a portal. ATLAS presented a new combination of the Higgs total and differential cross-section measurements in the two-photon and four-lepton channels, while CMS shared the first full Run-2 search for resonant di-Higgs production in several multi-lepton final states (see p18).

Powering ahead

The LHC experiments continue to demonstrate the power of hadron colliders to test the electroweak sector. Notable new results included the first observation of opposite-charge WWjj production at CMS, the first tri-boson (WWW) observation at ATLAS, and LHCb entering the game of W-boson mass measurements. A highlight of the talks covering QCD topics was a combined fit of the parton distribution function of the proton to differential cross-section measurements from ATLAS and HERA data. A wide range of new-physics searches were presented, including a dark-photon search from ATLAS with the full Run-2 data, and a CMS search for new scalars decaying into final states with Higgs bosons.

In flavour physics, the pattern of anomalies in rare leptonic and semi-leptonic processes continues to intrigue. Highlights in this area included new measurements of rare leptonic decays from LHCb in $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$ decays ($\ell = e, \mu, \tau$), where the decay involving a τ lepton was observed for the first time (see p10), and from Belle in $\Omega_c^0 \to \Omega^- \ell^+ \nu$ decays, where the ratio of the e–μ final-state branching ratios was found to be in agreement with the expectation of unity and where the μ decay had been measured for the first time. Similar studies of rare leptonic decays are now also taking place in the charm sector. The BESIII collaboration tested in one study the e–μ universality in a second decay mode and confirmed its agreement with the Standard Model. Participants also heard about the latest searches for the ultra-rare decay $K \to \pi \nu \bar{\nu}$ from KOTO, searching for the neutral kaon decay mode, and from NA62, which now has 3.4σ evidence for the charged kaon decay mode.

With the 2021 update on muon g-2 from Fermilab, and with the MEG-II, DeeMe and Mu3e experiments getting ready to search for muon-to-electron transitions, there is much excitement about charged-lepton physics. CP violation in beauty and charm remains a hot topic, with updates from LHCb, Belle and BESIII on D^0 and B_s oscillations and the CKM angle γ. In all these areas, the theoretical community continues to push the boundaries to make improved predictions. Among other things, theorists presented the latest global fits of Wilson coefficients, and several welcome developments in lattice QCD.

Hot-off-the-press was a combined search for spatial correlations between neutrinos and ultra-high energy cosmic rays

The highlights from the neutrino sector included the low-energy excess search by MicroBooNE (*CERN Courier* January/February 2022 p9) and the observation of the CNO cycle of solar neutrinos by Borexino (*CERN Courier* January/February 2022 p24). The latest results from the long-baseline experiments – T2K and recently NOvA – are starting to hint at large CP-violating effects in neutrino oscillations.

A series of talks on dark-matter searches spanned collider experiments, direct detection and astrophysical signatures. Some interesting anomalies persist, such as the DAMA annual modulation and the XENON1T low-energy excess (*CERN Courier* September/October 2020 p8). These will be challenged by a suite of next-generation detectors, such as PandaX-4T, XENONnT, LZ and DarkSide-20k.

The conference also included a rich programme of talks covering astrophysics with an emphasis on gravitational waves and multi-messenger astronomy. Hot-off-the-press was a combined search for spatial correlations between neutrinos and ultra-high energy cosmic rays, using data from the ANTARES, ▷

IceCube, Auger and TA collaborations, with no sign yet of a connection.

As well as many new results from experiments in operation, the conference included sessions devoted to R&D in accelerators, detectors, software and computing, covering both collider and non-collider experiments. With many new facilities proposed in the medium and long terms, technological challenges, which include power consumption, data rates and radiation tolerance, are immense and demand significant efforts in harnessing promising avenues such as high-temperature superconductors, quantum sensors or specialised computers. Common to all areas is the need to train and retain highly skilled people to lead these efforts in future.

A firm part of the Lepton Photon plenary programme is discussions around diversity, inclusion and outreach

A firm part of the Lepton Photon plenary programme is discussions around diversity, inclusion and outreach. A lively panel discussion covered many aspects of the former two topics and ended with a key message to the whole community: be an ally and take an active stance in support of minorities. The conference ended with traditional reports from the IUPAP commission on particles and fields and from ICFA, followed by strategy updates from Snowmass and the African Strategy for Fundamental and Applied Physics. While Snowmass is an established process for regular updates of the US strategy for the field based on widespread community input both from the US and internationally (*CERN Courier* January/February 2022 p43), the African strategy is the first of its kind and is testament to the continent's ambition and growing importance in physics research (*CERN Courier* November/December 2021 p22). The next conference will take place in Melbourne in July 2023.

Marco Gersabeck *University of Manchester* and **Mark Williams** *University of Edinburgh*.

ULTRA-HIGH-FREQUENCY GRAVITATIONAL WAVES: A THEORY AND TECHNOLOGY ROADMAP

Exploring the early universe with GWs

Seven years after the direct detection of gravitational waves (GWs), particle physicists around the world are preparing for the next milestone in GW astronomy: the search for a cosmological stochastic GW background. Current and planned GW observatories roughly cover 12 orders of magnitude from the nHz to kHz regimes, in which astrophysical models predict sizable GW signals from the merging of compact objects such as black-hole and neutron-star mergers, as observed by the LIGO/Virgo collaborations. It is also expected that the universe contains a randomly distributed GW background, which is yet to be detected. This could be the result of various known and unknown astrophysical signals, which are too weak to be resolved individually, or could be due to hypothetical processes in the very early universe, such as phase transitions at high temperatures. The most promising region to search for the latter is arguably the ultra-high frequency (UHF) regime encompassing MHz and GHz GWs, which is beyond the reach of current detectors. The detection of such a stochastic GW background could therefore offer a powerful probe of the early universe and of physics beyond the Standard Model.

Challenges and opportunities

On 12–15 October a virtual workshop hosted by CERN explored theoretical models and detector concepts targeting the UHF GW regime. Following an initial meeting at ICTP Trieste in 2019 and the publication of a Living Review on UHF GWs, the goal of the workshop was to bring together theorists and experimentalists to discuss feasibility studies and prototypes of existing detector concepts as well as to review more recent proposals.


OSQAR

Laser precision *Light-shining-through-wall experiments, such as those made by OSQAR at CERN, can be adapted to GW detection.*

The wide range of detector concepts discussed demonstrates the rapid evolution of this field and shows the difficulty in choosing an optimal strategy. Tailoring "light shining through wall" experiments for GWs is one promising approach. In the presence of a static magnetic field, general relativity in conjunction with electrodynamics allows GWs to generate electromagnetic radiation at the same frequency, similar to the conversion of the hypothetical axion into photons. In this case, the bounds placed on axion-to-photon couplings, for example as determined by the CAST and OSQAR experiments at CERN or the ALPS experiments at DESY, can be recast as GW bounds.

Another approach, echoing that of the very first GW searches in the late 1960s, is to detect the mechanical deformation induced by GWs at the base of resonant-bar detectors, which can be implemented in the UHF regime using centimetre-sized bulk acoustic-wave devices common in radio-frequency engineering. Resonant microwave cavities are another approach to detect interactions between GWs and electromagnetism, and have been explored in the past, such as by the MAGO collaboration at CERN (2004–2007) or proposed as a modified version of the ADMX experiment at the University of Washington. Further proposals include the precise measurement of optically levitated nanoparticles, transitions in Bose–Einstein condensates, mesoscopic quantum systems, cosmological detectors and magnon systems. The sheer variety of systems, the majority of which are much smaller and less costly than long-baseline interferometric detectors, offers a new playground for creative ideas and underlines the cross-disciplinary nature of this field. Working groups set up during the workshop will investigate some of the most promising ideas in more detail within the next months.

Complementing the discussion about detector concepts, theorists presented BSM models that predict violent processes in the early universe, which could source strong GW signals. These arise, for example, in models of inflation at the transition phase between inflation and the radiation-dominated universe, or from spontaneous symmetry-breaking processes. Since these processes occur isotropically everywhere in the universe, the expected signal is a diffuse GW background. Moreover, some relics of these processes, such as topological defects and primordial black holes, may have survived until the late universe and may still be actively emitting GWs.

The current sensitivity of all proposed and existing detector concepts is several orders of magnitude away from the expected cosmological GW signals. Given that the first laser-interferometer GW detectors built in the 1970s were eight orders of magnitude below the sensitivity of the currently operating LIGO/Virgo/KAGRA observatories, however, there is every reason to think that the search for UHF GWs is the beginning, and not the end, of the story.

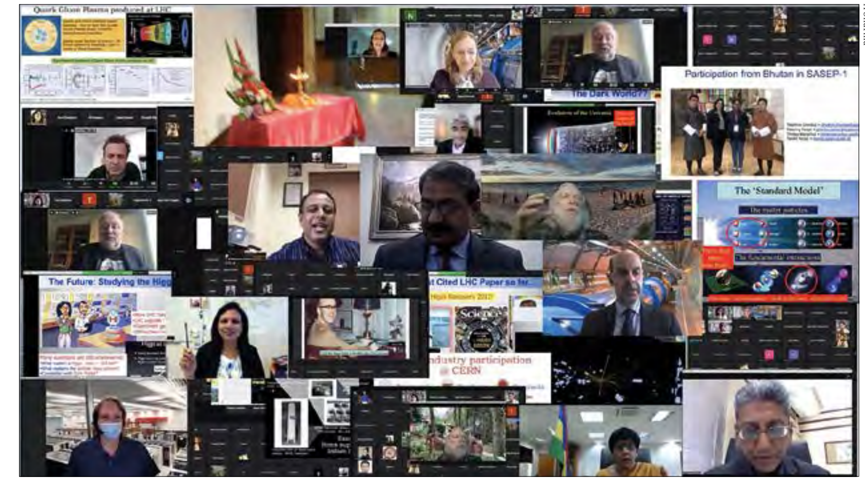
Valerie Domcke *CERN*.

THIRD SOUTH ASIAN HIGH ENERGY PHYSICS INSTRUMENTATION WORKSHOP

Connecting CERN and South Asia

The decision by CERN in 2010 to introduce a policy of geographical enlargement to attract new member states, including from outside Europe, marked a prominent step towards the globalisation of high-energy physics. It aimed to strengthen relations with countries that can bring scientific and technological expertise to CERN and, in return, allow countries with developing particle-physics communities to build capacity. From South Asia, researchers have made significant contributions to the pioneering activities of CERN over the past decades, including the construction of the LHC.

The first CERN South Asian High Energy Physics Instrumentation (SAHEPI) workshop, held in Kathmandu, Nepal, in 2017, came into place shortly after Pakistan (July 2015) and India (January 2017) became CERN Associate Member States, and follows similar regional approaches in Latin America and South-East Asia (*CERN Courier* October 2017 p28). Also, within the South Asia region, CERN has signed bilateral international cooperation agreements with Bangladesh (2014), Nepal (2017) and Sri Lanka (2017). The second workshop took place in Colombo, Sri Lanka, in 2019. The third edition of SAHEPI took place virtually on 21 October 2021, hosted by the University of Mauritius in collaboration with CERN. Its aim was to consolidate the dialogue from the first two workshops while strengthening the scientific cooperation between CERN and the South Asia region.


A Sharma

Science for society *The participants of the SAHEPI-3 workshop discussed some of the applications that have been developed for particle physics that also benefit society.*

"SAHEPI has been very successful in strengthening the scientific cooperation between CERN and the South Asia region and reinforcing intra-regional links," said Emmanuel Tsesmelis, head of relations with Associate Members and non-Member States at CERN. "SAHEPI provides the opportunity for countries to enhance their existing contacts and to establish new connections within the region, with the objective of initiating new intra-regional collaborations in particle physics and related technologies, including the promotion of exchange of researchers and students within the region and also with CERN."

SAHEPI has been very successful in strengthening the scientific cooperation between CERN and the South Asia region and reinforcing intra-regional links

Despite its virtual mode, SAHEPI-3 witnessed the largest participation yet, with 210 registrants. Representatives from Afghanistan, Bangladesh, Bhutan, India, Maldives, Mauritius, Nepal, Pakistan and Sri Lanka attended, with at least one senior scientist and one student from each country. Societal applications of technologies developed for particle physics were key highlights of SAHEPI-3, explained Archana Sharma, senior advisor for relations with international organisations at CERN: "In this decade, disruptive innovation underpinning the importance of science and technology is making a huge impact towards the United Nations Sustainable Development Goals. CERN plays its role at the forefront, whether it is advances in science and technology or dissemination of that knowledge with an emphasis on inclusive engagement."

Country representatives presented several highlights of the ongoing experimental programmes in collaboration with CERN and other international projects. India's contributions across the ALICE experiment, its plans to join the IPPOG outreach group, its activities in the Worldwide LHC Computing Grid, industrial involvement and contributions to CMS were presented. For Afghanistan, representatives described the participation of the country's first student in the CERN Summer Student Programme (2019) and the completion of masters' degrees by two faculty members based on measurements at ATLAS. The country hopes to team up with particle physicists outside Afghanistan to teach online courses at the physics faculty at Kabul University, provide postgraduate scholarships to students and involve more female faculty members at the International Centre for Theoretical Physics in Trieste.

Thriving initiatives

Pakistan shared its contributions to the LHC experiments as well as accelerator projects such as CLIC/CTF3 and Linac4, and its role in the CMS tracker alignment and resistive plate chambers. Nepal representatives described the development of supercomputers at Kathmandu University (KU) and acknowledged the donation agreement between KU and CERN, receiving servers and related hardware to set up a high-performance computing facility. In Sri Lanka, delegates highlighted a rising popularity of the CERN Summer Student Programme and mentioned its initiative of an island-wide online teacher-training programme to promote particle physics. The representative from Bangladesh reported on the country's long tradition in theoretical particle physics and plans for devel- ▷

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oping the experimental community in partnership with CERN. Maldives and Bhutan continue to be growing members from South Asia at CERN, with Bhutan preparing to host the second South Asia science education programme in a hybrid mode this year.

Chief guest Leela Devi Dookun-Luchoomun, vice-prime minister and minister of education, tertiary education, science and technology of Mauritius, informed the audience about the formation of a research and development unit in her ministry and gave her strong support to a partnership between CERN and Mauritius. Vice-chancellor of the University of Mauritius, Dhanjay Jhurry, expressed his deep appreciation of SAHEPI and indicated his support for future initiatives via a partnership between CERN and the University of Mauritius.

Sustainable development

SAHEPI also forms part of broader efforts for CERN to emphasise the role of fundamental research in development, notably to advance the United Nations Sustainable Development Goals agenda (see p51). In this regard, discussions took place for a follow-up on the first-of-its-kind professional development programme for high-school teachers of STEM subjects from South Asia, held in New Delhi in 2019, with Bhutan volunteering to host the next event in 2023.

The motivation and enthusiasm of participants was notable

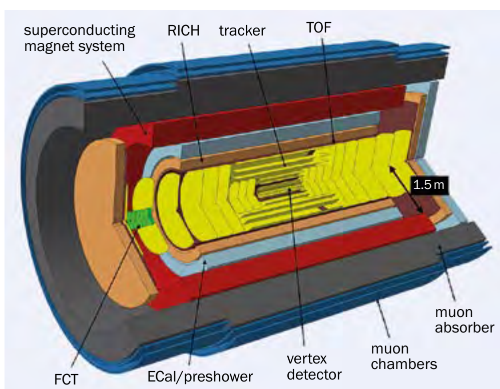
The motivation and enthusiasm of SAHEPI participants was notable, and the efforts in support of research and education across the region were clear. Proceedings of the workshop will be presented to representatives of the governments from the participating countries to raise awareness at the highest political level of the growth of the community in the region and its value for broader societal development. Discussions will follow in 2023 at SAHEPI-4, helping CERN continue to engage further with particle-physics research and education across South Asia for the benefit of the field as a whole.

Chetna Krishna *CERN.*

ALICE 3 WORKSHOP

Plotting a course towards ALICE 3

The ALICE detector has undergone significant overhauls during Long Shutdown 2 to prepare for the higher luminosities expected during Runs 3 and 4 of the LHC, starting this year (*CERN Courier* July/August 2021 p29). Further upgrades of the inner tracking system and the addition of a new forward calorimeter are being planned for the next long shutdown, ahead of Run 4 beginning in 2029. A series of physics questions will still remain inaccessible with Run 3 and 4, requiring major improvements in the detector performance and an ability to collect an even greater integrated luminosity for Run 5 and beyond, as noted in the recent update of the European strategy for particle physics. At the beginning of 2020, the ALICE collaboration formed dedicated working groups to work out the physics case, the physics performance, and a detector concept for a next-generation heavy-ion experiment called "ALICE 3".



J Klein

Next generation *ALICE 3 will make use of novel and innovative technologies to address otherwise inaccessible physics questions.*

Understanding equilibrium

To advance the project further, the ALICE collaboration organised a hybrid workshop on October 18 and 19, attracting more than 300 participants. Invited speakers on theory and experimental topics reviewed relevant physics questions for the 2030s, and members of the ALICE collaboration presented detector plans and physics performance studies for ALICE 3. Two key areas are the understanding of how thermal equilibrium is approached in the quark–gluon plasma (QGP) and the precise measurement of its temperature evolution.

Heavy charm and beauty quarks are ideal probes to understand how thermal equilibrium is approached in the QGP, since they are produced early in the collision and are traceable throughout the evolution of the system. Measurements of azimuthal distributions of charm and beauty hadrons, as well as charm–hadron pairs, are particularly sensitive to the interactions between heavy quarks and the QGP. In heavy-ion collisions, heavy charm quarks are abundantly produced and can hadronise into rare multi-charm baryons. The production yield of such particles is expected to be strongly enhanced compared to proton–proton collisions because the free propagation of charm quarks in the deconfined plasma allows the combination of quarks from different initial scatterings.

Concerning the temperature evolution of the QGP electromagnetic radiation is a powerful probe. Since real and virtual photons emitted throughout the evolution of the system are not affected by the strong interaction, differential measurements of dielectron pairs produced from virtual photons give access to the temperature evolution in the plasma phase. Given the high temperature and density of the QGP, chiral symmetry is expected to be restored. ALICE 3 will allow us to study the underlying mechanisms from the imprint on the dielectron spectrum.

To achieve the performance required for these measurements and the broader proposed ALICE 3 physics programme, a novel detector concept has been envisioned. At its core is a tracker based on silicon pixel sensors, covering a large pseudorapidity range and installed within a new superconducting magnet system. To achieve the ultimate pointing resolution, a retractable high-resolution vertex detector is to be placed in the beam pipe. The tracking is complemented by particle identification over the full acceptance, realised with different technologies, including silicon-based time-of-flight sensors. Further specialised detectors are being studied to extend the physics reach.

ALICE 3 will exploit completely new detector components to significantly extend the detector capabilities and to fully exploit the physics potential of the HL-LHC. The October workshop marked the start of the discussion of ALICE 3 with the community at large and of the review process with the LHC experiments committee.

Jochen Klein *CERN and* **Marco van Leeuwen** *Nikhef/Utrecht University.*

NEUTRONS IN SCIENCE, TECHNOLOGY AND APPLICATIONS

Celebrating 20 years of n_TOF

The Neutron Time Of Flight (n_TOF) facility at CERN, a project proposed by former Director-General Carlo Rubbia in the late 1990s, started operations in 2001. Its many achievements during the past two decades, and future plans in neutron-science worldwide, were the subject of a one-day in-person/virtual event "NSTAPP" organised by the n_TOF collaboration at CERN on 22 November.

J Ordan/R Franqueira Ximenes

Preparing the future *The installation of the third-generation n_TOF spallation target in the target pit.*

At n_TOF, a 20 GeV/c proton beam from the Proton Synchrotron (PS) strikes an actively cooled pure-lead neutron spallation target. The generated neutrons are water-moderated to produce a spectrum that covers 11 orders of magnitude in energy from GeV down to meV. At the beginning, n_TOF was equipped with a single experimental station, located 185 m downstream from the spallation target. In 2014, a major upgrade saw the construction and operation of a new experimental test area located 20 m above the production target to allow measurements of very low-mass samples. Last year, during Long Shutdown 2, a new third-generation, nitrogen-cooled spallation target was installed and successfully commissioned to prolong the experiment's lifetime by 10 years. A new irradiation and experimental station, called NEAR, was also added to perform activation measurements relevant for nuclear astrophysics and measurements in collaboration with the R2E (Radiation to Electronics) project that are difficult at other facilities.

During 20 years of activities, the n_TOF collaboration has carried out more than 100 experiments with considerable impact on nuclear astrophysics, advanced nuclear technologies and applied nuclear sciences, including novel medical applications.

Understanding the origin of the chemical elements through slow-neutron-capture has been a particular highlight. The high instantaneous neutron flux, which is only available at n_TOF thanks to the short proton pulse delivered by the PS, provided key reaction rates relevant to big-bang nucleosynthesis and stellar evolution (the former attempting to explain the discrepancy between the predicted and existing amount of lithium by investigating ^{7}Be creation and destruction, and the latter determining the chemical history of our galaxy).

Basic nuclear data are also essential for the development of nuclear-energy technology. It was this consideration that motivated Rubbia to propose a spallation neutron source at CERN in the first place, prompting a series of accurate neutron cross-section measurements on minor actinides and fission products. Neutron reaction processes on thorium, neptunium, americium and curium, in addition to minor isotopes of uranium and plutonium, have all been measured at n_TOF. These measurements provide the nuclear data necessary for the development of advanced nuclear systems, such as the increase of safety margins in existing nuclear plants as well as to enable generation-IV reactors and accelerator-driven systems, or even enabling new fuel cycles that reduce the amount of long-lived nuclear species.

Contributions from external laboratories, such as J-PARC (Japan), the Chinese Spallation Neutron Source (China), SARAF (Israel), GELINA (Belgium), GANIL (France) and Los Alamos (US), highlighted synergies in the measurement of neutron-induced capture, fission and light-charged-particle reactions for nuclear astrophysics, advanced nuclear technologies and medical applications. Moreover, technologies developed at CERN have also influenced the creation of two startups, Transmutex and Newcleo. The former focuses on accelerator-driven systems for energy production, for which the first physics validation was executed at the FEAT and TARC experiments at the CERN PS in 1999, while the latter plans to develop critical reactors based on liquid lead.

With the recent technical upgrades and the exciting physics programme in different fields, such as experiments focusing on the breaking of isospin symmetry in neutron–neutron scattering and pursuing its core experimental activities, the n_TOF facility has a bright future ahead.

Marco Calviani *CERN and* **Alberto Mengoni** *ENEA and INFN Bologna.*

BRUNO TOUSCHEK MEMORIAL SYMPOSIUM

Commemorating collider pioneer Bruno Touschek

Bruno Touschek was born in Vienna on 3 February 1921. His mother came from a well-to-do Jewish family and his father was a major in the Austrian Army. Bruno witnessed the tragic consequences of racial discrimination that prevented him from completing both his high school and university studies in Austria. But he also experienced the hopes of the post-war era and played a role in the post-war reconstruction. With the help of his friends, he continued his studies in Hamburg, where he worked on

F Touschek

Unique expertise *Bruno Touschek, pictured here in the 1950s, was one of the first physicists in Europe who was skilled in elementary particle theory and in the functioning of accelerators.*

the 15 MeV German betatron proposed by Rolf Widerøe and learnt about electron accelerators. After the war he obtained his PhD at the University of Glasgow in 1949, where he was involved in theoretical studies and in the building of a 300 MeV electron synchrotron. Touschek emerged from the early-post-war years as one of the first physicists in Europe endowed with a unique expertise in the theory and functioning of accelerators. His genius was nurtured by close exchanges with Arnold Sommerfeld, Werner Heisenberg, Max Born and Wolfgang Pauli, among others, and flourished in Italy, where he arrived in 1953, called by Edoardo Amaldi, his first biographer and first Secretary-General of CERN.

In 1960 Touschek proposed and built ▷

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the first electron–positron storage ring, Anello di Accumulazione (AdA), which started operating in Frascati in February 1961. The following year, in order to improve the injection efficiency, a Franco-Italian collaboration was born that brought AdA to Orsay. It was here that the "Touschek effect", describing the loss and scattering of charged particles in storage rings, was discovered and the proof of collisions in an electron–positron ring was obtained.

AdA paved the way to the electron–positron colliders ADONE in Italy, ACO in France, VEPP-2 in the USSR and SPEAR in the US. Bruno spent the last year of his life at CERN, from where – already quite ill – he was brought to Innsbruck, Austria, where he passed away on 25 May 1978 aged just 57.

Bruno Touschek's life and scientific contributions were celebrated at a memorial symposium from 2 to 4 December, held in the three institutions where Touschek has left a lasting legacy: Sapienza University of Rome, INFN Frascati National Laboratories and Accademia Nazionale dei Lincei. Contributions also came from the IJCLab, and sponsorship from the Austrian Embassy in Italy.

F Touschek

Innovative expressionism *Bruno Touschek's playful portrayal of T D Lee and parity violation.*

In addition to Touschek's impact on the physics of particle colliders, the three-day symposium addressed the present landscape. Carlo Rubbia and Ugo Amaldi gave a comprehensive overview of the past and future of particle colliders, followed by talks about physics at ADONE and LEP, and proposed machines, such as a muon collider, the Future Circular Collider at CERN and the Circular Electron Positron Collider in China, as well as new developments in accelerator techniques. ADONE's construction challenges were remembered. Developments in particle physics since the 1960s – including the quark model, dual models and string theory, spontaneous symmetry breaking and statistical physics – were described in testimonies from the universities of Rome, Frascati, Nordita and Collège de France.

Touschek's direct influence was captured in talks by his former students, from Rome and the Frascati theory group, which he founded in the mid-1960s. His famous lectures on statistical mechanics, given from 1959 to 1960, were remembered by many speakers. Giorgio Parisi, who graduated with Nicola Cabibbo, recollected the years in Frascati after the observation of a large hadron multiplicity in e^+e^- annihilations made by ADONE, and the ideas leading to QCD.

The final day of the symposium, which took place at the Accademia dei Lincei where Touschek had been a foreign member since 1972, turned to future strategies in high-energy physics, including neutrinos and other messengers from the universe. Also prominent were the many benefits brought to society by particle accelerators, reaffirming the intrinsic broader value of fundamental research.

Touschek's life and scientific accomplishments have been graphically illustrated in the three locations of the symposium, including displays of his famous drawings on academic life in Rome and Frascati. LNF's visitor centre was dedicated to Touschek, in the presence of his son Francis Touschek.

Luisa Bonolis *MPIWG Berlin,* **Luciano Maiani** *CERN and* **Giulia Pancheri** *INFN Frascati.*

Further reading

E Amaldi 1981 CERN-81-19.

KIT

Neutrino kinks *Precise measurements of β-decay spectra using the KATRIN experiment are potentially sensitive to keV-scale heavy neutral leptons.*

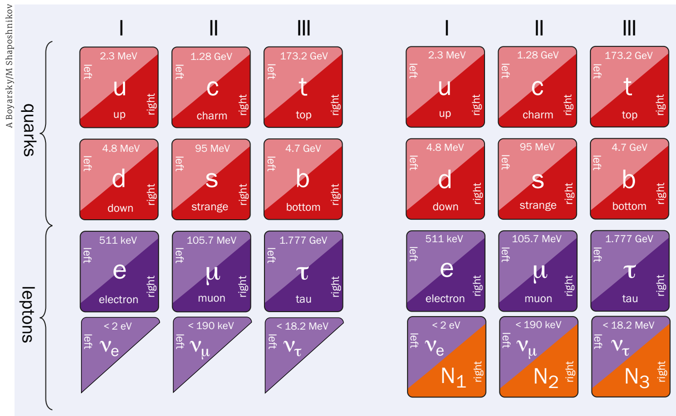
TURNING THE SCREW ON RIGHT-HANDED NEUTRINOS

Extending the elementary-particle inventory with heavy neutral leptons could solve the key observational shortcomings of the Standard Model, explain Alexey Boyarsky and Mikhail Shaposhnikov, with some models placing the new particles in reach of current and proposed experiments.

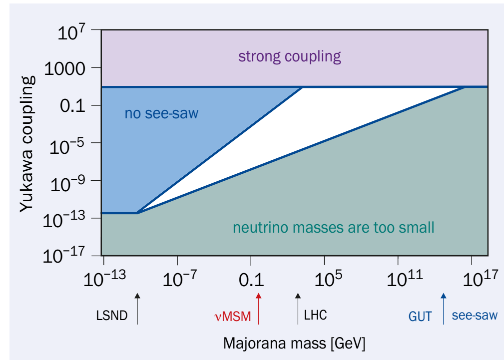
In the 1960s, the creators of the Standard Model made a smart choice: while all charged fermions came in pairs, with left-handed and right-handed components, neutrinos were only left-handed. This "handicap" of neutrinos allowed physicists to accommodate in the most economical way important features of the experimental data at that time. First, such left-handed-only neutrinos are naturally massless, and second, individual leptonic flavours (electron, muon and tau) are automatically conserved.

It is now well established that neutrinos have masses and that the neutrino flavours mix with each other, in similarity with quarks. If this were known 55 years ago, Weinberg's seminal 1967 work "A Model of Leptons" would be different: in addition to the left-handed neutrinos, it would very likely also contain their right-handed counterparts. The structure of the Standard Model (SM) dictates that these new states, if they exist, are the only singlets with respect to weak-isospin and hyper-charge gauge symmetry and thus do not participate directly in electroweak interactions (see "On the other hand" figure). This makes right-handed neutrinos (also referred to as sterile neutrinos, singlet fermions or heavy neutral leptons) very special: unlike charged quarks and leptons, which get their masses from the Yukawa interaction with the Brout–Englert–Higgs field, the masses of right-handed neutrinos depend on an additional parameter – the Majorana mass – which is not related to the vacuum expectation value and which results in the violation of lepton-number conservation. As

THE AUTHORS
Alexey Boyarsky *Leiden University and* **Mikhail Shaposhnikov** *Swiss Federal Institute of Technology Lausanne.*



On the other hand *The fermion content of the Standard Model (left) and its extension in the neutrino sector (right).*



Options abound *The masses of heavy neutral leptons (HNLs) consistent with neutrino experiments span many orders of magnitude. The vertical axis here shows the Yukawa coupling of HNLs to lepton doublets.*

such, right-handed neutrinos are also sometimes referred to as Majorana leptons or Majorana fermions.

Leaving aside the possible signals of eV-scale neutrino states reported in recent years, all established experimental signatures of neutrino oscillations can be explained by the SM with the addition of two heavy-neutral leptons (HNLs). If there were only one HNL, then two out of three SM neutrinos would be massless; with two HNLs, only one of the SM neutrinos is massless – this is not excluded experimentally. Any larger number of HNLs is also possible.

The simplest way to extend the SM in the neutrino sector is to add several HNLs and no other new particles. Already this class of theories is very rich (different numbers of HNLs and different values of their masses and couplings imply very different phenomenology), and contains several different scenarios explaining not only the observed masses and flavour oscillations of the SM neutrinos but also other phenomena that are not accommodated by the SM. The scenario in which the Majorana masses of right-handed neutrinos are much higher than the electroweak scale is known as the "type I see-saw model", first put forward in the late 1970s. The theory with three right-handed neutrinos (the same as the number of generations in the SM) with their masses below the electroweak scale is called the neutrino minimal standard model (νMSM), and was proposed in the mid-2000s.

> **How much time it will take to discover HNLs, if they indeed exist, depends crucially on their masses**

Would these new particles be useful for anything else besides neutrino physics? The answer is yes. The first, lightest HNL N_1 may serve as a dark-matter particle, whereas the other two HNLs $N_{2,3}$ not only "give" masses to active neutrinos but can also lead to the matter–antimatter asymmetry of the universe. In other words, the SM extended by just three HNLs could solve the key outstanding observational problems of the SM, provided the masses and couplings of the HNLs are chosen in a specific domain.

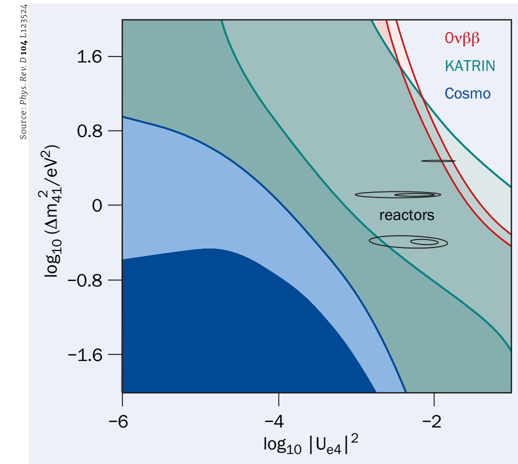
The leptonic extension of the SM by right-handed neutrinos is quite similar to the gradual adaptation of electroweak theory to experimental data during the past 50 years. While the bosonic sector of the electroweak model remains intact from 1967, with the discoveries of the W and Z bosons in 1983 and the Higgs boson in 2012, the fermionic sector evolved from one to two to three generations, revealing the remarkable symmetry between quarks and leptons. It took about 20 years to find all the quarks and leptons of the third generation. How much time it will take to discover HNLs, if they indeed exist, depends crucially on their masses.

The value of the Majorana mass, and therefore the physical mass of an HNL, is arbitrary from a theoretical point of view and cannot be found from neutrino-oscillation experiments. The famous see-saw formula that relates the observed masses of the active neutrinos to the Majorana masses of HNLs has a degeneracy: change the Yukawa couplings of HNLs to neutrinos by a factor x and the HNL masses by a factor x^2, and the active neutrino masses and the physics of their oscillations remain intact. The scale of HNL masses thus can be any number from a fraction of an eV to 10^{15} GeV (see "Options abound" figure). Moreover, there could be several HNLs with very different masses. Indeed, even in the SM the masses of charged fermions, though they share a similar origin, differ by almost six orders of magnitude.

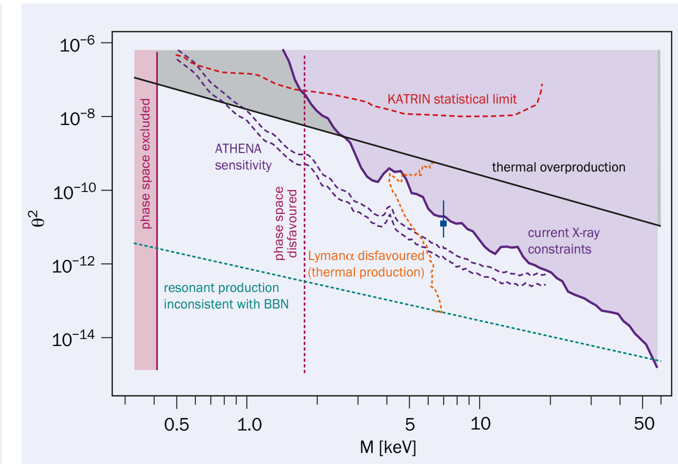
Motivated by the value of the active neutrino masses, the HNL could be light, with masses of the order of 1 eV. Alternatively, similar to the known quarks and charged leptons, they could be somewhere around the GeV or Fermi scale. Or they could be close to the grand unification scale, 10^{15} GeV, where the strong and electromagnetic interactions are thought to be unified. These possibilities have different theoretical and experimental consequences.

The case of the light sterile neutrino

The see-saw formula tells us that if the mass of HNLs is around 1 eV, their Yukawa couplings should be of the order of 10^{-12}. Such light sterile neutrinos can be potentially observed in neutrino experiments, as they can be involved



Cosmological bounds *Marginalised 68% (light shade) and 95% (dark shade) constraints on the mass splitting and mixing matrix element U_{e4} from cosmology (blue), tritium β-decay measurements by KATRIN (green) and neutrinoless double-β-decay experiments (0νββ, red), compared with the preferred regions coming from reactor anomalies (black), excluding the most recent predictions (Phys. Rev. D* **104** *L071301) hinting at the demise of the reactor antineutrino anomaly.*



Dark-matter constraints *Sterile-neutrino dark matter (DM) faces several constraints. The solid lines represent largely model-independent constraints from applying the exclusion principle to DM in dwarf galaxies (purple) and from the non-observation of X-rays from $N_1 \to \nu\gamma$ decays (violet), with the dashed violet lines showing estimates from the future ATHENA mission and the blue square marking the interpretation of the 3.5 keV excess as decaying sterile-neutrino DM. Above the line marked "thermal overproduction", the abundance of sterile neutrinos would exceed the observed DM density. All other constraints, shown by different coloured dotted lines, depend on the sterile-neutrino production mechanism.*

in the oscillations together with the three active neutrino species. Several experiments – including LSND, GALLEX, SAGE, MiniBooNE and BEST – have reported anomalies in neutrino-oscillation data (the so-called short-baseline, gallium and reactor anomalies) that could be interpreted as a signal for the existence of light sterile neutrinos. However, it looks difficult, if not impossible, to reconcile the existence of these states with recent negative results of other experiments such as MINOS+, MicroBooNE and IceCUBE, accounting for additional constraints coming from β-decay, neutrinoless double-β decay and cosmology (*CERN Courier* January/February 2022 p9).

The parameters of light sterile neutrinos required to explain the experimental anomalies are in strong tension with the cosmological bounds (see "Cosmological bounds" figure). For example, their mixing angle with the ordinary neutrinos should be sufficiently large that these states would have been produced abundantly in the early universe, affecting its expansion rate during Big Bang nucleosynthesis and thus changing the abundances of the light elements. In addition, light sterile neutrinos would affect the formation of structure. Having been created in the hot early universe with relativistic velocities, they would have escaped from forming structures until they cooled down in much later epochs. This so-called "hot dark matter" scenario would mean that the smallest structures, which form first, and the larger ones, which require much more time to develop, would experience different amounts of dark matter. Moreover, the presence of such particles would affect baryon acoustic oscillations and therefore impact the value of the Hubble constant deduced from them.

Besides tensions between the experiments and cosmological bounds, light sterile neutrinos do not provide any solution to the outstanding problems of the SM. They cannot be dark-matter particles because they are too light, nor can they produce the baryon asymmetry of the universe as their Yukawa couplings are too small to give any substantial contribution to lepton-number violation at the temperatures (> 160 GeV) at which the anomalous electroweak processes with baryon non-conservation have a chance to convert a lepton asymmetry into a baryon asymmetry.

Three Fermi-scale heavy neutral leptons

Another possible scale for HNL masses is around a GeV, plus or minus a few orders of magnitude. Right-handed neutrinos with such masses do not interfere with active-neutrino oscillations because the corresponding length over which these oscillations may occur is far too small. As only two active-neutrino mass differences are fixed by neutrino-oscillation experiments, it is sufficient to have two HNLs $N_{2,3}$ with appropriate Yukawa couplings to active neutrinos: to get the correct neutrino masses, they should not be smaller than ~10^{-8} (compared to the electron Yukawa coupling of ~10^{-6}). These two HNLs may produce the baryon asymmetry of the universe, as we explain later, whereas the lightest singlet fermion, N_1, may interact with neutrinos much more weakly and thus can be a dark-matter particle (although unstable, its lifetime can greatly exceed the age of the universe).

Three main considerations determine the possible range of masses and couplings of the dark-matter sterile neu-

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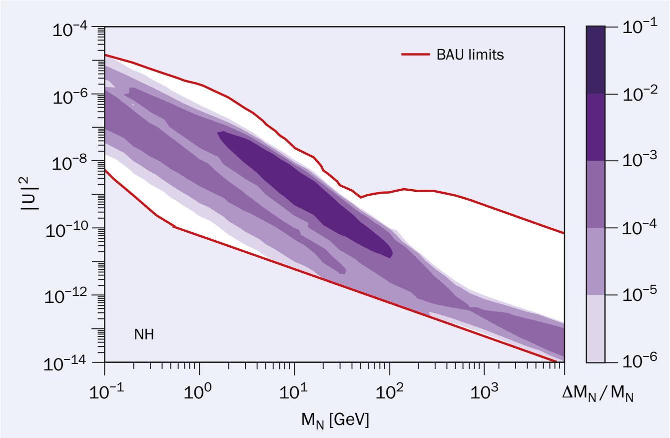


Baryon-asymmetry constraints *The observed value of baryon asymmetry of the universe can be reproduced if the mass and mixing angle between HNLs and active neutrinos is between the red curves. The shades of purple indicate the maximal mass-degeneracy between two HNLs consistent with baryogenesis for the normal neutrino-mass ordering.*

trino (see "Dark-matter constraints" figure). The first is cosmological production. If N_1 interact too strongly, they would be overproduced in $\ell^+\ell^- \to N_1\nu$ reactions and make the abundance of dark matter larger than what is inferred by observations, providing an upper limit on their interaction strength. Conversely, the requirement to produce enough dark matter results in a lower bound on the mixing angle that depends on the conditions in the early universe during the epoch of N_1 production. Moreover, the lower bound completely disappears if N_1 can also be produced at very high temperatures by interactions related to gravity or at the end of cosmological inflation.

Neutrino experiments and robust conclusions from observational cosmology call for extensions of the SM

The second consideration is X-ray data. Radiative $N_1 \to \gamma\nu$ decays produce a narrow line that can be detected by X-ray telescopes such as XMM-Newton or Chandra, resulting in an upper limit on the mixing angle between sterile and active neutrinos. While this upper limit depends on the uncertainties in the distribution of dark matter in the Milky Way and other nearby galaxies and clusters, as well as on the modelling of the diffuse X-ray background, it is possible to marginalise these to obtain very robust constraints.

The third consideration for the sterile neutrino's properties is structure formation. If N_1 is too light, a very large number-density of such particles is required to make an observed halo of a small galaxy. As HNLs are fermions, however, their number density cannot exceed that of a completely degenerate Fermi gas, placing a very robust lower bound on the N_1 mass. This bound can be further improved by taking into account that light dark-matter particles remain relativistic until late epochs and therefore suppress or erase density perturbations on small scales. As a result, they would affect the inner structure of the halos of the Milky Way and other galaxies, as well as the matter distribution in the intergalactic medium, in ways that can be observed via gravitational-lensed galaxies, gaps in the stellar streams in galaxies and the spectra of distant quasars.

The upper limits on the interaction strength of sterile neutrinos fixes the overall scale of active neutrino masses in the νMSM. The dark-matter sterile neutrino effectively decouples from the see-saw formula, making the mass of one of the active neutrinos much smaller than the observed solar and atmospheric neutrino-mass differences and fixing the masses of the two other active neutrinos to approximately 0.009 eV and 0.05 eV (for the normal ordering) and to the near-degenerate value 0.05 eV for the inverted ordering.

HNLs at the GeV scale and beyond

Our universe is baryon-asymmetric – it does not contain antimatter in amounts comparable with the matter. Though the SM satisfies all three "Sakharov conditions" necessary for baryon-asymmetry generation (baryon number non-conservation, C and CP-violation, and departure from thermal equilibrium), it cannot explain the observed baryon asymmetry. The Kobayashi–Maskawa CP-violation is too small to produce any substantial effects, and departures from thermal equilibrium are tiny at the temperatures at which the anomalous fermion-number non-conserving processes are active. This is not the case with two GeV-scale HNLs: these particles are not in thermal equilibrium for temperatures above a few tens of GeV, and CP violation in their interactions with leptons can be large. As a result, a lepton asymmetry is produced, which is converted into baryon asymmetry by the baryon-number violating reactions of the SM.

The requirement to get baryon asymmetry in the νMSM puts stringent constraints on the masses and coupling of HNLs (see "Baryon-asymmetry constraints" figure). The mixing angle of these particles cannot be too large, otherwise they equilibrate and erase the baryon asymmetry, and it cannot be below a certain value because it would make the active neutrino masses too small. We know that their mass should be larger than that of the pion, otherwise their decays in the early universe would break the success of Big Bang nucleosynthesis. In addition, the masses of two HNLs should be close to each other so as to enhance CP-violating effects. Interestingly, the HNLs with these properties are within the experimental reach of existing and future accelerators, as we shall see.

The final possible choice of HNL masses is associated with the grand unification scale, $\sim 10^{15}$ GeV. To get the correct neutrino masses, the Yukawa couplings of a pair of these superheavy particles should be of the order of one, in which case the baryon asymmetry of the universe can be produced via thermal leptogenesis and anomalous baryon- and lepton-number non-conservation at high temperatures. The third HNL, if interacting extremely weakly, may play the role of a dark-matter particle, as described previously. Another possibility is that there are

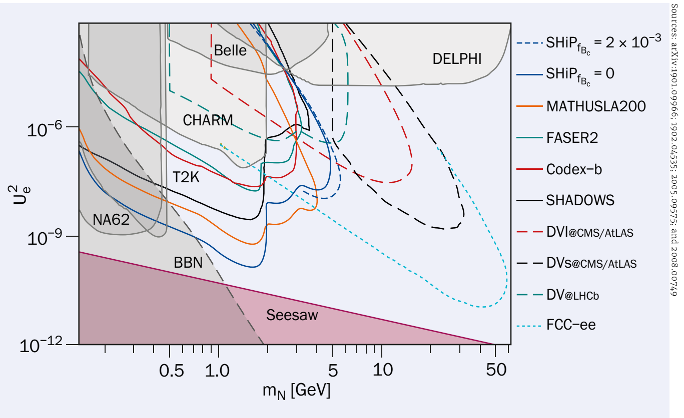
three superheavy HNLs and one light one, to play the role of dark matter. This model, as well as that with HNL masses of the order of the electroweak scale, may therefore solve the most pressing problems of the SM. The only trouble is that we will never be able to test it experimentally, since the masses of $N_{2,3}$ are beyond the reach of any current or future experiment.

Experimental opportunities

It is very difficult to detect HNLs experimentally. Indeed, if the masses of these particles are within the reach of current and planned accelerators, they must interact orders of magnitude more weakly than the ordinary weak interactions. As for the dark-matter sterile neutrino, the most promising route is indirect detection with X-ray space telescopes. The new X-ray spectrometer XRISM, which is planned to be launched this year, has great potential to unambiguously detect a signal from dark-matter decay. Like many astrophysical observatories, however, it will not be able to determine the particle origin of this signal. Thus, complementary laboratory searches are needed. One experimental proposal that claims a sufficient sensitivity to enter into the cosmologically relevant region is HUNTER, based on radioactive atom trapping and high-resolution decay-product spectrometry. Sterile neutrinos with masses of around a keV can also show up as a kink in the β-decay spectrum of radioactive nuclei, as discussed by the ambitious PTOLEMY proposal. The current generation of experiments that study β-decay spectra – KATRIN and Troitsk nu-mass – also perform searches for keV HNLs, but they are sensitive to significantly larger mixing angles than required for a dark-matter particle. Extending the KATRIN experiment with a multi-pixel silicon drift detector, TRISTAN, will significantly improve the sensitivity here.

The most promising perspectives to find $N_{2,3}$ responsible for neutrino masses and baryogenesis are experiments at the intensity frontier. For HNL masses below 5 GeV (the beauty threshold) the best strategy is to direct proton beams at a target to create K, D or B mesons that decay producing HNLs, and then to search for HNL decays through "nothing → leptons and hadrons" processes in a near detector. This strategy was used in the previous PS191 experiment at CERN's Proton Synchrotron (PS), NOMAD, BEBC and CHARM at the Super Proton Synchrotron (SPS) and NuTeV at Fermilab. There are several proposals for future experiments along these lines. The proposed SHiP experiment at the SPS Beam Dump Facility has the best potential as it can potentially cover almost all parameter space down to the lowest bound on coupling constants coming from neutrino masses. The SHiP collaboration has already performed detailed studies and beam tests, and the experiment is under consideration by the SPS and PS experiments committee. A smaller-scale proposal, SHADOWS, covers part of the interesting parameter space.

The search for HNLs can be carried out at the near detectors of DUNE at Fermilab and T2K/T2HK in Japan, which are due to come online later this decade. The LHC experiments ATLAS, CMS, LHCb, FASER and SND, as well as the proposed CODEX-b facility, can also be used, albeit



Electron coupling *Projected sensitivities to HNLs coupled to electrons. The filled areas correspond to regions excluded by past experiments, Big Bang nucleosynthesis and mixing angles below the see-saw bound. The contours show the sensitivity reach of future intensity-frontier experiments. The two SHiP exclusion curves correspond to two extreme assumptions on the poorly known fraction of B_c mesons at the relevant (Beam Dump Facility) energy. Dedicated intensity-frontier experiments and FCC-ee probe different parts of the parameter space and are complementary to each other.*

with fewer chances to enter deeply into the cosmologically interesting part of the HNL parameter space. The decays of HNLs can also be searched for at future huge detectors such as MATHUSLA. And, going to larger HNL masses, breakthroughs can be made at the proposed Future Circular Collider FCC-ee, studying the processes $Z \to \nu N$ with a displaced vertex (DV) corresponding to the subsequent decay of N to available channels (see "Electron coupling" figure).

Conclusions

Neutrino experiments and robust conclusions from observational cosmology call for extensions of the SM. But the situation is very different from that in the period preceding the discovery of the Higgs boson, where the consistency of the SM together with other experimental results allowed us to firmly conclude that either the Higgs boson had to be discovered at the LHC, or new physics beyond the SM must show up. Although we know for sure that the SM is incomplete, we do not have a firm prediction about where to search for new particles nor what their masses, spins, interaction types and strengths are.

Experimental guidance and historical experience suggest that the SM should be extended in the fermion sector, and the completion of the SM with three Majorana fermions solves the main observational problems of the SM at once. If this extension of the SM is correct, the only new particles to be discovered in the future are three Majorana fermions. They have remained undetected so far because of their extremely weak interactions with the rest of the world. ●

Further reading

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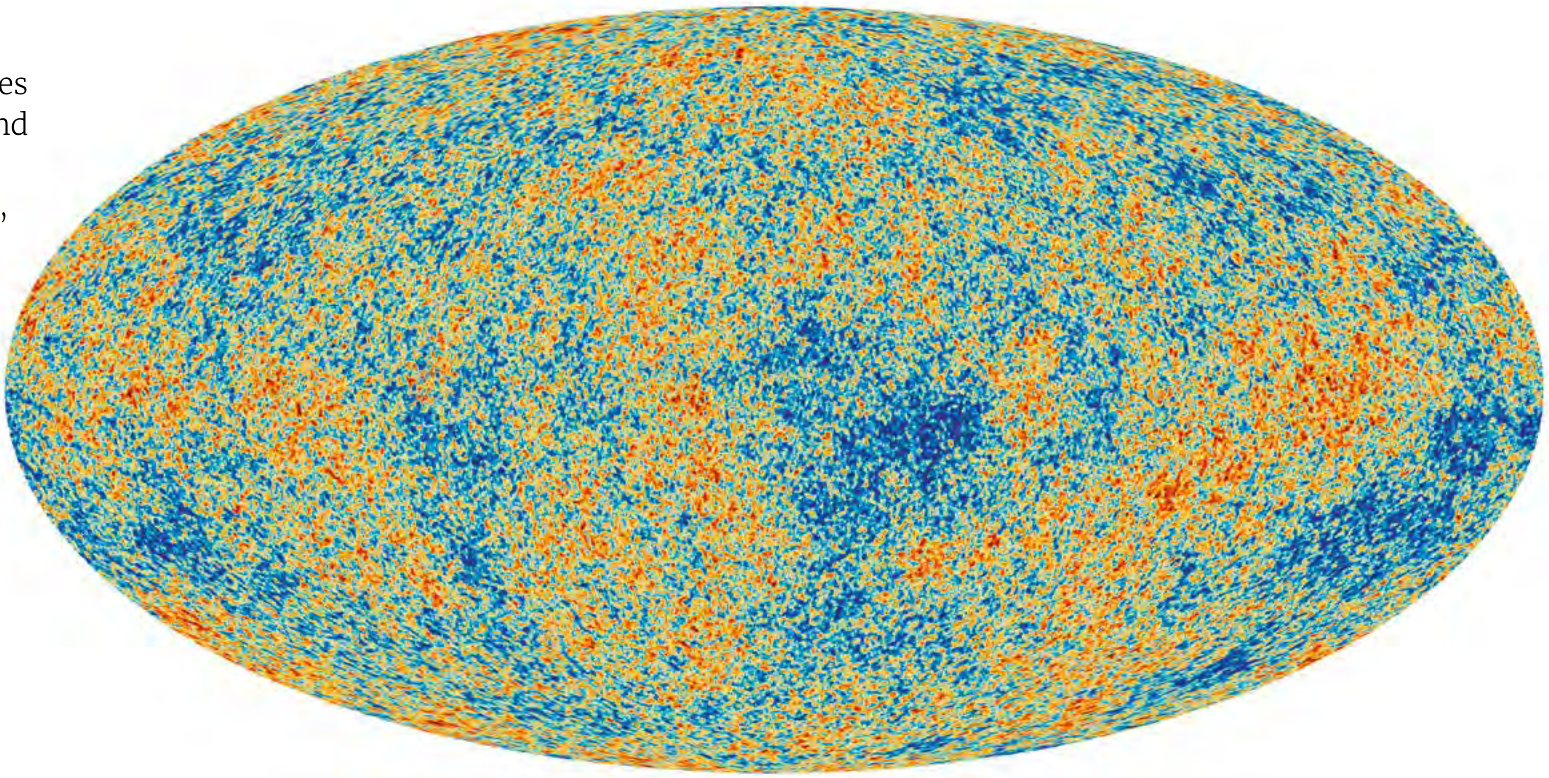
EXPLORING THE CMB LIKE NEVER BEFORE

A newly endorsed ground-based observatory to study the anisotropies in the cosmic microwave background (CMB) will deliver transformative discoveries in fundamental physics, cosmology, astrophysics and astronomy, writes Julian Borrill.



Relic radiation *The temperature anisotropies of the cosmic microwave background imprinted on the sky, as observed by Planck, show fluctuations that correspond to regions of slightly different densities, representing the seeds of all cosmological structure formation. (Credit: ESA and the Planck Collaboration)*

To address the major questions in cosmology, the cosmic microwave background (CMB) remains the single most important phenomenon that can be observed. Not this author's words, but those of the recent US National Academies of Sciences, Engineering, and Medicine report *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* (Astro2020), which recommended that the US pursue a next-generation ground-based CMB experiment, CMB-S4, to enter operation in around 2030.

The CMB comprises the photons created in the Big Bang. These photons have therefore experienced the entire history of the universe. Everything that has happened has left an imprint on them in the form of anisotropies in their temperature and polarisation with characteristic amplitudes and angular scales. The early universe was hot enough to be completely ionised, which meant that the CMB photons constantly scattered off free electrons. During this period the primary CMB anisotropies were imprinted, tracing the overall geometry of the universe, the fraction of the energy density in baryons, the number of light-relic particles and the nature of inflation. After about 375,000 years of expansion the universe cooled enough for neutral hydrogen atoms to be stable. With the free electrons rapidly swept up by protons, the CMB photons simply free-streamed in whatever direction they were last moving in. When we observe the CMB today we therefore see a snapshot of this so-called last-scattering surface.

The continued evolution of the universe had two main effects on the CMB photons. First, its ongoing expansion stretched their wavelengths to peak at microwave frequencies today. Second, the growth of structure eventually formed galaxy clusters that changed the direction, energy and polarisation of the CMB photons that pass through them, both from gravitational lensing by their mass and from inverse Compton scattering by the hot gas that makes up the inter-cluster medium. These secondary anisotropies therefore constrain all of the parameters that this history depends on, from the moment the first stars formed to the number of light-relic particles and the masses of neutrinos.

As noted by the Astro2020 report, the history of CMB research is that of continuously improving ground and balloon experiments, punctuated by comprehensive measurements from the major satellite missions COBE, WMAP and Planck. The increasing temperature and polarisation sensitivity and angular resolution of these satellites is evidenced in the depth and resolution of the maps they produced (see "Relic radiation" image). However, such maps are just our view of the CMB – one particular realisation of a random process. To derive the underlying cosmology that gave rise to them, we need to measure the amplitude of the anisotropies on various angular scales (see "Power spectra" figure, p36). Following the serendipitous discovery of the CMB in 1965, the first measurements of the temperature anisotropy were made by COBE in 1992. The first peak in the temperature power spectrum was measured by the BOOMERanG and MAXIMA balloons in 2000, followed by the E-mode polarisation of the CMB by the DASI experiment in 2002, and the B-mode polarisation by the South Pole Telescope and POLARBEAR experiments in 2015.

For the first time, the entire community is coming together to build an experiment defined by achieving critical science thresholds

CMB-S4, a joint effort supported by the US Department of Energy (DOE) and the National Science Foundation (NSF), will help write the next chapter in this fascinating adventure. Planned to comprise 21 telescopes at the South Pole and in the Chilean Atacama Desert instrumented with more than 500,000 cryogenically-cooled superconducting detectors, it will exceed the capabilities of earlier generations of experiments by more than an order of magnitude and deliver transformative discoveries in fundamental physics, cosmology, astrophysics and astronomy.

The CMB-S4 challenge

Three major challenges must be addressed to study the CMB at such levels of precision. Firstly, the signals are extraordinarily faint, requiring massive datasets to reduce the statistical uncertainties. Secondly, we have to contend with systematic effects both from imperfect instruments and from the environment, which must be controlled to exquisite precision if they are not to swamp the signals. Finally, the signals are obscured by other sources of microwave emission, especially galactic synchrotron and dust emission. Unlike the CMB, these sources do not have a black-body spectrum, so it is possible to distinguish between CMB and non-CMB sources if observations are made at enough microwave frequencies to break the degeneracy.

CMB-S4 will be able to adopt and adapt the best of all previous experiments' technologies and methodologies

This third challenge actually proves to be an astrophysical blessing as well as a cosmological curse: CMB observations are also excellent legacy surveys of the millimetre-wave sky, which can be used for a host of other science goals. These range from cataloguing galaxy clusters, to studying the Milky Way, to detecting spatial and temporal transients such as gamma-ray bursts via their afterglows.

Coming together

In 2013 the US CMB community came together in the Snowmass planning process, which informs the deliberations of the decadal Particle Physics Project Prioritization Panel (P5). We realised that achieving the sensitivity needed to make the next leap in CMB science would require an experiment of such magnitude (and therefore cost) that it could only be accomplished as a community-wide endeavour, and that we would therefore need to transition from multiple competing experiments to a single collaborative one. By analogy with the US dark-energy programme, this was designated a "Stage 4" experiment, and hence became known as CMB-S4.

In 2014 a P5 report made the critical recommendation that the DOE should support CMB science as a core piece of its programme. The following year a National Academies report identified CMB science as one of three strategic priorities for the NSF Office of Polar Programs. In 2017 the DOE, NSF and NASA established a task force to develop a conceptual design for CMB-S4, and in 2019 the DOE took "Critical Decision 0", identifying the mission need and initiating the CMB-S4 construction project. In 2020 Berkeley Lab was appointed the lead laboratory for the project, with Argonne, Fermilab and SLAC all playing key roles. Finally, late last year, the long-awaited Astro2020 report unconditionally recommended CMB-S4 as a joint NSF and DOE project with an estimated cost of $650 million. With these recommendations in place, the CMB-S4 construction project could begin.

From the outset, CMB-S4 was intended to be the first sub-orbital CMB experiment designed to reach specific critical scientific thresholds, rather than simply to maximise the science return under a particular cost cap. Furthermore, as a community-wide collaboration, CMB-S4 will be able to adopt and adapt the best of all previous experiments' technologies and methodologies – including operating at the site best suited to each science goal. One third of the major questions and discovery areas identified across the six Astro2020 science panels depend on CMB observations.

The critical degrees of freedom in the design of any observation are the sky area, frequency coverage, frequency-dependent depth and angular resolution, and observing cadence. Having reviewed the requirements across the gamut of CMB science, four driving science goals have been identified for CMB-S4.

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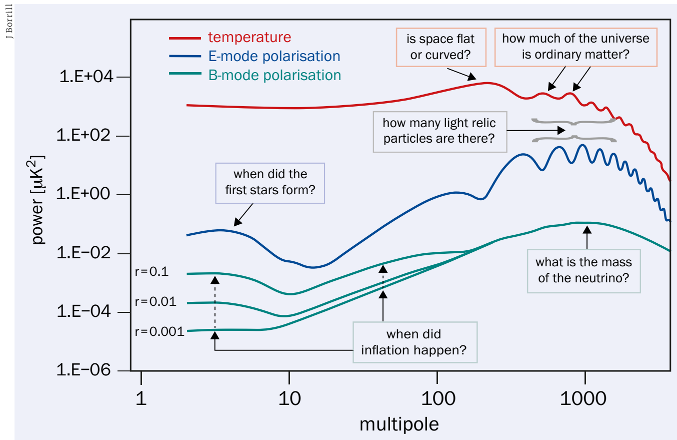
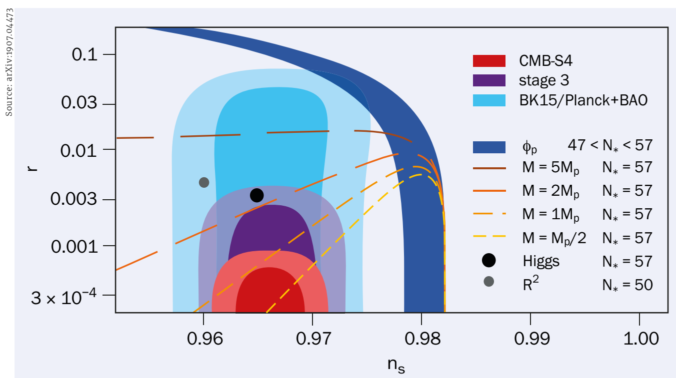
J Borrill



Power spectra *The temperature and polarisation power spectra of the CMB, illustrating features that can answer key questions in cosmology and fundamental physics. The CMB polarisation is decomposed into a curl-free E-mode and divergence-free B-mode by analogy with electromagnetism, with r quantifying the scalar-to-tensor ratio (the size of the B-modes relative to that of the temperature power spectrum).*

Source: arXiv:1907.04473



Constraining inflation *Current (light blue and purple) and anticipated (red) CMB-S4 constraints on the scalar-to-tensor ratio r compared with the predictions of various inflationary models that naturally explain the observed value of the spectral "tilt" of the power spectrum, $n_s = 0.965$. The popular Starobinsky and Higgs inflation models are shown as grey and black circles. The lines show models with different masses of the inflaton in units of the Planck mass M_P and N_* is the number of e-folds. The corresponding inflation potentials ϕ_P all either polynomially or exponentially approach a plateau.*

The first is to test models of inflation via the primordial gravitational waves they naturally generate. Such gravitational waves are the only known source of a primordial B-mode polarisation signal. The size of these primordial B-modes is quantified by the ratio of their power to that of the temperature power spectrum – the scalar-to-tensor ratio, designated r. For the largest and most popular classes of inflationary models, CMB-S4 will make a 5σ detection of r, while failure to make such a measurement will put an upper limit of $r \leq 0.001$ at 95% confidence, setting a rigorous constraint on alternative models (see "Constraining inflation" figure). The large-scale B-mode polarisation signal encoding r is the faintest of all the CMB signals, requiring both the deepest measurement and the widest low-resolution frequency coverage of any CMB-S4 science case.

The second goal concerns the dark universe. Dark matter and dark energy make up 95% of the universe's mass-energy content, and their particular form and composition impact the growth of structure and thus the small-scale CMB anisotropies. The collective influence of the three known light-relic particles (the Standard Model neutrinos) has already been observed in CMB data, but many new light species, such as axion-like particles and sterile neutrinos, are predicted by extensions of the Standard Model. CMB-S4's goal, and the most challenging measurement in this arena, is to detect any additional light-relic species with freeze-out temperatures up to the QCD phase-transition scale. This corresponds to constraining the uncertainty on the number of light-relic species N_{eff} to ≤ 0.06 at 95% confidence (see "Light relics" figure). Precise measurements of the small-scale temperature and E-mode polarisation signals that encode this signal require the largest sky area of any CMB-S4 science case. In addition, since the sum of the masses of the neutrinos impacts the degree of lensing of the E-mode polarisation into small-scale B-modes, CMB-S4 will be able to constrain this sum around a fiducial value of 58 meV with a 1σ uncertainty ≤ 24 meV (in conjunction with baryon acoustic oscillation measurements) and ≤ 14 meV with better measurements of the optical depth to reionisation.

The third science goal is to understand the formation and evolution of galaxy clusters, and in particular to probe the early period of galaxy formation at redshifts z > 2. This is enabled by the Sunyaev–Zel'dovitch (SZ) effect, whereby CMB photons are up-scattered by the hot, moving gas in the intra-cluster medium. This shifts the CMB photons' frequency spectrum, resulting in a decrement at frequencies below 217 GHz and an increment at frequencies above, therefore allowing clusters to be identified by matching up the corresponding cold and hot spots. A key feature of the SZ effect is its red-shift independence, allowing us to generate complete, flux-limited catalogues of clusters to the survey sensitivity. The small-scale temperature signals needed for such a catalogue require the highest angular resolution and the widest high-resolution frequency coverage of all the CMB-S4 science cases.

Finally, CMB-S4 aims to explore the mm-wave transient sky, in particular the rate of gamma-ray bursts to help constrain their mechanisms (a few hours to days after the initial event, gamma-ray bursts are observable at longer wavelengths). CMB-S4 will be so sensitive that even its daily maps will be deep enough to detect mm-wave transient phenomena – either spatial from nearby objects moving across our field, or temporal from distant objects exploding in our field. This is the only science goal that places constraints on the survey cadence, specifically on the lag between repeated observations of the same point on the sky. Given its large field of view, CMB-S4 will be an excellent tool for serendipitous discovery of transients but less useful for follow-up observations. The plan is therefore to issue daily alerts for other teams to follow up with targeted observations.

Survey design

While it would be possible to meet all of the CMB-S4 science goals with a single survey, the result – requiring the sensitivity of the inflation survey across the area of the light-relic survey – would be prohibitively expensive. Instead, the requirements have been decoupled into an ultra-deep, small-area survey to meet the inflation goal and a deep, wide-area survey to meet the light-relic goal, the union of these providing a two-tier "wedding cake" survey for the cluster and gamma-ray-burst goals.

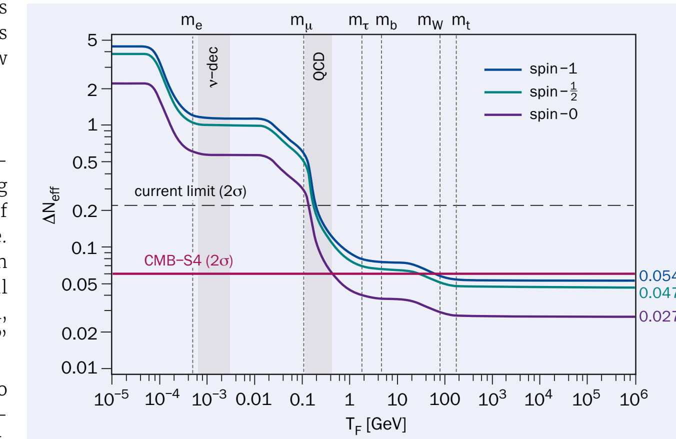
Having set the survey requirements, the task was to identify sites at which these observations can most efficiently be made, taking into account the associated cost, schedule and risk. Water vapour is a significant source of noise at microwave frequencies, so the first requirement on any site is that it be high and dry. A handful of locations meet this requirement, and two of them – the South Pole and the high Chilean Atacama Desert – have both exceptional atmospheric conditions and long-standing US CMB programmes. Their positions on Earth also make them ideally suited to CMB-S4's two-survey strategy: the polar location enables us to observe a small patch of sky continuously, minimising the time needed to reach the required observation depth, and the more equatorial Chilean location enables observations over a large sky area.

Finally, we know that instrumental systematics will be the limiting factor in resolving the extraordinarily faint large-scale B-mode signal. To date, the experiments that have shown the best control of such systematics have used relatively small-aperture (~0.5 m) telescopes. However, the secondary lensing of the much brighter E-mode signal to B-modes, while enabling us to measure the neutrino-mass sum, also obscures the primordial B-mode signal coming from inflation. We therefore need a detailed measurement of this medium- to small-scale lensing signal in order to be able to remove it at the necessary precision. This requires larger, higher-resolution telescopes. The ultra-deep field is therefore itself composed of coincident low- and high-resolution surveys.

A key feature of CMB-S4 is that all of the technologies are already well-proven by the ongoing Stage 3 experiments. These include CMB-S4's "founding four" experiments, the Atacama Cosmology Telescope (ACT) and POLARBEAR/Simons Array (PB/SA) in Chile, and BICEP/Keck (BK) and the South Pole Telescope (SPT) at the South Pole, which have pairwise-merged into the Simons and South Pole Observatories (SO and SPO). The ACT, PB/SA, BK and SPT are all single-aperture, single-site experiments, while SO and SPO are dual-aperture, single sites. CMB-S4 is therefore the first experiment able to take advantage of both apertures and both sites.

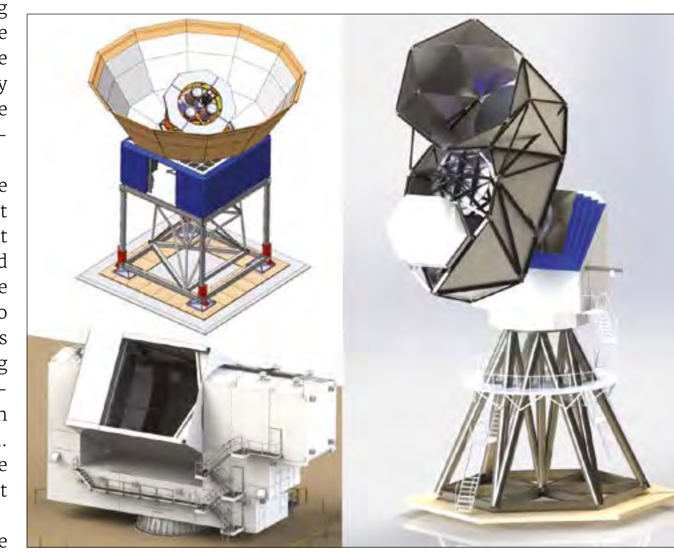
The key difference with CMB-S4 is that it will deploy these technologies on an unprecedented scale. As a result, the primary challenges for CMB-S4 are engineering ones, both in fabricating detector and readout modules in huge numbers and in deploying them in cryostats on telescopes with unprecedented systematics control. The observatory will comprise: 18 small-aperture refractors collectively fielding about 150,000 detectors across eight frequencies for measuring large angular scales; one large-aperture reflector with about 130,000 detectors across seven frequencies for measuring medium-to-small angular scales in the ultra-deep survey from the South Pole; and two large-aperture reflectors collectively fielding about 275,000 detectors across six frequencies for measuring medium-to-

Source: arXiv:1907.04473



Light relics *Current (black) and anticipated (magenta) CMB-S4 constraints on the effective number of light-relic species $N_{eff} = N_{SMeff} + \Delta N_{eff}$, with $N_{SMeff} = 3.045$ from neutrinos. The plot shows the contributions of a single massless particle (which decoupled from the SM at freeze-out temperature T_F) to N_{eff}, with the displayed values on the right indicating observational thresholds for particles with different spins.*

CMB-S4



Looking up *The full facility will employ 18 0.5 m small-aperture telescopes (top left), three per mount, fielding 150,000 detectors; one 5 m large-aperture telescope (right) fielding 130,000 detectors; and two 6 m large-aperture telescopes fielding 275,000 detectors (bottom left).*

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small angular scales in the wide-deep survey from Chile (see "Looking up" image, p37). The final configuration maximises the use of available atmospheric windows to control for microwave foregrounds (particularly synchrotron and dust emission at low and high frequencies, respectively), and to meet the frequency-dependent depth and angular-resolution requirements of the surveys.

Covering the frequency range 20–280 GHz, the detectors employ dichroic pixels at all but one frequency (to maximise the use of the available focal plane) using superconducting transition-edge sensors, which have become the standard in the field. A major effort is already underway to scale up the production and reduce the fabrication variance of the detectors, taking advantage of the DOE national laboratories and industrial partners. Reading out such large numbers of detectors with limited power is a significant challenge, leading CMB-S4 to adopt the conservative but well-proven time-domain multiplexing approach. The detector and read-out systems will be assembled into modules that will be cryogenically cooled to 100 mK to reduce instrument noise. Each large-aperture telescope will carry an 85-tube cryostat with a single wafer per optics tube; and each small-aperture telescope will carry a single optics tube with 12 wafers per tube, with three telescopes sharing a common mount.

Prototyping of detector and readout fabrication lines, and building up module assembly and testing capabilities, is expected to begin in earnest this year. At the same time, the telescope designs will be refined and the data acquisition and management subsystems developed. The current schedule sees a staggered commissioning of the telescopes in 2028–2030, and operations running for seven years thereafter.

Shifting paradigms

CMB-S4 represents a paradigm shift for sub-orbital CMB experiments. For the first time, the entire community is coming together to build an experiment defined by achieving critical science thresholds in fundamental physics, cosmology, astrophysics and astronomy, rather than by its cost cap. CMB-S4 will span the entire range of CMB science in a single experiment, take advantage of the best of all worlds in the design of its observation and instrumentation, and make the results available to the entire CMB community. As an extremely sensitive, two-tiered, multi-wavelength, mm-wave survey, it will also play a key role in multi-messenger astrophysics and transient science. Taken together, these measurements will constitute a giant leap in our study of the history of the universe. ●

Further reading

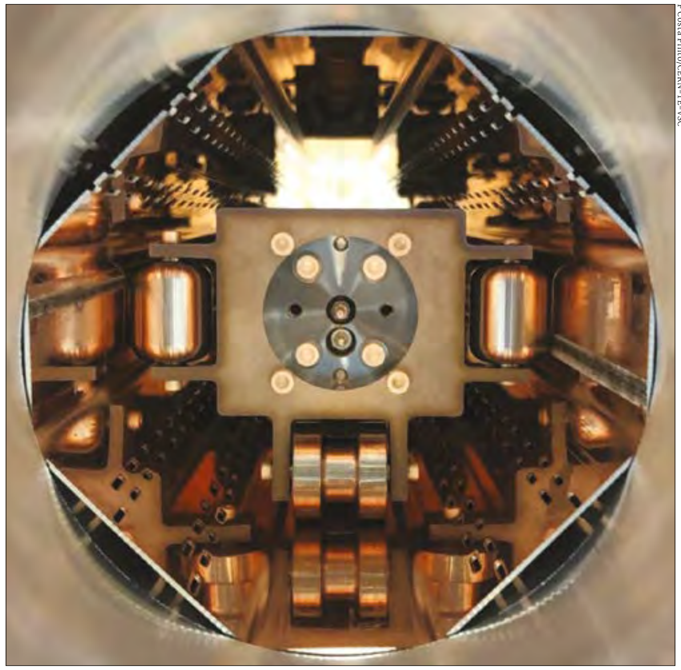
https://cmb-s4.org.

THE AUTHOR

Julian Borrill *Lawrence Berkeley National Laboratory and UC Berkeley, CMB-S4 project data scientist and collaboration co-spokesperson.*

THE LS2 VACUUM CHALLENGE

CERN's vacuum group has completed an intense period of activity during Long Shutdown 2 to prepare the accelerator complex for more luminous operation through LHC Run 3 and beyond, describes Paolo Chiggiato.



Beam screen *Testing the carbon coating of a beam screen for the HL-LHC.*

The second long-shutdown of the CERN accelerator complex (LS2) is complete. After three years of intense works at all levels across the accelerators and experiments, beams are expected in the LHC in April. For the accelerators, the main LS2 priorities were the consolidation of essential safety elements (dipole diodes) for the LHC magnets, several interventions for the High-Luminosity LHC (HL-LHC) and associated upgrades of the injection chain via the LHC Injectors Upgrade project. Contributing to the achievement of these and many other planned parallel activities, the CERN vacuum team has completed an intense period of work in the tunnels, workshops and laboratories.

Particle beams require extremely low pressure in the pipes in which they travel to ensure that their lifetime is not limited by interactions with residual gas molecules and to minimise backgrounds in the physics detectors. During LS2, all of the LHC's arcs were vented to the air after warm-up to room temperature and all welds were leak-checked after the diode consolidation (with only one leak found among the 1796 tests performed). The vacuum team also replaced or consolidated around 150 turbomolecular pumps acting on the cryogenic insulation vacuum. In total, 2.4 km of non-evaporable-getter (NEG)-coated beampipes were also opened to the air at room temperature – an exhaustive programme of work spanning mechanical repair and upgrade (across 120 weeks), bake-out (90 weeks) and NEG activation (45 weeks). The vacuum level in these beampipes is now in the required range, with most of the pressure readings below 10^{-10} mbar.

The vacuum control system was also significantly improved by reducing single points of failure, removing confusing architectures and, for the first time, using mobile vacuum equipment controlled and monitored wirelessly. In view of the higher LHC luminosity and the consequent higher radioactivity dose during Run 3 and beyond, the vacuum group has developed and installed new radiation-tolerant electronics controlling 100 vacuum gauges and valves in the LHC dispersion suppressors. This was the first step of a larger campaign to be implemented in the next long-shutdown, including the production of 1000 similar electronics cards for vacuum monitoring. In parallel, the control software was renewed. This included the introduction of resilient, scalable and self-healing web-based frameworks used by the biggest names in industry.

In the LHC experimental areas, the disassembling of the vacuum chambers at the beginning of LS2 required 93 interventions and 550 person-hours of work in the caverns, with the most impressive change in vacuum hardware implemented in CMS and LHCb (see "Interaction points" images). In CMS, a new 7.3 m-long beryllium beam-pipe with an internal diameter of 43.4 mm was installed and 12 new aluminium chambers were manufactured, surface-finished and NEG-coated at CERN. The mechanical installation, including alignments, pump-down and

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Paolo Chiggiato *head of the CERN vacuum, surfaces and coatings group.*

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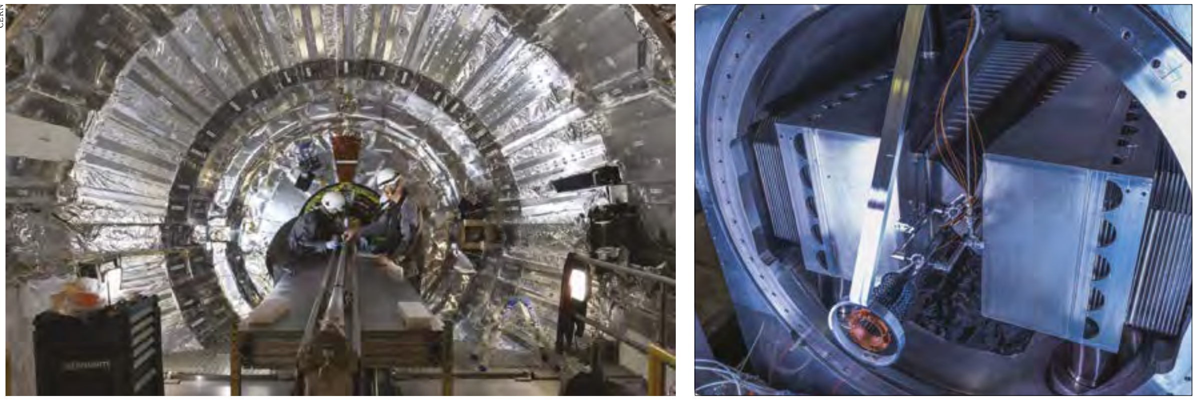
Interaction points *The installation of the CMS beampipe (left) and the RF boxes of the LHCb Vertex Locator (right).*


SPS inspection *Members of the vacuum team in the SPS in 2019.*

leak detection, took two months, while the bake-out and venting with ultra-pure neon required a further month. In LHCb, the vacuum team contributed to the new Vertex Locator (VELO). Its "RF box" – a delicate piece of equipment filled with silicon detectors, electronics and cooling circuits designed to protect the VELO without affecting the beams – is situated just a few mm from the beam with an aluminium window thinned down to 150 µm by chemical etching and then NEG-coated. As the VELO encloses the RF box and both volumes are under separated vacua, the pump-down is a critical operation because pressure differences across the thin window must be lower than 10 mbar to ensure mechanical integrity. The last planned activity for the vacuum team in LS2, the bake-out of the ATLAS beam pipes, took place in February.

Vacuum challenges

From the list of successful achievements, it could be assumed that vacuum activities in LS2 have gone smoothly, with the team applying well known procedures and practicing knowledge accumulated over decades. However, as might be expected when working with several teams in parallel and at the limits of technology, with around 100 km of piping under vacuum for the LHC alone, this is far from the case. Since the beginning of LS2, CERN vacuum experts have experienced several technical issues and obstacles, a few of which deserve a mention (see "Overcoming the LS2 vacuum obstacles" panel). All these headaches have challenged our regular way of working and allowed us to reflect on procedures, communication and reporting, and technical choices.

But the real moment of truth is still yet to come, when the intensity of the LHC beams reaches the new nominal value boosted by the upgraded injectors. Under the spotlight will be surface electron emission, which drives the formation of electron clouds and their consequences, including beam instabilities and heat load on the cryogenic system. The latter showed anomalously high values during Run 2, with strong inhomogeneity along the ring indicating an uneven surface conditioning. The question is what will happen to the heat load during Run 3? Thanks to the effort and achievements of a dedicated taskforce, the scrubbing and following physics runs will provide a detailed answer in a few months. Last year, the task force installed additional instrumentation in the cryogenic lines in selected positions and, after many months of detective work, identified the most probable culprit of the puzzling heat-load values: the formation of a non-native copper oxide layer during electron bombardment of hydroxylated copper surfaces at cryogenic temperatures. UV exposure in selected gas, local bakeout and plasma etching are among the mitigation techniques we are going to investigate.

The HL-LHC horizon

LS2 might only just have finished but we are already thinking about LS3 (2026–2028), whose leitmotif will be the finalisation of the HL-LHC project. Thanks to more focused beams at the collision points and an increased proton bunch population, the higher beam luminosity at CMS and ATLAS (peaking at a levelled value of $5\times10^{34}\,cm^{-2}s^{-1}$) will enable an integrated luminosity of $3000\,fb^{-1}$ in 12 years. For the HL-LHC vacuum systems, this requires a completely new design of the beam screens in the focusing area of the experiments, the implementation of carbon thin-film coatings in the unbaked beampipes to cope with the lower secondary electron yield threshold, and radiation-compatible equipment near the experiments and radiation-tolerant

Overcoming the LS2 vacuum obstacles


Unexpected interventions *Searching for foreign objects (left); a damaged bellow (middle); and a buckled RF finger (right).*

Forgotten sponge

During the first beam-commissioning of the PS, anomalous high proton losses were detected, generating pressure spikes and a high radioactive dose near one of the magnets. An endoscopic inspection (see image above, left) revealed the presence of an orange sponge that had been used to protect the vacuum chamber extremities before welding (and which had been left behind due to a miscommunication between the teams involved), blocking the lower half of the beam pipe. After days of investigation with the beams and interventions by technicians, the chamber was cut open and the offending object removed.

Leaky junctions

Having passed all tests before they were installed, new corrugated thin-walled vacuum chambers installed in the Proton Synchrotron Booster to reduce eddy-current effects suffered vacuum leaks after a few days of magnet pulsing. The leaks appeared in lip-welded junctions in several chambers, indicating a systematic production issue. Additional spare chambers were produced and, as the leaks remain tolerable, a replacement is planned during the next year-end technical stop. Until then, this issue will be the Sword of Damocles on the heads of the vacuum teams in charge of the LHC's injectors.

Powering mismatch

During the first magnet tests of the TT2 transfer line, a vacuum sector was suddenly air-vented. The support of the vacuum chambers was found to be broken; two bellows were destroyed (see image, middle), and the vacuum chamber twisted. The origin of the problem was a different powering scheme of the magnet embedding the chamber: faster magnetic pulses generated higher eddy-current and Lorentz forces that were incompatible with the beampipe design and supports. It was solved by inserting a thin insulation layer between vacuum flanges to interrupt the eddy current, a practice common in other parts of the injectors.

QRL quirks

The LHC's helium transfer lines (QRL) require regular checks, especially after warm-up and cool-down. During LS2, the vacuum team installed two additional turbomolecular pumps to compensate for the rate increase of a known leak in sector B12, allowing operation until at least the next long-shutdown. Another troubling leak which opened only for helium pressures above 7 bar was detected in a beam-screen cooling circuit. Fixing it would have required the replacement of the nearby magnet but the leak turned out to be tolerable at cryogenic temperatures, although its on/off behaviour remains to be fully elucidated.

Damaged disks

Installed following the incident in sector 3–4 shortly after LHC startup, the beam vacuum in the LHC arcs is protected against overpressure by 832 "burst disks". A 30 µm-thick stainless-steel disk membrane nominally breaks when the pressure in the vacuum system is 0.5 bar higher than the tunnel air pressure. Despite the careful venting procedure, 19 disks were either broken or damaged before the re-pumping of the arcs. Subsequent lab tests showed no damage in spare disks cycled 30 times at 1.1 bar. The vacuum teams replaced the damaged disks and are trying to understand the cause.

Buckled fingers

Before cool-down, a 34 mm-diameter ball fitted with a 40 MHz transmitter is pushed through the LHC beam pipes to check for obstacles. The typical defect is a buckling of the RF fingers in the plug-in modules (PIMs) that maintain electrical continuity as the machine thermally contracts. Unfortunately, in two cases the ball arrived damaged, and it took days to collect and identify all the broken pieces. A buckled finger was successfully found in sector 8–1, but another in sector 2–3 (see image, right) was revealed only when the pilot beam circulated. This forced a re-warming of the arc, venting of the beampipe and the replacement of the damaged PIM, followed by additional re-cooling and aperture and electrical tests.

electronics down to the dispersion suppressor zones.

The first piece of vacuum equipment concerned is the "VAX": a compact set of components, pumps, valves and gauges installed in an area of limited access and relatively high radioactivity between the last focusing magnet of the accelerator and the high-luminosity experiments. The VAX module is designed to be fully compatible with robot intervention, enabling leak detection, gasket change and complete removal of parts to be carried out remotely and safely.

Despite the massive shielding between the experiment caverns and the accelerator tunnels, secondary particles from high-energy proton collisions can reach accelerator components outside the detector area. At nominal HL-LHC luminosity, up to 3.8 kW of power will be deposited in the tunnel on each side of CMS and ATLAS, of which 1.2 kW is intercepted by the 60 m-long sequence of final focusing magnets. Such a power is incompatible with magnet cooling at 1.9 K and, in the long run, could cause the insulation of the

CERNCOURIER
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superconducting cables to deteriorate. To avoid this issue, the vacuum team designed a new beam screen equipped with tungsten-alloy shielding so that at least half of the power is captured before being transmitted to the magnet cold mass.

The new HL-LHC beam screens took several years of design and manufacturing optimisation, multi-physics simulations and tests with prototypes. The most intense study concerned the mechanical integrity of this complicated object when the hosting magnet undergoes a quench, causing the current to drop from nearly 20 kA to 0 kA in a few tenths of a second. The manufacturing learning phase is now complete and the beam-screen facility will be ready this year, including the new laser-welding robot and cryogenic test benches. Carbon coating is the additional novelty of the HL-LHC beam screens, with the purpose of suppressing electron clouds (see "Beam screen" image, p39). At the beginning of LS2 the first beam screens were successfully coated *in situ*, involving a small robot carrying carbon and titanium targets, and magnets for plasma confinement during deposition.

All eyes are on the successful restart of the CERN accelerator complex and the beginning of LHC Run 3

The vacuum team is also involved in the production of crab cavities, another breakthrough brought by the HL-LHC project (see p45). The surfaces of these complex-shaped niobium objects are treated by a dedicated machine that can provide rotation while chemically polishing with a mixture of nitric, hydrofluoric and phosphoric acids. The vacuum system of the cryomodules in which the cavities are cooled at 2 K was also designed at CERN.

Outlook

Vacuum technology for particle accelerators has been pioneered by CERN since its early days, with the Intersecting Storage Rings bringing the most important breakthroughs. Over the decades, the CERN vacuum group has merged surface-physics specialists, thin-film coating experts and galvanic-treatment professionals, together with teams of designers and colleagues dedicated to the operation of large vacuum equipment. In doing so, CERN has become one of the world's leading R&D centres for extreme vacuum technology, contributing to major existing and future accelerator projects at CERN and beyond (*CERN Courier* June 2018 p26). With the HL-LHC in direct view, the vacuum team looks forward to attacking new challenges. For now, though, all eyes are on the successful restart of the CERN accelerator complex and the beginning of LHC Run 3. ●

Further reading

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CRAB CAVITIES ENTER NEXT PHASE

CERN-PHOTO-201803-055-1

Rama Calaga describes the latest progress in building the superconducting radio-frequency "crab" cavities needed to maximise the scientific output of the High-Luminosity LHC.

Testing *The crab-cavity test facility in the SPS tunnel, where the second of two cavity designs (RF dipole) will be installed in 2023.*

The imminent start of LHC Run 3 following a vast programme of works completed during Long Shutdown 2 marks a milestone for the CERN accelerator complex. When stable proton beams return to the LHC this year (see p8), they will collide at higher energies (13.6 compared to 13 TeV) and with higher luminosities (containing up to 1.8×10^{11} protons per bunch compared to $1.3–1.4\times10^{11}$) than in Run 2. Physicists working on the LHC experiments can therefore look forward to a rich harvest of results during the next three years. After Run 3, the statistical gain in running the accelerator without a significant luminosity increase beyond its design and ultimate values will become marginal. Therefore, to maintain scientific progress and to exploit its full capacity, the LHC is undergoing upgrades that will allow a decisive increase of its luminosity during Run 4, expected to begin in 2029, and beyond.

Several technologies are being developed for this High-Luminosity LHC (HL-LHC) upgrade. One is new, large-aperture quadrupole magnets based on a niobium-tin superconductor. These will be installed on either side of the ATLAS and CMS experiments, providing the space required for smaller beam-spot sizes at the interaction points and shielding against the higher radiation levels when operating at increased luminosities. The other key technology, necessary to take advantage of the smaller beam-spot size at the interaction points, is a series of superconducting radio-frequency (RF) "crab" cavities that enlarge the overlap area of the incoming bunches and thus increase the probability of collisions. Never used before at a hadron collider, a total of 16 compact crab cavities will be installed on either side of each of ATLAS and CMS once Run 3 ends and Long Shutdown 3 begins.

At a collider such as the LHC, it is imperative that the two counter-circulating beams are physically separated by an angle, aka the crossing angle, such that bunches collide only in one single location over the common interaction region (where the two beams share the same beam pipe). The bunches at the HL-LHC will be 10 cm long and only 7 µm wide at the collision points, resembling thin long wires. As a result, even a very small angle between the bunches implies an immediate loss in luminosity. With the use of powerful superconducting crab cavities, the tilt of the bunches at the collision point can be precisely controlled to make it optimal for the experiments and fully exploit the scientific potential of the HL-LHC.

Radical concepts

The tight space constraints from the relatively small separation of the two beams outside the common interaction region requires a radically new RF concept for particle deflection, employing a novel shape and significantly smaller cavities than those used in other accelerators. Designs for such devices began around 10 years ago, with CERN settling on two types: double quarter wave (DQW) and RF-dipole (RFD). The former will be fitted around CMS, where bunches are separated vertically, and the latter around ATLAS, where bunches will be separated horizontally, requiring crab cavities uniquely designed for each plane. It is also planned to swap the crossing-angle planes and crab-cavity installations at a later stage during the HL-LHC operation.

In 2017, two prototype DQW-type cavities were built and assembled at CERN into a special cryomodule and tested at 2 K, validating the mechanical, cryogenic and RF functioning. The module was then installed in the

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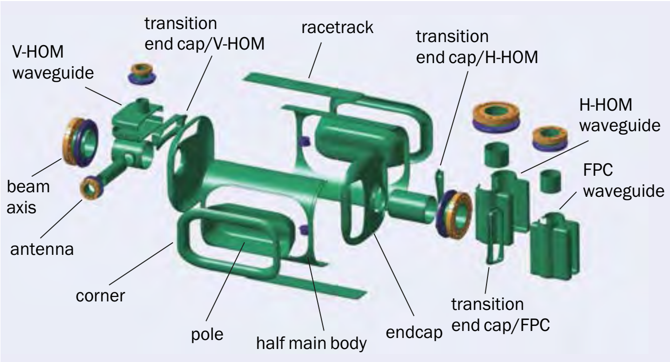
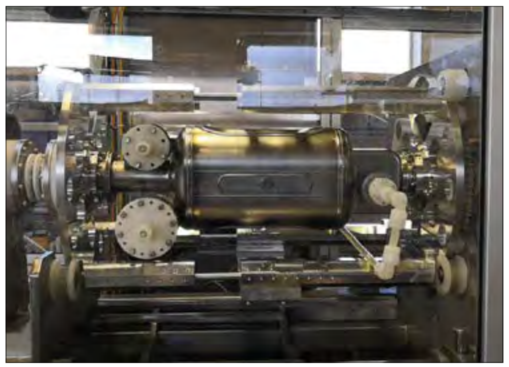
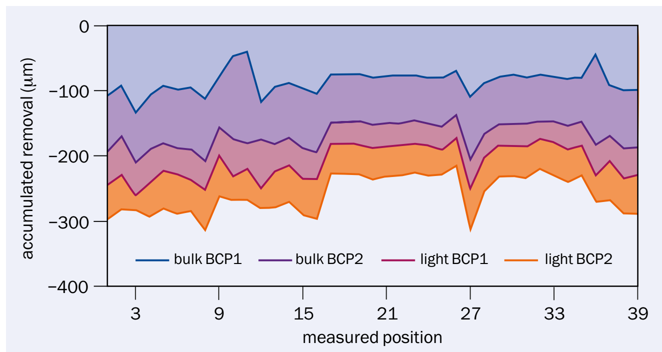


Fine machining *The RF-dipole cavity split into its manufacturing components, which are then assembled through a sequence of shaping, welding and brazing operations with metrology and radio-frequency measurements to achieve the final shape (left) and the final welded cavity (right).*





Chemical etching *The chemical-etching setup (left) with a rotational feature to uniformly remove the damaged RF surface during the manufacturing process, and the results measured on 39 points on the cavity surface using ultrasound (right).*

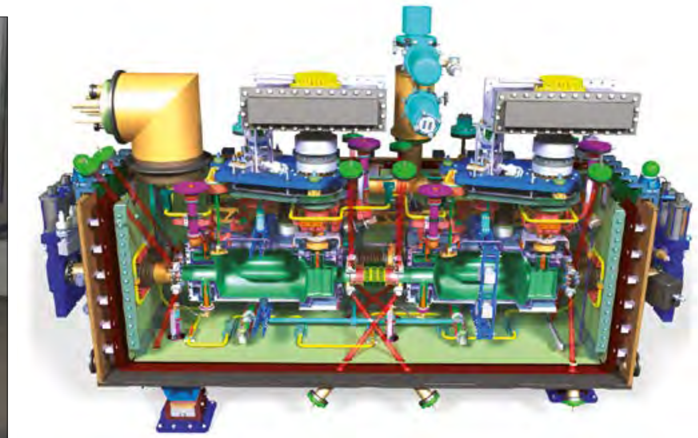
Super Proton Synchrotron (SPS) for beam tests, with the world's first "crabbing" of a proton beam demonstrated on 31 May 2018 (*CERN Courier* May 2018 p18). In parallel, the fabrication of two prototype RFD-type cavities from high-purity niobium was underway at CERN. Following the integration of the devices into a titanium helium tank at the beginning of 2021, and successful tests at 2 K reaching voltages well beyond the nominal value of 3.4 MV, the cavities were equipped with specially designed RF couplers, which are necessary for beam operations. The two cavities are now being integrated into a cryomodule at Daresbury Laboratory in the UK as a joint effort between CERN and the UK's Science and Technology Facilities Council (STFC). The cryomodule will be installed in a 15 m-long straight section (LSS6) of the SPS in 2023 for its first test with proton beams. This location in the SPS is equipped with a special by-pass and other services, which were put in place in 2017–2018 to test and operate the DQW-type module.

The manufacturing challenge

Due to the complex shape and micrometric tolerances required for the HL-LHC crab cavities, a detailed study was performed to realise the final shape through forming, machining, welding and brazing operations on the high-purity niobium sheets and associated materials (see "Fine machining" images). To ensure a uniform removal of material along the cavities' complex shape, a rotational buffer chemical polishing (BCP) facility was built at CERN for surface etching of the HL-LHC crab cavities. For the RFD and DQW, the rotational setup etches approximately 250 µm of the internal RF surface to remove the damaged cortical layer during the forming process. Ultrasound measurements were performed to follow the evolution of the cavity-wall thickness during the BCP steps, showing remarkable uniformity (see "Chemical etching" images).

Preparation of the RFD cavities involved a similar process as that for the DQW modules. Following chemical etching and a very high-temperature bake at 650 °C in a vacuum furnace, the cavities are rinsed in ultra-pure water at high pressure (100 bar) for approximately seven hours. This process has proven to be a key step in the HL-LHC crab-cavity preparation to enable extremely high fields and suppress electron-field emitters, which can limit the performance. The cavity is then closed with its RF ancillaries in an ISO4 cleanroom environment to preserve the ultra-clean RF surface, and installed into a special vertical cryostat to cool the cavity surface to its 2 K operating temperature (see "Clean and cool" image, top). Both RFD cavities reached performances well above the nominal

Clean and cool *The RF dipole cavity being prepared in the SM18 ISO4 cleanroom prior to testing at 2 K (top), and the cold magnetic shield assembly (bottom).*



Cryomodule *Cross section of the RF dipole cryomodule comprising a two-cavity string and the respective RF, cryogenic, vacuum, mechanical and alignment interfaces (top), and the outer vacuum vessel manufactured in Italy under a contract by the STFC–CERN collaboration (bottom).*

target of 3.4 MV. RFD1 reached more than 50% over the nominal voltage and RFD2 reached above a factor of two (7 MV) – a world-record deflecting field in this frequency range. These performances were reproducible after the assembly and welding of the helium tank owing to the careful preparation of the RF surface throughout the different steps of assembly and preparation.

The helium tank provides a volume around the cavity surface that is maintained at 2 K with superfluid helium (see "Clean and cool" image, bottom). Due to sizeable deformations during the cool-down process from ambient temperature, a titanium vessel which has a thermal behaviour close to that of the niobium cavity is used. A magnetic shield between the cavity and the helium tank suppresses stray fields in the operating environment and further preserves cavity performance. Following the tests with helium tanks, the cavities were equipped with higher-order-mode couplers and field antennae to undergo a final test at 2 K before cryostating them into a two-cavity string.

The crab cavities require many ancillary components to allow them to function. This overall system is known as a cryomodule (see "Cryomodule" image, top) and ensures that the operational environment is correct, including the temperature, stability, vacuum conditions and RF frequency of the cavities. Technical challenges arise due to the need to assemble the cavity string in an ISO4 cleanroom, the space constraints of the LHC (leading to the rectangular compact shape), and the requirement of fully welded joints (where typically "O" rings would be used for the insulation vacuum).

Design components

The outer vacuum chamber (OVC) of the cryomodule provides an insulation vacuum to prevent heat leaking to the environment as well as providing interfaces to any external connections. Manufactured by ALCA Technology in Italy, the OVC used a rectangular design where the cavity string is mounted to a top-plate that is lowered into the rest of the OVC, and includes four large windows to allow access for repair *in situ* if required (see "Cryomodule" image, bottom). Since the first DQW prototype module, several cryomodule interfaces including cryogenic and vacuum components were updated to be fully compatible with the final installation in the HL-LHC.

Since superconducting RF cavities can have a higher

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surface resistance if cooled below their transition temperature in the presence of a magnetic field, they need to be shielded from Earth's magnetic field and stray fields in the surrounding environment. This is achieved using a warm magnetic shield manufactured in the OVC, and a cold magnetic shield mounted inside the liquid-helium vessel. Both shields, which are made from special nickel-iron alloys, are manufactured by Magnetic Shields Ltd in the UK.

Status and outlook

The RFD crab-cavity pre-series cryomodule will be assembled this year at Daresbury lab, where the infrastructure on site has been upgraded, including an extension to the ISO4 cleanroom area and the introduction of an ISO6 preparation area. A bespoke five-tonne crane has also been installed and commissioned to allow the precise lowering of the delicate cavity string into the outer vacuum vessel.

Parallel activities are taking place elsewhere. The HL-LHC crab-cavity programme has developed into a mature project supported by a large number of collaborating institutions around the world. In the US, the Department of Energy is supporting the HL-LHC Accelerator Upgrade Project to coordinate the efforts and leverage the expertise of a group of US laboratories and universities (FNAL, BNL, JLAB, SLAC, ODU) to deliver the series RFD cavities for the HL-LHC. In 2021, two RFD prototype cavities were built by the US collaboration and exceeded the two most important functional project requirements for crab cavities – deflecting voltage and quality factor. After this successful demonstration, the fabrication of the pre-series cavities was launched.

The HL-LHC crab-cavity programme has developed into a mature project supported by a large number of collaborating institutions around the world

Crab cavities were first implemented in an accelerator in 2006, at the KEKB electron–positron collider in Japan, where they helped the collider reach record luminosities. A different "crab-waist" scheme is currently employed at KEKB's successor, SuperKEKB, helping to reach even higher luminosities (*CERN Courier* September/October 2020 p13). The development of ultra-compact, very-high-field cavities for a high-energy hadron collider such as the HL-LHC is even more challenging, and will be essential to maximise the scientific output of this flagship facility beyond the 2030s.

Beyond the HL-LHC, the compact crab-cavity concepts have been adopted by future facilities, including the proton–proton stage of the proposed Future Circular Collider; the Electron–Ion Collider under construction at Brookhaven; bunch compression in synchrotron X-ray sources to produce shorter pulses; and ultrafast particle separators in proton linacs to separate bunches of secondary particles for different experiments. The full implementation of this technology at the HL-LHC is therefore keenly awaited. ●

OPINION
VIEWPOINT

Standing up for sustainability

The International Year of Basic Sciences for Sustainable Development 2022 is a call to action for particle physicists to promote the links between curiosity-driven research and sustainable development, says Michel Spiro.

M Brice/CERN

Michel Spiro *is president of the International Union of Pure and Applied Physics, chair of the CERN & Society Foundation board, and was president of the CERN Council in 2010–2013.*

The COVID-19 pandemic has cost more than five million lives and disrupted countless more. Without the results of decades of curiosity-driven research, however, the situation would have been much worse. The pandemic therefore serves as a stark and brutal reminder of the links between basic science and the balanced, sustainable and inclusive development of our planet.

The International Year of Basic Sciences for Sustainable Development (IYBSSD), proclaimed by the United Nations (UN) general assembly on 2 December 2021, is a key moment of mobilisation to convince economic and political leaders, as well as the public, of the critical links between basic research and the 2030 Agenda for Sustainable Development adopted by all UN member states in 2015. Due to their evidence-based nature, universality and openness, basic sciences not only contribute to expanding knowledge and improving societal welfare, but also help to reduce societal inequality, improve inclusion and foster intercultural dialogue and peace. They are thus central in achieving the UN Agenda's 17 Sustainable Development Goals.

Virtuous circle

Many examples of basic sciences' transformative contribution to society are so widespread that they are taken for granted. The web was born at CERN from the needs of global particle physics; general relativity underpins the global positioning system; search engines and artificial intelligence rely on brilliant mathematics and statistical methods; mobile phones derive from the discovery of transistors; and Wi-Fi from developments in astronomy. The discovery of DNA, positron emission tomography, magnetic resonance imaging and radiotherapy have transformed medical diagnostics and treatments, while advances in basic physics, chemistry and materials science are reducing pollution and revolutionising the generation and storage of renewable energy.

Basic science, together with applied scientific research and technological applications, is thus one of the key elements of the virtuous circle that allows the sustainable development of society. Yet, basic sciences are often not as prominent as they should be in discussions concerning societal, environmental and economic development. The aims of the IYBSSD are to focus global attention on the enabling role of basic science and to improve the collaboration between basic sciences and policy-making.

Particle physics has a major role to play in making the IYBSSD a success

The IYBSSD, led by the International Union of Pure and Applied Physics – which will celebrate its centenary in 2022 – has received strong support from around 30 international science unions and organisations active in physics, mathematics, chemistry, life science and social science, along with 70 national and international academies of sciences, and 30 Nobel laureates and Fields medallists. A series of specific activities coordinated at local, national and international levels will aim to promote inclusive collaboration (with special attention paid to gender balance), enhance basic-science training and education, and encourage the full implementation of open-access publishing and open data in the basic sciences.

The IYBSSD inauguration ceremony will take place at UNESCO on 8 July, and a closing ceremony is planned to take place at CERN in 2023, hopefully timed with the completion of the Science Gateway building. Events of all sorts proposed by countries, territories, scientific unions, organisations and academies endorsed by the steering committee will occur throughout the year.

The role of particle physics

As one of the most basic sciences of all, particle physics has a major role in making the IYBSSD a success. The high-energy physics community should use all the available opportunities in 2022 and 2023, be it through conferences, workshops, collaboration meetings or other activities, to place our field under the auspices of the IYBSSD. We need to show how this community advances science for the benefit of society, how much it re-enchants our world and therefore makes it worth sustaining, how much it contributes in its practice to openness, equity, diversity and inclusion, and to multicultural dialogue and peace. The CERN model is emblematic of these contributions. Many of the programmes of the CERN & Society foundation also promote these values in line with the IYBSSD objectives.

The need for humanity to maintain and develop high levels of interest and participation in basic sciences makes awareness-raising initiatives such as the IYBSSD critical. Following the recent international years of physics, chemistry, mathematics and astronomy, it is now time for us to get behind this unprecedented, global interdisciplinary initiative. www.iybssd2022.org

OPINION
INTERVIEW

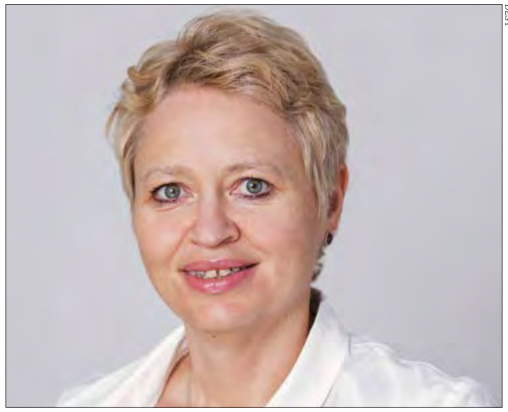
New directions at DESY

Beate Heinemann talks about her new role as director of particle physics at DESY and the importance of building a future collider that benefits both science and society.

What attracted you to the position of DESY director of particle physics?
DESY is one of the largest and most important particle-physics laboratories in the world. I was born and grew up in Hamburg and took my first career steps at DESY during my university studies. I received my PhD there in 1999 and returned as a scientist in 2016, so I know the lab very well. It is a great lab and department, with many opportunities and so many excellent people. I am sure it will be fun to work with all of them and to develop a strategy for the future.

What previous management roles do you think will serve you best at DESY?
Being ATLAS deputy spokesperson from 2013 to 2017 was one of the best roles I've had in my career, and I benefitted hugely from the experience. I was fortunate to have an excellent spokesperson in Dave Charlton and I learned a lot from him, as well as from many others I worked with. I try to understand enough details to make educated decisions but not to micromanage. I also think motivating people, listening to them and promoting their talents is key to achieving common goals.

What are the current and upcoming experiments at DESY?
The biggest on-going experimental activities in particle physics are the ATLAS and CMS experiments. We have large groups in both, and for each we are building a tracker end-cap based on silicon-strip detectors at our detector assembly facility, primarily together with German universities. This is a huge undertaking that is currently ongoing for the HL-LHC. Another important activity is to build a vertex detector to be installed in 2023 at the Belle II experiment running at KEK in Japan. We also have a significant programme of local experiments covering axion searches. One of the big projects next summer will be the start of the ALPS II experiment, which will look for axion-like particles by shining an intense laser on a "wall" and seeing if any laser photons appear on the other side, having been transformed into axions by a large magnetic field. We have two other axion experiments planned: BabyIAXO, which looks for axion-like particles coming from the Sun, for which construction is now starting; and MadMax, which looks for axions in the dark-matter halo. Axions were postulated by Peccei and Quinn to solve the strong-CP problem but are also a good candidate for dark matter if they exist. A further experiment, which DESY theorist Andreas Ringwald and I proposed, LUXE, would deliver the European XFEL 16.5 GeV electron beam into a high-intensity laser so that the beam electrons experience a very strong electromagnetic field within their rest frame. LUXE would reach the so-called Schwinger limit, and allow us to see what happens when QED becomes strong and transitions from the perturbative to the non-perturbative regime.


DESY

First female director
Beate Heinemann took over as DESY's director of particle physics in February, and is also professor of experimental particle physics at the Albert Ludwig University of Freiburg.

There are many accelerators at DESY, such as PETRA, where the gluon was discovered in the 1970s. Today, PETRA is one of the best synchrotron-radiation facilities in the world and is used for a wide range of science, for example imaging of small structures such as viruses. It is an application of accelerators where the impact on society is more direct and obvious than it is in particle physics.

How can we increase the visibility of particle physics to society?
This is a very important point. The knowledge we get from particle physics today is clear, but it is less clear how we can transfer this knowledge to help solve pressing problems in society, such as climate change or a pandemic. Humankind desires to increase its knowledge, and it is important that we continue with fundamental research purely to increase our knowledge. We have already come so far in the past 5000 years. And, many technical innovations were made for that purpose alone but then resulted in transformative changes. Take the idea of the accelerator. It was developed at Berkeley during the 1930s with no particular application in mind, but today is used routinely around the world to prolong life by irradiating tumours. Or the transistor, without which there would not be any computers, which was developed in the 1920s based on the then-emerging understanding of atoms. It is important to promote both targeted research that directly addresses problems as well as fundamental research, which every now and again will result in groundbreaking changes. When thinking about our projects and experiments we need to keep in mind if and how any of our technical developments can be made in a way that addresses big societal problems.

It is important that we inspire the general public, in particular the young, about science. Educational programmes are key, such as Beamline for Schools, which is one of CERN's flagship schemes. This was hosted by DESY during Long Shutdown 2 and a team at DESY will continue the collaboration.

CERN recently launched its Quantum Technology Initiative. Does DESY have plans in this area?

DESY received funding from the state of Brandenburg to build a centre for quantum computing, the CTQA, which is located at DESY's Zeuthen site. Karl Jansen, one of our scientists there, has spent most of his life working on lattice QCD calculations and is leading this effort. I myself am involved in research using quantum computing for particle tracking at the LUXE experiment. The layout of the tracker for this experiment is simpler compared to the LHC experiments, which is why we want to do it here first. We have to understand how to use quantum computers in conjunction with classical computers to solve actual problems efficiently. There is no doubt that quantum computing solves questions that are otherwise not possible, and we also think they will be able to solve problems more efficiently by using less resources compared to classical machines. That could also contribute to reducing the impact of computing on climate change.

What was your participation in the 2020 update of the European strategy for particle physics (ESPPU) and how have things progressed since?

It was exciting to be part of the ESPPU drafting process. I was very impressed by the sincerity and devotion of the people in the hall in Bad Honnef when the process concluded. There was a lot of respect and understanding of the different views on how to balance the scientific ambitions with the realities of funding, R&D needs and other factors.

The ESPPU recommended first and foremost to complete the HL-LHC upgrade. This is a big undertaking and demands our focus. For the future, an electron–positron Higgs factory is the highest priority, in addition to ramping up accelerator R&D. Last year an accelerator R&D roadmap was prepared following the ESPPU recommendation. Very different directions are laid out, and now the task is to understand how to prioritise and streamline the different directions, and to ensure the relevant aspects are progressing significantly by the next update (probably in 2026). For instance CERN's main focus is R&D on the next generation of magnets for a new hadron machine, while DESY has a strong progamme in plasma-wakefield accelerators for electron machines. But both DESY and CERN are also contributing to other aspects and there are other labs and universities in Europe which make important contributions. At DESY we also try to exploit synergies between developing new accelerators for photon science and high-energy physics.


DESY/Heiner Müller-Elsner

Chasing axions *The ALPS II experiment, which will start operating next summer, will search for conversions of photons to axions and back in a strong magnetic field provided by former HERA dipoles.*

What is the best machine to follow the LHC?

The next machine needs to be a collider that can measure the Higgs properties at the per-cent and even in some cases the per-mille level – a Higgs factory. In addition to the excellent scientific potential, factors to consider are timescale and cost, but also making it a "green" accelerator and considering its innovation potential. Finding a good balance there is not easy, and there are several proposals that were studied as part of the ESPPU.

What are your three most interesting open questions in particle physics?

Mine are related to the Higgs boson. One is the matter–antimatter asymmetry, because the exact form of the electroweak phase transition is closely related to the Higgs field. If it was a smooth transition, it cannot explain the matter–antimatter asymmetry; if it was violent, it could potentially be able to explain it. We should be able to learn something about this with the HL-LHC, but to know for sure we need a future collider. The second question is why is there a muon? Flavour physics fascinates me, and the Higgs-boson is the only particle that distinguishes between the electron, the muon and the tau, which is why I would like to study it extensively. The third question is what is dark matter? One intriguing possibility is that the Higgs boson decays to dark-matter particles, and with a Higgs factory we could measure this, even if it only happens for 0.3% of all Higgs bosons. The Higgs boson is so important for understanding our universe, that's why we need a Higgs factory, although we will already learn a lot from the LHC and HL-LHC.

Today, women make up more than 30% of the scientists at DESY, whereas in 2005 it was less than 10%

Is the community doing a good job in communicating beyond the field?

It is crucial that scientists communicate scientific facts, especially now when there are "post-truth" tendencies in society. We have a duty as people who are publicly funded to communicate our work to the public. Many people are excited about the origin of the universe and the fundamental laws of physics we are studying. Activities such as the CERN and DESY open days attract many visitors. We also see really good turnouts at public lectures as well as during our "science on tap" activity in Hamburg. I gave a talk about the first minutes of the universe, and the bar was packed and people had many questions during one of these events. We should all spend some of our time communicating science. Of course, we have to mostly do the actual research, otherwise we do not have anything to communicate.

You are the first female director in DESY's 60-year history. What do you think about the situation for women in physics, for instance the "25 by '25" initiative?

The 25 by '25 initiative is good. We have been fortunate at DESY that there was a strong drive from the German government. Research funding has increased a lot during the past 10–15 years and there was dedicated funding available to attract women to large research centres. Today, women make up more than 30% of the scientists at DESY, whereas in 2005 it was less than 10%. Having special programmes unfortunately appears to be necessary as change happens too slowly by itself otherwise. Having women in visible roles in science is important. I myself was inspired by several women in particle physics, such as Beate Naroska, the only female professor at the physics department when I was a student, Young-Kee Kim, who was spokesperson of the CDF experiment when I was a postdoc and later deputy-director of Fermilab, and last but not least Fabiola Gianotti, who was spokesperson of ATLAS when I joined and is now the Director-General of CERN.

Interview by **Kristiane Novotny** *CERN.*

OPINION REVIEWS

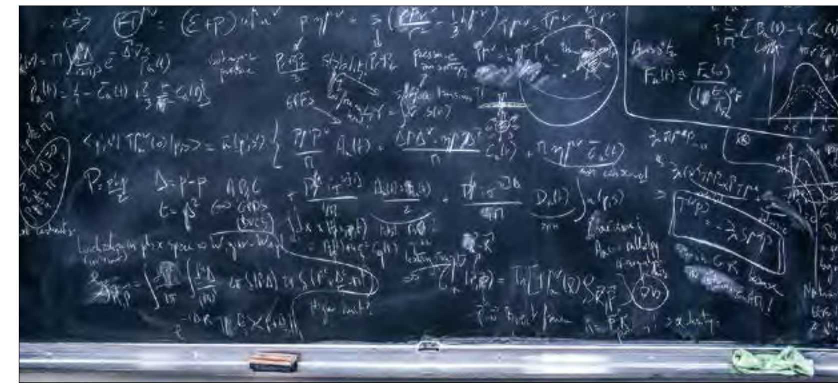
Form follows function in QCD

Hadron Form Factors: From Basic Phenomenology to QCD Sum Rules

By Alexander Khodjamirian

CRC Press

In the 1970s, the study of low-energy (few GeV) hadron–hadron collisions in bubble chambers was all the rage. It seemed that we understood very little. We had the SU(3) of flavour, Regge theory and the S-matrix to describe hadronic processes, but no overarching theory. Of course, theorists were already working on perturbative QCD and this started to gain traction when experimental results from the Big European Bubble Chamber at CERN showed signs of the scaling violations and made an early measurement of the QCD scale, Λ_{QCD}. We have been living with the predictions of perturbative QCD ever since, at increasingly higher orders. But there have always been non-perturbative inputs, such as the parton distribution functions.



Higher orders *QCD relies heavily on non-perturbative inputs.*

Hadron Form Factors: From Basic Phenomenology to QCD Sum Rules takes us back to low-energy hadron physics and shows us how much more we know about it today. In particular, it explores the formalism for heavy-flavour decays, which is particularly relevant at a time when it seems that the only anomalies we observe with respect to the Standard Model appear in various B-meson decays. It also explores the connections between space-like and time-like processes in terms of QCD sum rules connecting perturbative and non-perturbative behaviour.

The general introduction reminds us of the formalism of form factors in the atomic case. This is generalised to mesons and baryons in chapters 2 and 3, after the introduction of QCD in chapter 1, with an emphasis on quark and gluon electroweak currents and their generalisation to effective currents. Hadron spectroscopy is reviewed from a modern perspective and heavy-quark effective theory is introduced. In chapter 2, the formalism for the pion form factor, which is related to the pion decay constant, is introduced via e–π scattering. Due emphasis is placed on how one may measure these quantities. I also appreciated the explanation of how a pseudoscalar particle such as the pion can decay via the axial vector current – a question often raised by smart undergraduates. (Clue: the axial vector current is not conserved). Next, the π_{e3} decay is considered and generalised to K-, D- and B-meson semileptonic decays. Chapter 3 covers the baryon form factors and their decay constants, and chapter 4 considers hadronic radiative transitions. Chapter 5 relates the pion form factor in the space-like region to its counterpart in the time-like region in $e^+e^- \to \pi^+\pi^-$, where one has to consider resonances and widths. Relationships are developed, whereby one can see that by measuring pion and kaon form factors in e^+e^- scattering one can predict the widths of decays such as $\tau \to \pi\pi\nu$ and $\tau \to KK\nu$. In chapter 6, non-local hadronic matrix elements are introduced to extend the formalism to deal with decays such as $\pi \to \gamma\gamma$ and $B \to K\mu\mu$.

The book shifts gears in chapters 7–10. Here, QCD is used to calculate hadronic matrix elements. Chapter 7 covers the calculation of the form factors in the infinite momentum frame, whereby the asymptotic form factor can be expressed in terms of the pion decay constant and a pion distribution amplitude describing the momentum distribution between two valence partons in the pion. In chapter 8, the QCD sum rules are introduced. The two-point correlation of quark current operators can be calculated in perturbative QCD at large space-like momenta, and the result is expressed in terms of perturbative contributions and the QCD vacuum condensates. This can then be related through the sum rule to the hadronic degrees of freedom in the time-like region. Such sum rules are used to gain information on both condensate densities or quark masses from accurate hadronic data and hadronic decay constants and masses from QCD calculations. The connection is made to parton–hadron duality and to the operator product expansion. Some illustrative examples of the technique, such as the calculation of the strange-quark mass and the pion decay constant, are also given. Chapter 9 concerns the light-cone expansion and light-cone dominance, which is then used to explain the role of light-cone sum rules in chapter 10. The use of these sum rules in calculating hadron form factors is illustrated with the pion form factor and also with the heavy-to-light form factors necessary for $B \to \pi$, $B \to K$, $D \to \pi$, $D \to K$ and $B \to D$ decays.

Overall, this book is not an easy read, but there are many useful insights. This is essentially a textbook, and a valuable reference work that belongs in the libraries of particle-physics institutes around the world.

Amanda Cooper-Sarkar
University of Oxford.

Fear of a Black Universe: An Outsider's Guide to the Future of Physics

By Stephon Alexander

Basic Books

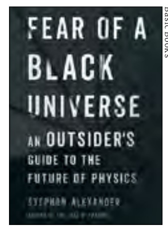
Basic Books

Enjoy the ride *Stephon Alexander's new book looks at how thinking outside the mainstream can be used to explore some of the greatest mysteries in physics.*

Stephon Alexander is a professor of theoretical physics at Brown University, specialising in cosmology, particle physics and quantum gravity. He is also a self-professed outsider, as the subtitle of his latest book *Fear of a Black Universe* suggests. His first book, *The Jazz of Physics*, was published in 2016. *Fear of a Black Universe* is a rallying cry for anyone who feels like a misfit because their identity or outside-the-box thinking doesn't mesh with cultural norms. By interweaving historical anecdotes and personal experiences, Alexander shows how outsiders drive innovation by making connections and asking questions insiders might dismiss as trivial.

Alexander is Black and internalised his outsider sense early in his career. As a postdoc in the early 2000s, he found that his attempts to engage with other postdocs in his group were rebuffed. He eventually learned from his friend Brian Keating, who is white, the reason why: "They feel that they had to work so hard to get to the top and you got in easily, through affirmative action". Instead of finding his peers' rejection limiting, Alexander reinterpreted their dismissal as liberating: "I've come to realise that when you fit in, you might have to worry about maintaining your place in the proverbial club...so I eventually became comfortable being the outsider. And since I was never an insider, I didn't have to worry that colleagues might laugh at me for my unlikely approach."

Alexander argues that true breakthroughs come from "deviants". He draws parallels between outsiders in physics and graffiti artists, who were considered vandals until the art world recognised their talent and contributions. Alexander recounts his own "deviance" in a humorous and sometimes self-deprecating manner. He recalls a talk he gave at a conference about his first independent paper, which involved reinterpreting the universe as a three-dimensional membrane orbiting a five-dimensional black hole. During the talk he was often interrupted, eventually prompting a well-respected Indian physicist to stand up and shout "Let him finish! No one ever died from theorising."



Basic Books

Alexander took these words to heart, and asks his readers to do the same during the speculative discussions in the second part of his book. Here, Alexander intersperses mainstream physics with some of his self-described "strange" ideas, acknowledging that some readers might write him off as an "oddball crank". He explores the intersection of physics with philosophy, biology, consciousness, and searches for extraterrestrial life. Some sections – such as the chapter on alien quantum computers generating the effect of dark energy – feel more like science fiction than science. But Alexander reassures readers that, while many of his ideas are strange, so are many experimentally verified tenants of physics. "In fact, the likelihood that any one of us will create a new paradigm because we have violated the norms... is very slim" he observes.

Science wise, this book is not for the faint-hearted. While many other public-facing physics books slowly wade readers into early-20th-century physics and touch on more abstract concepts only in the final chapters, part I of *Fear of a Black Universe* dives directly into relativity, quantum mechanics and emergence. Part II then launches into a much deeper discussion about supersymmetry, baryogenesis, quantum gravity and quantum computing. But the strength of Alexander's new work isn't in its retellings of Einstein's thought experiments or even its deconstruction of today's cosmological enigma. More than anything, this book makes a case for cultivating diversity in science that goes beyond "gesticulations of identity politics".

Fear of a Black Universe is both mind-bending and refreshing. It approaches physics with a childlike curiosity and allows the reader to playfully contemplate questions many have but few discuss for fear of sounding like a crank. This book will be enjoyable for scientists and science enthusiasts who can set cultural norms aside and just enjoy the ride.

Sarah Charley *deputy editor of* Symmetry *magazine.*

Your Adventures at CERN: Play the Hero Among Particles and a Particular Dinosaur!

By Letizia Diamante, illustrations by Claudia Flandoli

World Scientific Publishing

World Scientific Publishing

Billed as a bizarre adventure filled with brain-tickling facts about particles and science wonders, *Your Adventures at CERN* invites young audiences to experience a visit to CERN in different guises.

The reader can choose one of three characters, each with a different story: a tourist, a student and a researcher. The stories are intertwined, and the choice of the reader's actions through the book changes their journey, rather than following a linear chronology. The stories are filled with puzzles, mazes, quizzes and many other games that challenge the reader. Engaging physics references and explanations, as well as the solutions to the quizzes, are given at the back of the book.

Author Letizia Diamante, a biochemist turned science communicator who previously worked in the CERN press office, portrays the CERN experience in an engaging and understandable way. The adventures are illustrated with funny jokes and charismatic characters, such as "Schrödy", a hungry cat that guides the reader through the adventures in exchange for food. Detailed hand-drawn illustrations by Claudia Flandoli are included, together with photographs of CERN facilities that take the reader directly into the heart of the lab. Moreover, the book includes several historical facts about particle physics and other topics, such as the city of Geneva and the extinct dinosaurs from the Jurassic era, which is named after the nearby Jura mountains on the border between France and Switzerland. A particle-physics glossary and extra information, such as fun cooking recipes, are also included at the end.

Although targeted mainly at children, this book is also suitable for teenagers and adults looking for a soft introduction to high-energy physics and CERN, offering a refreshing addition to the more mainstream popular particle-physics literature.

Bryan Pérez Tapia *editorial assistant.*

Have you got what it takes to teach?

CERN alumni describe teaching as one of the toughest but most rewarding things they have done, and how a research background in particle physics brings significant benefits, finds Matthew Chalmers.

A Sanchez/ICTP

LHC lessons *A 2017 ICTP Physics Without Frontiers event saw students analyse LHC data via the CEVALE2VE project, one of several ways teachers can inspire students with the world of research.*

Particle physicists are no strangers to outreach, be it giving public talks, writing popular books or taking part in science shows. But how many are brave enough to enter a career in teaching, arguably the most important science-communication activity of all? CERN alumni who have returned to the classroom reveal teaching to be one of the hardest but most rewarding things they have ever done.

"I *love* my job," exclaims Octavio Dominguez, who completed his PhD in 2013 studying the appearance of electron-cloud build-up in the LHC before deciding to switch to teaching. Having personally benefitted from some excellent teachers who previously sparked an "unquenchable curiosity", he says, the idea of being a teacher had been on his mind ever since he was at secondary school. "The profession is definitely not exempt of challenges. Well, in fact I can say it's the most difficult thing I've ever done... But if I keep doing it, it's because the feedback from students is absolutely priceless. It's truly amazing seeing my students evolve into the best version of themselves."

Job satisfaction

Despite giving as many as 25 lessons per week, including presentations and practicals, and spending long hours outside school preparing materials and marking assignments, happiness and personal satisfaction are cited as the main rewards of working as a teacher. "I particularly enjoy seeing the enthusiasm in students' eyes – it is something that cannot be explained with words," says Eleni Ntomari, who was a summer student at CERN in 2006, then a PhD student and postdoc working on the CMS experiment. "From the outside, teaching might not appear difficult, but in reality it is not just a profession but a 'project' with no timetable and a continuation of trying to learn new things in order to become more efficient and helpful for your students." Ntomari took advantage of every teaching opportunity that academic life offered, from being a lab instructor, becoming a CERN guide and giving talks at local schools when a teaching opportunity in Greece arose during her postdoctoral fellowship at DESY. "I realised teaching was highly gratifying, so I decided to continue my career as a physics teacher in secondary and high schools."

Teachers of STEM subjects are in acute demand. In the US, physics has the most severe teacher shortage followed by mathematics and chemistry, with large surpluses of biology and earth-science teachers, according to the Cornell physics teacher education coalition. Furthermore, around two thirds of US high-school physics teachers do not have a degree in physics or physics education. The picture is similar in Europe, with a brief teacher survey carried out by the European Physical Society in 2020 revealing the overwhelming opinion that a serious problem exists: 81% of respondents believed there is a shortage of specialist teachers in their country, of which 87% thought that physics is being taught by non-specialists.

Initiatives such as the UN International Day of Education on 24 January help to bring visibility and recognition to the profession, says Dominguez: "Education is one of the principal means to change the world for the better, but I feel that the teaching profession is frequently disregarded by many people in our society," he says. "I've spent most of my career as a teacher in schools in deprived areas of the UK, and now I'm doing my second year in one of the most affluent schools in the country. This has given me a new perspective on society and has helped me understand better why some behaviour patterns appear."

The CERN effect

The fascinating machines and thought-provoking concepts underpinning particle physics make a research background at CERN a major bonus in the classroom, explains Alexandra Galloni, a CERN summer student in 1995 who completed her PhD at the DELPHI experiment in 1998, spent a decade in IT consultancy, and is now head of science and technology at one of the UK's top-performing secondary schools. "I milked my PhD as much as I could – I promised a visit from Brian Cox to my first school at interview, and although I didn't pull that one off, contacts at CERN have enriched life both at school and on many of the CERN trips I inevitably ended up running. The Liverpool LHCb team have hosted incredible 'Particle Schools' at CERN for students and staff from many schools almost every year since then, leading to gushing feedback from all involved."

Keeping in touch with events at CERN has also led to exciting moments for the students, she adds, such as watching the Higgs-discovery announcement in 2012, applying for Beamline for Schools in 2014, taking part in the ATLAS Open Data project and participating in Zoom calls with CERN contacts about future colliders and antimatter. "The surrounding tasks to teaching can be gruelling, and I would be lying if I said I didn't resent the never-ending to-do list and lack of being able to plan much personal time during term-time. But I love the variety, the unexpected moments and the human interaction in the classroom."

CERN offers many professional-development programmes for teachers to keep up-to-date with developments in particle physics and related areas, as well as dedicated experiment sessions at "S'Cool LAB", the coordination of the highly popular Beamline for Schools competition and internships for high-school students. These efforts are also underpinned by an education-research programme that has seen five PhD theses produced during the past five years as well as 67 published articles since the programme began in 2009. "We are reaching out to all our member states and beyond to enthuse the next generations of STEM professionals and contribute to their science education," says Sascha Schmeling, who leads the CERN teacher and student programmes. "Engaging the public with fundamental research is a vital part of CERN's mission."

Matthew Chalmers *with additional reporting from the CERN Office of Alumni Relations on the occasion of the International Day of Education.*

Appointments and awards

M Brice

2021 IOP awards

The 2021 UK Institute of Physics (IOP) awards recognised several high-energy and nuclear physicists across three categories.

In the gold-medal category David Deutsch (pictured top left; University of Oxford) won the Isaac Newton Prize for founding the discipline of quantum computation and establishing quantum computation's fundamental idea, now known as the 'qubit'; and Ian Chapman of the UKAEA (UK Atomic Energy Authority) received the Richard Glazebrook Prize for outstanding leadership of the UKAEA and the world's foremost fusion research and technology facility, the Joint European Torus, and the progress it has delivered in plasma physics, deuterium-tritium experiments, robotics and new materials.

Among the 2021 silver medallists, experimentalist Mark Lancaster (top right; University of Manchester) earned the James Chadwick Prize for distinguished, precise measurements in particle physics, particularly of the W-boson mass and the muon's anomalous magnetic moment; Michael Bentley (University of York) received the Ernest Rutherford Prize for his contributions to the understanding of fundamental symmetries in atomic nuclei; and Jerome Gauntlett (Imperial College London) won the John William Strutt Lord Rayleigh Prize for applications of string theory to quantum field theory, black holes, condensed-matter physics and geometry.

Finally, in the bronze-medal category for early-career researchers, the Daphne Jackson Prize for exceptional contributions to physics education went to accelerator physicist Chris Edmonds (bottom left; University of Liverpool) in recognition of his work improving access for the visually impaired, for example via the Tactile Collider project; and the Mary Somerville Prize for exceptional contributions to public engagement in physics went to XinRan Liu (University of Edinburgh) for his promotion of UK research and innovation to national and international audiences.

Acknowledging physicists who have contributed to the field generally, 2021 honorary IOP fellowships were granted to Lyn Evans (bottom right; for sustained and distinguished contributions to, and leadership in, the design, construction and operation of particle accelerator systems, and in particular the LHC); and climate physicist Tim Palmer, a proponent of building a "CERN for climate change" (*CERN Courier* Jul/Aug 2021 p49), for pioneering work exploring the nonlinear dynamics and predictability of the climate system.

From physics to politics

On 10 January, theoretical high-energy physicist Robbert Dijkgraaf (University of Amsterdam) was sworn in by King Willem-Alexander as minister of education, culture and science of the Netherlands,

G Porter

joining the fourth cabinet of prime minister Mark Rutte, on behalf of the social-liberal party D66. Succeeding Ingrid van Engelshoven, Dijkgraaf steps down as director of the Institute for Advanced Study in Princeton after almost 10 years of service. He asserts the opening of higher education in the Netherlands as one of his biggest priorities, stating that education should "arm" itself against COVID-19 and prepare for a future with the virus.

IAS appoints 10th director

The Institute for Advanced Study (IAS) in Princeton has announced historian David Nirenberg (University of Chicago) as its new director and Leon Levy Professor,

A Kane

effective from July. He becomes the 10th director of the 92-year-old institute, replacing Robbert Dijkgraaf (see above). Nirenberg graduated in history at Yale and received an MA and PhD from Princeton University, and was visiting scholar in the IAS School of Historical Studies in 1996. "The appointment of a humanities scholar is a bold choice, which departs from several decades of directors trained in science and mathematics, but reaffirms the importance of cross-disciplinary collaboration at IAS," said Charles Simonyi, chair of the IAS board.

Mack is new Hawking Chair

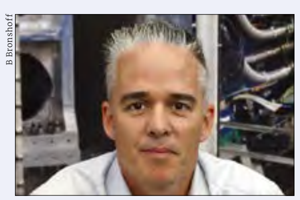
Theoretical cosmologist Katie Mack (North Carolina State University) has been appointed Hawking Chair in Cosmology and Science Communication at the Perimeter Institute, Canada, effective from June. Mack's research focuses on dark matter and the evolution of the universe. In 2020 she

The News & Observer

published her first book *The End of Everything (Astrophysically Speaking)*, exploring five ways in which the universe could end. Hawking was one of her biggest inspirations, she says: "He once described Perimeter as a 'grand experiment in theoretical physics' and I am thrilled to be part of that experiment."

Communication in LION

Experimental particle physicist Ivo van Vulpen (Nikhef and University of Amsterdam) has been appointed professor by special appointment in science communication at the Leiden Institute of Physics (LION). The five-year, one-day-per-week position was created by the Netherlands' Physical Society on the occasion of its centenary



in January. Van Vulpen, author of the popular book *How to find a Higgs Boson* (*CERN Courier* Nov/Dec 2020 p47), is a member of the ATLAS collaboration. "It's good that Leiden took this initiative," he declares. "It shows the scientific community that they are taking science communication seriously."

RECRUITMENT

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CERNCOURIER
Volume 62 Number 2 March/April 2022
IOP Publishing

PEOPLE OBITUARIES

LUCIANO GIRARDELLO 1937–2022

Deep thoughts, vision and culture

Italian theoretical physicist Luciano Girardello passed away in January, aged 84. He made important contributions to quantum field theory, supersymmetry and supergravity, and will always be remembered by friends and colleagues for his irony, vision and great humanity.

Born on 10 September 1937, Luciano graduated at the University of Milano. After a first postdoctoral fellowship at Boulder, Colorado, he worked at many institutions across the world, including Harvard University, the École normale supérieure in Paris and CERN. Upon his return to Italy, he became professor at the University of Milano, where he spent several years, and in 2000 he moved to the new University of Milano-Bicocca, contributing to the creation of its physics department, where he remained for the rest of his career.

Luciano was interested in all aspects of fundamental physics, from quantum field theory to gravity, and made seminal contributions to the foundations of supersymmetry and supergravity in their early days. In a fruitful collaboration with other pioneers of the subjects, including Eugène Cremmer, Sergio Ferrara and Antoine Van Proeyen, he investigated the coupling of matter in supergravity, which is fundamental for the experimental search for supersymmetry, the modern theory of gravitation and the effective theories of string compactifications. Luciano was one of the first to study the mechanisms of supersymmetry breaking, rooting the theory in reality. In the final part of his career, he applied the AdS/CFT correspondence, or gauge/gravity duality, to the understanding of fundamental problems in quantum field theory. He was not interested in theoretical speculations or mathematical tricks but rather in understanding the nature of things and in the cross-fertilisation of fields and ideas. Many of his contributions to physics were born in the corridors of the CERN theory division, in long days and endless nights spent with friends and collaborators.

Luciano's wide and original lectures on different topics at the universities of Milano and Milano-Bicocca inspired students for more than 30 years. His deep thoughts, vision and culture also informed and educated many generations of talented young physicists who are now active in the international arena. Greatly admired as a physicist, he will be remembered by those who had the good fortune to know him well as a great human being, a cultivated and refined person, and an old-time gentleman.


Family photograph

Luciano was interested in all aspects of fundamental physics, from quantum field theory to gravity.

His friends and colleagues.

COSTAS KOUNNAS 1952–2022

A talented, many-faceted physicist

Renowned Cypriot–French theoretical physicist Costas Kounnas passed away suddenly on 21 January, two days before his 70th birthday. Born in Famagusta, Cyprus, Costas did his undergraduate studies at the National and Kapodistrian University of Athens before moving to Paris for his advanced degree. His studies were interrupted by military service during the events in Cyprus in 1974, after which he completed his PhD at the École polytechnique, carrying out important calculations of QCD effects in deep inelastic scattering and jets. He joined the CNRS in 1980, and later took up a postdoctoral fellowship at CERN, where he made seminal contributions to models of supersymmetry and supergravity. In particular, he helped develop supergravity models in which supersymmetry was broken spontaneously without generating any vacuum energy – a bugbear of globally supersymmetric theories. Working with Costas on these models was one of our most exhilarating collaborations.

Costas then moved to Berkeley where he became a world expert in the construction of string models, showing in particular how they could be formulated directly in four dimensions, without invoking the compactification of extra dimensions. In 1987 he took up a position at the École normale supérieure in Paris, where he remained for the rest of his career, apart from a CERN staff position between 1993 and 1998. Many of his best-known papers during these periods concerned cosmological aspects of string models, loop corrections and the breaking of supersymmetry – topics in which he was a world leader. He was also director of the theoretical physics group at the École normale supérieure between 2009 and 2013.

Among his accolades, Costas was awarded the Paul Langevin Prize of the French Physical Society in 1995 and the Gay-Lussac Humboldt Prize in 2013 for outstanding scientific contributions, especially to cooperation between Germany and France. In addition, he received a prestigious Research Award from the Adolf von Humboldt Foundation in 2014.

His many friends mourn the passing, not just of a distinguished theoretical physicist, but also of a warm colleague with a great heart that he was not shy of wearing on his sleeve. Costas enjoyed participating exuberantly in scientific discussions, always with the overriding aim of uncovering the truth. We remember a joyful and energetic friend who was passionate about many other aspects of life beyond science, including his many friendships and his home island of Cyprus. He was active in efforts to develop its relations with CERN, where it is now an Associate Member on its way towards full membership.

Costas Kounnas at CERN in 1995.

John Ellis *King's College London/CERN and* **Dimitri Nanopoulos** *Texas A&M University.*

David Saxon 1945–2022

An exceptional leader and experimentalist

Experimental particle physicist David Saxon passed away on 23 January. A native of Stockport, south of Manchester, where his father was a parish minister, he attended the University of Oxford and obtained his doctorate measuring pion–nucleon scattering at the Rutherford Laboratory, followed by a short postdoc there. His doctoral research took him to Paris and Berkeley, where in both cases he reported that his arrival was marked by the onset of student riots.

After a period at Columbia University, he moved to Illinois to work in Leon Ledermann's group at the newly built Fermilab. Here he helped to develop electron and muon identification techniques, which would prove fruitful in future electroweak experiments. The group did not discover the W and Z, but did find a signal that was later associated with charm mesons. Returning to Rutherford, soon to be Rutherford Appleton Laboratory (RAL), in 1974 David was quickly promoted to senior researcher. Realising that the future lay in "counter" physics, rather than bubble chambers, he worked on hadron–proton scattering in the resonance region. With the PETRA collider at DESY announced soon afterwards, David helped to form the UK contribution to the TASSO experiment, which made important measurements of electron–positron scattering. The PETRA experiments would go on to discover the gluon, enabling the Standard Model to be constructed with confidence.

After PETRA came HERA, which remains the world's only high-energy electron–proton collider. David first led the RAL team working on the central tracking detector for the ZEUS experiment, but it was not long before he was invited to the newly reinstituted Kelvin professorship at the University of Glasgow, where he arrived in 1990 and spent the remainder of his academic career. He built the group significantly, its present healthy state founded on what he achieved. In addition to taking Glasgow into ZEUS, he nurtured many other activities – in particular involvement in the ALEPH experiment at LEP – and was instrumental in the design of central tracking systems for projects that eventually combined to become ATLAS.


University of Glasgow

David Saxon was a major force in UK particle physics.

David was instrumental in the design of central tracking systems for projects that eventually combined to become ATLAS

He was hardly installed in Glasgow before being appointed for several years as chair to the UK's former Particle Physics Committee. There was no more important position to hold at the time, and David's good sense, insight and intelligence helped to enable the subject to survive and prosper during a time when funding was tight and the UK funding system was being reorganised. Undaunted, he convinced the group in Glasgow that now was an excellent opportunity to host the 1994 edition of ICHEP.

David was one of the most sociable of people, always a good team player and invariably provocative and stimulating in conversation. Inevitably, the call came to move higher up in the university, first as a highly regarded head of department and later as dean of the science faculty – a post he occupied until shortly before his retirement. Meanwhile, he served on numerous local, national and international committees, including the UK CERN delegation and CERN policy committees, where his perceptiveness was always in demand. The UK recognised his distinguished and important contributions to science with the award of an OBE.

It was a sadness that his final years were marked by Parkinson's disease, but he still participated in CERN Council meetings. He was at all times supported by his wife Margaret, with whom he had a son and a daughter, and found strength and comfort in his church membership. Those who were fortunate enough to know and work with David will never forget his positive and energetic character, always fair-minded, competitive without being aggressive, and caring. He will be much missed, and inspirational memories will remain.

Peter Bussey *and* **Tony Doyle** *on behalf of the Glasgow group.*

Ronald Shellard 1948–2021

A tireless promoter of Brazilian physics

Ronald Shellard began his journey in physics in the 1970s at the University of São Paulo, where he took his undergraduate degree, and at the Institute of Theoretical Physics of São Paulo State University, where he completed his master's in 1973. He received his doctorate, titled "Particle physics field theory, dynamical symmetry breakdown at the two loop and beyond", from the University of California, Los Angeles in 1978 after also spending time at the University of California, Santa Barbara.

After a period working in theoretical particle physics, Shellard devoted himself to experimental and astroparticle physics. He joined the DELPHI collaboration at the former LEP collider at CERN in 1989, and in 1995 he joined the Pierre Auger Observatory, where he made an outstanding contribution both as a researcher and as an articulator of Brazilian collaboration. Remaining in the astroparticle field, during the past decade he was also involved in the Cherenkov Telescope Array, the Large Array Telescope for Tracking Energetic Sources and the Southern Wide Field Gamma-Ray Observatory.

Shellard played a key role in efforts to make Brazil an official member of CERN

From 2009 to 2013, Shellard was vice-president of the Brazilian Physical Society. He participated tirelessly on various initiatives to promote Brazilian physics, such as the establishment of the exchange programme with the American Physical Society, the strengthening of the Brazilian physics Olympiad, the in-depth study of physics and national development, the establishment of the internship programme of high-school teachers at CERN, and the initiative to create a professional master's degree in physics teaching. He was a member of the Brazilian Academy of Science since 2017, director of the Centro Brasileiro de Pesquisas Físicas since 2015 and president of the Brazilian network of high-energy physics since 2019. He played a key role in efforts to make Brazil an official member of CERN – a process that appears to be reaching a successful conclusion, with the CERN Council voting in September 2021 to grant to Brazil the status of Associate Member State, pending the signature of the corresponding agreement and its ratification by Brazilian authorities. Active until a few days before he passed away on 7 December, Ron was very excited about this news and was making plans for the next steps of the accession procedure.


LIP

Ronald Shellard was a long-time proponent of Brazil joining CERN as an Associate Member State.

Ron Shellard had an innovative and sensibly optimistic spirit, with a comprehensive and progressive vision of the crucial role of physics, and science in general, for the progress of Brazilian society. He exerted a great influence on the formation of the research community in high-energy physics. He was the advisor of several graduate students and had a permanent commitment to the training of new scientists and the dissemination and popularisation of science in the country.

Leandro de Paula *Federal University of Rio de Janeiro.*

Bernhard Spaan 1960–2021

Shaping heavy-flavour physics

Bernhard Spaan, an exceptional particle physicist and a wonderful colleague, unexpectedly passed away on 9 December, much too early at the age of 61.

Bernhard studied physics at the University of Dortmund, obtaining his diploma thesis in 1985 working on the ARGUS experiment at DESY's electron–positron collider DORIS. Together with CLEO at Cornell, ARGUS was the first experiment dedicated to heavy-flavour physics, which became the central theme of Bernhard's research work for the following 36 years. Progressing from ARGUS and CLEO to the higher-statistics experiments BaBar and ultimately LHCb, for which he made early contributions, he was one of the pioneering leaders in the next generation of heavy-flavour experiments at both electron–positron and hadron colliders.

While working on tau-lepton decays at ARGUS for his doctorate, Bernhard led a study of tau decays to five charged pions and a tau neutrino, which resulted in the world's best upper limit for the tau-neutrino mass at the time. He also pioneered a new method of reconstructing the pseudo mass of the tau lepton by approximating the tau direction with the direction of the hadronic system. This method led to a new tau-lepton mass, which was an important ingredient to resolve the long-standing deviation from lepton universality as derived from the measurements of the tau lifetime, mass and leptonic branching fraction.

In 1993 Bernhard joined McGill University in Montreal, where he contributed to CLEO operation, data-taking and analysis, and was brought into contact with the formative stages of an asymmetric electron–positron B-factory at SLAC. He was an author of the BaBar letter of intent in 1994 and remained a leading member of the collaboration for the following two decades.


TU Dortmund

Bernhard Spaan worked on the ARGUS, CLEO, BaBar and LHCb experiments.

Bernhard saw the unique potential of a dedicated B experiment at the LHC and joined the LHCb collaboration

In 1996 Bernhard started a professorship at Dresden where, together with Klaus Schubert, he built a strong German BaBar participation including involvement in the construction and operation of the calorimeter. At that time, BaBar was pioneering the use of distributed computing resources for data-processing. As one of the proponents of this approach, Bernhard played a crucial role in the German contribution via the computing centre at Karlsruhe, later "GridKa". Building on the success of the electron–positron B-factories, Bernhard saw the unique potential of a dedicated B experiment at the LHC and joined the LHCb collaboration in 1998.

Bernhard's scientific journey came full circle when he accepted a professorship at Dortmund University in 2004, which he used to significantly grow his LHCb participation. The Dortmund group is one of LHCb's largest, with a long list of graduate students and main research topics including the determination of the CKM angles β and γ governing CP violation in rare B decays. In parallel with LHC Run 1 and 2 data-taking, Bernhard investigated the possibility of using scintillating fibres for a novel tracking detector capable of operating at much larger luminosities. In all phases of the "SciFi" detector, which was recently installed ahead of LHC Run 3, he supported the project with his ideas, his energy and the commitment of his group.

Bernhard was an outstanding experimental physicist whose many contributions shaped the field of experimental heavy-flavour physics. He was also a great communicator. His ability to resolve conflicts and to find compromises brought many additional tasks to Bernhard, whether as dean of the Dortmund faculty, chair of the national committee for particle physics, member of R-ECFA or chair of the LHCb collaboration board. When help was needed, Bernhard never said "no".

We have lost a tremendous colleague and a dear friend who will be sorely missed not only by us, but the wider field.

Andrey Golutvin *Imperial College London,* **David MacFarlane** *SLAC and* **Ulrich Uwer** *Heidelberg University.*

CERNCOURIER

VOLUME 62 NUMBER 2 MARCH/APRIL 2022

IOP Publishing

BACKGROUND

Notes and observations from the high-energy physics community

Check out the bison cam

Fermilab

Fans of the Fermilab bison, rejoice: a new webcam allows these fine beasts to be observed 24 hours a day, seven days a week (fnal.gov/pub/about/bisoncam). Founding director Robert Wilson established the storied herd in 1969 as a symbol of the history of the Midwestern prairie. What began with a bull and four cows has grown to an almost 30-strong herd. In 2015, a genetic study confirmed the herd to be 100% bison, with no evidence of cattle genes. In 2016 president Obama signed the National Bison Legacy Act declaring the American bison the national mammal of the US.

Astronomy strikes back

M Lewinsky

Tech tracks *Starlink satellites after launch.*

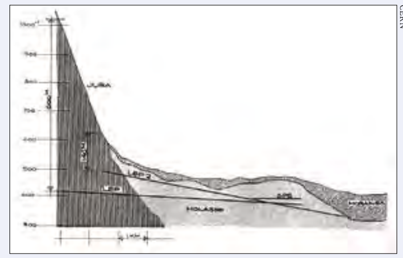
Concerned about the negative impact of large satellite constellations such as Starlink on ground-based optical and radio astronomy, the International Astronomical Union (IAU) has established a Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference. The centre's hosts, NOIRLab and the SKA Observatory, selected on 3 February, will team up with industry to find a solution that suits all parties. "The new centre is an important step towards ensuring that technological advances do not inadvertently impede our study and enjoyment of the sky," said IAU president Debra Elmegreen.

59 MJ

The new record for sustained fusion energy set by the Joint European Torus on 21 December with a fusion pulse lasting more than five seconds, almost three times higher than the previous energy record set by the UK-based facility in 1997

From the archive: March 1982

Tilting LEP



CERN

The new proposed location (LEP2).

The section of LEP which passes deep under the Jura has long been recognized as the riskiest part of the civil engineering programme. The new location became possible on accepting that the accelerator could be built on an incline (about 1.8 degrees). LEP could then be moved to the east towards Lake Geneva, remaining in the molasse. Also the maximum depth below the surface is reduced to 150 m. This both reduces the maximum water pressure which could be experienced and makes it feasible to intervene from the surface. Thus the machine construction can be attacked with increased confidence. There are of course some disadvantages. The length of the bypass which could make electron–proton collisions possible at some later date is doubled, and the tilting of the LEP plane requires a more sophisticated pumping system for the water cooling.

● Based on text from pp61–62 of *CERN Courier* March 1982.

Compiler's note

Although yet to witness electron–proton collisions, the tunnel now hosting the LHC was a prudent investment for CERN. Today, engineers are converging on the placement of a 91 km tunnel with an average depth of approximately 250 m for a proposed Future Circular Collider emulating the LEP+LHC success. The FCC tilt will be chosen to ensure that the tunnel is constructed in the most favourable geology and to minimise shaft depths.

Media corner

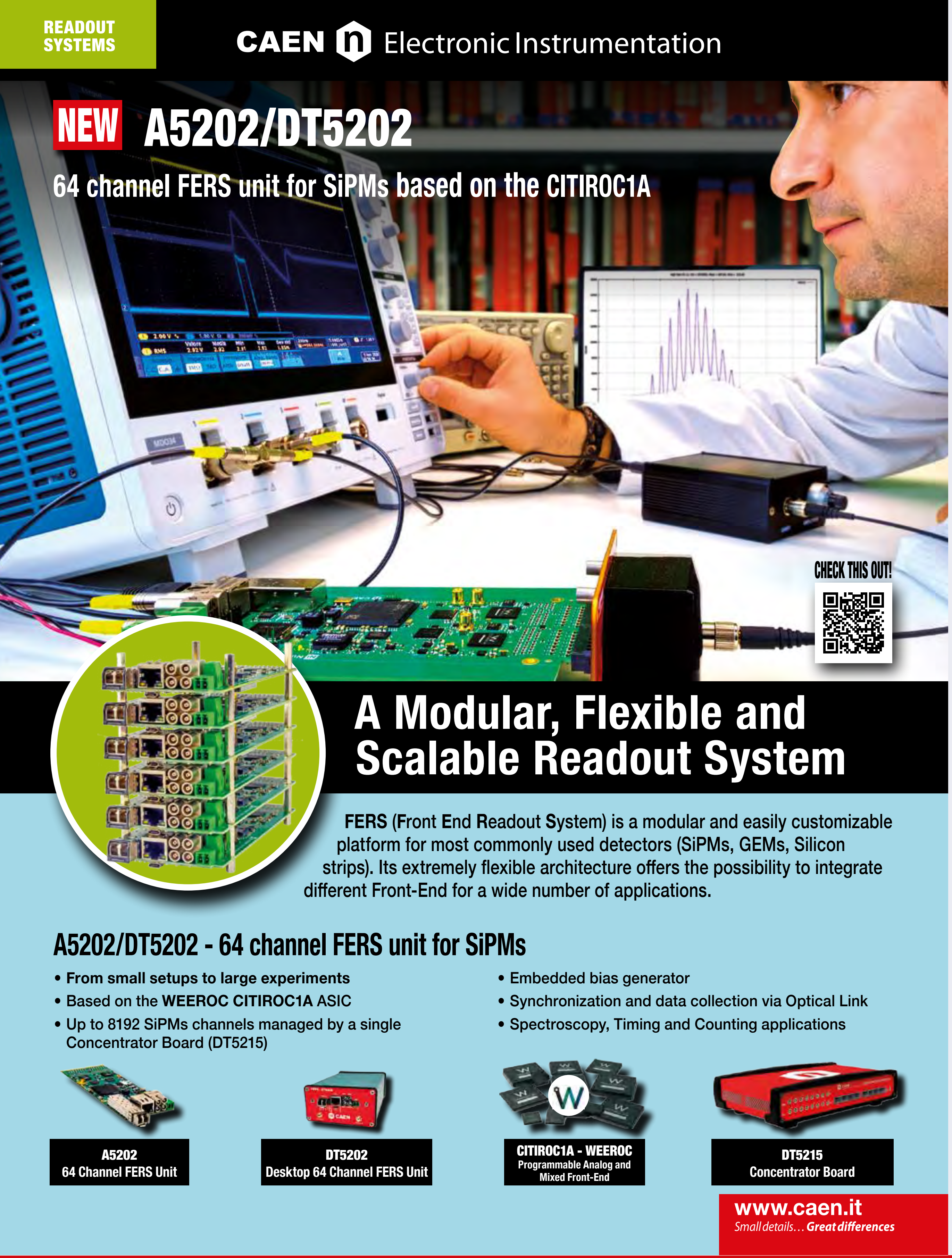
"The laser can be a beast… I'm not sure what the laser gods do on a good or bad day."
Accelerator physicist **Andreas Maier** explaining the promise of laser-driven plasma wakefield accelerators (*Optica*, 1 February).

"Until a few years ago, I would think that physicists and computer scientists were living in parallel worlds."
Electrical engineer **Eleni Diamanti** discussing quantum machine learning (*Quanta*, 4 February).

"Holes are nice in Emmental and Stilton cheese, but we can't afford a hole in the EU research area."
Robert-Jan Smits, former director-general of research and innovation at the European Commission, quoted in *Science Business* (10 February) on Swiss and UK participation in Horizon Europe.

"Interventions that aim to fix young girls and women instead of fixing institutional structures and processes based on evidence, have made, and will make, progress extremely slow."
Astrophysicist **Prajval Shastri** discussing gender in science in *The Indian Express* (17 February).

"It's clear to me that doubling the NSF budget is rational, reasonable and much needed."
Rita Colwell, a former National Science Foundation director, quoted in *Nature* (4 February) on the passing of the America COMPETES Act.



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