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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A new chapter for the LHC

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, stretching a course into the High-Luminosity LHC, which by the late 2020s will provide at least 10 times more data than collected so far.

Prospects in searches (p.99), precision measurements (p.117), flavour physics (p.145) and heavy-ions (p.147) show Run 3 to be anything but business as usual. The detectors are in better shape than ever, with the new LRD/VELO (p.98) 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 (p.99 and 101), new research directions are being forged—complemented by the new forward-experiments PA0R and SNbpiLHC and a rich fixed-target programme (p.95).

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 (p.99). 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 (p.98) is a first for the Americas, while the same month saw the 1945 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 (p.107 and 109).

Russian 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.

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 (p.97).

It is often said it serves 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.

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

Matthew Chalmers
Editor
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 2018 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 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 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 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. The granting of contracts as associated members of the CERN periphery to any new individuals affiliated to home institutions in Russia and Belarus.

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.

Science for peace

Other European institutions with longstanding 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 EURORadio. A declaration initiated by the Max Planck Society and supported by the Lindau Nobel Laureate Meetings has been signed by 55 Nobel Laureates, while the 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 800 signatures, while almost 200 Russian researchers participating in CERN experiments have signed an open letter standing strongly for resolving the conflict through diplomacy and negotiations.

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 CHF 220,000 Swiss francs by the time of closing on 22 March. The initiative 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.
**CERN 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 member status is a stepping stone on the path towards full membership and will enable Brazil to send one mentor to the CERN pre-school programme, the Portuguese-language student programme, and the CERN postgraduate programme.

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**Application**

**Compact XFELs for all**

Originalised considered a troublesome byproduct of particle accelerators designed to fundamental and modelled when they are shut down, CERN has been working on a way to make these particles more affordable and accessible. In the early 2000s, a collaborative approach was developed at CERN to survey and improve the efficiency of the CLIC project. This approach included a prototype of the CLIC X-band linac, which has since been improved and is now operational at the Compact Light Institute. The prototype includes all of the essential components of a full-scale CLIC linac, including the RF cavities, focusing magnets, and beam manipulation systems. The prototype was commissioned in 2019 and has since been used to test different operational modes and configurations.

**Conclusion**

The Compact XFEL is a promising technology for the future of particle physics, providing a cost-effective and scalable solution for the needs of both industry and research institutions. With ongoing developments and improvements, the Compact XFEL is set to play a significant role in advancing our understanding of fundamental physics and driving innovation in related fields.
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 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 57 billion project, which would collide electrons and positrons to study the Higgs boson in detail (CERN Courier January/February 2019 p9). In 2018 the International Committee for Future Accelerators (ICFA) backed a 20 km-long ILC operating at a centre-of-mass energy of 256 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 p11).

Planning and progress

In June 2021, a 59 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, work plan and required resources for an ILC “pre-lab”. At the same time, KEK and the Japanese Association of High Energy Physicists submitted a report to MEXT summarising progress on the ILC 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 an international collaborative research project, 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 high-energy physics community is committed to further advance international technological and engineering development in the accelerator area.

Work in progress... (Photo: Shinya Hasegawa)

In writing its report, the IDT was tasked by KEK and the Japanese ILC community to continue efforts to expand the broad support from various stakeholders in Japan and abroad by building up trust and mutual understanding.

Regarding 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 various 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 research 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 newly centralised international organisation to strengthen KEK communications to the public. (See full report: NewsAnalysis v4, p11.)

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

Thermonuclear explosions fuel cosmic rays

Thermonuclear explosions fuel cosmic rays

Normally, RS Ophiuchi is a faint astronomical object, with a brightness of about 5000 light years from Earth. Once every 15 years or so, however, it brightens dramatically, leaking about one day after the peak in optical brightness. For H.E.S.S., which observed it, the 11 May 2012 to 2.75 GeV energy range, the peak only occurred three days after the optical peak, indicating a significant hardening of the emission spectrum with time.

Hadrone 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 decay into gamma rays. 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 were accelerated up to 1 TeV, producing the observed gamma-rays. However, it took an additional two days for the source to further accelerate such hadrons to produce the gamma-rays detectable by 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 and the novel observations from H.E.S.S. The alternative theory of a leptonic origin of the gamma rays is more difficult to test, due to the smaller energy density of the shock that would need to be converted into electron acceleration. The recent results from H.E.S.S. may help to test models of the origin of cosmic rays and the hadron/gamma-ray correlation to the puzzle of cosmic-ray origins.

Further reading

H.E.S.S. Collaboration 2022 Science 376:77.
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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 identi-cal-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 sets of quarks. 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 3). 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.

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 4). 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 diphoton 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 global significance of 1.6σ. 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 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 antimatter 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 collisions.
The primary goal of the ultra-relativistic 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 after heavy ion collisions is imprinted in the momentum distributions of final-state particles. The azimuthal-anisotropy flow coefficient $v_n$ and the mean transverse momentum (p$_T$) 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 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 $v_2$ and (p$_T$) in terms of the modified Pearson coefficient $\beta$. The measurements were performed in lead–lead (PbPb) and xenon–xenon (XeXe) collisions at centre-of-mass energies of 5.02 and 5.44 TeV, respectively. As the correlations between $v_2$ and (p$_T$) are found 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.

The measurements show a positive correlation between $v_2$ and (p$_T$) 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–cascade effective theory with gluon saturation) and Trenot, a parameterised model with no nucleons as the relevant degree of freedom. The centrality dependence of $\beta$ is better described by IP-Glasma than by Trenot. In particular, the positive measured values of $\beta$ suggest an effective nuclear width of the order of 0.3–0.5 fm, which is significantly smaller than what has been extracted in all Bayesian analyses using Trenot 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 quark–gluon deformation parameter $\beta$ of the “$\sigma$-quark meson, potentially opening a new window for studying nuclear structure with ultra-relativistic heavy-ion collisions.”

Further reading
Big Science Business Forum 2022 will be the second edition of a one-stop-shop for European companies and other stakeholders to learn about Europe’s Big Science organisations’ future investments and procurements worth billions of euros. The forum will offer you a chance to:

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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 Alpines 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 increasing 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-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 (q=6). On the theory side, various new signatures for extended Higgs sectors were proposed.

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 920 GeV. CMS has hatched such events, exceeding the SM prediction with a local significance of 9σ or 1.6 GeV when taking into account the full range of parameter space searched (p45). Modest excesses with a global significance of 2–3σ 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 correspond to statistical fluctuations of the SM expectation or signals of new physics.

Flavour anomalies

The persistent set of tensions between predictions and measurements in semi-leptonic b → sℓℓ decay rates (ℓ = e, μ) were much discussed. LHCh 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 → eν decay from B factories, 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 charm decays or leptons at high transverse momentum) to get more information on operators beyond the SM that would contribute to the anomalies (p44).

Updates from LHCb on several b → sℓℓ→ decay branching fractions with a precision limited by the sample size and precise measurements of charmed particle lifetimes, including the individual world’s best D and Λ0 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 μ = g−2, for which the SM prediction and the recent Fermilab measurement stand at 2.5, as apart or less, depending on whether the hadronic vacuum polarisation contribution...
The hottest issues and neutrinos were reviewed

far-reaching implications in cosmology and particle physics. The (g−2) experiment at Fermilab presented its final result, placing a lower limit on the BNB reactor antineutrino anomaly.

Another very important question is the possible existence of “sterile” neutrinos that do not participate in weak interactions, for which theoretical motivations are 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 (LAMP, 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, MiniBooNE 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 ongoing XENON1T experiment, for example, should elucidate the ~3.5σ 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 regimes 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 the ongoing run of the Hobby Eberly.

The many theory talks described various aspects of the SM proposal — including extra scalars and/or fermions and/or extra symmetries — aimed at explaining the Higgs Violation (g−2), the hierarchy among Yukawa couplings, neutrino oscillations and dark matter. Overall, the broad spectrum of informative presentations brilliantly covered the present landscape. A number of questions in phenomenological high-energy physics and shine a light on the many interesting pathways that demand further exploration.

Monica Pepe Altarelli (CERN) and Ulrich Ellwanger (ILC)

Snowmass back at KITP

Phenomenological models mentioned some promising theoretical mechanisms for answering them and the experimental opportunities that follow.

Snowmass Theory Frontier

From 21 to 25 February, the Kavli Institute of Theoretical Physics in Santa Barbara, California, hosted the Theory Frontier conference of the US Particle Physics Community. Measuring physics (Snowmass 2021) organized 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 events 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 Silva Silverstein (Stanford) on quantum gravity and cosmology and Xi Dong (UC Santa Barbara) on geometry and entanglement, David Gross (KITP) spelled 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 theories and cosmology. Melissa Simons-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 generalisations and applications of the Simsions-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 generalisations and applications of the conformal bootstrap to the infrared.

The second and third days of the conference spanned the entire spectrum of activity within high-energy theory, consolidated around quantum information science with talks by Tom Hartman (Cornell), Raphael Boussou (Harvard), Harald Lammert (Fermilab) and Yoni Kahn (Illinois); Markus Wiesemann (MPI), Felix Kling (DESY) and Ian Moult (CERN) surveyed the review of effective field theory approaches and recent findings in neutrino theory were covered by Alex Friedland (OLAC), Mu-Chun Chen (UC Irvine) and Zahra Tabrizi (Northwestern).

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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 bore well for future discussions with the whole community.

Nicholas Bzdak (CERN) and Daniel Green (UC Santa Barbara) surveyed the press questions and beyond the key themes and models, some promising theoretical mechanisms for answering them and the experimental opportunities that follow.

Field notes

Global market leader for precision magnetometers

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The search for sterile neutrinos is motivated by a series of tensions in short-baseline experiments using neutrinos from accelerators (LAMP, Mini-BooNE), 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, MiniBooNE 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 ongoing XENON1T experiment, for example, should elucidate the ~3.5σ 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 regimes 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 the ongoing run of the Hobby Eberly.

The many theory talks described various aspects of the SM proposal — including extra scalars and/or fermions and/or extra symmetries — aimed at explaining the Higgs Violation (g−2), the hierarchy among Yukawa couplings, neutrino oscillations and dark matter. Overall, the broad spectrum of informative presentations brilliantly covered the present landscape. A number of questions in phenomenological high-energy physics and shine a light on the many interesting pathways that demand further exploration.

Monica Pepe Altarelli (CERN) and Ulrich Ellwanger (ILC)
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 factories” 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–HI), 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–e+e− facility.

The proposed R&D efforts for the FCC–ee align with the requests of the 2020 update of the European Strategy for Particle Physics (ESPP). Key activities of the FCC–ee feasibility study include the development of a regional implementation scenario in collaboration with the host states of CERN, presented.

Over the past several months, a new benchmark scenario for a 91 km–circumfer- ence factory has been established, balancing the optimisation of the machine performance, physics output and terri- torial constraints (see pg7). In addition, work is ongoing to develop a sustainable operational model for FCC taking into account human and financial resources and aiming to minimise environmental impact. Ongoing testing and prototyp- ing 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.

Physics programme

A central element of the overall FCC 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. Key activities of the FCC–ee feasibility study include the development of a regional implementation scenario in collaboration with the host states of CERN, presented.

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Next steps

The progress described at the 5th FCC Physics Workshop is reassuring for the overall FCC programme. While the latter is still far beyond the Higgs factory alone. The impressive potential of the full FCC programme thus allows the different energy stages (ranging from the Z pole at 91 GeV to the tt– threshold at 369 GeV) to 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 (CDF/Cacheri January/February 2022 pg9). 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–e+e− physics further intensified the connections between the electron– and hadron–based communities.

The impressive potential of the full FCC programme is also inspiring theoretical work. This ranges from overcoming 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 tt– threshold at 369 GeV). In particular, the possibility for a direct measurement of the electron Yukawa coupling by extensive operation at the Higgs pole (125 GeV) raises unri- valed challenges, which will be further explored within the FCC sustainability study. The main challenge here is to reduce the spread in the centre–of–mass energy by a factor of around to while maintaining...
Gravitational-wave astronomy turns to AI

Detection and Analysis of Gravitational Waves in the Era of Multi-Messenger Astronomy

New frontiers in gravitational-wave (GW) astronomy have been opened by the combination of a large, multimessenger sky. By observing and localizing GWs in conjunction with electromagnetic observations of gravitational-wave sources, researchers have the potential to resolve the astrophysical nature of these events and reveal new physics.

How the detection of GW dispersion would be possible and how correlations and symmetries: if a GW propagates according to a modified dispersion relation, its frequency shifts upon 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 the more sophisticated astrophysical analysis of GW detector simulations were the focus 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 successfully used to develop detector noise, signal processing, data analysis for signal detections and for reducing the non-astrophysical background of GW searches. These algorithms are applied to extract GW signals 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 approaches that have been developed for the modelling, real-time detection and signal analysis. New strategies will play an increasingly important role in the future analysis of GWs, leading to new discoveries.

Overunsupervised sensitivity

These new sources will require new techniques to detect gravitational waves. In particular, the LIGO and Virgo detectors have an excellent sensitivity to gravitationally-wave emitting objects, and they have observed signals from binary black-hole mergers and a handful of signals from binary neutron star systems. In the next decade, the ongoing physics and engineering efforts, the improvement of the detector networks, and the increase in the sensitivity of the LIGO-Virgo observatories will allow us to detect a large number of events, such as supermassive black holes, primordial black holes, and extreme mass-ratio binaries.

Out of this world

A computer simulation of gravitational waves emitted by a supernova

Deirdre Shoemaker (Texas) showed how machine learning algorithms are used to perform real-time data analysis and to perform signal detections for advanced detector noise, signal processing, data analysis and to understand the origin of matter and the evolution of the universe. As more GW observations with increased detector sensitivities spur astrophysical and multi-messenger detections, new challenges that require close collaboration with all GW researchers will appear.

Closing remarks

Circular collisions help to unravel the most fundamental questions in physics. They allow researchers to test gravity and the evolution of the universe. As more GW observations with increased detector sensitivities spur astrophysical and multi-messenger detections, new challenges that require close collaboration with all GW researchers will appear. The next step for a successful use of ML in GW science will be the integration of ML techniques with more traditional approaches that have been developed for the modelling, real-time detection and signal analysis. New strategies will play an increasingly important role in the future analysis of GWs, leading to new discoveries.

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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.

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

THE AUTHOR

Johannes Gutleber
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Despise the long time scales involved, the local population should already be engaged from the feasibility study stage.

The European Physical Journal
"EP Plus"

THE SEARCH FOR NEW PHYSICS: TAKE THREE

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

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

A side from the discovery of the Higgs boson, the absence of additional elementary-particle covaries 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 a 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.

Running a yet-to-be-instituted 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-antisymmetry 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 general detector and improved understanding of backgrounds, 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 in the 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. 

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lemptons 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 construction 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 selection of signal candidate events at unprecedented rates, for example to test exotic Higgs-boson decays into long-lived particles with branching ratios below the 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 required a particularly large dataset. Examples of the latter are searches for electroweakinos, which have a production cross-section at the LHC and magnitude smaller than those of strongly interacting SUSY particles. First results based on Run 2 data surpassed the sensitivity of the LEP experiments, involving combinations of partially decayed neutralinos in which electroweakinos can decay into only SM particles. This results in complicated final states containing electroweakinos and a relative light Higgs. Here the challenging background determination could only be achieved thanks to machine-learning techniques, which layout and constrain the 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 co-annihilating dark matter. At the LHC, coupling to dark-sector particles and non-Maxwellian production of these “smuons” result in a 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 started to probe leptoquark models suggested by the 8-TeV anomalies using Run 2 data (see “Leptoquark” figure). While the analysis of key channels is ongoing, Run 3 data will allow the experiments to probe a larger fraction of the relevant parameter space. Furthermore, consistent models of leptoquarks include 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.

In summary, searches for new physics at Run 3 will bring significant gains in sensitivity beyond the previous results. 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.
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.

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 kinetic phase space of particles. Prime targets are regions where the discovery
**FEATURE LHC RUN 3**

Cross sections
The production cross section of various Standard Model processes ranging over 2 orders of magnitude, as measured by one LHC experiment (ATLAS).

**FEATURE LHC RUN 3**

### V o l u m e  6 2   N u m b e r  3   M a y / J u n e  2 0 2 2

**expectations**

It is now

**analysis**

proven that

**It is now**

It is now proven that with advanced analysis strategies we can surpass the expectations from projection studies 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 a 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 multipliers (EGMs) 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 2022 p32). The improved muon momentum resolution they bring also plays a critical role in the trigger systems by keeping the rate low.

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 2022 p30). 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 2022 p4), while a brand new vertex locator and tracking system will allow the reconstruction of charged particles (see p8). 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 3 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 30–40% 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 Higgs boson, simultaneous production of top quarks is also very sensitive to new physics at the top-quark mass. This has already been achieved in Run 2 using fit 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 polarization, which are sensitive to new physics by construction, inclusive cross sections of new 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.
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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 (p-p). 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 p27).

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 p43). 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 “FICs” (amplifying fibre) tracker have been installed (CERN Courier September/October 2021 p43).

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 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 1 TByte flowing from the VELO at full luminosity. A total of 53 silicon pixel detector modules, each with a sensitive surface of about 25 cm², are mounted in two detector halves located on either side of the LHC beams and perpendicular to the beam direction (see “Marvelous modules” image). An important feature of the LHCb VELO is that it moves. During injection of LHC proton beams, 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 1.1 mm to the beams (compared 8.8 mm previously), which is much closer than any of the other 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-pixel/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 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 per VELO half. The large radiation dose experienced by the silicon sensors is distributed by highly non-uniformly and concentrated in the region closest to the beams, with a peak dose 30% 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-
Microcooling
Top a silicon wafer into which microchannels (overlap for illustration only) are etched. Bottom: 3D X-ray tomography showing the microchannels, as well as the distribution of glue between the plate and tiles.

The circulation of coolant in microscopic channels embedded within a silicon wafer is an emergent technology, first implemented at CERN by the NA66 experiment. The Velo upgrade combines this with the use of bi-phase (liquid–to-gas) CO₂, 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 lm trenches etched into it, for an overall thickness of 595 lm. 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 LHC upgrades and several other future detectors.

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 500 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 alignment 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 use these results to assign a grade for each module. This allowed for continuous cross-checks between the two assembly sites. To quantify the effectiveness of the cooling, 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/W. This performance surpasses what is possible for, example, mono-phase microchannel cooling or other high-performance cooling technologies. 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 aluminium hot-pressed deformed sheets, the more complicated layout of the new Velo required them to be machined from solid blocks of small grain–sized forged aluminium. A highly specialised procedure was developed and carried out at Nîlechef using a precision five-axis milling machine (see “RF boxes” image).

In each process of re-coating, the Velo experience showed that the process of re-coating and covering of the layers is a critical step. To ensure the layering is uniform and without defects, the first layer of thin aluminium made from 300 µm-thick sheets is made from 300 µm-thick sheets. To further minimise the thickness in the region of 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-tone-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 boxes are the first obstacles that 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 printed circuit boards, the new design is made from aluminium fins welded together, the more complicated layout of the new Velo required them to be machined from solid blocks of small grain–sized forged aluminium. A highly specialised procedure was developed and carried out at Nîlechef using a precision five-axis milling machine (see “RF boxes” image).

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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 2015 and full approval the following year, the Velo upgrade reflects the ongoing collaboration between 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 security 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.

Further reading

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

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 $K^0 \rightarrow \mu^+\mu^-$ 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 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.

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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.
Most follow the expected pattern of the original quark model, whereas some are new forms of matter such as the doubly-heavy “tetraquark” \( T_{cc} \), 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 2009 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 the so-called transition in a b quark to a c quark, emitting a lepton and an antineutrino. In b → sℓℓ processes, the quark flavour changes through the emission of a b quark on a photon. This flavour-changing neutral-current (FCNC) 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 (RFK), which compare the decay rates of b → sℓℓ decays containing muons to those containing electrons, and R(D0), which compares b → sℓℓ decay rates with muons and tau leptons in the final state. The theoretical precision for these ratios reach O(1%) accuracy, but their measurement suffers from large uncertainties. Novel technologies such as graphics processing units have been incorporated in LHCb’s trigger system to speed up the processing of busy hadron 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 p. 41).

The flavour sector delivered a great harvest in the first ten 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 will push us further, and might unveil deeper layers of nature beyond the SM.

**Virtual production**

A boson diagram (top) and a penguin diagram (bottom).

**New couplings**

Constraints on the \( C_9 \) and \( C_{10} \) effective-field-theory coefficients relevant to the flavour anomalies. The 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 \( \Delta \)LHC constraints.

A promising opportunity to probe physics beyond the SM arises through b → sℓℓ and b → cℓν 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 → sℓℓ processes, the quark flavour changes through the emission of a b quark on a photon. This flavour-changing neutral-current (FCNC) 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.

**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 \( V_{ub} \). So far no measurement has yielded a significant disagreement with SM expectations. However, some of the open questions have not yet been turned.

**Luminous future**

The new dataset 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 in the sample size. The price to pay for this increased luminosity is the daunting number of overlapping collisions in a single proton–proton bunch crossing, which makes the task of selecting through billions of collisions to identify interesting events extremely challenging. 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 p. 41).

The LHCb upgrades completed during LS2 will also serve the experiment for Run 3 and the HL-LHC. 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 → cℓν decays. The expected improvement in the measurement of CP-violation observables is about 30%, and on the CKM angle \( \gamma \) to 1.5%. Further probes of new-photon-flavour non-universality are another key target. The ratios of electroweak penguin processes involving b → sℓℓ transitions, R(K) and R(D0), are expected to be determined with a precision between three to two per cent (see “Anomalous squre” 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 CP-conserving quantities such as the magnitudes of the CKM elements \( V_{cb} \) and \( V_{ub} \), and their mixing. Many directions are being pursued, including precision measurements targeting CP violation and mixing in charm and beauty, and measurements of CP-conserving quantities such as the magnitudes of the CKM elements \( V_{cb} \) and \( V_{ub} \), and their mixing. Many directions are being pursued, including precision measurements targeting CP violation and mixing in charm and beauty, and measurements of CP-conserving quantities such as the magnitudes of the CKM elements \( V_{cb} \) and \( V_{ub} \), and their mixing.

**Anomalous squeeze**

The precision expected on the ratios of B-meson decays involving b → sℓℓ transitions (R(K) and R(D0)) is expected to be determined with a precision between three to two per cent (see “Anomalous squre” figure). Further probes of possible lepton-flavour non-universality are another key target. The ratios of electroweak penguin processes involving b → sℓℓ transitions, R(K) and R(D0), are expected to be determined with a precision between three to two per cent (see “Anomalous squre” figure). Further probes of possible lepton-flavour non-universality are another key target. The ratios of electroweak penguin processes involving b → sℓℓ transitions, R(K) and R(D0), are expected to be determined with a precision between three to two per cent (see “Anomalous squre” figure). Further probes of possible lepton-flavour non-universality are another key target.
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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.

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, 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 these 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 planar (“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 a 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 even- by- event fluctuations and correlations, provide even greater sensitivity to medium properties and the initial-state dynamics. Precision measurements of the $\eta/s$, harmonics, charged-particle density, mean transverse momentum, 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
FEATURE LHC RUN 3

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.

Flow coefficients $\xi$ 

<table>
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<th>$v_2$</th>
<th>$v_3$</th>
<th>$v_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
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</table>

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

Jet multiplicity $\langle n_{ch}^{jet} \rangle$ 

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$R_{pp}$</th>
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<tbody>
<tr>
<td>0.5</td>
<td>0.87</td>
</tr>
<tr>
<td>1.0</td>
<td>0.78</td>
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<tr>
<td>2.0</td>
<td>0.65</td>
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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. $K_L$, $Λ$ and $Ξ^0$) 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 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, 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 jet quenching and collective behaviour, and whether such effects are observed across all nuclear collision systems.

To Run 3 and beyond

All four large experiments at the LHC have undergone significant upgrades during the last two years, to reach and achieve the collection of heavy-ion data at higher luminosities. The increase in luminosity by a factor of 10 in Run 3 allows us to make precision measurements of soft and hard probes of the QGP. Rare probes such as heavy-flavour hadrons will become accessible at the highest statistics, 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.

Freeze out

As the QGP expands and cools, it undergoes a phase transition into hadron gas in which quarks and gluons become confined into hadrons. At chemical freeze-out, inelastic collisions cease and the thermodynamic 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 lead ions. 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 ($0.55\,\text{MeV}$) and volume ($\sim1000\,\text{fm}^3$).

The increase in the LHC luminosity will allow us to perform measurements that were previously inaccessible.
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,
**Antimatter galore at ELENA**

Served directly by the Antiproton Decelerator (AD) for the past two decades, experiments at the AD are now moving to the new ELENA ring, which decelerates 5.3 MeV antiprotons from the AD to a final energy of 3.5 MeV. Now off-line for an upgrade, ELENA is the first project in the number of trapped antiprotons. Six experiments involving around 135 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 antimatter–hydrogen spectroscopy measurements, currently aiming for a precision of two parts per trillion in the transition from the ground state to the first excited state. By clocking the free-fall of antihydrogen atoms 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 2023 p9).

**ASACUSA** specialises in spectroscopic measurements of anti-helium, recently finding surprising behaviour (see p13). The experiment is also gearing up to perform an anti-K meson–hyperon spectroscopy in antihydrogen using atomic–beam techniques.

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**Methods complementary to ALPHA’s trapping techniques.** CIBAR and AigiS target direct measurements of the Earth’s gravitational acceleration on antihydrogen. CIBAR 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. AigiS, 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 Helio deflector. 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 p11). The data also allowed the collaboration to perform the first differential test of the weak equivalence principle using antiprotons, reaching the 1%-level, with experiment improvements soon expected to increase the sensitivities of both measurements. BASE 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 NA64 experiment** focuses on a neutrino beam, and its detectors are becoming a flashpoint in the race for the next generation of neutrino studies, searching for new physics and studying neutrino oscillations (see pp16–17). Following successful results from its first run, the collaboration continues to explore the neutrino flux composition at the future T2K and Hyper-Kamiokande facilities for precise measurements of neutrino mixing angles and the CP-violating phase.

**Different dimensions**

Taking CERN science into a different dimension, the PS1 also links to the Antiproton Factory via the Antiproton Decelerator (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 beam source is the PS Booster, which serves the ISOLDE facility. ISOLDE covers a diverse programme across the physics of exotic nuclei and includes experiments (MEDICIS devoted to the production of novel nuclei) that simulate the act of particulates when measured with magnetic spectrometers and CRIS, which focus on laser spectroscopy (CERN Courier September/October 2013 p3). To explore the region of the nuclei, Neuchâtel’s AEgIS team is working on an improved measurement of the mass differences of protons and antiprotons to be identified within 3% level, with experiment improvements expected to increase these sensitivities of both measurements. AEgIS 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.

**With the many physics opportunities opened up and the consolidation of our facilities, we are looking into a bright future**.
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.

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 done a similar power for a period of 40 years despite their vastly increased scientific output: from 1 TWh for LEP1 to 3.2 TWh for the LHC and possibly 1.4 TWh at the HL-LHC.

The GWh/fb metric has now been adopted by CERN as a key performance indicator (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 among scientific facilities, CERN was at the origin of the Energy for Sustainability 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 forecast and robust monitoring tools. Each year since 2012, 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.

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 the primary motivations for CERN to take energy-efficient measures: to reduce CERN’s carbon footprint, to reduce the costs of 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 an energy-saving uptick 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 13% 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.
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-I upgrade comprises seven main projects. The largest is the new inner tracker, the ITK, which will replace the entire inner detector (Pixel, SCT and TIB) 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 muon, 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.

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 synergistic 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 appreciation for those colleagues who 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 ITK 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.

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 (PTPs). The system had been designed to be capable of evolving into a dual–hardware trigger system with a level-1 trigger able to run up to 4 MHz, and the HTT system reconfigured as a level-2 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’s the status of the protoDUNE modules? The first protoDUNE module based on standard horizontal–drift ("single phase") technology has been successfully completed, with a 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
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This 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 2024, and I am still planning to be hands-on – that is the fun part.

the second based on vertical drift in 2028. For an experiment at such scale, this is non-trivial.

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 ENDER, 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 ERN1 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.

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The Adventure of the Large Hadron Collider: From the Big Bang to the Higgs Boson
By Daniel Denegri, Claude Goyot, Andreas Hoecker and Lydia Roos
World Scientific

With this ambitious book, the authors have produced a unique and exciting 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 strategy 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 75-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 deftly 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.

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, Spp–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 Run 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 SM in general provides an up-to-date collection of results from the LHC’s first to 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, 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 detector flavour and the other 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 new directions in 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 adventur. 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 substantial8 monograph Carlo Rubbia, founding father and tirelessly 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 2012, to all interested in the adventure of the LHC.

Peter Jenni
Albert-Ludwigs-University Freiburg and CERN.

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

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

Picture a scientist

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

“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 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 film tackles the difficulties faced by women in STEM careers. It centers 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 1990s and 1990s, 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 misrepresentations in the lab and described 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, only female Black scientists were exceptional, such as Dr. Trek’s communications officer Nyota Njah.

The film highlights the importance of female scientists speaking out to help people see beyond the tip of the iceberg and 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 all 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 voices 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.
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**PEOPLE CAREERS**

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.

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.”

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 FRESCA 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 pg. 29). 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 ALICE–cd 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 dynamics, 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 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 O”. 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 20 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."

Nick Mchride next CMS spokesperson
Patricia McBride, distinguished scientist at Fermilab, has been elected as the next spokesperson of the CMS collaboration. McBride graduated in physics at Carnegie Mellon University, and completed a PhD at Yale analysing charm decays at Fermilab’s KTeV experiment. Since joining CMS in 2007, 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 after LHCF Run 3 gets underway, and is therefore anticipating exciting times ahead: "CMS is looking forward to the Run 2 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."

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 p97) 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, Aart Toups (Fermilab) was elected co-spokesperson for the MicroBooNE experiment, joining Justin Evans (University of Manchester) in leading the 360-strong collaboration. A key part of Fermilab’s short- and long-baseline neutrino programme, MicroBooNE enables neutrino cross-section measurements to probe the possible existence of non-standard neutrinos (CERN Courier November/December 2022 pp). "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."

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) 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.

2022 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 Gauth (University of Geneva), Alexander Leopold (KTH Royal Institute of Technology), Stefano Popa (Translative University of Brazen) and Zachary Schillaci (Brandeis University). ATLAS students comprise more than a fifth of the 360-strong collaboration, contributing strongly and critically to all areas of the experiment while learning valuable skills for their degrees.

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 cool and trapped atoms with lasers, on behalf of the French president.
RECRUITMENT

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**Theoretical physicist Claude Bouchiat, who was born in Saint-Mandé (southern France) on 16 May 1932, passed away in Paris on 21 November.** He was a frequent visitor to the CERN theory group.

Bouchiat studied at the École Polytechnique in 1953–1959, 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.Y. 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 (now 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’s research covered a large domain that extended beyond particle physics. With Prentki and one of us (IJ), he studied the leading divergences of the weak interactions, which was a precursor to the introduction of charm, and with Danièle Arnaud and Jean-Louis Gervais showed how to build dual diagrams satisfying the unitarity constraints. There is also extended the anomaly equations in the divergence of the axial current to non-abelian theories. In the early 1980s, Bouchiat and collaborators used quantum field theory in the infinite momentum frame to shed light on the parton model.

**Claude Bouchiat 1932–2021**

A profound influence

The exceptionally wide creative range of his activities was most prominently manifested during the preparation of experiments at TGV–scale accelerators. In 1995–1997 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 assembly 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-Aline Bouchiat, was the precise computation of parity-violation effects resulting from virtual Z-boson exchange between electrons and nucleons. 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 64-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.

**Yulian Abramovich Budagov 1932–2021**

World-class experimentalist

Yulian Abramovich Budagov, a world-class experimental physicist and veteran JINR researcher, passed away on 30 December. Born in Moscow on 2 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 weak scattering form factors, observation of QCD colour screening, verification of the analytic properties of QCD–inter- action amplitudes, and observation of scaling

Pierre Fayet and Jean Ilipoulos
École Normale Supérieure.
Particle astrophysics pioneer

Thomas K Gaisser 1941–2022

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 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 particle astrophysics. He was a master of trino astronomy, and then in the emerging field of cosmic-ray physics. He 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 highest-energy particles that reach Earth, and for how that data can be used to probe fundamental questions in particle physics.

Tom's work was also vital in interpreting data from lower-energy neutrino experiments, such as MINOS and KamLAND. 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 investigated air showers as a means of making air show- ers a leading role for Tom in the IceCube Neutrino Observatory, where he served as spokesperson for 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 200 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 traveled 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 1995, 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.
CERN COURIER MAY/JUNE 2022

BACKGROUND

Notes and observations from the high-energy physics community

Noether tops the board

From 15 March to 4 April, inspired by the “March Madness” single-elimination college basketball tournament, Perimeter Institute’s Physics Fronts Battle of the Equations saw 96 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 bowed 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 dethroned Schrödinger’s hopes to set up a tense finale with Noether’s theorem, still fresh from victories over the Hubble’s RELICS programme using data collected during the individual star ever observed, Earth from Earendel – the farthest.

On 30 April 1962, Stanford University trustees signed the construction contract for SLAC, centered around a 3.3 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 to reach Earth from Earendel – the farthest individual star ever observed, using data collected during Hubble’s RELICS programme (Nature 603 85).

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 CERN’s new measurement of the W-boson mass (see p9).

“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 Norena speaking to EPS (19 March) on the possible falsification of real-number quantum theory (Nature 600 628).

“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 Russian ‘observer’ status while standing behind Russian scientists at the lab.”

Physics world editor Martin Durrani on the chilling impact on science of Russia’s invasion of Ukraine (6 March).

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 300 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 cm aperture and length of 70 cm. In this way, the existing tunneling 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 T.

First tests gave a central field of 5.3 T and a current of 350 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 6–10 T.

Based on text from p32 of CERN Courier June 1982.

Compiler’s note

The decision to proceed with the 22 km–circuiture 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 1969, however, a lack of financial 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 magnets, showing the two-layer structure of the coil.

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