WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2021 issue of *CERN Courier*.

Assembly of the tokamak for the ITER fusion experiment (cover feature, p34) is in full swing, marking a crucial new phase in the project. ITER is the culmination of more than half a century of efforts to magnetically confine and heat a plasma inside a large tube from which energy may eventually be extracted. Two decades of scheduled operations starting in 2025 will determine the integrated technologies, materials and physics regimes necessary for the commercial production of fusion-based electricity. As a large international collaboration relying on similar technologies, the project has a natural affinity with high-energy physics.

Heavy lifting is also taking place at CERN, with the second of the new ATLAS muon end-cap wheels (p27) making its way underground – one of countless activities that have taken place across the experiments and accelerator complex during Long Shutdown 2 to prepare for the LHC restart in the spring (p7).

Elsewhere in the issue: a tribute to the great Steven Weinberg (p43); precision luminosity measurements at CMS (p39); SKA project enters construction (p49); counting down to the next collider (p47); stirrings in the world of sterile neutrinos (p8); the latest meeting reports (p21); reviews (p55); careers (p57) and more.

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EDITOR: MATTHEW CHALMERS, CERN
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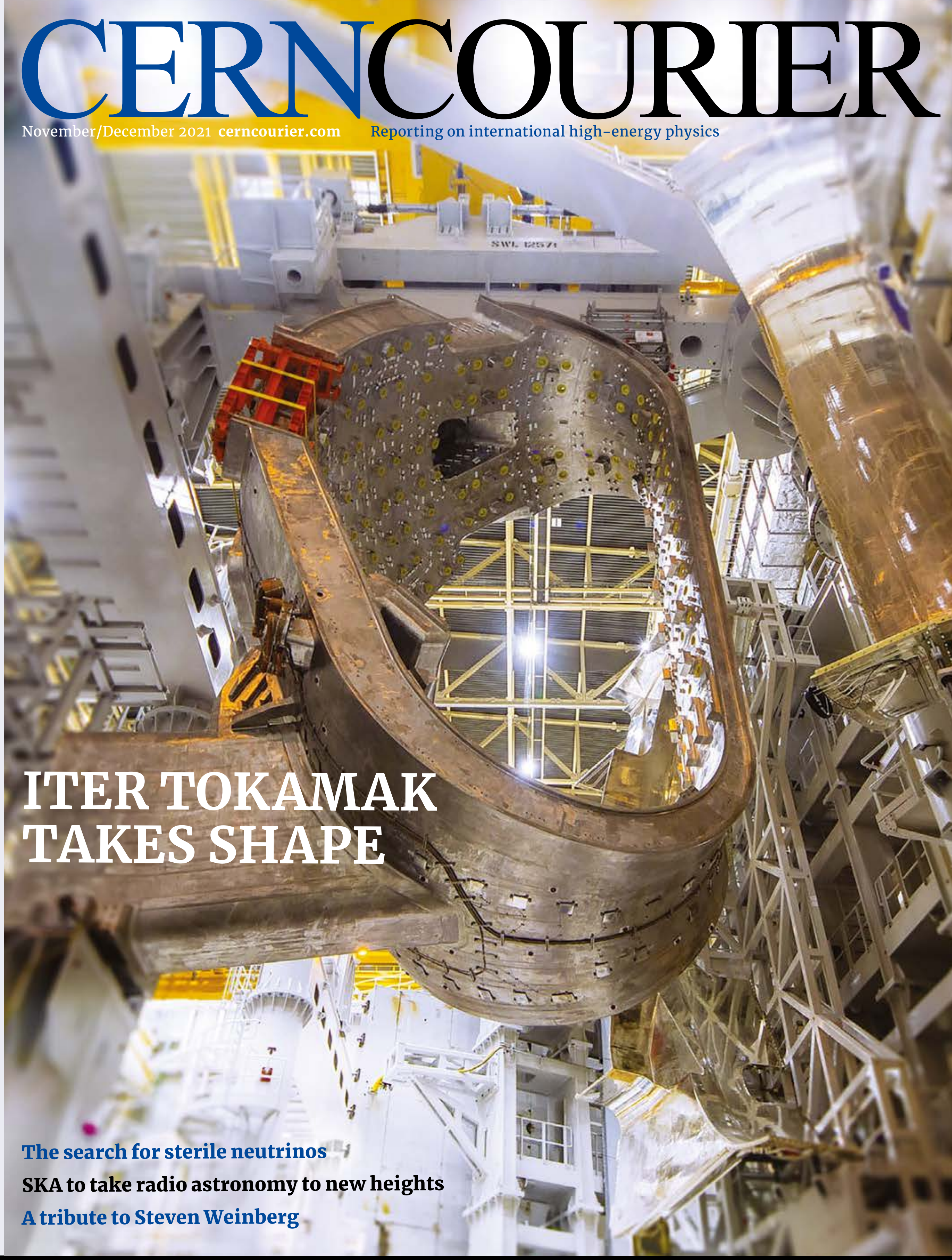

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FROM THE EDITOR

On track to tackle fusion's burning issues

Matthew Chalmers
Editor

Speaking in 1955 at the first Conference on the Peaceful Uses of Atomic Energy in Geneva, conference president Homi Bhabha predicted that a method would be found for liberating fusion energy in a controlled manner "within the next two decades". Technological realities were to dash such early optimism.

Exploring fusion energy by magnetically confining and heating a plasma inside a large tube has been a growing international effort for 70 years, with increasing investment in private ventures in recent years. The largest "tokamak" so far, the Joint European Torus (JET) located in the UK, produced first-plasma on time and on budget in 1983. Two years later, at the 1985 Geneva Summit, General Secretary Gorbachev of the former Soviet Union proposed to US President Reagan a next-generation plasma experiment built as a collaborative international project. In 2006, an international treaty establishing the ITER Organization was signed by China, the European Union, India, Japan, Korea, Russia and the US – together representing well-over half the world's population.

As a large international collaboration relying on similar technologies, the project has a natural affinity with high-energy physics. CERN entered a collaboration agreement with ITER in 2008 concerning the design of high-temperature superconducting current leads and other magnet technologies, and has helped with ITER's metallurgy, cryoplants, magnetic-field quality and safety systems based on its experience with the LHC. ITER's use of 600 tonnes of niobium-tin strands likewise offers valuable experience for the development and production of high-field magnets for a potential future circular collider.

CERN entered a collaboration agreement with ITER in 2008

Whereas JET demonstrated a record plasma Q-value (the ratio of plasma heating input to output) of 0.67, ITER seeks a Q-value of at least 10, demonstrating the first self-sustaining or "burning" fusion plasma. ITER will not capture the energy it produces, and a working "plant" Q-value would be lower due to electrical conversion and other practical factors. But two decades of scheduled ITER operations will determine the integrated technologies, materials and physics regimes necessary for the commercial production of fusion-based electricity.

ITER Organization

Input only *Part of a power system to reduce harmonic distortions in the AC current that ITER draws from the grid.*

At 23,000 tonnes, ITER will be almost twice as massive as the CMS detector. Its vacuum vessel is 10 times bigger than anything before it, while its central solenoid must contain internal forces of 60 MN – twice the thrust of the Space Shuttle at take-off. A decade since construction began in the South of France, ITER's giant tokamak is now being assembled, with first-plasma scheduled for December 2025 and deuterium–tritium operations beginning in the mid-2030s (p34).

Life after LS2

Heavy lifting is also taking place at CERN, with the second of the new ATLAS muon end-cap wheels (p27) making its way underground as the *Courier* went to press. It is one of numerous upgrades large and small to the LHC experiments that have taken place during Long Shutdown 2, along with an unfathomable amount of work across the CERN accelerator complex to prepare for more luminous operations during LHC Run 3 and beyond (p7).

Also in this issue: a tribute to the great Steven Weinberg (p43); precision luminosity measurements at CMS (p39); counting down to the next collider (p47); rumblings in the world of sterile neutrinos (p8); the latest meeting reports (p21); reviews (p55); careers (p57) and more.

Reporting on international high-energy physics

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Editor Matthew Chalmers
Deputy editor Mark Rayner
Editorial assistant Craig Edwards
Archive contributor Peggie Rimmer
Astrowatch contributor Merlin Kole
E-mail cern.courier@cern.ch

Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Laboratory correspondents
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SLAC National Accelerator Laboratory Melinda Baker
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

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Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Tom Houlden
Recruitment sales Chris Thomas
Advertisement production Katie Graham
Marketing and circulation Laura Gillham, Jessica Pratten

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

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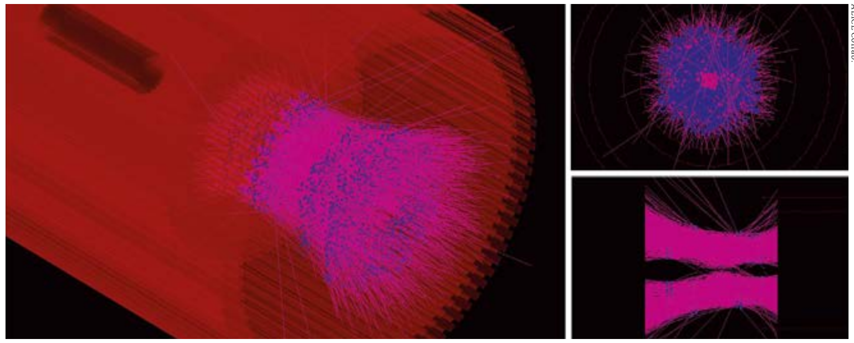
NEWS ANALYSIS

LARGE HADRON COLLIDER

Protons back with a splash

After a three-year hiatus, protons are once again knocking on the LHC's door, as physicists make final preparations for the start of Run 3. At the beginning of October, a beam of 450 GeV protons made its way from the Super Proton Synchrotron (SPS) down the TI2 beamline towards Point 2, where it struck a dump block and sprayed secondary particles into the ALICE experiment (see image). Beam was also successfully sent down the other SPS–LHC transfer line, TI8, which meets the LHC near to where the LHCb experiment is located.

Commissioning the transfer lines marks the latest milestone in the reawakening of CERN's accelerator complex, which closed down at the end of 2018 for Long Shutdown 2 (LS2). LHC beam tests were scheduled to begin in earnest on 18 October, just after the *Courier* went to press, during which the operation team will circulate counter-rotating beams in the LHC. The tests are expected to last for two weeks, with collisions in the experiments at 450 GeV per beam also planned.



ALICE Collab.

In business *Upstream "splash" muons in the ALICE Muon Forward Tracker recorded on 9 October, allowing the collaboration to check that its rejuvenated and recently closed detector is working as expected ahead of Run 3 next year.*

Final countdown

Beams have been back at CERN since the spring. After a comprehensive two-year overhaul, the Proton Synchrotron (PS) accelerated its first beams on 4 March and has recently started supplying experiments in the newly refurbished East Area and at the new ELENA ring at the Antimatter Factory. Connecting the brand-new Linac4 to the upgraded PS Booster (which also serves ISOLDE) was a major step in the upgrade programme. Together, they now provide the PS with a 2 GeV beam, 0.6 GeV up from before, for which the 60-year-old machine had to be fitted out with refurbished magnets, new beam-dump systems, instrumentation, and upgraded RF and cooling systems. LS2 saw an even greater overhaul of the SPS, including the addition of a new beam-dump system, a refurbished RF system that now includes the use of solid-state amplifier technology, and a major overhaul of the control system. Combined with the LHC Injectors Upgrade project (the main focus of LS2), the accelerator complex is now primed for more intense beams, in particular for the High-Luminosity LHC (HL-LHC) later this decade.

The first bunch was injected from the PS into the SPS on 12 April, building up to "LHC-like" beams of up to 288 bunches a few weeks later. The SPS delivers beams to all of CERN's North Area experiments, which include a new facility, NA55, approved in 2019 to investigate fast-neutron production for better understanding of the background in underground neutrino experiments. It also drives the AWAKE experiment, which performs R&D for plasma-wakefield acceleration and entered its second run in July with the goal of demonstrating acceleration gradients of 1 GV/m while preserving the beam quality. The restart of North Area experiments will also see pilot runs for new experiments such as AMBER (the successor of COMPASS) and NA64μ (NA64 running with muon beams).

Brighter and more powerful

When the LHC comes back online for physics in May 2022, it will not only be more luminous (with up to 1.8×10^{11} protons per bunch compared to 1.3–1.4×10^{11} during Run 2), but it will also operate at higher energies. This year, the majority of the LHC's 1232 dipole magnets were trained to carry 6.8 TeV proton beams, compared to 6.5 TeV before, which involves operating with a current of 11.5 kA (with a margin of 0.1 kA). Following the beam tests this autumn, magnet training for the final two of the machine's eight sectors will take place during a scheduled maintenance period from 1 November to 21 February. After that, the LHC tunnel and experiment areas will be closed for a two-week-long "cold checkout", with beam commissioning commencing on 7 March and first stable beams expected during the first week of May.

Meanwhile, the LHC experiments are continuing to ready their detectors for the bumper Run-3 data harvest ahead: at least 160 fb^{-1} (as for Run 2) to ATLAS and CMS; 25 fb^{-1} to LHCb (compared to 6 fb^{-1} in Run 2); and 7.5 nb^{-1} of Pb–Pb collisions to ALICE (compared to 1.3 nb^{-1} in Run 2). The higher integrated luminosities expected for ALICE and LHCb are largely possible thanks to the ability of their upgraded detectors to handle the Run-3 data rate, with LHCb teams currently working around the clock to ensure their brand-new sub-detectors are in place. New forward-experiments, FASER, FASERν and SND@LHC, which aim to make the first observations of collider neutrinos and open new searches for feebly interacting particles, are also gearing up to take first data when the LHC comes back to life.

"The injector performance reached in 2021 is just the start of squeezing out the potential they have been given during LS2, paving the way for the HL-LHC, but also benefiting the LHC's performance during Run 3," says Rende Steerenberg, head of the operations group. "Having beam back in the entire complex and routinely providing the experimental facilities with physics is testimony to the excellent and hard work of many people at CERN."

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NEUTRINOS

MicroBooNE homes in on sterile neutrino

Excitement is building in the search for sterile neutrinos – long-predicted particles that would constitute physics beyond the Standard Model. Although impervious to the electromagnetic, weak and strong interactions, such a fourth "right-handed" neutrino flavour could reveal itself by altering the rate of standard-neutrino oscillations – tantalising hints of which were reported by Fermilab's MiniBooNE experiment in 2007. In a preprint published last week, neighbouring experiment MicroBooNE strongly disfavours a mundane explanation for such hints, with further scrutiny by the collaboration expected to be announced later this month.

"If the MiniBooNE effect is indeed a sterile neutrino, this of course would be a major discovery that would revolutionise particle physics, opening up a whole new sector to explore," says MicroBooNE co-spokesperson Justin Evans of the University of Manchester.

The story of the sterile neutrino began in the 1990s, when the LSND experiment at Los Alamos reported seeing 88±23 (3.8σ) more electron antineutrinos than expected in a beam of accelerator-generated muon antineutrinos. This apparent short-baseline oscillation from muon to electron antineutrinos was incompatible with the oscillation rates established by Super-Kamiokande in 1998 and SNO in 2002, and would have to occur via an unknown intermediate neutrino flavour with a mass of about an electronvolt. This hypothesised neutrino was dubbed sterile, as it would have to be insensitive to all interactions but gravity for it to have remained undiscovered for this long.

MicroBooNE

Trailblazing TPC *MicroBooNE can shed light on the MiniBooNE anomaly by differentiating electromagnetic showers from electrons and photons.*

Accumulating anomalies

The plot thickened in 2007 when the MiniBooNE experiment at Fermilab tried to reproduce the LSND anomaly. The team also saw an excess of electron-like signals, though not quite at the energy corresponding to the LSND effect. The significance of the MiniBooNE anomaly grew to 4.5σ by the time the experiment finished running in November 2018. But a mundane possible explanation poured cold water on hopes for new physics: as a mineral-oil Cherenkov detector, MiniBooNE could not differentiate electrons from photons, and one particularly tricky-to-model background process might be contributing more photons than expected.

"High-energy single photons can be produced when a neutrino scatters on a nucleon via a neutral-current interaction and excites the nucleon to a Δ(1232) resonance," explains CERN theorist Joachim Kopp. "Most of the time, the resonance decays to a pion and a nucleon, but there is a rare decay mode to a nucleon and a photon. The rate for this mode is very hard to predict, and many of us suspected that there could be something wrong with predictions for this background."

Enter MicroBooNE, a liquid-argon time-projection-chamber sibling experiment to MiniBooNE that is capable of studying neutrino interactions in photographic detail, and differentiating the two signals. Having detected its first neutrino interactions in 2015, the MicroBooNE team has now set a limit on the neutral-current $\Delta \rightarrow N\gamma$ process that is more than a factor of 50 better than existing constraints, explains Evans. "With this MicroBooNE result, we reject a $\Delta \rightarrow N\gamma$ model of the low-energy excess at 94.8% confidence, a strong indication that we must look elsewhere for the source of the excess."

Now that MicroBooNE has strongly disfavoured a leading-photon model for the MiniBooNE anomaly, attention shifts to the electron hypothesis – which would hint at the existence of a sterile neutrino, or something more exotic, if proven. And we don't have long to wait. The MicroBooNE collaboration plans to release its search for an electron-like low-energy excess on 27 October, with results from three independent analyses looking at a range of inclusive and exclusive channels.

"Beyond that, there is more to come," says Evans. "Our current round of results use only the first half of the total MicroBooNE data-set, and this is a programme that is only just beginning, with ICARUS and SBND within Fermilab's short-baseline programme now coming online to turn this into a multi-baseline exploration of the richness of neutrino physics with unparalleled detail."

The global picture is complex. In 2019, for example, the MINOS+ experiment at Fermilab failed to confirm the MiniBooNE signal (*CERN Courier* March/April 2019 p7). Were the sterile neutrino to exist, it should also have significant cosmological consequences that remain unobserved. But the anomalies are accumulating, says Kopp.

"LSND and MiniBooNE are quite consistent, and the short-baseline reactor experiments require parameters in the same region of parameter space, though these results are very much in flux and it's not clear which ones are trustworthy, so it's hard to make precise statements. The good news is that there's realistic hope of resolving these puzzles over the next few years."

Further reading

MicroBooNE collaboration 2021 arXiv.org:2110.00409.
V Brdar and K Kopp 2021 arXiv:2109.08157.

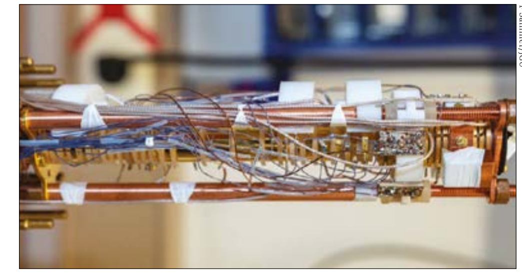
ANTIMATTER

BASE demonstrates two-trap cooling

In a significant technological advance for antimatter research, the BASE (Baryon Antibaryon Symmetry Experiment) collaboration at CERN's Antimatter Factory has used laser-cooled ions to cool a proton more quickly and to lower temperatures than is possible using existing methods. The new technique, which introduces a separate Penning trap, promises to reduce the time needed to cool protons and antiprotons to sub-Kelvin temperatures from hours to seconds, potentially increasing the sample sizes available for precision matter-antimatter comparisons by orders of magnitude. As reported in *Nature* on 25 August, the collaboration's test setup at the University of Mainz also reached temperatures approximately 10 times lower than the limit of the established resistive-cooling technique.

"The factor-10 reduction in temperature that has been achieved in our paper is just a first step," says BASE deputy spokesperson Christian Smorra of the University of Mainz and RIKEN. "With optimised procedures we should be able to reach particle temperatures of order 20 to 50 mK, ideally in cooling times of order 10 seconds. Previous methods allowed us to reach 100 mK in 10 hours."

The new setup consists of two Penning traps separated by 9 cm. One trap contains a single proton. The other contains a cloud of beryllium ions that are laser-cooled using conventional techniques. The proton is cooled as its kinetic energy is transferred through a superconducting resonant electric circuit into the cooler beryllium trap. The proton and the beryllium ions can be thought of as mechanical oscillators within the magnetic and electric fields of the Penning traps, explains lead author Matthew Bohman of the Max Planck Institute for Nuclear Physics in



F Sämmer/JGU

Antiproton prospects *The BASE collaboration's new two-trap sympathetic-cooling setup at the University of Mainz.*

Heidelberg and RIKEN. "The resonant electric circuit acts like a spring, coupling the oscillations – the oscillation of the proton is damped by its coupling to the conventionally cooled cloud of beryllium ions."

The collaboration's unique two-trap sympathetic-cooling technique was first proposed in 1990 by Daniel Heinzen and David Wineland. Wineland went on to share the 2012 Nobel Prize in Physics for related work in manipulating individual particles while preserving quantum information. The use of a resonant electric circuit to couple the two Penning traps is an innovation by the BASE collaboration which speeds up the rate of energy exchange relative to Heinzen and Wineland's proposal from minutes to seconds. The technique is useful for protons, but game-changing for antiprotons. A two-trap setup is attractive for antimatter because a single Penning trap cannot easily accommodate particles with opposite charges, and laser-cooled ions are nearly always positively charged, with electrons stripped away. BASE previously cooled antiprotons by coupling them to a superconducting resonator at around 4 K, and painstakingly selecting the lowest energy antiprotons in the ensemble over many hours.

"With two-trap sympathetic cooling by laser-cooled beryllium ions, the limiting temperature rapidly approaches that of the ions, in the milli-Kelvin range," explains Bohman. "Our technique shows that you can apply the laser-physics toolkit to exotic particles like antiprotons: a good antiproton trap looks pretty different from a good laser-cooled ion trap, but if you're able to connect them by a wire or a coil you can get the best of both worlds."

The BASE collaboration has already measured the magnetic moment of the antiproton with a record fractional precision of 1.5 parts per billion at CERN's antimatter factory. When deployed there, two-trap sympathetic cooling has the potential to improve the precision of the measurement by at least a factor of 20. Any statistically significant difference relative to the magnetic moment of the proton would violate CPT symmetry and signal a dramatic break with the Standard Model.

"Our vision is to continuously improve the precision of our matter–antimatter comparisons to develop a better understanding of the cosmological matter–antimatter asymmetry," says BASE spokesperson Stefan Ulmer of RIKEN. "The newly developed technique will become a key method in these experiments, which aim at measurements of fundamental antimatter constants at the sub-parts-per-trillion level. Further developments in progress at the BASE-logic experiment in Hanover will even allow the implementation of quantum-logic metrology methods to read-out the antiproton's spin state."

Further reading

M Bohman *et al.* 2021 *Nature* **596** 514.

EARLY UNIVERSE

BICEP crunches primordial gravitational waves

The BICEP/Keck collaboration has published the strongest constraints to date on primordial gravitational waves, ruling out parameter space for models of inflation in the early universe. A conjectured rapid expansion of the universe during the first fraction of a second of its existence, inflation was first proposed in the late 1970s to explain the surprising uniformity of the universe over scales that should not otherwise have been connected, and may have left an imprint in the polarisation of the cosmic-microwave background (CMB). Despite a high-profile false detection of gravitational-wave-induced "B-modes" by BICEP in 2014, which was soon explained as a mismodelling of the galactic-dust foreground, the search for primordial gravitational waves remains one of the most promising avenues to study particle physics at extremely high energies, as inflation is thought to require a particle-physics explanation such as the scalar "inflaton" field proposed by Alan Guth.

The telescopes take their best data during the six-month-long Antarctic night

In its latest publication, the BICEP/Keck collaboration has managed to significantly improve the upper bound on the strength of gravitational waves produced during the epoch of inflation. "This is important for theorists because it further constrains the allowed range of viable models of inflation, and certain 'standard' types of models are now clearly disfavoured," explains CERN ▷

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theorist Kai Schmitz. "It's also a great experimental achievement because it demonstrates that the sources of systematic uncertainties such as dust emission in our Milky Way are under good control. That's a good sign for future observations."

The BICEP/Keck collaboration searches for the imprint of gravitational waves in the polarisation pattern of the CMB, emitted 380,000 years after the Big Bang. Telescopes at the South Pole receive incoming CMB photons and focus them through plastic lenses onto detectors in the focal plane that are cooled to 300 mK, explains principal investigator Clem Pryke of the University of Minnesota. As the telescopes scan the sky they record the tiny changes in temperature due to the intensity of the incoming microwaves. The detectors are arranged in pairs with each half sensitive to one of two orthogonal linear polarisation components. The telescopes take their best data during the six-month-long Antarctic night, during which intrepid "winter-overs" maintain the detectors and upload data via satellite to the US for further analysis.

BICEP2

Polarising *Data from the BICEP2 Telescope (pictured), the Keck Array and the BICEP3 Telescope have squeezed parameter space for models of inflationary cosmology.*

"The big change since 2014 was to make measurements in multiple frequency bands to allow the removal of the galactic foreground," says Pryke. "Back then we had data only at 150 GHz and were relying on models and projections of the galactic foreground – models that turned out to be optimistic as far as the dust is concerned. Now we have super-deep maps at 95, 150 and 220 GHz allowing us to accurately remove the dust component."

The current analysis uses data recorded by BICEP2, the Keck Array and BICEP3 up to 2018. Since then, the collaboration has installed a new, more capable, telescope platform called the BICEP Array designed to increase sensitivity to primordial gravitational waves by a factor of three, in collaboration with a large-aperture telescope at the South Pole called SPT3G. With 21 telescopes at the South Pole and in the Chilean Atacama desert, the proposed CMB Stage-4 project plans to improve sensitivity by a further factor of six in the 2030s.

Further reading

BICEP/Keck Collaboration 2021 *Phys. Rev. Lett.* **127** 151301.

AWARDS

2021 Nobel Prize recognises complexity

On 5 October, Syukuro Manabe (Princeton), Klaus Hasselmann (MPI for Meteorology) and Giorgio Parisi (Sapienza University of Rome) were announced as the winners of the 2021 Nobel Prize in Physics for their groundbreaking contributions to the understanding of complex physical systems, which provided rigorous scientific foundations to our understanding of Earth's climate. Sharing half the 10 million Swedish kronor award, Manabe and Hasselmann were recognised "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming". Parisi, who started out in high-energy physics, received the other half of the award "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales".

B Sabatini J Knop/MPG N Manabe

Climate pioneers *Nobel winners (from left) Giorgio Parisi, Klaus Hasselmann and Syukuro Manabe.*

In the early 1960s, Manabe developed a radiative-convective model of the atmosphere and explored the role of greenhouse gases in maintaining and changing the atmosphere's thermal structure. It was the beginning of a decades-long research programme on global warming that he undertook in collaboration with the Geophysical Fluid Dynamics Laboratory, NOAA. Hasselmann, who was founding director of the Max Planck Institute for Meteorology in Hamburg from 1975 to 1999, developed techniques that helped establish the link between anthropogenic CO_2 emissions and rising global temperatures. He published a series of papers in the 1960s on non-linear interactions in ocean waves, in which he adapted Feynman-diagram formalism to classical random-wave fields.

Parisi, a founder of the study of complex systems, enabled the understanding and description of many different and apparently entirely random materials and phenomena in physics, biology and beyond, including the flocking of birds. Early in his career, he also made fundamental contributions to particle physics, the most well-known being the derivation, together with the late Guido Altarelli and others, of the "DGLAP" QCD evolution equations for parton densities. "My mentor Nicola Cabibbo was usually saying that we should work on a problem only if working on the problem is fun," said Parisi following the announcement. "So I tried to work on something that was interesting and which I believed that had some capacity to add something."

As per last year, the traditional December award ceremony will take place online due to COVID-19 restrictions.

QUANTUM TECHNOLOGY

CERN unveils roadmap for quantum technology

Launched one year ago, the CERN Quantum Technology Initiative (QTI) will see high-energy physicists and others play their part in a global effort to bring about the next "quantum revolution", whereby phenomena such as superposition and entanglement are exploited to build novel computing, communication, sensing and simulation devices (*CERN Courier* September/October 2020 p47).

On 14 October, the CERN QTI coordination team announced a strategy and roadmap to establish joint research, educational and training activities, set up a supporting resource infrastructure, and provide dedicated mechanisms for exchange of knowledge and technology. Oversight for the CERN QTI will be provided by a newly established advisory board composed of international experts nominated by CERN's 23 Member States.

QUANTUM TECHNOLOGY INITIATIVE

As an international, open and neutral platform, describes the roadmap document, CERN is uniquely positioned to act as an "honest broker" to facilitate cross-disciplinary discussions between CERN Member States and to foster innovative ideas in high-energy physics and beyond. This is underpinned by several R&D projects that are already under way at CERN across four main areas: quantum computing and algorithms; quantum theory and simulation; quantum sensing, metrology and materials; and quantum communication and networks. These projects target applications such as quantum-graph neural networks for track reconstruction, quantum support vector machines for particle classification, and quantum generative adversarial networks for physics simulation, as well as new sensors and materials for future detectors, and quantum-key-distribution protocols for distributed data analysis.

Education and training are also at the core of the CERN QTI. Building on the success of its first online course on quantum computing, the initiative plans to extend its academia–industry training programme to build competencies across different R&D and engineering activities for the new generation of scientists, from high-school students to senior researchers.

Co-chairs of the CERN QTI advisory board, Kerstin Borras and Yasser Omar, stated: "The road map builds on high-quality research projects already ongoing at CERN, with top-level collaborations, to advance a vision and concrete steps to explore the potential of quantum information science and technologies for high-energy physics".

Further reading

https://quantum.cern.

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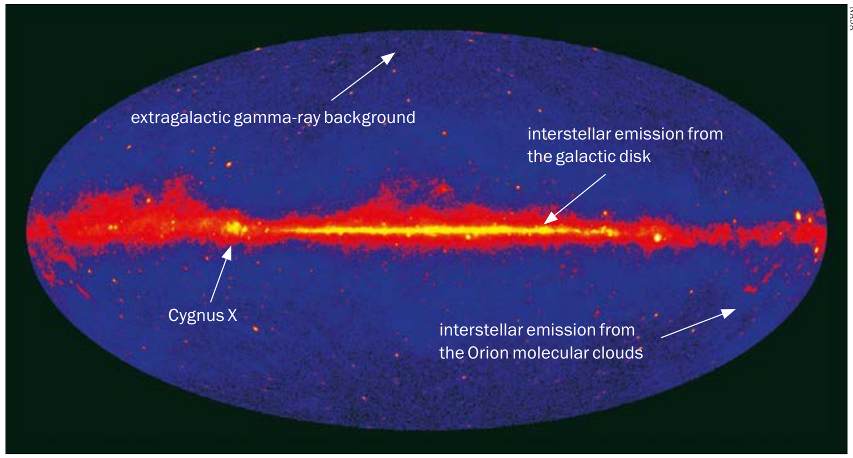
ASTROWATCH

Star-forming galaxies rule gamma-ray sky

The diffuse photon background that fills the universe does not limit itself to the attention-hogging cosmic microwave background, but spans a wide spectrum extending up to TeV energies. The origin of the photon emission at X-ray and gamma-ray wavelengths, first discovered in the 1970s, remains poorly understood. Many possible sources have been proposed, ranging from active galactic nuclei to dark-matter annihilation. Thanks to many years of gamma-ray data from the Fermi Large Area Telescope (Fermi-LAT), a group from Australia and Italy has now produced a model that links part of the diffuse emission to star-forming galaxies (SFGs).

As their name implies, SFGs are galaxies in which stars are formed, and therefore also die through supernova events. Such sources, which include our own Milky Way, have gained interest from gamma-ray astronomers during the past decade because several resolvable SFGs have been shown to emit in the 100 MeV to 1 TeV energy range. Given their preponderance, SFGs are thus a prime-suspect source of the diffuse gamma-ray background.

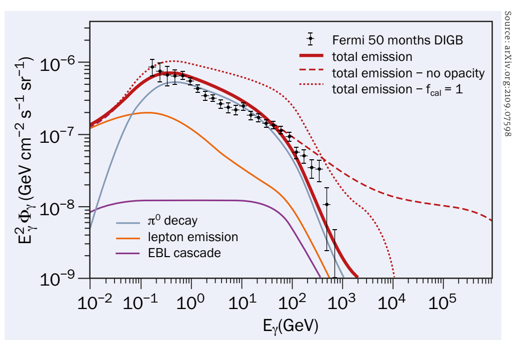


Diffuse sky *Fermi-LAT's five-year sky map, indicating the various diffuse components that make up 80% of all photons detected.*

Clear correlation

The source of gamma rays within SFGs is very likely the interaction between cosmic rays and the interstellar medium (ISM). The cosmic rays, in turn, are thought to be accelerated within the shockwaves of supernova remnants, after which they interact with the ISM to produce a hadronic cascade. The cascade includes neutral pions, which decay into gamma rays. This connection between supernova remnants and gamma rays is strengthened by a clear correlation between the star-formation rate in a galaxy and the gamma-ray flux they emit. Additionally, such sources are theorised to be responsible for the neutrino emission detected by the IceCube observatory over the past few years, which also appears to be highly isotropic.

Based on additional SFG gamma-ray sources found by Fermi-LAT, which could be used for validation, the Australian/Italian group developed a physical model to study the contribution of SFGs to the cosmic diffuse gamma-ray background. The model used to predict the gamma-ray emission from galaxies starts with the spectra of charged cosmic-rays produced in the numerous supernovae remnants within a galaxy, and greatly benefits from data collected from several such remnants present in the Milky Way. Subsequently the production and energies of gamma rays through their interaction of cosmic rays with the ISM is modelled, followed by the gamma-ray transport to Earth, which includes losses due to interactions with low-energy photons leading to pair production.



Good fit *The observed gamma-ray background (black points) compared to the new model prediction (thick red line) and its various components (DIGB, diffuse isotropic γ-ray background; EBL, extragalactic background light).*

The main uncertainty in previous models was the efficiency of a galaxy to transform the energy from cosmic rays into gamma rays, since it is not possible to use our own galaxy to measure it. The big breakthrough in the new work is a more thorough theoretical modelling of this efficiency, which was first tested extensively using data from resolved SFG sources. After such tests proved successful, the model could be applied to predict the gamma-ray emission properties of galaxies spanning the history of the universe. These predictions indicate that the low-energy part of the spectrum can be largely attributed to galaxies from the so-called cosmic noon: the period when star formation in large galaxies was at its peak, about 10 billion years ago. Nearby galaxies, on the other hand, explain the high-energy part of the spectrum, which, for old and distant sources, is absorbed in the intergalactic medium by low-energy photons undergoing pair production with TeV emission. Overall, the model predicts not only the spectral shape but also the overall flux (see "Good fit" figure), negating the need for other possible sources such as active galactic nuclei or dark matter.

These new results once again indicate the importance of star-forming regions for astrophysics, after also recently being proposed as a possible source of PeV cosmic rays by LHAASO (*CERN Courier* July/August 2021 p11). Furthermore, it shows the potential for an expansion to other astrophysical messengers, with the authors stating their ambition to apply the same model to radio-emission and high-energy neutrinos.

Further reading

M Ajello *et al.* 2020 *ApJ* **894** 88.
M Roth *et al.* 2021 *Nature* **597** 341.

NEWS DIGEST

ESA/NASA

Thomas Pesquet and the Lumina experiment on the ISS.

Optical-fibre dosimetry in orbit

On 18 August, ESA astronaut Thomas Pesquet activated the Lumina experiment inside the International Space Station (ISS). The experiment employs two several-km-long optical fibres that experience a partial loss of transmitted power when exposed to radiation. The technology is the fruit of a collaboration between the French Space Agency and CERN, which also requires bespoke radiation monitoring in the LHC.

Early dark energy

Two fits to cosmic microwave background (CMB) data from the Atacama Cosmology Telescope in Chile favour the existence of "early dark energy" (EDE) over the unmodified ΛCDM model at more than 2σ, though the situation is less clear when data from the Planck satellite is added (arXiv:2109.04451 and arXiv:2109.06229). Currently accepted as the standard model of cosmology, ΛCDM includes dark energy (via a cosmological constant Λ), cold dark matter and ordinary matter, but yields a Hubble constant in tension with the recession of supernovae when applied to measurements of the CMB. An additional dark-energy component, EDE, that behaves like a cosmological constant at early times and then "dilutes away like radiation or faster," was proposed by Vivian Poulin and colleagues in 2019 to resolve the tension (*Phys. Rev. Lett.* **122** 221301).

ISOLTRAP weighs in on tin-100

With full shells of both protons and neutrons, tin-100 is "doubly magic". Furthermore, with 50 apiece, it is also the heaviest self-conjugate nucleus – a particularly enticing target for study due to enhanced short-range proton–neutron pairing interactions that influence its decay via the weak interaction. However, recent studies of tin-100's beta decay at RIKEN and GSI yielded incompatible values for its mass. The ISOLTRAP experiment at CERN's ISOLDE facility has now weighed-in in favour of the GSI measurement by measuring the mass of indium-100, its neighbour on the nuclear chart (*Nat. Phys.* **17** 1099). In light of ISOLTRAP's measurement, the RIKEN value would render tin-100 doubly un-magic, say the team – an idea no nuclear physicist would entertain, given strong theoretical predictions to the contrary.

U. of Western Australia

Tabletop antennas search for gravitational waves.

Hunting high-frequency gravitational waves

Physicists in Australia have reported two rare events in an initial 153 days of observations with high-quality-factor "bulk-acoustic-wave cavities" designed to look for high-frequency gravitational waves (GWs). The detection technique relies on vibrations inducing a voltage in a cooled and shielded quartz disk; a SQUID then amplifies the signals. The two events might have been caused by a GW-generating event such as the merging of primordial black holes, says the team, but no definite claim can yet be made as to their origin. A second-generation implementation of the detector should be able to rule out most possible explanations (*Phys. Rev. Lett.* **127** 071102).

LHCb measures the W mass

On 2 September, the LHCb collaboration published its first measurement of the mass of the W boson, matching the precision of the LEP experiments combined (arXiv:2109.01113). Based on 2016 data, LHCb achieved a value of 80,354 ± 32 MeV, compared with a precision of 33 MeV obtained by the final combination by ALEPH, DELPHI, L3 and OPAL. Existing data should allow LHCb to compete with the world-best precision of 16 MeV obtained by combining the CDF and DØ measurements at the Tevatron, and the 19 MeV obtained by ATLAS in 2018, says the team. A global electroweak fit yields a value of 80,354 ± 7 MeV, lagging behind knowledge of the mass of the Z boson, which is pinned down within 2 MeV by the LEP experiments.

COMPASS points to triangle singularity

The COMPASS experiment at CERN has reported that the "a_1(1420)" signal observed by the collaboration in 2015 is likely not a new exotic hadron after all, but the first sighting of a so-called triangle singularity – an interacting cascade of on-mass-shell hadron decays dreamt up independently in 1959 by Lev Landau and Richard Cutkosky, which can easily be mistaken for a resonance (*Phys. Rev. Lett.* **127** 082501). The new COMPASS analysis is the first time that a bump in a decay spectrum has been convincingly explained as more likely due to a triangle singularity than a resonance. A tempting interpretation had been that a_1(1420) might be a $ds\bar{u}\bar{s}$ tetraquark, but the collaboration's detailed partial-wave analysis shows that no new resonance is required.

Milestone for energy-recovery linacs

Physicists at Technische Universität Darmstadt have accelerated electron beams to 41 MeV in a linac before deceleration and reacceleration in the opposite direction, while recovering and recycling 80% of the beam's kinetic energy. The experiment at the university's S-DALINAC linac is the first time a superconducting linear electron accelerator has been successfully operated in a multi-turn energy-recovery mode, says the team. First proposed by Maury Tigner in 1965, energy-recovery linacs convert the kinetic energy of used particle bunches back into stored electromagnetic energy in radio-frequency cavities, in a reversal of the acceleration process. The potential energy savings could reduce the wall-plug power of accelerator facilities by a significant factor.

TU Darmstadt

The S-DALINAC linac has been operated in energy-recovery mode.

Nanophotonics choreography

Silicon-chip-based acceleration of charged particles has the potential to reduce the cost and size of accelerators by orders of magnitude. But phase-space focusing and bunching is a major stumbling block. Physicists in Germany have now demonstrated the "alternating phase focusing" of electrons over a distance of 77.7 μm (*Nature* **597** 498). Such channels could be arbitrarily long and accelerate electron beams to MeV for applications in hospitals and industry, says the team.

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ATLAS

First observation of WWW production

The W boson was first directly observed in 1983 using the Super Proton Synchrotron proton–antiproton collider at CERN, resulting in a Nobel Prize the following year. Almost four decades later, the ATLAS collaboration has observed the simultaneous production of three W bosons for the first time.

The study of multi-boson processes involving boson self-interactions provides unique insight into the nature of electroweak symmetry breaking and therefore enables rigorous tests of the Standard Model (SM). Likewise, deviations from SM predictions could indicate hints of beyond-Standard Model physics through, for example, interactions that exist at energies beyond the current reach of the LHC which avoid the requirement to create the particle directly. These effects could potentially result from interactions with virtual particles in loops or new amplitudes generated by a tree-level exchange. In an effective field theory (EFT) approach, the possible new interactions are represented by operator terms with anomalous triple and quartic gauge couplings, both of which are present in WWW production.

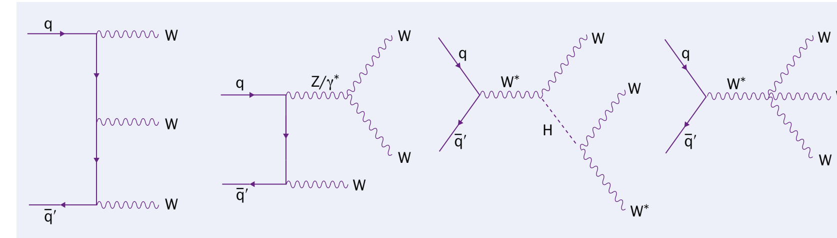


Fig. 1. *Example Feynman diagrams for the leading-order production of WWW events.*

Signal events

At leading order, the WWW signal is produced through the different mechanisms presented in the Feynman diagrams shown in figure 1. While there are many decay modes, ATLAS used four final-state channels where the signal-to-background ratio is big enough to observe the signal. The first three channels result from the decay of two of the Ws into charged lepton–neutrino pairs, with the same electric-charge sign of the charged leptons, and the decay of the third W into a pair of quarks observed as hadronic jets: the two-lepton (2l) channel, with flavour combinations ee, eμ and μμ. Additionally, WWW production is measured in the three-lepton (3l) channel, where each W decays into a charged lepton–neutrino pair, requiring no same-flavour opposite-sign charged-lepton pairs, and thus reducing the Z-boson background.

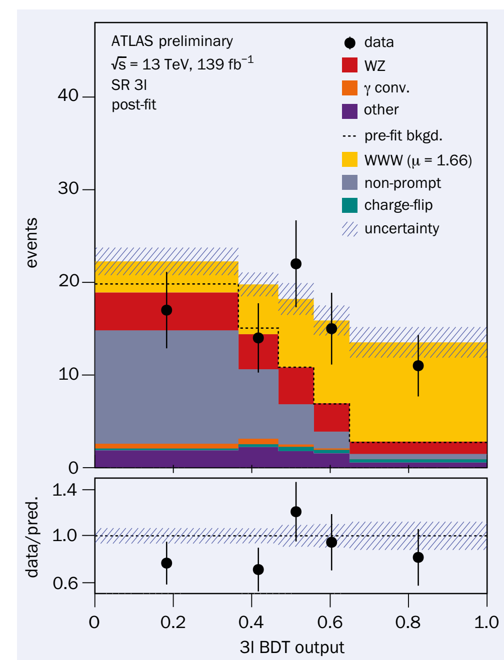


Fig. 2. *The BDT distribution of the WWW three-lepton channel.*

A multivariate analysis using a boosted decision tree (BDT) was used to discriminate the signal from the background, with the BDT trained using 12 discriminating input variables in the 2l channel and 11 input variables in the 3l channel. A binned maximum likelihood fit was performed on the BDT distributions with four free-floating parameters: the signal strength and three normalisation factors for the dominant WZ background. The BDT distributions were fitted in the four signal regions simultaneously with the trilepton invariant mass distribution in three WZ control regions (WZ plus 0, 1, ≥ 2 jets). The resulting BDT distribution for the 3l channel is shown in figure 2.

The large event samples (139 fb^{-1}) provided by the full Run-2 data set, the implementation of multivariate techniques, and an improved ATLAS detector and reconstruction performance enabled the observation and the cross-section measurement of this rare process. The observed (expected) significance of the measurement is 8.2 (5.4) standard deviations compared to the hypothesis with no WWW signal. The cross section is measured to be 850 ± 100 (stat.) ± 80 (syst.) fb, as derived from the observed signal strength (the ratio of measured to predicted yields) of 1.66 ± 0.28. The observed signal significance is within 2.4σ of the SM prediction. The full Run-3 data set is anticipated to more than double the number of signal events and will enable a more precise measurement of WWW production. Higher precision cross-section measurements and detailed differential distributions will elucidate the compatibility with the SM, and an EFT approach can quantify the sensitivity to anomalous gauge couplings in a search for new physics.

Further reading

ATLAS Collab. 2021 ATLAS-CONF-2021-039.

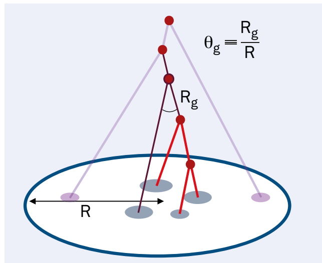
ALICE

Quark–gluon plasma narrows jets

A new measurement by the ALICE collaboration has demonstrated for the first time that jets become narrower after "quenching" in quark–gluon plasma (QGP). RHIC and LHC data show that the QGP behaves like a strongly-coupled liquid with very low viscosity, but it is an open question how this arises from the asymptotic limit of weakly-coupled quarks and gluons at short lengths. The new results provide quantitative new insights into the hot and dense medium created in heavy-ion collisions and how it modifies the substructure of jets and dissipates part of their energy.

An important property of the QGP is its ability to "resolve" nearby partons as effectively independent colour charges above the medium's characteristic resolution scale – a parameter that is very poorly predicted by theory, but thought to be in the vicinity of a femtometre or less. In recent years, jet quenching has been proposed to determine this scale. Jets originate from a single quark or gluon that showers into more partons, either by radiating a gluon or splitting into a quark–antiquark pair. When a jet moves through the medium, each individual splitting results in two distinct colour charges that, depending on their angular separation and the medium's resolution length, can interact as one coherent object or two independent charges. At the LHC, we can put our understanding of this resolution scale to test using special measurements of the angular structure of jets. This allows us to test whether wider jets are more likely to be resolved.

To identify the relevant two-prong splittings, ALICE "groomed" jets using track clustering. The algorithm reclusters and unwinds the jet shower to find the first parton splitting satisfying a grooming condition (top figure). The excellent tracking resolution in ALICE allows for very precise measurements of jet substructure even at small angular distance scales. The angular width of the jet was found to be significantly modified in Pb–Pb compared to pp collisions (right figure). In particular, wider splittings are suppressed in Pb–Pb compared to pp collisions, demonstrating that the interaction of jets with the QGP filters out wide jets.



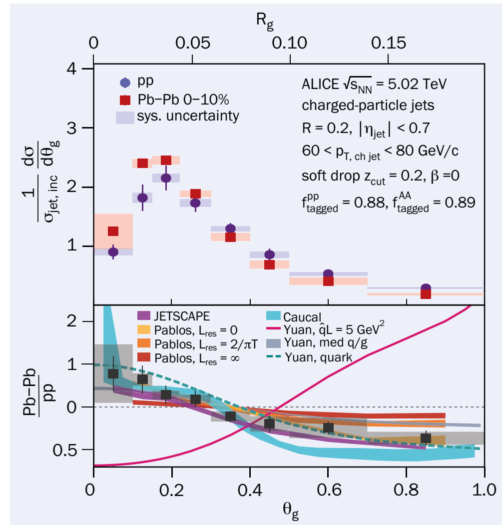


Fig. 1. *Above: hadrons from a jet (ovals) are reclustered into a tree structure, and the low-energy, wide-angle particles are removed in order to identify the first "hard" splitting, shown in dark purple. Right: the distribution of the angle between the two prongs of the "hard" splitting measured by ALICE, in both proton–proton and Pb–Pb collisions. The lower panel shows the Pb–Pb/p–p ratio in comparison with theoretical models.*

The excellent tracking resolution in ALICE allows for very precise measurements of jet substructure

This measurement is the first of its kind to be fully corrected for large background effects, allowing direct quantitative comparisons with theoretical calculations of jet quenching. Most theoretical models describe the general narrowing trend seen in the data, despite the different implementations of jet-medium interactions. The data is consistent with models implementing an incoherent interaction in which the medium resolves the splittings (Pablos, $L_{res}=0$). Interestingly, however, another calculation demonstrates this narrowing effect with a fully coherent interaction, in which the jet splittings are not resolved, but by modifying the initial quark and gluon fractions (Yuan, quark). While the precision of the data currently precludes a precise extraction of the medium's resolving power within a given model, the measurement places quantitative constraints on medium properties, and demonstrates for the first time a direct modification to the angular structure of jets in heavy-ion collisions. This opens the door to increasingly precise measurements with the high-precision data anticipated in LHC Run 3.

Further reading

ALICE Collaboration 2021 arXiv:2107.12984.

LHCb

LHCb studies the intrinsic charm of the proton

The possibility that the proton wave function may contain a $|uudc\bar{c}\rangle$ component in addition to the $g \to c\bar{c}$ splitting arising from perturbative gluon radiation has been debated for decades. In favour of such "intrinsic charm" (IC), light-front QCD (LFQCD) calculations predict that non-perturbative IC manifests as percent-level valence-like charm content in the parton distribution functions (PDFs) of the proton. On the other hand, if the charm-quark content is entirely perturbative in nature, the charm PDF should resemble that of the gluon and decrease sharply at large momentum fractions, x. The proton could also contain intrinsic beauty, but suppressed by a factor of order m_c^2/m_b^2. The picture for intrinsic strangeness is somewhat murkier due to the lighter mass of the strange quark.

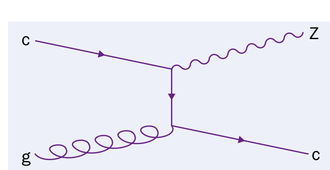


Fig. 1. *$gc \to Zc$ scattering is sensitive to valence-like intrinsic charm.*

Measurements of charm–hadron production in deep-inelastic scattering and in fixed-target experiments, with typical momentum transfers below Q = 10 GeV, have been interpreted as evidence both for and against the IC predicted by LFQCD. Even though such experiments are in principle sensitive to valence-like c-quark content, interpreting low-Q data is challenging since it requires a careful theoretical treatment of hadronic and nuclear effects. Recent global PDF analyses, which also include measurements by ATLAS, CMS and LHCb, are inconclusive and can only exclude a relatively large IC component carrying more than a few percent of the momentum of the proton.

Using its Run-2 data, LHCb recently studied IC by making the first measurement of the fraction of Z+jet events that contain a charm jet in the forward region of proton–proton collisions. Since Zc production is inherently at large Q, above the electroweak scale, hadronic effects are small. A leading-order Zc production mechanism is $gc \to Zc$ scattering (figure 1), where in the forward region one of the initial partons must have large x, hence Zc production probes the valence-like region.

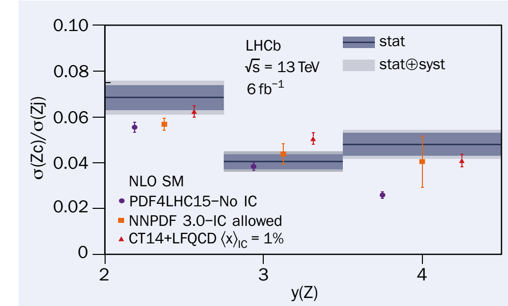


Fig. 2. *The measured production cross-section ratio (grey bands) for three intervals of forward Z rapidity, compared to theory predictions without IC (purple circles), with the charm PDF shape allowed to vary, hence permitting IC (orange squares), and with IC as predicted by LFQCD with a mean momentum fraction of 1% (red triangles). The predictions are offset in each interval to improve visibility.*

The spectrum observed by LHCb exhibits a sizable enhancement at forward Z rapidities (figure 2), consistent with the effect expected if the proton wave function contains the $|uudc\bar{c}\rangle$ component predicted by LFQCD. Incorporating these results into global PDF analyses should strongly constrain the large-x charm PDF, both in size and shape – and could reveal that the proton contains valence-like intrinsic charm.

These results demonstrate the unique sensitivity of the LHCb experiment to the valence-like content of the proton. Looking forward to Run 3, increased luminosity will lead to a substantial improvement in the precision of this measurement, which should provide an even clearer picture of just how charming the proton is.

Further reading

LHCb Collaboration 2021 arXiv:2109.08084.

CMS

Muon detector probes long-lived particles

New ways to detect long-lived particles (LLPs) are opening up avenues for searching for physics beyond the Standard Model (SM). LLPs could provide evidence for a hidden dark sector of particles that includes dark-matter candidates and could be studied via "portal interactions" with the visible universe. By employing the CMS experiment's muon spectrometer in a novel way, the collaboration has recently deployed a powerful new technique for detecting LLPs that decay between 6 and 10 metres from the primary interaction point.

An LLP decaying in the endcap muon spectrometer volume should produce a particle shower when its decay products interact with the return yoke of the CMS solenoid. The secondary particles produced by the shower would traverse the gaseous regions of the cathode-strip chamber (CSC) detector and produce a large multiplicity of signals on the wire anodes and strip cathodes. Localised hits are reconstructed by combining these signals using a density-based clustering algorithm. This is the first time the CSC detectors have been used as a sampling calorimeter to try to detect and identify LLP decays.

Searching for CSC clusters with a sufficiently large number of hits suppresses background processes while maintaining a high efficiency for detecting potential LLP decays. The large amount of steel in the CMS return yoke nearly eliminates "punch-through" hadrons that are not fully stopped by the calorimeter, potentially mimicking the signature of an LLP. The largest remaining source of backgrounds is known LLPs produced by SM processes such as the neutral kaon, K_L. These particles are copiously produced in LHC collisions and, on rare occasions, traverse the material without being stopped. Kaons are predominantly produced with much lower energies than the signal LLPs and therefore result in clusters with a smaller number of hits. Requiring clusters with more than 130 CSC hits suppresses these dominant background events to a negligible level (see figure 1).

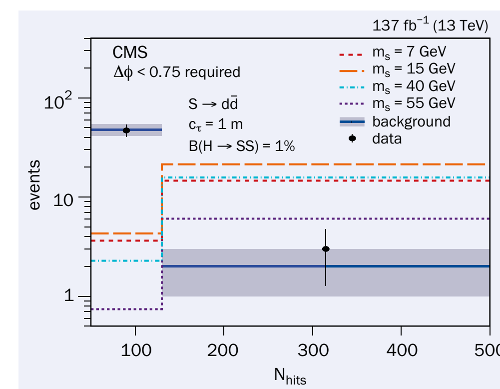


Fig. 1. *Distributions of the number of hits in the cluster (N_{hits}) in the search region. Signal models where the Higgs boson plays the role of the dark-portal messenger are shown (dashed lines). The Higgs boson is assumed to decay to dark-sector scalar particles with masses of 7 (red), 15 (orange), 40 (cyan) or 55 GeV (purple), while the dark scalar decays with a macroscopic displacement to quarks.*

Using the full Run-2 dataset, the CMS collaboration detected no excess of particle-shower events above the expected backgrounds, setting constraints on a benchmark-simplified model of scalar LLP production mediated by the Higgs boson (a so-called Higgs portal model). This search improves on the previous best results by more than a factor of six (two) for an LLP mass of 7 GeV (≥ 15) GeV for a proper decay length ($c\tau$) of the scalar larger than 100 m. It is the first to be sensitive to LLP decays with $c\tau$ up to 1000 m and masses between 40 and 55 GeV at branching ratios of the Higgs to a pair of LLPs below 20%.

This novel approach to identifying showers in muon detectors opens up an exciting new programme of searches for LLPs in a wide variety of theoretical models. Potential frameworks range from Higgs-portal models to other portals to a dark sector, including neutrinos, axions and dark photons. The on-going development of a dedicated Level-1 and High-Level Trigger focusing on particle showers detected in the CMS muon spectrometer promises an order of magnitude improvement in the discovery sensitivity for LLPs in the forthcoming run of the LHC.

Further reading

CMS Collaboration 2021 arXiv:2107.04838.

IPAC 2021: light sources and the rest

Image courtesy of IPAC and LNLS/CNPEM

The prestigious big-physics event, IPAC 2021, was hosted in a fully virtual format this year. It was organised from 24 to 28 May by the Brazilian Center for Research in Energy and Materials (CNPEM), located in Campinas. Cosylab's Andraz Kosuta reports on his experiences at what he and his colleagues found to be a highly successful event, despite the constraints of its virtual format.

The May 2021 event was my first IPAC and one of my first scientific domain conferences. Nevertheless, I was duly impressed by the Whova virtual-event platform that underpinned the Brazilian conference and was similar to a social-media application. A nice touch was the organisers' effort to encourage people to connect by collecting virtual passport stamps. Participants could use a wealth of Whova's built-in features: chats, video meets, calls, poster and session listings, session attendances and booth activity. It was easy to reach out to people by simply sending them a message on their contact cards.

The conference website was informative and the book of abstracts was available on time. It was good that we could preview the posters in advance and have live talks at the presentation itself. The poster sessions turned out to be the most convenient way to break the ice with people you did not know, and the presenters were timely in their arrival. There were also plenty of opportunities to catch up with people after the presentations.

Big-physics plans aplenty

Undoubtedly, the unofficial central theme of the IPAC 2021 conference was fourth-generation (4G) light sources that employ free-electron lasers (FELs) to generate X-rays by electrons flying through a periodic magnetic field. These 4G facilities will expand the boundaries for X-ray science in imaging condensed and living matter, ranging from the metre to the nanometre scale, and enabling new solutions for today's challenges in fields such as the environment, health, energy and innovation.

An excellent example of an essential, new 4G light source is the European Synchrotron Radiation Facility (ESRF) in Grenoble, the world's first fourth-generation high-energy synchrotron and currently the brightest X-ray source. The latter opened for business, wholly rebuilt, as the ESRF–EBS (Extremely Brilliant Source) in August 2020, while its actual commissioning was completed months before the planned date.

SOLARIS's novel hard X-ray facility, provided by JINR (the Joint Institute for Nuclear Research), is nearing its new-building construction phase, and the French SOLEIL project is expected to start in 2023, pending approval of its national synchrotron budget. At HZDR, they are also planning to build a new ELBE (electron linac for beams with high brilliance and low emittance) that will progress research on quanta, antiparticles, neutrons and more.

There are a multitude of planned new FELs and announcements of synchrotron upgrades, such as the Spanish ALBA II project, the SPECIES beamline upgrade at Sweden's MAX IV, the US's new Advanced Photon Source at ANL, the Advanced Light Source at Berkeley Lab and the new Diamond Light Source II (DLS 2) in the UK.

There are many more examples, with the new Swiss Light Source 2.0 at the Paul Scherrer Institute, the Canadian Light Source 2.0, the Australian Synchrotron 2, Germany's BESSY III at the Helmholtz Association and the SPring-8-II of JASRI (the Japan Synchrotron Radiation Research Institute).

Beams, colliders and nucleons

Scientific planners are also pushing forward upgraded sources of intense secondary beams of short-lived rare isotopes such as FRIB at Michigan State University and the EU-funded Facility for Antiproton and Ion Research (FAIR) at Darmstadt.

The project teams at the colliders are not standing still either, devising upgrades for, for example, the LHC, ILC, NICA, FCC and CEPC. A case in point is JINR's plans to transfer the nuclotron beam from HILAC (the Heavy-Ion Linear Accelerator) to the NICA Accelerator Complex's collider in Dubna by the spring of 2022.

At the same time, SNS, FNAL, KEK (JPARC) and C-ADS are designing new high-power proton and neutron sources. Of course, there are many smaller projects in various fields of big physics that also raised the imagination at IPAC 2021, among them the deployment of new control or experimental methods, detectors, injectors and ion sources.

Still the king

I found the virtual aspect of IPAC 2021 to provide me with a more comfortable experience than running around in person. Nevertheless, nothing beats the exciting hurly-burly of a live conference! It is perhaps of interest – but to no one's surprise – that no single vote or comment at IPAC 2021 favoured an entirely remote conference. Everybody seemed to be firmly in favour of in-person events returning as soon as the battle against COVID-19 makes this possible. However, IPAC 2021 confirmed its reputation as the place to be for big-physics project news.

ABOUT THE AUTHOR

Andraz Kosuta joined Cosylab in 2020 and worked on device integration with EPICS before moving on to the sales team. Outside of work, Andraz enjoys staying active by playing football, riding his mountain bike and travelling.

https://www.cosylab.com/

e-mail: andraz.kosuta@cosylab.com

FIELD NOTES

Reports from events, conferences and meetings

EPS-HEP Conference 2021

Breaking records at EPS-HEP

In this year's unusual Olympic summer, high-energy physicists pushed back the frontiers of knowledge and broke many records. The first one is surely the number of registrants to the EPS-HEP conference, hosted online from 26 to 30 July by the University of Hamburg and DESY: nearly 2000 participants scrutinised more than 600 talks and 280 posters. After 18 months of the COVID pandemic, the community showed a strong desire to meet and discuss physics with international colleagues.

The conference offered the opportunity to hear about analyses using the full LHC Run-2 data set, which is the richest hadron-collision data sample ever recorded. The results are breathtaking. As my CERN colleague Michelangelo Mangano explained recently to summer students, "The LHC works and is more powerful than expected, the experiments work and are more precise than expected, and the Standard Model works beautifully and is more reliable than expected." About 3000 papers have been published by the LHC collaborations in the past decade. They have established the LHC as a truly multi-messenger endeavour, not so much because of the multitude of elementary particles produced – 200 trillion b-quarks, 40 billion electroweak bosons, 300 million top quarks and 10 million Higgs bosons – but because of the diversity of scientifically independent experiments that historically would have required different detectors and facilities, built and operated by different communities. "Data first" should always remain the leitmotif of the natural sciences.

EPS-HEP 2021

EPS-HEP 2021 *A record 2000 participants took part online.*

Refined understanding

Paula Alvarez Cartelle (Cambridge) reminded us that the LHC has revealed new states of matter, with LHCb confirming that four or even five quarks can assemble themselves into new long-lived bound states, stabilised by the presence of two charm quarks. For theorists, these new quark-molecules provide valuable input data to tune their lattice simulations and to refine their understanding of the non-perturbative dynamics of strong interactions.

While Run 1 was a time for inclusive measurements, a multitude of differential measurements were performed during Run 2. Paolo Azzurri (INFN Pisa) reviewed the transverse momentum distribution of the jets produced in association with electroweak gauge bosons. These offer a way to test quantum chromodynamics and electroweak predictions at the highest achievable precision through higher-order computations, resummation and matching to parton showers. The work is fuelled by remarkable theoretical tours de force reported by Jonas Lindert (Sussex) and Lorenzo Tancredi (Oxford), which build on advanced mathematical techniques, including inspiring new mathematical developments in algebraic geometry and finite-field arithmetic. We experienced a historical moment: the LHC definitively became a precision machine, achieving measurements reaching and even surpassing LEP's precision. This new situation also induced a shift more towards precision measurements, model-independent interpretations and Standard Model (SM) compatibility checks, and away from model-dependent searches for new physics. Effective-field-theory analyses are therefore gaining popularity, explained Veronica Sanz (Valencia and Sussex).

We know for certain that the SM is not the ultimate theory of nature. How and when the first cracks will be revealed is the big question that motivates future collider design studies. The enduring and compelling "B anomalies" reported by LHCb could well be the revolutionary surprise that challenges our current understanding of the structure of matter. The ratios of the decay widths of B mesons, either through charged or neutral currents, $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$, could finally reveal that the electron, muon and tau lepton differ by more than just their masses.

> **200 trillion b-quarks, 40 billion electroweak bosons, 300 million top quarks and 10 million Higgs bosons**

The statistical significance of the lepton flavour anomalies is growing, reported Franz Muheim (Edinburgh and CERN), creating "cautious" excitement and stimulating the creativity of theorists like Ana Teixeira (Clermont-Ferrand), who builds new physics models with leptoquarks and heavy vectors with different couplings to the three families of leptons, to accommodate the apparent lepton-flavour-universality violations. Belle II should soon bring new additional input to the debate, said Carsten Niebuhr (DESY).

Long-awaited results

The other excitement of the year came from the long-awaited results from the muon g-2 experiment at Fermilab, presented by Alex Keshavarzi (Manchester). The spin precession frequency of a sample of 10 billion muons was measured with a precision of a few hundred parts per million, confirming the deviation from the SM prediction observed nearly 20 years ago by the E821 experiment at Brookhaven. With the current statistics, the deviation now amounts to 4.2σ. With an increase by a factor 20 of the data-set foreseen in the next run, the measurement will soon become systematics limited. Gilberto Colangelo (Bern) also discussed new and improved lattice computations of the hadronic vacuum polarisation, significantly reducing the discrepancy between the theoretical prediction and the experimental measurement. The jury is still out – and the final word might come from the g-2/EDM experiment at J-PARC.

Accelerator-based experiments might not be the place to prove the SM wrong. Astrophysical and cosmological observations have already taught us that SM matter only constitutes 95% of the stuff that the universe is made of. The traditional idea that the gap in the energy budget ▷

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of the universe is filled by new TeV-scale particles that stabilise the electroweak scale under radiative corrections is fading away. And a huge range of possible dark-matter scales opens up a rich and reinvigorated experimental programme that can profit from original techniques exploiting electron and nuclear recoils caused by the scattering of dark-matter particles. A front-runner in the new dark-matter landscape is the QCD axion originally introduced to explain why strong interactions do not distinguish matter from antimatter. Babette Döbrich (CERN) discussed the challenges inherent in capturing an axion, and described the many new experiments around the globe designed to overcome them.

Progress could also come directly from theory

Progress could also come directly from theory. Juan Maldacena (IAS Princeton) recalled the remarkable breakthroughs on the black-hole information problem. The Higgs discovery in 2012 established the non-trivial vacuum structure of space–time. We are now on our way to understanding the quantum mechanics of this space–time.

Like at the Olympics, where breaking records requires a lot of work and effort by the athletes, their teams and society, the quest to understand nature relies on the enthusiasm and the determination of physicists and their funding agencies. What we have learnt so far has allowed us to formulate precise and profound questions. We now need to create opportunities to answer them and to move ahead.

One cannot underestimate how quickly the landscape of physics can change, whether the B-anomalies will be confirmed or whether a dark-matter particle will be discovered. Let's see what will be awaiting us at the next EPS-HEP conference in 2023 in Hamburg – in person this time!

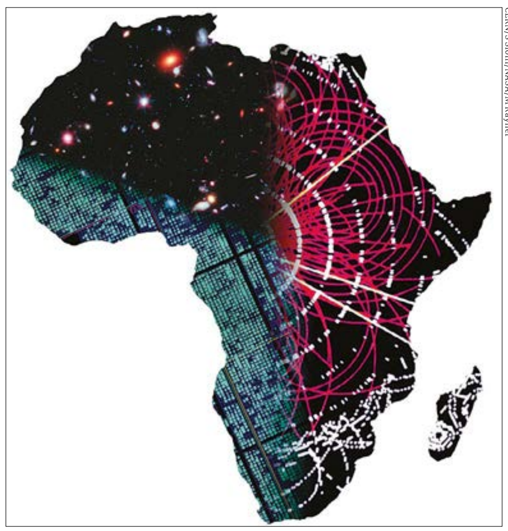
Christophe Grojean *DESY and Humboldt University.*

AFRICAN STRATEGY FOR FUNDAMENTAL AND APPLIED PHYSICS

African physicists begin strategy process

Africa's science, innovation, education and research infrastructures have over the years been undervalued and under-resourced. This is particularly true in physics. The African Strategy for Fundamental and Applied Physics (ASFAP) initiative aims to define the education and physics priorities that can be most impactful for Africa. The first ASFAP community town hall was held from 12 to 15 July. The event was virtual, with 147 people participating, including international speakers and members of the ASFAP community. The purpose of the meeting was to initiate a broad and community-driven discussion and action programme, leading to a final strategy document in two to three years' time.

The first day began with an overview of the ASFAP by Simon Connell (University of Johannesburg) on behalf of the steering committee and addresses by Shamila Nair-Bedouelle (UNESCO assistant director-general for natural sciences), Sarah Mbi Enow Anyang Agbor (African Union commissioner for human resources, science and technology) and Raissa Malu (member of the Democratic Republic of Congo's Presidential Panel to the African Union). These honoured guests encouraged delegates to establish a culture of gender balance in African physics. Later, in a dedicated forum for women in physics, Iroka Chidinma Joy (chief engineer at the National Space Research and Development Agency) noted that women are drastically underrepresented in scientific fields across the continent, and pointed out a number of cultural, religious and social barriers that prevent women from pursuing higher education. Barriers can come as early as primary education: in most cases, girls are not encouraged to take leading roles in conducting science experiments in classrooms. Improved strategies should include outreach, mentorship, dedicated funding for women, the removal of age limits for women wishing to conduct scientific research or further their education, and awards and recognition for women who excel in scientific fields.



CERN/S Sioni/NASA/M Rayner

Fundamental and applied *Strategy subjects range from cosmology and computing to instrumentation and education.*

Community-driven

Representatives of scientific organisations such as the African Physical Society, the Network of African Science Academies and the African Academy of Science all presented messages of support for ASFAP, and delegates from other regions, including Japan, China, India, Europe, the US and Latin America, all presented their regional strategies. The consensus is that strategic planning should be a bottom-up and community-driven process, even if this means it may take two to three years to produce a final report.

The meeting was updated on the progress of a diverse and well-established range of working groups (WGs) on accelerators, astrophysics and cosmology; computing and the fourth industrial revolution (4IR); energy needs for Africa; instrumentation and detectors; light sources; materials physics; medical physics; nuclear physics; particle physics; and community engagement (CE), which comprises physics education (PE), knowledge transfer, entrepreneurship and stakeholder and governmental-agency engagement. The WGs must also maintain dynamic communications with each other as key topics often impact multiple working groups.

Marie Clémentine Nibamureke (University of Johannesburg) highlighted the importance of the CE WG's vision "to improve science education and research in African countries in order to position Africa as a co-leader in science research globally". Convener Jamal Mimouni (Mentouri University) stressed that for ASFAP to establish a successful CE programme, it is crucial to reflect on challenges in teaching and learning physics in Africa – and on why students may be reluctant to choose physics as their study field. Nibamureke explained that the CE WG is seeking to appoint liaison officers between all the ASFAP working groups. Sam Ramaila (University of Johannesburg), representing the PE WG, indicated four main points the group has identified as crucial for the transformation and empowering of ▷ physics practices in Africa: strengthening teacher training; developing 21st-century skills and competences; introducing the 4IR in physics teaching and learning; and attracting and retaining students in physics programmes. Ramaila identified problem-based learning, self-directed learning and technology-enhanced learning as new educational strategies that could make a difference in Africa if applied more widely.

We are now soliciting inputs for the development of the African Strategy for Fundamental and Applied Physics

On the subject of youth engagement, Mounia Laassiri (Mohammed V University) led a young-person's forum to discuss the major issues young African physicists face in their career progression: outreach, professional development and networking will be a central focus for this new forum going forwards, she explained, and the forum aims to encourage young physics researchers to take up leadership roles. So far, there are about 40 members of the young-people's forum. Laassiri explained that the long-term vision, which goes beyond ASFAP, is to develop into an association of young physicists affiliated to the African Physical Society.

The ability to generate scientific innovation and technological knowledge, and translate this into new products, is vital for a society's economic growth and development. The ASFAP is a key step towards unlocking Africa's potential. We are now soliciting inputs for the development of the African Strategy for Fundamental and Applied Physics. Letters of interest may be submitted by individuals, research groups, professional societies, policymakers, education officials and research institutes on anything they think is an issue, needs to be improved, or is important for fundamental or applied physics education and research in Africa.

Azwinndini Muronga *Nelson Mandela University,* **Tabbetha Dobbins** *Rowan University,* **Gihan Kamel** *Helwan University,* **Chilufya Mwewa** *BNL and* **Uwineza Marie Clémentine Nibamureke** *University of Johannesburg.*

INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS

Artificial-neutrino experiments near precision era

NuFact 2021

Hybrid *NuFact 2021 took place online and in Cagliari, Italy.*

The 22nd International Workshop on Neutrinos from Accelerators (NuFact 2021) was held from 6 to 11 September, attracting a record 450 participants either online or in Cagliari, Italy. NuFact addresses topics in neutrino oscillations and neutrino-scattering physics, neutrino beams, muon physics, neutrinos beyond the Standard Model and the latest generation of neutrino detectors. The 2021 edition was organised by the Cagliari Division of INFN, the Italian Institute for Nuclear Physics and the University of Milano-Bicocca.

Precision era

At the time of the first NuFact in 1999, it wasn't at all clear that accelerator experiments could address leptonic CP violation in neutrinos. Fits still ignored θ_{13}, which expresses the relatively small coupling between the third neutrino mass eigenstate and the electron, and the size of the solar-oscillation mass splitting, which drives the CP-violating amplitude. Today, leading experiments testify to a precision era of neutrino physics where every parameter in the neutrino mixing matrix must be fitted. TK2, NOvA and MINERvA all reported new analyses and speakers from Fermilab updated the conference on the commissioning of the laboratory's short-baseline experiments ICARUS, MicroBooNE and SBND, which seek to clarify experimental hints of additional "sterile" neutrinos. After a long journey from CERN to Fermilab, the ICARUS detector, the largest and most downstream of the three liquid-argon detectors in the programme, has been filled with liquid argon, and data taking is now in full swing.

As we strive to pin down the values of the neutrino mixing matrix with a precision approaching that of the CKM matrix, NuFact serves as a key forum for collaborations between theorists and experimentalists. Simon Corrodi (Argonne) showed how the latest results from Fermilab on the g-2 anomaly may suggest new physics in lepton couplings, with potential implications for neutrino couplings and neutrino propagation. Collaboration with accelerator physicists is also important. After the discovery in 2012 that θ_{13} is nonzero, the focus of experiments with artificial sources of neutrinos turned to the development of multi-MW beams and the need for new facilities. Keith Gollwitzer (Fermilab) kicked off the discussion by summarising Fermilab's outstanding programme at the intensity frontier, paving the way for DUNE, and Megan Friend (KEK) presented impressive progress in Japan last year. The J-PARC accelerator complex is being upgraded to serve the new T2K near detector, for which the final TPC anode and cathode are now being tested at CERN. The J-PARC luminosity upgrade will also serve the Hyper-Kamiokande experiment, which is due to come online on approximately the same timeline as DUNE. Though the J-PARC neutrino beam will be less intense and by design more monochromatic than that from Fermilab to DUNE, the Hyper-Kamiokande detector will be both closer and larger, promising comparable statistics to DUNE, and addressing the same physics questions at a lower energy.

A lively round-table discussion featured a dialogue between two of the experiments' co-spokespersons, Stefan Söldner-Rembold (Manchester) and Francesca Di Lodovico (King's College London). Both emphasised the complementarity of DUNE and Hyper-Kamiokande, and the need to reduce systematic uncertainties with ad-hoc experiments. J-PARC director Takahashi Kobayashi explored this point in the context of data-driven models and precision experiments such as ENUBET and nuSTORM. Both experiments are in the design phase, and could operate in parallel with DUNE and Hyper-Kamiokande in the latter half of this decade, said Sara Bolognesi (Saclay) and Kenneth Long (Imperial). A satellite workshop focused on potential synergies between these two CERN-based projects and a muon-collider demonstrator, while another workshop explored physics goals and technical challenges for "ESSnuSB" – a proposed neutrino beam at the European Spallation Source in Lund, Sweden. In a plenary talk, Nobel laureate and former CERN Director-General Carlo Rubbia went further still, exploring the possibility of a muon collider at the same facility.

The next NuFact will take place in August 2022 in Salt Lake City, Utah.

Walter M Bonivento *INFN Cagliari and* **Francesco Terranova** *University of Milano Bicocca and INFN.*

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LOOP SUMMIT

Loop Summit convenes in Como

Loop Summit 2021

Invitational *Participants at the Loop Summit 2021.*

Precision calculations in the Standard Model and beyond are very important for the experimental programme of the LHC, planned high-energy colliders and gravitational-wave detectors of the future. Following two years of pandemic-imposed virtual discussions, 25 invited experts gathered from 26 to 30 July at Cadenabbia on Lake Como, Italy, to present new results and discuss paths into the computational landscape of this year's "Loop Summit".

The conference surveyed topics relating to multi-loop and multi-leg calculations in quantum chromodynamics (QCD) and electroweak processes. In scattering processes, loops are closed particle lines and legs represent external particles. Both present computational challenges. Recent progress on many inclusive processes has been reported at three- or four-loop order, including for deep-inelastic scattering, jets at colliders, the Drell–Yan process, top-quark and Higgs-boson production, and aspects of bottom-quark physics. Much improved descriptions of scaling violations of parton densities, heavy-quark effects at colliders, power corrections, mixed QCD and electroweak corrections, and high-order QED corrections for e^+e^- colliders have also recently been obtained. These will be important for many processes at the LHC, and pave the way to physics at facilities such as the proposed Future Circular Collider (FCC).

Weighty considerations

Although merging black holes can have millions of solar masses, the physics describing them remains classical, and quantum gravity happened, if at all, shortly after the Big Bang. Nevertheless, quantum field theory provides an elegant way to solve Einsteinian gravity. At this year's Loop Summit, perturbative approaches to gravity were discussed that use field-theoretic methods at the level of the 5th and 6th post-Newtonian approximations, where the nth post-Newtonian order corresponds to a classical n-loop calculation between black-hole world lines. These calculations allow predictions of the binding energy and periastron advance of spiralling-in pairs of black holes, and relate them to gravitational-wave effects. In these calculations, the classical loops all link to world lines in classical graviton networks within the framework of an effective-field-theory representation of Einsteinian gravity.

Other talks discussed important progress on advanced analytic computation technologies and new mathematical methods such as computational improvements in massive Dirac-algebra, new ways to calculate loop integrals analytically, new ways to deal consistently with polarised processes, the efficient reduction of highly connected systems of integrals, the solution of gigantic systems of differential equations, and numerical methods based on loop-tree duality. All these methods will decrease the theory errors for many processes due to be measured in the high-luminosity phase of the LHC, and beyond.

Half of the meeting was devoted to developing new ideas in subgroups. In-person discussions are invaluable for highly technical discussions such as these – there is still no substitute for gathering around the blackboard informally and jotting down equations and diagrams. The next Loop Summit in this triennial series will take place in summer 2024.

Johannes Blümlein *and* **Peter Marquard** *DESY.*

INTERNATIONAL SUMMER SCHOOL ON HADRON COLLIDER PHYSICS

10th anniversary for HASCO school

HASCO

Göttingen greats *At the residence of novelist and femme de lettres Therese Heyne.*

The 10th International Summer School on Hadron Collider Physics (HASCO) took place at the University of Göttingen from 18 to 26 July. After more than a year of lockdown and social isolation, we wanted to again give our young students the opportunity to attend courses and ask questions in person, meet international students of similar age, and junior and senior scientists from the particle-physics community. The school welcomed 40 undergraduate students and lecturers virtually and 50 in person. For the latter group, a highlight was a historical walkabout to the private houses of Max Born, Werner Heisenberg, Emmy Noether, Maria Goeppert-Mayer, David Hilbert, Richard Courant, James Franck and Max Planck. Students spent a week in discussion with lecturers from the University of Göttingen, partner universities and CERN. The focus was on the fundamentals of quantum field theory and current issues in hadron-collider physics, including quantum chromodynamics and jets, statistical methods of data analysis, the top quark, supersymmetry and the Higgs boson. A special focus this year was on machine learning and artificial intelligence.

Arnulf Quadt *University of Göttingen.*

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Revolutions *The first of the ATLAS New Small Wheels (NSW-A) ready for transport to Point 1 of the LHC. On the right is NSW-C where, at the time of the photograph in July 2021, only a few sectors had been installed.*

WHEELS IN MOTION FOR ATLAS UPGRADE

New muon end-cap wheels currently being installed in the ATLAS detector will provide precision tracking and triggering at high rates for Run 3 and beyond.

The Large Hadron Collider (LHC) complex is being upgraded to significantly extend its scientific reach. Following the ongoing 2019–2022 long shutdown, the LHC is expected to operate during Run 3 at close to its design of 7 TeV per beam and at luminosities more than double the original design. After the next shutdown, currently foreseen in 2025–2027, the High-Luminosity LHC (HL-LHC) will run at luminosities of $5–7\times10^{34}\,cm^{-2}s^{-1}$. This corresponds to 140–200 simultaneous interactions per LHC bunch crossing ("pileup"), which is three to four times the Run-3 expectation and up to eight times above the original LHC design value. The ATLAS experiment, like others at the LHC, is undergoing major upgrades for the new LHC era.

Coping with very high interaction rates while maintaining low transverse-momentum (p_T) thresholds for triggering on electrons and muons from the targeted physics processes will be extremely challenging at the HL-LHC. Another issue for the ATLAS experiment is that the perfor-

THE AUTHORS

The ATLAS muon New Small Wheels team.

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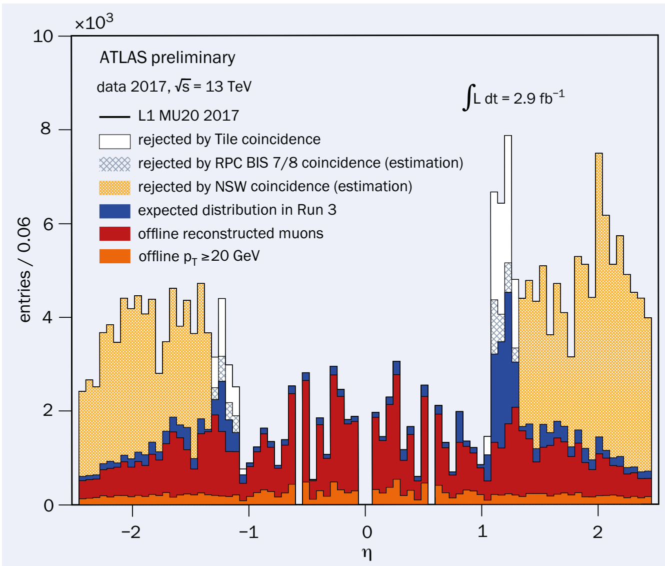
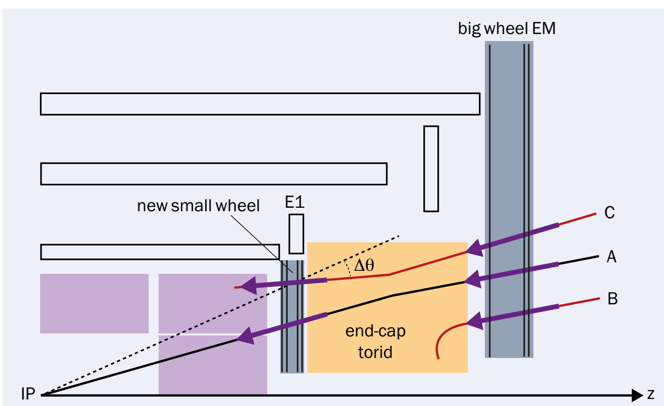


Good muons *The pseudorapidity distribution of muon candidates passing the level-1 ATLAS trigger with $p_T > 20$ GeV from 2017 Run-2 data, showing the regions expected to be rejected using the NSW in Run 3 and beyond (orange). Almost all triggered muons (blue histogram) are "good" muons (red).*



Real or fake? *Sketch of a quarter section of ATLAS showing different "muon" trajectories. Only trajectory A corresponds to a muon produced at the LHC interaction point (IP), while trajectories B and C are from the fake signals that dominate the Level-1 trigger rate.*

mance of its muon tracking chambers, particularly in the end-cap regions of the detector, degrades with increasing particle rates. If the original chambers were used for the HL-LHC, it would lead to a loss in the efficiency and resolution of muon reconstruction.

Muons are vital for efficiently triggering on, and thus precisely studying, processes in the electroweak sector such as Higgs, W and Z physics. It is therefore essential that the ATLAS detector cover as much volume as possible across the pseudorapidity distribution $\eta = -\ln \tan\theta/2$, where θ is the angle with respect to the proton beam axis. In the central region of the detector, corresponding to a pseudorapidity $|\eta| < 1$, there is a good purity of muons originating from the proton collision point (see "Good muons" figure). In the end caps, $|\eta| > 1.3$, significant contributions, the so-called "fake" muon signals (see "Real or fake?" figure), arise from other sources. These include cavern backgrounds and muons produced in the halo of the LHC proton beams, both of which increase with larger instantaneous luminosities. Without modifications to the detector, the fake-muon trigger rates in the end caps would become unsustainable at the HL-LHC, requiring the muon p_T thresholds in the Level-1 trigger to be raised substantially.

To resolve these issues, the ATLAS collaboration decided, as part of its major Phase-I upgrade, to replace the existing ATLAS muon small wheels with the "New Small Wheels" (NSW), capable of reconstructing muon track segments locally with 1 mrad resolution for both the Level-1 trigger and for offline reconstruction. The NSW will allow low-p_T thresholds to be maintained for the end-cap muon triggers even at the ultimate HL-LHC luminosity.

The low-p_T region for leptons is of critical importance to the ATLAS physics programme. As an example, Higgs-boson production via vector-boson fusion (VBF) is a powerful channel for precision Higgs studies, and low-p_T end-cap lepton triggers are crucial for selecting $H\rightarrow\tau\tau$ events used to study Higgs-boson Yukawa couplings. Within the current tracking detector acceptance of $|\eta| < 2.5$, the fraction VBF of $H\rightarrow\tau\tau$ events with the leading muons having p_T above 25 GeV (typical Run-2 threshold) is 60%, while this fraction drops to 28% for a p_T threshold of 40 GeV (expected typical HL-LHC threshold if no changes to the detectors are made). Maintaining, or even reducing, the muon p_T threshold is critical for extending the ATLAS physics programme in higher luminosity LHC operation.

Frontier technologies

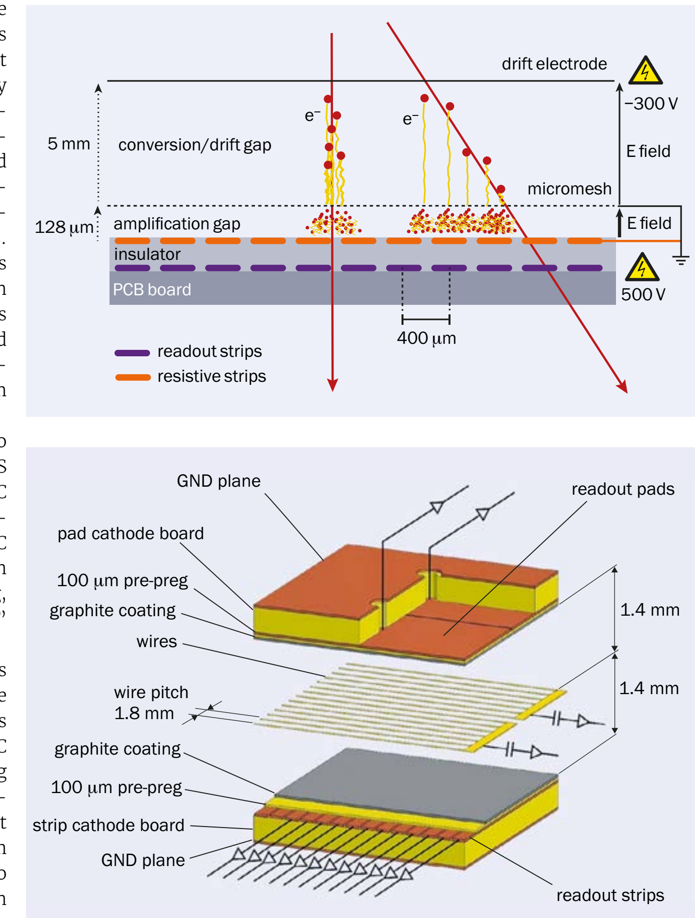
The ATLAS NSW is a set of precision tracking and trigger detectors able to work at high rates with excellent spatial and time resolution using two innovative technologies: MicroMegas (MM) and small-strip thin-gap chambers (sTGC). These detectors will provide the muon Level-1 trigger system with online track segments with good angular resolution to confirm that they originate from the interaction point, reducing triggers from fake muons. They will also have timing resolutions below the 25 ns interbunch time, enabling bunch-crossing identification. With the NSW, ATLAS will keep the full acceptance of its muon tracking system at the HL-LHC while maintaining a low Level-1 p_T threshold of around 20 GeV.

The ATLAS collaboration chose MM and sTGC technologies for the NSW after a detailed scrutiny of several available options. The idea was to build a robust and redundant system, using research-frontier and cost-effective technologies. Each NSW wheel has 16 sectors, with each sector containing four MM chambers and six sTGC chambers. Each sector, with a total surface area ranging from about 4 to 6 m², has eight sensitive planes of MM and eight of sTGC along the muon track direction. The 16 overall measurement planes allow for redundancy in the track reconstruction.

MM detectors were proposed in the 1990s in the framework of the Micro-Pattern Gaseous Detectors (MPGD) R&D programme including the RD51 project at CERN (see "Robust and redundant" figure, top). They profit from the development of photolithographic techniques for the design of high-granularity readout patterns and, in parallel, from the development of specialised front-end electronics with an increased number of channels. A dedicated R&D programme introduced, developed and realised the concept of resistive MM detectors. The main challenge for ATLAS was to scale the detectors from a few tens of cm in size to chambers of 2–3 m² with a geometry under control at the level of tens of µm. This required additional R&D together with a very detailed mechanical design of the detectors. The resulting detectors represent the largest and most complex MPGD system ever built.

Thin-gap chambers have been used for triggering and to provide the azimuthal coordinate of muons in the ATLAS muon spectrometer end caps since the beginning of LHC operations, and were used previously in the OPAL experiment at LEP. The sTGC is an extension of established TGC technology to allow for precise online tracking that can be used both in the trigger and in offline muon tracking, with a strip pitch of 3.2 mm (see "Robust and redundant" figure, bottom).

A common readout front-end chip, named VMM, was developed for the readout of the MM strips and of the active elements of the sTGC (strips, pads and wires). This chip is a novel "amplifier-shaper-discriminator" front-end ASIC able to perform amplification and shaping, peak finding and digitisation of the detector signals. The overall system has about 2 million MM and 350,000 sTGC readout channels. The ATLAS trigger, using information from both detectors, will identify track segments pointing to the interaction region and share this information with the muon trigger.



Robust and redundant *Top: the layout and operating principle of the MicroMegas detectors. Bottom: the gap structure of the small-strip thin-gap chambers (sTGC) showing the wires, readout pads and strips.*

International enterprise

The construction of the 128 MM and 192 sTGC chambers has been a truly international enterprise shared among several laboratories. The construction of the MM was shared among five construction consortia in France, Germany, Greece, Italy and Russia, with infrastructure and technical expertise inherited from the construction of the ATLAS Muon Spectrometer Monitored Drift Tube chambers. The construction of the sTGC was shared among five consortia located in Canada, Chile, China, Israel and Russia, including both institutes from the original TGC construction and new ones.

A key challenge in realising both technologies was the use of large-area circuit boards produced by industry. For the case of the MM, high-voltage instabilities observed since the construction of the first large-size prototypes were mostly due to the quality of the printed circuit boards. Two aspects in particular were investigated: the cleanliness of the surfaces, and the actual measured values of the board resistivity that were in many cases not large enough to prevent electrical discharges in the detector. For both problems, detailed mitigation protocols were developed and shared among the consortia: a cleaning protocol including polishing and washing of all the surfaces and a "passivation" procedure designed to mask detector regions with lower resistance where most of the discharges were observed to take place.

For the sTGC, the principal difficulty in the circuit-board production was maintaining mechanical tolerances and electrical integrity over the large areas. Considerable R&D and quality control were required before and during the board production, and when combined with X-ray measurements at CERN the sTGC layers are aligned to better than 100 µm.

Along with the chamber construction, several tests were carried out at the construction sites to evaluate the chamber quality. Some of the first full-size prototypes together with the first production chambers were exposed to test beams. All the sTGC chambers and a large fraction of the MM chambers were also tested at CERN's GIF++ irradiation facility to evaluate their behaviour

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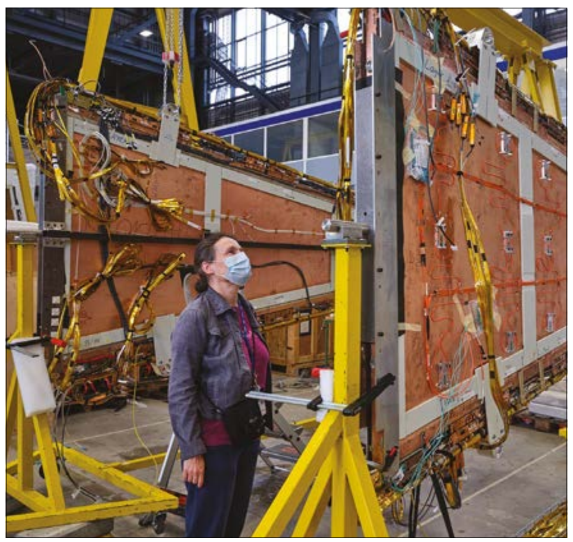
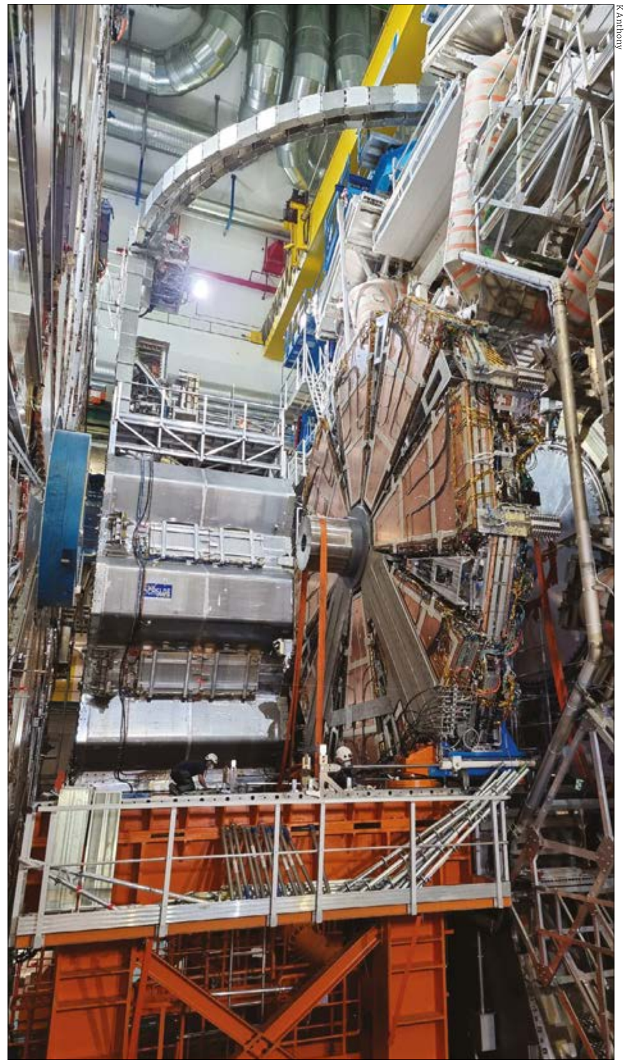
M Brice/CERN



Taking stock *Two MicroMegas double-wedges (top) and two small-strip thin-gap chamber wedges (bottom) in the stocking areas. In both cases the systems are equipped with services and front-end electronics.*



K Anthony

In place *The first New Small Wheel (NSW-A) very close to its final position between the barrel and end-cap toroid magnets in ATLAS on 15 July 2021.*

under a particle rate comparable to the one expected at the HL-LHC.

The integration of both MM and sTGC chambers to form the wheel sectors took place at CERN from 2018 to 2021. Four MM chambers form a double-wedge, assembled accounting for the severe alignment requirements, which is then equipped with all the necessary services and the final front-end electronics (see "Taking stock" image). The systems were fully tested in a dedicated cosmic-ray test stand to verify the functionality of the detector and to evaluate the detector efficiency. For the sTGCs, three chambers were glued to fibreglass frames using precision inserts on a granite table to form a wedge. After long-term high-voltage tests, the sTGC wedges were equipped with front-end electronics, cooling, and readout cables and fibres. All the sTGC chambers were tested with cosmic rays at the construction sites, and a few were also tested at CERN.

To form each sector, two sTGC wedges and one MM double-wedge were sandwiched together. The sectors were then precisely mounted on "spokes" installed on the large shielding disks that form the NSW wheels, along with a precision optical alignment system that allows the chamber positions to be tracked by ATLAS in real time (see "Revolutions" image, p27). After completing final electrical, cooling and gas connections during 2020 and 2021, all sectors were commissioned and tested on the wheel. One unexpected problem encountered on the first sectors on wheel A was the presence of a noise level in the front-end

electronics that was significantly higher than observed during integration. A large and ultimately successful effort was put in place to mitigate this new challenge, for example by improving the grounding and shielding, and adding filtering to the power supplies.

This final success follows more than a decade of research, design and construction by the ATLAS collaboration. The NSW initiative dates to early LHC operation, around 2010, and the technical design report was approved in 2013, with construction preparation starting soon afterwards. The impact of the COVID-19 pandemic on the NSW construction schedule was significant, mostly at the construction sites, where delays of up to a few months were accrued, but the project is now on schedule for completion during the current LHC shutdown.

The endgame

Prior to lowering the NSW into the ATLAS experimental cavern, other infrastructure was installed to prepare for detector operation. The service caverns were equipped with electronics racks, high-voltage and low-voltage power supplies, gas distribution systems, cooling infrastructure for electronics, as well as control and safety systems. Where possible, existing infrastructure from the previous ATLAS small wheels was repurposed for the NSW.

On 6 July, the first wheel, NSW-A, was shipped from Building 191 on the CERN site to LHC Point 1 and then, less than a week later, lowered into its position in ATLAS (see "In place" image, p30). With the first NSW in its final position, the extensive campaign of connecting low voltage, high voltage, gas, readout fibres and electronics cooling was the next step. These connections were completed for NSW-A in July and August 2021, and an extensive commissioning programme is ongoing. In addition to powering both the chambers and the readout electronics, the integration of the NSW into the ATLAS controls and data-acquisition system is occurring at Point 1. NSW-A is planned to be fully integrated into ATLAS for the LHC pilot-beam run in October 2021, and then NSW-C will be lowered and installed.

Despite a tight schedule, ATLAS is now close to the completion of its Phase-I upgrade goal of having both NSW-A and NSW-C installed for the start of Run 3. The period up to February 2022 will be needed to complete commissioning and testing. Starting from March 2022, a very important "commissioning with beam" phase will be carried out to ensure stable collisions in Run 3. Even with the challenges of developing new technologies while working across a dozen countries during the COVID-19 pandemic, the ATLAS New Small Wheel upgrade will be ready for the exciting, new higher luminosities that will open up a novel era of LHC physics. ●

ATLAS is now close to the completion of its Phase-I upgrade goal of having both NSW-A and NSW-C installed for the start of Run 3

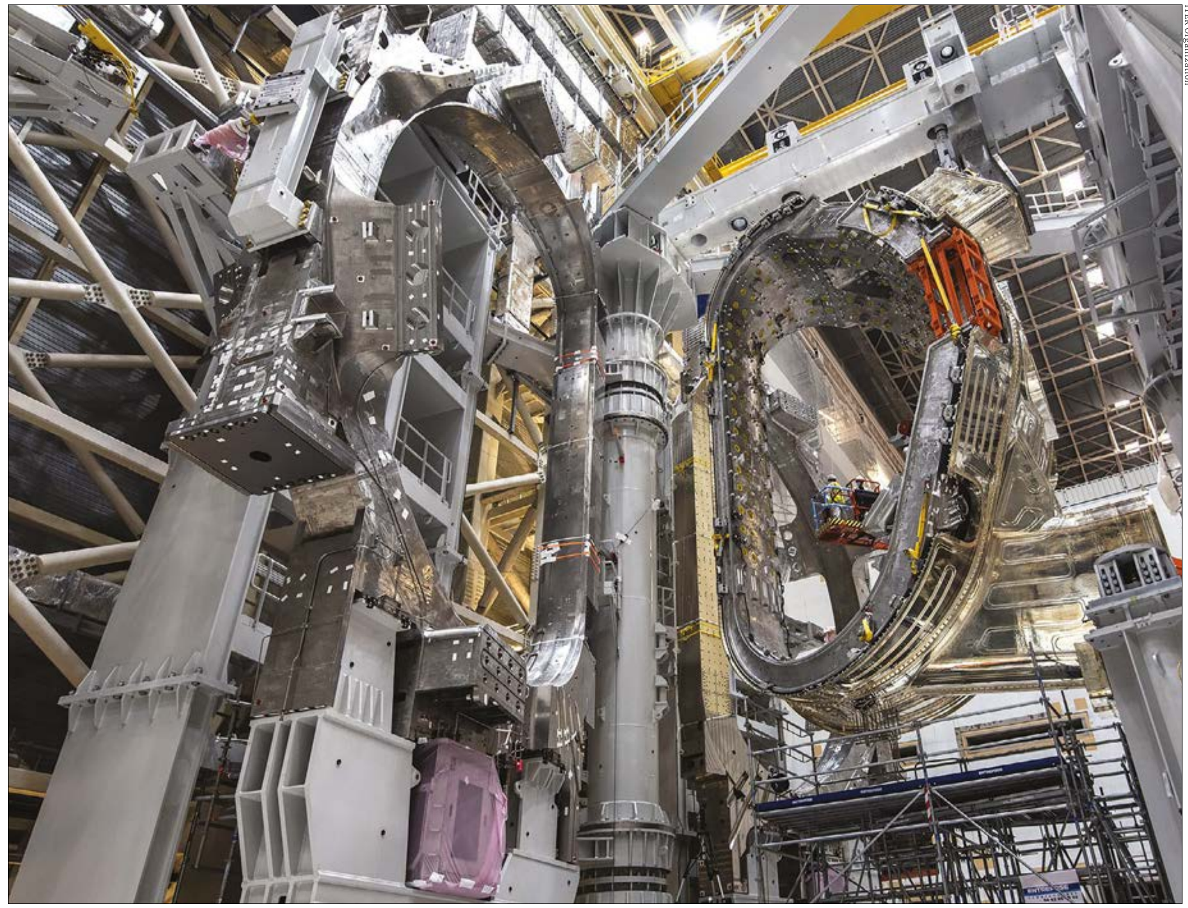
ITER POWERS AHEAD

Assembly of the tokamak that will confine a 150-million-degree plasma inside the ITER fusion experiment marks a crucial new phase in the project, describes Tim Luce.

At the heart of the ITER fusion experiment is an 18 m-tall, 1000-tonne superconducting solenoid – the largest ever built. Its 13 T field will induce a 15 MA plasma current inside the ITER tokamak, initiating a heating process that ultimately will enable self-sustaining fusion reactions. Like all-things ITER, the scale and power of the central solenoid is unprecedented. Fabrication of its six niobium-tin modules began nearly 10 years ago at a purpose-built General Atomics facility in California. The first module left the factory on 21 June and, after traveling more than 2400 km by road and then crossing the Atlantic, the 110 tonne component arrived at the ITER construction site in southern France on 9 September. During a small ceremony marking the occasion, the director of engineering and projects for General Atomics described the job as: "among the largest, most complex and demanding magnet programmes ever undertaken" and "the most important and significant project of our careers."

The US is one of seven ITER members, along with China, the European Union, India, Japan, Korea and Russia, who ratified an international agreement in 2007. Each member shares in the cost of project construction, operation and decommissioning, and also in the experimental results and any intellectual property. Europe is responsible for the largest portion of construction costs (45.6%), with the remainder shared equally by the other members. Mirroring the successful model of collider experiments at CERN, the majority (85%) of ITER-member contributions are to be delivered in the form of completed components, systems or buildings – representing untold hours of highly skilled work both in the member states and at the ITER site.

Among the largest, most complex and demanding magnet programmes ever undertaken



Shaping up *A D-shaped toroidal magnet coil being attached to its vacuum-vessel sector in August 2021.*

First plasma

Assembly of the tokamak, which got under way in 2020, marks an advance to a crucial new phase for the ITER project. Production of its 18 D-shaped coils that provide the toroidal magnetic field, each 17 m high and weighing 350 tonnes, is in full swing, while its circular poloidal coils are close to completion. The remaining solenoid modules and all other major tokamak components are scheduled to be on site by mid-2023. Despite the impact of the global pandemic, the ITER teams are working towards the baseline target for "first plasma" by the end of 2025, with more than 2000 persons on site each day.

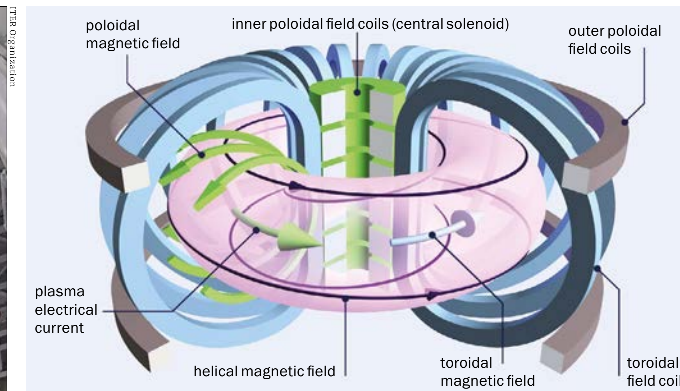
ITER's purpose is to demonstrate the scientific and technological feasibility of fusion power for peaceful purposes. Key objectives are defined for this demonstration, namely: production of 500 MW of fusion power with a ratio of fusion power to input heating power (Q) of at least 10 for at least 300 seconds, and sustainment of fusion power with Q = 5 consistent with steady-state operation. The key factor in reaching these objectives is the world's largest tokamak, a concept whose name comes from a Russian acronym roughly translated "toroidal chamber with magnetic coils". This could also describe CERN's Large Hadron Collider (LHC), but as we will see, the two magnetic confinement schemes are significantly different.

ITER chose deuterium and tritium (heavier variants of ordinary hydrogen) for its fuel because the D–T cross-section is the highest of all known fusion reactions. However, the energy at which the cross-section is maximum (~65 keV) is equivalent to almost 1 billion degrees. As a result, the fuel will no longer be in the form of gas as it is introduced but in the plasma state, where it is broken down to its electrically charged components (ions and electrons). As in the LHC, the electric charge introduces the possibility to hold the ions and electrons in place using magnetic fields generated by electromagnets – in both cases by superconducting magnets held at temperatures near absolute zero to avoid massive electrical consumption.

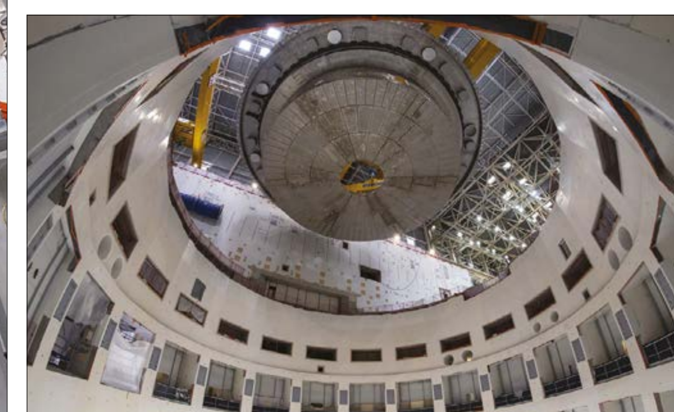
A simple picture of how the magnets in ITER work together to confine a plasma with temperatures greater than 100 million degrees begins with the toroidal field coils (see "Trapping a plasma" figure). Eighteen of these are arranged to make a magnetic field that is circular-centered on a vertical line. Charged particles, to the crudest approximation, follow the magnetic field, so it would seem that the problem of confining them is solved. However, at the

THE AUTHOR

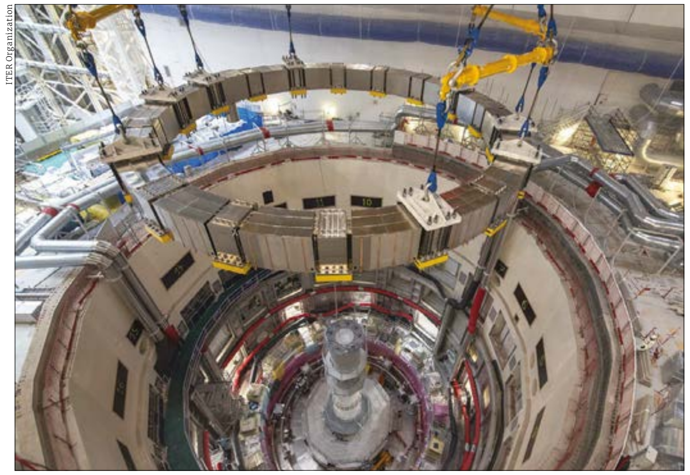
Tim Luce *is head of science and operation at ITER.*



Trapping a plasma *The key magnetic elements necessary to confine a plasma in a torus-shaped tokamak.*



Heavy lifting *ITER's cryostat base was the first major component to be installed at the bottom of the 30 metre-deep "machine well" in April 2020.*



ITER Organization

Poloidal descent *The first of ITER's poloidal field coils, 17 m in diameter and weighing close to 350 tonnes, being positioned at the bottom of the tokamak pit on 16 September 2021.*

next level of approximation, the charged particles actually make small "gyro-orbits", like beads on a wire. This introduces a difficulty because the "gyroradius" of these orbits depends on the strength of the magnetic field, and the toroidal magnetic field increases in strength closer to the vertical line defining its centre. This means that the gyroradius is smaller on the inner part of the orbit, which leads to a vertical motion of the charged particles. Since the direction of motion depends on the charge of the particle, however, the opposite charges move away from each other. This makes a vertical electric field which, when combined with the toroidal field, rapidly expels charged particles radially outward – eliminating confinement! Two Russian physicists, Tamm and Sakharov, proposed the idea in the 1950s that a current flowing in the plasma in the toroidal direction would generate a net helical field and charged particles flowing along the total field would short out the electric field, leading to confinement. This was the invention of the tokamak magnetic confinement concept.

Magnetic configuration

In ITER, this current is generated by the powerful central solenoid, aligned on the vertical line at the centre of the toroidal field. It acts as the primary winding of a transformer, with the plasma as the secondary. There remains one more issue to address, again with magnets. The pressure and current in the plasma result in a force that tries to push the plasma further from the vertical line at the centre. To counter this force in ITER, six "poloidal field" coils are aligned – again about the vertical centerline – to generate vertical fields that push the plasma back toward the vertical line and also shape the plasma in ways that enhance the performance. A number of correction coils will complete ITER's complex magnetic configuration, which will demonstrate the deployment of the Nb_3Sn conductor – the same as is being implemented for high-field accelerator magnets at the High-Luminosity LHC and as proposed for future colliders – on a massive scale. CERN signed a collaboration agreement with ITER in 2008 concerning the design of high-temperature superconducting current leads and other magnet technologies, and acted as one of the "reference" laboratories for testing ITER's superconducting strands.

ITER will provide crucial information about both the science and technology necessary for a fusion power plant

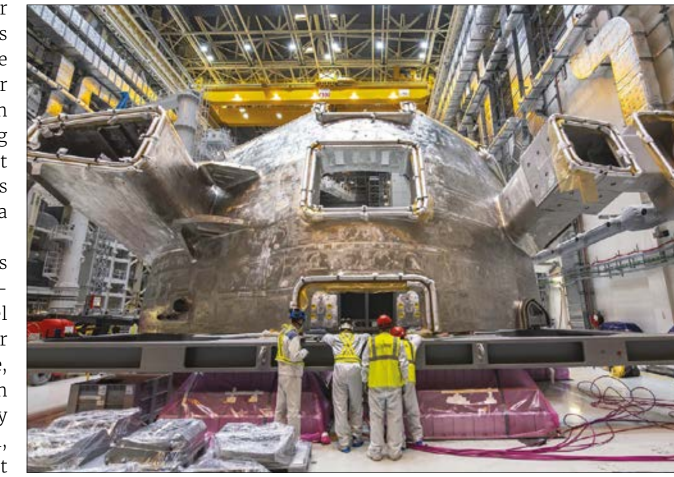
Despite the pandemic disrupting production and transport, the first step of ITER's tokamak assembly sequence – the installation of the base of the cryostat into the tokamak bioshield – was achieved in May 2020. The ITER cryostat, which must be made of non-magnetic stainless steel, will keep the entire (30 m diameter by 30 m high) tokamak assembly at the low temperatures necessary for the magnets to function. It comes in four pieces (base, lower and upper cylinders, and lid) that are welded together in the tokamak building. At 1250 tonnes, the cryostat-base lift was the heaviest of the entire assembly sequence, its successful completion officially starting the assembly sequence (see "Heavy lifting" image). Later in 2020, the lower cylinder was then installed and welded to the base.

Bottle up

With the "bottle" to hold the tokamak placed in position, installation of the electromagnets could begin. The two poloidal field coils at the bottom of the tokamak, PF6 and PF5, had to be installed first. PF6 was placed inside the cryostat earlier this year (see "Poloidal descent" image), while the second was lifted into place this September. The next big milestone is the assembly and installation of the first "sector" of the tokamak. The vacuum vessel in which the fusion plasma is made is divided into nine equal sectors (like the slices of an orange), due to limitations on the lifting capacity and to facilitate parallel fabrication of these large objects. Each sector of the vacuum vessel (see "Monster moves" image) has two toroidal field coils associated with it.

In August, this vacuum vessel and its associated thermal shields were assembled together with the toroidal field coils on the sector sub-assembly tool for the first time (see "Shaping up" image). Once joined into a single unit, it will be installed in the cryostat in late 2021. The second vacuum-vessel sector arrived on site in August and will be assembled with the two associated toroidal-field coils already on site, with a target to install the final unit in the cryostat early in 2022. Sector components are scheduled to arrive, be put together, and then installed in the cryostat and welded together in assembly-line fashion, with the closure of the vacuum vessel scheduled for the end of 2023. The six central-solenoid modules are also to be assembled outside the cryostat into a single structure and installed in the cryostat shortly before closure. Following the arrival of the first module this summer, the second is complete and ready for shipping. Of the remaining four niobium-titanium poloidal field magnets, three are being fabricated on-site because they are too large to transport by road and all four are in advanced stages of production.

Of course, there is more to ITER than its tokamak. In parallel, work on the supporting plant is under way. Four large transformers, which draw the steady-state electrical power from the grid, have been in operation since early 2019, while the medium- and low-voltage load centres that power clients in the plant buildings have been turned over to the operations division. The secondary and tertiary cooling systems, the chilled water and demineralised water plants, and the compressed-air and breathable-air plants are also currently being commissioned. The three large transformers that connect the pulsed power supplies for the magnets and the plasma heating systems have been qualified for operation on the 400 kV grid. The next big steps are the start of functional testing of the cryoplant and the reactive power compensation at the end of this year, and of the magnet power supplies and the first plasma heating system early in 2022.



ITER Organization

Monster moves *The latest vacuum-vessel sector, weighing 440 tonnes, arrived at ITER in late August 2021.*

ITER Organization/E. Riche

From above *The 180-hectare ITER site in May 2021, with the 60 m-high assembly building seen in the centre.*

Perhaps the most common question one encounters when talking about ITER is: when will tokamak operations begin? Following the closure of the vacuum vessel in 2023, the current baseline schedule includes one year of installation work inside the cryostat before its closure, followed by integrated commissioning of the tokamak in 2025, culminating in "first plasma" by the end of 2025. By mandate from ITER's governing body, the ITER Council, this schedule was put into place in 2016 as the "fastest technically achievable", meaning no contingency. Clearly the pandemic has impacted the ability to meet that schedule, but the actual impact is still not possible to determine accurately. The challenge in this assessment is that 85% of the ITER components are delivered as in-kind contributions from the ITER members, and the pandemic has affected and continues to affect the manufacturing work on items that take years to complete. The components now being installed were substantially complete at the onset of the pandemic, but even these deliveries have encountered difficulties due to the disruption of the global shipping industry. Component installation in the tokamak complex has also been impacted by limited availability of components, goods and services. The possibility of recovery actions or further restrictions is not possible to predict with the needed accuracy today. In this light, the ITER Council has challenged us to do the best possible effort to maintain the baseline schedule, while preparing an assessment of the impact for consideration of a revised baseline schedule next year. The ITER Organization, domestic agencies in the ITER members responsible for supplying in-kind components, and contractors and suppliers around the world are working together to meet this additional challenge.

What the future holds

ITER is expected to operate for 20 years, providing crucial information about both the science and the technology necessary for a fusion power plant. For the science, beyond the obvious interest in meeting ITER's performance objectives, qualitative frontiers will be crossed in two essential areas of plasma physics. First, ITER will be the first "burning" plasma, where the dominant heating power to sustain the fusion output comes directly from fusion itself. Aspects of the relevant physics have been studied for many years, but the operating point of ITER places it in a fundamentally different regime from present experiments. The same is true of the second frontier: the handling of heat and particle exhaust in ITER. There is a qualitative difference predicted by our best simulation capabilities between the ITER operating point and present experiments. This is also the first touch-point between the physics and the technology: the physics must enable the survival of the wall, while the wall must allow the plasma physics to yield the conditions needed for the fusion reactions. Other essential technologies such as the means to make new fusion fuel (tritium), recycling of the fuel in use in real-time and remote handling for maintenance activities will all be pioneered in ITER.

While ITER will demonstrate the potential for fusion energy to become the dominant source of energy production, harnessing that potential requires the demonstration not just of the scientific and technical capabilities but of the economic feasibility too. The next steps along that path are true demonstration power plants – "DEMOs" in fusion jargon – that explore these steps. ITER members are already exploring DEMO options, but no commitments have yet been made. The continuing advance of ITER is critical not just to motivate these next steps but also as a vision of a future where the world is powered by an energy source with universally available fuel and no impact on the environment. What a tremendous gift that would be for future generations. ●

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COUNTING COLLISIONS PRECISELY AT CMS

Beyond the setting of new records, precise knowledge of the luminosity at particle colliders is vital for future physics analyses, explains Georgios K Krintiras.

Year after year, particle physicists celebrate the luminosity records established at accelerators around the world. On 15 June 2020, for example, a new world record for the highest luminosity at a particle collider was claimed by SuperKEKB at the KEK laboratory in Tsukuba, Japan. Electron–positron collisions at the 3 km-circumference machine had reached an instantaneous luminosity of $2.22\times10^{34}\,cm^{-2}s^{-1}$ – surpassing the 27 km-circumference LHC's record of $2.14\times10^{34}\,cm^{-2}s^{-1}$ set with proton–proton collisions in 2018. Within a year, SuperKEKB had celebrated a new record of $3.1\times10^{34}\,cm^{-2}s^{-1}$ (*CERN Courier* September/October 2021 p8).

Beyond the setting of new records, precise knowledge of the luminosity at particle colliders is vital for physics analyses. Luminosity is our "standard candle" in determining how many particles can be squeezed through a given space (per square centimetre) at a given time (per second); the more particles we can squeeze into a given space, the more likely they are to collide, and the quicker the experiments fill up their tapes with data. Multiplied by the cross section, the luminosity gives the rate at which physicists can expect a given process to happen, which is vital for searches for new phenomena and precision measurements alike. Luminosity milestones therefore mark the dawn of new eras, like the B-hadron or top-quark factories at SuperKEKB and LHC (see "High-energy data" figure, p40). But what ensures we didn't make an accidental blunder in calculating these luminosity record values?

Intense *The start of Run-2 physics in the CMS control room.*

Physics focus

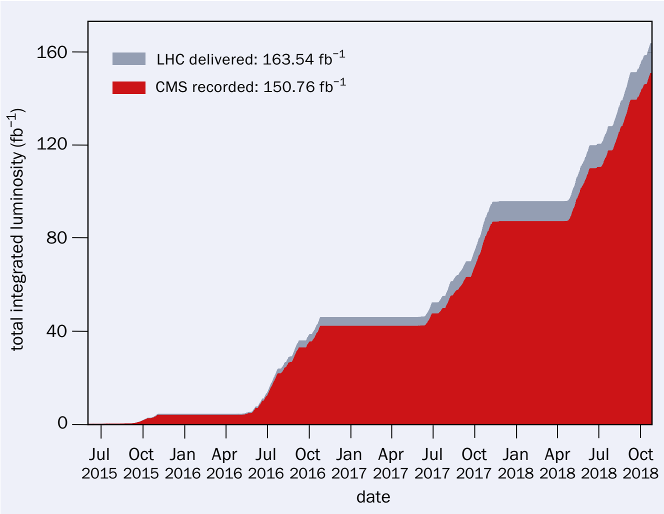
Physicists working at the precision frontier need to infer with percent-or-less accuracy how many collisions are needed to reach a certain event rate. Even though we can produce particles at an unprecedented event rate at the LHC, however, their cross section is either too small (as in the case of Higgs-boson production processes) or impacted too much by theoretical uncertainty (for example in the case of Z-boson and top-quark production processes) to enable us to establish the primary event rate with a high level of confidence. The solution comes down to extracting one universal number: the absolute luminosity.

The fundamental difference between quantum electrodynamics (QED) and chromodynamics (QCD) influences how luminosity is measured at different types of colliders. On the one hand, QED provides a straightforward path to high precision because the absolute rate of simple final states is calculable to very high accuracy. On the other, the complexity in QCD calculations shapes the luminosity determination at hadron colliders. In principle, the luminosity can be inferred by measuring the total number of interactions occurring in the experiment (i.e. the inelastic cross section) and normalising to the theoretical QCD prediction. This technique was used at the Sp$\bar{p}$S and Tevatron colliders. A second technique, proposed by Simon van der Meer at the ISR (and generalised by Carlo Rubbia for the p$\bar{p}$ case), could not be applied to such single-ring colliders. However, this van der Meer-scan method is a natural choice at the double-ring RHIC and LHC colliders, and is described in the following.

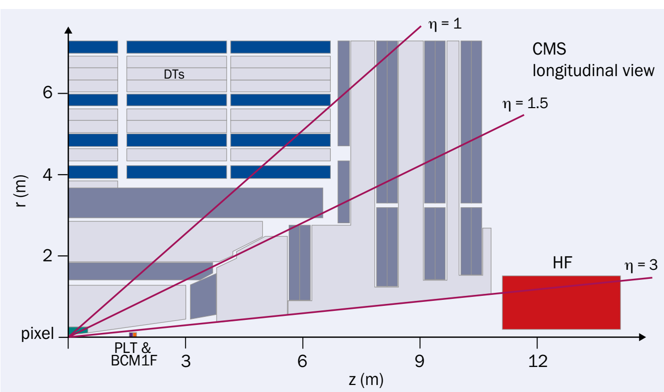
Absolute calibration

The LHC-experiment collaborations perform a precise luminosity inference from data ("absolute calibration") by relating the collision rate recorded by the subdetectors to the luminosity of the beams. With the implementation of multiple collisions per bunch crossing ("pileup") and intense collision-induced radiation, which acts as a back-

THE AUTHOR
Georgios K Krintiras
University of Kansas, on behalf of the CMS collaboration.

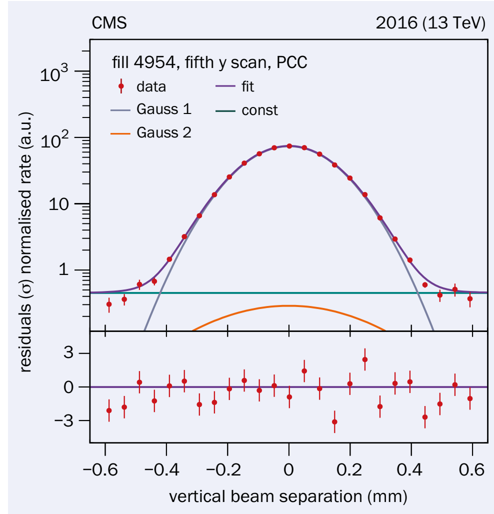


High-energy data *The integrated proton–proton luminosity recorded by the CMS experiment at the LHC during Run 2 (2015–2018).*



Luminometers *Schematic view of the CMS detector highlighting the location of the luminometers: the silicon pixel subdetector (in two, barrel and endcap, regions); the Pixel Luminosity Telescope (PLT); the single-crystal diamond Fast Beam Conditions Monitor (BCM1F); drift tubes (DTs) in the muon subdetector and the forward hadron calorimeter (HF). Directly behind the HF, two ionisation chambers (RAMSES) are also used as luminosity monitors, but not shown.*

ground source, dedicated luminosity-sensitive detector systems called luminometers also had to be developed (see "Luminometers" figure). To maximise the precision of the absolute calibration, beams with large transverse dimensions and relatively low intensities are delivered by the LHC operators during a dedicated machine preparatory session, usually held once a year and lasting for several hours. During these unconventional sessions, called van der Meer beam-separation scans, the beams are carefully displaced with respect to each other in discrete steps, horizontally and vertically, while observing the collision rate in the luminometers (see "Closing in" figure). This allows the effective width and height of the



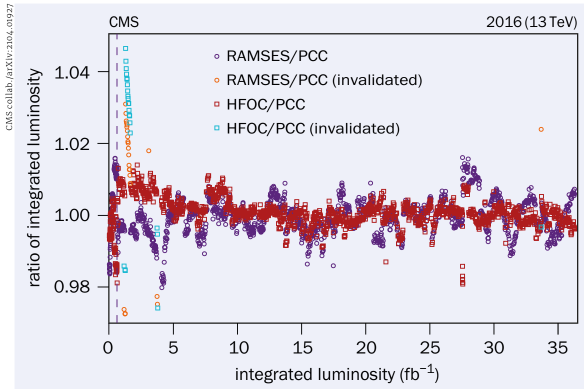
Closing in *When LHC bunches gradually approach each other, they produce a beam-separation-dependent event rate (red points), whose maximum sits at 0. The LHC experiments measure luminosity via the size of the bunches (vertical direction). The curves correspond to a parametrisation and its subcomponents ("Gauss 1/2" and "const"), while the bottom panel shows the level of agreement between the data and fit.*

two-dimensional interaction region, and thus the beam's transverse size, to be measured. Sources of systematic uncertainty are either common to all experiments and are estimated *in situ*, for example residual differences between the measured beam positions and those provided by the operational settings of the LHC magnets, or depend on the scatter between luminometers. A major challenge with this technique is therefore to ensure that the obtained absolute calibration as extracted under the specialised van der Meer conditions is still valid when the LHC operates at nominal pileup (see "Stability shines" figure).

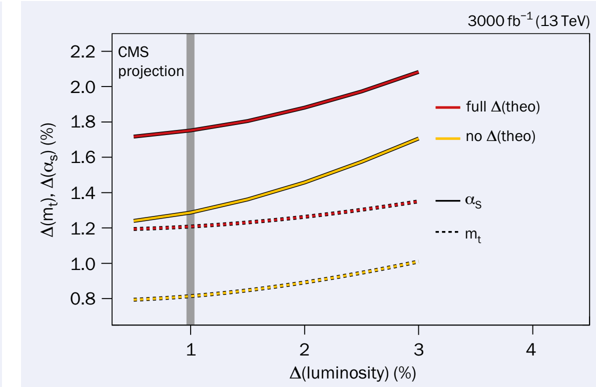
Stepwise approach

Using such a stepwise approach, the CMS collaboration obtained a total systematic uncertainty of 1.2% in the luminosity estimate (36.3 fb^{-1}) of proton–proton collisions in 2016 – one of the most precise luminosity measurements ever made at bunched-beam hadron colliders. Recently, taking into account correlations between the years 2015–2018, CMS further improved on its preliminary estimate for the proton–proton luminosity at higher collision energies of 13 TeV. The full Run-2 data sample corresponds to a cumulative ("integrated") luminosity of 140 fb^{-1} with a total uncertainty of 1.6%, which is comparable to the preliminary estimate from the ATLAS experiment.

In the coming years, in particular when the High-Luminosity LHC (HL-LHC) comes online, a similarly precise luminosity calibration will become increasingly important as the LHC pushes the precision frontier further. Under those conditions, which are expected to produce 3000 fb^{-1} of proton–proton data by the end of LHC opera-



Stability shines *During proton–proton data-taking in 2016 the ratio of luminosities between luminometers are seen to agree remarkably well with each other. HFOC and PCC denote the implemented algorithms using data from the hadron calorimeter and silicon-pixel subdetector, respectively, while invalidated entries correspond to data not further processed in luminosity-related analyses.*



Precision frontier *Expected uncertainties in the measurement of top-quark mass m_t (dashed lines) and strong coupling constant α_s (solid lines) as a function of the uncertainty in the luminosity for the cases when the full experimental and theoretical (red lines) or only the expected experimental uncertainties (yellow lines) are considered. The vertical grey bar shows the "precision frontier" target uncertainty of 1%.*

tions in the late 2030s (see "Precision frontier" figure), the impact from (at least some of) the sources of uncertainty is expected to be larger due to the expected high pileup. However, they can be mitigated using techniques already established in Run 2 and/or are currently under deployment. Overall, the strategy for the HL-LHC should combine three different elements: maintenance and upgrades of existing detectors; development of new detectors; and adding dedicated readouts to other planned subdetectors for luminosity and beam monitoring data. This will allow us to meet the tight luminosity performance target (≤ 1%) while maintaining a good diversity of luminometers.

Given that accurate knowledge of luminosity is a key ingredient of most physics analyses, experiments also release precision estimates for specialised data sets, for example using either proton–proton collisions at lower centre-of-mass energies or involving nuclear collisions at different per-nucleon centre-of-mass energies, as needed by the ALICE but also ATLAS, CMS and LHCb experiments. On top of the van der Meer method, the LHCb collaboration uniquely employs a "beam-gas imaging" technique in which vertices of interactions between beam particles and gas nuclei in the beam vacuum are used to measure the transverse size of the beams without the need to displace them. In all cases, and despite the fact that the experiments are located at different interaction points, their luminosity-related data are used in combination with input from the LHC beam instrumentation. Close collaboration among the experiments and LHC operators is therefore a key prerequisite for precise luminosity determination.

Protons versus electrons

Contrary to the approach at hadron colliders, the operation of the SuperKEKB accelerator with electron–positron collisions allows for an even more precise luminosity determination. Following well-known QED processes, the Belle II experiment recently reported an almost unprecedented precision of 0.7% for data collected during April–July 2018. Though electrons and positrons conceptually give the SuperKEKB team a slightly easier task, its new record for the highest luminosity set at a collider is thus well established.

SuperKEKB's record is achieved thanks to a novel "crabbed waist" scheme, originally proposed by accelerator physicist Pantaleo Raimondi. In the coming years this will enable the luminosity of SuperKEKB is to be increased by a factor of almost 30 to reach its design target of 8×10^{35} $cm^{-2} s^{-1}$. The crabbed waist scheme, which works by squeezing the vertical height of the beams at the interaction point, is also envisaged for the proposed Future Circular Collider (FCC-ee) at CERN. It also differs from the "crab-crossing" technology, based on special radiofrequency cavities, which is now being implemented at CERN for the high-luminosity phase of the LHC. While the LHC has passed the luminosity crown to SuperKEKB, taken together, novel techniques and the precise evaluation of their outcome continue to push forward both the accelerator and related physics frontiers. ●

Close collaboration among the experiments and LHC operators is a key prerequisite for precise luminosity determination

Further reading

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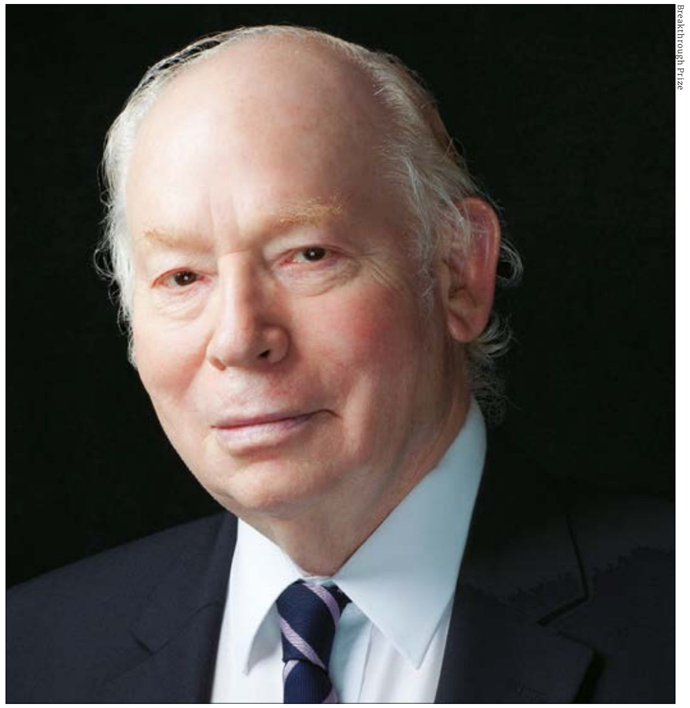
THE END OF AN ERA



Breakthrough Prize

Giant *Steven Weinberg photographed in 2020 on the occasion of the award of a Special Breakthrough Prize in Fundamental Physics.*

Steven Weinberg is one of a small group of scientists who have radically changed the way we understand the universe and our place in it, writes Luis Álvarez-Gaumé

On 23 July, the great US theoretical physicist Steve Weinberg passed away in hospital in Austin, Texas, aged 88. He was a towering figure in the field, and made numerous seminal contributions to particle physics and cosmology that are part of the backbone of our current understanding of the fundamental laws of nature. He is part of the reduced rank of scientists who, in the course of history, have radically changed the way we understand the universe and our place in it.

Weinberg was born in New York, the son of Jewish immigrants, Eve and Frederick Weinberg. He attended the Bronx High School of Science, where he met Sheldon Glashow, later to become his Harvard colleague and with whom he would share the 1979 Nobel Prize in Physics. Towards the end of high school, Weinberg was already set on becoming a theoretical physicist. He obtained his undergraduate degree at Cornell University in 1954, and then spent a year doing graduate work at the Niels Bohr Institute in Copenhagen, after which he returned to the US to complete his graduate studies at Princeton. His PhD advisor was Sam Treiman and his thesis topic was the application of renormalisation theory to the effects of strong interactions in weak processes. Weinberg obtained his degree in 1957 and then spent two years at Columbia University. From 1959 to 1969 he was at Lawrence Berkeley Laboratory and later UC Berkeley, where he got his tenure in 1964. He was on leave at Harvard (1966–1967) and MIT (1967–1969), where he became professor of physics (1969–1973) and then moved to Harvard (1973–1983), where he succeeded Julian Schwinger as Higgins Professor of Physics. Weinberg joined the faculty of the University of Texas at Austin as the Josey Regental Professor of Physics in 1982, and remained there for the rest of his life.

Immense contributions

Perhaps his best known contribution to physics is his formulation of electroweak unification in the context of gauge theories and using the Brout–Englert–Higgs mechanism of symmetry breaking to give mass to the W and Z bosons, while sparing the photon (*CERN Courier* November 2017 p25). The names Glashow, Weinberg and Salam are forever associated with the spontaneously broken SU(2) × U(1) gauge theory, which unified the electromagnetic and weak interactions and provided a large number of predictions that have been experimentally confirmed. The most concise and elegant presentation of the theory appears in Weinberg's famous 1967 paper: "A Model of Leptons", one of the most cited papers in the history of physics, and a great example of clear science writing (*CERN Courier* November 2017 p31). At the time, the first family of quarks and leptons was known, but the second was incomplete. After a substantial amount of experimental and theoretical work, we now have the full formulation of the Standard Model (SM) describing our best knowledge of the fundamental laws of nature. This is a collective journey starting with the discovery of the electron in 1897, and concluding with the discovery of the scalar particle of the SM (the Higgs boson) at CERN

THE AUTHOR
Luis Álvarez-Gaumé *director, Simons Center for Geometry and Physics, SUNY at Stony Brook, and senior physicist (emeritus), CERN.*

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Visiting CERN *Weinberg with former CERN Director-General Rolf Heuer (left) and underground with former ATLAS spokesperson Peter Jenni (right) during a visit to the lab in July 2009.*

Weinberg was deeply involved with the building of the Standard Model before and beyond his 1967 paper

in 2012. Weinberg was deeply involved with the building of the SM before and beyond his 1967 paper.

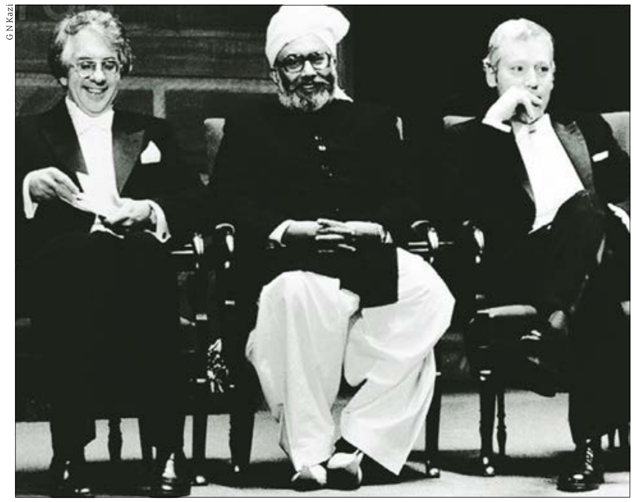
It is impossible to do justice to all the scientific contributions of Weinberg's career, but we can list a few of them. In the early 1960s he embarked on the study of symmetry breaking, and wrote a seminal contribution with Goldstone and Salam describing in detail and in full generality the mechanism of spontaneous symmetry breaking in the context of quantum field theory, providing sound bases to the earlier discoveries of Nambu and Goldstone. Around the same time, he worked out the general structure of scattering amplitudes with the emission of arbitrary numbers of photons and gravitons. It is remarkable that this work has played a very important role in the recent study of asymptotic symmetries in general relativity and gauge theories (for example, Bondi–Metzner–Sachs symmetries and generalisations, and the general theory of Feynman amplitudes).

From jets to GUTs

Together with George Sterman, Weinberg started the study of jets in QCD, whose importance in modern high-energy experiments can hardly be exaggerated. He (and independently Frank Wilczek) realised that in the Peccei–Quinn mechanism invoked to solve the strong-CP problem, there is a light pseudoscalar particle lurking in the background. This is the infamous axion, also a prime candidate for dark-matter particles and whose experimental search has been actively pursued for decades. Weinberg was one of the pioneers in the formulation of effective field theories that transformed the traditional approach to quantum field theory. He was the founder of chiral perturbation theory, one of the initiators of relativistic quantum theories at finite temperature, and of asymptotic safety, which has been used in some approaches to quantum gravity. In 1979 he (and independently Leonard Susskind) introduced the notion of technicolour – an alternative to the Brout–Englert–Higgs mechanism in which the scalar particle of the SM appears as a composite fermion, which some find more appealing, but so far has little experimental support. Finally, we can mention his work on grand unification together with Howard Georgi and Helen Quinn, where they used the renormalisation group to understand in detail how a single coupling in the ultraviolet evolves in such a way that in the infrared it generates the coupling constants of the strong, weak and electromagnetic interactions.

Astronomical arguments

Steven Weinberg also made profound contributions in his work on the cosmological constant. In 1989 he used astronomical arguments to indicate that the vacuum energy is many orders of magnitude smaller than would be expected from modern theories of elementary particles. His bound on its possible value based on anthropic reasoning is as deep as it is unsettling. And it agrees surprisingly well with the measured value, as inferred from observations of receding, distant supernovae. It shatters Einstein's dream of unification, when he asked himself whether the Almighty had any choice in creating the universe. Anthropic reasoning opens the door to theories of the multiverse that may also be considered as inevitable in some versions of inflationary cosmology, and in the theory of the string landscape of possible vacua for our universe. Among all the parameters of the current standard models of cosmology and particle physics, the question of which are environmental and which are fundamental becomes meaningful. Some of their values may ultimately have only a purely statistical explanation based on anthropism. "It's a depressing kind of solution to the problem," remarked Weinberg recently in the *Courier*: "But as I've said: there are many conditions that we impose on the laws of nature, such as logical consistency, but we don't have the right to impose the condition that the laws should be such that they make us happy!" (*CERN Courier* March/April 2021 p51). On the one hand, his work led to the unification of the weak and electromagnetic forces;



Nobel recognition *Sheldon Lee Glashow, Abdus Salam and Steven Weinberg share the 1979 Nobel Prize in Physics (left). Shortly after the award, Weinberg came to CERN to give a seminar "The rise and fall of baryon number" on 19 December 1979 (right).*

on the other the landscape of possibilities points against a unique universe. The tension between both points of view continues.

Weinberg also mastered the art of writing for non-experts. One of the most influential science books written for the general public is his masterpiece *The First Three Minutes* (1977), which provides a wonderful exposition of modern cosmology, the expansion of the universe, the cosmic microwave background radiation, and of Big Bang nucleosynthesis. Towards the end of the epilogue he formulated his famous statement that generated heated discussions with philosophers and theologians: "The more the universe seems comprehensible, the more it seems pointless." In the next paragraph he tempers the coldness somewhat: "The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy." But the implied meaning that the laws of nature have no purpose continues to be as provocative as when it was made originally. The debate will linger on for a long time.

Controversies and passions

Weinberg's non-technical books exhibit an extraordinary erudition in numerous subjects. His approach is original and thorough, and always illuminating. He did not shy away from delicate and controversial discussions. Weinberg was a declared atheist, with a rather negative opinion on the influence of religion on human history and society. He showed remarkable courage to be outspoken and to engage in public debates about it. Again in his 1977 book, he wrote: "Anything that we scientists can do to weaken the hold of religion should be done and may in the end be our greatest contribution to civilisation." Needless to say, such statements raised a number of blisters in some quarters. He was also a champion of scientific reductionism, something that was not very well received in many philosophical communities. He was clearly passionate about science and scientific principles, and in defence of the search for truth. In *Dreams of a Final Theory* (2011) he described his fight to avoid the demise of the Superconducting Super Collider (SSC). His ardent and convincing argument about the value of basic science, and also its importance as a motor of economic and technological growth, were not enough to convince sufficient members of the House of Representatives and the project was cancelled in 1993. It was a very hard blow to the US and global high-energy physics communities. The discussion had another great scientist on the other side: Phil Anderson, who passed away in 2020. It is not obvious if Anderson was against particle physics, or against big science. What is clear is that given the size of the budget deficit in the US (now and then), what was saved by not building the SSC did not go to "table top" science.

Normal humans would need to live several lives to accomplish so much

In a 2015 interview to *Third Way*, Weinberg explained his philosophy and strategy when writing for the general public: "When we talk about science as part of the culture of our times, we would better make it part of that culture by explaining what we are doing. I think it is very important not to write down to the public. You have to keep in mind that you are writing for people who are not mathematically trained, but are just as smart as you are." This empathy and respect for the reader is immediately apparent as soon as you open any of his books, and together with the depth and breadth of his insight, explains their success.

He also excelled in the writing of technical books. In the early 1960s Weinberg became interested in astrophysics and cosmology, leading, among other things, to the landmark *Gravitation and Cosmology* (1971). The book became an instant classic, and it is still useful to learn about many aspects of general relativity and the early universe. In the 1990s he

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published a masterful three-volume set on *The Quantum Theory of Fields*, which is probably the definitive treatment on the subject in the 20th century. In 2008 he published *Cosmology*, an important update of his 1971 work, providing self-contained explanations of the ideas and formulas that are used and tested in modern cosmological observations. He also published *Lectures on Quantum Mechanics* in 2015, among one of the very best books on the subject, where the depth of his knowledge and insight shine throughout. The man had not lost his grit. Only this year, he published what he described as an advanced undergraduate textbook *Foundations of Modern Physics*, based on a lecture course he was asked to give at Austin. What distinguishes his scientific books from many others is that, in addition to the care and erudition with which the material is presented, they are also interspersed with all kinds of golden nuggets. Weinberg never avoids some of the conceptual difficulties that plague the subjects, and it is a real pleasure to find deep and inspiring clarifications.

It is not possible to list all his awards and honours, but let's mention that he was elected to the US National Academy of Sciences in 1972, was awarded the Dannie Heineman Prize for Mathematical Physics in 1977 and the Nobel Prize in Physics in 1979. He was also a foreign honorary member of the Royal Society of London, received a Special Breakthrough Prize in Fundamental Physics in 2020, and has been invited to give the most prestigious lectures on the planet. Normal humans would need to live several lives to accomplish so much.

His legacy will continue to inspire physicists for generations to come

A great general

Lately, Weinberg was interested in fundamental problems in the foundations and interpretation of quantum mechanics, and in the study of gravitational waves and what we can learn about the distribution of matter in the universe between us and their sources – two subjects of very active current research. In a 2020 preprint "Models of lepton and quark masses", he returned to a problem that he last tackled in 1972, the fermion mass hierarchy.

He also continued lecturing until almost the very end. Weinberg was an avid reader of military history, as evidenced in some of his writings, and as with a great general, he died with his boots on.

The news of his demise spread like a tsunami in our community, and led us into a state of mourning. When such a powerful voice is permanently silenced, we are all inevitably diminished. His legacy will continue to inspire physicists for generations to come.

Steven Weinberg is survived by his wife Louise, professor of law at the University of Texas, whom he married in 1954, his daughter Elizabeth, a medical doctor, and a granddaughter Gabrielle. ●

Embracing change to secure the future

Ursula Bassler reflects on the challenges in building the next major collider at CERN.

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Ursula Bassler *is director of research at the CNRS National Institute of Nuclear and Particle Physics, and president of the CERN Council from January 2019 to December 2021.*

CERN-PHOTO-202004-057-9

Long view *CERN's Meyrin site photographed by drone in April 2020.*

Twenty-five years. That is the time we have from now to ensure a smooth transition between the LHC and the next major collider at CERN. Twenty-five years to approve a project, find the necessary funding, solve administrative problems and define a governance model; to dig a tunnel, equip it with a cutting-edge accelerator, and design and build experiments at the limits of technology.

One of the most memorable moments of my time as president of the CERN Council came on 19 June 2020, when delegates from CERN's Member States adopted a resolution updating the European strategy for particle physics. The implementation of the European strategy recommendations is now in full swing, based around two major topics for CERN's long-term future: the Future Circular Collider (FCC) feasibility study with an organisational schema in place, and the elaboration of roadmaps for advanced accelerator and detector technologies. At the next strategy update towards the middle of the decade, we should be able to decide if the first phase of the FCC – an electron–positron collider operating at centre-of-mass energies from 91 GeV (the Z mass) to 365 GeV (above the $t\bar{t}$ production threshold) – can be built, paving the way for a hadron collider with an energy of at least 100 TeV in the same tunnel. By then, we should also have a clearer picture of the potential of novel accelerator technologies, such as muon colliders or plasma acceleration.

Besides the purely technical questions, many other challenges lie ahead. It will be indispensable to attract major interregional partners to CERN's next large project. Together with the scientific impact, the socioeconomic benefits of skills and technologies built through large research infrastructures are increasingly recognised, which makes a new collider an appealing prospect for states to participate in. But what collaboration model can we elaborate together that is fair and efficient? How can we build bridges to other projects currently discussed, such as the ILC? The US recently started its own "Snowmass" strategy process, which may also impact the decisions ahead.

Neither the implementation of the technology roadmaps nor the FCC feasibility study, and far less its construction, can be carried out by CERN alone. Without a tight network of collaboration and exchanges it will not be possible to find the brains, the hands and the financial resources to ensure that CERN continues to thrive in the long term. The collaboration and support from laboratories and institutes in CERN's Member and Associate Member States and beyond are crucial. Can we imagine new ways to enhance and to intensify the collaboration, to spread the quality and to share the savoir faire? Understanding where difficulties may lay merits continued efforts.

For projects that reach far into the century, we will need the curiosity, creativity and motivation of young people entering our field

For projects that reach far into the century, we will need the curiosity, creativity and motivation of young people entering our field. Efforts such as the recent ECFA early-career researcher survey are salutary. But are there other means through which we can broaden the freedom and creativity for young scientists within our highly organised collaborations? If there are silver linings to the pandemic, one is surely the increased accessibility to scientific discourse for a greater range of young and diverse researchers that our adaptation to virtual meetings has demonstrated.

Societal acceptance will also be crucial in convincing local communities to accept the impact of a new, big project. Developing environmentally friendly technologies is one factor, especially if we can contribute with innovative solutions. In this context, the launch in September 2020 of CERN's first public environment report (with a second report about to be published) is timely. CERN's new education and outreach centre, the Science Gateway, will also significantly increase the number of people who can visit and be inspired by CERN.

The enormous amount of work that has taken place during Long Shutdown 2 lays the foundation for the HL-LHC later this decade. However, beyond ensuring the success of this flagship programme, and that of CERN's large and diverse portfolio of non-collider experiments, we must clearly and carefully explain the case for continued exploration at the energy frontier. To other scientists: we all benefit from mutual exchange and stimulation. To teachers and educators: we can contribute to make science fascinating and help attract young people into STEM subjects. To society: we can help increase scientific literacy, which is crucial for democracies to distinguish sense from, well, nonsense.

Twenty-five years is not long. And no matter our individual roles at CERN, we each have our work cut out. Together, we need to stand behind this unique laboratory, be proud of its past achievements, and embrace the changes necessary to build its – and our – future.

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OPINION INTERVIEW

Having the right connections is key

With construction of the Square Kilometre Array Observatory (SKAO) under way, director-general Philip Diamond describes what it took to launch the largest radio telescope ever built and what its key science goals are.

Having led the SKAO for almost a decade, how did it feel to get the green light for construction in June this year?
The project has been a long time in gestation and I have invested much of my professional life in the SKA project. When the day came, I was 95% confident that the SKAO council would give us the green light to proceed, as we were still going through ratification processes in national parliaments. I sent a message to my senior team saying: "This is the most momentous week of my career" because of the collective effort of so many people in the observatory and across the entire partnership over so many years. It was a great feeling, even if we couldn't celebrate properly because of the pandemic.

What will the SKA telescopes do that previous radio telescopes couldn't?
The game changer is the sheer size of the facility. Initially, we're building 131,072 low-frequency antennas in Western Australia ("SKA-Low") and 197 15 m-class dishes in South Africa ("SKA-Mid"). This will provide us with up to a factor of 10 improvement in our ability to see fainter details in the universe. The long-term SKA vision will increase the sensitivity by a further factor of 10. We've got many science areas, but two are going to be unique to us. One is the ability to detect hydrogen all the way back to the epoch of reionisation, also called the "cosmic-dawn". The frequency range that we cover, combined with the large collecting area and the sensitivity of the two radio telescopes, will allow us to make a "movie" of the universe evolving from a few hundred million years after the Big Bang to the present day. We probably won't see the first stars but will see the *effect* of the first stars, and we may see some of the first galaxies and black holes.

SKAO

Focused *Radio astronomer Philip Diamond has been SKAO director-general since October 2012.*

The second key science goal is the study of pulsars, especially millisecond pulsars, which emit radio pulses extremely regularly, giving astronomers superb natural clocks in the sky. The SKA will be able to detect every pulsar that can be detected on Earth (at least every pulsar that is pointing in our direction and within the ~70% of the sky visible by the SKA). Pulsars will be used as a proxy to detect and study gravitational waves from extreme phenomena. For instance, when there's a massive galaxy merger that generates gravitational waves, we will be able to detect the passage of the waves through a change in the pulse arrival times. The SKA telescopes will be a natural extension of existing pulsar-timing arrays, and will be working as a network but also individually.

Another goal is to better understand the influence of dark matter on galaxies and how the universe evolves, and we will also be able to address questions regarding the nature of neutrinos through cosmological studies.

How big is the expected SKA dataset, and how will it be managed?
It depends where you look in the data stream, because the digital signal processing systems will be reducing the data volume as much as possible. Raw data coming out of SKA-Low will be 2 Pb per second – dramatically exceeding the entire internet data rate. That data goes from our fibre network into data processing, all on-site, with electronics heavily shielded to protect the telescopes from interference. Coming out from there, it's about 5 Tb of data per second being transferred to supercomputing facilities off-site, which is pretty much equivalent to the output generated by SKA-Mid in South Africa. From that point the data will flow into supercomputers for on-the-fly calibration and data processing, emerging as "science-ready" data. It all flows into what we call the SKA Regional Centre network, basically supercomputers dotted around the globe, very much like that used in the Worldwide LHC Computing Grid. By piping the data out to a network of regional centres at a rate of 100 Gb per second, we are going to see around 350 Pb per year of science data from each telescope.

And you've been collaborating with CERN on the SKA data challenge?
Very much so. We signed a memorandum of understanding three years ago, essentially to learn how CERN distributes its data and how its processing systems work. There are

things we were able to share too, as the SKA will have to process a larger amount of data than even the High-Luminosity LHC will produce. Recently we have entered into a further, broader collaboration with CERN, GÉANT and PRACE [the Partnership for Advanced Computing in Europe] to look at the collaborative use of supercomputer centres in Europe.

SKAO's organisational model also appears to have much in common with CERN's?

If you were to look at the text of our treaty you would see its antecedents in those of CERN and ESO (the European Southern Observatory). We are an intergovernmental organisation with a treaty and a convention signed in Rome in March 2019. Right now, we've got seven members who have ratified the convention, which was enough for us to kick-off the observatory, and we've got countries like France, Spain and Switzerland on the road to accession. Other countries like India, Sweden, Canada and Germany are also following their internal processes and we expect them to join the observatory as full members in the months to come; Japan and South Korea are observers on the SKAO council at this stage. Unlike CERN, we don't link member contributions directly to gross domestic product (GDP) – one reason being the huge disparity in GDP amongst our member states. We looked at a number of models and none of them were satisfactory, so in the end we invented something that we use as a starting point for negotiation and that's a proxy for the scientific capacity within countries. It's actually the number of scientists that an individual country has who are members of the International Astronomical Union. For most of our members it correlates pretty well with GDP.

Is there a sufficient volume of contracts for industries across the participating nations?

Absolutely. The SKA antennas, dishes and front-ends are essentially evolutions of existing designs. It's the digital hardware and especially the software where there are huge innovations with the SKA. We have started a contracting process with every country and they're guaranteed to get at least 70% of their investment in the construction funds back. The SKAO budget for the first 10 years – which includes the construction of the telescopes, the salaries of observatory staff and the start of first operations – is €2 billion. The actual telescope itself costs around €1.2 billion.

Nasief Manie/SARAO

Rising up *"SKA-MPI", the Max Planck Society-funded prototype dish, being assembled at the South African site in early 2019.*

We put a lot of effort into conveying the societal impact of the SKA

Why did it take 30 years for the SKA project to be approved?

Back in the late 1980s/early 1990s, radio astronomers were looking ahead to the next big questions. The first mention of what we call the SKA was at a conference in Albuquerque, New Mexico, celebrating the 10th anniversary of the Very Large Array, which is still a state-of-the-art radio telescope. A colleague pulled together discussions and wrote a paper proposing the "Hydrogen Array". It was clear we would need approximately one square kilometre of collecting area, which meant there had to be a lot of innovation in the telescopes to keep things affordable. A lot of the early design work was funded by the European Commission and we formed an international steering committee to coordinate the effort. But it wasn't until 2011 that the SKA Organisation was formed, allowing us to go out and raise the money, put the organisational structure in place, confirm the locations, formalise the detailed design and then go and build the telescopes. There was a lot of exploration surrounding the details of the intergovernmental organisation – at one point we were discussing joining ESO.

Building the SKA 10 years earlier would have been extremely difficult, however. One reason is that we would have missed out on the big-data technology and innovation revolution. Another relates to the cost of power in these remote regions: SKA's Western Australia site is 200 km from the nearest power grid, so we are powering things with photovoltaics and batteries, the cost of which has dropped dramatically in the past five years.

What are the key ingredients for the successful management of large science projects?

One has to have a diplomatic manner. We've got 16 countries involved all the way from China to Canada and in both hemispheres, and you have to work closely with colleagues and diverse people all the way up to ministerial level. Being sure the connections with the government are solid and having the right connections are key. We also put a lot of effort into conveying the societal impact of the SKA. Just as CERN invented the web, Wi-Fi came out of radio astronomy, as did a lot of medical imaging technology, and we have been working hard to identify future knowledge-transfer areas.

It also would have been much harder if I did not have a radio-astronomy background, because a lot of what I had to do in the early days was to rely on a network of radio-astronomy contacts around the world to sign up for the SKA and to lobby their governments. While I have no immediate plans to step aside, I think 10 or 12 years is a healthy period for a senior role. When the SKAO council begins the search for my successor, I do hope they recognise the need to have at least an astronomer, if not radio astronomer.

Finally, it is critical to have the right team, because projects like this are too large to keep in one person's head. The team I have is the best I've ever worked with. It's a fantastic effort to make all this a reality.

What are the long-term operational plans for the SKA?

The SKA is expected to operate for around 50 years, and our science case is built around this long-term aspiration. In our first phase, whose construction has started and should end in 2028/2029, we will have just under 200 dishes in South Africa, whereas we'd like to have potentially up to 2500 dishes there at the appropriate time. Similarly, in Western Australia we have a goal of up to a million low-frequency antennas, eight times the size of what we're building now. Fifty years is somewhat arbitrary, and there are not yet any funded plans for such an expansion, but the dishes and antennas themselves will easily last for that time. The electronics are a different matter. That's why the Lovell Telescope, which I can see outside my window here at SKAO HQ, is still an active science instrument after 65 years, because the electronics inside are state of the art. In terms of its collecting area, it is still the third largest steerable dish on Earth!

How do you see the future of big science more generally?

If there is a bright side to the COVID-19 pandemic, it has forced governments to recognise how critical science and expert knowledge are to survive, and hopefully that has translated into more realism regarding climate change for example. I look at science as an interlinked ecosystem: the hard sciences like physics build infrastructures designed to answer fundamental questions and produce technological impact, but they also train science graduates who enter other areas. The SKAO governments recognise the benefits of what South African colleagues call human capital development: that scientists and engineers who are inspired by and develop through these big projects will diffuse into industry and impact other areas of society. My experience of the senior civil servants that I have come across tells me that they understand this link.

I look at science as an interlinked ecosystem

Interview by **Matthew Chalmers**.

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OPINION LETTERS

The silicon age, a wider view

In the July/August issue, Chris Damerell discussed silicon pixel detectors, with emphasis on the development of monolithic devices, where he is an eminent contributor. Another dimension of the silicon revolution that has taken place in particle physics since 1980 concerns silicon micro-strip detectors, and the general introduction of matched integrated circuits (ICs) with massively parallel signal processing. Application-specific ICs (ASICs) shaped subsequent physics experiments enormously, in particular allowing interaction rates to be increased by many orders of magnitude for enhanced physics capabilities. Critical here is the integration on a small, low-power custom chip of the fully parallel readout of many sensing elements, together with local processing and storage of signals. This enabled progress towards the LHC (where the interaction rate is more than 10,000 times that in LEP), not only for silicon vertexing but in all types of detectors, including liquid-argon or scintillator-crystal calorimeters and large wire-chambers for muon tracking. Moreover, it contributed to a more compact design of colliding-beam experiments and reduced power dissipation. Compared to the ~1 Hz rates with bubble-chamber photographs, and the kHz rates possible with wire-chambers, silicon sensors and custom chips brought recording far into the MHz domain. New nanoelectronics circuits in future may even allow GHz interaction rates, measured with < 10 ps timing precision, thanks to smaller transistors and very thin silicon sensor layers. Silicon did not replace earlier detector materials: gas, liquids or scintillators, but complements them specifically for the study of the charm and bottom quarks, which build particles with characteristic lifetimes > 10^{-13} s and decay lengths of a fraction of a mm.

Perhaps arbitrarily, one can distinguish four main factors that contributed to the success of silicon in high-energy physics. The first was the recognition that properly manufactured semiconductor crystals, and thin ($\ll$ mm) silicon diodes in particular, can deliver very fast signals with full efficiency for individual, minimum ionising quanta. The second was microscopic segmentation of the rectifying diode structures, which both improves tracking precision and reduces electronic noise at the input of the signal processors. A third important factor was the buildup of expertise in custom-chip design in our own institutes. Our groups were educated in the IC design and manufacturing process in collaboration with professional teams such as from EPFL, Leuven or the University of Pennsylvania, but obviously were themselves well aware of the circuit application. The Microelectronics User Group meetings, initiated in 1990 by François Bourgeois, also brought our scientists in contact with industry specialists to achieve semi-professional performance. At first, a variety of foundries supplied our custom ICs, but now with CERN and the Europractice programme at IMEC as focal points, our community can access relatively advanced chip technologies, even while the quantities that we need are mostly sub-critical from the manufacturer's viewpoint. Finally, an essential factor for the application of silicon devices in the extreme radiation environment at the LHC is the capability to make them survive long enough. Traditional hardening for space and military use was, and often still is, achieved by special, and usually secret treatments during manufacturing. In our approach, survivability was made possible for commercially available standard 0.25 μm CMOS technology by adapted transistor layout methods, guard rings and radiation-tolerant circuit concepts. Following aerospace best-practice, the LHC experiments implemented rigorous quality-assurance protocols with extensive radiation testing for all ICs and for complete electronics systems. After the first 10 years of LHC operation, contrary to initial expectations, it turns out that the silicon sensors suffered slightly more from radiation effects than most of the ICs. Yet, some of these ICs are now also being replaced in the upgrades, not because of damage but for desirable improvements in functionality, speed and power dissipation per sensor element.

C Goessling

Critical chips *The UA2 tubular inner silicon detector prior to insertion in the late 1980s, where the packaged 16-channel AMPLEX readout chips (white squares) are visible.*

As Damerell argues, after the discovery of the top quark at Fermilab in 1995 it became "obligatory" to install silicon vertex detectors as a standard part of experiments. Today, equally obvious is the need for sophisticated, high-speed electronics at the cutting edge that can deal with extremely high rates, and at low power dissipation. As in your cellphone or camera, some local "on-chip intelligence" may help reduce the need for voluminous data transmission. Then, perhaps more than 1000 interactions per bunch crossing can be digested at an "HL^2-LHC", as long as available accelerator energies can only allow fleetingly rare views through the windows of nature.

Erik Heijne *IEAP-CTU Prague/CERN.*

Gravitational waves and storage rings

We read with interest your July/August article "Accelerators meet gravitational waves" (p18). However, the person who made the first steps in exploring the physics of the interactions of gravitational waves with particles in storage rings, Daniel Zer-Zion, is not mentioned. We believe he was the first to propose this technique, and he, along with Jan Willem van Holten, also developed first estimates of the gravitational effects in a storage ring: D Zer-Zion 1998 CERN-EP/98-63; D Zer-Zion 2000 *Nucl. Phys. B Proc. Suppl.* **81** 335; D Zer-Zion 2000 *Astropart. Phys.* **14** 239; J W van Holten 1999 arXiv:gr-qc/9906117.

Mats Lindroos *European Spallation Source and* **David Plane** *retired from CERN.*

OPINION REVIEWS

Exploding myths about antimatter

Antimatter: What It Is and Why It's Important in Physics and Everyday Life

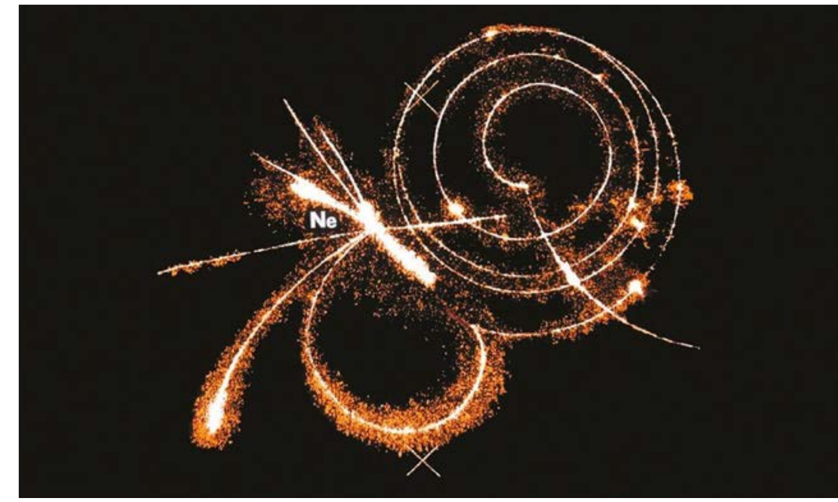
By Beatriz Gato-Rivera

Springer

Antimatter captivates the popular imagination. Beatriz Gato-Rivera, a former CERN fellow in theoretical physics and now a researcher at the Spanish National Research Council, recently published a noteworthy book on the subject, entitled *Antimatter: What It Is and Why It's Important in Physics and Everyday Life*. Substantially extending her text *Antimateria*, from the outreach collection "Qué Sabemos De", this work will also be of interest to experts, thanks to well documented anecdotes of historical interest.

Gato-Rivera sets out with a detailed exploration of the differences between atoms and antiatoms, as well as of matter–antimatter annihilation, motivating the reader to delve into a fairly complete introduction to particle physics: the concepts that underpin the Standard Model, and some that lie beyond. She then focuses on diverse aspects of antimatter science, beginning with the differences between antimatter, dark matter and dark energy, and the different roles they play in the universe. This touches upon the observed accelerating expansion of the universe. In particular, Gato-Rivera discusses dark-matter and dark-energy candidates, attempts to detect dark matter and its relation to the fate of the universe. She also carefully explains the distinction between primordial and secondary antimatter, and their roles in cosmology.

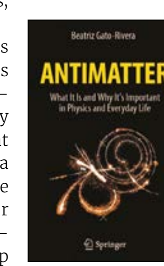
Next up, a historical chapter reviews the major landmarks of the discovery of antimatter particles, from elementary antiparticles to anti-hadrons, and anti-nuclei to antiatoms. In particular, the ground-breaking discovery of the first antiparticle, the positron, is described in excellent detail. In a separate appendix, Gato-Rivera passionately clears up a historical controversy about its discovery. The positron was first found in cosmic rays by Carl Anderson and later artificially produced en masse in particle accelerators. Gato-Rivera then turns to a detailed historical overview of cosmic-ray research, from balloon experiments to large-scale ground-based detectors, finally culminating in modern space-based detectors on board satellites and the ISS. The next chapter covers the production of antimatter by particle collisions in accelerators at high energies, including a brief history of the facilities at CERN.



Annihilation *An antiproton collides with an atom of gaseous neon in the PS-179 experiment at CERN's Low-Energy Antiproton Ring in 1984.*

The focus is then put on one of the most interesting and important conundrums in particle physics and astrophysics: the apparent huge asymmetry between matter and antimatter in the observed universe. This touches upon the processes of the primordial creation of matter and antimatter, and on the open question of whether anti-stars, or even anti-galaxies, could exist somewhere in the universe.

Gato-Rivera returns to Earth to discuss current experiments in particle physics such as those at CERN's Antimatter Factory, asking whether antiatoms really have the same properties as atoms, at least as far as their excitation spectra and gravitational pull is concerned. The author doesn't shy away from popular questions such as whether antimatter anti-gravitates and would float up away from Earth. While the answers to these questions are firmly predicted in theory, there could be surprises, like the discovery of CP violation in the 1950s, so it is important to actually test these fundamental properties.



The book finishes by exploring practical uses of antimatter in everyday life, such as the use of positron emission tomography scanners to detect positrons emitted from short-lived radioactive substances administered to patients. The same principle is also used in material analysis, for example to test the mechanical integrity of turbine blades. But sceptical words dash any hopes of using antimatter as an energy source: the effort of artificially producing a single gram of antimatter would be prohibitive.

Gato-Rivera's semi-popular text is comprehensive and well structured, with a minimum of mathematical expressions and technicalities. It will be most profitable for a scientifically educated audience with an interest in particle physics, however, experienced researchers who are interested in the history of the subject will also enjoy reading it.

Wolfgang Lerche *CERN.*

Ghost Particle
screened at CineGlobe on 26 August

Directed by Geneva Guerin

Claustrophobia. South Dakota. A clattering elevator lowers a crew of hard-hat-clad physicists 1500 metres below the ground. 750,000 tonnes of rock are about to be excavated from this former gold mine at the Sanford Underground Research Facility (SURF) to accommodate the liquid-argon time projection chambers (TPCs) of the international Deep Underground Neutrino Experiment (DUNE). Towards the end of the decade, DUNE will track neutrinos that originate 1300 km away at Fermilab in Chicago, addressing leptonic CP violation as well as an ambitious research programme in astrophysics.

Having set the scene, director Geneva Guerin, co-founder of Canadian production company Cinécoop, cuts to a wide expanse: a climber scaling a rock face near the French–Swiss border. Francesca Stocker, the star of the film and then a PhD student at the University of Bern, narrates, relating the scientific method to rock climbing. Stocker and her fellow protagonists are engaging, and the film vividly captures the human spirit surrounding the birth of a modern particle-physics detector.

But the viewer is not allowed to settle for long in any one location. After zipping to CERN, and a tour through its corridors accompanied by eerie cello music, we meet Stocker in her home kitchen, explaining how she got interested in science as a child. Next, we hop to Federico Sánchez, spokesperson of the T2K experiment in Japan, explaining the basics of the Standard Model.


Ghost Particle

Inside protoDUNE *Francesca Stocker, star of* Ghost Particle.

T2K, and its successor Hyper-Kamiokande, DUNE's equal in ambition and scope, both feature in the one-hour-long film. But the focus is on the development of the prototype DUNE detector modules that have been designed, built and tested at the CERN Neutrino Platform – and here the film is at its best. Guerin had full access to protoDUNE activities, allowing her to immerse the viewer with the peculiar but oddly fitting accompaniment of a solo didgeridoo inside the protoDUNE cryostat. We gatecrash celebrations when the vessel was filled with liquid argon and the first test-beam tracks were recorded. The film focuses on detailed descriptions of the workings of TPCs and other parts of the apparatus rather than accessible explanations of the neutrino's fascinating and mysterious nature. Unformatted plots and graphics are pulled from various sources. While authentic, this gives the film an unpolished, home-made feel.

Ghost Particle

Given the density of the exposition in some parts, beyond the most enthusiastic popular-science fans, *Ghost Particle* seems best tailored for physics students encountering experimental neutrino physics for the first time – a point that Guerin herself made during a live Q&A following the CineGlobe screening: "I was aiming at people like me – those who love science documentaries," she told the capacity crowd. "Originally I envisaged a three-part series over a decade or more, but I realised that I don't think it is possible to explain a neutrino for a general audience, so maybe it's something for educational purposes, to help future generations get introduced to this exciting programme."

As the credits roll, powerfully the rickety SURF elevator continues its 12-minute descent into the bowels of the Earth.

Matthew Chalmers *editor.*

LIGO: The Way the Universe Is, I Think, screened at CineGlobe, CERN, on 26–28 August

Directed by Hussain Currimbhoy, Carrie McCarthy and Mark Pedri

This short film focuses on mechanic turned physicist Rana Adhikari, who contributed to the 2016 discovery of gravitational waves with the Laser Interferometer Gravitational-wave Observatory (LIGO). A laid-back, confident character, Adhikari takes us through the basics of LIGO, while touching upon the future of the field and the public's view on fundamental research, all while directors Currimbhoy, McCarthy and Pedri facilitate the conversation, which runs at just over 12 minutes.

Following high-school, Adhikari spent time as a car mechanic. Upon reading Einstein's *The Meaning of Relativity* during Hurricane Erin, however, he decided that he wanted to "test the speed of light." Now, he is a professor at Caltech and a member of the LIGO collaboration, and was awarded a 2019 New Horizons in Physics Prize for his role in the gravitational-wave discovery.

In the film, recorded in 2018, Adhikari explains how fundamental research can be something everyone can get behind, in a world where it is "easy to think we're all doomed," and describes the power that rests on collaborations to show the importance of coming together, expressing, "It is a statement of collective willpower." Through varying shots of him at a blackboard, in and around his experiment, and documentary-style face-to-face discussions, the audience quickly gets to know a positive thinker for whom work is clearly a passion, not a job.


M Pedri

Universal music *In* LIGO: The Way the Universe is, I Think, *Rana Adhikari relates vibrating guitar strings to gravitational waves.*

The directors trust Adhikari to take centre stage and explain the world of gravitational waves through accurate metaphors that seem freestyled, yet concise. A sharp cut to a shot of turtles seems unnatural at first, before transforming into an analogy of Adhikari himself – the turtles going underwater and popping their heads up into different streams representing Adhikari's curiosity, and how he got into the field in the first place.

Lasers weren't created to scan items in supermarkets

The film is littered with music references, most notably comparisons between guitar strings and the vibrations that LIGO physicists are searching for. After playing a short, smooth riff, Adhikari states his unusual way of analysing data. "It is easier to do maths later – sometimes it's better to just feel it." He then plays us the "sound" file of two black holes colliding; a short chirp that is repeated as punchy statements about the long history of gravitational waves are overlayed onto the film.

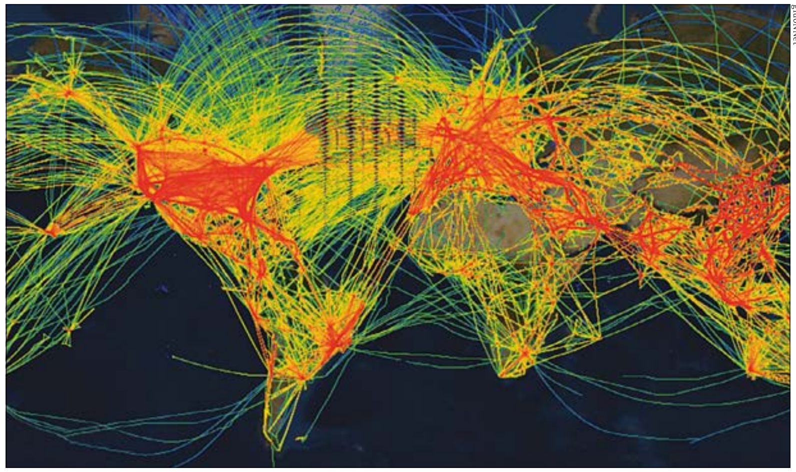
Towards the end, the focus takes a shift towards the public's view on fundamental research. "Lasers weren't created to scan items in supermarkets," states Adhikari. "We should be exploring fundamentals driven by curiosity." The film closes on Adhikari discussing the future of LIGO, tapping a glass to cause a lengthy ring representing the search for longer-wavelength gravitational waves.

Through Adhikari's story, *LIGO: The way the universe Is, I think* will inspire anyone who feels alienated or intimidated by fundamental research.

Craig Edwards *editorial assistant.*

Making complexity irrelevant

Headed by two ATLAS physicists, gluoNNet applies data-mining and machine-learning techniques to benefit wider society, writes Craig Edwards.


gluoNNet

Plane tracking *One day's worth of flight data, consisting of more than four billion data points.*

Describing itself as a big-data graph-analytics start-up, gluoNNet seeks to bring data analysis from CERN into "real-life" applications. Just two years old, the 12-strong firm based in Geneva and London has already aided clients with decision making by simplifying open-to-public datasets. With studies predicting that in three to four years almost 80% of data and analytics innovations may come from graph technologies, the physicist-based team aims to be the "R&D department" for medium-sized companies and help them evaluate massive volumes of data in a matter of minutes.

gluoNNet co-founder and president Daniel Dobos first joined CERN in 2002, focusing on diamond and silicon detectors for the ATLAS experiment. A passion to share technology with a wider audience soon led him to collaborate with organisations and institutes outside the field. In 2016 he became head of foresight and futures for the United Nations-hosted Global Humanitarian Lab, which strives to bring up-to-date technology to countries across the world. Together with co-founder and fellow ATLAS collaborator Karolos Potamianos, an Ernest Rutherford Fellow at the University of Oxford, the pair have been collaborating on non-physics projects since 2014. An example is the THE Port Association, which organises in-person and online events together with CERN IdeaSquare and other partners, including "humanitarian hackathons".

gluoNNet was a natural next step to bring data analysis from high-energy physics into broader applications. It began as a non-profit, with most work being non-commercial and helping non-governmental organisations (NGOs). Working with UNICEF, for example, gluoNNet tracked countries' financial transactions on fighting child violence to see if governments were standing by their commitments. "Our analysis even made one country – which was already one of the top donors – double their contribution, after being embarrassed by how little was actually being spent," says Dobos.

But Dobos was quick to realise that for gluoNNet to become sustainable it had to incorporate, which it did in 2020. "We wanted to take on jobs that were more impactful, however they were also more expensive." A second base was then added in the UK, which enabled more ambitious projects to be taken on.

Tracking flights

One project arose from an encounter at CERN IdeaSquare. The former head of security of a major European airline had visited CERN and noticed the particle-tracking technology as well as the international and collaborative environment; he believed something similar was needed in the aviation industry. During the visit a lively discussion about the similarities between data in aviation and particle tracking emerged. This person later became a part of the Civil Aviation Administration of Kazakhstan, which gluoNNet now works with to create a holistic overview of global air traffic (see image above). "We were looking for regulatory, safety and ecological misbehaviour, and trying to find out why some airplanes are spending more time in the air than they were expected to," says Kristiane Novotny, a theoretical physicist who wrote her PhD thesis at CERN and is now a lead data scientist at gluoNNet. "If we can find out why, we can help reduce flight times, and therefore reduce carbon-dioxide emissions due to shorter flights."

Using experience acquired at CERN in processing enormous amounts of data, gluoNNet's data-mining and machine-learning algorithms benefit from the same attitude as that at CERN, explains Dobos. "CERN's understanding of big data is different to other's. For some companies, what doesn't fit in an Excel sheet is considered 'big data', whereas at CERN this is miniscule." Therefore, it is no accident that most in the team are CERN alumni. "We need people who have the CERN spirit," he states. "If you tell people at CERN that we want to get to Mars by tomorrow, they will get on and think about how to get there, rather than shutting down the idea."

Though it's still early days for gluoNNet, the team is undertaking R&D to take things to the next level. Working with CERN openlab and the Middle East Technical University's Application and Research Center for Space and Accelerator Technologies, for example, gluoNNet is exploring the application of quantum-computing algorithms (namely quantum-graph neural networks) for particle-track reconstruction, as well as industrial applications, such as the analysis of aviation data. Another R&D effort, which originated at the Pan European Quantum Internet Hackathon 2019, aims to make use of quantum key distribution to achieve a secure VPN (virtual private network) connection.

One of gluoNNet's main future projects is a platform that can provide an interconnected system for analysts and decision makers at

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companies. The platform would allow large amounts of data to be uploaded and presented clearly, with Dobos explaining, "Companies have meetings with data analysts back and forth for weeks on decisions; this could be a place that shortens these decisions to minutes. Large technology companies start to put these platforms in place, but they are out of reach for small and medium sized companies that can't develop such frameworks internally."

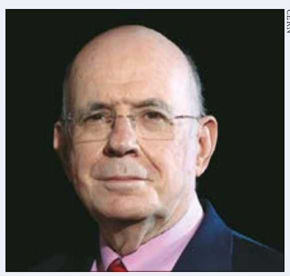
The vast amounts of data we have available today hold invaluable insights for governments, companies, NGOs and individuals, says Potamianos. "Most of the time only a fraction of the actual information is considered, missing out on relationships, dynamics and intricacies that data could reveal. With gluoNNet, we aim to help stakeholders that don't have in-house expertise in advanced data processing and visualisation technologies to get insights from their data, making its complexity irrelevant to decision makers."

Craig Edwards *editorial assistant.*

Appointments and awards

Council elects new president

On 24 September, the CERN Council announced the election of theoretical high-energy physicist Eliezer Rabinovici as its 24th president, replacing Ursula Bassler who concludes her three-year term at the end of December (see p47). Rabinovici will begin his mandate on 1 January 2022 for a period of one year, renewable twice. A professor at the Hebrew University of Jerusalem, Rabinovici's main fields of research are quantum field theory and string theory. He was chair of Israel's high-energy committee



CERN

in 2004–2020 and vice-president of the CERN Council in 2016–2018. "CERN is a special place where science and collaboration meet to answer some of the most fundamental questions about the world we live in," says Rabinovici. "Throughout my 16 years as a member of the CERN Council, I have time after time been captivated by the commitment, collaboration and knowledge of people who work together towards the same mission."

From ILL to ESS

On 1 November, Helmut Schober took over as director-general of the European Spallation Source (ESS) in Sweden, succeeding particle-physicist John Womersley, who has led the facility since 2016. Schober, a physicist with research interests

C Tresca

in the spectroscopy of functional materials, was previously director of the Institut Laue-Langevin in Grenoble. He joins the ESS at an important time in the project, with civil construction coming to an end and installation works for technical equipment and commissioning intensifying. "ESS will be an absolutely necessary building block for preserving Europe's long-standing, global leadership in neutron science," he said.

New multimessenger director

Particle and astroparticle physicist Miguel Mostafá has been appointed director of the Center for Multimessenger Astrophysics (formerly Center for Particle and Gravitational Astrophysics) at Penn State University, replacing Péter Mészáros, who has been director since 2007. The centre aims to understand high-energy processes in the universe, and is involved in several international projects, including the Pierre Auger and IceCube observatories.

Penn State

Mostafá, who began his career at the DØ experiment at the Tevatron, says he hopes to continue to enhance the visibility of the centre.

Dirac medal winners 2021

The International Centre for Theoretical Physics has awarded its 2021 Dirac Medal to (pictured clockwise from top left) Alessandra Buonanno (Max Planck Institute), Thibault Damour (IHÉS), Frans Pretorius (Princeton) and Saul Teukolsky (Caltech/Cornell) "for establishing the predicted properties of gravitational waves in the curvature of space–time

T Rinaldo; F Blas/CNRS; Caltech; Princeton

produced when stars or black holes spiral together and merge", which was crucial for the first direct detection of gravitational waves by LIGO in 2015.

Optical-clock Breakthrough

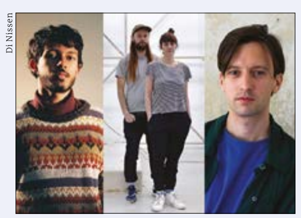
The 2022 Breakthrough Prize in Fundamental Physics has been awarded to Hidetoshi Katori (University of Tokyo/RIKEN) and Jun Ye (University of Colorado/JILA) for their work in developing optical-lattice clocks. Based on the interaction between photons and the excited state of certain atoms, optical clocks are able to measure and compare frequencies to exceptional precision, making them powerful tools for determining fundamental constants and other measurements. The winners will share a prize of $3 million.

Impact for MgB_2 klystrons

A collaboration between Hitachi, KEK and CERN has been awarded the 2021 Science and Technology Impact Prize (awarded by the Cryogenics and Superconductivity Society of Japan) for its development of MgB_2 solenoids for klystrons. The use of MgB_2 superconductor results in a factor-seven reduction in power, which more than halves the acceleration power requirements for the main linacs of the proposed Compact Linear Collider, for which the technology is being explored. MgB_2 magnets operating at around 25 K are also expected to be widely applicable to other fields, including MRI magnets.

Connect residency

Arts at CERN and the Swiss Arts Council Pro Helvetia have awarded artistic residencies for the first edition of Connect, an international programme to connect the arts with fundamental



Di Nissen

science. Kamil Hassim (left) aims to create resonant instruments drawing on connections between ancient wisdom and modern scientific knowledge, Andrea Anner and Thibault Brevet ("AATB", middle) will explore representations of space and time using industrial robotic arms, and Ian Purnell (right) will explore the visual concept of black holes.

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PEOPLE OBITUARIES

Simon Eidelman 1948–2021

A remarkable physicist and colleague

Simon Eidelman, a leading researcher at the Budker Institute of Nuclear Physics in Novosibirsk, Russia, and a professor of Novosibirsk State University (NSU), passed away on 28 June. He was a key member of experimental collaborations at Novosibirsk, CERN and KEK, and a leading author in the Particle Data Group. Eidelman served the high-energy physics community in a variety of ways, including as Novosibirsk's correspondent for this magazine for more than 20 years.

Simon (Semyon) Eidelman was born in Odessa in 1948. He went to Novosibirsk aged 15 to participate in a national mathematics Olympiad, and ended up staying to attend a special high school for extraordinarily gifted students. He then studied physics at NSU. Even before graduating, in 1968 Simon joined the Budker Institute and remained there his entire professional life. In parallel, he was a faculty member at NSU and held the high-energy physics chair for 10 years. Simon always cared for, helped and supported students and young colleagues.

Meson expert

Eidelman's scientific activity mostly concerned experiments at e^+e^- colliders, beginning with participation in the discovery of multi-hadron events at the pioneering VEPP-2 collider. In 1974 he moved to experiments with the OLYA detector at the upgraded VEPP-2M, where a comprehensive study of e^+e^- annihilation into hadrons was performed up to an energy of 1.4 GeV. Later, this detector was moved to the VEPP-4 collider, where high-precision measurements of the J/ψ and ψ' masses were performed. Simon's work at VEPP-2 and VEPP-4, and the analysis of the so-called box anomaly, made him one of the world's leading experts on vector mesons. Together with Lery Kurdadze and Arkady Vainshtein, he also performed the first comparison of QCD sum rules with experiment.

Simon was a key member of several major experimental collaborations: KEDR, CMD-2 and CMD-3 at Novosibirsk, LHCb at CERN and Belle, Belle II and g-2/EDM at J-PARC. Recently he contributed to the KLF proposal at JLab to build a secondary beam of neutral kaons to be used with the GlueX setup for strange-hadron spectroscopy. Just last year he proposed to measure the charged kaon mass with unprecedented precision using the Siddharta X-ray experiment at DAFNE in Frascati – which would have yielded a dramatic improvement on determinations of the masses of charmonium-like exotic mesons.

Thanks to his deep understanding of hadron-production cross sections, Simon became one of the pioneers in the evaluation of the hadronic contribution to the anomalous magnetic moment of the muon, g-2. He was a founding member of the Muon g-2 Theory Initiative and a key contributor to its first white paper, published last year, which provides the community consensus for the Standard Model prediction. He was also an authority on strongly interacting hadrons and resonances, as well as the τ lepton and two-photon physics.

Simon was a key author in the international Particle Data Group (PDG) for 30 years, leading the PDG subgroup responsible for meson resonances since 2006. In recognition of his contributions, he was chosen to be the first author of the 2004 edition of the *Review of Particle Physics*. He was also a great source of inspiration for the Quarkonium Working Group (QWG). Attendees of the QWG workshops will remember his lucid presentations, his great enthusiasm for research and his keen scientific insights. Moreover, he was greatly appreciated for his wisdom and calm counsel during intense discussions.


Family archive

Simon Eidelman served the high-energy physics community in multiple ways.

Simon became one of the pioneers in the evaluation of the hadronic contribution to the anomalous magnetic moment of the muon

Superb editor

Thanks to his deep knowledge and wide scientific horizons, combined with a wonderful sense of humour and a kind and friendly nature, Simon possessed a unique ability to galvanise colleagues into joint projects within many international collaborations and meetings. He was also deeply engaged in training the next generations of physicists, most recently being the driving force behind the school on muon g-2.

Simon was also a superb scientific editor. He had a rare gift of formulating scientific problems and results clearly and concisely, providing an invaluable contribution to the very large number of papers that he authored, co-authored and refereed. Several international meetings have been dedicated to Simon's memory, including CHARM 2021 and the 4th Plenary Workshop of the Theory Initiative.

We have lost a remarkable physicist, and a dear and kind person. All who had the privilege of knowing and working with Simon Eidelman will always remember him as an invaluable colleague.

His friends and colleagues from around the world.

Miguel Virasoro 1940–2021

From strings to complexity

On 23 July, the Italian–Argentinian theorist Miguel Ángel Virasoro, one of the founders of string theory and an initiator of complexity studies, passed away. His scientific contributions were outstanding and stimulated an impressive number of subsequent developments. He was an extraordinarily intelligent visionary with a great sense of humour.

Born in Buenos Aires in 1940, Virasoro enrolled in physics at the University of Buenos Aires in 1958. However, in 1966 General Juan Carlos Onganía successfully led a coup d'état in Argentina, establishing a dictatorship that would last until 1973. The faculty of science at Buenos Aires became a centre of opposition: the police broke into the university, massacring the occupants. In the following months, some 300 professors emigrated abroad.

Virasoro finished his thesis working from home; at the end of 1966, as soon as he obtained his doctorate, he moved to the Weizmann Institute, Israel, invited by a newly appointed young Argentinian professor, Hector Rubinstein. A few months earlier, Gabriele Veneziano had also arrived as a graduate student. The three of them, together with Marco Ademollo, began a long series of investigations into the physics of strong interactions that eventually led to string theory. Although the first step towards string theory was Veneziano's "open-string" model in 1968, those preliminary results established the conceptual framework in which Veneziano's model could be conceived. A few months later, stimulated by Veneziano's work, Virasoro extended it to a model describing closed strings.

Miguel Virasoro led an eventful life.

The Virasoro condition

In the following years, first at the University of Wisconsin, then at Berkeley, Virasoro did brilliant work on string theory. In 1969 he made the fundamental observation that string theory could only be made free of pathologies by fixing a certain parameter. This "Virasoro condition" allowed for the existence of an infinite number of symmetries generated by an infinite set of operators obeying a "Virasoro algebra" – a tool at the basis of countless subsequent studies. The Virasoro condition proved to be a killer for string theory as a description of strong interactions, but it opened the way to the 1974 Scherk–Schwarz reinterpretation of it as a quantum theory of gravity, in which one particular closed string corresponds to the graviton.

In 1973 democracy was restored in Argentina; Virasoro returned to his own country and was elected, still very young, dean of the faculty of science in Buenos Aires, a politically exposed position. In 1975 he accepted an invitation to spend a year at Princeton. During his stay in the US, however, Videla's 1976 coup d'état brought dictatorship back to Argentina, in a more cruel form than before: many professors and students were slaughtered at the university. Virasoro was not only fired, but he was told that, had he returned to Argentina, he would be arrested or worse.

He moved to Europe, and after a year in Paris, arrived in Italy, first in Turin and then, from 1981, at La Sapienza in Rome, where he remained for 30 years as a full professor, taking Italian citizenship. Having started to investigate the relationship between the emerging theory of quarks and gluons (QCD) and string theory, in 1983 he changed direction. He began to work with Giorgio Parisi on the statistical mechanics of complex systems, first with other Parisian physicists (Marc Mézard, Nicolas Sourlas and Gerard Toulouse) and then with Mézard alone, who had moved to Rome for two years. The group obtained important results on which the bases of the physical theory of complexity rest and also wrote a book on these results. In 1988 Virasoro became passionate about studying how, starting from neural networks, we can understand the functioning of the brain.

From 1995 to 2002 he was called to direct the International Centre for Theoretical Physics (ICTP) in Trieste. Sharing the vision of its founder Abdus Salam, Virasoro was convinced of the role that theoretical physics could have in building the capacity of developing countries. He decided to enlarge and diversify ICTP's scientific programme. Within the condensed-matter group, he established a strong subgroup in statistical mechanics and its applications, which was the beginning of quantitative biology. He established a joint project with the Beijer Institute and the Fondazione Eni Enrico Mattei in environmental and ecological economics, and founded an ICTP group devoted to the physics of weather and climate. He also succeeded in rendering compulsory the Italian contribution to the ICTP, and securing a significant increase in the contribution in 2000.

Back in Rome, in the last years before his 2011 retirement, he worked on applications of physical theories to finance, an activity that he continued in Argentina, where he returned, at the Universidad Nacional de General Sarmiento. In 2009 he received the Enrico Fermi Prize from the Italian Physical Society and in 2020 was awarded the ICTP Dirac medal for his work on string theory.

Miguel Virasoro cherished the ability to use knowledge learned in one field to make progress on a different one, opening up new vistas. He will be sorely missed.

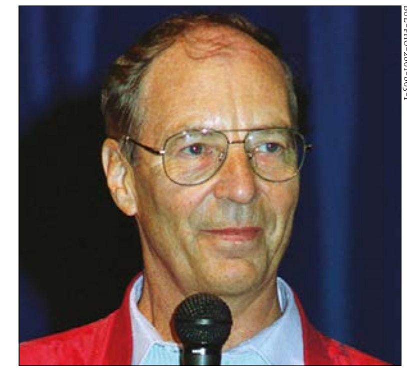
Daniele Amati *SISSA*, **Giorgio Parisi** *INFN Rome and* **Gabriele Veneziano** *CERN.*

Egil Lillestøl 1938–2021

An exceptional communicator

Norwegian experimental particle physicist Egil Sigurd Lillestøl passed away in Valence, France, on 27 September. He will be remembered as a passionate colleague with exceptional communication and teaching skills, and a friend with many personal interests. He was able to explain the most complex systems and mechanisms in physics so that even the layperson felt they understood it.

Egil Lillestøl obtained his PhD from the University of Bergen in 1970. By which time he had already spent three years (1964–1967) as a fellow at CERN. He was appointed associate professor at his alma mater the same year, and then left for Paris in 1973 where he was a guest researcher at Collège de France. In 1984 Lillestøl was appointed full professor in experimental particle physics in Bergen, where he became central in the PLUTO collaboration at DESY, DELPHI and then ATLAS at CERN.



Egil Lillestøl acted as coordinator for Norway's CERN activities.

Over time, CERN became Lillestøl's main laboratory, first as a paid associate, later as a guest professor and eventually as a staff member, contributing to the management of the experimental programme and significantly improving the conditions for the visiting scientists at the laboratory.

In Norway he acted as national coordinator of CERN activities in preparation for the LHC. He was instrumental in the organisation of the community and discussions of future funding models at the national level, in particular to accommodate the long-term commitments needed for the ATLAS and ALICE construction projects.

Egil Lillestøl played a pivotal role in the CERN Schools of Physics from 1992 until 2009, relaunching the European School of High-Energy Physics as annual events organised in collaboration with JINR, and establishing a new biennial series of schools in Latin America from 2001. He worked tirelessly on preparations for each event, in collaboration with local organisers in each host country, as well as on-site during the two-week-long events. The Latin-American schools were an important element in increasing the involvement of scientists and institutes from the region in the CERN experimental programme, for which he deserves much credit. Beyond his official duties, he took great pleasure in interacting with the participants of the schools during their free time, and in the evenings he could often be found playing piano to accompany their singing.

As a founding member of the International Thorium Energy Committee, Lillestøl was a strong proponent for thorium-based nuclear power. He was also one of the main drivers behind the UNESCO-supported travelling exhibition "Science bringing nations together", organised jointly by JINR and CERN.

As a teacher and a lecturer, Lillestøl was a role model. He always tailored his presentations to match the audience. His tabletop book *The Search for Infinity*, co-authored with Gordon Fraser and Inge Sellevåg, became a bestseller and has been published in nine language editions.

Egil Lillestøl was a bon viveur who spread joy around him. He had an impressive repertoire of anecdotes, including topics such as how to cold-smoke salmon. He enjoyed sports and was active in the CERN clubs for cycling, skiing and sailing. He leaves behind his wife and former colleague, Danielle, and two adult children from his first marriage.

His friends and colleagues.

Helmut Weber 1947–2021

Straightforward and uncompromising

Helmut Weber, CERN director of administration from 1992 to 1994, passed away on 16 July. Born in 1947, he obtained his PhD from the Technical University of Vienna, after which he pursued a steep career in the aerospace industry, where he acquired considerable managerial proficiency. Prior to joining CERN, Helmut had been chairman of the board of directors of Skyline Products (US), and member of the board of directors of the ERC (France).

Helmut played a significant role during CERN's transition from the LEP era to the LHC project. During his three-year appointment, as successor to Georges Vianès and predecessor to Maurice Robin, he was able to implement many necessary improvements to the CERN administration. Examples include the reorganisation of the finance division (split into procurement and accounting divisions) and the creation of a CERN-wide working group to standardise administrative procedures using a common online database. He also resolved a number of looming issues carried forward from the LEP era, such as the debt to the CERN Pension Fund and the financial claims made by the Euro-LEP consortium.

Helmut Weber photographed in 2014.

Furthermore, together with Meinhard Regler and the active support of CERN (including Kurt Hübner and Philip Bryant), Helmut promoted AUSTRON, a project proposal for a pulsed high-flux neutron spallation source as an international research centre for central Europe. Although this project could unfortunately not be realised due to lack of funding, the MedAustron facility for proton/ion therapy and research was eventually built as an alternative in Wiener Neustadt. It is now fully operational, serving as a successful example of technology transfer from elementary particle physics to medical applications.

Helmut Weber's most important legacy is, however, his straightforward, uncompromising and honest character that helped to resolve many contentious internal issues at CERN. When he left the organisation, he had made many friends amongst his former colleagues, who will always remember him and miss him.

His friends and former colleagues.

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BACKGROUND

Notes and observations from the high-energy physics community

Little Amal at CERN


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As part of an 8000 km, four-month-long artistic voyage beginning in Turkey and ending in the UK, a 3.5 m-tall animated puppet of a Syrian child refugee stopped at CERN on 29 September where she met representatives of ICTP Physics Without Frontiers, which works to educate and train physics and mathematics university students worldwide. Little Amal, a symbol of support and hope for people in exile, is taking part in more than 100 events across eight countries to focus attention on the urgent needs of child refugees, who make up half of all refugees in the world: www.walkwithamal.org/the-amal-fund/.

48.25 g

Total mass, roughly equal to that of a golf ball, of the 100 nm-thick gold layer coating the 25 m² primary mirror of NASA's soon-to-be-launched James Webb Space Telescope, to optimise the reflection of infrared light.

Media corner

"The American physicist Richard Feynman thought that 'nobody understands quantum mechanics'. That is no longer true."

Editorial in *The Guardian* (30 August) in response to Carlo Rovelli's book *Helgoland* (*CERN Courier* July/August 2021 p55), but swiftly dismantled on the letters page in the following days.

"People from all over the world cannot agree on what is the best music band, they cannot agree on what is the best football team, and nevertheless they succeeded to build together a piece of equipment that requires incredible compatibility."

Eliezer Rabinovici, the new president of the CERN Council, talking about the LHC in the *Jerusalem Post* (7 October).

"Un beau collier de perles plutôt qu'un sac percé contenant des billes."

Le Monde's **David Larousserie** (25 August) describes the new double-open-charm tetraquark discovered by LHCb (*CERN Courier* September/October 2021 p7) as "a beautiful pearl necklace rather than a pierced bag of beads".

"Although clever low-energy experiments can often reveal a subtle new effect if they're designed correctly, there's no substitute for an all-purpose, brute-force solution."

Science writer **Ethan Siegel** makes the case for a Future Circular Collider in *Forbes* magazine (7 September).

"CO_2 is regarded as one of the refrigerants with the smallest environmental footprint. In addition, its extraction is cheaper and less harmful to the environment than the production of synthetic refrigerants."

Gasworld (10 September) reporting on CERN's plans to expand the use of CO_2 at the LHC, following a successful trial at the LHCb experiment.

From the archive: November 1981

Are protons forever?

On a 'grand unification' picture one can make rough estimates of the characteristic energy where all the interactions, strong and electroweak, become comparable. For the simplest versions, at least, the answer is about 10^{15} GeV. Out there we would encounter all kinds of new physics, new gauge bosons, etc. Among them is the expectation of baryon non-conservation and the instability of the proton. The predicted lifetime is about 10^{31} years, give or take perhaps one or two powers of ten. A number of experiments are now under way in search of proton instability. The stakes are obviously very high.


Tunnel Routier sous le Mont-Blanc

The 12 km Mont-Blanc road tunnel linking France and Italy through the Alps. In a side gallery, an experiment by a CERN/Frascati/Milan/Turin collaboration will look for signs of proton decay and other new phenomena.

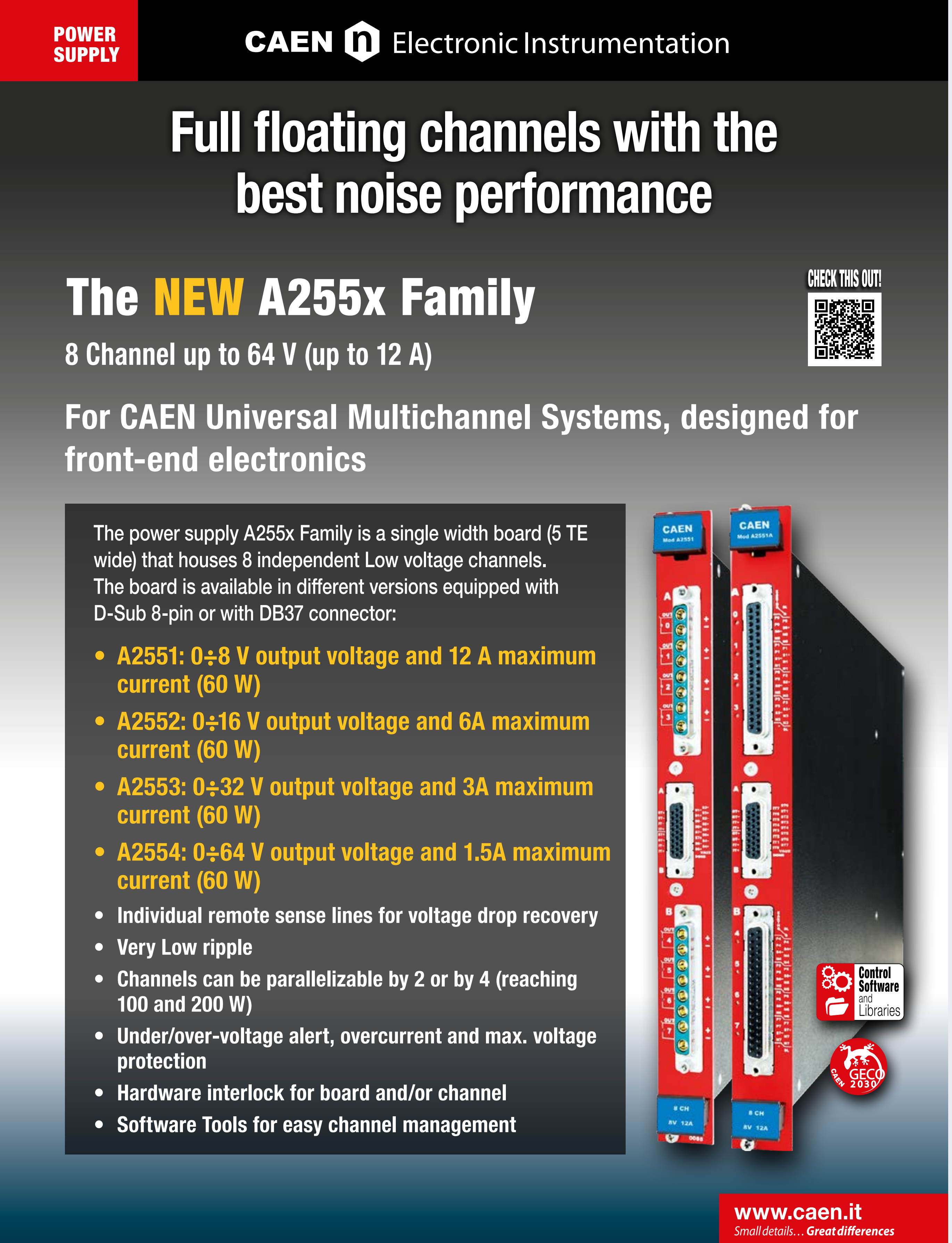
● Based on text from p390 and pp407–408 of *CERN Courier* November 1981.

Compiler's note

The universe is estimated to be around 10^{10} years old and to contain some 10^{80} protons, the Eddington number, N_{Edd}. Proton decay, a key prediction of grand unification theories, is still unobserved. The most precise lower limit for the half-life is around 10^{34} years, measured during two decades of data-taking with the Super-Kamiokande underground neutrino detector in Japan, holding 22.5 kton of ultrapure water. Hyper-Kamiokande, with eight times the fiducial mass, is planned to start operation in 2027. Sir Arthur Eddington, an avid cyclist, devised another number, lesser known but easier to measure than N_{Edd}. Dubbed E, it's the largest integer for which one has cycled at least E miles on at least E different days. "Maximise your E number" – a slogan for our time?

30 years of open science

"Regardless of the specifics of arXiv's future," remarked founder Paul Ginsparg on the preprint server's 30th anniversary in August, "preprint dissemination is no longer heterodox and the current trend of increased spread is unlikely to reverse." (*Nat. Rev. Phys.* **3** 602). Despite early doubts that preprint distribution would be relevant outside of high-energy physics, arXiv's history has been one of continuous growth into new fields, catalysed by occasional spikes in interest, such as iron-pnictide superconductors in 2008 and machine learning since 2015, notes Ginsparg. "So far, no community that has adopted arXiv for rapid dissemination has since abandoned it." A long-time supporter of arXiv, in September CERN become an "arXiv champion of open science" for 2022, with increased financial support and joint projects to further improve the platform.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