WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2022 issue of *CERN Courier.*

Beams are back at the LHC! As a spruced-up accelerator complex prepares to produce brighter collisions at a higher energy than before, this issue surveys the Run 3 physics prospects in searches (p29), precision measurements (p33), flavour (p43) and heavy-ion (p47) physics. Major upgrades such as the new LHCb VELO (p38) have put the detectors in better shape than ever. Together with improved triggers and analysis tools, new research avenues are being opened at the LHC, complemented by a diverse fixed-target programme (p51).

Investigations assessing the feasibility of a Future Circular Collider at CERN step up a gear (p23 and 27), while physicists evaluate the status of an International Linear Collider in Japan (p10). In the experimental world, a new measurement of the W mass has made headlines (p9) and intriguing results were discussed at Moriond (p19).

At CERN: ATLAS upgrade coordinator Francesco Lanni looks ahead to his new role as leader of the Neutrino Platform (p57); heavy-machinist Florian Hofmann reveals life as a technician (p65); the latest LHC-experiment results (p15); progress with the High-Energy Ventilator (p13); greater energy efficiency (p55); and The Adventure of the Large Hadron Collider (p61).

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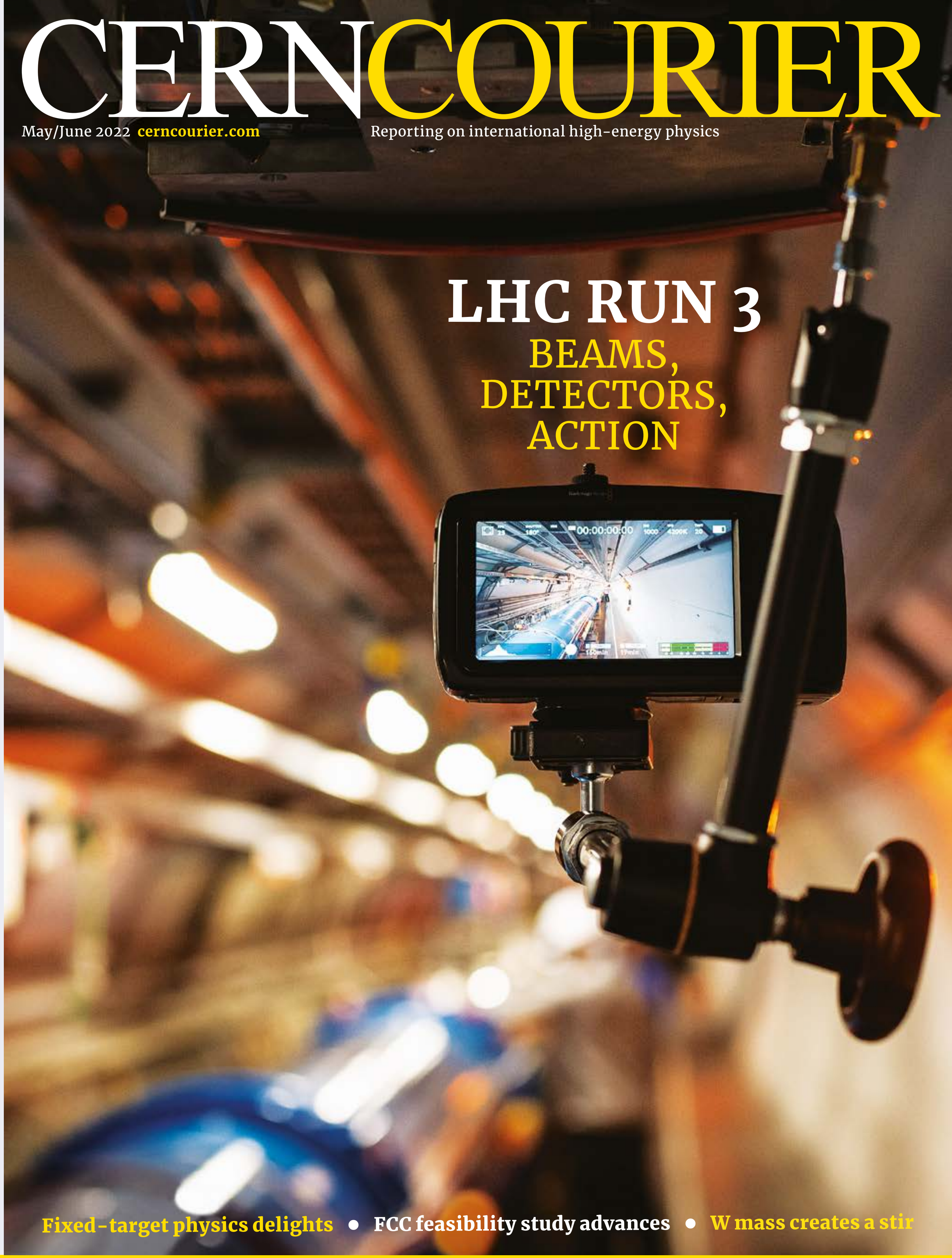
DIGITAL EDITION CREATED BY IOP PUBLISHING



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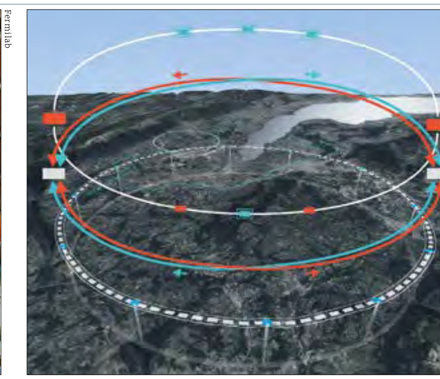
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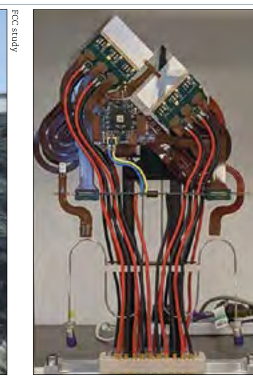
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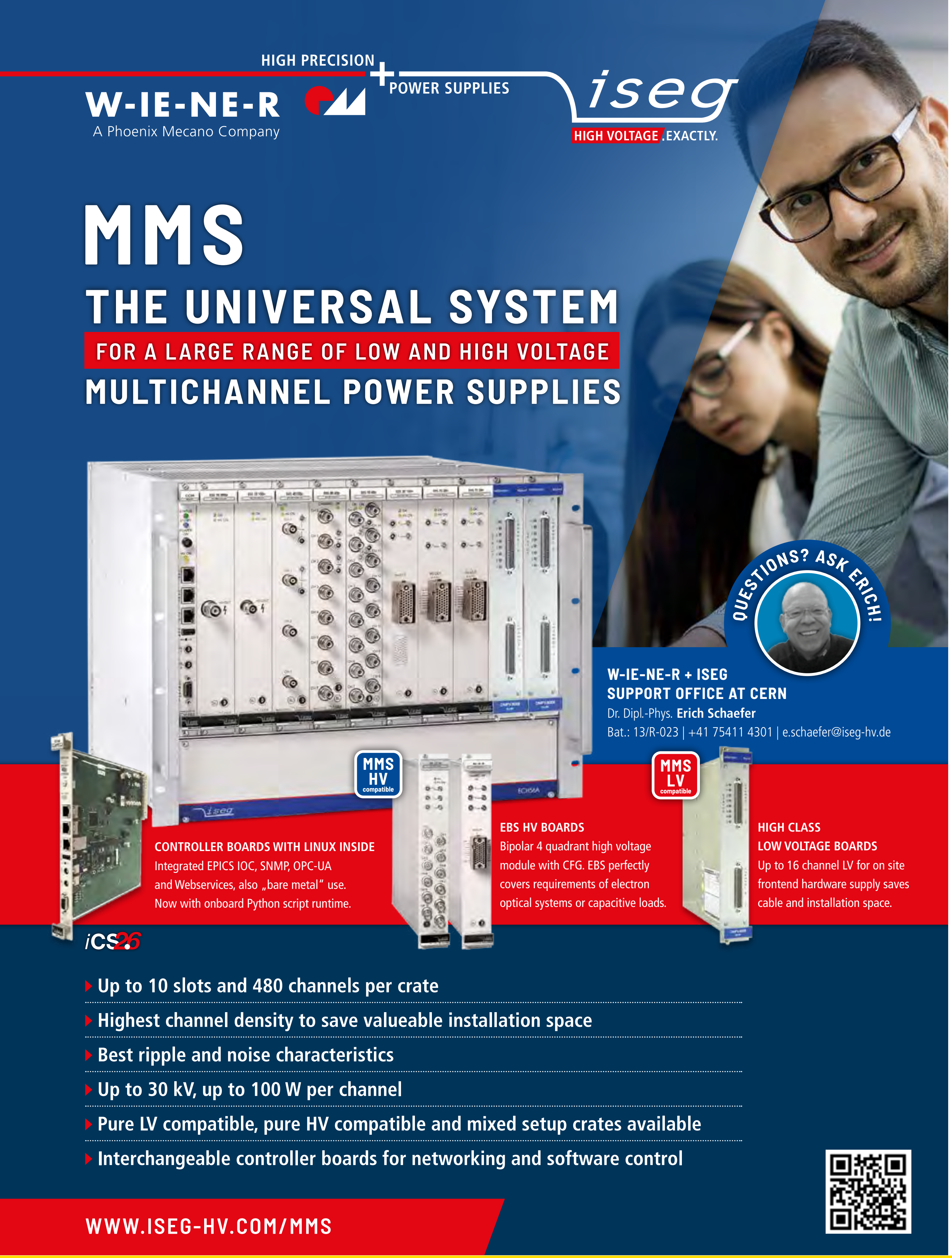


FROM THE EDITOR

A new chapter for the LHC

Matthew Chalmers
Editor

The enormous scientific progress enabled by the LHC, surpassing expectations, makes it easy to forget that the machine is still getting into its stride. The imminent start of Run 3 will see a stronger accelerator complex produce brighter collisions at a higher energy, steering a course to the High-Luminosity LHC, which by the late 2030s will provide at least 10 times more data than collected so far.

Prospects in searches (p29), precision measurements (p33), flavour physics (p43) and heavy-ions (p47) show Run 3 to be anything but business as usual. The detectors are in better shape than ever, with the new LHCb VELO (p38) among the last of numerous upgrades during LS2. Together with improved triggers and analysis tools, knowledge from Runs 1 and 2 and other interesting results (p9 and 19), new research directions are being forged – complemented by the new forward-experiments FASER and SND@LHC and a rich fixed-target programme (p51).

Sweeping upgrades and maintenance work during LS2 – including an overhaul of the SPS and the consolidation of all 1232 LHC dipole-magnet diode assemblies to enable 6.8 TeV operations – have resulted in a rejuvenated accelerator complex with injectors primed for high-luminosity operations. In terms of energy used per luminosity delivered, Run 3 will also be more efficient than previous runs (p55). Beams were scheduled to be injected in the LHC shortly after the *Courier* went to press, with first physics expected in June.

Force for unity

It is difficult to imagine the LHC's success were it not for the cross-border collaboration hard-wired into the CERN model, with thousands of researchers spanning 110 nationalities involved. The accession of Brazil as a CERN Associate Member State (p8) is a first for the Americas, while the same month saw An-Najah National University become the first university in Palestine to join ATLAS. The robustness of the CERN model bodes well for a visionary Future Circular Collider proposed to follow the LHC (p23 and 27).

Russian and Ukrainian researchers work together across CERN's programmes, the vast majority on the LHC experiments

Russia's contributions to the LHC, including the delivery of 360 dipole and 185 quadrupole magnets and the work of more than a dozen Russian institutes in building the detectors, were recognised with CERN Observer status. But relations with Russian scientists began as early as the 1950s, with CERN and JINR contributing to bridge the gap between East and West. Ukraine joined CERN as an Associate Member State in 2016, also strengthening a relationship dating much earlier. Today, Russian and Ukrainian researchers work together across CERN's programmes, the vast majority on the LHC experiments.


CERN

Shine on *The LHC, a beacon of international collaboration.*

Six weeks after the invasion of Ukraine by Russian forces on 24 February, thousands of lives have been lost and cities and infrastructures destroyed. While insignificant by comparison, the relationship between science and politics has faced its toughest test in recent memory. Following the CERN Council's suspension of Russia and JINR's Observer status and decision not to engage in new collaborations with Russian institutes, its June session will consider more difficult questions regarding existing collaboration agreements (p7).

It is often said but deserves repeating that CERN was founded to provide a force for unity in post-war Europe – a model that has since been adopted by SESAME in Jordan and as the basis for the proposed SEEIIST facility in South East Europe. As noted by CERN's 23 Member States, Russia's aggression runs against everything for which the Organization stands: uniting nations and people for the peaceful pursuit of knowledge.

Reporting on international high-energy physics

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

CERN
IOP Publishing

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

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

ISSN 0304-288X

NEWS ANALYSIS

CERN

Council responds to Russia's invasion of Ukraine

At an extraordinary session of the CERN Council on 8 March, the 23 Member States of CERN condemned, in the strongest terms, the military invasion of Ukraine by the Russian Federation on 24 February. The Council deplored the resulting loss of life and humanitarian impact, as well as the involvement of Belarus in the unlawful use of force against Ukraine.

Ukraine joined CERN as an Associate Member State in 2016 and Ukrainian scientists have long been active in many of the laboratory's activities. Russian scientists also have a long and distinguished involvement with CERN, and Russia was granted Observer status in recognition of its contributions to the construction of the LHC.

The Council decided that: CERN will promote initiatives to support Ukrainian collaborators and Ukrainian scientific activity in high-energy physics; the Observer status of Russia is suspended until further notice; and CERN will not engage in new collaborations with Russia and its institutions until further notice. In addition, the CERN management stated that it will comply with all applicable international sanctions.

The Council also expressed its support to the many members of CERN's Russian scientific community who reject the invasion: "CERN was established in the aftermath of World War II to bring nations and people together for the peaceful pursuit of science: this aggression runs against everything for which the Organization stands. CERN will continue to uphold its core values of scientific collaboration across borders as a driver for peace."

Two weeks later at its March session, strongly condemning statements by those Russian institutes that have expressed support for the invasion and stressing that its decisions are taken to express its solidarity with the Ukrainian people and its commitment to science for peace, the Council decided to suspend the participation of CERN scientists in all scientific committees of institutions located in Russia and Belarus, and vice versa. It also decided to suspend or, failing that, cancel all events jointly arranged between CERN and institutions located in those countries, and to suspend the granting of contracts as associated members of the CERN personnel to any new individuals affiliated to home institutions in Russia and Belarus.

Solidarity
The international high-energy physics community stands in support of Ukraine.

Illustrator: N Kitch/natekitch.com

Measures were also introduced regarding the Joint Institute of Nuclear Research (JINR), with which CERN has had scientific relations for more than 60 years. The Council decided to suspend the participation of CERN scientists in all JINR scientific committees, and vice versa; to suspend or, failing that, cancel all events jointly arranged between CERN and JINR; that CERN will not engage in new collaborations with JINR until further notice; and that the Observer status of JINR at the Council is suspended and CERN will not exercise the rights resulting from its Observer status at JINR, until further notice.

At its June session, the Council will decide on further measures regarding the suspension of international cooperation agreements and related protocols, as well as any other agreements concerning participation in CERN's scientific programme.

CERN was established to bring nations and people together for the peaceful pursuit of science

Science for peace

Other European institutions with long-standing scientific relationships with Russia, such as DESY and the ESRF, have also taken measures in response to the invasion. On 4 March the European Commission suspended co-operation with Russia on research and innovation, and on 28 February ESA announced that it will fully implement sanctions imposed on Russia by its 22 member states, making a scheduled 2022 launch for the ExoMars programme "very unlikely". Russia's future cooperation on the International Space Station is also uncertain.

The EPS, APS and national physical societies in Europe have released statements strongly condemning the Russian invasion and announcing various measures, as have organisations including IAEA, IUPAP and EUROfusion. A declaration initiated by the Max Planck Society and supported by the Lindau Nobel Laureate Meetings has been signed by 150 Nobel Laureates, while 77 Breakthrough Prize Laureates have signed an open letter standing in solidarity with the people of Ukraine. A letter from Russian scientists and science journalists attracted around 5000 signatories, while almost 200 Russian researchers participating in CERN experiments have signed an open letter standing strongly for resolving the conflict through diplomacy and negotiations.

At CERN, actions have been initiated to support employed and associated members of personnel of Ukrainian nationality and their families. The CERN community has also raised funds for the Red Cross's operations in Ukraine. With the CERN directorate deciding to match, from the CERN budget, donations made by the personnel, and in addition to a financial contribution from the CERN Staff Association, the collection raised 820,000 Swiss francs by the time of closing on 22 March.

The initiatives of many members of the personnel further demonstrate CERN's solidarity and community spirit. The theoretical physics department has created a web page listing initiatives from the scientific community, and the users office also has useful information.

CERNCOURIER
VOLUME 62 NUMBER 3 MAY/JUNE 2022
IOP Publishing
CERN

CERN

Brazil to join CERN as Associate Member State

On 3 March, CERN Director-General Fabiola Gianotti and Brazilian minister for science, technology and innovation Marcos Pontes signed an agreement admitting Brazil as an Associate Member State of CERN. The associate membership will enter into force once Brazil has completed all necessary accession and ratification processes.

Brazil will be the first country in Latin America to join CERN as an Associate Member State, marking a significant step in a geographical enlargement process that was initiated in 2010. Formal cooperation between CERN and Brazil started in 1990 with the signature of an international cooperation agreement, allowing Brazilian researchers to participate in the DELPHI experiment at LEP. Today, Brazilian institutes participate in all the main experiments at the LHC and are also involved in other experiments, such as ALPHA, ProtoDUNE at the Neutrino Platform, ISOLDE, Medipix and RD51. Brazilian nationals also participate very actively in CERN training and outreach programmes, including the summer student programme, the Portuguese-language teacher programme and the Beamline for Schools competition.

CERN-PHOTO-202203-036-6

Official *Brazilian minister of science, technology and innovation Marcos Pontes and CERN Director-General Fabiola Gianotti on the occasion of the signature of the agreement between Brazil and CERN.*

Over the past decade, Brazil's experimental particle-physics community has doubled in size. At the four main LHC experiments alone, more than 180 Brazilian scientists, engineers and students collaborate in fields ranging from hardware and data processing to physics analysis. Beyond particle physics, CERN and Brazil's National Centre for Research in Energy and Materials have also been formally cooperating since December 2020 on accelerator R&D and applications.

"The accession of Brazil to CERN Associate Membership creates a robust framework for collaboration in research, technology development and innovation," said Marcos Pontes. "I am certain that this partnership will take the Brazilian science, technology and innovation sector to a whole new level of development."

As an Associate Member State, Brazil will attend meetings of the CERN Council and finance committee. Brazilian nationals will be eligible for limited-duration staff positions, fellowships and studentships, while Brazilian companies will be able to bid for CERN contracts, increasing opportunities for industrial collaboration in advanced technologies.

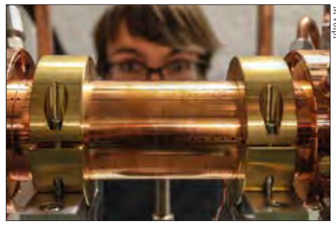
"We are very pleased to welcome Brazil as an Associate Member State," said Fabiola Gianotti. "Over the past three decades, Brazilian scientists have contributed substantially to many CERN projects. This agreement enables Brazil and CERN to further strengthen our collaboration, opening up a broad range of new and mutually beneficial opportunities in fundamental research, technological developments and innovation, and education and training activities."

Applications

Compact XFELs for all

Originally considered a troublesome byproduct of particle accelerators designed to explore fundamental physics, synchrotron radiation is now an indispensable research tool across a wide spectrum of science and technology. The latest generation of synchrotron-radiation sources are X-ray free electron lasers (XFELs) driven by linacs. With sub-picosecond pulse lengths and wavelengths down to the hard X-ray range, these facilities offer unprecedented brilliance, exceeding that of third-generation synchrotrons based on storage rings by many orders of magnitude. However, the high costs and complexity of XFELs have meant that there are only a few such facilities currently in operation worldwide, including the European XFEL at DESY and LCLS-II at SLAC.

CompactLight, an EU-funded project involving 23 international laboratories and academic institutions, three private companies and five third parties, aims to use emerging and innovative accelerator technologies from particle physics to make XFELs more affordable, compact, power-efficient and performant. In the early stages of the project, a dedicated workshop was held at CERN to survey the X-ray characteristics needed by the many user communities. This formed the basis for a design based on the latest concepts for bright electron photo-injectors, high-gradient X-band radio-frequency structures developed in the framework of the Compact Linear Collider (CLIC), and innovative superconducting short-period undulators. After four years of work, the CompactLight team has completed a conceptual design report describing the proposed facility in detail.



M Volpi

CLIC tech *A prototype of the CLIC X-band structure at the heart of the CompactLight linac.*

The 360-page report sets out a hard X-ray (16–0.25 keV) facility with two separate beamlines offering soft and hard X-ray sources with a pulse-repetition rate of up to 1 kHz and 100 Hz, respectively. It includes a facility baseline layout and two main upgrades, with the most advanced option allowing the operation of both soft and hard X-ray beamlines simultaneously. The technology also offers preliminary evaluations of a very compact, soft X-ray FEL and of an X-ray source based on inverse Compton scattering, considered an affordable solution for university campuses, small labs and hospitals.

CompactLight is the most significant current effort to enable greater diffusion of XFEL facilities, says the team, which plans to continue its activities beyond the end of its Horizon 2020 contract, improving the partnership and maintaining its leadership in compact acceleration and light production. "Compared to existing facilities, for the same operating wavelengths, the technical solutions adopted ensure that the CompactLight facility can operate with a lower electron beam energy and will have a significantly more compact footprint," explains project coordinator Gerardo D'Auria. "All these enhancements make the proposed facility more attractive and more affordable to build and operate."

- Based on an article in *Accelerating News*, 4 March.

Fermilab

CDF puts W mass in tension with Standard Model

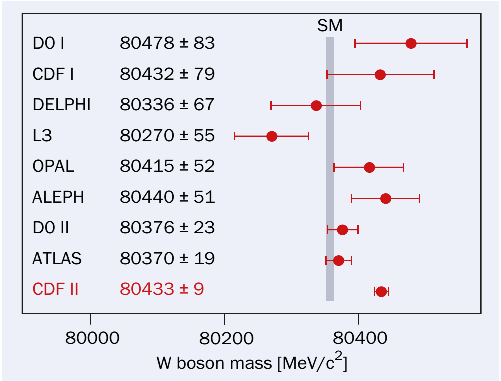
Ever since the W boson was discovered at the CERN Sp$\bar{p}$S four decades ago, successive collider experiments have pinned down its mass at increasing levels of precision. Unlike the fermion masses, the W mass is a clear prediction of the Standard Model (SM). At lowest order in electroweak theory, it depends solely on the mass of the Z boson and the value of the weak mixing angle. But higher-order corrections introduce an additional dependence on the gauge couplings and the masses of other SM particles, in particular the heavy top quark and Higgs boson. With the precision of electroweak calculations exceeding that of direct measurements, better knowledge of the measured W mass provides a vital test of the SM's consistency.

A new measurement by the CDF collaboration based on data from the former Tevatron collider at Fermilab throws a curveball into this picture. Published in *Science* on 7 April, the CDF W-mass measurement – the most precise to date – stands 7σ above the SM prediction, upsetting decades of steady convergence between experiment and theory.

"I would say the immediate reaction was silence," says Chris Hays, one of the CDF analysis leads, of the moment the measurement was unblinded on 19 November 2020. "Then there was some discussion to ensure the unblinding worked, i.e. that the value was correct, and to decide what the next steps would be."

CDF physicists have been measuring the mass of the W boson for more than 30 years via its decays to a lepton and a neutrino. In 2012, shortly after the Tevatron shut down, CDF published a W mass of 80,387 ± 12 (stat) ± 15 (syst) MeV based on 2.2 fb^{-1} of data, which significantly exceeded the precision of all previous measurements at that time combined. After 10 years of careful analysis and scrutiny of the full Tevatron dataset (8.8 fb^{-1}, corresponding to about 4.2 million W-boson candidates), and taking into account an improved understanding of the detector and advances in the theoretical and experimental understanding of the W's interactions with other particles, the new CDF result is twice as precise: 80,433.5 ± 6.4 (stat) ± 6.9 (syst) MeV.

In addition to the four-fold increase in statistics, the measurement benefits from a better understanding of systematic uncertainties. One significant change concerns the proton/antiproton parton distribution functions, where the addition of LHC data has reduced the uncertainty from 10 to 3.9 MeV while slightly raising the central value of the 2012 result.



Source: Science 376 170

Outlier *The latest CDF measurement (bottom) compared to those from its sister experiment DØ, the LEP experiments and ATLAS. The recent LHCb result – 80,354 ± 32 MeV/c² (see p34) – was published after the submission of the CDF paper.*

"The 2012 and 2022 CDF values are in agreement at better than 2σ accounting for the fact that approximately 25% of the events are in common, so the internal tension is not so significant," explains CDF collaborator Mark Lancaster, who was an internal reviewer for the result. "But the tension with other results – particularly ATLAS at 80,370 ± 19 MeV and the SM at 80,357 ± 6 MeV – is significant."

It's now up to theorists and other experiments to follow up on the CDF result, comments CDF co-spokesperson David Toback of Texas A&M University. "If the difference between the experimental and expected value is due to some kind of new particle or subatomic interaction, which is one of the possibilities, there's a good chance it's something that could be discovered in future experiments," he says.

Cross checks

Results from the LHC experiments are crucial to enable a deeper understanding. One of the challenges in measuring the W mass in high-rate proton–proton collisions at the LHC is event "pile-up", which makes it hard to reconstruct the missing transverse energy from neutrinos. The higher collision energy at the LHC compared to the Tevatron also means W bosons are produced with larger transverse momenta with respect to the beam axis, which needs to be properly modelled to measure the W mass precisely.

The CDF result reiterates the central importance of precision measurements in the search for new physics

ATLAS published the first high-precision measurement of the W mass at the LHC in 2018 based on data collected at a centre-of-mass energy of 7 TeV, and is currently working on new measurements. LHCb published its first measurement (80,354 ± 32 MeV) in September, and estimates that an uncertainty of 20 MeV or less is achievable with existing data. CMS is also proceeding with analyses that should soon see its first public result. "As the CDF result shows, precision physics can be a challenging and lengthy process," says CMS physics co-ordinator Florencia Canelli. "It takes a very long time to understand all aspects of the data to the level of precision required for a competitive W-mass measurement, and it takes years to build up the knowledge of the detector necessary to be able to address all the issues satisfactorily."

The CDF result reiterates the central importance of precision measurements in the search for new physics, describe Claudio Campagnari (UC Santa Barbara) and Martijn Mulders (CERN) in a *Perspective* article accompanying the CDF paper. They point to the increased precision that will be available at the High-Luminosity LHC and the capabilities of future facilities such as the proposed Future Circular Collider FCC-ee, which "would offer the best prospects for an improved W-boson mass measurement, with a projected sensitivity of 7 ppm". Such a measurement would also demand the SM electroweak calculations be performed at higher orders, a challenge firmly in the sights of the theory community.

Following the discovery of the Higgs boson, it is not easy to tweak the SM parameters without ruining the excellent agreement with numerous measurements. Furthermore, unlike calculations such as that of the muon anomalous magnetic moment, which relies on significant input from QCD, the prediction of the W mass relies mostly on "cleaner" electroweak computations. Surveying possible new physics that could push the W mass higher than expected, the CDF paper points to hypotheses that offer a deeper understanding of the Higgs field, including supersymmetry and Higgs-boson compositeness.

"Supersymmetry could make a change to the SM prediction of the W mass, although it seems difficult to explain as big an effect as seen experimentally," says theorist John Ellis. "But one prediction I can make with confidence is a tsunami of arXiv papers in the weeks ahead."

Further reading

CDF Collaboration 2022 *Science* **376** 170.

CERNCOURIER
Volume 62 Number 3 May/June 2022
IOP Publishing

International Linear Collider

Report re-evaluates case for the ILC in Japan

An advisory panel to the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) has called on proponents of the International Linear Collider (ILC) to re-evaluate their plans. In particular, noting the global situation and the progress in other future-collider proposals, the expert panel recommends that the issue of Japan hosting the ILC should be temporarily shelved in forthcoming ILC activities.

The Japanese high-energy physics community proposed Japan to host the ILC shortly after the discovery of the Higgs boson in 2012. Since then, MEXT and bodies including the Science Council of Japan (SCJ) have been examining all aspects of the estimated $7 billion project, which would collide electrons and positrons to study the Higgs boson in detail (*CERN Courier* January/February 2021 p35). In 2018 the International Committee for Future Accelerators (ICFA) backed a 20 km-long ILC operating at a centre-of-mass energy of 250 GeV – half the energy set out in the 2013 technical design report. But the following year MEXT, with input from the SCJ, announced that it had "not yet reached declaration" for hosting the ILC and that further discussion and greater international commitment were necessary (*CERN Courier* May/June 2019 p8).

R Hori/KEK

Work in progress *A simulation of the proposed International Linear Collider.*

Planning and progress

In June 2021, a 50 page-long report published by the ILC International Development Team (IDT), which was established in 2020 (*CERN Courier* November/December 2020 p9), set out the organisational framework, implementation model, work plan and required resources for an ILC "pre-lab". At the same time, KEK and the Japan Association of High Energy Physicists submitted a report to MEXT summarising progress on ILC activities over the past three years. Having evaluated this progress, the ILC advisory panel to MEXT released its findings on 14 February.

While recognising the academic significance of particle physics, the importance of a Higgs factory and the value of international collaborative research, the panel concluded that there is no progress in the international cost sharing for the ILC and that it is premature to proceed with an ILC pre-lab based on the premise that the Japanese government will express its interest in hosting the facility. It recommended that ILC proponents reflect upon the increasing strain in the financial situation of the related countries and reevaluate the plan in a global manner, in particular taking into account the progress in studies such as the Future Circular Collider (FCC). The question of hosting the ILC in Japan should be "decoupled", recommended the report, and development work in key technological areas be carried out by further strengthening the international collaboration among institutes and laboratories. The panel also urged the research community to continue efforts to expand the broad support from various stakeholders in Japan and abroad by building up trust and mutual understanding.

Responding to the advisory panel's findings on 22 March, KEK stated that it will re-examine the path for realising the ILC as a Higgs factory, taking into account the progress in other fronts including the FCC feasibility study. Also, in collaboration with the ILC-IDT, KEK will propose a framework to ICFA to address some of the pressing accelerator R&D issues for the ILC pre-lab. "KEK and the Japanese ILC community is committed to further advance important technological and engineering development in the accelerator area," stated KEK, also announcing a new centrally managed organisation to strengthen ILC communications to the public, academia and industry.

Writing in *ILC Newsline* on 22 March, ILC-Japan chair Shoji Asai of the University of Tokyo sought to clarify the advisory panel's statements, pointing out the "rather ambiguous" Japanese language: "It is easy to react by saying 'ILC is dead' or 'Japan is not interested'. However, this is not a project that can be talked about in such a simple manner." Regarding the panel's statement about the FCC: "Some interpret this line as the recommendation to choose between the ILC and the FCC. It is NOT. There is a clear understanding of the timing difference between the two projects."

KEK and the Japanese ILC community is committed to further advance important technological and engineering development in the accelerator area

On 11 April, ICFA published a statement reaffirming its position that the concept for the ILC is technically robust and has reached a level of maturity "which supports its moving forward with the engineering design study toward its timely realisation". ICFA commits to continuing efforts within the IDT over the next year to coordinate the global research community's activities, in particular to further strengthen international collaboration among institutes and laboratories to advance international collaboration toward important R&D activities, and will continue to encourage intergovernmental discussion between Japan and potential partner nations on the ILC.

"Since Japan has never hosted a large international research facility in the past, the cautious attitude of the Japanese government is in some way understandable," says Tatsuya Nakada, head of the ILC-IDT. "Linear colliders should remain as a viable option for the future Higgs factory and beyond. In this context, ICFA support for the Japanese community proposing the ILC as a global project hosted in Japan is very important."

Astrowatch

Thermonuclear explosions fuel cosmic rays

Normally, RS Ophiuchi is a faint astronomical object at a distance of about 5000 light years from Earth. Once every 15 years or so, however, it brightens dramatically to the point it becomes visible to the naked eye, only to disappear again within several days. This object, classified as a recurrent nova, is not a single star but rather a binary system consisting of a white dwarf and a red giant. Due to the proximity of the white dwarf to its massive companion, it slowly accumulates matter from which it forms a thin atmospheric-like layer on its surface. Over time, this atmosphere becomes denser and heats up until it reaches a critical temperature of around 20 million K. The thermonuclear explosion initiated at this temperature rapidly spreads across the dwarf's surface, causing all the remaining material to be blown away. This process, which in the case of RS Ophiuchi occurs between every 9 to 26 years, makes the object visible in the optical region. However, the process has also been theorised to be capable of producing cosmic rays.

DESY/H.E.S.S.

Shocking *An artist's impression of the RS Ophiuchi outburst.*

The results show a clear correlation between the theoretical predictions of hadronic production of gamma rays by recurring novae

Bipolar shape

The first recorded explosion on RS Ophiuchi was in 1898 after it was discovered in optical images by Williamina Fleming in 1905. A more recent explosion in 2006 was observed in detail by Hubble, while the last one occurred in August 2021. Hubble's 2006 images show a shock wave propagating from the object. The shock, which is originally radially symmetric, gets distorted by the gas present in the orbital plane of the binary system. This gas slows down the shock in the orbital plane, leading to a final bipolar shape capable of accelerating electrons and hadrons to high energies. These accelerated charged particles can reach Earth in the form of cosmic rays, but due to the influence of magnetic fields it is not possible to directly trace these back to the source. The high-energy gamma rays produced by some of these cosmic rays, on the other hand, do point directly to the source. Gamma rays formed in this way during the 2021 explosion have recently been used by the H.E.S.S. collaboration to test cosmic-ray acceleration models.

After the initial detection of the brightening of the source in optical wavelengths, the ground-based H.E.S.S. facility in Namibia pointed its five telescopes (which are sensitive to the Cherenkov light emitted as TeV gamma rays induce showers in the atmosphere) to the source. In parallel, the space-based Fermi-LAT telescope, which directly detects gamma rays in the ~100 MeV to ~500 GeV energy range, observed the target for a duration of several weeks. The emission measured by both telescopes as a function of time shows the maximum energy flux as measured by Fermi-LAT peaking about one day after the peak in optical brightness. For H.E.S.S., which covered the 250 GeV to 2.5 TeV energy range, the peak only occurred three days after the optical peak, indicating a significant hardening of the emission spectrum with time.

Hadronic origin

These results match what would be expected from a hadronic origin of these gamma rays. The shock wave produced by the thermonuclear explosion is capable of accelerating charged particles every time they traverse the shock. Magnetic fields, which are in part induced by some of the accelerated hadrons themselves, trap the charged particles in the region, thereby allowing these to traverse the shock many times. Some of the hadrons collide with gas in the surrounding medium to produce showers in which neutral pions are produced, which in turn produce the gamma rays detected on Earth. The maximum energy of these gamma rays is about an order of magnitude lower than the hadrons that induced the showers. This implies that one day after the explosion, hadrons had been accelerated up to 1 TeV, producing the photons detected by Fermi-LAT, while it took an additional two days for the source to further accelerate such hadrons up to the 10 TeV required to produce the emission visible to H.E.S.S. These timescales, as well as the measured energies, match with the theoretical predictions for sources with the same size and energy as RS Ophiuchi.

The results, published in *Science* by the H.E.S.S. collaboration, show a clear correlation between the theoretical predictions of hadronic production of gamma rays by recurring novae. The alternative theory of a leptonic origin of the gamma rays is more difficult to fit due to the relatively large fraction of the shock energy that would need to be converted into electron acceleration. The measurements form an almost direct way to test models of the origin of cosmic rays and thereby add several important pieces to the puzzle of cosmic-ray origins.

Further reading

H.E.S.S. Collaboration 2022 *Science* **376** 77.

CERNCOURIER

Volume 62 Number 3 May/June 2022

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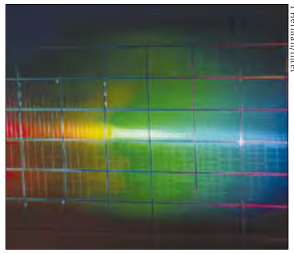
NEWS DIGEST

Ventilator advances
Two years ago, the COVID-19 pandemic prompted physicists and engineers from LHCb to propose a high-quality, low-cost ventilator for use both in and out of hospital intensive-care units. A conceptual design and first performance evaluation for the device, dubbed "HEV", has now been published (*R. Soc. Open Sci.* **9** 211519). The HEV design has been adapted by the STFC-funded HPLV project for low- and middle-income countries, and working prototypes have been successfully deployed at universities in Brazil, Germany, Greece, Mexico and Switzerland, including add-ons such as the provision of compressed air independently of the hospital supply. Several licences have been signed by CERN's knowledge-transfer group with external entities, says the team, and HEV is applicable beyond the COVID-19 pandemic.

Largest CP violation
At a CERN seminar on 15 March, LHCb reported interesting behaviour in the CP properties of charged charmless B-meson decays to three light mesons. CP asymmetries were observed in $B^{\pm}\to K^{\pm}K^{+}K^{-}$, $B^{\pm}\to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm}\to \pi^{\pm}K^{+}K^{-}$ decays, while for $B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}$ decays they were found to be absent. Huge CP violation effects were seen in different kinematical regions, with the sign of CP violation flipping twice in the low $\pi^{+}\pi^{-}$ invariant mass region of $B^{\pm}\to \pi^{\pm}\pi^{+}\pi^{-}$ decays. Furthermore, in a specific kinematical region of this decay clustered around the χ_c meson mass, the CP asymmetry was found to be as high as 75% – the largest ever observed.

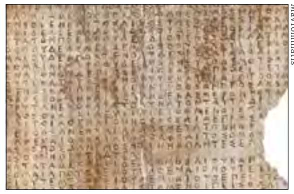
A leap for Si qubits
Researchers from Intel and TU Delft have fabricated silicon quantum dots in a 300 mm semiconductor manufacturing facility using all-optical lithography and fully industrial processing, demonstrating an exceptionally good yield and key performance indicators comparable to commonly observed values. In addition to scalability, the coherence properties of qubits in the face of microscopic charge fluctuations are key factors for a quantum computer. The team demonstrated relaxation times of over 1 s at 1 T and coherence times of more than 3 ms (*Nat. Electron.* **5** 184).


A wafer with quantum-dot qubits.

Antiprotonic surprise
Unexpected behaviour of antiprotonic helium, in which an antiproton and electron orbit a helium nucleus, has been reported by the ASACUSA collaboration at CERN. Immersing the hybrid matter-antimatter helium atoms in liquid helium and illuminating them with a laser, the team saw a decrease in the width of the antiprotonic spectral lines compared to measurements in gaseous helium, despite numerous collisions with matter atoms. On cooling to the superfluid phase, an abrupt further narrowing was observed, revealing the atom's hyperfine structure. The spectral lines were much sharper than those of many other matter atoms immersed in liquid helium. The behaviour could be used to search for low-velocity cosmic antiprotons or antideuterons in astrophysical experiments, to measure particle masses precisely and to study condensed-matter effects, say the researchers (*Nature* **603** 411).

End of ANTARES
Exactly 16 years after ANTARES was deployed in the Mediterranean Sea on 14 February 2006, the cables connecting it to land were severed and the task of hauling its 885 optical modules from the deep is ready to begin. Employing about 0.1 km^3 of natural seawater as the detector medium, the first operating deep-sea neutrino telescope turned Cherenkov light from muon-induced showers into point-like searches for neutrinos of extra-terrestrial origin. Together with IceCube, ANTARES helped to constrain the origin of the diffuse-like astrophysical neutrino spectrum and enabled searches for new physics, not to mention shedding light on the behaviour of local sperm whales. The 2016 detection of gravitational waves prolonged its lifetime to look for associated cosmic neutrinos, and the telescope paved the way for its successor KM3NeT being deployed nearby.

Epigraphy turns to AI
Teaming up with researchers from DeepMind Technologies, historians Yannis Assael, Thea Sommerschield and co-workers have used machine learning to successfully reconstruct ancient Greek texts from stone fragments. Having been trained on more than 78,000 texts, the neural network, named Ithaca, dated inscriptions relevant to the political history of Athens to around 421 BCE. Conventional dating methods based on the letter form dated the inscriptions either at around 446/5 or 420 BCE. These dates are historically important, since the earlier date refers to a point when Athens dominated the sea, whereas the date found by the neural network suggests that the inscriptions were made when Sparta took over and dominated both land and sea territories (*Nature* **603** 280).


Part of one of the re-dated inscriptions.

CALET on cosmic nickel
A new measurement of the cosmic-ray nickel spectrum by the CALET experiment on the ISS surpasses all previous measurements in precision and energy reach. Measuring the differential energy spectrum from 8.8 to 240 GeV/n using more than five years of data, the team found that nickel displays a very similar flux in shape and energy dependence to iron despite being much less abundant. The results suggest that the origin, acceleration and propagation of nickel and iron might be due to the same mechanism. Together with previous CALET results on electron, proton and light nuclei spectra in the multi-TeV energy region, along with AMS-02 and other results, the measurement marks a further step towards an understanding of the acceleration and propagation mechanisms of charged particles in our galaxy. (*Phys. Rev. Lett.* **128** 131103).

DESY teams up on computing
To deal with burgeoning datasets and strengthen computation research, DESY together with the University of Hamburg and Hamburg University of Technology has created the Center for Data and Computing in Natural Science in the newly emerging "Science City Bahrenfeld". Split into four pillars – astro and particle physics, photon science, systems biology and controls of accelerators – the facility aims to link the natural sciences with methodologically oriented research in computer science and applied mathematics, with its inaugural symposium taking place on 26–28 April.

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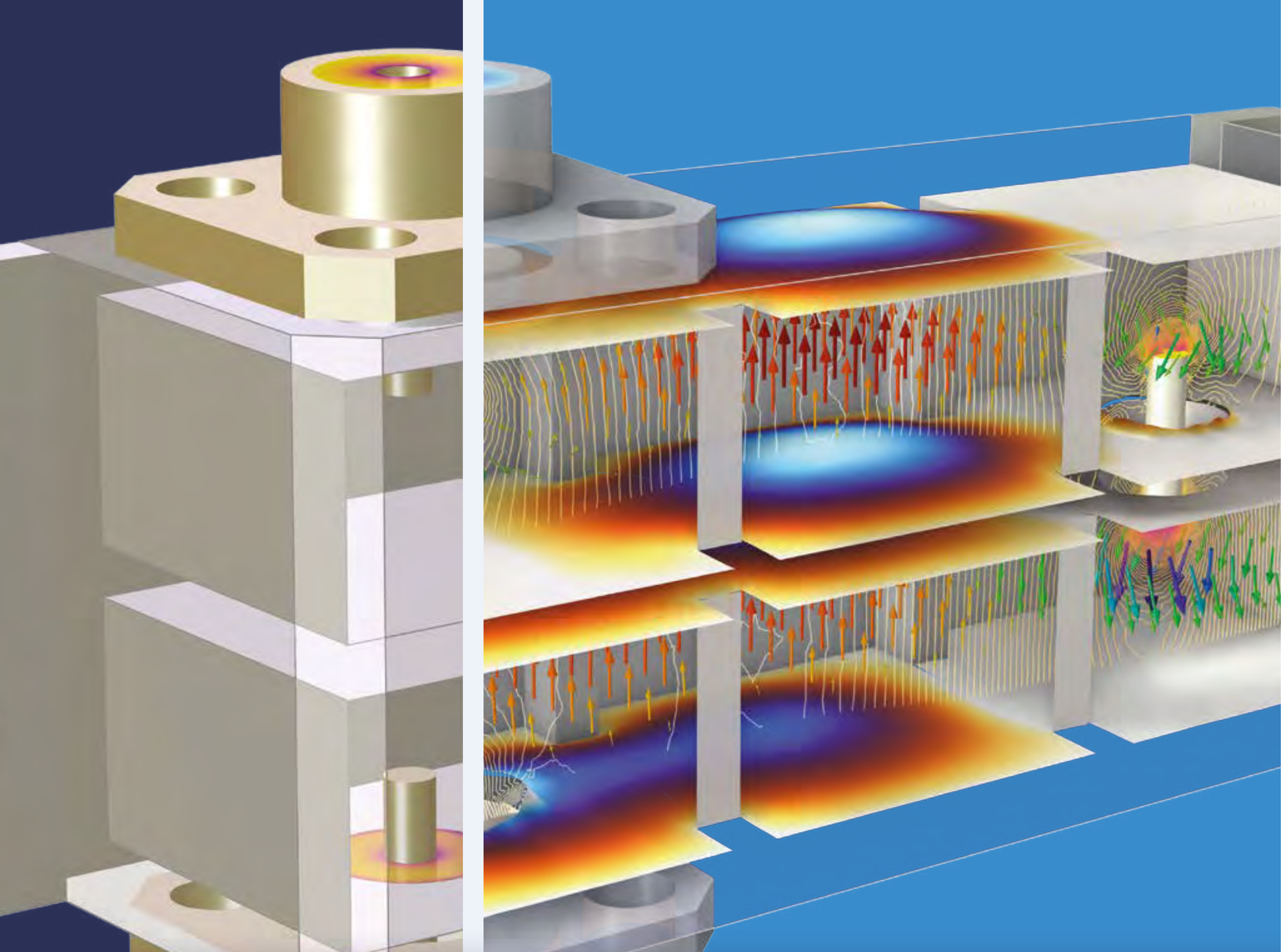

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Dijet excess intrigues at CMS

The Standard Model (SM) has been extremely successful in describing the behaviour of elementary particles. Nevertheless, conundrums such as the nature of dark matter and the cosmological matter–antimatter asymmetry strongly suggest that the theory is incomplete. Hence, the SM is widely viewed as an effective low-energy limit of a more fundamental underlying theory that must be modified to describe particles and their interactions at higher energies.

A powerful way to discover new particles expected from physics beyond the SM is to search for high-mass dijet or multi-jet resonances, as these are expected to have large production cross-sections at hadron colliders. These searches look for a pair of jets originating from a pair of quarks or gluons, coming from the decay of a new particle "X" and appearing as a narrow bump in the invariant dijet-mass distribution. Since the energy scale of new physics is most likely high, it is natural to expect these new particles to be massive.

CMS and ATLAS have performed a suite of single-dijet-resonance searches. The next step is to look for new identical-mass particles "X" that are produced in pairs, with (resonant mode) or without (non-resonant mode) a new intermediate, heavier particle "Y" being produced and decaying to pairs of X. Such processes would yield two dijet resonances and four jets in the final state: the dijet mass would correspond to particle X and the four-jet mass to particle Y.

The CMS experiment was also motivated to search for Y→XX→four jets by a candidate event recorded in 2017, which was presented by a previous CMS search for dijet resonances (figure 1). This spectacular event has four high-transverse-momentum jets forming two dijet pairs, each with an invariant mass of 1.9 TeV and a four-jet invariant mass of 8 TeV.

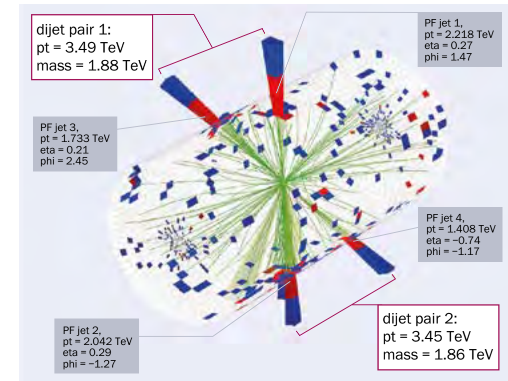

Fig. 1. *Display of the highest mass event with a four-jet mass of 8 TeV, in which each pair of jets has a dijet mass of 1.9 TeV.*

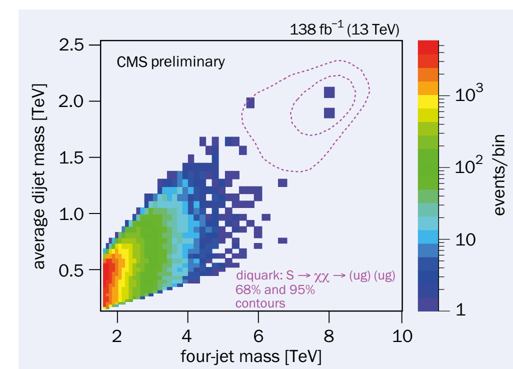

Fig. 2. *Number of events observed (colour scale) within bins of the four-jet mass and the average mass of the two dijets. Purple ellipses show the 1 and 2σ resolution contours from a signal simulation of a four-jet resonance, with a mass of 8.4 TeV, decaying to a pair of dijet resonances, each with a mass of 2.1 TeV.*

The CMS collaboration recently found another very similar event in a new search optimised for this specific Y→XX→four-jet topology. These events could originate from quantum-chromodynamic processes, but those are expected to be extremely rare (figure 2). The two candidate events are clearly visible at high masses and distinct from all the rest. Also shown in the figure (in purple) is a simulation of a possible new-physics signal – a diquark decaying to vector-like quarks – with a four-jet mass of 8.4 TeV and a dijet mass of 2.1 TeV, which very nicely describes these two candidates.

The hypothesis that these events originate from the SM at the observed X and Y masses is disfavoured with a local significance of 3.9σ. Taking into account the full range of possible X and Y mass values, the compatibility of the observation with the SM expectation leads to a global significance of 1.6σ.

The upcoming LHC Run 3 and future High-Luminosity LHC runs will be crucial in telling us whether these events are statistical fluctuations of the SM expectation, or the first signs of yet another groundbreaking discovery at the LHC.

Further reading

CMS Collab. 2022 CMS-PAS-EXO-21-010.

LHCb

LHCb constrains cosmic antimatter production

During their 10 million-year-long journey through the Milky Way, high-energy cosmic rays can collide with particles in the interstellar medium, the ultra-rarefied gas filling our galaxy and mostly composed of hydrogen and helium. Such rare encounters are believed to produce most of the small number of antiprotons, about one per 10,000 protons, that are observed in high-energy cosmic rays. But this cosmic antimatter could also originate from unconventional sources, such as dark-matter annihilation, motivating detailed investigations of antiparticles in space. This effort is currently led by the AMS-02 experiment on the International Space Station, which has reported results with unprecedented accuracy (*CERN Courier* March/April 2020 p9).

The interpretation of these precise cosmic antiproton data calls for a better understanding of the antiproton production mechanism in proton-gas ▷

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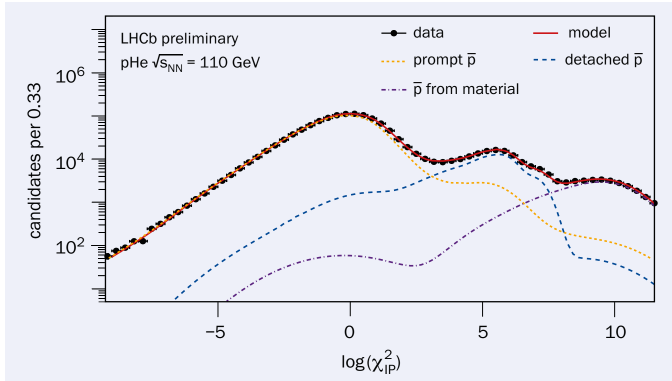
collisions. Here, experiments at accelerators come to the rescue. The LHCb experiment has the unique capability of injecting gas into the vacuum of the LHC accelerator. By injecting helium, cosmic collisions are replicated in the detector and their products can be studied in detail. LHCb already provided a first key input into the understanding of cosmic antimatter by measuring the amount of antiprotons produced at the proton–helium collision vertex itself (*CERN Courier* May 2017 p12). In a new study, this measurement has been extended by including the significant fraction (about one third) of antiprotons resulting from the decays of antihyperons such as $\bar{\Lambda}$, which contain a strange antiquark also produced in the collisions.

These antiprotons are displaced from the collision point in the detector, as the antihyperons can fly several metres through the detector before decaying. Different antihyperon states and decay chains are possible, all contributing to the cosmic antiproton flux. To count them, the LHCb team exploited two key features of its detector: the ability to distinguish antiprotons from other charged particles via two ring-imaging Cherenkov (RICH) detectors, and the outstanding resolution of the LHCb vertex locator. Thanks to the latter, when checking the compatibility of the identified antiproton tracks with the collision vertex, three classes of antiprotons can be clearly resolved (figure 1):



Source: LHCb-PAPER-2022-006

Fig. 1. *Measurement of the displacement of candidate antiproton tracks from the collision vertex. "Prompt" antiprotons peak at 0, whereas if the value is above 3, they most likely originate from "detached" antihyperon decays or in secondary collisions with the detector material.*

"prompt" particles originating from the proton–helium collision vertex; detached particles from $\bar{\Lambda}$ decays; and more separated particles produced in secondary collisions with the detector material.

The majority of the detached antiprotons are expected to originate from $\bar{\Lambda}$ particles produced at the collision point decaying to an antiproton and a positive pion. A second study was thus performed to fully reconstruct these decays by identifying the decay vertex. The results of this complementary approach show that about 75% of the observed detached antiprotons originate from $\bar{\Lambda}$ decays, in good agreement with theoretical predictions.

These new results provide an important input for modelling the expected antiproton flux from cosmic collisions. No smoking gun for an exotic source of cosmic antimatter has emerged yet, while the accuracy of this quest would profit from more accelerator inputs. Thus, the LHCb collaboration plans to expand its "space mission" with the new gas target SMOG2 (*CERN Courier* May/June 2020 p20). This facility/device could also enable collisions between protons and hydrogen or deuterium targets, further strengthening the ties between the particle and astroparticle physics communities.

Further reading

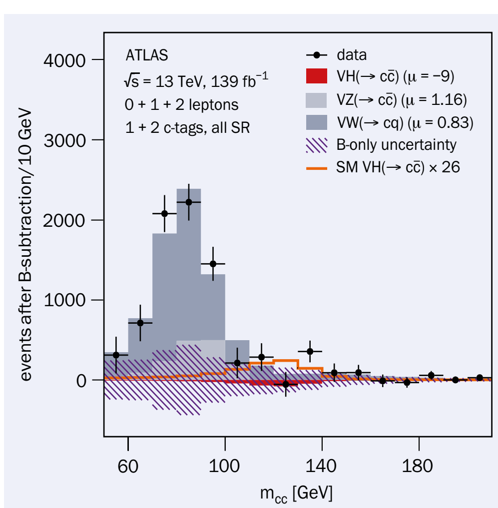
LHCb Collab. 2022 LHCb-PAPER-2022-006.

ATLAS

Higgs-boson charm coupling weaker than bottom

Within the Standard Model (SM), the Higgs boson is predicted to interact with (or couple to) quarks with a strength proportional to their mass. By measuring these interaction strengths, physicists can test this prediction and gain insight into possible physics beyond the SM, where such couplings can be modified. In a new analysis exploiting the full Run-2 dataset, the ATLAS collaboration experimentally excludes new-physics scenarios which predict that decays of the Higgs boson to a pair of charm quarks ($H\rightarrow cc$) are as frequent as those to bottom quarks ($H\rightarrow bb$).

The search for $H\rightarrow cc$ is hampered by abundant background processes. In order to identify charm-quark signatures, a new multivariate classification method was developed to tag hadrons within jets, while simultaneously reducing the probability of misidentifying jets originating from a bottom quark. To maximise the sensitivity to the signal,



Source: arXiv:2201.11428

Fig. 1. *The distribution of the invariant mass of the two jets, after background subtraction.*

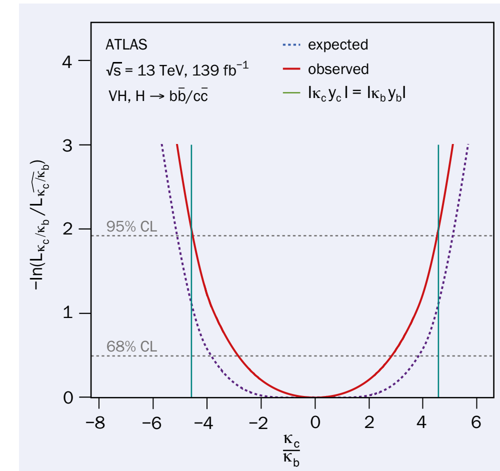
events with one or two charm-tagged jets were selected. Background processes were further suppressed by selecting Higgs-boson events produced together with a weak boson, VH(cc), where the weak boson (V = W or Z) decays to 0, 1 or 2 electrons or muons. In total, 44 regions were fitted simultaneously to measure the $H\rightarrow cc$ process.

In the SM, the $H\rightarrow cc$ process accounts for only 3% of all Higgs-boson decays. The ATLAS analysis found no significant sign for this process in the data, setting an upper limit on the rate of the VH(cc) process 26 times the SM rate at 95% confidence level. This limit constrains the Higgs-to-charm coupling strength to less than 8.5 times the predicted SM value. The analysis strategy is validated by measuring events with two vector bosons that contain the decay of a W boson to one charm quark, VW(cq), or the decay of a Z boson to two charm quarks, VZ(cc), whose rates are found to ▷

agree with the predictions. The combined dijet-mass distribution, after subtraction of the backgrounds, is shown in figure 1.

Since $H\rightarrow cc$ and $H\rightarrow bb$ decays lead to very similar signatures in the ATLAS detector, a combined analysis of both processes is key to a common interpretation. The multivariate classification method is used to identify jets as originating from a bottom quark, a charm quark or lighter quarks. Since a fraction of the $H\rightarrow bb$ events passes the selection criteria of the $H\rightarrow cc$ analysis and vice versa, the individual analyses are designed to ensure that no collision events are counted twice. This orthogonality between the analyses enabled a simultaneous measurement of the two processes for the first time.

Within the SM, the ratio of the couplings of bottom and charm quarks to



Source: arXiv:2201.11428

Fig. 2. *Likelihood scan (red) of the ratio of the Higgs-charm and Higgs-bottom coupling modifiers. The vertical green lines indicate the scenario of equal couplings.*

the Higgs boson is given by their mass ratio: $m_b/m_c = 4.578 \pm 0.008$, obtained from lattice-QCD calculations. With its novel combination of $H\rightarrow cc$ and $H\rightarrow bb$ decays, the ATLAS analysis excludes the hypothesis that the Higgs-boson interaction with charm quarks is stronger than or equal to the interaction with bottom quarks at 95% confidence level (figure 2). For the first time, this measurement establishes that the Higgs-boson coupling is smaller for charm quarks than for bottom quarks.

Further reading

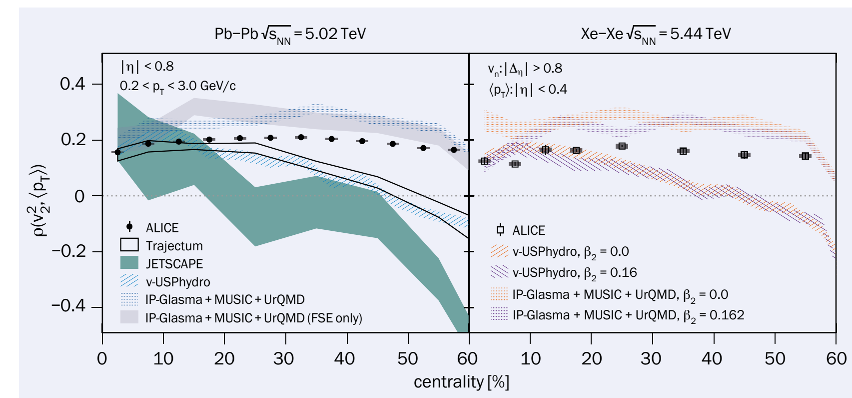
ATLAS Collab. 2022 arXiv:2201.11428.

ALICE

Accessing the precursor stage of QGP formation

The primary goal of the ultrarelativistic heavy-ion collision programme at the LHC is to study the properties of the quark–gluon plasma (QGP), a state of strongly interacting matter in which quarks and gluons are deconfined over large distances compared to the typical size of a hadron. The rapid expansion of the QGP under large pressure gradients is imprinted in the momentum distributions of final-state particles. The azimuthal-anisotropy flow coefficients v_n and the mean transverse momentum $\langle p_T\rangle$ of particles, which are described by hydrodynamic models, have been extensively measured by experiments at the LHC and at the RHIC collider. These observables are also used as experimental inputs to global Bayesian analyses that provide information on both the initial stages of the heavy-ion collision, before QGP formation, and on key transport coefficients of the QGP itself, such as the shear and bulk viscosities. However, due to the limited constraints on the initial conditions, uncertainties remain in the QGP's transport coefficients

The ALICE collaboration recently reported correlations between v_n and $\langle p_T\rangle$ in terms of the modified Pearson coefficient ρ. The measurements were performed in lead–lead (PbPb) and xenon–xenon (XeXe) collisions at centre-of-mass energies per nucleon–nucleon collision of 5.02 and 5.44 TeV, respectively. As the correlations between v_n and $\langle p_T\rangle$ are predicted to be mainly driven by the shape and size of the initial profile of the energy distribution in the transverse plane, these studies provide a new approach to characterise the initial state.



Source: arXiv:2111.06106

Fig. 1. *The correlation of the squared anisotropic flow v_n^2 and the mean transverse momentum $\langle p_T\rangle$ as a function of collision centrality for PbPb (left) and XeXe (right) collisions.*

The measurements show a positive correlation between v_n and $\langle p_T\rangle$ in both PbPb and XeXe collisions (figure 1). These measurements are compared to hydrodynamic calculations using the initial-state models IP-Glasma (based on the colour-glass-condensate effective theory with gluon saturation) and Trento, a parameterised model with nucleons as the relevant degrees of freedom. The centrality dependence of ρ is better described by IP-Glasma than by Trento. In particular, the positive measured values of ρ suggest an effective nucleon width of the order of 0.3–0.5 fm, which is significantly smaller than what has been extracted in all Bayesian analyses using Trento initial conditions. The Pearson correlation measurements can now be included in Bayesian analyses to better constrain the initial state in nuclear collisions, thus impacting the resulting QGP parameters. As a bonus, the measurements in XeXe collisions are sensitive to the quadrupole deformation parameter β_2 of the ^{129}Xe nucleus, potentially opening a new window for studying nuclear structure with ultrarelativistic heavy-ion collisions.

Further reading

ALICE Collab. 2021 arXiv:2111.06106.

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FIELD NOTES

Reports from events, conferences and meetings

RENCONTRES DE MORIOND: ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES

Closing in on open questions

Around 140 physicists convened for one of the first in-person international particle-physics conferences in the COVID-19 era. The Moriond conference on electroweak interactions and unified theories, which took place from 12 to 19 March on the Alpine slopes of La Thuile in Italy, was a wonderful chance to meet friends and colleagues, to have spontaneous exchanges, to listen to talks and to prolong discussions over dinner.

The LHC experiments presented a suite of impressive results based on increasingly creative and sophisticated analyses, including first observations of rare Standard Model (SM) processes and the most recent insights in the search for new physics. ATLAS reported the first observation of the production of a single top quark in association with a photon, a rare process that is sensitive to the existence of new particles. CMS observed for the first time the electroweak production of a pair of opposite-sign W bosons, which is crucial to investigate the mechanism of electroweak symmetry breaking. The millions of Higgs bosons produced so far at the LHC have enabled detailed measurements and open a new window on rare phenomena, such as the rate of Higgs-boson decays to a charm quark–antiquark pair. CMS presented the world's most stringent constraint on the coupling between the Higgs boson and the charm quark, improving their previous measurement by more than a factor of five, while ATLAS measurements demonstrated that it is weaker than the coupling between the Higgs boson and the bottom quark (p16). On the theory side, various new signatures for extended Higgs sectors were proposed.

L Fayard

In person *Physicists enjoying exchanges in 3D at the 56th Rencontres de Moriond.*

Of special interest is the search for heavy resonances decaying to high-mass dijets. CMS reported the observation of a spectacular event with four high transverse-momentum jets, forming an invariant mass of 8 TeV. CMS now has two such events, exceeding the SM prediction with a local significance of 3.9σ, or 1.6σ when taking into account the full range of parameter space searched (p15). Moderate excesses with a global significance of $2–2.5\sigma$ were observed in other channels, for example in a search by ATLAS for long-lived, heavy charged particles and in a search by CMS for new resonances that decay into two tau pairs. Data from Run 3 and future High-Luminosity LHC runs will show whether these excesses are statistical fluctuations of the SM expectation or signals of new physics.

The LHC experiments presented a suite of impressive results based on increasingly creative and sophisticated analyses

Flavour anomalies

The persistent set of tensions between predictions and measurements in semi-leptonic $b \to s\, \ell^+\ell^-$ decays ($\ell = e, \mu$) were much discussed. LHCb has used various decay modes mediated by strongly suppressed flavour-changing neutral currents to search for deviations from lepton flavour universality (LFU). Other measurements of these transitions, including angular distributions and decay rates (for which the predictions are affected by troublesome hadronic corrections) as well as analyses of charged-current $b \to c\tau^-\bar{\nu}$ decays from BaBar, Belle and LHCb also show a consistent pattern of deviations from LFU. While none are individually significant enough to constitute clear evidence of new physics, they represent an intriguing pattern that can be explained by the same new-physics models. Theoretical talks on this subject proposed additional observables (based on baryon decays or leptons at high transverse momenta) to get more information on operators beyond the SM that would contribute to the anomalies (p44). Updates from LHCb on several $b \to s\, \ell^+\ell^-$-related measurements with the full Run 1 and Run 2 datasets are eagerly awaited, while Belle II also has the potential to provide essential independent checks. The integrated SuperKEKB luminosity has now reached a third of the full Belle dataset, with Belle II presenting several impressive new results. These include measurements of the $b \to s\, \ell^+\ell^-$ decay branching fractions with a precision limited by the sample size and precise measurements of charmed particle lifetimes, including the individual world-best D and Λ_c^+ lifetimes, proving the excellent tracking and vertexing capabilities of the detector.

The other remarkable deviation from the SM prediction is the anomalous magnetic moment of the muon $(g-2)_\mu$, for which the SM prediction and the recent Fermilab measurement stand 4.2σ apart – or less, depending on whether the hadronic vacuum polarisation contribution ▷

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to $(g-2)_\mu$ is calculated using traditional "dispersive" methods or a recent lattice QCD calculation. The jury is still out on the theory side, but the ongoing analysis of Run 2 and Run 3 data at Fermilab will soon reduce the statistical uncertainty by more than a factor of two.

The hottest issues in neutrinos – in particular their masses and mixing – were reviewed. The current leading long-baseline experiments – NOvA in the US and T2K in Japan – have helped to refine our understanding of oscillations, but the neutrino mass hierarchy and CP-violating phase remain to be determined. A great experimental effort is also being devoted to the search for neutrinoless double-beta decay (NDBD) which, if found, would prove that neutrinos are Majorana particles and have far-reaching implications in cosmology and particle physics. The GERDA experiment at Gran Sasso presented its final result, placing a lower limit on the NDBD half-life of 1.8×10^{26} years.

The hottest issues in neutrinos were reviewed

Another very important question is the possible existence of "sterile" neutrinos that do not participate in weak interactions, for which theoretical motivations were presented together with the robust experimental programme. The search for sterile neutrinos is motivated by a series of tensions in short-baseline experiments using neutrinos from accelerators (LSND, MiniBooNE), nuclear reactors (the "reactor antineutrino anomaly") and radioactive sources (the "gallium anomaly"), which cannot be accounted for by the standard three-neutrino framework. In particular, MicroBooNE has neither confirmed nor excluded the electron-like low-energy excess observed by MiniBooNE (*CERN Courier* November/December 2021 p8). While tensions between solar-neutrino bounds and the reactor antineutrino anomaly are mostly resolved, the gallium anomaly remains.

Dark matter and cosmology

The status of dark-matter searches both at the LHC and via direct astrophysical searches was comprehensively reviewed. The ongoing run of the 5.9 tonne XENONnT experiment, for example, should elucidate the 3.3σ excess observed by XENON1T in low-energy electron recoil events (*CERN Courier* September/October 2020 p8). The search for axions, which provide a dark-matter candidate as well as a solution to the strong-CP problem, cover different mass ranges depending on the axion coupling strength. The parameter space is wide, and Moriond participants heard how a discovery could happen at any moment thanks to experiments such as ADMX. The status of the Hubble tension was also reviewed.

The many theory talks described various beyond-the-SM proposals – including extra scalars and/or fermions and/or gauge symmetries – aimed at explaining LFU violation, $(g-2)_\mu$, the hierarchy among Yukawa couplings, neutrino masses and dark matter. Overall, the broad spectrum of informative presentations brilliantly covered the present status of open questions in phenomenological high-energy physics and shine a light on the many rich paths that demand further exploration.

Monica Pepe Altarelli *CERN and* **Ulrich Ellwanger** *IJCLab.*

SNOWMASS THEORY FRONTIER

Snowmass back at KITP

From 23 to 25 February, the Kavli Institute of Theoretical Physics (KITP) in Santa Barbara, California, hosted the Theory Frontier conference of the US Particle Physics Community Planning Exercise, "Snowmass 2021" organised by the APS Division of Particles and Fields (DPF). The event brought together theorists from the entire spectrum of high-energy physics to sketch a decadal vision for high-energy theory, and was also one of the first large in-person meetings for the US particle-physics community since the start of the COVID-19 pandemic.

The conference began in earnest with Juan Maldacena's (IAS) vision for formal theory in the coming decade, highlighting promising directions in quantum field theory and quantum gravity. Following talks by Eva Silverstein (Stanford) on quantum gravity and cosmology and Xi Dong (UC Santa Barbara) on geometry and entanglement, David Gross (KITP) recalled the role of string theory in the quest for unification and emphasised its renewed promise in understanding QCD.

Heroic attempts

A comprehensive overview of recent progress in quantum field theory followed. Clay Córdova's (Chicago) summary of supersymmetric field theory touched on the classification of superconformal field theories, improved understanding of maximally supersymmetric theories in diverse dimensions, and connections between supersymmetric and non-supersymmetric dynamics. David Simmons-Duffin (Caltech) made a heroic attempt to convey the essentials of the conformal bootstrap in a 15-minute talk, while Shu-Heng Shao (IAS) surveyed generalised global symmetries and Ibrahima Bah (Johns Hopkins) detailed geometric techniques guiding the classification of superconformal field theories.

The first afternoon began with Raman Sundrum's (Maryland) vision for particle phenomenology (see "Phenomenological" figure). Tim Tait (UC Irvine) followed with an overview of dark-matter models and motivation, drawing a contrast between the more top-down perspective on dark matter prevalent during the previous Snowmass process in 2013 (also hosted by KITP) and the much broader bottom-up perspective governing today's thinking. Devin Walker (Dartmouth) and Gilly Elor (Mainz) brought the first day's physics talks to a close with bosonic dark matter and new ideas in baryogenesis.

R Sundrum

Phenomenological *Raman Sundrum's talk surveyed the pressing questions motivating physics beyond the Standard Model, some promising theoretical mechanisms for answering them and the experimental opportunities that follow.*

The final session of the first day was devoted to issues of equity and inclusion in the high-energy theory community, with DPF early-career member Julia Gonski (Columbia) making a persuasive case to give a voice to early-career physicists. Preceding a lively panel discussion, Howard Georgi (Harvard) delivered a compelling speech on the essential value of diversity in physics, recalling Ann Nelson's legacy and reminding the packed auditorium that "progress will not happen at all unless the good people who think that there is nothing they can do actually wake up and start doing."

The second and third days of the conference spanned the essentials of the spectrum of activity within high-energy theory, consolidated around quantum information science with talks by Tom Hartman (Cornell), Raphael Bousso (Berkeley), Hank Lamm (Fermilab) and Yoni Kahn (Illinois). Marius Wiesemann (MPI), Felix Kling (DESY) and Ian Moult (Yale) discussed simulations for collider physics, and Michael Wagman (Fermilab), Huey-Wen Lin (Michigan State) and Thomas Blum (Connecticut) emphasised recent progress in lattice gauge theory. Developments in precision theory were covered by Bernhard Mistlberger (CTP), Emanuele Mereghetti (LANL) and Dave Soper (Oregon), and the status of scattering-amplitudes applications by Nima Arkani-Hamed (IAS), Mikhail Solon (Caltech) and Henriette Elvang (Michigan). Masha Baryakhtar (Washington), Nicholas Rodd (CERN) and Daniel Green (UC San Diego) reviewed astroparticle and cosmology theory, followed by an overview of effective field theory approaches in cosmology and gravity by Mehrdad Mirbabayi (ICTP) and Walter Goldberger (Yale). Isabel Garcia Garcia (KITP) discussed alternative approaches to effective field theories in gravitation, and recent findings in neutrino theory were covered by Alex Friedland (SLAC), Mu-Chun Chen (UC Irvine) and Zahra Tabrizi (Northwestern). Bridging these themes with talks on amplitudes and collider physics, machine learning for particle theory and cosmological implications of dark-sector models were talks by Lance Dixon (SLAC), Jesse Thaler (MIT) and Neal Weiner (New York). Connections with the many other "frontiers" in the Snowmass process were underlined by Laura Reina (Florida State), Lian-Tao Wang (Chicago), Pedro Machado (Fermilab), Flip Tanedo (UC Riverside), Steve Gottlieb (Indiana), and Alexey Petrov (Wayne State).

The rich programme demonstrated the vibrancy of high-energy theory at this interesting juncture for the field

The rich programme demonstrated the vibrancy of high-energy theory at this interesting juncture for the field, following the discovery of the final missing piece of the Standard Model, the Higgs boson, in 2012. The many thematic threads and opportunities covered bode well for final discussions with the whole community at the main Snowmass Community Summer Study in Seattle on 17–26 July (*CERN Courier* January/February 2022 p43).

Nathaniel Craig *UC Santa Barbara.*

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5TH FCC PHYSICS WORKSHOP

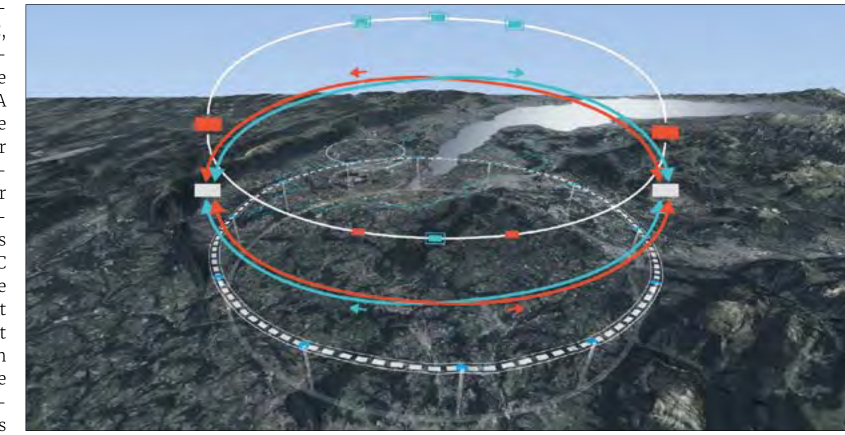
Spotlight on FCC physics

Ten years after the discovery of a Standard Model-like Higgs boson at the LHC, particle physicists face profound questions lying at the intersection of particle physics, cosmology and astrophysics. A visionary new research infrastructure at CERN, the proposed Future Circular Collider (FCC), would create opportunities to either answer them or refine our present understanding. The latest activities towards the ambitious FCC physics programme were the focus of the 5th FCC Physics Workshop, co-organised with the University of Liverpool as an online event from 7 to 11 February. It was the largest such workshop to date, with more than 650 registrants, and welcomed a wide community geographically and thematically, including members of other "Higgs factory" and future projects.

The overall FCC programme, comprising an electron–positron Higgs and electroweak factory (FCC-ee) as a first stage followed by a high-energy proton–proton collider (FCC-hh), combines the two key strategies of high-energy physics. FCC-ee offers a unique set of precision measurements to be confronted with testable predictions and opens the possibility for exploration at the intensity frontier, while FCC-hh would enable further precision and the continuation of open exploration at the energy frontier. The February workshop saw advances in our understanding of the physics potential of FCC-ee, and discussions of the possibilities provided at FCC-hh and at a possible FCC-eh facility.

The proposed R&D efforts for the FCC align with the requests of the 2020 update of the European strategy for particle physics and the recently published accelerator and detector R&D roadmaps established by the Laboratory Directors Group and ECFA (*CERN Courier* January/February 2022 p7). Key activities of the FCC feasibility study, including the development of a regional implementation scenario in collaboration with the host states of CERN, were presented.

Over the past several months, a new baseline scenario for a 91 km-circumference layout has been established, balancing the optimisation of the machine performance, physics output and territorial constraints (see p27). In addition, work is ongoing to develop a sustainable operational model for FCC taking into account human and financial resources and striving to minimise its environmental impact. Ongoing testing and prototyping work on key FCC-ee technologies will demonstrate the technical feasibility of this machine, while parallel R&D developments on high-field magnets pave the way to FCC-hh.



FCC study

Next steps *The progress described at the 5th FCC Physics Workshop is reassuring for the future of the FCC feasibility study.*

Physics programme

A central element of the overall FCC physics programme is the precise study of the Higgs sector. FCC-ee would provide model-independent measurements of the Higgs width and its coupling to Standard Model (SM) particles, in many cases with sub-percent precision and qualitatively different to the measurements possible at the LHC and HL-LHC (*CERN Courier* January/February 2021 p29). The FCC-hh stage has unique capabilities for measuring the Higgs-boson self-interactions, profiting from previous measurements at FCC-ee. The full FCC programme thus allows the reconstruction of the Higgs potential, which could give unique insights into some of the most fundamental puzzles in modern cosmology, including the breaking of electroweak symmetry and the evolution of the universe in the first picoseconds after the Big Bang.

Presentations and discussions throughout the week showed the impressive breadth of the FCC programme, extending far beyond the Higgs factory alone. The large integrated luminosity to be accumulated by FCC-ee at the Z-pole enables high-precision electroweak measurements and an ambitious flavour-physics programme. While the latter is still in the early phase of development, it is clear that the number of B mesons and tau-lepton pairs produced at FCC-ee significantly surpasses those at Belle II, making FCC-ee the flavour factory of the 2040s. Ongoing studies are also revealing its potential for studying interactions and decays of heavy-flavour hadrons and tau leptons, which may provide access to new phenomena including lepton-flavour universality-violating processes (*CERN Courier* January/February 2022 p35). Similarly, the capabilities of FCC-ee to study beyond-the-SM signatures such as heavy neutral leptons have come into further focus. Interleaved presentations on FCC-ee, FCC-hh and FCC-eh physics further intensified the connections between the lepton- and hadron-collider communities.

The impressive potential of the full FCC programme is also inspiring theoretical work. This ranges from overarching studies on our understanding of naturalness, to concrete strategies to improve the precision of calculations to match the precision of the experimental programme.

The physics thrusts of the FCC-ee programme inform an evaluation of the run plan, which will be influenced by technical considerations on the accelerator side as well as by physics needs and the overall attractiveness and timeliness of the different energy stages (ranging from the Z pole at 91 GeV to the $t\bar{t}$ threshold at 365 GeV). In particular, the possibility for a direct measurement of the electron Yukawa coupling by extensive operation at the Higgs pole (125 GeV) raises unrivalled challenges, which will be further explored within the FCC feasibility study. The main challenge here is to reduce the spread in the centre-of-mass energy by a factor of around 10 while maintaining ▷

the high luminosity, requiring a monochromatisation scheme long theorised but never applied in practice.

Concrete detector concepts for FCC-ee were discussed, helping establish a coherent set of requirements to fully benefit from the statistics and broad variety of physics channels available. The primary experimental challenge at FCC-ee is how to deal with the extremely high instantaneous luminosities. Conditions are most demanding at the Z pole, with the luminosity surpassing $10^{36}\,cm^{-2}s^{-1}$ and the rate of physics events exceeding 100 kHz. Since collisions are continuous, it is not possible to employ "power pulsing" of the front-end electronics as has been developed for detector concepts at linear colliders. Instead, there is a focus on developing fast, low-power detector components and electronics, and on efficient and lightweight solutions for powering and cooling. With the enormous data samples expected at FCC-ee, statistical uncertainties will in general be tiny (about a factor of 500 smaller than at LEP). The experimental challenge will be to minimise systematic effects towards the same level.

Breathtaking possibilities

The mind-boggling integrated luminosities delivered by FCC-ee would allow SM particles – in particular the W, Z and Higgs bosons and the top quark, but also the b and c quarks and the tau lepton – to be studied with unprecedented precision. The expected number of Z bosons produced (5×10^{12}) is more than five orders of magnitude larger than the number collected at LEP, and more than three orders of magnitude larger than that envisioned at a linear collider. The high-precision measurements and the observation of rare processes made possible by these large data samples will open opportunities for new-physics discoveries, including the direct observation of very weakly-coupled particles such as heavy-neutral leptons, which are promising candidates to explain the baryon asymmetry of the universe (*CERN Courier* March/April 2022 p27).

The detectors that will be located at two (possibly four) FCC-ee interaction points must be designed to fully profit from the extraordinary statistics. Detector concepts under study feature: a 2T solenoidal magnetic field (limited in strength to avoid blow-up of the low-emittance beams crossing at 30 mrad); a small-pitch, thin-layer vertex detector providing an excellent impact-parameter resolution for lifetime measurements; a highly transparent tracking system providing a superior momentum resolution; a finely segmented calorimeter system with

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IDEAs *Curved silicon with a 2.5 cm radius of curvature on a carbon-fibre support, demonstrating the feasibility of making low-mass, rigid FCC-ee detector systems.*

excellent energy resolution for electrons and photons, isolated hadrons and jets; and a muon system. To fully exploit the heavy-flavour possibilities, at least one of the detector systems will need efficient particle-identification capabilities allowing π/K separation over a wide momentum range, for which there are ongoing R&D efforts on compact, light RICH detectors.

With overlapping requirements, designs for FCC-ee can follow the example of detectors proposed for linear colliders. The CLIC-inspired CLD concept – featuring a silicon-pixel vertex detector and a silicon tracker followed by a 3D-imaging, highly granular calorimeter system (a silicon-tungsten ECAL and a scintillator-steel HCAL) surrounded by a superconducting solenoid and muon chambers interleaved with a steel return yoke – is being adapted to the FCC-ee experimental environment. Further engineering effort is needed to make it compatible with the continuous-beam operation at FCC-ee. Detector optimisation studies are being facilitated by the robust existing software framework that has recently been integrated into the FCC study.

The IDEA (Innovative Detector for an Electron-positron Accelerator) concept, specifically developed for a circular electron–positron collider, brings in alternative technological solutions. It includes a five-layer vertex detector surrounded by a drift chamber, enclosed in a single-layer silicon "wrapper". The distinctive element of the He-based drift chamber is its high transparency. Indeed, the material budget of the full tracking system, including the vertex detector and the wrapper, amounts to only about 5% (10%) of a radiation length in the barrel (forward) direction. The drift chamber promises superior particle-identification capabilities via the use of a cluster-counting technique that is currently under test-beam study. In the baseline design, a thin low-mass

With overlapping requirements, designs for FCC-ee can follow the example of detectors proposed for linear colliders

solenoid is placed inside a monolithic, 2m-deep, dual-readout fibre calorimeter. An alternative (more expensive) design also features a finely segmented crystal ECAL placed immediately inside the solenoid, providing an excellent energy resolution for electrons and photons.

Recently, work has started on a third FCC-ee detector concept comprising: a silicon vertex detector; a light tracker (drift chamber or full-silicon device); a thin, low-mass solenoid; a highly-granular noble liquid-based ECAL; a scintillator-iron HCAL; and a muon system. The current baseline ECAL design is based on lead/steel absorbers and active liquid-argon, but a more compact option based on tungsten and liquid-krypton is an interesting option. The concept design is currently being implemented inside the FCC software framework.

All detector concepts are under evolution and there is ample room for further innovative concepts and ideas.

Closing remarks

Circular colliders reach higher luminosities than linear machines because the same particle bunches are used over many turns, while detectors can be installed at several interaction points. The FCC-ee programme greatly benefits from the possibility of having four interaction points to allow the collection of more data, systematic robustness and better physics coverage – especially for very rare processes that could offer hints as to where new physics could lie. In addition, the same tunnel can be used for an energy-frontier hadron collider at a later stage.

The FCC feasibility study will be submitted by 2025, informing the next update of the European strategy for particle physics. Such a machine could start operation at CERN within a few years of the full exploitation of the HL-LHC in around 2040. CERN, together with its international partners, therefore has the opportunity to lead the way for a post-LHC research infrastructure that will provide a multi-decade research programme exploring some of the most fundamental questions in physics. The geographical distribution of participants in the 5th FCC Physics Workshop testifies to the global attractiveness of the project. In addition, the ongoing physics and engineering efforts, the cooperation with the host states, the support from the European physics community and the global cooperation to tackle the open challenges of this endeavour, are reassuring for the next steps of the FCC feasibility study.

Mogens Dam *Niels Bohr Institute and* **Frank Simon** *Max Planck Institute for Physics.*

DETECTION AND ANALYSIS OF GRAVITATIONAL WAVES IN THE ERA OF MULTI-MESSENGER ASTRONOMY

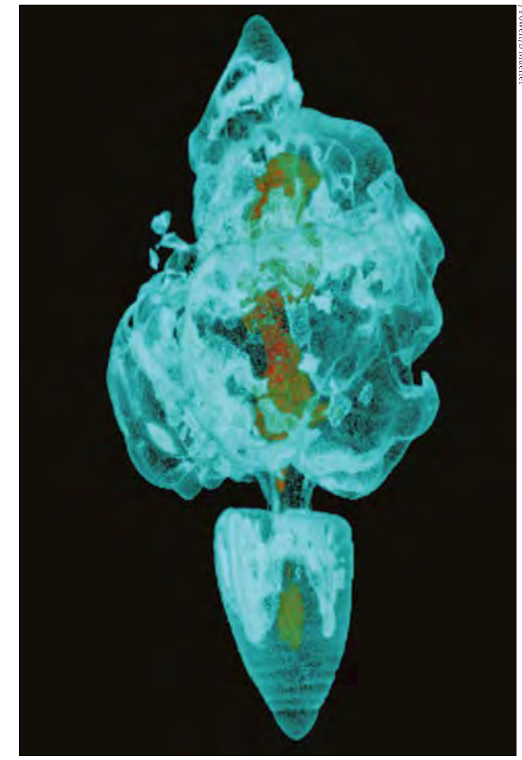
Gravitational-wave astronomy turns to AI

New frontiers in gravitational-wave (GW) astronomy were discussed in the charming and culturally vibrant region of Oaxaca, Mexico from 14 to 19 November. Around 37 participants attended the hybrid Banff International Research Station for Mathematical Innovation and Discovery (BIRS) "Detection and Analysis of Gravitational Waves in the Era of Multi-Messenger Astronomy: From Mathematical Modelling to Machine Learning" workshop. Topics ranged from numerical relativity to observational astrophysics and computer science, including the latest applications of machine-learning algorithms for the analysis of GW data.

GW observations are a new way to explore the universe's deepest mysteries. They allow researchers to test gravity in extreme conditions, to get important clues on the mathematical structure and possible extension of general relativity, and to understand the origin of matter and the evolution of the universe. As more GW observations with increased detector sensitivities spur astrophysical and theoretical investigations, the analysis and interpretation of GW data faces new challenges that require close collaboration with all GW researchers. The Oaxaca workshop focused on a topic that is currently receiving a lot of attention: the development of efficient machine-learning (ML) methods and numerical-analysis algorithms for the detection and analysis of GWs. The programme gave participants an overview of new-physics phenomena that could be probed by current or next-generation GW detectors, as well as data-analysis tools that are being developed to search for astrophysical signals in noisy data.

Unprecedented sensitivity

Since their first detections in 2015, the LIGO and Virgo detectors have reached an unprecedented GW sensitivity. They have observed signals from binary black-hole mergers and a handful of signals from binary neutron star and mixed black hole–neutron star systems. In discussing the role that numerical relativity plays in unveiling the GW sky, Pablo Laguna and Deirdre Shoemaker (Texas) showed how it can help in understanding the physical signatures of GW events, for example by distinguishing black hole–neutron star binaries from binary black-hole mergers. On the observational side, several talks



J Powell/B Mueller

Out of this world *A computer simulation of gravitational waves emitted by a supernova.*

focused on possible signatures of new physics in future detections. Adam Coogan (Montréal and Mila) and Gianfranco Bertone (Amsterdam and chair of EuCAPT) discussed dark-matter halos around black holes. Distinctive GW signals could help to determine whether dark matter is made of a cold, collision-less particle via signatures of intermediate mass-ratio inspirals embedded in dark-matter halos. In addition, primordial black holes could be dark-matter candidates.

Bernard Mueller (Monash) and Pablo Cerdá-Durán (Valencia) described GW emission from core-collapse supernovae for which the range of current detectors is limited to the Milky Way, where the rate of supernovae is about one per century. Lorena Magaña Zertuche (Mississippi) talked about the physics of black-hole ring-down – the process whereby gravitational waves are emitted in the aftermath of a binary black-hole merger – which is crucial for understanding astrophysical black holes and testing general relativity. Finally, Leïla Haegel (Paris) described how the detection of GW dispersion would indicate the breaking of Lorentz symmetry: if a GW propagates according to a modified dispersion relation, its frequency modes will propagate at different speeds, changing the phase evolution of the signals with respect to general relativity.

Multi-flavoured

Applications of different flavours of ML algorithms to GW astronomy, ranging from the detection of GWs to their characterisation in detector simulations, were the focus of the rest of the workshop. ML has seen a huge development in recent years and has been increasingly used in many fields of science. In GW astronomy, a variety of supervised, unsupervised and reinforcement ML algorithms, such as deep learning, neural networks, genetic programming and support vector machines, have been developed. They have been used to successfully deal with detector noise, signal processing, data analysis for signal detections and for reducing the non-astrophysical background of GW searches. These algorithms must be able to deal with large data sets and demand a high accuracy to model theoretical waveforms and to perform searches at the limit of instrument sensitivities. The next step for a successful use of ML in GW science will be the integration of ML techniques with more traditional numerical-analysis methods that have been developed for the modelling, real-time detection and signal analysis.

The BIRS workshop provided a broad overview of the latest advances in this field, as well as open questions that need to be solved to apply robust ML techniques to a wide range of problems. These include reliable background estimation, modelling gravitational waveforms in regions of the parameter space not covered by full numerical relativity simulations, and determining populations of GW sources and their properties. Although machine learning for GW astronomy is in its infancy, there is no doubt that it will play an increasingly important role in the detection and characterisation of GWs, leading to new discoveries.

Marco Cavaglia *Missouri University of Science and Technology,* **Shaon Ghosh** *Montclair State University,* **Elena Cuoco** *European Gravitational Observatory and* **Jade Powell** *Swinburne University of Technology.*

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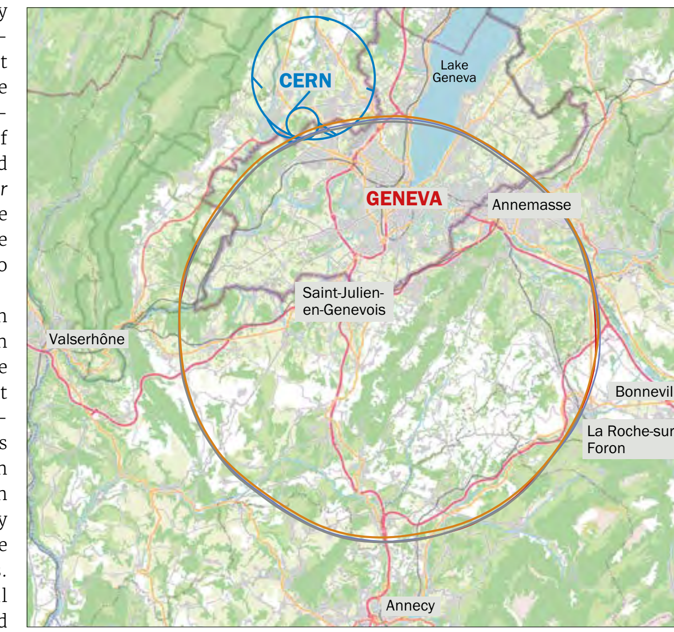
IOP Publishing

HOST STATES GEAR UP TO WORK ON FCC

The strong support and cooperation of administration services in France and Switzerland are reassuring for the next steps of the Future Circular Collider feasibility study, describes Johannes Gutleber.

In preparing the long-term future of high-energy physics after the LHC, the 2020 update of the European strategy for particle physics recommended that Europe, together with its international partners, explore the technical and financial feasibility of a future proton–proton collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron–positron Higgs and electroweak factory as a possible first stage (*CERN Courier* July/August 2020 p7). In 2021 a new chapter opened for the Future Circular Collider (FCC) feasibility study with the development of the preferred layout and placement scenario for this visionary possible new research infrastructure.

Following the publication of the FCC conceptual design report in 2019 (*CERN Courier* January/February 2019 p38), an interdisciplinary team from CERN and CERN's host-state authorities worked to ensure that the preferred placement scenario aligned with the regional requirements and environmental constraints in France and Switzerland. This included Cerema (the Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning) in France and departments from the Canton of Geneva. A key challenge in constructing a new 90–100 km-circumference tunnel for a future collider concerns subsurface areas. Here, the FCC study has brought together international leaders in the construction industry along with French and Swiss universities, thus profiting from local expertise, to develop geological studies. Thanks to this colossal effort, more than 100 scenarios with different layout geometries and surface sites have been analysed, leading to a number of potential options.



Closing the loop *Different working hypotheses (coloured rings) for a 91 km-circumference FCC placement scenario with eight surface sites, taking into account geological conditions, surface constraints, infrastructure and resources. The present LHC and SPS rings are shown in blue.*

Preferred placement

In June 2021 an international committee independently reviewed the results of these studies, recommending a specific, 91 km-circumference layout with a four-fold symmetry and eight surface sites (see "Closing the loop" image). This configuration balances the requirement for maximising the scientific output of the FCC within territorial constraints and project implementation risks. To validate the feasibility of this placement scenario, further data about the surface and the geology are needed. This entails specific site investigations to optimise the locations of surface sites in view of infrastructure and environmental constraints, and to gain a more realistic understanding of the geological conditions.

In line with these planned activities, the Préfet de la Région Auvergne-Rhône-Alpes has been mandated by the French government to coordinate the involvement of all relevant services in France in close cooperation with Switzerland, and the local authorities and communities potentially affected by such a project. A few weeks later, on 10 December, the Swiss Federal Council announced its decision to strengthen support for current CERN projects and future developments, including the FCC: "In addition to its considerable contributions to science and innovation, CERN has also brought significant economic benefits to Switzerland, and the Geneva region in particular," stated the Federal Council announcement. "Switzerland must

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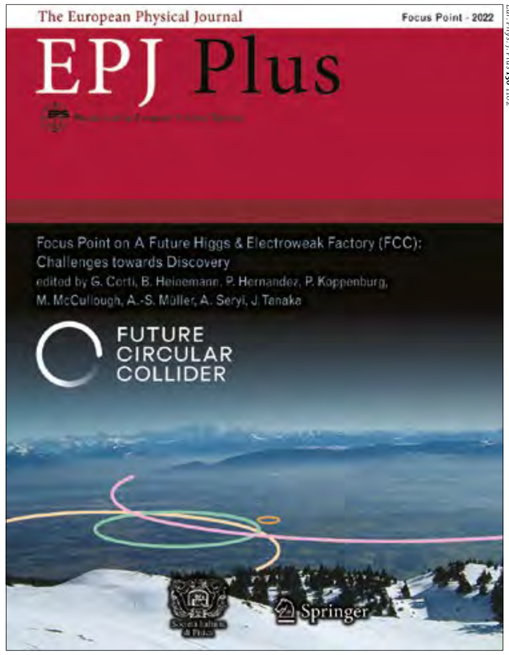


Going deeper *A special issue of the* European Physics Journal, *published open-access in March* (Eur. Phys. J. Plus **136** 1102), *explores the status and challenges of a future circular Higgs and electroweak factory.*

promote CERN's long-term development potential, particularly in terms of spatial planning, which has prompted the Federal Council to initiate work on a federal sectorial plan focusing on CERN projects."

In parallel with activities at the federal level, the Canton of Geneva has created a support unit involving about 20 different offices to work with CERN. The first meeting between the newly established group and the CERN FCC team took place in December 2021, paving the way for a roadmap of activities from 2022 onwards to analyse the FCC requirements and the constraints that will apply during the different project phases.

Local engagement

As the FCC feasibility study moves from a generic to a specific geographical level, dialogues between government officials, local elected representatives and citizens become increasingly important. Consequently, CERN – together with France and Switzerland – has created a permanent group to communicate with all stakeholders in both countries. The first activities involve identifying and analysing the needs and expectations of the populations in the relevant areas, and preparing non-invasive activities on the surface, such as environmental analyses and detailed planning of geophysical and geotechnical investigations to be carried out from 2024.

Despite the long time scales involved, the local population should already be engaged from the feasibility study stage

Developing a scenario for such a geographically distributed infrastructure raises numerous challenges at both large and small scales, and therefore calls for thoughtful planning. One example is the connection of surface sites to the French high-capacity electrical network, which involves planning for electricity lines with voltages above 63 kV. A second example is the connection between selected surface sites and the transport network to allow the efficient removal of excavated materials and the movement of construction materials. At the local level, one of the issues that working groups in France and Switzerland face is the provision of land plots. Since the launch of the FCC study in 2014, no less than 400 ha of candidate surface-site areas had to be discarded due to the designation of new environmental protection zones, agricultural protection areas and the development of housing and infrastructure projects.

Despite the long time scales involved, the local population should already be engaged from the feasibility study stage in developing the vision for CERN's post-LHC future. This year, a series of meetings will take place with the communes that would potentially host the surface sites in both France and Switzerland. The activity will be accompanied by an environmental initial-state analysis and an agricultural-economics study, which will create the baselines for impact studies. These, in turn, will form the cornerstone of the *Éviter-réduire-compenser* (avoid-reduce-compensate) principle, anchored in French environmental law, which the FCC study has adopted from the beginning to ensure a well-balanced, scientifically excellent and territorially acceptable project scenario. A further issue that should be carefully explored is the accessibility of the surface sites; certain candidate areas are in zones that lack road or train access, for example. It is also important for regional administration services in France and Switzerland to establish contacts for FCC-related trans-border traffic in time to understand the needs and the possibilities on a time frame of 10–15 years.

Building the future

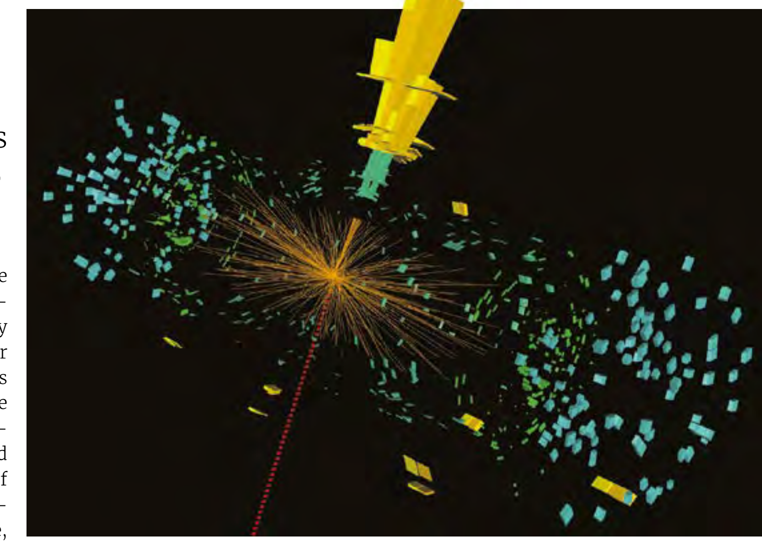
These recent developments offer a glimpse of the ongoing work needed to prepare for a new research infrastructure in the Geneva region, and highlight the importance of the timely completion of a geo-localised scenario on a timescale of around a decade. In parallel, machine, detector and physics studies by the global FCC collaboration continue across 150 institutes in 30 countries (*CERN Courier* January/February 2022 p7).

It takes time and care to build a mutual understanding of the possibilities and constraints, both within the engineering domains at CERN and the public administration services in France and Switzerland, along with the development of the required legal and administrative frameworks. Tripartite working-group meetings involving CERN, representatives of the Canton of Geneva and representatives of the Auvergne-Rhône-Alpes region are now taking place on a regular basis.

Clearly, the strong support and cooperation of public administration services in both host states is a reassuring condition for the next steps of the FCC feasibility analysis. The recent FCC physics workshop (see p23) reaffirms the interest of the physics community in the long-term scientific research programme offered by this future endeavour. The commitment of the community is the precondition for continued efforts to develop the FCC project scenario with an extended group of regional and local stakeholders. ●

THE SEARCH FOR NEW PHYSICS: TAKE THREE

Improved experimental techniques and new guidance from lower-energy experiments put the LHC in a better position than before to address the question of naturalness, describe Patrick Rieck and Aurelio Juste



Striking out *An ATLAS mono-jet event containing a single energetic jet and large missing transverse energy. (Credit: ATLAS)*

Aside from the discovery of the Higgs boson, the absence of additional elementary-particle discoveries is the LHC's main result so far. For many physicists, it is also the more surprising one. Such further discoveries are suggested by the properties of the Higgs boson, which are now established experimentally to a large extent. The Higgs boson's low mass, despite its susceptibility to quantum corrections from heavy particles that should push it orders-of-magnitude higher, and its hierarchy of coupling strengths to fermions present extreme, "unnatural" values that so far lack an explanation. Therefore, searches for new physics at the TeV energy scale remain strongly motivated, irrespective of the no-show so far.

Naturalness has triggered the development of many new-physics models, but the large extent of their parameter space allows them to evade exclusion again and again. Whereas the discoveries of the past decades, including that of the Higgs boson, were driven by precise quantitative predictions, the search for physics beyond the Standard Model (SM) simply requires more perseverance.

LHC Run 3 will bring long-awaited new insights to the question of naturalness with respect to Higgs physics, as well as to many other SM puzzles such as the nature of dark matter or the cosmological matter–antimatter asymmetry. With considerably more data and a slightly higher centre-of-mass energy than at Run 2, in addition to new triggers and improved event reconstruction and physics-analysis techniques, a significant increase in sensitivity compared to the current results will be achieved. Searches for new phenomena with Run 3 data will also benefit from a much improved definition of the physics targets, thanks to information gathered during Run 2 and the various anomalies observed at lower energies.

The story so far

During the past 12 years, a broad search programme has emerged at the LHC in parallel with precision measurements (see p33). Initially, the most favoured new-physics scenario was supersymmetry (SUSY), a new fermion–boson symmetry that gives rise to supersymmetric partners of SM particles and naturally leads to a light Higgs boson close to the masses of the W and Z bosons. SUSY is expected to produce events containing jets and missing transverse energy (MET), the study of which at Run 2 placed exclusion limits on gluino masses as high as 2.3 TeV. More challenging searches for stop quarks, with background processes up to a million times more frequent than the predicted signal, were also performed thanks to the excellent performance of the ATLAS and CMS detectors. Yet, no signs of stops have been found up to a mass of 1.3 TeV, excluding a sizeable fraction of the SUSY parameter space suggested by naturalness arguments. Further SUSY searches were performed, including those for only weakly interacting SUSY particles ("electroweakinos"), where the Run 2 data allowed the experiments to surpass the sensitivity achieved by LEP in some scenarios. Half a century since SUSY was first proposed, ATLAS and CMS have demonstrated that the simplest models containing TeV-scale sparticle masses are not realised in nature (see "Stop quarks and electroweakinos" figure, p30).

In fact, a large number of new-physics searches during LHC Run 1 and Run 2 targeted models other than SUSY, many of which also address the question of naturalness. Signs of extra spatial dimensions have been searched for in "mono-jet" events containing a single energetic jet and large MET, which could be caused by excited gravitons propagating in a higher dimensional space. Searches for vector-like quarks, as suggested by models with a composite Higgs boson, covered numerous complex final states with

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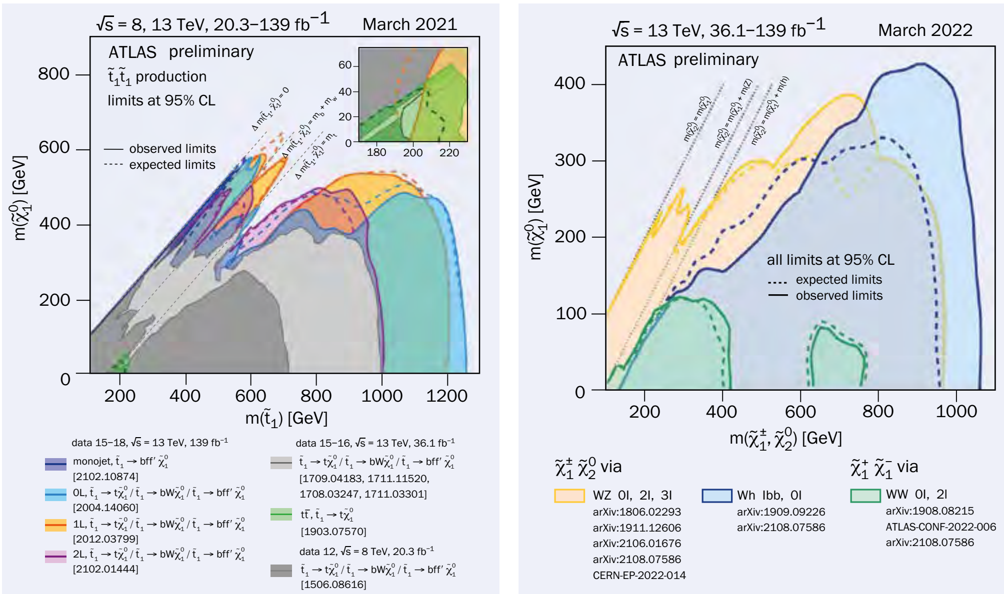


Stop quarks and electroweakinos *Mass exclusion limits on supersymmetric top-quark partners and neutralino particles determined by ATLAS from a variety of final states (left) and on supersymmetric partners of the gauge and Higgs bosons (right), showing that a large fraction of the parameter space suggested by naturalness is excluded.*

decays into all of the heavier known elementary particles. In these and other searches, the Higgs boson has entered the experimental toolkit, for example via the identification of high-momentum Higgs-boson decays reconstructed as large-radius jets.

The Higgs sector itself has been the subject of new-physics searches. These target additional Higgs bosons that would arise from an extended Higgs sector and exotic decays of the known Higgs boson, for instance into weakly interacting massive particles (WIMPs), which are candidates for dark matter. Improvements in both theoretical and data-driven background determinations have also allowed searches for Higgs-boson decays into invisible particles, with the Run 2 dataset setting an upper limit of 10% on their rate.

Searches for dark matter also continued to be performed in traditional channels, for example via the mono-jet signature. To increase the accuracy of this search using the full Run 2 statistics, theorists contributed differential background predictions that go beyond the next-to-leading order in perturbation theory to achieve an unprecedented background uncertainty of only 3% at MET values above 1 TeV. The resulting constraints on WIMP dark matter are complementary to those achieved with ultrasensitive detectors deep underground as well as astroparticle experiments. The absence of dark-matter signals in such established search channels led to the development of new models that predict a number of relevant but previously unexplored signatures.

LHC Run 3 will allow searches to go significantly beyond the sensitivity achieved with the Run 2 data

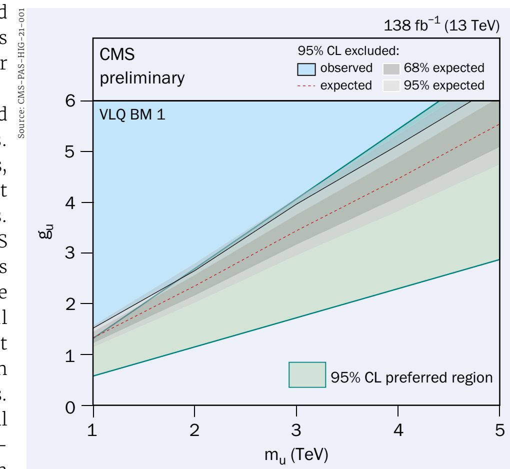
In several respects, searches for new physics at the LHC experiments have gone well beyond what was foreseen at the time of their design. "Scouting" data streams were introduced to store small-size event records suitable for di-jet and di-muon resonance searches such that recording rates could be increased by up to two orders of magnitude within the available bandwidth. Consequently, the mass reach of these searches was extended to lower values whereas previously this was impossible due to the high background rates at low masses. Long-lived particle searches also opened a new frontier, motivating proposals for new LHC detectors.

Overall, LHC Run 1 and Run 2 led to an enormous diversification of new-physics searches at the energy frontier by ATLAS and CMS, with complementary searches conducted by LHCb targeting lower invariant masses. The absence of new-physics signals despite the exploration of a multitude of signatures with unforeseen precision is a strong experimental result that feeds back to the phenomenology community to shape this programme further. While the analysis of Run 2 data is still ongoing, the experience gained so far in terms of experimental techniques and investigated signatures puts the experimental collaborations in a better position to search for new physics at Run 3.

Experimental improvements

LHC Run 3 will allow searches to go significantly beyond the sensitivity achieved with the Run 2 data. ATLAS and CMS are expected to collect datasets with an integrated luminosity of up to 300 fb^{-1}, adding to the 140 fb^{-1} collected in Run 2. Taking into account the additional, smaller benefit provided by the increase in the centre-of-mass energy from 13 to 13.6 TeV, new-physics search sensitivities will generally increase by a factor of two in terms of cross sections. Additional gains in sensitivity will result from the exploration of new territory in several respects.

Already at the level of data acquisition, significant improvements will increase the sensitivity of searches. The CMS higher level trigger system has been reinforced using graphics processing units to increase the recording rate in the data scouting stream from 9 to 30 kHz. ATLAS has extended this technique to encompass more final states,



Leptoquarks *Mass exclusions for spin-1 leptoquarks depending on the coupling strength to fermions, g_U, as determined by CMS using Run 2 events containing pairs of tau leptons. The green band indicates the 95% confidence region which fits the low-energy data. Run 3 data will increase the sensitivity to test a significant fraction of this parameter space.*

including photons and b-jets. These techniques extend the sensitivity to hadronic resonances with low masses and weak coupling strengths to a domain that has never been probed before.

The particularly challenging searches for new long-lived particles will also benefit from experimental advances. ATLAS has improved the reconstruction of displaced tracks, reducing the amount of fake tracks by a factor of 20 at similar efficiencies compared to the current data analysis. New, dedicated triggers have been developed by ATLAS and CMS to identify electrons, muons and tau-leptons displaced from the primary interaction vertex. These trigger developments will allow the collection of signal candidate events at unprecedented rates, for example to test exotic Higgs-boson decays into long-lived particles with branching ratios far below the current experimental limits.

Likewise, ongoing developments in machine learning will contribute to the Run 3 search programme. While Run 1 physics analyses used generic, simple algorithms to distinguish between hypotheses, in Run 2 more powerful approaches of deep learning were introduced. For Run 3 their development continues, using a multitude of different algorithms tailored to the needs of event reconstruction and physics analysis to increase the reach of new-physics searches further.

New signatures

The Run 3 data will also be scrutinised in view of final states that either have been proposed more recently or that require a particularly large dataset. Examples of the latter are searches for electroweakinos, which have a production cross-section at the LHC at least two orders of magnitude smaller than strongly interacting SUSY particles. First results based on Run 2 data surpassed the sensitivity of the LEP experiments, including tests of unconventional "R-parity violating" scenarios in which electroweakinos can decay into only SM particles. This results in complicated final states containing electrons, muons and many jets but relatively low MET. Here, the challenging background determination could only be achieved thanks to machine-learning techniques, which lay the ground for further searches for particularly rare and challenging SUSY signals at Run 3.

If R-parity is not a symmetry, SUSY does not provide a WIMP dark-matter candidate. Among alternative explanations of the nature of this substance, models with bound-state dark matter are gaining increasing attention. In this new approach, strong interactions similar to quantum chromodynamics determine the particle spectrum in a dark sector that includes stable dark-matter candidate particles such as dark pions. At the LHC, coupling between such dark-sector particles and known ones would result in "semi-visible" jets comprising both types of particle (traditional dark-matter searches at the LHC have avoided such events to reduce background contributions). With the Run 2 data, CMS has already provided the very first collider constraints on these dark sectors, and more results from both ATLAS and CMS will follow in this and other proposed dark-sector scenarios.

Multiple deviations from the SM observed at lower energies are starting to shape the search programme at the energy frontier. The long-standing anomaly in the magnetic moment of the muon has recently reached a significance of 4.2σ, motivating increased efforts in searching for possible causes. One is the pair-production of a supersymmetric partner of the muon, for which models fit the low-energy data if the mass of this "smuon" is below 1 TeV and hence within the reach of the LHC. Another is to look for vector-like leptons, which are suggested by consistent extensions of the SM apart from SUSY, using final states containing a large number of leptons.

Moreover, the anomalies in B-meson decays consistently reported by BaBar, Belle and LHCb (see p43) have a strong and growing impact on the Run 3 search programme. Explanations for these anomalies require new particles with TeV-scale masses to fit the size of the observed effects and a hierarchy of fermion couplings to fit the deviations from lepton-flavour universality. Intriguingly these two requirements happen to coincide with the two peculiarities of the Higgs boson. Particular attention is now given to leptoquark searches investigating several production and decay modes. ATLAS and CMS have already started to probe leptoquark models suggested by the B-meson anomalies using Run 2 data (see "Leptoquarks" figure). While the analysis of key channels is ongoing, Run 3 will allow the experiments to probe a large fraction of the relevant parameter space. Furthermore, consistent models of leptoquarks include more new particles, namely colour-charged and colour-neutral bosons, vector-like quarks and vector-like leptons. These predict a variety of new-physics signatures that will further shape the Run 3 search programme.

Multiple deviations from the SM observed at lower energies are starting to shape the search programme at the energy frontier

In summary, searches for new physics at Run 3 will bring significant gains in sensitivity beyond the benefit provided by the increased amount of data. In particular, potential explanations of the anomalies observed at lower energies will be tested. Assuming that these anomalies point to new physics, the relevant searches with Run 3 data have a good chance of finding the first deviations from the SM at the TeV energy scale. Such an outcome would be of the utmost importance for particle physics, strengthening the case for the proposed Future Circular Collider at CERN. ●

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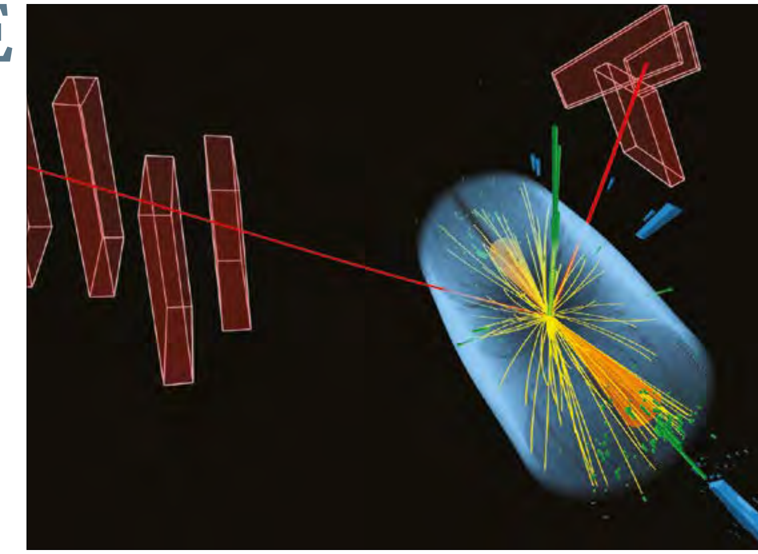
PUSHING THE PRECISION FRONTIER

Abideh Jafari describes how larger datasets, upgraded detectors and novel analysis methods will allow the Standard Model to be scrutinised at unprecedented levels of precision during Run 3.



Critical physics *A candidate vector-boson-scattering event at CMS, in which vector bosons emitted from each of the incoming quarks interact with one other. Credit: CMS*

Confronted with multiple questions about how nature works at the smallest scales, we exploit precise measurements of the Standard Model (SM) to seek possible answers. Those answers could further confirm the SM or give hints of new phenomena. As a hadron collider, the LHC was primarily built as a discovery machine. After more than a decade of operation, however, it has surpassed expectations. Alongside the discovery of the Higgs boson and a broad programme of direct searches for new phenomena (see p29), ultra-precise measurements on a wide range of parameters have been carried out. These include particle masses, the width of the Z boson and the production cross-sections of various SM processes ranging over 10 orders of magnitude (see "Cross sections" figure, p34); the latter are connected to a multitude of measurements including differential distributions and particle properties.

An example that is unique to the LHC is the measurement of the Higgs-boson mass, which was determined to a precision of 0.12% by CMS in 2019. Also of vital importance are the strengths of the Higgs-boson couplings to other known particles (see "Coupling strengths" figure, p34). According to the SM, these couplings must be proportional to a particle's mass. Nicely following the SM expectation, every coupling in this plot is extracted using various measurements of the Higgs-boson production and decay channels. Besides the remarkable agreement with the SM, the plot shows the result of the Higgs-boson decay to muons, which is challenging to measure because of the muon's small mass.

The LHC-experiment collaborations are currently concluding their Run 2 measurements using proton–collision data recorded at 13 TeV while getting ready for the Run 3 startup. From several notable achievements with the Run 2 data, one can point to the measurement of a fundamental parameter of the SM, the mass of the W boson with a precision of 0.02% by ATLAS and of 0.04% in the forward region by LHCb (see "W mass" figure, p34). Precision measurements of the W-boson mass are crucial for testing the consistency of the SM, as radiative corrections connect it with the masses of the top quark and the Higgs boson (see p9). A future combination of the LHCb result with similar measurements from ATLAS and CMS can reduce the significant uncertainty of parton distribution functions on this parameter. Although the particle masses are crucial elements of the SM, it is not always possible to determine them directly. In the case of quarks, except for the heaviest top quark, their immediate hadronisation makes the properties of a bare quark inaccessible. Observed for the first time by ALICE, the QCD "dead cone" (an angular region of suppressed gluon emissions surrounding a heavy quark that is proportional to the quark's mass) in charmed jets may be a possible way to ultimately access the heavy-quark mass directly.

The coupling structure of the SM, especially between heavy particles, is another key aspect that is being pinned down by ATLAS and CMS. In 2017 the experiments marked an important milestone in this regard with the observation of WW scattering – a first step in a diverse programme of measurements of vector boson scattering (VBS), in which vector bosons emitted from each of the incoming quarks interact with one other (see "Critical physics" image). As VBS processes are sensitive to the self-interaction of four gauge bosons as well as to the exchange of a virtual Higgs boson, they remain a central part of the LHC physics programme during Run 3 and beyond, where the additional data will become a decisive factor.

Run 3 preparations

The LHC is about to start a new endeavour at an unprecedented energy (13.6 TeV as opposed to 13 TeV) and with an instantaneous luminosity on average 1.5 times higher than in Run 2. In addition to higher statistics, the larger energy reach of Run 3 provides a unique opportunity to study unexplored territories in the kinematic phase space of particles. Prime targets are regions where the discovery

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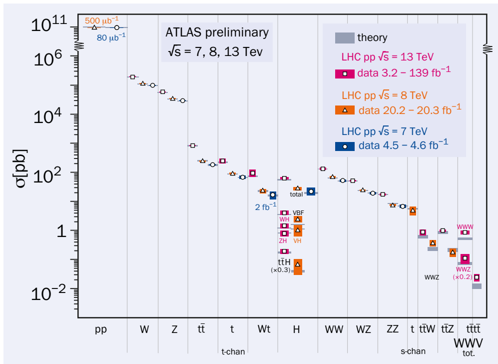
Cross sections *The production cross section of various Standard Model processes ranging over 10 orders of magnitude, as measured by one LHC experiment (ATLAS).*



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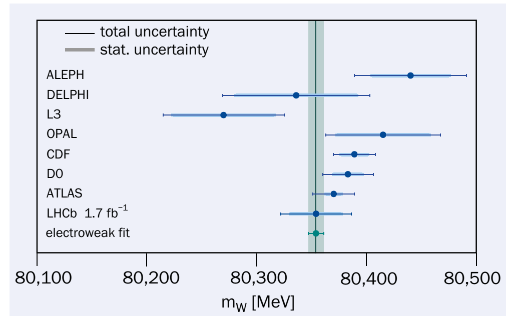
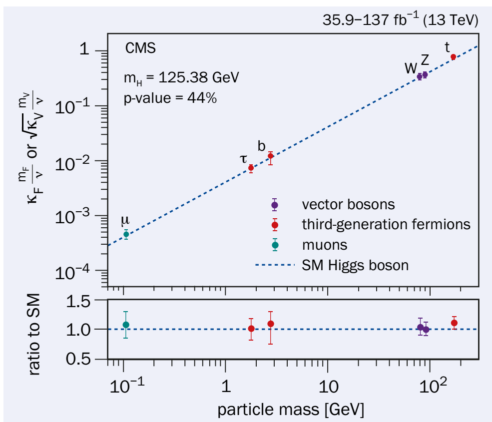


Adapted from *JHEP* **01** 036

W mass *Measurements of the mass of the W boson compared to the SM prediction, not including the latest CDF measurement (p9).*

Coupling strengths *Predicted versus measured (CMS) values of the coupling strengths between the Higgs boson and other Standard Model particles.*



Source: *JHEP* **01** 148/HIG-19-006/ATLAS-CONF-2020-027

of possible new phenomena is mainly awaiting additional data, and those where the insufficient size of the data sample is the main limiting factor on the precision.

A major challenge ahead is the increased number of additional interactions within the same or nearby bunch crossings, called pileup. The large rate of interactions puts strain on different parts of the detectors as well as their trigger systems. Relying on cutting-edge technologies, experiments at the LHC have performed extensive upgrades in several subsystems, hardware and software to cope with the associated complexities and exploit the full potential of the data. In some cases, this has involved the installation of new detectors or an entire renewal, or extension, of existing subdetectors. Examples are the New Small Wheel (NSW) muon detector in ATLAS and the muon gas electron multiplier (GEM) detectors in CMS. These gas-based detectors, which are designed in view of the High-Luminosity LHC (HL-LHC) and will be partially operational during Run 3, are installed in the endcap area of the experiments where a significant increase is expected in the particle flux (*CERN Courier* November/December 2021 p27). The improved muon momentum resolution they bring also plays a critical role in the trigger systems by keeping the rate low.

It is now proven that with advanced analysis strategies we can surpass the expectations from projection studies

In the ALICE experiment, among other important upgrades, the inner tracker system has faced a complete renewal of the silicon-based detectors for enhanced low-momentum vertexing and tracking capabilities (*CERN Courier* July/August 2021 p29). At LHCb, in addition to new front-end electronics for higher-rate triggering and readout, the ring-imaging Cherenkov detector has been upgraded to deal with the large-pileup environment (*CERN Courier* September/October 2021 p43), while a brand new vertex locator and tracking system will allow the reconstruction of charged particles (see p38). In parallel to the hardware, the LHC experiments have accomplished a substantial upgrade in software and computing, including the implementation of fast readout systems and the use of state-of-the-art graphics processing units.

Physics ahead

The series of upgrades undertaken during Long Shutdown 2 will enable the experiments to pursue a rich physics programme during Run 3 and to get ready for Run 4 at the HL-LHC. The preparation also involves Monte Carlo event generation at the new centre-of-mass energy, full simulation of collision events in the new detectors, and designing new methods with modern tools to identify particles and analyse the data. The additional data of Run 3, together with innovative analysis techniques, will result in reduced uncertainties and therefore push the precision frontier forward. The experience from Run 2 is of great value in this regard.

It is now proven that with advanced analysis strategies which make maximal use of the available data, we can surpass the expectations from projection studies. An example is the Higgs-boson decay to muons. Whereas early Run 3 projections suggested an uncertainty of about 20% with 300 fb^{-1} of LHC data, in 2020 the CMS experiment achieved such precision using Run 2 data alone (*CERN Courier* September/October 2020 p7). In the latest projections, a further improvement of 30–35% is expected thanks to the advanced analysis strategies developed during Run 2. The projected uncertainties in Higgs-boson couplings to other SM particles, including vector bosons and third-generation leptons, are also expected to be reduced. The Higgs-boson interaction with the heaviest known particle, the top quark, is of particular interest as it may give insights into the existence and energy scale of new physics above 100 GeV. Besides the famous $t\bar{t}H$ process, simultaneous production of four top quarks is also very sensitive to the top quark's Yukawa interaction with the Higgs boson. Exhibiting the heaviest SM final state, "four-top" is one of the rarest but most important processes. Following evidence reported by ATLAS in 2021, Run 3 data may fully establish its observation.

Among rare processes that may shed light on electroweak symmetry breaking, one can point to the VBS production of longitudinally polarised W bosons. The longitudinal polarisation is a result of electroweak symmetry breaking through which vector bosons acquire mass from their interaction with the Brout–Englert–Higgs field. Given that the analysis of Run 2 data has reached the expected significance (about 1σ) of the HL-LHC with the same luminosity, we look forward to Run 3 to test the SM with more data and further channels.

Run 3 excitement

The excitement about LHC Run 3 is not restricted to rare phenomena and new discoveries. Well-established processes such as top-quark, W- and Z-boson production are pivotal for a firm understanding of the SM. The upcoming data will provide us with gigantic statistics that translates to a significantly higher precision on the measured properties of these particles in addition to various fundamental parameters of the SM. The latter include the mass of the top quark, the precise determination of which is a critical factor in the stability of vacuum. Early Run 3 projection studies predicted an uncertainty of 1.5 GeV on the top-quark mass. This has already been achieved in Run 2 using $t\bar{t}$ differential cross-section measurements, and will be further reduced with the upcoming Run 3 data.

Such levels of precision also provide invaluable feedback to the theory community, whose tremendous efforts in modelling and state-of-the-art calculations and simulations are the basis of our measurements. Thanks to the increasing sophistication and precision of SM calculations, any statistically significant deviation from theory can be an unambiguous sign of new physics. Therefore, precision measurements in Run 3 can act as a gateway to new discoveries. These include measurements of properties such as vector-boson polarisation, which are sensitive to new physics by construction, inclusive cross sections of VBS and other rare processes, and differential distributions where new phenomena can appear in the tails.

In October 2021, stable proton beams were circulated and collided at a centre-of-mass energy of 900 GeV in the LHC for the first time since 2018. While preparing for the start up in May this year, the experiments made use of these data for a special period of commissioning to ensure their readiness to collect data in Run 3. The successful outcome of the commissioning brought further enthusiasm and motivation to the LHC-experiment collaborations, who very much look forward to executing their far-reaching Run 3 physics plans. ●

The upcoming data will provide us with gigantic statistics that translate to significantly higher precision

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VELO'S VOYAGE INTO THE UNKNOWN

The installation of LHCb's all-new Vertex Locator is part of a major upgrade that will extend the experiment's capabilities to search for physics beyond the Standard Model, describe Stefano de Capua, Wouter Hulsbergen and David Hutchcroft.

The first 10 years of the LHC have cemented the Standard Model (SM) as the correct theory of known fundamental particle interactions. But unexplained phenomena such as the cosmological matter–antimatter asymmetry, neutrino masses and dark matter strongly suggest the existence of new physics beyond the current direct reach of the LHC. As a dedicated heavy-flavour physics experiment, LHCb is ideally placed to allow physicists to look beyond this horizon.

Measurements of the subtle effects that new particles can have on SM processes are fully complementary to searches for the direct production of new particles in high-energy collisions (p43). As-yet unknown particles could contribute to the mixing and decay of beauty and charm hadrons, for example, leading to departures from the SM in decay rates, CP-violating asymmetries and other measurements. Rare processes for which the SM contribution occurs through loop diagrams are particularly promising for potential discoveries. Several anomalies recently reported by LHCb in such processes suggest that the cherished SM principle of lepton-flavour universality is under strain, leading to speculation that the discovery of new physics may not be far off (*CERN Courier* May/June 2021 p17).

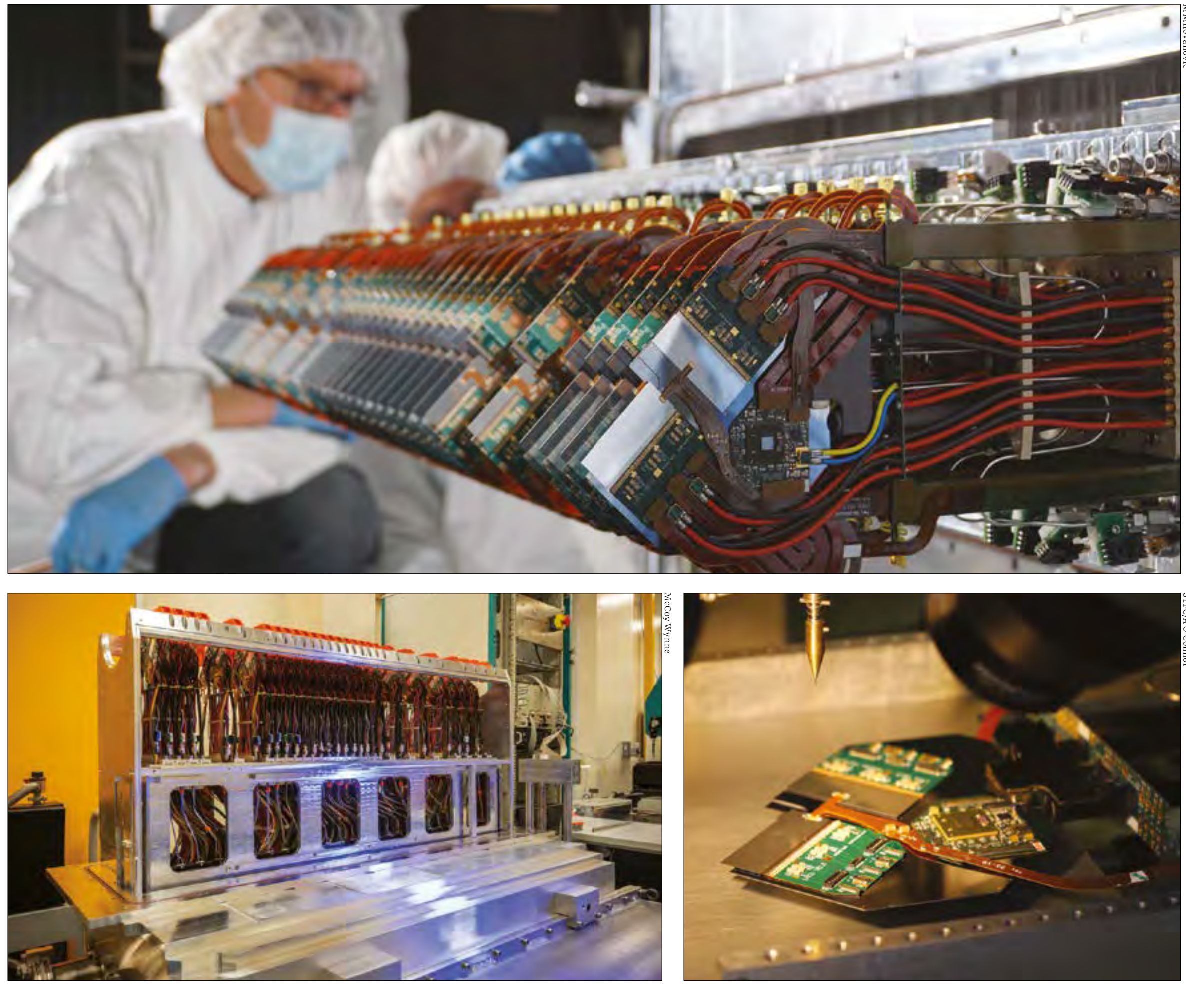
Unique precision

In addition to precise theoretical predictions, flavour-physics measurements demand vast datasets and specialised detector and data-processing technology. To this end, the LHCb collaboration is soon to start taking data with an almost entirely new detector that will allow at least 50 fb^{-1} of data to be accumulated during Run 3 and Run 4, compared to 10 fb^{-1} from Run 1 and Run 2 (*CERN Courier* January/February 2019 p34). This will enable many observables, in particular the flavour anomalies, to be measured with a precision unattainable at competing experiments.

To allow LHCb to run at an instantaneous luminosity 10 times higher than during Run 2, much of the detector system and its readout electronics have been replaced, while a flexible full-software trigger system running at 40 MHz allows the experiment to maintain or even improve trigger efficiencies despite the larger interaction rate. During Long Shutdown 2, upgraded ring-imaging Cherenkov detectors and a brand new "SciFi" (scintillating fibre) tracker have been installed (*CERN Courier* September/October 2021 p43).

THE AUTHORS

Stefano de Capua *University of Manchester,* **Wouter Hulsbergen** *Nikhef and* **David Hutchcroft** *University of Liverpool.*



Marvellous modules *Inspecting the alignment (top); a fully assembled detector half (bottom left); and wire bonding of the ASICs to the front-end hybrids (bottom right).*

A major part of LHCb's metamorphosis – in process at the time of writing – is the installation of a new Vertex Locator (VELO) at the heart of the experiment.

The VELO encircles the LHCb interaction point, where it contributes to triggering, tracking and vertexing. Its principal task is to pick out short-lived charm and beauty hadrons from the multitude of other particles produced by the colliding proton beams. Thanks to its close position to the interaction point and high granularity, the VELO can measure the decay time of B mesons with a precision of about 50 fs.

The original VELO was based on silicon-strip detectors. Its upgraded version employs silicon pixel detectors to cope with the increased occupancies at higher luminosities and to stream complete events at 40 MHz, with an expected torrent of up to 3 Tb/s flowing from the VELO at full luminosity. A total of 52 silicon pixel detector modules, each with a sensitive surface of about 25 cm^2, are mounted in two detector halves located on either side of the LHC beams and perpendicular to the beam direction (see "Marvellous modules" image). An important feature of the LHCb VELO is that it moves. During injection of LHC protons, the detectors are parked at a safe distance of 3 cm from the beams. But once stable beams are declared, the two halves are moved inward such that the detector sensors effectively enclose the beam. At that point the sensitive elements will be as close as 5.1 mm to the beams (compared to 8.2 mm previously), which is much closer than any of the other large LHC detectors and vital for the identification and reconstruction of charm- and beauty-hadron decays.

The VELO's close proximity to the interaction point requires a high radiation tolerance. This led the collaboration to opt for silicon-hybrid pixel detectors, which consist of a 200 µm-thick "p-on-n" pixel sensor bump-bonded to a 200 µm-thick readout chip with binary pixel readout. The CERN/Nikhef-designed "VeloPix" ASIC stems from the Medipix family and was specially developed for LHCb. It is capable of handling up to 900 million hits per second per chip, while withstanding the intense radiation environment. The data are routed through the vacuum via low-mass flex cables engineered by the University of Santiago de Compostela, then make the jump to atmosphere through a high-speed vacuum interface designed by Moscow State University engineers, which is connected to an optical board developed by the University of Glasgow. The data are then carried by optical fibres with the rest of the LHCb data to the event builder, trigger farm and disk buffers contained in modular containers in the LHCb experimental area.

The VELO modules were constructed at two production sites: Nikhef and the University of Manchester, where all the building blocks were delivered from the many institutes involved and assembled together over a period of about 1.5 years. After an extensive quality-assurance programme to assess the mechanical, electrical and thermal performance of each module, they were shipped in batches to the University of Liverpool to be mounted into the VELO halves. Finally, after population with modules, each half of the VELO detector was transported to CERN for installation in the LHCb experiment. The first half was installed on 2 March, and the second is being assembled.

Microchannel cooling

Keeping the VELO cool to prevent thermal runaway and minimise the effects of radiation damage was a major design challenge. The active elements in a VELO module consist of 12 front-end ASICs (VeloPix) and two control ASICs (GBTX), with a nominal power consumption of about 1.56 kW for each VELO half. The large radiation dose experienced by the silicon sensors is distributed highly non-uniformly and concentrated in the region closest to the beams, with a peak dose 60% higher than that experienced by the other LHC tracking detectors. Since the sensors are bump-bonded to the VeloPix chips, they are in direct contact with the ASICs, which are the main source of heat. The detector is also operated under vacuum, making heat removal espe-

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Microcooling *Top: a silicon wafer into which microchannels (overlaid for illustration only) are etched. Bottom: 3D X-ray tomography showing the microchannels, as well as the distribution of glue between the plate and the tiles.*

cially difficult. These challenging requirements led LHCb to adopt microchannel cooling with evaporative CO_2 as the coolant (see "Microcooling" image).

The circulation of coolant in microscopic channels embedded within a silicon wafer is an emergent technology, first implemented at CERN by the NA62 experiment. The VELO upgrade combines this with the use of bi-phase (liquid-to-gas) CO_2, as used by LHCb in previous runs, in a single innovative system. The LHCb microchannel cooling plates were produced at CERN in collaboration with the University of Oxford. The bare plates were fabricated by CEA-Leti (Grenoble, France) by atomic-bonding two silicon wafers together, one with 120 × 200 µm trenches etched into it, for an overall thickness of 500 µm. This approach allows the design of a channel pattern to ensure a very homogeneous flow directly under the heat sources. The coolant is circulated inside the channels through exit and entry slits that are etched directly into the silicon after the bonding step. The cooling is so effective that it is possible to sustain an overhang of 5 mm closest to the beam, thus reducing the amount of material before the first measured points on each track. The use of microchannels to cool electronics is being investigated both for future LHCb upgrades and several other future detectors.

Keeping the VELO cool to prevent thermal runaway and minimise the effects of radiation damage was a major design challenge

Module assembly and support

The microchannel plate serves as the core of the mechanical support for all the active components. The silicon sensors, already bump-bonded to their ASICs to form a tile, are precisely positioned with respect to the base and glued to the microchannel plate with a precision of 30 µm. The thickness of the glue layer is around 80 µm to produce low thermal gradients across the sensor. The front-end ASICs are then wire-bonded to custom-designed kapton–copper circuit boards, which are also attached to the microchannel substrate. The ASICs' placement requires a precision of about 100 µm, such that the length and shape of the 420 wire-bonds are consistent along the tile. High-voltage, ultra-high-speed data links and all electrical services are designed and attached in such a way to produce a precise and lightweight detector (a VELO module weighs only 300 g) and therefore minimise the material in the LHCb acceptance.

Every step in the assembly of a module was followed by checks to ensure that the quality met the requirements. These included: metrology to assess the placement and attachment precision of the active components; mechanical tests to verify the effects of the thermal stress induced by temperature gradients; characterisation of the current-voltage behaviour of the silicon sensors; thermal performance measurements; and electrical tests to check the response of the pixel matrix. The results were then uploaded to a database, both to keep a record of all the measurements carried out and to run tests that assign a grade for each module. This allowed for continuous cross-checks between the two assembly sites. To quantify the effectiveness of the cooling design, the change in temperature on each ASIC as a function of the power consumption was measured. The LHCb modules have demonstrated thermal-figure-of-merit values as low as 2–3 K cm^2 W^{-1}. This performance surpasses what is possible with, for example, mono-phase microchannel cooling or integrated-pipe solutions.

The delicate VELO modules are mounted onto two precision-machined bases, each housed within a hood (one for each side) that provides isolation from the atmosphere. The complex monolithic hoods were machined from one-tonne billets of aluminium to provide the vacuum tightness and the mechanical performance required. The hood and base system is also articulated to allow the detector to be retracted during injection and to be centred accurately around the collision point during stable beams. Pipes and cables for the electrical and cooling services are designed to absorb the approximately 3 cm motion of each VELO half without transferring any force to the modules, to be radiation tolerant, and to survive flexing thousands of times.

Following the completion of each detector half, performance measurements of each module were compared with those taken at the production sites. Further tests ensured there are no leaks in the high-pressure cooling system

RF boxes *Milling the solid aluminium block (left), and the completed RF foils in the closed position (right).*

or the vacuum volumes, in addition to safety checks that guarantee the long-term performance of the detector. A final set of measurements checks the alignment of the detector along the beam direction, which is extremely difficult once the VELO is installed. Before installation, the detectors are cooled close to their –30°C operating temperature and the position of the tips of the modules measured with a precision of 5 µm. Once complete, each half-tonne detector half is packed for transport into a frame designed to damp-out and monitor vibrations during its 1400 km journey by road from Liverpool to CERN.

RF boxes

One of the most intriguing technological challenges of the VELO upgrade was the design and manufacture of the RF boxes that separate the two detector halves from the primary beam vacuum, shielding the sensitive detectors from RF radiation generated by the beams and guiding the beam mirror currents to minimise wake-fields. The sides of the boxes facing the beams need to be as thin as possible to minimise the impact of particle scattering, yet at the same time they must be vacuum-tight. A further challenge was to design the structures such that they do not touch the silicon sensors even under pressure differences. Whereas the RF boxes of LHCb's previous VELO were made from 300 µm-thick hot-pressed deformed sheets of aluminium foils welded together, the more complicated layout of the new VELO required them to be machined from solid blocks of small grain-sized forged aluminium. This highly specialised procedure was developed and carried out at Nikhef using a precision five-axis milling machine (see "RF boxes" image).

In early prototypes, micro-enclosures led to small vacuum leaks when machining thin layers. A 3D forging technique, performed by block manufacturer Loire Industrie (France), reduced the porosity of the casts sufficiently to eliminate this problem. To form the very thin sides of a box, the inside of the block was milled first. It was then positioned on an aluminium mould. The 1 mm space between box and mould was filled with heated liquid wax, which forms a strong and stable bond at room temperature. The remaining material was then machined until a sturdy flange and box with a wall about 250 µm thick remained, or just over 1% of the original 325 kg block. To further minimise the thickness in the region closest to the beams, a procedure was developed at CERN to remove more material with a chemical agent, leaving a final wall with a thickness between 150 and 200 µm. The final step was the application of a Torlon coating on the inside for electrical insulation to the sensors, and a non-evaporable getter coating on the outside to improve the beam vacuum. The two boxes were installed in the vacuum tank in spring 2021, in advance of the insertion of the VELO modules.

Let collisions commence

LHCb's original VELO played a pivotal role in the experiment's flavour-physics programme. This includes the 2019 discovery of CP violation in the charm sector, numerous matter–antimatter asymmetry measurements and rare-decay searches, and the recent hints of lepton non-universality in B decays. The upgraded VELO detector – in conjunction with the new software trigger, the RICH and SciFi detectors, and other upgrades – will extend LHCb's capabilities to search for physics beyond the SM. It will remain in place for the start of High-Luminosity LHC operations in Run 4, contributing to the full exploitation of the LHC's physics potential.

Proposed 15 years ago, with a technical design report published in 2013 and full approval the following year, the VELO upgrade reflects the dedication and work of more than 150 people at 13 institutes over many years. The device is now in final construction. One half is installed and is undergoing commissioning in LHCb, while the other is being assembled, and will be delivered to CERN for installation during a dedicated machine stop during May. The assembly and installation has been made considerably more challenging by COVID-19-related travel and working restrictions, with final efforts taking place around the clock to meet the tight LHC schedule. Everyone in the LHCb collaboration is therefore looking forward to seeing the first data from the new detectors and continuing the success of the LHC's world-leading flavour-physics programme. ●

The VELO upgrade reflects the dedication and work of more than 150 people at 13 institutes over many years

Further reading

E Buchanan *et al.* 2022 arXiv:2201.12130.
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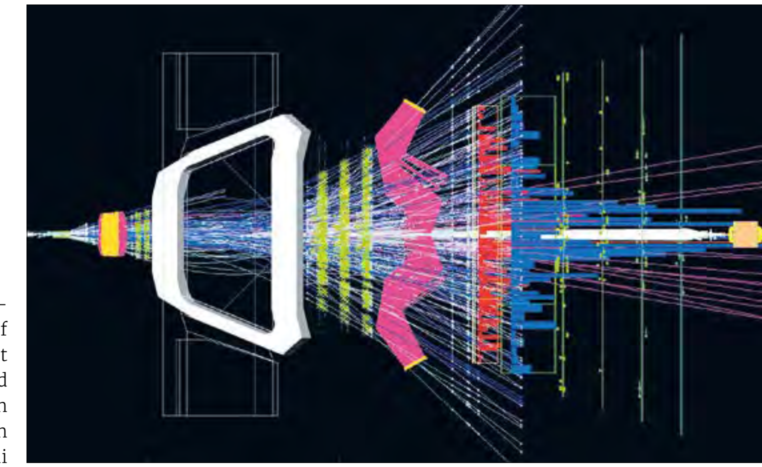
CERNCOURIER
Volume 62 Number 3 May/June 2022
IOP Publishing

A FLAVOUR OF RUN 3 PHYSICS

In addition to significant improvements on the precision of CP-violating and rare B-decay observables, Run 3 will bring the flavour anomalies into sharp focus. Basem Khanji gives the full story.



Asymmetric complexity *Particle debris from a particularly busy collision event passing through the various layers of the LHCb detector. (Credit: LHCb)*

The famous "November revolution" in particle physics in winter 1974 was sparked by the discovery of the charm quark by two independent groups at Brookhaven and SLAC. It signalled the existence of a second generation of fermions, and was therefore a milestone in establishing the Standard Model (SM). Less widely known is that, four years earlier, the Glashow–Iliopoulos–Maiani (GIM) mechanism had postulated the existence of the charm quark to explain the smallness of the $K^0 \to \mu^+\mu^-$ branching fraction. In addition, in the summer of 1974, the puzzling smallness of the mass difference between neutral kaons, which was apparent from kaon mixing, led Gaillard and Lee to conclude, correctly, that the charm mass should be below 1.5 GeV.

Many historical discoveries in particle physics have followed this pattern: a measurement in flavour physics generated a theoretical breakthrough, which in turn led to a direct discovery. The 1977 discovery of the beauty quark at Fermilab was a confirmation of the Cabibbo–Kobayashi–Maskawa (CKM) mechanism postulating the existence of three generations of fermions, which was put forward following the experimental discovery of CP violation in the kaon system in 1964. In 1987, hints of a surprisingly large value for the top-quark mass were inferred from the first measurement of B^0-meson oscillations at the Argus experiment, and confirmed in 1995 by the discovery of the top quark at the Tevatron.

This critical role of the flavour sector in particle physics is by no means accidental. Since new particles can contribute virtually via loops or box diagrams, precision measurements in flavour physics in tandem with precise theoretical predictions can provide sensitive probes to indirectly search for new particles or interactions at high energy scales. Could the historical role of flavour measurements in elucidating new-particle discoveries be about to repeat itself at the LHC?

The flavour promise

Following the Higgs-boson discovery in 2012, the next target at the LHC was clear: to search for an indisputable sign of an eagerly awaited mass peak as a signature for a new particle beyond the SM. So far, however, it seems nature might have something else in store. To unearth the new physics that is strongly motivated to exist – to explain phenomena such as the arbitrary mass hierarchy of elementary particles, the matter–antimatter imbalance in the universe and the origin of the CKM matrix – we should also consider the historically successful route though flavour physics.

Flavour processes are governed by loop diagrams such as "box" and "penguin" diagrams (see "Virtual production" figure, p44), in which new heavy particles can contribute virtually and alter our expectations. The key word here is "virtually". This peculiarity of quantum physics allows us to probe new physics at very high energy scales, even if the collision energy is not sufficient to produce new particles directly. Any significant discrepancy between flavour measurements and theoretical calculations would provide us with a valuable lead towards hidden new physics.

Cooking up a storm

On the experimental side, the main ingredient required is a large sample of beauty and charm hadrons. This makes the LHC, and the LHCb experiment in particular, the ideal place to carefully test the flavour structure of the SM. Not only does the LHC have a record energy reach, it also combines a large production cross-section for beauty and charm hadrons with a very high instantaneous luminosity. There is one catch, however. Due to the nature of quantum-chromodynamics, a large number of hadrons are produced in proton–proton collisions, saturating the different sub-detectors (see "Asymmetric complexity" image). Flavour measurements require a full understanding of this complex event environment, which is a much more challenging task compared to that at e^+e^- colliders where only a low number of particles is produced in each collision.

Since the inauguration of the LHC, its four main experiments have discovered more than 50 new hadronic states.

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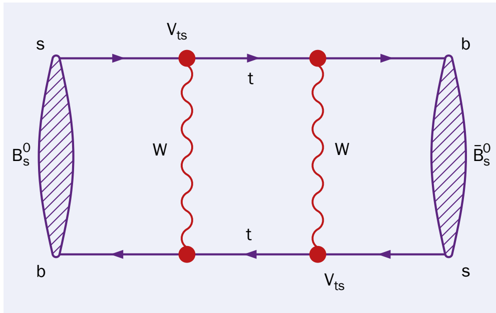
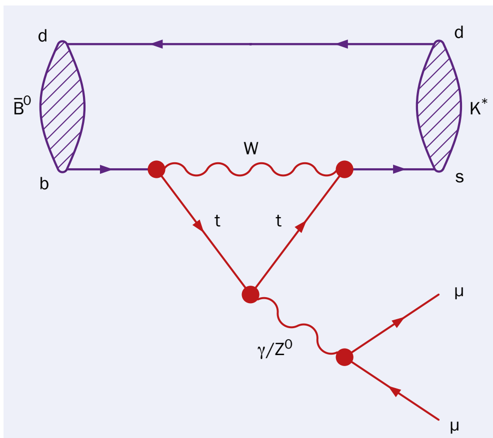




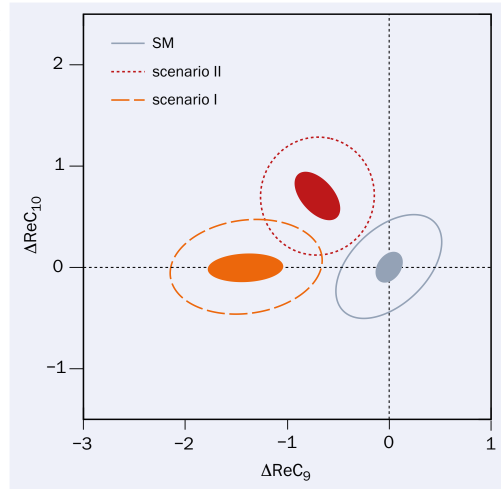
Virtual production *A box diagram responsible for $B_s^0-\bar{B}_s^0$ mixing (top), and a penguin diagram facilitating a $b\to s\ell\ell$ flavour transition in a neutral B-meson decay (bottom).*

Most follow the expected pattern of the original quark model, whereas some are new forms of matter such as the doubly-heavy "tetraquark" T_{cc}^+ or bound states of five quarks, the so-called pentaquarks, discovered by LHCb. Since the early planning of the LHC, the mission of the flavour community was to better understand the behaviour of beauty and charm quarks. Indeed, in 2019 LHCb was the first single experiment to observe the mixing and CP violation of neutral charm mesons. Similarly for beauty decays, the first observation of time-integrated and time-dependent CP-violating B_s decays was made at the LHC. The unique properties and structure of the CKM matrix connect seemingly unrelated flavour observables, most of which are accessible through B decays. Accurate flavour measurements thus simultaneously allow the CKM matrix to be probed, and precise theory predictions to be scrutinised.

Unturned stones

Today, the LHC dominates the flavour sector, with an important parallel programme ongoing at Belle II in Japan. Between them, the LHC experiments have made the most precise measurement of matter–antimatter oscillations in the neutral B system, measured CP violation in B mesons, discovered rare B decays and determined CKM elements such as V_{tb}. So far no measurement has yielded a significant disagreement with SM expectations. However, some interesting hints have emerged, and a couple of stones have not yet been turned.

Since the inauguration of the LHC, its four main experiments have discovered more than 50 new hadronic states



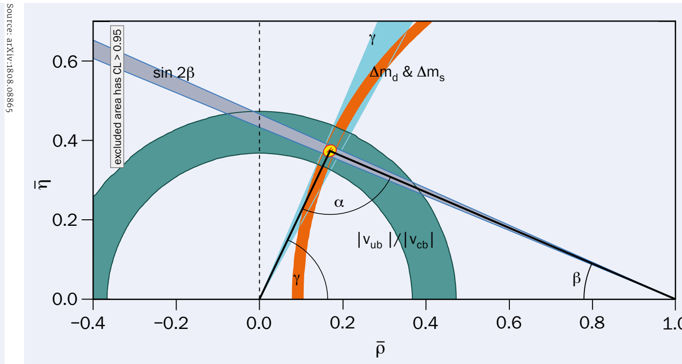
New couplings *Constraints on the C_9 and C_{10} effective-field-theory coefficients relevant to the flavour anomalies. 3σ regions from Run 3 data are shown for a vector–axial–vector (red dotted) and a purely vector new-physics contribution (orange dashed), compared to the no-new-physics case (grey). Solid ellipses denote HL-LHC constraints.*

A promising opportunity to probe physics beyond the SM arises through $b\to s\ell\ell$ and $b\to c\ell\nu$ transitions in various hadron decays. The latter proceed through tree-level transitions in processes that are abundant and well-understood: the decay is mediated by a charged W boson that changes the b quark into a c quark, emitting a lepton and an antineutrino. In $b\to s\ell\ell$ processes, the quark flavour changes through the emission of a Z boson or a photon. This flavour-changing neutral-current process occurs through a higher order penguin diagram, and underlies a breed of suppressed and thus rare hadron decays. The SM makes a slew of precise predictions for flavour observables for both types of transitions. However, new-physics models include yet-unobserved particles that can potentially contribute virtually.

A number of flavour observables are particularly well predicted within the SM. Well-known examples are the lepton-flavour-universality observables R(K), which compare the decay rates of $b\to s\ell\ell$ decays containing muons to those containing electrons, and R(D), which compares $b\to c\ell\nu$ decay rates with muons and tau leptons in the final state. The theoretical precision for these ratios reach an impressive relative uncertainty of about 1%. But other measurable flavour quantities in these two transitions, such as absolute decay rates or angular observables, are more challenging due to the limited knowledge of gluon exchange between hadrons in the initial and final states.

Intriguingly, all $b\to s\ell\ell$ flavour observables measured by the b-factories LHCb, Belle and BaBar, and also ATLAS and CMS, collectively, point in a similar direction away from SM predictions. This has led to speculation that new heavy particles are changing the rate of B-meson decays to different lepton flavours, violating the SM principle

Anomaly squeeze *The precision expected on the ratios of B-meson decays involving $b\to s\ell\ell$ transitions R(K) and $b\to c\ell\nu$ processes $R(D^*)$, and on the branching ratio of $B^0\to\mu^+\mu^-$, with data from Run 3 and the HL-LHC.*



Triangulating *The CKM unitarity triangle, showing the expected precision with which SM consistency can be probed at Run 3. The consistency between the CP violation observable β and $|V_{ub}|$, and between the CP violation observable γ and B_s^0 mixing frequency Δm_s, will be scrutinised to high accuracy.*

of lepton-flavour universality. The contributions of such particles are quantified "effectively" – similar to the way Fermi described weak decays in terms of a single coupling constant instead of the underlying W-boson propagator. New particles that contribute to B decays can affect many different types of couplings, depending on their spin or handedness. Remarkably, the current flavour anomalies seem to affect only one or two effective couplings (left-handed vector and axial couplings, known as C_9 and C_{10}), and these can be visualised in a single two-dimensional plane of new-physics contributions (see "New couplings" figure). Data from $b\to c\ell\nu$ transitions also exhibit hints for anomalous lepton-flavour non-universality.

The picture that seems to be emerging could be explained by models that involve leptoquarks or Z′ bosons (*CERN Courier* May/June 2019 p33). The flavour anomalies measured at the LHC disagree with the SM at the level of 2–3.5σ, which is insufficient to confirm the presence of new physics. To address these and other unanswered questions in the flavour sector, the available data sample need to be expanded.

Luminous future

The LHCb experiment will operate at Run 3 at an increased instantaneous luminosity, and with an improved data acquisition system. Together, this will enable a 10-fold increase of the sample size. The price to pay for this increased luminosity is the daunting number of overlapping collisions in a single proton-bunch crossing, which makes the task of sifting through billions of collisions to identify interesting topologies a challenge. Novel technologies such as graphics processing units have been incorporated in LHCb's trigger system to speed up the processing of busy hadronic events, while new detectors have been built to reconstruct charged particle tracks, find the vertex position and to identify the particle species using state-of-the-art readout electronics (see p38). The LHCb upgrades completed during LS2 will also serve the experiment for Run 4 beginning in 2029, which is the start of the ambitious High-Luminosity LHC (HL-LHC) project.

During the next few years of Run 3, the LHCb experiment is expected to collect an integrated luminosity of 20–25 fb^{-1} (compared to 6 fb^{-1} in Run 2). This will enable significant improvements on the precision of CP-violation observables and rare B-decay measurements. The expectation is to improve the precision on possible CP violation in $B_s^0-\bar{B}_s^0$ mixing to 10^{-3}, on CP violation in the interference between mixing and decay in $B_s\to J/\psi\varphi$ decays to about 14 mrad, and on the CKM angle γ to 1.5°. Further probes of possible lepton-flavour non-universality are another key target. The ratios of electroweak penguin processes involving $b\to s\ell\ell$ transitions, R(K) and $R(K^*)$, are expected to be determined with a precision between three to two per cent, and ratios of semileptonic $b\to c\ell\nu$ processes $R(D^*)$ to a precision below one per cent (see "Anomaly squeeze" figure).

The flavour programme in the era of the HL-LHC is even more rich and diverse. Many directions are being pursued, including precision measurements targeting CP violation and mixing in charm and beauty, and measurements of the CP-conserving quantities such as the magnitudes of the CKM elements V_{ub}, V_{cb} and V_{tb}. The end goal is to study every possible constraint to scrutinise the overall CKM picture within the SM (see "Triangulating" figure). Regarding the anomalous $b\to s\ell\ell$ and $b\to c\ell\nu$ transitions, the long-term projections for the LHC experiments are clear: if new phenomena are found, then their detailed characteristics will be established. The large data sample at the end of the HL-LHC will also allow tests of lepton-flavour violation in $b\to s\ell\ell$ transitions involving tau leptons. The power of such indirect searches is their ability to elucidate the energy scale at which new particles might be present, and could point the way for the next generation of colliders.

The flavour sector delivered a great harvest in the first 10 years of LHC operations: new particles and new forms of matter were discovered, new behaviour of matter was established, stringent constraints on the CKM matrix were set and intriguing flavour anomalies have appeared. That success is only the beginning. The higher luminosity phase of the LHC beginning with Run 3 will undoubtedly generate further knowledge of particle physics, and might unveil deeper layers of nature beyond the SM. ●

The flavour sector delivered a great harvest in the first 10 years of LHC operations

CERNCOURIER

VOLUME 62 NUMBER 3 MAY/JUNE 2022

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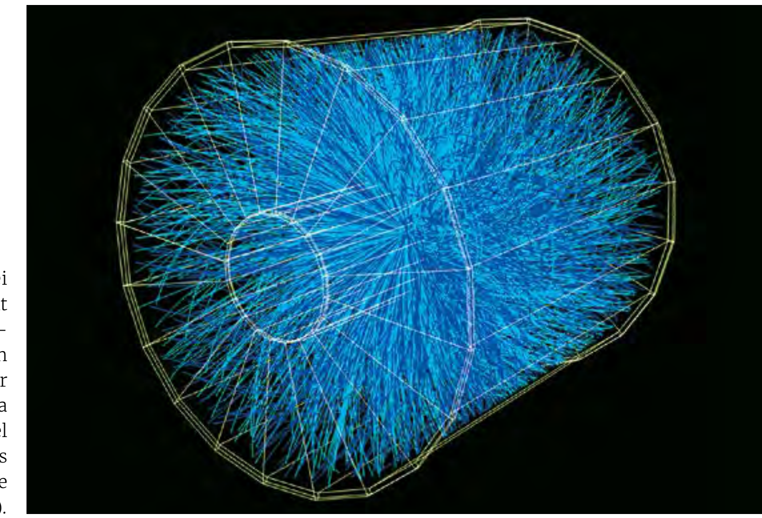
HEAVY-ION PHYSICS: PAST, PRESENT AND FUTURE

Run 3 will take physicists closer to a unified description of QCD phenomenology, from the microscopic level to the emergent bulk properties of the quark–gluon plasma. Alice Ohlson explains.



Hot and dense *Tracks from a lead–lead collision recorded by the ALICE TPC. (Credit: ALICE)*

Ultra-relativistic collisions between heavy nuclei probe the high-temperature and high-density limit of the phase diagram of nuclear matter. These collisions create a new state of matter, known as the quark–gluon plasma (QGP), in which quarks and gluons are no longer confined in hadrons but instead behave quasi-freely over a relatively large volume. By creating and studying this novel state of matter, which last existed in the microseconds after the Big Bang, we gain a deeper understanding of the strong nuclear force and quantum chromodynamics (QCD).

Nearly 50 years ago, the first relativistic heavy-ion collision experiments were performed at the Bevatron at Berkeley, reaching energies of 1 to 2 GeV. Since then, heavier ions were collided at higher energies at Brookhaven's AGS, CERN's SPS and Brookhaven's RHIC facilities. Since 2010, heavy-ion physics has entered the TeV regime with lead–lead (PbPb) collisions at 2.76 and 5.02 TeV at the LHC. While the ALICE detector is designed specifically to focus on such collisions, all four large LHC experiments have active heavy-ion physics programmes and are contributing to our understanding of extreme QCD matter.

In a heavy-ion collision, the initial energy deposited by the colliding nuclei undergoes a fast equilibration, within roughly 10^{-24} s, to form the QGP. The resulting deconfined and thermalised medium expands and cools over the next few 10^{-24} s, before the quarks and gluons recombine to form a hadron gas. It is the goal of heavy-ion experiments at the LHC to use the detected final-state hadrons to reconstruct the properties and dynamical behaviour of the system throughout its evolution. So far, the LHC experiments have delivered a series of results that are sensitive to various aspects of the heavy-ion collision system, with Run 3 set to push our understanding much further.

Properties and dynamics

The initial energy-density distribution and subsequent expansion of the heavy-ion collision system is largely determined by the geometrical overlap of the colliding nuclei. Collisions can range from head-on "central" collisions, where the nuclear overlap is large, to glancing "peripheral" collisions where the overlap region is smaller and roughly almond-shaped. Since the interaction region in non-central events is not rotationally symmetric, anisotropic pressure gradients build up. These preferentially boost particles along the minor axis of the ellipsoidal overlap region, resulting in an observable anisotropy in the distribution of final-state hadrons. The distribution of the particles in the azimuthal angle can be described well by a Fourier cosine series, where the largest term is the second harmonic, characterised by the parameter v_2, due to the ellipsoidal shape of the nuclear overlap region. Fluctuations in the positions of the individual constituent nucleons lead to significant higher-order terms. It was discovered that these Fourier coefficients, v_n, are best described by models where the QGP dynamics obeys hydrodynamic equations, and thus behaves as a liquid exhibiting what we call "collective flow".

Remarkably, in order to fit hydrodynamic models to experimental data it is necessary for the medium's viscosity to be very low, corresponding to a shear-viscosity to entropy-density ratio of the order $\eta/s \sim 0.1$. With a shear viscosity that is orders of magnitude smaller than other materials, the QGP is known as the "perfect" liquid. Measurements of the higher order harmonics, as well as their event-by-event fluctuations and correlations, provide even greater sensitivity to medium properties and the initial-state dynamics. Precision measurements of the v_n harmonics, charged-particle density, mean transverse momentum p_T, and mean-p_T fluctuations by ALICE have been used to extract the shear and bulk viscosity of the system as a function of temperature (see "Flow coefficients" figure).

While the QGP created in heavy-ion collisions is too small

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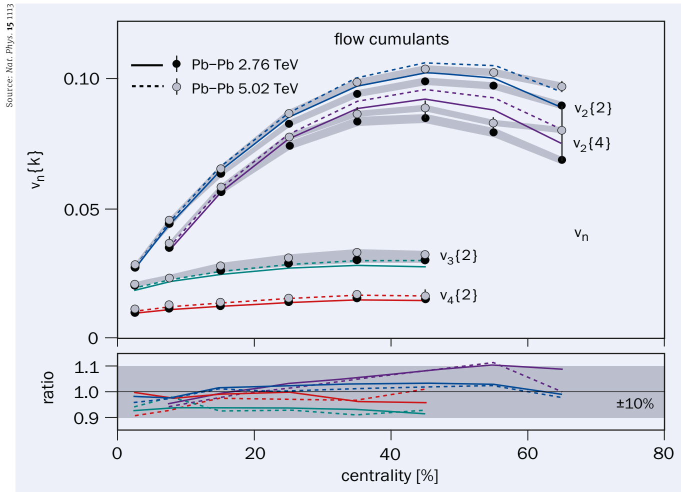
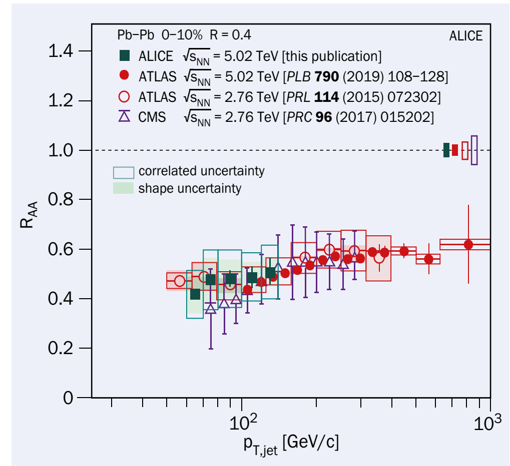


Flow coefficients *A global Bayesian fit to ALICE measurements of the centrality dependence of the flow coefficients v_2, v_3 and v_4 is used to extract the viscosity of the QGP system.*



Jet quenching *Suppression of the number of reconstructed jets with respect to the expected yields from an equivalent number of independent pp collisions, R_{AA}, for which ALICE, ATLAS and CMS provide complementary measurements.*

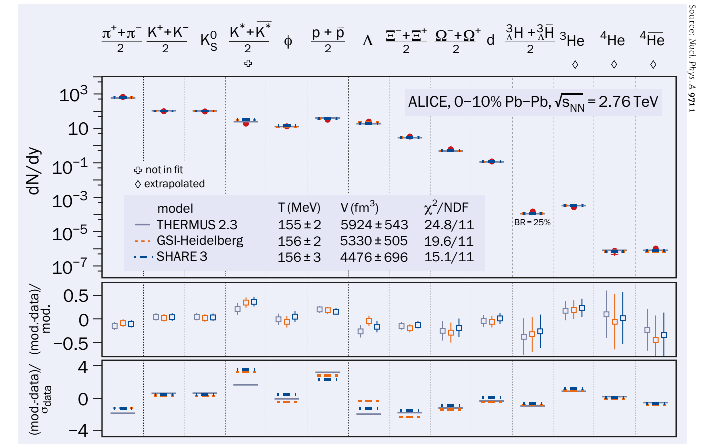
and short-lived to be examined with conventional probes, its properties can be investigated using the products of hard (high momentum-transfer, q^2) scatterings that occur in the early stages of the collision and then propagate through the medium as it evolves. The production rates of these internally generated hard probes can be calculated in perturbative QCD and thus are considered calibrated probes of the QGP medium. The high-momentum quarks and gluons produced in these hard scatterings traverse the medium and fragment into collimated jets of hadrons. While these jets appear as a small signal on top of a large, fluctuating background, advances in re-clustering algorithms as well as the higher production rates of jets at the LHC have made it possible to study jets with high precision across a wide range of energies.

Compared to jets in proton–proton (pp) collisions, jets in nucleus–nucleus (AA) collisions appear significantly suppressed or "quenched" due to their interactions with the medium (see "Jet quenching" figure). This is in contrast to electroweak probes, which interact only minimally with the coloured QGP medium. When the presence of hard scattering is identified by a high-p_T jet, photon or Z boson, the recoiling jet measured in the opposite direction is often reconstructed with a significantly lower energy, indicating that some of its energy has been transferred and absorbed by the medium. Recent, detailed jet-structure studies show that jets in heavy-ion collisions are softer (they fragment into lower-p_T hadrons) and broader than their counterparts in pp collisions, due to their interactions with the surrounding coloured QGP medium.

Another class of hard probes are heavy-flavour hadrons, since even heavy quarks (charm and beauty) with low p_T are produced in high-q^2 processes. Similar to jets, which mainly come from the fragmentation of light quarks and gluons, heavy hadrons are also suppressed in heavy-ion collisions relative to pp collisions. Recent precision measurements at the LHC of the yield of D mesons (containing charm quarks) as well as non-prompt D and J/ψ mesons (from the decays of hadrons containing beauty quarks), compared to the yields in pp collisions, demonstrate a mass-dependent suppression. This observation is consistent with the "dead cone" effect, which predicts that quarks with larger masses will be less significantly suppressed than those with smaller masses. The suppression of quarkonia (quark–antiquark bound states) depends on the binding energy, with loosely bound states such as the ϒ(3S) and ψ(2S) more likely to become dissociated in the hot and dense medium than the tightly bound ϒ(1S) and J/ψ(1S) states. However, it was discovered at the LHC that final-state J/ψ are actually less suppressed than in lower energy AA collisions at RHIC. This was attributed to the larger number of charm quarks being produced at LHC energies, which enhances the probability that charm and anti-charm quarks can recombine to form J/ψ states within the QGP. These dual effects of suppression and recombination are considered a signature of the production of a deconfined, thermalised medium in heavy-ion collisions.

Freeze out

As the QGP expands and cools, it undergoes a phase transition into a hadron gas in which quarks and gluons become confined into hadrons. At chemical freeze-out, inelastic collisions cease and the thermochemical properties of the system become fixed. Comparing ALICE measurements of the inclusive yields of multiple hadron species with a model of statistical hadronisation shows excellent agreement over nine orders of magnitude in mass, from pions to anti-^{4}He nuclei (see "Statistical production" figure). This indicates that the bulk chemistry of the QGP freeze-out can be described by purely statistical particle production from a system in thermal equilibrium with a common temperature (155 MeV) and volume (~5000 fm^3).



Statistical production *Thermal-model fits to the p_T-integrated yields of many hadron species measured in ALICE show excellent agreement with data.*

One of the first surprising results to come from the LHC was the discovery of azimuthal correlations between particles over large distances in pseudorapidity in small collision systems, pp and pPb. These long-range correlations are observed in heavy-ion collisions, where they are traditionally attributed to anisotropic flow (parameterised by v_n coefficients). However, the presence of collective behaviour in small systems, where a QGP was not expected to be formed, raised many questions about our understanding of both large and small nuclear collisions.

A second surprising observation was made in the measurement of the ratios of strange and multistrange hadrons (e.g. K^0_S, Λ, Ξ and Ω) with respect to pions, as a function of the number of particles produced in the collision (multiplicity). The enhancement of strangeness production in AA compared to pp collisions was historically predicted as a signature of the formation of a QGP, although it is now understood as being due to the suppression of strangeness in small systems. However, measurements by ALICE showed a smooth increase in the strangeness enhancement with multiplicity across all collision systems: pp, pPb, XeXe and PbPb – opening further questions about the presence of a thermalised medium in both small and large systems.

In contrast, the suppression of hard probes, which has long been viewed as a complementary effect to anisotropic flow, has not been observed in pp or pPb collisions within current experimental uncertainties. In order to gain a more complete understanding of QCD from the soft to the hard scales, and from small to large systems, we must expand our experimental programmes.

To Run 3 and beyond

All four large experiments at the LHC have undergone significant upgrades during Long Shutdown 2 to extend their reach and allow the collection of heavy-ion data at higher luminosities. The increase in luminosity by a factor of 10 in Runs 3 and 4 at the LHC will allow us to make precision measurements of soft and hard probes of the QGP. Rare probes such as heavy-flavour hadrons will become accessible with high statistical precision, and we will be able to explore the charm and beauty sector at a level commensurate with that of the strangeness studies in Runs 1 and 2. Jet measurements will become significantly more precise as we further explore the medium-induced modification of well-calibrated probes such as γ- and Z-tagged jets.

Our understanding of collective behaviour and the medium evolution will be enhanced by studies of the correlations and fluctuations of flow coefficients, which provide additional and complementary information above and beyond what we learn from v_n alone. Measurements that were severely statistically-limited in Runs 1 and 2, such as those of virtual photons produced as thermal radiation, will be performed with unprecedented precision in Runs 3 and 4. The higher order fluctuations of identified particles, which are expected to be sensitive to critical behaviour around the phase transition, will also come within reach in Runs 3 and 4 and make it possible to map out the phase diagram of QCD matter in great detail.

Furthermore, studies of small systems will continue to shed light on the development of QGP-like signals from pp to AA collisions. In particular, oxygen nuclei will be collided at the LHC, which will allow us to investigate collective effects in collisions with a geometry similar to PbPb collisions but with multiplicities of the order of those in pp and pPb collisions. High-precision and multi-differential jet measurements in pp, pPb and OO collisions will finally allow us to resolve open questions about the relationship between jet quenching and collective behaviour, and whether such effects are observed across all nuclear collision systems. Through these experimental measurements, we will make major progress in our understanding of nuclear matter from small to large collision systems, towards our ultimate goal of a unified description of QCD phenomenology from the microscopic level to the emergent bulk properties of the QGP.

While the heavy-ion physics programme in Runs 3 and 4 will provide deep insights into the rich field of QCD phenomenology, open questions will remain that can only be addressed with further advancements in detector performance and with the significant increase in heavy-ion luminosity anticipated in Run 5 (expected in 2035–2038). This extension of the LHC heavy-ion programme through the 2030s has been supported by the 2020 update of the European strategy for particle physics, and the LHC-experiment collaborations are exploring the potential for novel measurements in light- and heavy-ion collision systems based on their planned detector upgrades. In particular, ALICE is proposing to build a new dedicated heavy-ion experiment, ALICE 3, based on a large-acceptance ultra-light (low material budget) silicon tracking system surrounded by multiple layers of particle identification technology (*CERN Courier* March/April 2022 p24). The increase in the LHC luminosity coupled with state-of-the-art detector upgrades will allow us to dramatically extend our experimental reach and perform measurements that were previously inaccessible. The goals of the future heavy-ion programme at the LHC – from measuring electromagnetic radiation from the QGP and exotic heavy-flavour hadrons to beyond-the-Standard-Model searches for axions – will provide unprecedented insight into the fundamental constituents and forces of nature. ●

The increase in the LHC luminosity will allow us to perform measurements that were previously inaccessible

North Area *The EHN1 experimental hall in the North Area, showing the Morpurgo magnet (left) and the NA61 experiment (right).*

SCIENCE DIVERSITY AT THE INTENSITY AND PRECISION FRONTIERS

The North and East experimental areas of CERN enable a wide range of measurements, from precision tests of the Standard Model to detector R&D. Kristiane Bernhard-Novotny takes a tour of their upcoming programmes.

While all eyes focus on the LHC restart, a diverse landscape of fixed-target experiments at CERN have already begun data-taking. Driven by beams from smaller accelerators in the LHC chain, they span a large range of research programmes at the precision and intensity frontiers, complementary to the LHC experiments. Several new experiments join existing ones in the new run period, in addition to a suite of test-beam and R&D facilities.

At the North Area, which is served by proton and ion beams from the Super Proton Synchrotron (SPS), new physics programmes have been underway since the return of beams last year. Experiments in the North Area, which celebrated its 40th anniversary in 2019 (*CERN Courier* March/April 2019 p19), are located at different secondary beamlines and span QCD, electroweak physics and QED, as well as dark-matter searches. "During Long Shutdown 2, a major overhaul of the North Area started and will continue during the next 10 years to provide the best possible beam and infrastructure for our users," says Yacine Kadi, leader of the North Area consolidation project. "The most critical part of the project is to prepare for the future physics programme."

The first phase of the AMBER facility at the M2 beamline is an evolution of COMPASS, which has operated since 2002 and focuses on the study of the gluon contribution to the nucleon spin structure. By measuring the proton charge radius via muon–proton elastic scattering, AMBER aims to clarify the long-standing proton–radius puzzle, offering a complementary approach to previous electron–proton scattering and spectroscopy measurements. A new data-acquisition system will enable the collaboration to measure the antiproton production cross-section to improve the sensitivity of searches for cosmic antiparticles from possible dark-matter annihilation. A third AMBER programme will concentrate on measurements of the kaon,

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CERNCOURIER
VOLUME 62 NUMBER 3 MAY/JUNE 2022
IOP Publishing
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East Area *The newly renovated East Area hosts the CLOUD experiment (cylinder on the left), and the CHARM irradiation facility (concrete block on the right).*

pion and proton charge radii via Drell-Yan processes using heavy targets.

A second North Area experiment specialising in hadron physics is NA61/SHINE, which underwent a major overhaul during Long Shutdown 2 (LS2), including the re-use of the vertex detector from the ALICE experiment. Building on its predecessor NA49, the 17 m-long NA61/SHINE facility, situated at the H2 beamline, focuses on three main areas: strong interactions, cosmic rays and cross-section measurements for neutrino physics. The collaboration continues its study of the energy dependence of hadron production in heavy-ion collisions, in which NA49 found irregularities. It also aims to observe the critical point at which the phase transition from a quark–gluon plasma to a hadron gas takes place, the threshold energy for which is only measurable at the SPS rather than at the higher energy LHC or RHIC experiments. By measuring hadron production from pion-carbon interactions, meanwhile, the team will study the properties of high-energy cosmic rays from cascades of charged particles. Finally, using kaons and pions produced from a target replicating that of the T2K experiment in Japan, NA61/SHINE will help to determine the neutrino flux composition at the future DUNE and Hyper-Kamiokande experiments for precise measurements of neutrino mixing angles and the CP-violating phase.

New physics

Situated at the same H2 beamline, the new NA65 "DsTau" experiment will study the production of D_s mesons. This is important because D_s decays are the main source of ν_τ's in a neutrino beam, and are therefore relevant for neutrino-oscillation studies. After a successful pilot run in 2018, a measurement campaign began in 2021 to determine the ν_τ-production flux.

At the K12 secondary beamline, NA62 continues its measurement of the ultra-rare charged kaon decay to a charged pion, a neutrino and an antineutrino, which is very sensitive to possible physics beyond the Standard Model. The collaboration aims to increase its sensitivity to a level (10%) approaching theoretical uncertainties, thanks to further data and experimental improvements to the more than 200 m-long facility. One is the installation during LS2 of a muon veto hodoscope that helps to determine whether a muon is coming from a kaon decay or from other interactions. Since 2021, NA62 also operates as a beam-dump experiment, where its primary focus is to search for feebly-interacting particles. Here, the ability to determine whether muons come from the target absorber is even more important since they make up most of the background.

Dark interactions

Searching for new physics is the focus of NA64 at the H4 beamline, which studies the interaction between an electron beam and an active target to look for a hypothetical dark-photon mediator connecting the SM with a possible dark sector. With at least five times more data expected this year, and up to 10 times more data during the period of LHC Run 3, it could be possible to determine whether the dark mediator, should it exist, is either an elastic scalar or a Majorana particle. Adding further impetus to this programme is an unexpected 17 MeV peak reported in e^+e^- internal pair production by the ATOMKI experiment and, more significantly, the tension between the measured and predicted values of the anomalous magnetic moment of the muon $(g-2)_\mu$, for which possible explanations include models that invoke a dark mediator. During a planned muon run at the M2 beamline, the collaboration aims to cover the relevant parameter space for the $(g-2)_\mu$ anomaly.

NA63 also receives electrons from the H4 beamline and uses a high-energy electron beam to study the behaviour of scattered electrons in a strong electromagnetic field. In particular, the experiment tests QED at higher orders, which have a gravitational analogue in extreme astroparticle physics phenomena such as black-hole inspirals and magnetars. The NA63 team will continue its measurements in June.

Besides driving the broad North Area physics programme, the SPS serves protons to AWAKE – a proof-of-principle experiment investigating the use of plasma wakefields driven by a proton bunch to accelerate charged particles. Following successful results from its first run, the collaboration aims to further develop methods to modulate the proton bunches to demonstrate scalable plasma-wakefield technology, and to prepare for the installation of a second plasma cell and an electron-beam system using the whole CNGS tunnel at the beginning of LS3 in 2026.

Located on the main CERN site, receiving beams from the Proton Synchrotron (PS), the East Area underwent a complete refurbishment during LS2, leading to a 90% reduction in its energy consumption. Its main experiment is CLOUD, which simulates the impact of particulates on cloud formation. This year, the collaboration will test a new detector component called FLOTUS, a 70 litre quartz chamber extending the simulation from a period of minutes to a maximum of 10 days. The PS also feeds the n_TOF facility, which last year marked 20 years of service to neutron science and its applications (*CERN Courier* March/April 2022 p25). A new third-generation

Antimatter galore at ELENA

Served directly by the Antiproton Decelerator (AD) for the past two decades, experiments at the CERN Antimatter Factory are now connected to the new ELENA ring, which decelerates 5.3 MeV antiprotons from the AD to 100 keV to allow a 100-fold increase in the number of trapped antiprotons. Six experiments involving around 350 researchers use ELENA's antiprotons for a range of unique measurements, from precise tests of CPT invariance to novel studies of antimatter's gravitational interactions.

The ALPHA experiment focuses on antihydrogen-spectroscopy measurements, recently reaching an accuracy of two parts per trillion in the transition from the ground state to the first excited state. By clocking the free-fall of antiatoms released from a trap, it is also planning to measure the gravitational mass of antihydrogen. ALPHA's recent demonstration of laser-cooled antihydrogen has opened a new realm of precision on anti-hydrogen's internal structure and gravitational interactions to be explored in upcoming runs (*CERN Courier* May/June 2021 p9).

ASACUSA specialises in spectroscopic measurements of antiprotonic helium, recently finding surprising behaviour (see p13). The experiment is also gearing up to perform hyperfine-splitting spectroscopy in antihydrogen using atomic-beam methods complementary to ALPHA's trapping techniques.

Slow down *Experiments in the AD hall.*

GBAR and AEgIS target direct measurements of the Earth's gravitational acceleration on antihydrogen. GBAR is developing a method to measure the free-fall of antihydrogen atoms, using sympathetic laser cooling to cool antihydrogen atoms and release them, after neutralisation, from a trap directly injected with antiprotons from ELENA, maximising antihydrogen production. AEgIS, having established pulsed formation of antihydrogen in 2018, is following a different approach based on measuring the vertical drop of a pulsed cold beam of antihydrogen atoms travelling horizontally through a device called a Moiré deflectometer.

BASE uses advanced Penning traps to compare matter and antimatter with extreme precision, recently finding the charge-to-mass ratios of protons and antiprotons to be identical within 16 parts per trillion (*CERN Courier* March/April 2022 p10). The data also allowed the collaboration to perform the first differential test of the weak equivalence principle using antiprotons, reaching the 3% level, with experiment improvements soon expected to increase the sensitivities of both measurements. The BASE team is also working on an improved measurement of the antiproton magnetic moment, the implementation of a transportable antiproton trap called BASE-STEP and improved searches for millicharged particles.

The newest AD experiment, PUMA, which is preparing for first commissioning later this year, aims to transport trapped antiprotons collected at ELENA to ISOLDE where, from next year, they will be annihilated on exotic nuclei to study neutron densities at the surface of nuclei.

"Thanks to the beam provided by ELENA and the major upgrades of the experiments, we hope to see big progress in ultra-precise tests of CPT invariance, first and long-awaited antihydrogen-based studies of gravity, as well as the development of new technologies such as transportable antimatter traps," says Stefan Ulmer, head of the AD user committee.

spallation target installed and commissioned in 2021 will enable new n_TOF measurements relevant for nuclear astrophysics.

Different dimensions

Taking CERN science into an altogether different dimension, the PS also links to the Antimatter Factory via the Antiproton Decelarator (AD) and ELENA rings, where several experiments are poised to test CPT invariance and antimatter gravitational interactions at increased levels of precision (see "Antimatter galore at ELENA" panel). Even closer to the proton beam source is the PS Booster, which serves the ISOLDE facility. ISOLDE covers a diverse programme across the physics of exotic nuclei and includes MEDICIS (devoted to the production of novel radioisotopes for medical research), ISOLTRAP (comprising four ion traps to measure ions) and COLLAPS and CRIS, which focus on laser spectroscopy (*CERN Courier* September/October 2021 p36). Its post-accelerators REX/HIE-ISOLDE increase the beam energy up to 10 MeV/u, making ISOLDE the only facility in the world that provides radioactive ion-beam acceleration in this energy range.

Stable and highly customisable beams at the North and East areas also facilitate important detector R&D and test-beam activities. These include the recently approved Water-Cherenkov Test Experiment, which will help to develop detector techniques for long-baseline neutrino experiments, and new detector components for the LHC experiments and proposed future colliders. The CERN Neutrino Platform is dedicated to the development of detector technologies for neutrino experiments across the world. Upcoming activities including ongoing contributions to the future DUNE experiment in the US, in particular the two huge DUNE cryostats and R&D for "vertical drift" liquid-argon detection technology (see p57). In the East Area, the mixed-field irradiation (CHARM) and proton-irradiation (IRRAD) facilities provide key input to detector R&D and electronics tests, similar to the services provided by the SPS-driven GIF irradiation facility and HiRadMat.

Fixed-target experiments in the North and East areas, along with experiments at ISOLDE and the AD, demonstrate the importance of diverse physics studies at CERN, when the best path to discover new physics is unclear. Some of these experiments emerged within the Physics Beyond Colliders initiative and there are many more on the horizon, such as KLEVER and the SPS Beam Dump Facility. "With the many physics opportunities mapped out by Physics Beyond Colliders and the consolidation of our facilities, we are looking into a bright future," says Johannes Bernhard, head of the liaison to experiments section in the beams department. "We are always aiming to serve our users with the highest beam quality and performance possible." •

With the many physics opportunities mapped out and the consolidation of our facilities, we are looking into a bright future

CERNCOURIER

VOLUME 62 NUMBER 3 MAY/JUNE 2022

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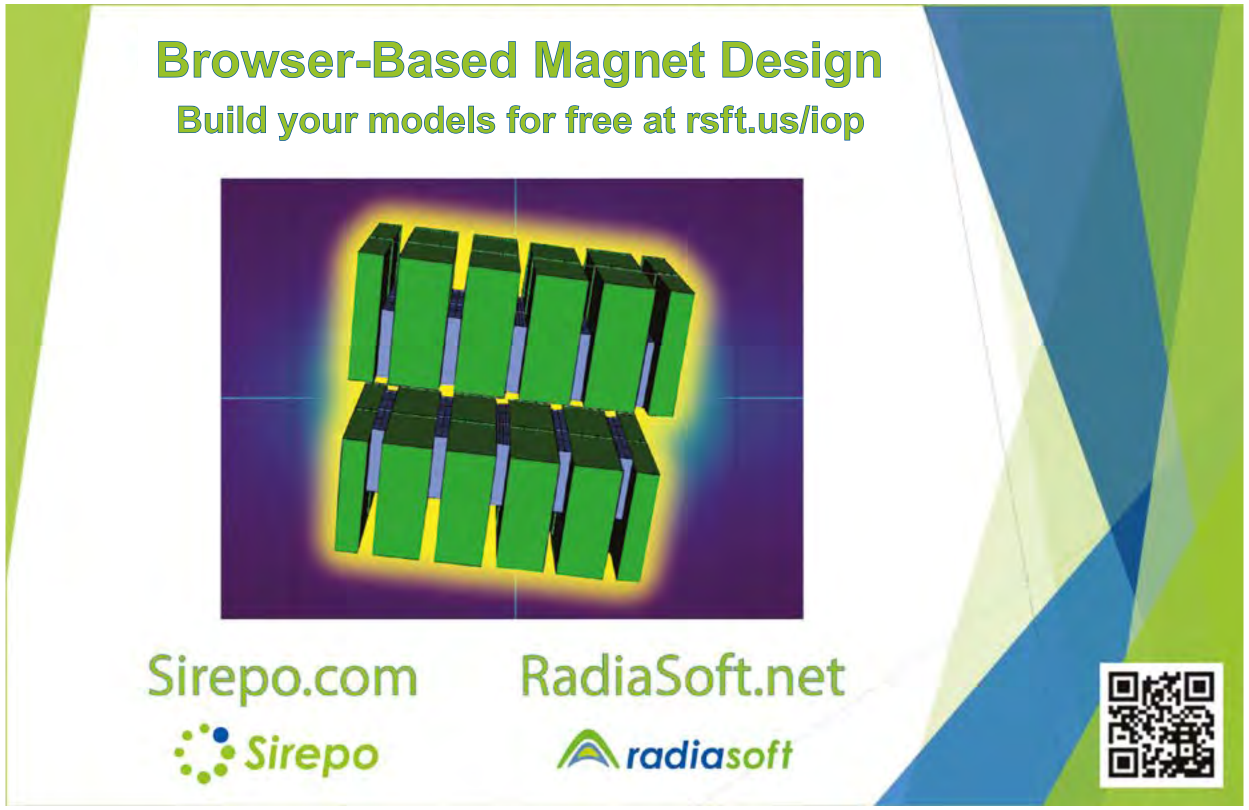


OPINION VIEWPOINT

Less, better, recover

For the LHC and future facilities, it is vital that each MWh of energy consumed brings demonstrable value to CERN's scientific output, says Serge Claudet.

S Claudet

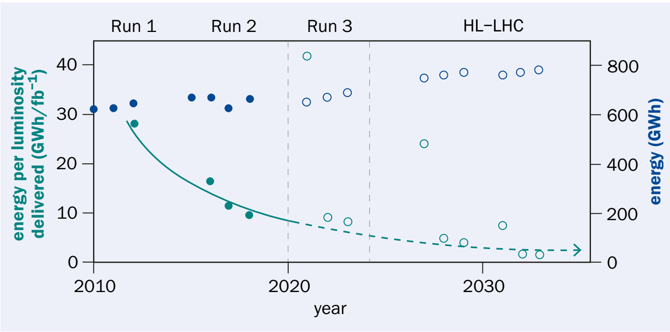
Serge Claudet *is chair of the CERN energy management panel.*

The famous "Livingston diagram", first presented by cyclotron co-inventor Milton Stanley Livingston in 1954, depicts the rise in energy of particle accelerators as a function of time. To assess current and future facilities, however, we need complementary metrics suited to the 21st century. As the 2020 update of the European strategy for particle physics demonstrated, such metrics exist: instead of weighing up colliders solely on the basis of collision energy, they consider the capital cost or energy consumption with respect to the luminosity produced.

Applying these metrics to the LHC shows that the energy used during the upcoming Run 3 will be around three times lower than it was during Run 1 for similar luminosity performance (see "Greener physics" figure). The High-Luminosity LHC (HL-LHC) will operate with even greater efficiency. In fact, CERN accelerators have drawn a similar power for a period of 40 years despite their vastly increased scientific output: from 1 TWh for LEP2 to 1.2 TWh for the LHC and possibly 1.4 TWh at the HL-LHC.

The GWh/fb^{-1} metric has now been adopted by CERN as a key performance indictor (KPI) for the LHC, as set out in CERN's second environmental report published last year. It has also been used to weigh up the performance of various Higgs factories. In 2020, for example, studies showed that an electron–positron Future Circular Collider is the most energy efficient of all proposed Higgs factories in the energy range of interest (*Nat. Phys.* **16** 402). But this KPI is only part of a larger energy-management effort in which the whole community has an increasingly important role to play.

In 2011, with the aim to share best practices amongst scientific facilities, CERN was at the origin of the Energy for Sustainable Science at Research Infrastructures workshop series. A few years later, prompted by the need for CERN to move from protected-tariff to market-based electricity contracts, the CERN energy management panel was created to establish solid forecasts and robust monitoring tools. Each year since 2017, we send virtual "electricity bills" to all group leaders, department heads and directors, which has contributed to a change of culture in the way CERN views energy management.



S Claudet

Greener physics *Energy consumed (blue) and per luminosity delivered (green) by previous (solid circles) and future (open circles) LHC runs.*

There will be no future large-scale science projects without major energy-efficiency and recovery objectives

Best practice

Along with the market-based energy contract, energy suppliers have a duty by law (with tax-incentive mechanisms) to help their clients consume less. A review of energy consumption and upgrades conducted between CERN and its electricity supplier EDF in 2017 highlighted best practices for operation and refurbishment, leading to the launch of the LHC-P8 (LHCb) heat-recovery project for the new city area of Ferney-Voltaire. Similar actions were proposed for LHC-P1 (ATLAS) to boost the heating plant at CERN's Meyrin site, and heat recovery has been considered as a design and adjudication parameter for the new Prevessin Computer Centre. Besides an attractive 5–10 year payback time, such programmes make an important contribution to reducing CERN's carbon footprint.

Energy efficiency and savings are an increasingly important element in each CERN accelerator infrastructure. Completed during Long Shutdown 2, the East Area renovation project led to an extraordinary 90% reduction in energy consumption, while the LHC Injectors Upgrade project also offered an opportunity to improve the injectors' environmental credentials. Energy economy was also the primary motivation for CERN to adopt new regenerative power converters for its transfer lines (*CERN Courier* January/February 2022 p39). These efforts build on energy savings of up to 100 GWh/y since 2010, for example by introducing free cooling and air-flow optimisation in the CERN Computer Centre, and operating the SPS and the LHC cryogenics with the minimum of necessary machines. CERN buildings are also aligning with energy-efficiency standards, with the renovation of up to two buildings per year planned over the next 10 years.

This year, a dedicated team at CERN is being put together concerning alignment with the ISO50001 energy-management standard, which could bring significant subsidies. A preliminary evaluation was conducted in November 2021, demonstrating that 54% of ISO expectations is already in place and a further 15% is easily within reach.

The mantra of CERN's energy-management panel is "less, better, recover". We also have to add "credible" to this list, as there will be no future large-scale science projects without major energy-efficiency and recovery objectives. Today and in the future, we must therefore all work to ensure that every MWh of energy consumed brings demonstrable scientific advances.

OPINION
INTERVIEW

Taking the neutrino stage

As he winds down his term as ATLAS upgrade coordinator, Francesco Lanni looks ahead to his new role as leader of the CERN Neutrino Platform.

You've worked on ATLAS since the early days?
Yes, having trained as a high-energy physics experimentalist with a focus on detector R&D, I joined ATLAS in 1998 and began working on the liquid-argon (LAr) calorimeter. I then got involved in the LAr calorimeter upgrade programme, when we were looking at the possible replacement of the on-detector electronics. I then served as leader for the trigger and data-acquisition upgrade project, before being elected as upgrade coordinator by the ATLAS collaboration in October 2018, with a two-year mandate starting in March 2019 and a second term lasting until February 2023. Because of the new appointment to the Neutrino Platform I will step down and enter a transition mode until around October.

What are the key elements of the ATLAS upgrade?
The full Phase-II upgrade comprises seven main projects. The largest is the new inner tracker, the ITk, which will replace the entire inner detector (Pixel, SCT and TRT) with a fully silicon detector (five layers of pixels and four of strip sensors) significantly extended in the forward region to exploit the physics reach at the High-Luminosity LHC. The ITk has been the most challenging project because of its technical complexity, but also due to the pandemic. Some components, such as the silicon-strip sensors, are already in production, and we are currently steering the whole project to complete pre-production by the end of the year or early 2023. The other projects include the LAr and the scintillating-tile calorimeters, the muons, trigger and data acquisition, and the high-granularity timing detector. The Phase-II upgrades are equivalent in scope to half of the original construction, and despite the challenges ATLAS can rely on a strong and motivated community to successfully complete the ambitious programme.


ATLAS

Moving on *Francesco Lanni joins the CERN staff, having been a senior scientist at Brookhaven National Laboratory.*

What are the stand-out activities during your term?
The biggest achievement is that we were able to redefine the scope of the trigger-systems upgrade. Until the end of 2020 we were planning a system based on a level-0 hardware trigger using calorimeter and muon information, followed by an event filter where tracks were reconstructed by associative memory-based processing units (HTT). The system had been designed to be capable of evolving into a dual-hardware trigger system with a level-0 trigger able to run up to 4 MHz, and the HTT system reconfigured as a level-1 track trigger to reduce the output rate to less than 1 MHz. We reduced this to one level by removing the evolution requirements and replacing the HTT processors with commodity servers. This was a complex and difficult process that took approximately two years to reach a final decision. Let me take this opportunity to express my sincere appreciation for those colleagues who carried the development of the HTT for many years: their contribution has been essential for ATLAS, even if the system was eventually not chosen. The main challenge of the ATLAS upgrade has been and will be the completion of the ITk in the available timescale, even after the new schedule for Long Shutdown 3.

What led you to apply for the position of Neutrino Platform leader?
Different factors, personal and professional. From a scientific point of view, I have been interested in LAr time-projection chambers (TPCs) for neutrino physics for many years, and in the challenge of scalability of the detector technology to the required sizes. Before being ATLAS upgrade coordinator, I had a small R&D programme at Brookhaven for developing LAr TPCs, and I worked for a couple years in the MicroBooNE collaboration on the electronics, which had to work at LAr temperatures. So, I have some synergetic work behind me. On a personal level, I'm obviously thrilled to formally become part of the CERN family. However, it has also been a difficult decision to move away from ATLAS, where I have spent more than 20 years collaborating with excellent colleagues and friends.

What have been the platform's main achievements so far?
Overall I would highlight the fact that the Neutrino Platform was put together in a very short time following the 2013 European strategy update. This was made possible by the leadership of my predecessor Marzio Nessi, a true force of nature, and the constant support of the CERN management. The refurbishment of ICARUS has been a significant technical success, as has the development and construction of the huge protoDUNE models for the two far detectors of LBNF/DUNE in the US.

What's the status of the protoDUNE modules?
The first protoDUNE module based on standard horizontal-drift ("single phase") technology has been successfully completed, with series production of the anode plane assembly starting now. Lately, the CERN group has contributed significantly to the vertical-drift concept, which is the baseline

technology for the second DUNE far detector. This was initially planned to adopt "dual phase" detection but has now been adapted so that the full ionisation charge is collected in liquid-argon after a long vertical drift. Recently, before I came on board, the team demonstrated the ability to drift and collect ionisation charges over a distance of 6 m, which requires the high voltage to be extremely stable and the liquid-argon to be very pure to have enough charge collected to properly reconstruct the neutrino event. There is still work to be done but we have demonstrated that the technology is already able to reach the requirements. The full single-phase DUNE detector has to be closed and cooled down in 2028, and the second based on vertical drift in 2029. For an experiment at such scale, this is non-trivial.

I am still planning to be hands-on – that is the fun part

What else is on the agenda?

The construction of the LBNF/DUNE cryostats is a major activity. CERN has agreed to provide two cryostats, which is a large commitment. The cryostat technology has been adapted from the natural-gas industry and the R&D phase should be completed soon, while we start the process of looking for manufacturers. We are also completing a project together with European collaborators involving the upgrade of the near detector for the T2K experiment in Japan, and are supporting other neutrino experiments closer to home, such as FASER at the LHC. Another interesting project is ENUBET, which has achieved important results demonstrating superior control of neutrino fluxes for cross-section measurements.

What are the platform's long-term prospects?

One of the reasons I was interested in this position was to help understand and shape the long-term perspective for neutrino physics at CERN. The Neutrino Platform is a kind of tool that has a self-contained mandate. The question is whether and how it should or could continue beyond, say, 2027 and whether we will need to use the full EHN1 facility because we have other labs on-site to do smaller-scale tests for innovative detector R&D. Addressing these issues is one of my primary goals. There is also interest in Gran Sasso's DarkSide experiment, which will use essentially the same cryostat technology as DUNE to search for dark matter. As well as taking care of the overall management and budget of the Neutrino Platform, I am still planning to be hands-on – that is the fun part.

What do you see as the biggest challenges ahead?

For the next two years the biggest challenge is the delivery of the two cryostats, which is both technical and subject to external constraints, for instance due to the increase in the costs of materials and other factors. From the management perspective, one has to acknowledge that the previous leadership created a fantastic team. It is relatively small but very motivated and competent, so it needs to be praised and maintained.

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

OPINION REVIEWS

The LHC experience up close

The Adventure of the Large Hadron Collider: From the Big Bang to the Higgs Boson

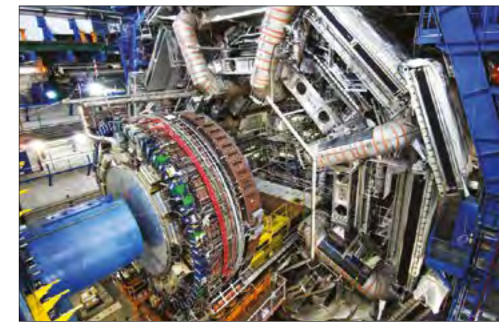
By Daniel Denegri, Claude Guyot, Andreas Hoecker and Lydia Roos

World Scientific

With this ambitious book, the authors have produced a unique and excellent account of particle physics that goes way beyond a description of the LHC project. Its 600 pages are a very pleasant, although tough in places, read. The book serves as a highly valuable refresher of modern concepts of particle physics, recalling theoretical ideas as well as explaining advanced detector technologies and analysis methods that set the stage for the LHC experiments and the Higgs-boson discovery. Even though the focus converges on the Higgs boson, the full LHC project and its rich physics playground are well covered, and furthermore embedded in the broader context of particle physics and cosmology, as the subtitle indicates.

In a way, it is a multi-layered book, which makes it appealing for the selective reader. Each layer is in itself of great value and highly recommendable. The overarching presentation is attractive, with great photos, nicely prepared graphics and diagrams, and a clear structure guiding readers through the many chapters. Quite unique are the more than 50 inserted text boxes, typically one to three pages long, which explain in a concise way the concepts used in the main text. Experts may wish to skip some of them, but they are very educational (at least as a refresher) for most readers, as they were for me. The text boxes are ideal for students and science enthusiasts of all ages, although some are more demanding than others.

To start, the authors take the reader off into a substantial 170-page introduction to particle physics in general, and to the Standard Model (SM) in particular. Its theoretical ideas and their mathematical formulations, as well as its key experimental foundation, are clearly presented. The authors also explore with a broad view what the SM cannot explain. Some material in these introductory chapters are the most demanding parts of the book. The theoretical text boxes are a good opportunity for physics students to recall previously-acquired mathematical notions, but they are clearly not meant for non-experts, who can readily skip them and concentrate more on the very nicely documented historical accounts. A short and accessible chapter "Back to the Big Bang" concludes the introductions by embedding particle physics into the broader picture of cosmology.



Higgs quest *One ATLAS end-cap calorimeter and the toroidal magnet in 2007.*

Next, the LHC and the ATLAS and CMS experiments enter the stage. The LHC project and its history is introduced with a brief reminder of previous hadron colliders (ISR, Sp$\bar{\text{p}}$S and Tevatron). The presentation of the two general-purpose detectors comes with a short refresher on particle detection and collider experiments. Salient technical features, and collaboration aspects including some historical anecdotes, are covered for ATLAS and CMS. The book continues with the start-up of the machine, including the scary episode of the September 2008 incident, followed by the breathtaking LHC performance after the restart in November 2009 with Runs 1 and 2, until Long Shutdown 2, which began in 2019.

The story of the Higgs-boson discovery is set within a comprehensive framework of the basics of modern analysis tools and methods, a chapter again of special value for students. Ten years later, it is a pleasure to read from insiders how the discovery unfolded, illustrated with plenty of original physics plots and photographs conveying the excitement of the 4 July 2012 announcement. A detailed description of the rich physics harvest testing the Higgs sector as well as challenging the SM in general provides an up-to-date collection of results from the LHC's first 10 years of physics operations.

A significant chapter "Quest for new physics" follows, giving the reader a good impression of the many searches hunting for physics beyond the SM. Their relations to, and motivations from, theoretical speculations and astroparticle-physics experiments are explained in an accessible and attractive way.

A book about the LHC wouldn't be complete without an excursion to the physics and detectors of flavour and hot and dense matter. With the dedicated experiments LHCb and ALICE, respectively, the LHC has opened exciting new frontiers for both fields. The authors cover these well in a lean chapter introducing the physics and commenting on the highlights so far.

A look ahead and conclusion round off this impressive document about the LHC's main mission, the search for the Higgs boson. Much more SM physics has since been extracted, as is amply documented. However, as the last chapter indicates, the journey to find directions to new physics beyond the SM must go on, first with the high-luminosity upgrades of the LHC and its experiments, and then preparing for future colliders reaching either much higher precision on the Higgs-boson properties or higher energies for exploring higher mass particles. Current ideas for such projects that could follow the LHC are briefly introduced.

The authors are not science historians, but central actors as experimental physicists fully immersed in the LHC adventure. They deliver lively first-hand and personal accounts, all while carefully respecting the historical facts. Furthermore, the book is preceded by a bonus track: the reader can enjoy an inspiring and substantial foreword by Carlo Rubbia, founding father and tireless promoter for the LHC project in the 1980s and early 1990s.

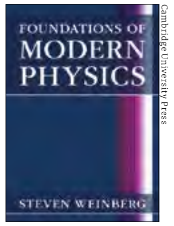
I can only enthusiastically recommend this book, which expands significantly on the French version published in 2014, to all interested in the adventure of the LHC.

Peter Jenni *Albert-Ludwigs-University Freiburg and CERN.*

Foundations of Modern Physics

By Steven Weinberg

Cambridge University Press



Cambridge University Press

Knowing that it will be his last, it is with a mixture of gratitude and sadness that we welcome the new monograph *Foundations of Modern Physics*, a textbook for undergraduate students and a source of reflection for teachers and researchers, by the late Steven Weinberg. If we exclude his works for the layperson such as *The First Three Minutes* or *Dreams of a Final Theory*, this is Weinberg's first book for undergraduate students. The idea behind it is plausible but rarely stressed: the foundations of modern physics ultimately rest on the successful development of the notion of fundamental constituents. While common wisdom attributes the origin of modern physics to Galileo and Newton, the original corpuscular intuition goes back to Democritus, Epicurus and Lucretius. Weinberg already suggested in *To Explain the World: the Discovery of Modern Science* that the existence of fundamental constituents, after nearly two millennia of relentless scrutiny, is the ultimate foundation of all the physical sciences.

With smooth language enriched by historical remarks, Weinberg describes the tortuous path that corroborated the corpuscular intuition of the Greek thinkers. The perfect gases, described in chapter 1, led to the Avogadro number, the first fragile bridge between the macroscopic and the corpuscular description of matter. In chapter 2, readers surf through the Maxwellian theory of transport phenomena that define the transition between hydrodynamics and the atomic (or molecular) hypothesis. This ends with three pivotal landmarks: the discreteness of the electric charge, the celebrated results of Einstein and Perrin on Brownian motion (allowing a direct measurement of the Avogadro number) and the black-body radiation puzzle. Chapters 3 and 4 are devoted to early quantum theory and the special theory of relativity. Quantum mechanics is introduced in chapter 5 and the physics of the atomic nucleus in chapter 6. The tenets of the corpuscular description of matter and radiation are combined in the framework of quantum field theory in the final chapter.

By using the notion of fundamental constituents as the guiding historical and theoretical principle, Weinberg manages to lay the foundations of diverse disciplines (hydrodynamics, statistical mechanics, kinetic theory, thermodynamics, special relativity, quantum mechanics and even field theory) in less than 300 pages.

The flamboyant imagination of Lucretius in *De rerum natura* could not have conceived of the possibility of human missions to Mars or the existence of colliders. Nonetheless, his corpuscular intuition was one of the essential seeds that eventually developed into the roots of modern physics. We must all admit, despite claims to the contrary, that modernity is not bound to coincide with recency because good ideas take an exceedingly long time to mature. Weinberg's time capsule for students of future generations is that truly modern physicists are not always contemporaries.

Massimo Giovannini *CERN and INFN Milano-Bicocca.*

Picture a scientist

Directed by Ian Cheney and Sharon Shattuck, screened at the CERN Globe on 10 February 2022

pictureascientist.com

Being a scientist does not rely on race or gender but only on the love for science

"If you had to picture a scientist, what would it look like?" That is the question driving the documentary film *Picture a Scientist*, first released in April 2020 and screened on 10 February this year at the CERN Globe of Science and Innovation. Directed by Emmy-nominated Sharon Shattuck and Ian Cheney, whose previous productions include *From This Day Forward* (2016) and *The Long Coast* (2020), respectively, the 97 minute film tackles the difficulties faced by women in STEM careers. It is centered on the experiences of three US researchers – molecular biologist Nancy Hopkins (MIT), chemist Raychelle Burks (St. Edward's University) and geologist Jane Willenbring (UC San Diego) – among others who have faced various forms of discrimination during their careers.

Hopkins talks about the difficulties she faced as a student in the 1950s and 1960s, when the education system didn't offer many maths and science lessons to girls, and shares an experience of sexual harassment involving a famous biologist during a lab visit. Willenbring also experienced various mistreatments, including inappropriate nicknames and harassment from a colleague during a 1999 field trip in Antarctica. The film describes how these two anecdotes are just the tip of the iceberg of discrimination that has historically affected female scientists and is still present today. Less visible examples include being ignored in meetings, being treated as a trainee, receiving inappropriate emails and not getting proper credit for work.

Burks, who is Black, explains how the situation is even worse for women of different ethnic groups, as they are even more underrepresented in science. During her childhood, she recalls, most female Black scientists were fictional, such as *Star Trek*'s communications officer Nyota Uhura.

The film highlights the importance of female scientists speaking out to help people see beyond the tip of the iceberg and allow them to act. Hopkins recounts how she once wrote a letter to the president of MIT in which she described systemic and invisible discrimination such as office space being larger for men than for women. Supported and encouraged by female colleagues, it led to a request to the dean of MIT for greater equality. Another example ultimately led the president of Boston University to dismiss the male researcher who had bullied Willenbring, after receiving many reports of gender harassment.

However, even though progress has been made, the film makes it clear – for example through graphs showing the considerable underrepresentation of women in science – that there is still much to do. "By its own nature science itself should be always evolving," says Burks: we should be able to identify the idea of a scientist as someone fascinated about research rather than based on its stereotype.

Videos recreating scenes of the bullying described and footage from old TV shows showing the historical mistreatment of women complement candid accounts from those who have experienced discrimination, allowing the viewer to understand their experiences in an impactful way. Some scenes are hard to watch, but are necessary to understand the problem and therefore take steps to increase the recognition of women in STEM careers.

This film raises the often silenced voice of female scientists who have been discriminated against, and makes it clear that being a scientist does not rely on race or gender but only on the love for science. "If you believe that passion and ability for science is evenly distributed among the sexes, then if you don't have women, you have lost half of the best people," states Hopkins. "Can we really afford to lose those top scientists?"

Bryan Pérez Tapia *editorial assistant.*

It all starts in the workshop

Exploring the fundamental laws of the universe relies on the dedication of skilled CERN technicians. Bryan Pérez Tapia talks to heavy-machinist Florian Hofmann.

Tailor-made *Florian Hofmann in front of a 5-axis milling and turning machine in the MME workshop.*

State-of-the-art particle accelerators and detectors cannot be bought off the shelf. They come to life in workshops staffed by teams of highly skilled engineers and technicians – such as heavy-machinist Florian Hofmann from Austria, who joined CERN in October 2019.

Florian is one of several hundred engineers and technicians employed by CERN to develop, build and test equipment, and keep it in good working order. He works in the machining and maintenance workshop of the mechanical and materials engineering (MME) group, which acts as a partner to many projects and experiments at CERN. "We tightly collaborate with all CERN colleagues and we offer our production facility and knowledge to meet their needs," he explains. "Sometimes the engineers, the project leaders or even the scientists come to see how the parts of their work come together. It is a nice and humbling experience for me because I know they have been conceiving components for a very long time. Our doors are open and you don't need special permission – everyone can come round!"

Before joining CERN, Florian began studying atmospheric physics at the University of Innsbruck. After two semesters, he realised that even though he liked science he preferred not to practise it, so decided to change to engineering and programming. After completing his studies and working in diverse fields such as automotive, tool making and water power plants, he joined CERN. Like many of his colleagues, his expertise and genuine curiosity for his work helps Florian to find tailor-made solutions for CERN's challenging projects, every one of which is different, he explains. "Years ago the job used to be a traditional mechanics job, but today the cutting-edge technologies involved make this the Formula One of production."

> **Today, the cutting-edge technologies involved make this the Formula One of production**

Heavy metal

Florian is currently working on aluminium joints for the vacuum tank of the kicker magnets for the Proton Synchrotron, a fundamental component on which the technicians collaborate with many other groups. The workshop is also contributing to numerous important projects such as the FRESCA2 cryostat, which is visible at the entry of the workshop, and the crab cavities for the High-Luminosity LHC upgrade (*CERN Courier* March/April 2022 p45). The radio-frequency quadrupole for Linac4, which now drives all proton production at CERN, was built here, as was the cryostat for the ICARUS neutrino detector now taking data at Fermilab and parts of the AMS-02 detector operating on the International Space Station. In the 1960s, the workshop was responsible for the construction of the Big European Bubble Chamber detector that revealed the existence of the neutral current and is now an exhibit in the CERN Microcosm.

Before any heavy-machinery work begins, the machining team simulates the machining process to avoid failures or technical issues during fabrication. Although the software is highly reliable, Florian and his co-workers have to stand by to control and steer the machine, modifying commands when needed and ensuring that the activity is carried out as required. Every machine has one person in charge, the so-called technical referent, but the team receives basic training on multiple machines to allow them to jump onto a different one if necessary. The job stands out for its dynamism, Florian explains. "At the MME workshop, we perform many diverse manufacturing processes needed for accelerator technologies, not only milling and turning of the machine but also welding of exotic materials, among others. The possibilities are countless."

Florian's enthusiasm reflects the mindset of the MME workshop team, where everyone is aware of their contributions to the broader science goals of CERN. "This is a team sport. When you join a club you need it to have good management, and I think that here, because of our supervisors and our group responsibility, you are made to feel like everyone is pushing in the same direction." Being curious, eager to learn and open-minded are important skills for CERN technicians, he adds.

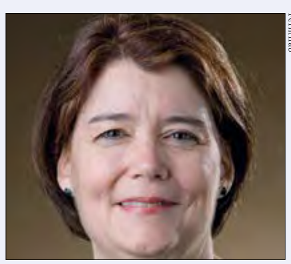
"When you come to CERN you always leave with more than you can bring, because the experience of contributing to science, to bring nations together towards a better world, is really rewarding. I think everybody needs to ask themselves what they want and what kind of world they want to live in."

Bryan Pérez Tapia *editorial assistant.*

Appointments and awards

FAIR second term
Experimental particle physicist and a former ALICE spokesperson Paolo Giubellino has been granted a second term as scientific managing director of the GSI Helmholtz Centre for Heavy Ion Research and the Facility for Antiproton and Ion Research in Europe (FAIR GmbH). He first joined the facility in January 2017, leading the execution of FAIR "Phase 0". His second five-year term, which started in January this year, will focus on preparing experiments for the start of the FAIR facility, for which construction of its control centre officially started on 29 March. "The coming years are decisive for firmly shaping FAIR as one of the top scientific laboratories in the world, involving the wide international FAIR scientific community," says Giubellino. "FAIR has an enormous potential to produce groundbreaking results in a broad range of research areas."

Mcbride next CMS spokesperson
Patricia McBride, distinguished scientist at Fermilab, has been elected as the next spokesperson of the CMS collaboration. She will take over from current spokesperson Luca Malgeri in the autumn, becoming the first woman to lead the 3000-strong collaboration. McBride graduated in physics at Carnegie Mellon University, and completed a PhD at Yale analysing charm decays at Fermilab's E630 experiment. Since joining CMS in 2005, she has served as deputy head of CMS computing, head of the CMS Center at Fermilab and as deputy CMS spokesperson from 2018 to 2020. She will take up the leadership of CMS soon after LHC Run 3 gets under way, and is therefore anticipating exciting times ahead: "CMS is looking forward to the Run 3 physics programme and at the same time will be pushing to keep the detector upgrades for the HL-LHC on track," she says. "It will be a challenging but exciting time for the collaboration."



Fermilab

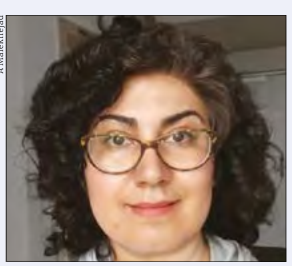
DUNE

Bertolucci joins DUNE
Fermilab has announced the appointment of Sergio Bertolucci (INFN Bologna), who was CERN director of research and computing in 2009–2015, as DUNE co-spokesperson beginning in April. Replacing Stefan Söldner-Rembold, who has held the position since 2018, he joins Gina Rameika, who was elected co-spokesperson of the experiment last year. DUNE is an international neutrino experiment for which prototype detector modules are being built at CERN (see p57) and is due to be installed in a cavern currently being excavated at SURF in South Dakota later this decade.

MicroBooNE elect Toups
On 7 February, Matt Toups (Fermilab) was elected co-spokesperson for the MicroBooNE experiment, joining Justin Evans (University of Manchester) in leading the 210-strong collaboration. A key part of Fermilab's short-baseline neutrino programme, MicroBooNE enables neutrino cross-section measurements to probe the possible existence of non-standard neutrinos (*CERN Courier* November/December 2021 p8). "We're entering in this phase in the collaboration where we're hitting our stride in terms of reconstructing the data, making sense out of it and putting out premier physics results that the community can really sink their teeth into," says Toups. "I think it's our golden era of physics results."

R Hahn

Buchalter Cosmology Prize
Theoretical physicist Azadeh Maleknejad, currently a CERN fellow, has been awarded the second prize of the 2021 Buchalter Cosmology Prize for her work "SU(2)$_R$ and its Axion in Cosmology: A Common Origin for Inflation, Cold Sterile Neutrinos, and Baryogenesis" (arXiv:2012.11516), cited by the jury as a compelling new perspective on some of the most important questions in cosmology. The annual prizes were created in 2014 by Ari Buchalter to support the development of new theories with potential to produce a breakthrough in our understanding of the universe.



A Maleknejad

2021 ATLAS thesis awards
On 24 February, the ATLAS collaboration recognised the outstanding work of six PhD students who have made important contributions to the experiment. Selected from a total of 36 nominations, for work spanning the Higgs boson, dark-matter searches and detector development, were: Jackson Burzynski (Simon Fraser University), Giulia Di Gregorio (INFN and University of Pisa), Manuel Guth (University of Geneva), Alexander Leopold (KTH Royal institute of Technology), Stefan Popa (Transilvania University of Brasov) and Zachary Schillaci (Brandeis University). ATLAS students comprise more than a fifth of the 5500-strong collaboration, contributing strongly and critically to all areas of the experiment while learning valuable skills for their degrees.

CERN

Legion of Honour for Spiro
Michel Spiro, a former president of the CERN Council, was pronounced an officer of the Legion of Honour in a ceremony held at the Collège de France on 30 November. Spiro, who is president of the International Union of Pure and Applied Physics, chair of the CERN & Society Foundation board and a proponent of the International Year of Basic Sciences for Sustainable Development, was awarded the medal by Claude Cohen-Tannoudji, who shared the 1997 Nobel Prize in Physics for the development of methods to cool and trap atoms with lasers, on behalf of the French president.

CERN COURIER
Volume 62 Number 3 May/June 2022

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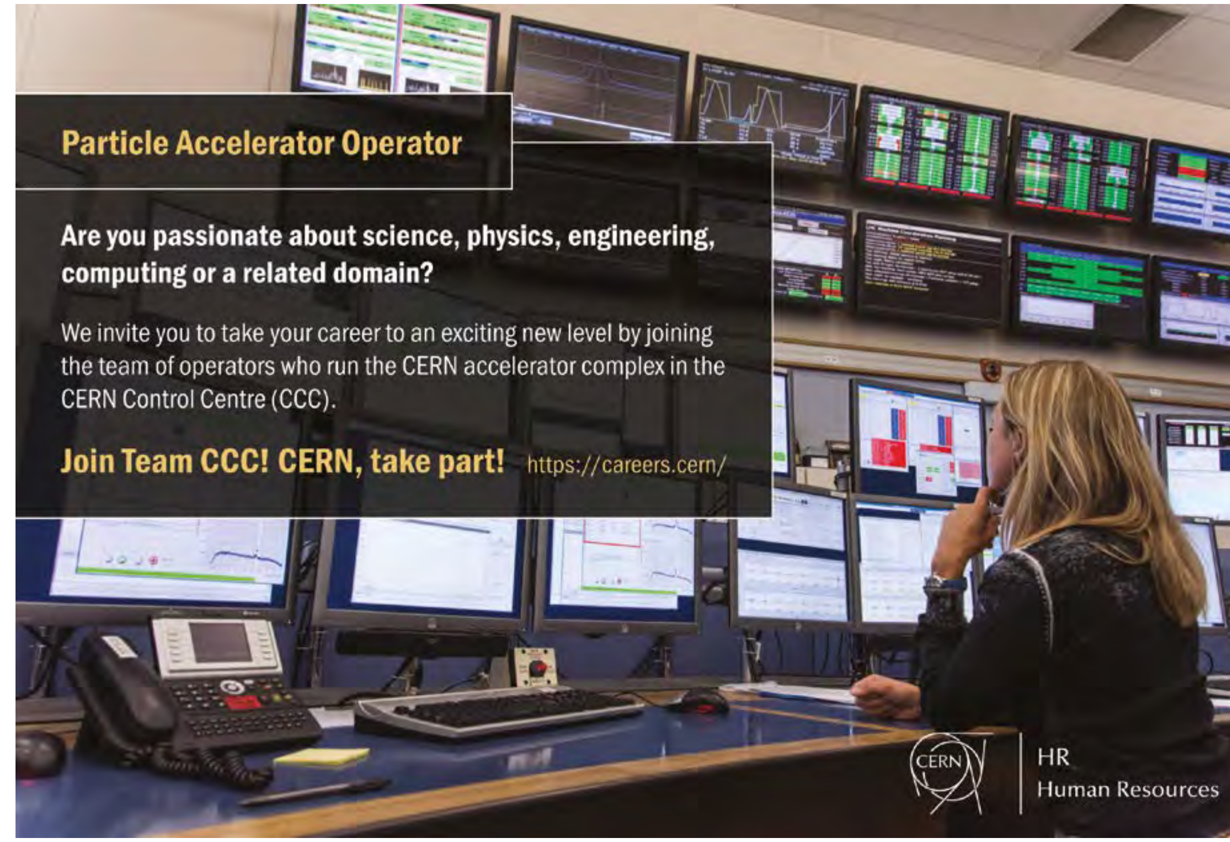
For further information regarding the recruitment process, please contact Anna Hansson Kalaris, Head of Division Human Resources, Anna.HanssonKalaris@ess.eu.

We look forward to receiving your application!



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PEOPLE OBITUARIES

Claude Bouchiat 1932–2021

A profound influence

Theoretical physicist Claude Bouchiat, who was born in Saint-Matré (southern France) on 16 May 1932, passed away in Paris on 25 November. He was a frequent visitor to the CERN theory group.

Bouchiat studied at the École Polytechnique in 1953–1955, and discovered theoretical high-energy physics after listening to a seminar by the late Louis Michel. In 1957, having been impressed by a conference talk given by C N Yang during a short visit to Paris, he decided to extend Michel's results on the electron spectrum in muon decays to include the effects of parity violation. This work led to the Bouchiat–Michel formula. He then joined the theoretical physics laboratory (newly created by Maurice Lévy) at the University of Orsay where, together with Philippe Meyer, he founded a very active group in theoretical particle physics. In the 1960s, during several visits to CERN, he collaborated with Jacques Prentki. In 1974 Bouchiat and Meyer moved to Paris and established the theoretical physics laboratory at the École Normale Supérieure (ENS).

Bouchiat family

Claude Bouchiat also worked on topics beyond particle physics.

Bouchiat's research covered a large domain that extended beyond particle physics. With Prentki and one of us (JI) he studied the leading divergences of the weak interactions, which was a precursor to the introduction of charm, and with Daniele Amati and Jean-Loup Gervais showed how to build dual diagrams satisfying the unitarity constraints. The trio also extended the anomaly equations in the divergence of the axial current to non-abelian theories. In the early 1970s, Bouchiat and collaborators used quantum field theory in the infinite momentum frame to shed light on the parton model. In 1972, with Meyer and JI, he formulated the anomaly cancellation condition for the Standard Model, establishing the vanishing sum of electric charges for quarks and leptons as essential for the mathematical consistency of the theory.

Probably his most influential contribution, carried out with his wife Marie-Anne Bouchiat, was the precise computation of parity-violation effects resulting from virtual Z-boson exchange between electrons and nuclei. They pointed out an enhancement in heavy atoms that rendered the tiny effect amenable to observation. This work opened a new domain of experimental research, starting first at ENS, which played an important role alongside the high-energy experiments at SLAC in confirming the structure of the weak neutral current. Examples of Bouchiat's contributions outside particle physics include his studies of the elasticity properties of DNA molecules and of the geometrical phases generated by non-trivial space topology in various atomic and solid-state physics systems.

During his 60-year-long career, Claude Bouchiat had a profound influence on the development of French theoretical high-energy physics. He helped nurture generations of young theorists, and many of his former students are well-known physicists today.

Pierre Fayet *and* **Jean Iliopoulos** *École Normale Supérieure.*

Yulian Aramovich Budagov 1932–2021

World-class experimentalist

Yulian Aramovich Budagov, a world-class experimental physicist and veteran JINR researcher, passed away on 30 December. Born in Moscow on 4 July 1932, he graduated from the Moscow Engineering Physics Institute in 1956 and joined the staff of the Joint Institute for Nuclear Research (JINR), to where his lifelong scientific career was connected. He made a significant contribution to the development of large experimental facilities and achieved fundamentally important results, including: the properties of top quarks; the observation of new meson decay modes; measurements of CP-violating and rare-decay branching ratios; the determination of νN scattering form factors; observation of QCD colour screening; verification of the analytical properties of πp interaction amplitudes; and observation of scaling regularities in the previously unstudied field of multiple processes.

JINR

Yulian Budagov had an exceptionally wide creative range.

The exceptionally wide creative range of his activities was most prominently manifested during the preparation of experiments at TeV-scale accelerators. In 1991–1993 he initiated and directly supervised the cooperation of JINR and domestic heavy-industry enterprises for the Superconducting Super Collider, and in 1994 became involved in the preparation of experiments for the Tevatron at Fermilab and for the LHC, then under construction at CERN. He led the development of a culture using laser-based metrology for precision assembly of large detectors, and the meticulous ▷

construction of the large calorimetric complex for the ATLAS experiment. Budagov also devised a system of scintillation detectors with wave-shifting fibres for heavy-quark physics at the Tevatron's CDF experiment, which helped measure the top-quark mass with a then-record accuracy. He was a leading contributor to JINR's participation in the physics programme for the ILC, and initiated unique work on the use of explosion welding to make cryogenic modules for the proposed collider.

In his later years, Budagov focused on the development of next-generation precision laser metrology, which has promising applications such as the stabilisation of luminosity at future colliders and the prediction of earthquakes. Precision laser inclinometers developed under his supervision allowed the time dependence of angular oscillations of Earth's surface to be measured with unprecedented accuracy in a wide frequency range, and are protected by several patents.

Yulian Aramovich Budagov successfully combined multifarious scientific and organisational activities with the training of researchers at JINR and in its member states. Based on the topics of research performed under his leadership, 60 dissertations were defended, 23 of which were prepared under his direct supervision. His research was published in major scientific journals of the Soviet Union, Russia, Western Europe and the US, and in proceedings of large international conferences. His works were awarded several JINR prizes, and he received medals of the highest order in Russia and beyond.

His memory will always remain in the hearts of all those who worked alongside him.

His friends and colleagues at JINR.

Thomas K Gaisser 1941–2022

Particle astrophysics pioneer

Thomas K Gaisser of the University of Delaware passed away on 20 February at the age of 81, after a short illness.

Tom was born in Evansville, Indiana, and graduated from Wabash College in 1962. He won a Marshall Scholarship that took him to the University of Bristol in the UK, where he received an MSc in 1965. He then went on to study theoretical particle physics at Brown University, receiving his PhD in 1967. After postdoctoral positions at MIT and the University of Cambridge, he joined the Bartol Research Institute in 1970, where his research interests tilted toward cosmic-ray physics.

Tom was a pioneer in gamma-ray and neutrino astronomy, and then in the emerging field of particle astrophysics. He was a master of extracting science from the indirect information collected by air-shower arrays and other particle astrophysics experiments. Early on, he studied the extensive air showers that are created when high-energy cosmic rays reach Earth. His contributions included the Gaisser–Hillas profile of longitudinal air showers and the Sybill Monte Carlo model for simulating air showers. He laid much of the groundwork for large experiments, such as Auger and IceCube, that provide high-statistics data on the high-energy particles that reach Earth, and for how that data can be used to probe fundamental questions in particle physics.

H Landsman/IceCube/NSF

Tom Gaisser preparing the deployment of an IceCube module during the 2005–2006 South Pole season.

Tom's work was also vital in interpreting data from lower-energy neutrino experiments, such as IMB and Kamioka. He provided calculations of atmospheric neutrino production that were important in establishing neutrino oscillations and, later, for searching for neutrino phenomena beyond the Standard Model.

Tom also contributed to experimental efforts. He was a key member of the Leeds–Bartol South Pole Air Shower Experiment (SPASE), which studied air showers as well as the muons these produce in the Antarctic Muon and Neutrino Detector Array (AMANDA). The combined observations were critical for calibrating AMANDA, and were important data for understanding the cosmic-ray composition. This work evolved into a leading role for Tom in the IceCube Neutrino Observatory, where he served as spokesperson between 2007 and 2011.

In IceCube, Tom focused on the IceTop surface array. Built, like SPASE, as a calibration tool and a veto-detector, its observations contributed to cosmic-ray physics covering a wide and unique energy range, from 250 TeV to EeV. It also made the first map of the high-energy cosmic-ray anisotropy in the Southern Hemisphere. Tom took to the task of building IceTop with gusto. For several summer seasons he travelled to Antarctica, staying there for weeks at a time to work on building the surface array, which consisted of frozen Auger-style water-Cherenkov detectors. He delighted in the hard physical labour and the camaraderie of everyone engaged in the project, from bulldozer drivers to his colleagues and their students. Tom became an ambassador of Antarctic science, in large part through a blog documenting his and his team's expeditions to the South Pole.

Tom may be best known to physicists through his book *Cosmic Rays and Particle Physics*. Originally published in 1990, it was updated to a second edition in 2016, coauthored with Ralph Engel and Elisa Resconi. It sits on the shelves of researchers in the field around the globe.

Throughout his career, Tom received many scientific awards. He became a fellow of the American Physical Society in 1984 and was internationally recognised with the Humboldt Research Award, the O'Ceallaigh Medal and the Homi Bhabha Medal and Prize, among others. His Antarctic contributions were recognised when a feature on the continent was named Gaisser Valley.

Francis Halzen *University of Wisconsin–Madison and* **Tom's friends and collaborators.**

BACKGROUND

Notes and observations from the high-energy physics community

Noether tops the board

Perimeter

From 15 March to 4 April, inspired by the "March Madness" single-elimination college basketball tournament, Perimeter Institute's *Physics Frenzy: Battle of the Equations* saw 16 equations compete for votes for the title of the all-time greatest equation in physics. More than 18,000 votes were cast. Despite strong campaigning by particle physicists, a razor-thin margin saw the Dirac equation knocked out by the Einstein field equations in the first round – although Heisenberg's uncertainty principle breezed past the Friedmann equations, only to then be eliminated by the Schrödinger equation. Having seen off Hamilton's equations and the second law of thermodynamics, Maxwell's equations dashed Schrödinger's hopes to set up a tense finale with Noether's theorem, still fresh from victories over the Planck–Einstein relation and the Einstein field equations. Proven by mathematician Emmy Noether in 1915, the neat relation connecting symmetries with conservation laws stole the show with 59% of the vote.

On 30 April 1962, Stanford University trustees signed the construction contract for SLAC, centered around a 3.2 km linear accelerator (first dubbed Project M and affectionately known as "the Monster") that went on to enable breakthrough discoveries in particle physics before evolving into an advanced X-ray source. This year, SLAC celebrates 60 years of science and discovery with a series of lectures and public events.

The time it took light to reach Earth from Earendel – the farthest individual star ever observed, using data collected during Hubble's RELICS programme (*Nature* 603 815).

12.9 bn years

From the archive: June 1982

Prototype niobium-tin dipole

The Département de Physique des Particules Elementaires at Saclay has for some time been working with the Institute of High Energy Physics at Serpukhov to develop superconducting magnets for use in the Soviet UNK project for a 3000 GeV proton accelerator. Now a prototype niobium-tin dipole has been successfully tested. This magnet has the same configuration as previous UNK dipoles built at Saclay, with a 90 mm aperture and length of 70 cm. In this way, the existing tooling and other equipment can be used. However, on imposing such a geometry, in particular the thickness of the coil, the attainable central field is limited to 6 T. This is relatively low, but the main objective was rather to develop appropriate technologies for handling the delicate niobium-tin rather than aiming right away for higher fields. Under the same conditions, niobium-titanium prototypes had reached 4.5 T.


A model of the cross-section of the new niobium-tin superconducting dipole magnets, showing the two-layer structure of the coil.

First tests gave a central field of 5.3 T and a current of 5550 A. During these tests, the protection systems unfortunately did not allow this value to be exceeded, even though the dipole looks capable of reaching 6 T. More tests are scheduled, but already the experience gained shows that dipoles could be built capable of attaining 8–10 T.

● Based on text from p182 of *CERN Courier* June 1982.

Compiler's note

The decision to proceed with the 21 km-circumference Soviet Accelerating and Storage Complex (UNK), offering high-luminosity proton–proton collisions at 6 TeV, followed the rapid growth of high-energy physics in the USSR during the 1960s and 1970s. In 1993, however, a lack of federal funding led the project to be downsized to a lower-energy fixed-target-only facility, for which the tunnel and much of the equipment was built at Protvino when the project was cancelled at the end of the 1990s. Niobium-tin dipole magnets are being developed for the High-Luminosity LHC, and are under consideration for the proposed future hadron collider FCC-hh.

Media corner

"The fact that we have two other experiments that agree with each other and the Standard Model and strongly disagree with this experiment is worrying to me."

Ben Allanach quoted in *BBC News* (8 April) on CDF's new measurement of the W-boson mass (see p9).

"We explore distances that are 10,000 times smaller than an atomic nucleus, so I think a reasonable person can doubt that we can ever really get significant knowledge about things that are so far away from things we can actually grasp. And this is what accelerators do — they bridge that gap."

Michael Peskin discussing the Higgs-boson discovery in a podcast from *Knowable Magazine* (29 March).

"We don't know which kind of theory describes our universe, but we know which kind of theory does not: a quantum theory with real numbers."

Miguel Navascués speaking to *El País* (19 March) on the possible falsification of real-number quantum theory (*Nature* **600** 625).

"CERN, though a prestigious outfit, is also an esoteric one. It is a long time since new discoveries in particle physics affected technology, industry or warfare."

The Economist (5 March) on science, diplomacy and the war in Ukraine.

"The CERN particle-physics lab struck the right balance by suspending Russia's 'observer' status while standing behind Russian scientists at the lab."

Physics World editor **Matin Durrani** on the chilling impact on science of Russia's invasion of Ukraine (18 March).

CERNCOURIER
Volume 62 Number 3 May/June 2022
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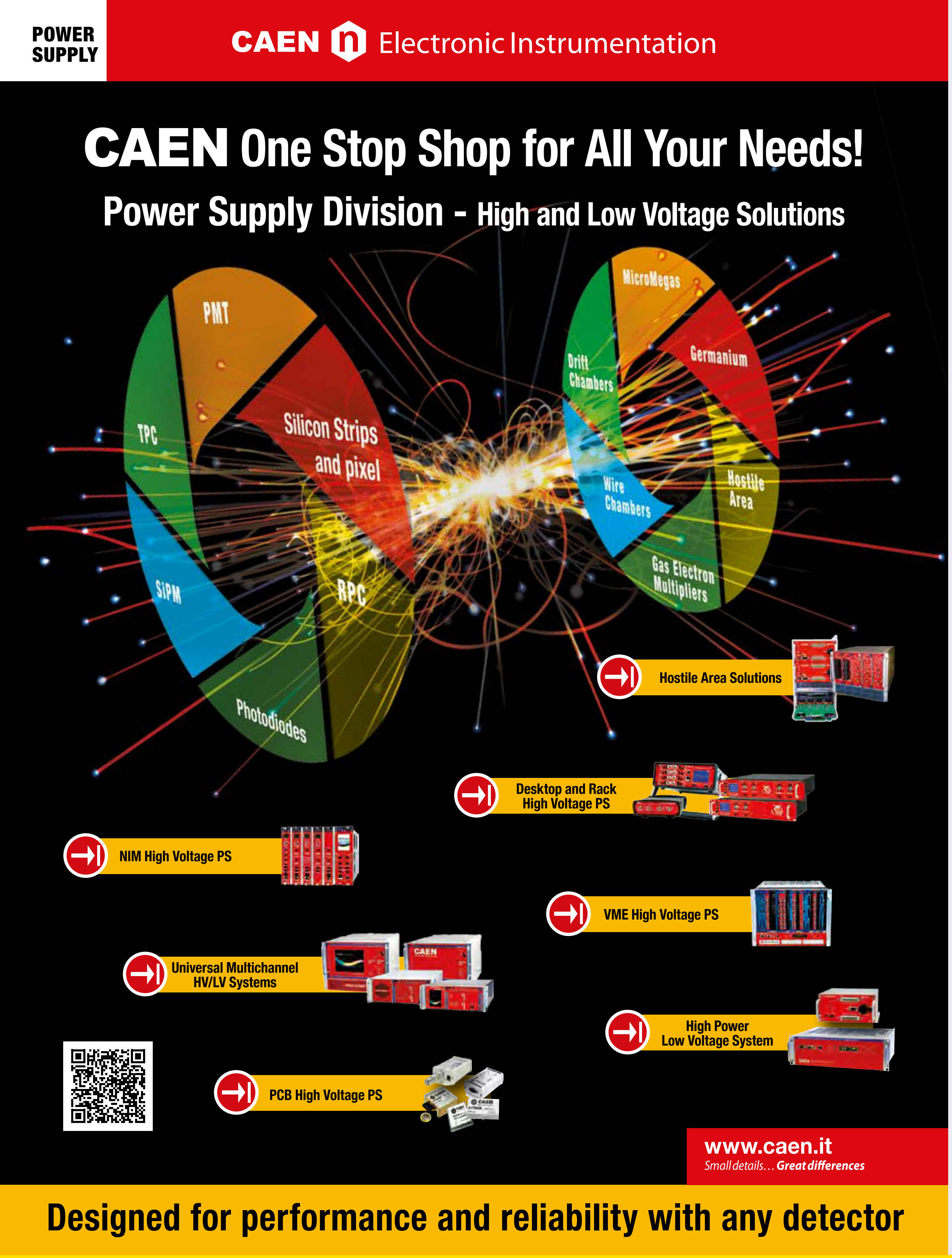
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