WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2023 issue of *CERN Courier*.

Further exploring the boundless efforts of the LHC-experiment collaborations to maximise the scientific output of the High-Luminosity LHC, the ALICE (p35) and LHCb (p22) collaborations set out their plans for major upgrades that are also of strategic interest for future collider experiments. Addressing why extending the study of nature at LHC energies is worth the considerable efforts involved, theorist Veronica Sanz argues that we all should embrace the paths that the Higgs' discovery has opened (p39), while Leonard Susskind reflects on 20 years of the string-theory landscape (p41).

Shorter term, the pursuit of the biggest questions continues to reap unexpected rewards. Five years since its creation out of efforts to test technologies for CLIC, the CLEAR facility at CERN has allowed groups from more than 30 institutions across more than 10 nations to advance applications ranging from compact X-ray sources to next-generation cancer treatments (p28), while autonomous-vehicle manufacturers are benefitting from CERN's expertise in machine learning (p9). Translating "big science" into applications is difficult, but, done well, helps companies to fast-track the development of innovative products, services and applications (p31).

All this and more in this issue, including sterile neutrinos (p8), inexplicable photons (p11), meeting reports (p17), reviews (p45), careers (p47) and a new spin on the Stern–Gerlach experiment (p54).

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EDITOR: MATTHEW CHALMERS, CERN
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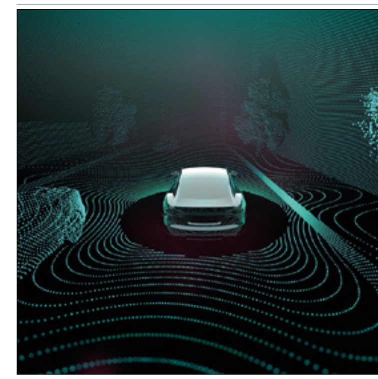

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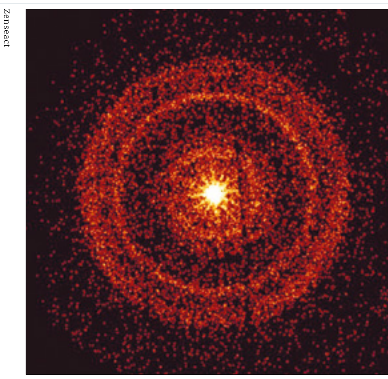

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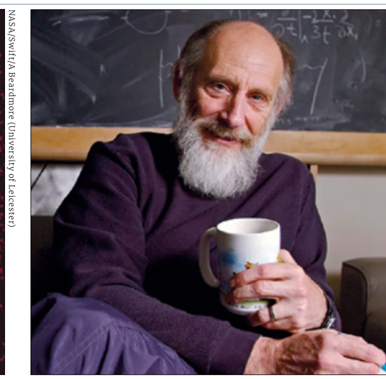

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FROM THE EDITOR

Paving the way for future exploration

Matthew Chalmers
Editor

This issue further explores the boundless efforts of the LHC-experiment collaborations to maximise the scientific output of the High-Luminosity LHC (HL-LHC), due to begin operations in 2029. Following reports on the ongoing ATLAS and CMS "Phase II" upgrades in the previous issue, the ALICE (p35) and LHCb (p22) collaborations set out their plans for major upgrades which are also of strategic interest for future collider experiments.

"ALICE 3" will be a new, compact, large-acceptance tracking and particle-identification detector with high readout rates. It is being proposed to address important questions about the quark–gluon plasma, including what are the conditions leading to the formation of hadrons, that will remain open even after the current LHC Run 3 and future Run 4. For "LHCb Upgrade II", rethinking the data acquisition, trigger and data processing, among other advances, will be vital to take advantage of the HL-LHC's five-times-higher average data rate, allowing a wide range of flavour observables to be explored with extreme precision.

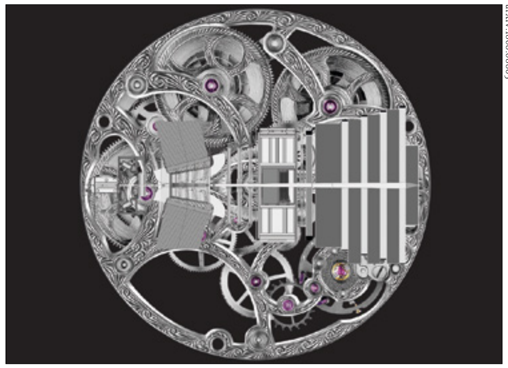
Both ALICE and LHCb underwent significant upgrades during Long Shutdown 2. If approved, their next metamorphoses will take place during Long Shutdown 4 beginning in 2033. This would serve physicists from Run 5 to the end of HL-LHC operations scheduled in 2041, fulfilling the recommendation of the 2020 European strategy update "that the full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark–gluon plasma, should be exploited".

Persistence pays

One may ask why extending the study of nature at LHC energies is worth the considerable efforts involved. After all, 10 years after the discovery of the Higgs boson, the hope that it would be accompanied by a supporting cast of TeV-scale particles has not yet materialised. That would be to misunderstand the meaning of fundamental exploration, argues this issue's Viewpoint; we all should embrace the paths that the Higgs' discovery has opened, renew the enthusiasm that built the LHC and be outspoken about the profound ideas we explore (p39).

We all should embrace the paths that the Higgs' discovery has opened

String theory is a case in point. It is now two decades since it was shown that this attempt to find a deeper theory has an inordinate number of possible solutions, none of which seem to correspond directly to our world. String-theory pioneer Leonard Susskind, who coined "the landscape" to sum-up this unsettling picture, describes the fascinating vistas that this half-century-long journey has painted so far (p41), while the "swampland" programme (p20) further attempts to root string theory in reality.



All in good time *Artwork from LHCb's Upgrade II framework TDR.*

Shorter term, the pursuit of the biggest questions continues to reap unexpected rewards. Five years since its creation out of efforts to test technologies for CLIC, the CLEAR facility at CERN has allowed groups from more than 30 institutions across more than 10 nations to advance applications ranging from compact X-ray sources to next-generation cancer treatments (p28), while autonomous-vehicle manufacturers are benefitting from CERN's expertise in machine learning (p9). Translating "big science" into applications is difficult, but, done well, helps companies to fast-track the development of innovative products, services and applications (p31).

All this and more in this issue, including sterile neutrinos (p8), inexplicable photons (p11), meeting reports (p17), reviews (p45), careers (p47) and a new spin on Stern–Gerlach (p54).

Reporting on international high-energy physics

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NEWS ANALYSIS

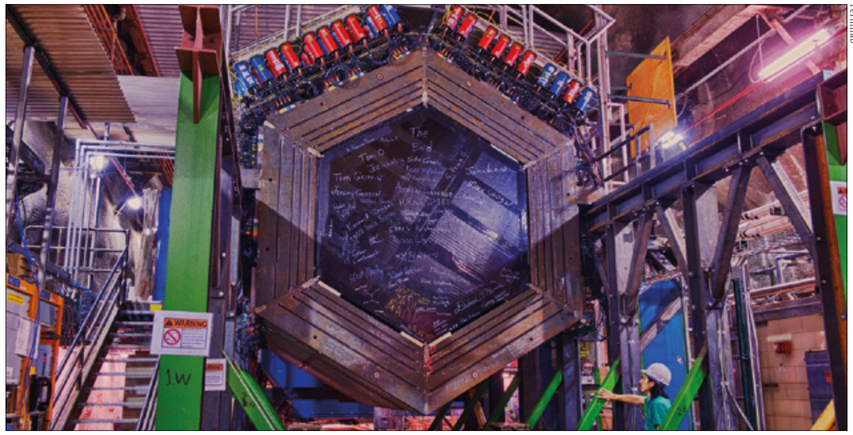
Proton structure

Neutrino scattering sizes up the proton

More than a century after its discovery, physicists are still working hard to understand how fundamental properties of the proton – such as its mass and spin – arise from its underlying structure. A particular puzzle concerns the proton's size, which is an important input to understand nuclei, for example. Inelastic electron–proton scattering experiments in the late 1950s revealed the spatial distribution of charge inside the proton, allowing its radius to be deduced. A complementary way to determine this "charge radius", and which relies on precise quantum-electrodynamics calculations, is to measure the shift it produces in the lowest energy levels of the hydrogen atom. Over the decades, numerous experiments have measured the proton's size with increasing precision.

By 2006, based on results from scattering and spectroscopic measurements, the Committee on Data for Science and Technology (CODATA) had established the proton charge radius to be 0.8760(78) fm. Then, in 2010, came a surprise: the CREMA collaboration at the Paul Scherrer Institut (PSI) reported a value of 0.8418(7) fm based a novel, high-precision spectroscopic measurement of muonic hydrogen. Disagreeing with previous spectroscopic measurements, and lying more than 5σ below the CODATA world average, the result gave rise to the "proton radius puzzle". While the most recent electron–proton scattering and hydrogen-spectroscopy measurements are in closer agreement with the latest muonic-hydrogen results, the discrepancies with earlier experiments are not yet fully understood.

Now, the MINERvA collaboration has brought a new tool to gauge the proton's size: neutrino scattering. Whereas traditional scattering measurements probe the proton's electric or magnetic charge distributions, which are encoded in vector form factors, scattering by neutrinos allows the analogous axial-vector form factor F_A, which characterises the proton's weak charge distribution, to be measured. In addition to providing a complementary probe of proton structure, F_A is key to precise measurements of neutrino-oscillation parameters at experiments such as DUNE, Hyper-K, NOvA and T2K.



Fermilab

Light gauge Located 100 m underground at Fermilab, MINERvA was designed to perform high-precision measurements of neutrino interactions with a wide range of materials.

MINERvA is a segmented scintillator detector with hexagonal planes made from strips of triangular cross-section, which are assembled into planes perpendicular to the incoming beam. By studying how a beam of muon antineutrinos produced by Fermilab's NuMI neutrino beamline interacts with a polystyrene target, which contains hydrogen closely bonded to carbon, the MINERvA researchers were able to make the first high-statistics measurement of the $\bar{\nu}_\mu p \rightarrow \mu^+ n$ cross-section using the hydrogen atom in polystyrene. Extracting F_A from 5580±180 signal events (observed over an estimated background of 12,500), they measured the nucleon axial charge radius to be 0.73(17) fm, in agreement with the electric charge radius measured with electron scattering.

"If we weren't optimists, we'd say [this measurement] was impossible," says lead author Tejin Cai, who proposed the idea of using a polystyrene target to access neutrino-hydrogen scattering while a PhD student at the University of Rochester. "The hydrogen and carbon are chemically bonded, so the detector sees interactions on both at once. But then, I realised that the very nuclear effects that made scattering on carbon complicated also allowed us to select hydrogen and would allow us to subtract off the carbon interactions."

A new experiment called AMBER, at the M2 beamline of CERN's Super Proton Synchrotron, is about to open another perspective on the proton charge radius. AMBER is the successor to COMPASS, which played a major role towards resolving the proton "spin crisis" (the finding, by the European Muon Collaboration in 1987, that quarks account for less than a third of the total proton spin) by studying the contribution to the proton spin from gluons. Instead of electrons, AMBER will use muon scattering at unprecedented energies (around 100 GeV) to access the small momentum-transfer needed to measure the proton radius. A future experiment at PSI called MUSE, meanwhile, aims to determine the proton radius through simultaneous measurements of muon– and electron–proton scattering.

AMBER is scheduled to start with a pilot run in September 2023 and to operate for up to three years, with the goal to find a value for the proton radius in the range 0.84–0.88 fm, as expected from previous experiments, and with an uncertainty of about 0.01 fm. "Some colleagues say that there is no proton-radius puzzle, only problematic measurements," says AMBER spokesperson Jan Friedrich of TU Munich. "The discrepancy between theory and experiments, as well as between individual experiments, will have to shrink and align as much as possible. After all, there is only one true proton radius."

Further reading
T Cai *et al.* 2023 *Nature* **614** 48.
J-P Karr *et al.* 2020 *Nat. Rev. Phys.* **2** 601.

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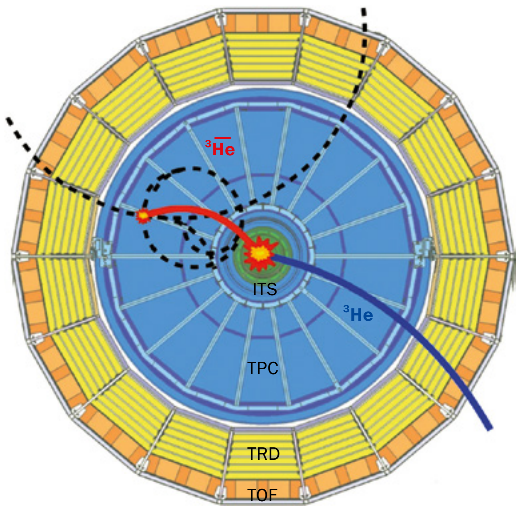
ANTIMATTER

ALICE looks through the Milky Way

Antinuclei can travel vast distances through the Milky Way without being absorbed, concludes a novel study by the ALICE collaboration. The results, published in December, indicate that the search for $^3\overline{\text{He}}$ in space is a highly promising way to probe dark matter.

First observed in 1965 in the form of the antideuteron ($\bar{p}\,\bar{n}$) at CERN's Proton Synchrotron and Brookhaven's Alternating Gradient Synchrotron, antinuclei are exceedingly rare. Since they annihilate on contact with regular matter, no natural sources exist on Earth. However, light antinuclei have been produced and studied at accelerator facilities, including recent precision measurements of the mass difference between deuterons and antideuterons and between ^{3}He and $^3\overline{\text{He}}$ by ALICE, and between the hypertriton and antihypertriton by the STAR collaboration at RHIC.

Antinuclei can in principle also be produced in space, for example in collisions between cosmic rays and the interstellar medium. However, the expected production rates are very small. A more intriguing possibility is that light antinuclei are produced by the annihilation of dark-matter particles. In such a scenario, the detection of antinuclei in cosmic rays could provide experimental evidence for the existence of dark-matter particles. Space-based experiments such as AMS-02 and PAMELA, along with the upcoming Antarctic balloon mission GAPS, are among a few experiments that are able to detect light antinuclei. But to be able to interpret future results, precise knowledge of the production and disappearance probabilities of antinuclei is vital.



Annihilation *Schematic showing a $^3\overline{\text{He}}$ annihilating in the gas of the ALICE time projection chamber (red) and a ^{3}He that does not undergo an inelastic reaction and reaches the time-of-flight detector (blue), with dashed curves representing charged (anti) particles produced in the $^3\overline{\text{He}}$ annihilation. (Source:* Nat. Phys. **19** *61)*

The latter is where the new ALICE study comes in. The unprecedented energies of proton–proton and lead–lead collisions at the LHC produce, on average, as many nuclei as antinuclei. By studying the change in the rate of $^3\overline{\text{He}}$ as a function of the distance to the production point, the collaboration was able to determine the inelastic cross section, or disappearance probability, of $^3\overline{\text{He}}$ nuclei for the first time. These values were then used as input for astrophysics simulations.

Two models of the $^3\overline{\text{He}}$ flux expected near Earth after the nuclei's journey from sources in the Milky Way were considered: one assumes that the sources are cosmic-ray collisions with the interstellar medium, and the other annihilations of hypothetical weakly interacting massive particles (WIMPs). For each model, the Milky Way's transparency to $^3\overline{\text{He}}$ – that is, its ability to let the nuclei through without being absorbed – was estimated. The WIMP dark-matter model led to a transparency of about 50%, whereas for the cosmic-ray model the transparency ranged from 25 to 90%, depending on the energy of the antinucleus. These values show that $^3\overline{\text{He}}$ originating from dark-matter or cosmic-ray collisions can travel distances of several kiloparsecs in the Milky Way without being absorbed, even from as far away as the galactic centre.

"This new result illustrates the close connection between accelerator-based experiments and observations of particles produced in the cosmos," says ALICE spokesperson Marco van Leeuwen. "In the near future, these studies will be extended to $^4\overline{\text{He}}$ and to the lower-momentum region with much larger datasets."

Further reading

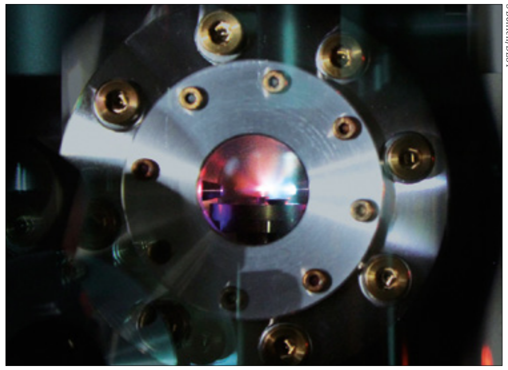
ALICE Collab. 2023 *Nat. Phys.* **19** 61.

ACCELERATORS

Plasma acceleration under the microscope

A team led by DESY researchers has used a noninvasive technique to measure the energy evolution of an electron bunch inside a laser-plasma accelerator for the first time, opening new possibilities to understand the fundamental mechanisms behind this next-generation accelerator technology.

Laser-driven plasma-wakefield acceleration, which is under study at DESY, SLAC and several other labs worldwide, promises to significantly reduce the size of particle accelerators. The idea is to use a high-power laser to create a plasma in a gas, in which charge displacements generate electric fields of the order 100 GV/m. Such fields can accelerate electron bunches to highly relativistic energies over short distances, outperforming conventional radio-frequency technologies by orders of magnitude. The AWAKE experiment at CERN, meanwhile, is a unique facility for the investigation of proton-driven plasma acceleration. Turning the concept of wakefield acceleration into a practical device, on the other hand, is a major challenge.



S Bohlen/DESY

Wakefield insight *Light from the 1 mm-long helium plasma in which the electrons were accelerated.*

In order to understand and thus improve the process of laser-plasma acceleration, which lasts for a period of femtoseconds to picoseconds, it is essential to observe as precisely as possible how the properties of the accelerated particles change in the plasma. Publishing their results in December, a team led by DESY's Simon Bohlen and Kristjan ▷ Põder tracked the evolution of the electron beam energy inside a laser-plasma accelerator with high spatial resolution. The feat was performed within a project called PLASMED X, which aims to develop a compact, narrowband and tunable X-ray source for medical imaging.

The team began by splitting the laser beam into two parts: one was used for electron acceleration, while the other was superimposed so that the light could be scattered by the electrons. Using an X-ray detector to measure the energy of Thomson-scattered photons at 20 points over a 400 μm section of the plasma, the team was able to reconstruct the energy evolution of the electrons over most of the accelerator length without disturbing either the electron beam or the acceleration process itself.

Turning the concept of wakefield acceleration into a practical device is a major challenge

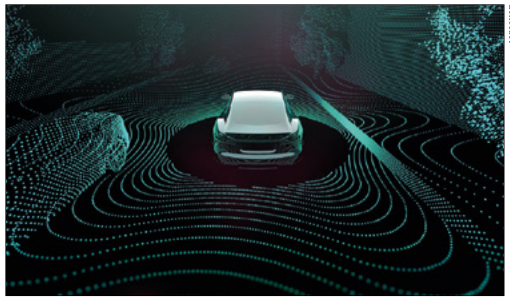
"We were able to show in our measurements that the acceleration gradient can change significantly over very short distances," says Bohlen. "With the new measurement method, we now have direct insight into a plasma acceleration process and can thus investigate the direct influence of different laser parameters or geometries of plasma cells on the acceleration process."

Further reading

S Bohlen *et al.* 2022 *Phys. Rev. Lett.* **129** 244801.

APPLICATIONS

Deep learning for safer driving



Zenseact

Hands-free *CERN and Sweden-based firm Zenseact explored ways to allow autonomous vehicles to make faster decisions.*

How quickly can a computer make sense of what it sees without losing accuracy? And to what extent can AI tasks on hardware be performed with limited computing resources? Aiming to answer these and other questions, car-safety software company Zenseact, founded by Volvo Cars, sought out CERN's unique capabilities in real-time data analysis to investigate applications of machine-learning to autonomous driving.

In the future, self-driving cars are expected to considerably reduce the number of road-accident fatalities. To advance developments, in 2019 CERN and Zenseact began a three-year project to research machine-learning models that could enable self-driving cars to make better decisions faster. Carried out in an open-source software environment, the project's focus was "computer vision" – an AI discipline dealing with how computers interpret the visual world and then automate actions based on that understanding.

"Deep learning has strongly reshaped computer vision in the last decade, and the accuracy of image-recognition applications is now at unprecedented levels. But the results of our research show that there's still room for improvement when it comes to running the deep-learning algorithms faster and being more energy-efficient on resource-limited on-device hardware," said Christoffer Petersson, research lead at Zenseact. "Simply put, machine-learning techniques might help drive faster decision-making in autonomous cars."

The need to react fast and make quick decisions imposes strict runtime requirements on the neural networks that run on embedded hardware in an autonomous vehicle. By compressing the neural networks, for example using fewer parameters and bits, the algorithms can be executed faster and use less energy. For this task, the CERN–Zenseact team chose field-programmable gate arrays (FPGAs) as the hardware benchmark. Used at CERN for many years, especially for trigger readout electronics in the large LHC experiments, FPGAs are configurable integrated circuits that can execute complex decision-making algorithms in periods of microseconds. The main result of the FPGA experiment, says Petersson, was a practical demonstration that computer-vision tasks for automotive applications can be performed with high accuracy and short latency, even on a processing unit with limited computational resources. "The project clearly opens up for future directions of research. The developed workflows could be applied to many industries."

The compression techniques in FPGAs elucidated by this project could also have a significant effect on "edge" computing, explains Maurizio Pierini of CERN: "Besides improving the trigger systems of ATLAS and CMS, future development of this research area could be used for on-site computation tasks, such as on portable devices, satellites, drones and obviously vehicles."

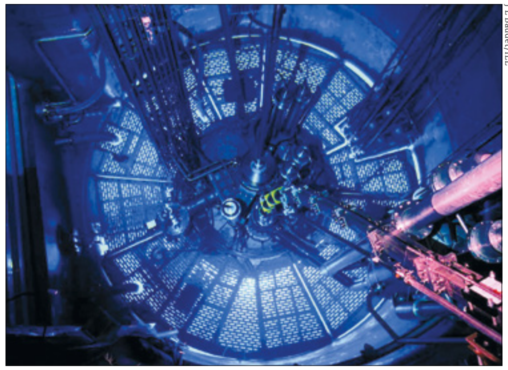
Further reading

N Ghielmetti *et al.* 2022 *Mach. Learn.: Sci. Technol.* **3** 045011.

T Aarrestad *et al.* 2021 *Mach. Learn.: Sci. Technol.* **2** 045015.

STERILE NEUTRINOS

STEREO rejects sterile neutrino



L Baudet/ILL

No news *ILL's high-flux reactor, at which the STEREO collaboration conducted their measurement of the $\bar{\nu}_e$ spectrum.*

The STEREO experiment, located at the high-flux research reactor at the Institut Laue-Langevin (ILL), Grenoble, is the latest to cast doubt on the existence of an additional, sterile neutrino state. Based on the full dataset collated from October 2017 until the experiment shut down in November 2020, the results support the conclusions of a global analysis of all neutrino data, that a normalisation bias in the beta-decay spectrum of ^{235}U is the most probable explanation for a deficit of electron neutrinos seen at reactor experiments during the past decade.

The confirmation of neutrino oscillations 25 years ago showed that the lepton content of a given neutrino evolves as it propagates, generating a change of flavour. Numerous experiments based on solar, atmospheric, accelerator, reactor and geological neutrino sources have determined the oscillation parameters in detail, reaffirming the three-neutrino picture obtained by precise measurements of the Z boson's decay width at LEP. However, several anomalies have also shown up, one of the most prominent being the so-called reactor antineutrino anomaly. Following a re-evaluation of the expected $\bar{\nu}_e$ flux from nuclear reactors by a team ▷

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at CEA and Subatech in 2011, a deficit in the number of $\bar{\nu}_e$ detected by reactor neutrino experiments appeared. Combined with a longstanding anomaly reported by short-baseline accelerator–neutrino experiments such as LSND and a deficit in $\bar{\nu}_e$ seen in calibration data for the solar-neutrino detectors GALLEX and SAGE, excitement grew that an additional neutrino state – a sterile or right-handed neutrino with non-standard interactions that arises in many extensions of the Standard Model – might be at play.

Designed specifically to investigate the sterile-neutrino hypothesis, STEREO was positioned about 10 m from the ILL reactor core to measure the evolution of the antineutrino energy spectrum from ^{235}U fission at short distances with high precision. Comprising six cells filled with gadolinium-doped liquid scintillator positioned at different distances from the reactor core, producing six spectra, the setup allows the hypothesis that $\bar{\nu}_e$ undergo a fast oscillation into a sterile neutrino to be tested independently of the predicted shape of the emitted $\bar{\nu}_e$ spectrum.

The measured antineutrino energy spectrum, based on 107,558 detected antineutrinos, suggests that the previously reported anomalies originate from biases in the nuclear experimental data used for the predictions, while rejecting the hypothesis of a light sterile neutrino with a mass of about 1 eV. "Our result supports the neutrino content of the Standard Model and establishes a new reference for the ^{235}U antineutrino energy spectrum," writes the team. "We anticipate that this result will allow progress towards finer tests of the fundamental properties of neutrinos but also to benchmark models and nuclear data of interest for reactor physics and for observations of astrophysical or geoneutrinos."

We anticipate that this result will allow progress towards finer tests of the fundamental properties of neutrinos

Gallium remains

STEREO's findings fit those reported recently by other neutrino-oscillation experiments. A 2021 analysis by the MicroBooNE collaboration at Fermilab, for example, favoured the Standard Model over an anomalous signal seen by its nearby experiment MiniBooNE, assuming the latter was due to the existence of a non-standard neutrino. Yet the story of the sterile neutrino is not over. In 2022, new results from the Baksan Experiment on Sterile Transitions (BEST) further confirmed the deficit in the $\bar{\nu}_e$ flux emitted from radioactive sources as seen by the SAGE and GALLEX experiments – the so-called gallium anomaly – which, if interpreted in the context of neutrino oscillations, is consistent with $\nu_e \rightarrow \nu_s$ oscillations with a relatively large squared mass difference and mixing angle.

"Under the sterile neutrino hypothesis, a signal in MicroBooNE, MiniBooNE or LSND would require the sterile neutrino to mix with both ν_e and ν_μ, whereas for the gallium anomaly, mixing with ν_e alone is sufficient," explains theorist Joachim Kopp of CERN. "Even though the reactor anomaly seems to be resolved, we'd still like to understand what's behind the others."

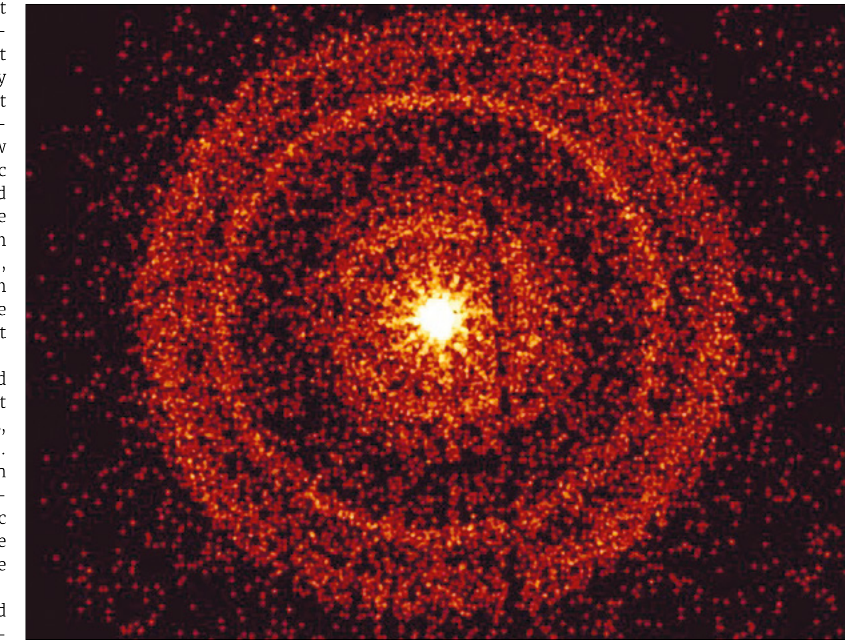
Further reading

STEREO Collab. 2023 *Nature* **613** 257.
A Letourneau *et al.* 2023 *Phys. Rev. Lett.* **130** 021801.
MicroBooNE Collab. 2023 *Phys. Rev. Lett.* **130** 011801.

ASTROWATCH

TeV photons challenge standard explanations

Gamma-ray bursts (GRBs) are the result of the most violent explosions in the universe. They are named for their bright burst of high-energy emission, mostly in the keV to MeV region, which can last from milliseconds to hundreds of seconds, and are followed by an afterglow that covers the full electromagnetic spectrum. The extreme nature and important role in the universe of these extragalactic events – for example in the production of heavy elements, potential cosmic-ray acceleration or even mass-extinction events on Earth-like planets – makes them one of the most studied astrophysical phenomena.


NASA/Swift/A Beardmore (University of Leicester)

Afterglow *GRB 221009A captured by NASA's Neil Gehrels Swift Observatory approximatively one hour after the record-breaking gamma-ray emission, showing bright rings formed by X rays scattering off dust layers within our galaxy.*

Since their discovery in 1967, detailed studies of thousands of GRBs show that they are the result of cataclysmic events, such as neutron-star binary mergers. The observed gamma-ray emission is produced (through a yet-unidentified mechanism) within relativistic jets that decelerate when they strike interstellar matter, resulting in the observed afterglow.

But interest in GRBs goes beyond astrophysics. Due to the huge energies involved, they are also a unique lab to study the laws of physics at their extremes. This once again became clear on 9 October 2022, when a GRB was detected that was not only the brightest ever but also appeared to have produced an emission that is difficult to explain using standard physics.

Eye-catching emission

"GRB 221009A" immediately caught the eye of the multi-messenger community, its gamma-ray emission being so bright that it saturated many observatories. As a result, it was also observed by a wide range of detectors covering the electromagnetic spectrum, including at energies exceeding 10 TeV. Two separate ground-based experiments – the Large High Altitude Air Shower Observatory (LHAASO) in China and the Carpet-2 air-shower array in Russia – claimed detections of photons with an energy of 18 TeV and 251 TeV, respectively. This is significantly higher, by an order of magnitude, than the previous record for TeV emission from GRBs reported by the MAGIC and HESS telescopes in 2019 (*CERN Courier* January/February 2020 p10). Adding further intrigue, such high-energy emission from GRBs should not be able to reach Earth at all.

For photons with energies exceeding several TeV, electron–positron pair-production with optical photons starts to become possible. Although the cross section for this process only just exceeds its threshold at an energy of 2.6 TeV, it is compensated by the billions of light years of space filled with optical light that the TeV photons need to traverse before reaching us. Despite uncertainties in the density of this so-called extragalactic background light, a rough calculation using the distance of GRB 221009A (z = 0.151) suggests that the probability for an 18 TeV photon to reach Earth is around 10^{-8}.

The reported measurements have thus far only been provided through alerts shared among the multi-messenger community, while detailed data analyses are still ongoing. Their significance, however, led to tens of beyond-the-Standard Model (BSM) explanations being posted on the arXiv preprint server within days of the alert. While each differs in the specific mechanism hypothesised, the overall idea is similar: instead of being produced directly in the GRB, the photons are posited to be a secondary product of BSM particles produced during or close to the GRB. Examples range from light scalar particles or right-handed neutrinos produced in the GRB and decaying within our galaxy, to photons that converted into axions close to the GRB and turned back into photons in the galactic magnetic field before reaching Earth.

Clearly we need to wait for the detailed analyses by LHAASO and Carpet-2 to confirm the measurements

Clearly the community needs to wait for the detailed analyses by the LHAASO and Carpet-2 collaborations to confirm the measurements. The published energy resolution of LHAASO keeps open the possibility that their results can be explained with Standard Model physics, while the 251 TeV emission from Carpet-2 is more difficult to attribute to known systematic effects. This result could, however, be explained by secondary particles resulting from an ultra-high energy cosmic-ray (UHECR) produced in the GRB which, although would not represent new physics, would still confirm GRBs as a source of UHECRs for the first time. Analysis results from both collaborations are therefore highly anticipated.

Further reading

S Balaji *et al.* 2023 arXiv:2301.02258.
Z-C Zhao *et al.* 2022 arXiv:2210.10778.
A L Melott *et al.* 2004 *IJA* **3** 55.

NEWS DIGEST

The DUNE caverns so far.

Digging deep for DUNE

Almost 50% of the excavation work needed to host the giant liquid-argon detectors for the Deep Underground Neutrino Experiment (DUNE) at SURF in South Dakota is complete, announced Fermilab on 17 January. Since works began in January 2021, around 400,000 tonnes of rock have been dug out and transported 1.5 km to the surface. Once complete in 2024, the underground area will comprise three large caverns: two will house four DUNE detector modules, while the third will be used for cryogenic support systems, detector electronics and data-acquisition equipment. Meanwhile 1300 km away at Fermilab, the construction contract to build the PIP-II accelerator, which will send bright beams of neutrinos to DUNE, has been awarded to Whittaker Construction & Excavating Inc.

LHCb data out in the open

In December 2022, as part of CERN's open-science policy (*CERN Courier* November/December 2022 p10), the LHCb collaboration publicly released its first data, comprising about 200 TB, or 20% of the experiment's Run 1 dataset. So far, the collaboration has made published results and preprocessed raw data, along with specific LHCb algorithms to help users reproduce results and carry out analyses, available for download on CERN's Open Data Portal, with further Run 1 releases in progress. Also in December, the CMS collaboration completed its full public release of Run 1 data, comprising 491 TB and accompanied by example codes. After having released Run 1 data in 2016, ATLAS too plans to release a sizeable fraction of Run 2 data at the end of this year.

HYPER dark matter

Faced with null results in the direct search for WIMP dark matter (DM), Gilly Elor of the University of Mainz and Robert McGehee and Aaron Pierce of the University of Michigan have proposed a new sub-GeV mass-DM candidate called HYPER (highly interactive particle relics). HYPERs, which are designed to evade tight cosmological bounds on existing DM candidates, refer to DM scenarios in which the mediator mass drops after the DM relic abundance is determined, thus boosting present-day interactions between dark and ordinary matter. As such, HYPERs can evade already excluded parameter spaces for sub-GeV DM particles, and could be detected by future superfluid helium or diamond-based detectors, say the authors (*Phys. Rev. Lett.* **130** 031803).

ATLAS shines like never before

In December, the ATLAS collaboration released the results of its Run 2 luminosity measurement – a key component of cross-section measurements and precision searches in the ATLAS physics programme. Improving upon the precision of the Run 1 luminosity by a factor of two, the collaboration's Run 2 integrated luminosity certified as good for physics analysis is found to be $140.1 \pm 1.2\,\mathrm{fb}^{-1}$. With an uncertainty of 0.83%, it is the most precise luminosity measurement at a hadron collider to date, and is comparable to the precision achieved for second-generation total cross-section experiments at the CERN ISR. To count the particles in the luminosity detectors, van der Meer beam-separation scans were performed during special runs, and the obtained calibration extrapolated and closely monitored during standard physics data-taking. CMS produced a Run 2 luminosity measurement in 2021 (*CERN Courier* November/December 2021 p39).

Webb finds its first exoplanet

Less than a year after entering science operations, the James Webb Space Telescope (JWST) has spotted its first exoplanet – an Earth-sized rocky planet orbiting the red-dwarf star LHS 475. Following up on earlier hints that this star might host a planet obtained by the Transiting Exoplanet Survey Satellite, Webb's near-infrared spectrometer was able to confirm the finding with only two transit observations. Orbiting its host in only two days, and at a distance of 41 light years from Earth, "LHS 475b" is among the closest rocky planets found so far, with a surface temperature and an unknown atmospheric composition that point towards a potentially inhabitable world. To date, astronomers have confirmed 5307 exoplanets, only a small fraction of which appear Earth-like.

An impression of LHS 475b by DeepAI's Fantasy World Generator.

Energy management certified

Demonstrating CERN's ongoing commitment to responsible energy management, the organisation was awarded the ISO 50001 certification on 2 February. Lasting for three years, this benchmark international standard for implementing systems and processes to continually improve energy performance entails setting up, monitoring and improving an energy-management system – which is aligned with CERN's Energy Policy, released in 2022 – along with the relevant legislation.

Capping ADMX sensitivity

The new CAPP-12TB haloscope, built around a powerful 12 T Nb_3Sn magnet at the Center for Axion and Precision Physics Research (CAPP) in South Korea, has reached critical "Dine–Fischler–Srednicki–Zhitnitsky" sensitivity to dark matter, excluding the axion-photon coupling $g_{a\gamma\gamma}$ down to $6.2 \times 10^{-16}\,\mathrm{GeV}^{-1}$ for axion-dark matter between 4.51 and 4.59 μeV at 90% confidence. This sensitivity further excludes "Kim–Shifman–Vainshtein–Zakharov" axion dark matter and pushes the experiment towards sensitivities comparable to those obtained by ADMX at the University of Washington (arXiv:2210.10961).

Cosmic muons for encryption

A novel idea called COSMOCAT, proposed by high-energy geophysicist Hiroyuki Tanaka (University of Tokyo), would transfer secure messages by using cosmic-ray muons as random-number generators. Following a Poisson process, arrival-time distributions of cosmic-ray muons are well-suited to create true and random-number sequences. The keys are generated by a technique called cosmic time synchronisation, which uses the speed of the muons to measure the distance between two vertically spaced detectors equipped with synchronised clocks. Knowing the distance between the two detectors, the sender thus knows the exact arrival time of cosmic muons at the receiver's detector. Thus, the key can be decoded by decoding the muon's arrival time without the need to exchange information between sender and receiver (*iScience* **26** 105897).

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Strong coupling probed beyond the TeV scale

Due to asymptotic freedom, the theory of quantum chromodynamics (QCD), which describes the strong interaction acting on quarks and gluons, becomes weaker at short-distance (high-energy) scales. The value of the strong coupling constant α_s at different scales can be determined using experimental observables that characterise the geometrical distribution of the outgoing hadrons from particle collisions. Among such observables are energy–energy correlations, which are obtained by computing the angular difference between all the possible pairs of final-state particles, weighted by the product of the normalised energies of the two particles involved.

Precision tests

Energy–energy correlations had a significant impact on early precision tests of QCD, such as those performed at the PETRA e^+e^- collider at DESY, where the gluon was discovered, and on the determination of α_s. At hadron colliders such as the LHC, where the longitudinal momentum of the colliding partons is unknown, longitudinally invariant quantities are defined instead. The transverse energy–energy correlation (TEEC) function is defined as the transverse energy-weighted azimuthal-angular distribution of jet pairs, covering the full cos(ϕ) range, where ϕ is the azimuthal angular difference between the two jets. The TEEC distribution peaks at the edges of the cos(ϕ) range due to self-correlations, i.e. the angle between a jet and itself, and due to di-jet back-to-back configurations arising from momentum conservation between both jets in the transverse plane. Moreover, due to additional gluon radiation, a central plateau whose height is sensitive to the value of α_s arises.

ATLAS has recently measured the TEEC distributions in multi-jet events and used them to determine α_s. The analysis is performed using the full data sample ($139\,fb^{-1}$) of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded during LHC Run 2. The measurements are presented in bins of the scalar sum of the transverse momenta of the two leading jets in the collision event (H_{T2}), and are corrected for detector effects. By fitting theoretical calculations to the experimental data, the value of α_s is determined in different kinematic regions, thereby testing the running of the strong coupling strength at high energy scales.

The results are 30% more precise than previous ATLAS measurements at 7 and 8 TeV, with a total systematic uncertainty of the order of 2.5% for the TEEC functions. The level of precision used for the theoretical predictions is equally important for the extraction of α_s as that of the data. Finite predictions as a function of the value of $\alpha_s(m_Z)$, where m_Z is the Z-boson mass, are calculated at next-to-next-to-leading order (NNLO) in perturbative QCD for three-jet configurations and corrected for non-perturbative effects, reducing the theoretical uncertainties in the central plateau from 6% at next-to-leading order (NLO) down to 2% for the NNLO predictions.

The ratio of data to theoretical predictions for the TEEC functions in the various H_{T2} bins is shown in figure 1. The overall description of the shape at NNLO is found to be in agreement with the data, thus confirming our understanding of strong interactions over a large range of momentum transfers. Values of α_s are determined from individual fits of the theoretical predictions to data in each H_{T2} bin. In addition, a global fit to the measured TEEC distributions results in $\alpha_s(m_Z) = 0.1175 \pm 0.0001\ (\text{stat.}) \pm 0.0006\ (\text{syst.})\ ^{+0.0034}_{-0.0017}\ (\text{theo.})$, where the theoretical uncertainty is dominated by the scale uncertainties that estimate the contribution of higher-order corrections. All extracted values of α_s agree with the recent world average.

This result represents the first α_s determination with NNLO accuracy in three-jet production. Figure 2 compares the fitted values of α_s with previous determinations from ATLAS and other experiments as a function of the momentum scale. The measurements clearly exhibit asymptotic freedom, and a significant improvement in precision compared to previous measurements.

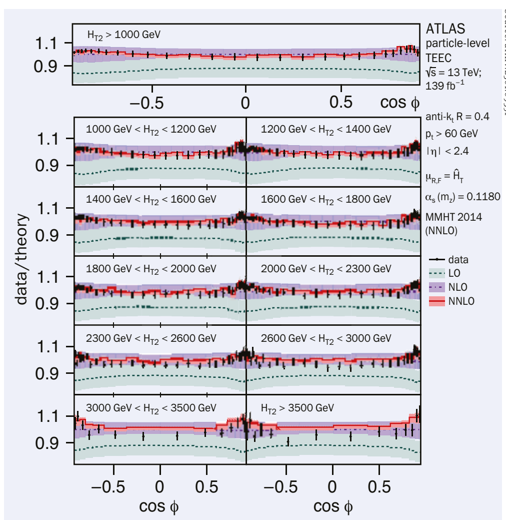


Fig. 1. *The ratios of the theoretical predictions for the TEEC functions at leading order (green) and NNLO (red) in perturbative QCD to the NLO calculations (purple), together with the ratios of the data (black points) to NLO predictions.*

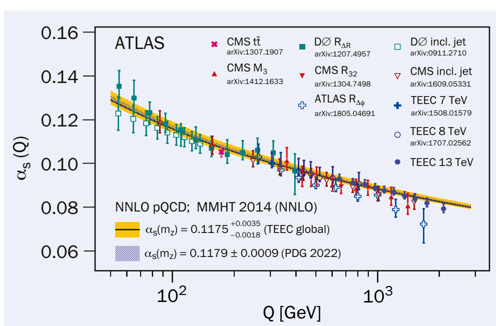


Fig. 2. *A comparison of the values of $\alpha_s(Q)$, determined from fits to the TEEC functions with the QCD prediction using the world average (blue band) as input and the value obtained from the global fit (yellow band). The value of the momentum transfer Q is chosen as half of the average renormalisation scale, $\hat{H}_T$, in order to compare with results from previous measurements, where $\hat{H}_T$ is the scalar sum of the transverse momenta of all final-state partons.*

Further reading

ATLAS Collab. 2023 arXiv:2301.09351.

ATLAS Collab. 2017 *Eur. Phys. J. C* **77** 872.

ATLAS Collab. 2015 *Phys. Lett. B* **750** 427.

LHCb

LHCb sees evidence for a new tetraquark state

Half a century since its inception, quantum chromodynamics (QCD) continues to prove itself as the correct description of the strong interaction between quarks and gluons. At low energies, however, perturbative calculations in QCD are not possible. Therefore, understanding the properties of hadrons usually requires the development of phenomenological models.

The study of exotic hadrons made up of more than three quarks offers a powerful way to gain a deeper understanding of the non-perturbative behaviour of QCD. The LHC has so far discovered no fewer than 23 new exotic hadrons, most of which were first observed by the LHCb experiment. In March 2021 the LHCb collaboration reported the observation of two tetraquarks with the $c\bar{c}u\bar{s}$ quark content – named $T^{\theta}_{\psi s1}(4000)^+$ and $T^{\theta}_{\psi s1}(4220)^+$ – in the decay $B^+ \to J/\psi\phi K^+$ (*CERN Courier* May/June 2021 p9). Now, based on a study of the isospin-symmetry-related decay $B^0 \to J/\psi\phi K^0_S$ using a sample of about 2000 candidate events, the collaboration has found evidence for a new tetraquark state, $T^{\theta}_{\psi s1}(4000)^0$, with a minimal quark content $c\bar{c}d\bar{s}$. The name of the new state follows a convention introduced by LHCb in 2022 to help simplify the exotic-hadron vista (*CERN Courier* September/October 2022 p8).

The $T^{\theta}_{\psi s1}(4000)^0$ state was found as a resonance in the $J/\psi K^0_S$ mass spectrum through an amplitude analysis, and is characterised as a horizontal band in the Dalitz plot (figure 1). Imposing isospin symmetry for all intermediate states except for the $T^{\theta}_{\psi s1}(4000)^{+/0}$ in the two B-meson decays, the signal significance is measured to be 4.0σ. The mass and width are found to be equal to those of the $T^{\theta}_{\psi s1}(4000)^+$ within uncertainties, which is consistent with the new state being an isospin partner of the $T^{\theta}_{\psi s1}(4000)^0$. If isospin symmetry between the two states is further applied, the $T^{\theta}_{\psi s1}(4000)^0$ significance increases to 5.4σ.

The $T^{\theta}_{\psi s1}(4000)^+$ and $T^{\theta}_{\psi s1}(4000)^0$ states are not the only pair of isospin partners of hidden-charm tetraquark candidates with strangeness. Recently the BESIII collaboration reported signals of the $T_{\psi s}(3985)^+$ and $T_{\psi s}(3985)^0$ states with a minimal quark content of $c\bar{c}u\bar{s}$ and $c\bar{c}d\bar{s}$, respectively. Although the tetraquark candidates seen by BESIII and LHCb have similar masses, the natural widths measured by each experiment are significantly different, indicating that they are distinct states.

Further studies and theoretical inputs are needed to determine the inner structure of such hidden-charm tetraquark candidates, for example whether they are compact tetraquarks, hadron molecules or produced due to kinematic effects. Despite continuous efforts, the detailed mechanisms responsible for binding multi-quark states have remained mysterious. With the start of LHC Run 3 and a new upgraded detector, the LHCb collaboration can look forward to finding further exotic states that shed light on the low-energy behaviour of QCD relevant to hadronic matter.

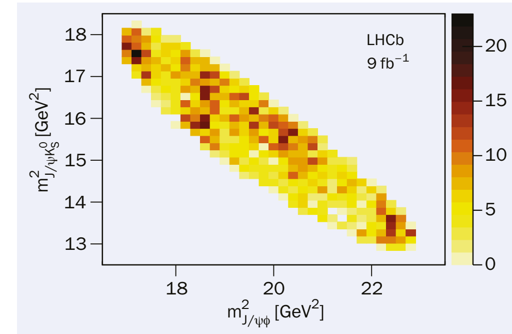


Fig. 1. *Dalitz plot of the $B^0 \to J/\psi\phi K^0_S$ decay, with vertical and horizontal bands indicating the intermediate states of the decay.*

Further reading

LHCb Collab. 2023 arXiv:2301.04899.

BESIII Collab. 2022 *Phys. Rev. Lett.* **129** 112003.

BESIII Collab. 2021 *Phys. Rev. Lett.* **126** 102001.

CMS

τ-lepton polarisation measured in Z-boson decays

Precision electroweak measurements are a powerful way to probe new physics, through the indirect effects predicted by quantum field theory. The electroweak mixing angle θ^{eff}_W is particularly sensitive to new phenomena related to electroweak symmetry breaking and the Brout–Englert–Higgs mechanism. It was measured at LEP in different processes; and at the LHC, thanks to the large number of collected events with Z-boson decays, the experiments can probe these effects with comparable sensitivity.

The CMS collaboration has reported a new measurement of the tau-lepton polarisation in the decay of Z bosons to a pair of tau leptons in proton–proton collisions at 13 TeV. The polarisation is defined as the asymmetry between the cross sections for the production of τ^- with positive and negative helicities, and is directly related to the electroweak mixing angle via the relation $P_\tau \approx -2(1-4\sin^2\theta^{\text{eff}}_W)$. The polarisation of the tau lepton is determined from the angular distributions of the visible tau decay products, leptonic or hadronic, with respect to the τ flight direction or relative to each other. A so-called optimal polarisation observable is constructed using all of these angular properties of the tau decay products. Since the spin states in $Z^0 \to \tau^-\tau^+$ are almost 100% anti-correlated, the sensitivity is improved by combining the spin observables of both τ leptons of the pair.

The average polarisation $\langle P_\tau \rangle$ is obtained by a template fit to the observed optimal τ-polarisation observables, using tau-lepton pairs with an invariant mass in the range 75–120 GeV. As summarised in figure 1, the best sensitivity of P_τ is found in the channel where one tau decays to a muon and the other decays hadronically, thanks to the good selection efficiency and reconstruction of the spin observable in this channel. The fully hadronic final state suffers from higher trigger thresholds, which lead to fewer events and distortions ▷

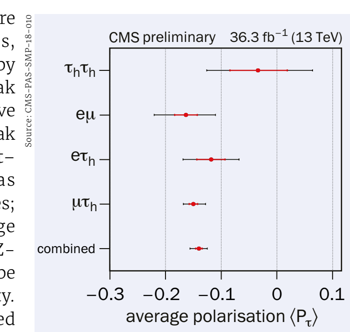


Fig. 1. *Fit results for the average τ-lepton polarisation for the four decay channels separately and for the combined fit to all channels and categories, showing statistical (inner error bars) and systematic (outer bars) uncertainties.*

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of the templates.

The average τ polarisation is corrected to the value at the Z pole, $P_\tau(Z^0) = -0.144 \pm 0.006$ (stat.) ± 0.014 (syst.), where the systematic uncertainty is dominated by the incorrect identification of the products of hadronically decaying tau leptons. The effective weak mixing angle is then determined as $\sin^2\theta_W^{eff} = 0.2319 \pm 0.0019$, in agreement with the Standard Model (SM) prediction. Figure 2 compares the tau-lepton asymmetry parameter (the negative of the polarisation) with results from previous experiments, demonstrating that the CMS measurement is nearly as precise as those of single LEP experiments.

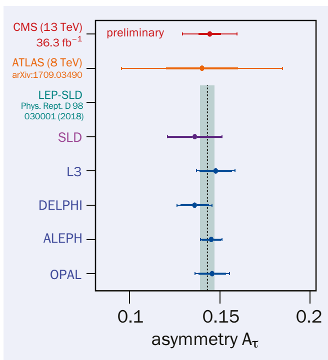


Fig. 2. *Comparison between the τ-lepton asymmetry measured by CMS and results from other experiments. The green band indicates the value obtained by combining SLD and LEP measurements. The ATLAS value corresponds to the 66–116 GeV mass range and has not been corrected to the Z-pole.*

Source: CMS-PAS-SMP-18-010

This measurement shows that LHC collision events, although much more complex than those collected at LEP, can provide precise determinations of the polarisation of the τ lepton, as well as of spin correlations between τ-lepton pairs. Such measurements are crucial to probe the CP properties of the Higgs boson's Yukawa coupling to τ leptons, which is an important step in the path to understand the Higgs sector of the SM.

Further reading

CMS Collab. 2022 CMS-PAS-SMP-18-010.

ALICE

Multi-strange production constrains hadronisation

One of the fundamental questions in quantum chromodynamics is how hadrons are produced in high-energy collisions. More specifically: what determines the relative production rates of baryons, which contain three valence quarks, and mesons, which consist of a quark and an antiquark?

In electron–positron, electron–proton and proton–proton collisions, where a small number of particles is produced, the hadronisation process is expected to be universal: it does not depend on the type of colliding particles, but only on the parent quark or gluon. It has been found, however, that in proton–proton and proton–lead collisions at LHC energies, the baryon-to-meson ratios p/π, Λ/K^0_S and Λ_c/D^0 are significantly larger than in e^+e^- and ep collisions. This enhancement, at intermediate transverse momentum p_T (1–5 GeV), in small systems is qualitatively similar to that observed in heavy-ion collisions, e.g. between lead ions. However, in heavy-ion collisions this behaviour has been related to the interplay between hadronisation and the creation and expansion of a hot and dense quark–gluon plasma (QGP) via so-called quark recombination involving partons from within the QGP.

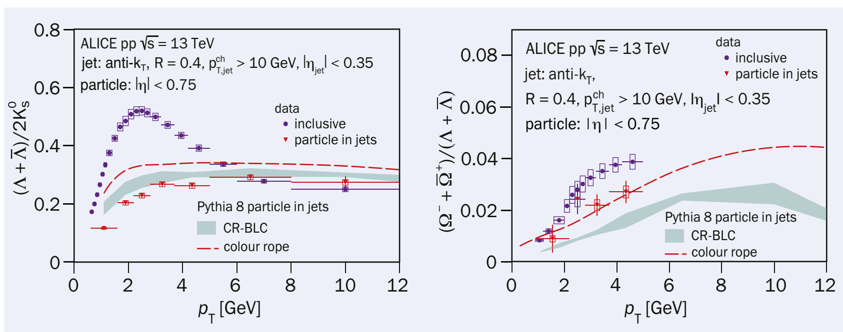


Fig. 1. *Ratios of Λ/K^0_S (left) and $\Omega^\pm/\Lambda$ (right) yields versus the transverse momentum in jets and inclusive measurements in pp collisions at a centre-of-mass energy of 13 TeV. The CR-BLC (green) model describes the Λ/K^0_S ratio inside jets, whereas the colour-rope (red dashed) model agrees better with the behaviour of the $\Omega^\pm/\Lambda$ ratio.*

Source: arXiv:2211.08936

To shed light on hadron-production mechanisms in collisions at the LHC, ALICE has performed a novel study of the production of strange and multi-strange hadrons inside and outside energetic jets in proton–proton and proton–lead collisions. The method separates particles produced in association with a hard scattering process (within jets) from those produced in soft processes with low momentum transfer that dominate the underlying event.

These measurements will help to improve the modelling of particle production at the LHC

The results show that the strange baryon-to-meson Λ/K^0_S ratio enhancement seen in the inclusive measurement is absent within the jet cone and restricted to soft-particle production processes outside the jet cone (figure 1, left). On the other hand, the multi-strange to single-strange hyperon yield ratio $\Omega^\pm/\Lambda$ (figure 1, right) shows a similar p_T dependence in the interval $2 < p_T < 5$ GeV inside and outside the jet cone, while different behaviour is observed for the $\Xi^\pm/\Lambda$ ratio (not shown). This suggests that the baryon production mechanism also depends on the strangeness content of the baryons; the production of hyperons in jets becomes similar to that in the underlying event for baryons with large strangeness content.

These measurements provide new input to understand the relative contribution of soft and hard processes to multi-strange hadron production, and thus will help to improve the modelling of particle production at the LHC. To illustrate how, two calculations with different hadronisation models are shown in the figure: one model includes string formation beyond leading colour (CR-BLC, blue band), while the other includes colour ropes (red dashed line). While one of the models describes the Λ/K^0_S ratio inside jets, the other shows a better agreement with the $\Omega^\pm/\Lambda$ ratio.

ALICE has also investigated the multiplicity dependence of strange baryon-to-meson and baryon-to-baryon ratios in jets in proton–lead collisions and compared it with those in proton–proton collisions. Within the current experimental precision, no difference between the two collision systems, nor a dependence on the event multiplicity, is observed. These studies will further benefit from the increased precision that will be achieved with the substantially larger data samples from ongoing LHC runs.

Further reading

ALICE Collab. 2022 arXiv:2211.08936.

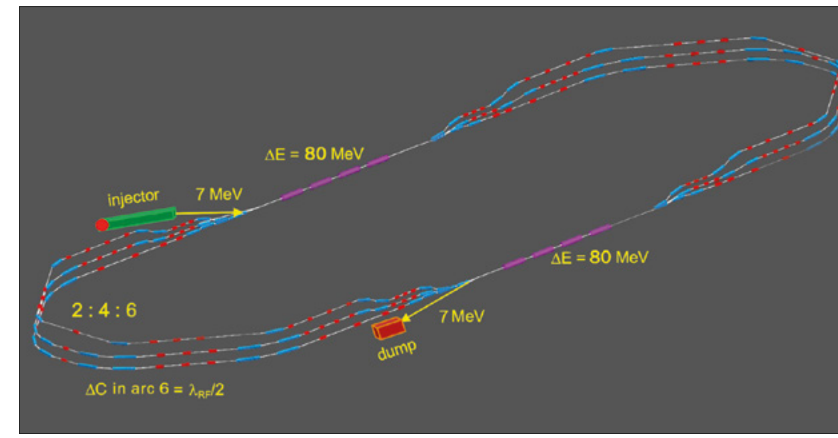
FIELD NOTES

Reports from events, conferences and meetings

LHeC/FCCeh and PERLE Workshop

Innovation on show for future ep/eA colliders

Following the publication of an updated conceptual design report in 2021, CERN continues to support studies for the proposed electron–hadron colliders LHeC and FCC-eh as potential options for the future, and to provide input to the next update of the European strategy for particle physics, with emphasis on FCC. LHeC would require the LHC to be modified, while FCC-eh is a possible operational mode of the proposed Future Circular Collider at CERN. A key factor in studies for a possible future "ep/eA" collider is power consumption, for which researchers around the world are exploring the use of energy recovery linacs at the high-energy frontier.



Energy recovery *The PERLE facility is poised to become Europe's leading centre for developing and testing sustainable accelerating systems.*

PERLE

The ep/eA programme finds itself at a crossroad between nuclear and particle physics, with synergies with astroparticle physics. It has the potential to empower the High-Luminosity LHC (HL-LHC) physics programme in a unique way, and allows for a deeper exploration of the electroweak and strong sectors of the Standard Model beyond what can be achieved with proton–proton collisions alone. In many cases, adding LHeC to HL-LHC data can significantly improve the precision of Higgs-boson measurements – similar to the improvements expected when moving from the LHC to HL-LHC.

The innovative spirit of the ep/eA community was demonstrated during the workshop "Electrons for the LHC – LHeC/FCCeh and PERLE" held at IJCLab from 26 to 28 October. As the ep/eA community moves from the former HERA facility and from the Electron-Ion Collider, currently under construction at Brookhaven, to higher energies at LHeC and FCC-eh, the threshold will be reached to study electroweak, top and Higgs physics in deep-inelastic scattering (DIS) processes for the first time. In addition, these programmes enable the exploration of the low Bjorken-x frontier orders of magnitude beyond current DIS results. At this stage, it is unclear what physics will be unlocked if hadronic matter is broken into even smaller pieces. In recent years, particle physicists have learned that the ultimate precision for Higgs-boson physics lies in the complementarity of e^+e^-, pp and ep collisions, as embedded in the FCC programme, for example. Exploiting this complementarity is key to exploring new territories via the Higgs and dark sectors, as well as zooming in on potential anomalies in our data.

At this stage, it is unclear what physics will be unlocked if hadronic matter is broken into even smaller pieces

The October workshop underlined the advantage of a joint ep/pp/eA/AA/pA interaction experiment, and the need to further document its added scientific value. For example, a precision of 1 MeV on the W-boson mass could be within reach. In short, the ep data allows constraints to be placed on the most important systematic uncertainty when measuring the W-boson mass with pp data.

Reduced power

Participants also addressed how to reduce the power consumption of LHeC and FCC-eh. PERLE, an expanding international collaboration revolving around a multi-turn demonstrator facility being pursued at IJCLab in Orsay for energy recovery linacs (ERLs) at high beam currents, is ready to become Europe's leading centre for developing and testing sustainable accelerating systems.

As demonstrated at the workshop, with additional R&D on ERLs and ep colliders we might be able to further reduce the power consumption of the LHeC (and FCC-eh) to as low as 50 MW. These values are to be compared with the GW power consumption if there was no energy recovery and therefore provide a power-economic avenue to extend the Higgs precision frontier beyond the HL-LHC. ERLs are not uniquely applicable to eA colliders, but have been discussed for future linear and circular e^+e^- colliders too. With PERLE and other sustainable accelerating systems, the ep/eA programme has the ambition to deliver a demonstration of ERL technology at high beam current, potentially towards options for an ERL-based Higgs factory.

Workshop participants are engaged to further develop an ep/eA programme with the ability to significantly enrich this overall strategy with a view to finding cracks in the Standard Model and/or finding new phenomena that further our understanding of nature at the smallest and largest scales.

Jorgen D'Hondt *VUB.*

BPU11 CONGRESS

A celebration of physics in the Balkans

The 11th General Conference of the Balkan Physical Union (BPU11 Congress) took place from 28 August to 1 September 2022 in Belgrade, with the Serbian Academy of Science and Arts as the main host. Initiated in 1991 in Thessaloniki, Greece, and open to participants globally, the series provides a platform for reviewing, disseminating and discussing novel research results in physics and related fields.

The scientific scope of BPU11 covered the full landscape of physics via 139 lectures (12 plenary and 23 invited) and 150 poster presentations. A novel addition was five roundtables dedicated to high-energy physics (HEP), widening participation, careers in physics, quantum and new technologies, and models of studying physics in European universities with a focus on Balkan countries. The hybrid event attracted about 476 participants (325 on site) from 31 countries, 159 of whom were students, and demonstrated the high level of research conducted in the Balkan states.

B Dzodan

Exciting times *BPU11 participants during a social event on the Sava-Danube.*

Roadmaps to the future

The first roundtable "HEP – roadmaps to the future" showed the strong collaboration between CERN and the Balkan states. Four out of 23 CERN Member States come from the region (Bulgaria, Greece, Serbia and Romania); two out of three Associate Member States in the pre-stage to membership are Cyprus and Slovenia; and two out of seven Associate Member States are Croatia and Turkey. A further four countries have cooperation agreements with CERN, and more than 400 CERN users come from the Balkans.

Kicking off the HEP roundtable discussions, CERN director for research and computing Joachim Mnich presented the recently launched accelerator and detector R&D roadmaps in Europe (*CERN Courier* January/February 2022 p7). Paris Sphicas (CERN and the University of Athens) reported on the future of particle-physics research, during which he underlined the current challenges and opportunities. These included: dark matter (for example the search for WIMPs in the thermal parameter region, the need to check simplified models such as axial-vector and di-lepton resonances, and indirect searches); supersymmetry (the search for "holes" in the low-mass region that will exist even after the LHC); neutrinos (whether neutrinos are Majorana or Dirac particles, their mass measurement and exploration of a possible "sterile" sector); as well as a comprehensive review of the Higgs sector.

CERN's Emmanuel Tsesmelis, who was awarded the Balkan Physical Union charter and honorary membership in recognition of his contributions to cooperation between the Balkan states and CERN, reflected on the proposed Future Circular Collider (FCC). Describing the status of the FCC feasibility study, due to be completed by the end of 2025, he stressed that the success of the project relies on strong global participation. His presentation initiated a substantial discussion about the role of the Balkan countries, which will be continued in May 2023 at the 11th LHCP conference in Belgrade.

The roundtable devoted to quantum technologies (QTs), chaired by Enrique Sanchez of the European Physical Society (EPS), was another highlight with strong relevance to HEP. Various perspectives on the different QT sectors – computing and simulation, communication, metrology and sensing – were discussed, touching upon the impact they could have on society at large. Europe plays a leading role in quantum research, concluded the panel. However, despite increased interest in QTs, including at CERN, issues such as how to obtain appropriate funding to enhance European technological leadership, remain. Discussions highlighted the opportunities for new generations of physicists from the Balkans to help build this "second quantum revolution".

In addition to the roundtables, four high-level scientific satellite events took place, attracting a further 150 on-site participants: the COST Workshop on Theoretical Aspects of Quantum Gravity; the SEENET-MTP Assessment Meeting and Workshop; the COST School on Quantum Gravity Phenomenology in the Multi-Messenger Approach; and the CERN–SEENET-MTP–ICTP PhD School on Gravitation, Cosmology and Astroparticle Physics. The latter is part of a unique regional programme in HEP initiated by SEENET-MTP (Southeastern European Network in Mathematical and Theoretical Physics) and CERN in 2015, and joined by the ICTP in 2018, which has contributed to the training of more than 200 students in 12 SEENET countries (*CERN Courier* September/October 2019 p45).

The BPU11 Congress, the largest event of its type in the region since the beginning of the COVID-19 pandemic, contributed to closer cooperation between the Balkan countries and CERN, ICTP, SISSA, the Central European Initiative and others. It was possible thanks to the support of the EPS, ICTP and CEI-Trieste, CERN, EPJ, as well as the Serbian ministry of science and institutions active in physics and mathematics in Serbia. In addition to the *BPU11 PoS Proceedings*, several articles based on invited lectures will be published in a focus issue of *EPJ Plus* "On Physics in the Balkans: Perspectives and Challenges", as well as in a special issue of *IJMPA*.

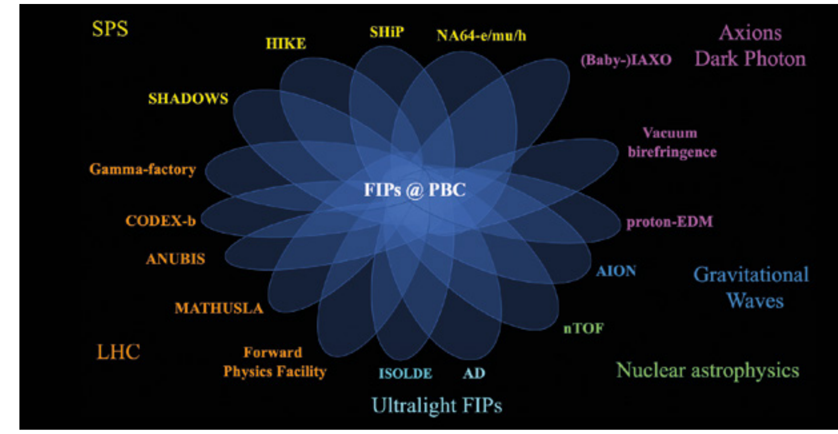
Goran Djordjević *University of Niš, BPU president 2018–2022.*

FEEBLY INTERACTING PARTICLES WORKSHOP

Chasing feebly interacting particles at CERN

What is the origin of neutrino masses and oscillations? What is the nature of dark matter? What mechanism generated the cosmological matter–antimatter asymmetry? What drove the inflation of our universe and provides an explanation to dark energy? What is the origin of the hierarchy of scales? These are outstanding questions in particle physics that still require an answer.

So far, the experimental effort has been driven by theoretical arguments that favoured the existence of new particles with relatively large couplings to the Standard Model (SM) and masses commensurate to the mass of the Higgs boson. Searching for these particles has been one of the main goals of the physics programme of the LHC. However, several beyond-the-SM theories predict the existence of light (sub-GeV) particles which interact very weakly with the SM fields. Such feebly interacting particles (FIPs) can provide elegant explanations to several unresolved problems in modern physics. Furthermore, searching for them requires specific and distinct techniques, creating new experimental challenges along with innovative theoretical efforts.



G Lanfranchi

FIPs@CERN *New experiments for hunting feebly interacting particles (FIPs) at CERN discussed within the Physics Beyond Colliers (PBC) initiative.*

FIPs are currently one of the most debated and discussed topics in fundamental physics and were recommended by the 2020 update of the European strategy for particle physics as a compelling field to explore in the next decade. The FIPs 2022 workshop held at CERN from 17 to 21 October was the second in a series dedicated to the physics of FIPs. It attracted 320 experts from collider, beam-dump and fixed-target experiments, as well as from the astroparticle, cosmology, axion and dark-matter communities, to discuss the progress in experimental searches and new developments in underlying theoretical models.

The main goal was to create a base for a multi-disciplinary and interconnected approach. The breadth of open questions in particle physics and their deep interconnection requires a diversified research programme with different experimental approaches and techniques, together with a strong and focused theoretical involvement. In particular, FIPs 2022, which is strongly linked with the Physics Beyond Colliders (PBC) initiative at CERN, aimed to shape the FIPs programme in Europe. Topics under discussion included the impact that FIPs might have in stellar evolution, Λ_{CDM} cosmological-model parameters, indirect dark-matter detection, neutrino physics, gravitational-wave physics and AMO (atomic-molecular-optical) physics. This was in addition to the searches currently being performed at colliders and extracted beamlines worldwide.

The main sessions were organised around three themes: light dark matter in particle and astroparticle physics and cosmology; ultra-light FIPs and their connection with cosmology and astrophysics; and heavy neutral leptons and their connection with neutrino physics. In addition, young researchers in the field presented and discussed their work in the "new ideas" sessions.

FIPs 2022 aimed to not only explore new answers to unresolved questions in fundamental physics, but also analyse the technical challenges and necessary infrastructure and collaborative networks required to answer them. Indeed, no single experiment or lab would be able to cover, by itself, the large parameter space in terms of the masses and couplings that FIPs models suggest. Synergy and complementarity among a great variety of experimental facilities are therefore paramount, calling for a deep collaboration across many labs and cross-fertilisation among different communities and experimental techniques. We believe that a network of interconnected laboratories can become a sustainable, flexible and efficient way of addressing particle-physics questions in the next millennium.

The next appointment for the community is the retreat/school "FIPs in the ALPs" to be held in Les Houches from 15 to 19 May 2023, followed by the next edition of the FIPs workshop at CERN in autumn 2024.

Gaia Lanfranchi *INFN and* **Maurizio Giannotti** *Barry University.*

HIGGS HUNTING 2022

Charting Higgs physics in Paris

The 12th Higgs Hunting workshop, which took place in Paris and Orsay from 12 to 14 September, presented an overview of recent and new results in Higgs-boson physics. The results painted an increasingly detailed picture of Higgs-boson properties, thanks to the many analyses now reporting results based on the full LHC Run 2 dataset, with an integrated luminosity of about 140 fb^{-1}. Searches for phenomena beyond the Standard Model (BSM) were also presented.

Deviations from theory will be followed up using Run 2 and Run 3 data

Highlights included new results from CMS on decays of Higgs bosons to b quarks and to invisible final states, and a new limit from ATLAS on lepton-flavour violating decays of the Higgs boson. Events with two Higgs bosons in the final state were used to set limits on interactions involving three Higgs bosons and between two Higgs bosons and two weak vector bosons. All the results remain compatible with Standard Model expectations, except for a small number of intriguing tensions in some BSM searches, such as small excesses in a search for heavier partners of the Higgs boson decaying to W-boson pairs and in a search for resonances produced alongside a Z boson and decaying to a pair ▷

of Higgs bosons. These deviations from theory will be followed up by ATLAS and CMS in further analyses using Run 2 and Run 3 data.

The 2022 workshop was special as the event marked the 10th anniversary of the Higgs-boson discovery. Two historical talks given by former ATLAS and CMS spokespersons Peter Jenni (University of Freiburg and CERN) and Jim Virdee (Imperial College) highlighted the long-term efforts that laid the foundation for the Higgs-boson discovery in 2012.

The workshop also hosted an in-depth discussion on future accelerators and related detector R&D. It focused on future efforts in Europe, the US and Latin America, and featured presentations by Karl Jakobs (University of Freiburg and chair of the European Committee for Future Accelerators), Meenakshi Narain (Brown University and convener of the energy-frontier group of the Snowmass process), Maria-Teresa Dova (National University of La Plata and representative for the Latin American strategy effort) and Emmanuel Perez (CERN), who discussed recent improvements in physics analyses at future colliders.

Recent theory developments were also extensively covered, in particular developments in higher-order computations by Michael Spira (PSI), which highlighted the agreement between experimental results and predictions. A review of recent theory progress towards future colliders was also presented by Gauthier Durieux (CERN), while Carlos Wagner (Enrico Fermi Institute and Kavli Institute for Cosmological Physics) discussed the new physics that can be explored via precise measurements of Higgs-boson couplings. Finally, a "vision" presentation by Marcela Carena (Fermilab) highlighted new opportunities for the study of electroweak baryogenesis in relation to Higgs-boson measurements.

On the hunt *New searches to study the Higgs boson in more detail were discussed from both the theoretical and experimental sides.*

Many experimental sessions were held regarding recent results on a wide variety of topics, some of which will be relevant in upcoming Run 3 measurements. This includes measurements related to potential CP-violating effects in the Higgs sector, as well as effective field theories. This latter topic allows a general description of deviations from Standard Model predictions in Higgs-boson measurements and beyond, and much improved measurements in this direction are expected in Run 3. The search for Higgs-boson pair production was also an important focus at the Paris meeting. The latest Run 2 analyses showed greatly improved sensitivity compared to earlier rounds, and further improvements are expected in Run 3. While sensitivity to the Standard Model signal is not expected until the High-Luminosity LHC, these searches should set strong constraints on BSM effects in the Higgs sector.

Concluding talks were given by Fabio Maltoni (Louvain) and Giacinto Piacquadio (Stony Brook). The next Higgs Hunting workshop will be held in Orsay and Paris from 11 to 13 September 2023.

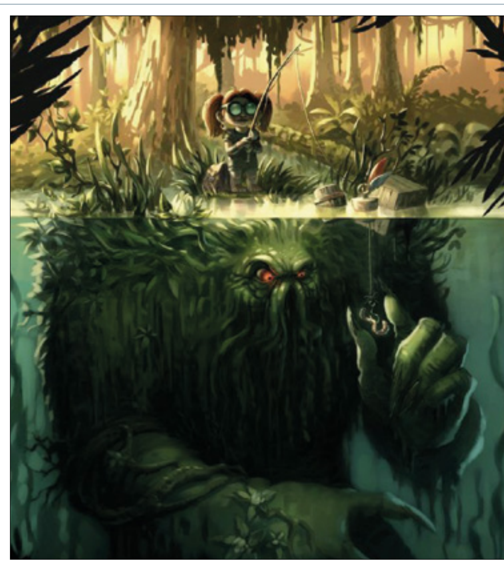
Nicolas Berger *Laboratoire d'Annecy de Physique des Particules and* **Louis Fayard** *Laboratoire de Physique des 2 infinis Irène Joliot-Curie.*

BACK TO THE SWAMP 2022

Connecting strings in Spain

Since its first revolution in the 1980s, string theory has been proposed as a framework to unify all known interactions. As such, it is a perfect candidate to embed the standard models of particle physics and cosmology into a consistent theory of quantum gravity. Over the past decades, the quest to recover both models as low-energy effective field theories (EFTs) of string theory has led to many surprising results, and to the notion of a "landscape" of string solutions reproducing many key features of the universe (see p41).

Initially, the vast number of solutions led to the impression that any quantum field theory could be obtained as an EFT of string theory, hindering the predictive power of the theory. In fact, recent developments have shown that quite the opposite is true: many respectable-looking field theories become inconsistent when coupled to quantum gravity and can never be obtained as EFTs of string theory. This set is known as the "swampland" of quantum field theories. The task of the swampland programme is to determine the structure and boundaries of the swampland, and from there extract the predictive power of string theory. Over the past few years, deep connections between the swampland and a fundamental understanding of open questions in high-energy physics, ranging from the hierarchy of fundamental scales to the origin and fate of the universe, have emerged.



What lurks beneath *The conference poster depicted a creature in the "swamp" testing a theory (the bait) proposed by an effective field theorist (the fisher).*

The Back to the Swamp workshop, held at Instituto de Física Teórica UAM/CSIC in Madrid from 26 to 28 September, gathered leading experts in the field to discuss recent progress in our understanding of the swampland, as well as its implications for particle physics and cosmology. In the spirit of the two previous conferences, Vistas over the Swampland and Navigating the Swampland, also hosted at IFT, the meeting featured 22 scientific talks and attracted about 100 participants.

The swampland programme has led to a series of conjectures that have sparked debate about how to connect string theory with the observed universe, especially with models of early-universe cosmology. This was reflected with several talks on the subject, ranging from new scrutiny of current proposals to obtain de Sitter vacua, which might not be consistently constructed in quantum gravity, new candidates for quintessence models that introduce a scalar field to explain the observed accelerated expansion of the universe, and scenarios where dark matter is composed of primordial black holes. Several talks covered the implications of the programme for particle physics and quantum field theories in general. Topics included axion-based proposals to solve the strong-CP problem from the viewpoint of quantum gravity, as well as how axion physics and approximate symmetries can link swampland ideas with experiment and how the mathematical concept of "tameness" could describe those quantum field theories that are compatible with quantum gravity. Progress on the proposal to characterise large-field distances and field-dependent weak couplings as emergent concepts, general bounds on supersymmetric quantum field theories from the consistency of axionic string worldsheet theories, and several proposals on how dispersive bounds and the boostrap programme are also relevant for swampland ideas. Finally, several talks covered more formal topics, such as a sharpened formulation of the distance conjecture, new tests of the tower weak gravity conjecture, the discovery of new corners in the string-theory landscape, and arguments in favour of and against Euclidean wormholes.

The swampland programme has led to conjectures about how to connect string theory with the observed universe

The new results demonstrated the intense activity in the field and highlighted several current aspects of the swampland programme. It is clear that the different proposals and conjectures driving the programme have sharpened and become more interconnected. Each year the programme attracts more scientists working in different specialities of string theory, and proposals to connect the swampland with experiment take a larger fraction of the efforts.

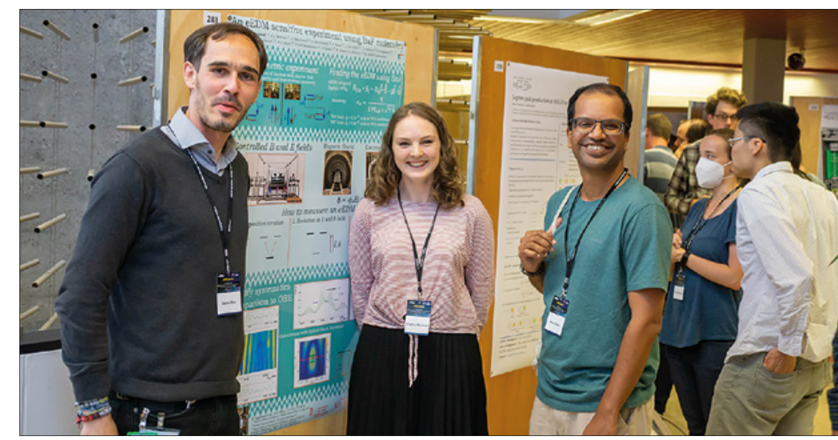
Luis E Ibáñez *Universidad Autonomá de Madrid,* **Fernando Marchesano** *IFT and* **Ángel M Uranga** *IFT.*

SYMMETRIES AND FUNDAMENTAL INTERACTIONS

Fundamental symmetries and interactions at PSI

The triennial workshop "Physics of Fundamental Symmetries and Interactions – PSI2022" took place for the sixth time at the Paul Scherrer Institut (PSI) in Switzerland from 17 to 22 October, bringing the worldwide fundamental symmetries community together. More than 190 participants, including some 70 young scientists, welcomed the close communication of an in-person meeting built around 35 invited and 25 contributed talks.

A central goal of the meeting series is to deepen relations between disciplines and scientists. This year, for the first time, participants connected with the FIPs workshop at CERN (p19) on the second day of the conference, due to the common topics discussed.



Workshop winner *Virginia Marshall (University of Groningen, centre), pictured with Dieter Ries (University of Mainz, left) and Amar Vutha (University of Toronto, right), won a NuPECC/PSI-sponsored award for a poster describing her electron EDM experiment.*

With PSI's leading high-intensity muon and pion beams, many topics in muon physics and lepton-flavour violation were highlighted. These covered rare muon decays ($\mu \to e\gamma$, $\mu \to 3e$) and muon conversion ($\mu \to e$), muonic atoms and proton structure, and muon capture. Presentations covered complementary experimental efforts at J-PARC, Fermilab and PSI. The status of the muon g-2 measurement was reviewed from an experimental and theoretical perspective, where lattice-QCD calculations from 2021 and 2022 have intensified discussions around the tension with Standard Model expectations.

Fundamental physics using cold and ultracold neutrons was a second cornerstone of the programme. Searches for a neutron electric dipole moment (EDM) were discussed in contributions by collaborations from TRIUMF, LANL, SNS, ILL and PSI, complemented by presentations on searches for EDMs in atomic and molecular systems. Along with new results from neutron-beta-decay measurements, the puzzle of the neutron lifetime keeps the community busy, with improving "bottle" and "beam" measurements presently differing by more than five standard deviations. Several talks highlighted possible explanations via neutron oscillations into sterile or mirror states.

The current status of direct neutrino-mass measurements and the future outlook down into the meV range was covered, together with updates on searches for neutrinoless double-beta decay. An overview of the hunt for the unknown at the dark-matter frontier was presented together with new limits and plans from various searches. Ultra-precise atomic clocks were discussed, allowing checks of general relativity and the Standard Model, as well as searches beyond established theories. The final session covered the latest results from antiproton and antihydrogen experiments at CERN, demonstrating the outstanding precision achieved in CPT tests with these probes. The workshop was a great success and participants look forward to reconvening at PSI2025.

Bernhard Lauss *and* **Klaus Kirch** *PSI.*

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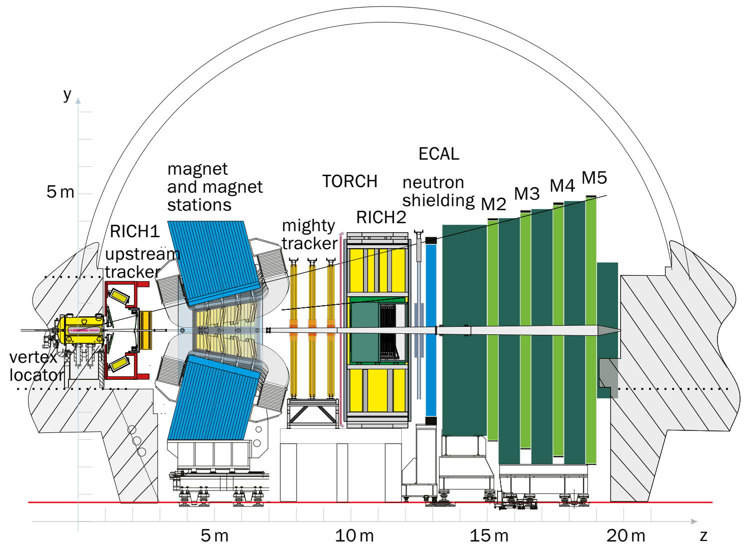
LHCb LOOKS FORWARD TO THE 2030s



Looking ahead *Schematic side-view of the LHCb Upgrade II detector, which will push the limits of technology to enable precision flavour physics in the daunting conditions of the HL-LHC. (Credit: LHCb)*

A major proposed upgrade of the LHCb detector for LHC Runs 5 and 6 would allow a wide range of flavour-physics observables to be explored with extreme precision. Lucia Grillo, Stefano Perazzini and Dorothea vom Bruch offer a snapshot of LHCb Upgrade II status and plans.

The LHCb collaboration is never idle. While building and commissioning its brand new Upgrade I detector, which entered operation last year with the start of LHC Run 3, planning for Upgrade II was already under way. This proposed new detector, envisioned to be installed during Long Shutdown 4 in time for High-Luminosity LHC (HL-LHC) operations continuing in Run 5, scheduled to begin in 2034/2035, would operate at a peak luminosity of $1.5\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$. This is 7.5 times higher than at Run 3 and would generate data samples of heavy-flavoured hadron decays six times larger than those obtainable at the LHC, allowing the collaboration to explore a wide range of flavour-physics observables with extreme precision. Unprecedented tests of the CP-violation paradigm (see "On point" figure) and searches for new physics at double the mass scales possible during Run 3 are among the physics goals on offer.

Attaining the same excellent performance as the original detector has been a pivotal constraint in the design of LHCb Upgrade I. While achieving the same in the much harsher collision environments at the HL-LHC remains the guiding principle for Upgrade II, the LHCb collaboration is investigating the possibilities to go even further. And these challenges need to be met while keeping the existing footprint and arrangement of the detector (see "Looking forward" figure). Radiation-hard and fast 3D silicon pixels, a new generation of extremely fast and efficient photodetectors, and front-end electronics chips based on 28 nm semiconductor technology are just a few examples of the innovations foreseen for LHCb Upgrade II, and will also set the direction of R&D for future experiments.

Rethinking the data acquisition, trigger and data processing, along with intense use of hardware accelerators such as field-programmable gate arrays (FPGAs) and graphics processing units (GPUs), will be fundamental to manage the expected five-times higher average data rate than in Upgrade I. The Upgrade II "framework technical design report", completed in 2022, is also the first to consider the experiment's energy consumption and greenhouse-gas emissions, as part of a close collaboration with CERN to define an effective environmental protection strategy.

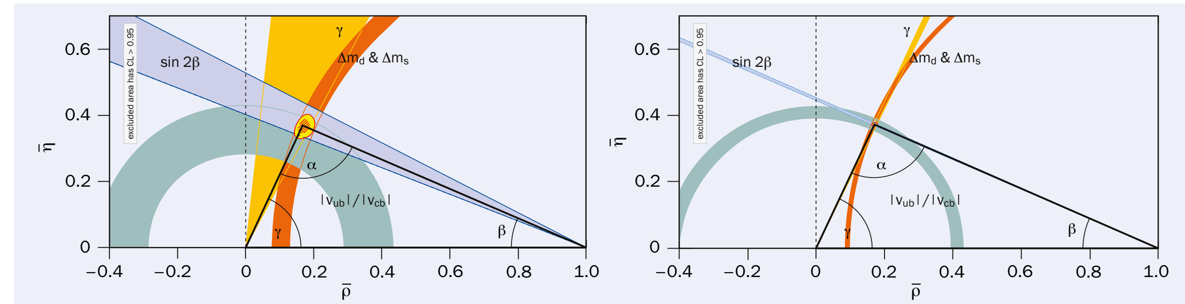
Extreme tracking

At the maximum expected luminosity of the HL-LHC, around 2000 charged particles will be produced per bunch crossing within the LHCb apparatus. Efficiently reconstructing these particles and their associated decay vertices in real time represents a significant challenge. It requires the existing detector components to be modified to increase the granularity, reduce the amount of material and benefit from the use of precision timing.

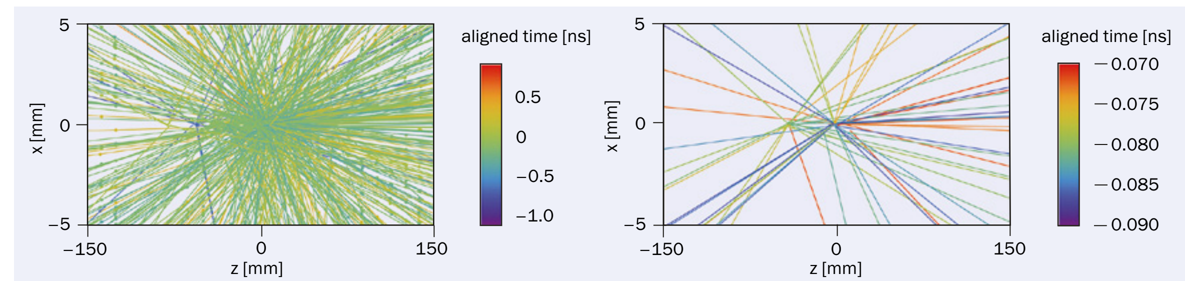
The new Vertex Locator (VELO) will be based, as it was for Upgrade I (*CERN Courier* May/June 2022 p38), on high-granularity pixels operated in vacuum in close proximity to the LHC beams. For Upgrade II, the trigger and online reconstruction will rely on the selection of events, or parts of events, with displaced tracks at the early stage of the event. The VELO must therefore be capable of independently reconstructing primary vertices and identifying displaced tracks, while coping with a dramatic increase in event rate and radiation dose. Excellent spatial resolution will not be sufficient, given the large density of primary interactions along the beam axis expected under HL-LHC conditions. A new coordinate – time – must be introduced.

THE AUTHORS

Lucia Grillo *University of Glasgow,* **Stefano Perazzini** *INFN Bologna and* **Dorothea vom Bruch** *CPPM, CNRS/IN2P3, Aix-Marseille University.*



On point *LHCb constraints on the apex of the Cabibbo–Kobayashi–Maskawa (CKM) unitary triangle with (left) inputs as of 2018 and (right) anticipated improvements with a 300 fb^{-1} HL-LHC dataset, assuming consistency with the Standard Model and expected improvements in lattice QCD.*



Precision timing *Illustration of the primary interactions and corresponding track density (left) generated for each bunch crossing at Upgrade II luminosities. Right: the same event with a time window of 20 ps applied to the primary interactions.*

The future VELO will be a true 4D-tracking detector that includes timing information with a precision of better than 50 ps per hit, leading to a track time-stamp resolution of about 20 ps (see "Precision timing" figure).

The new VELO sensors, which include 28 nm technology application-specific integrated circuits (ASICs), will need to achieve this time resolution while being radiation-hard. The important goal of a 10 ps time resolution has recently been achieved with irradiated prototype 3D-trench silicon sensors. Depending on the rate-capability of the new detectors, the pitch may have to be reduced and the material budget significantly decreased to reach comparable spatial resolution to the current Run 3 detector. The VELO mechanics have to be redesigned, in particular to reduce the material of the radio-frequency foil that separates the secondary vacuum – where the sensors are located – from the machine vacuum. The detector must be built with micron-level precision to control systematic uncertainties.

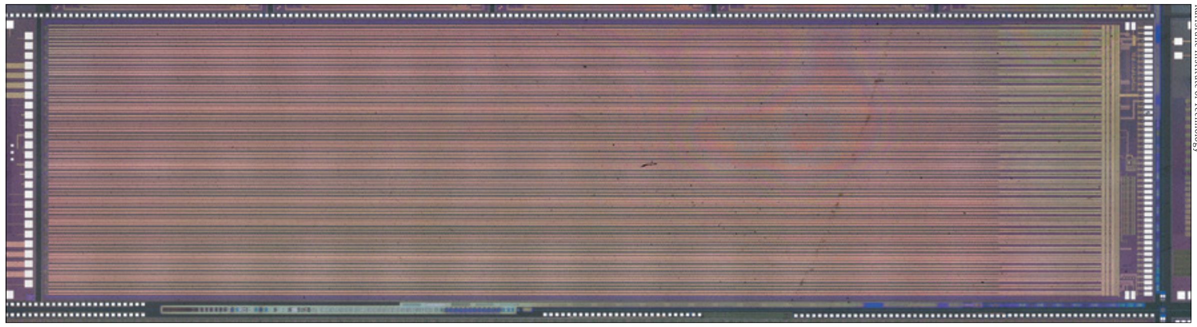
The tracking system will take advantage of a detector located upstream of the dipole magnet, the Upstream Tracker (UT), and of a detector made of three tracking stations, the Mighty Tracker (MT), located downstream of the magnet. In conjunction with the VELO, the tracking system ensures the ability to reconstruct the trajectory of charged particles bending through the detector due to the magnetic field, and provides a high-precision momentum measurement for each particle. The track direction is a necessary input to the photon-ring searches in Ring Imaging Cherenkov (RICH) detectors, which identify the particle species. Efficient real-time charged-particle reconstruction in a very high particle-density environment requires not only good detector efficiency and granularity, but also the ability to quickly reject combinations of hits not produced by the same particle.

The UT and the inner region of the MT will be instrumented with high-granularity silicon pixels. The emerging radiation-hard monolithic active pixel sensor (MAPS) technology is a strong candidate for these detectors. LHCb Upgrade II would represent the first large-scale implementation of MAPS in a high-radiation environment, with the first prototypes currently being tested (see "Mighty pixels" figure). The outer region of the MT will be covered by scintillating fibres, as in Run 3, with significant developments foreseen to cope with the radiation damage. The availability of high-precision vertical-coordinate hit information in the tracking, provided for the first time in LHCb by pixels in the high-occupancy regions of the tracker, will be crucial to reject combinations of track segments or hits not produced by the same particle. To substantially extend the coverage of the tracking system to lower momenta, with consequent gains for physics measurements, the internal surfaces of the magnet side walls will be instrumented with scintillating bar detectors, the so-called magnet stations (MS).

Extreme particle identification

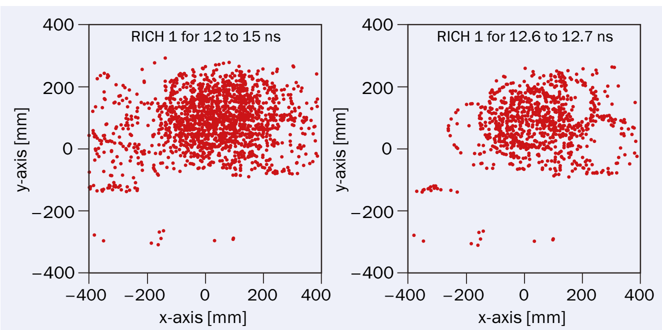
A key factor in the success of the LHCb experiment has been its excellent particle identification (PID) capabilities. PID is crucial to distinguish different decays with final-state topologies that are backgrounds to each other, and to tag the flavour of beauty mesons at production, which is a vital ingredient to many mixing and CP-violation measurements. For particle momenta from a few GeV/c up to 100 GeV/c, efficient hadron identification at LHCb is pro-

The future VELO will be a true 4D-tracking detector



Karlsruhe Institute of Technology

Mighty pixels *A microscope image of the first LHCb-dedicated high-voltage CMOS sensor.*

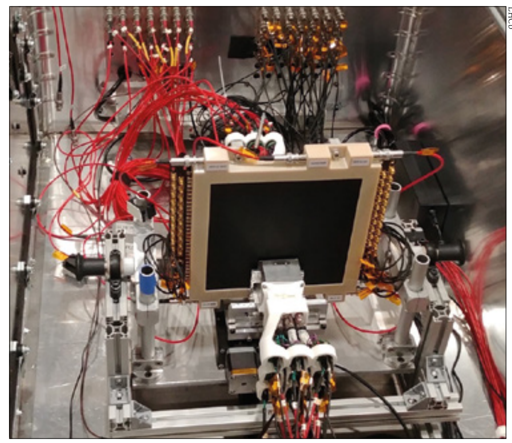


LHCb

RICH rewards *A simulation of the distribution of photon hits on the RICH photodetector plane for a typical Upgrade I event (left), and the same event applying a time window of 100 ps (right), allowing a cleaner identification of Cherenkov rings to be achieved.*

vided by two RICH detectors. Cherenkov light emitted by particles traversing the gaseous radiators of the RICHes is projected by mirrors onto a plane of photodetectors. To maintain Upgrade I performances, the maximum occupancy over the photodetector plane must be kept below 30%, the single-photon Cherenkov-angle resolution must be below 0.5 mrad, and the time resolution on single-photon hits should be well below 100 ps (see "RICH rewards" figure).

Next-generation silicon photomultipliers (SiPMs) with improved timing and a pixel size of $1\times1\,\mathrm{mm}^2$, together with re-optimised optics, are deemed capable of delivering these specifications. The high "dark" rates of SiPMs, especially after elevated radiation doses, would be controlled with cryogenic cooling and neutron shielding. Vacuum tubes based on micro-channel plates (MCPs) are a potential alternative due to their excellent time resolution (30 ps) for single-photon hits and lower dark rate, but suffer in high-rate environments. New eco-friendly gaseous radiators with a lower refractive index can improve the PID performance at higher momenta (above 80 GeV/c), but meta-materials such as photonic crystals are also being studied. In the momentum region below 10 GeV/c, PID will profit from TORCH – an innovative $30\,\mathrm{m}^2$ time-of-flight detector consisting of quartz plates where charged particles produce Cherenkov light. The light propagates by internal reflection to arrays of high-granularity MCP-PMTs optimised to operate at high rates, with a prototype already showing performances close to the target of 70 ps per photon.



LHCb

Spaghetti calorimetry *A SPACAL prototype being prepared for beam tests, with an LAPPD (by Incom) inserted between the front and back sections as a demonstrator for the MCP-based timing layer.*

Excellent photon and π^0 reconstruction and e–π separation are provided by LHCb's electromagnetic calorimeter (ECAL). But the harsh occupancy conditions of the HL-LHC impose the development of 5D calorimetry, which complements precise position and energy measurements of electromagnetic clusters with a time resolution of about 20 ps. The most crowded inner regions will be equipped with so-called spaghetti calorimeter (SPACAL) technology, which consists of arrays of scintillating fibres either made of plastic or garnet crystals arranged along the beam direction, embedded in a lead or tungsten matrix. The less-crowded outer regions of the calorimeter will continue to be instrumented with the current "Shashlik" technology with refurbished modules and increased granularity. A timing layer, either based on MCPs or on alternated tungsten and silicon-sensor layers placed within the front and back ECAL sections, is also a possibility to achieve the ultimate time resolution. Several SPACAL prototypes have already demonstrated that time resolutions down to an impressive 15 ps are feasible (see "Spaghetti calorimetry" image).

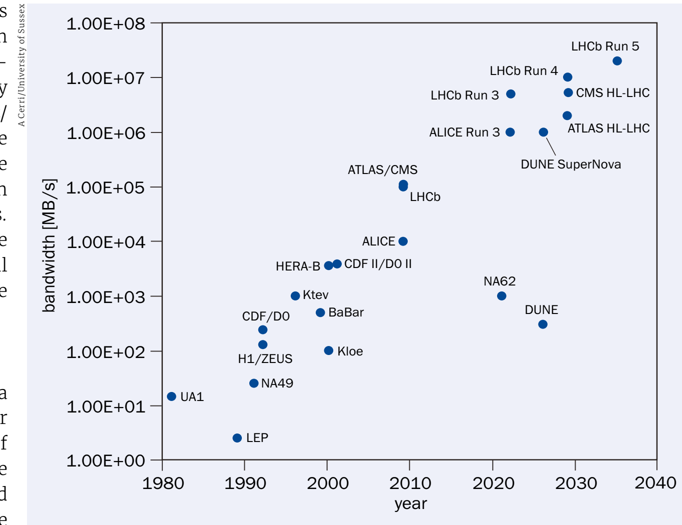
The final main LHCb subdetector is the muon system, based on four stations of multiwire proportional chambers (MWPCs) interleaved with iron absorbers. For Upgrade II, it is proposed that MWPCs in the inner regions, where the rate will be as high as a few $\mathrm{MHz/cm}^2$, are replaced with new-generation micro-pattern gaseous detectors, the micro-RWELL, a prototype of which has proved able to reach a detection efficiency of approximately 97% and a rate-capability of around $10\,\mathrm{MHz/cm}^2$. The outer regions, characterised by lower rates, will be instrumented either by reusing a large fraction (~95%) of the current MWPCs or by implementing other solutions based on resistive plate chambers or scintillating-tile-based detectors. As with all Upgrade II subdetectors, dedicated ASICs in the front-end electronics, which integrate fast time-to-digital converters or high-frequency waveform samplers, will be necessary to measure time with the required precision.

Trigger and computing

The detectors for LHCb Upgrade II will produce data at a rate of up to 200 Tbit/s (see "On the up" figure), which for practical reasons needs to be reduced by four orders of magnitude before being written to permanent storage. The data acquisition therefore needs to be reliable, scalable and cost-efficient. It will consist of a single type of custom-made readout board combined with readily available data-centre hardware. The readout boards collect the data from the various sub-detectors using the radiation-hard, low-power GBit transceiver links developed at CERN and transfer the data to a farm of readout servers via next- generation "PCI Express" connections or Ethernet. For every collision, the information from the subdetectors is merged by passing through a local area network to the builder server farm.

With up to 40 proton–proton interactions, every bunch crossing at the HL-LHC will contain multiple heavy-flavour hadrons within the LHCb acceptance. For efficient event selection, hits not associated with the proton–proton collision of interest need to be discarded as early as possible in the data-processing chain. The real-time analysis system performs reconstruction and data reduction in two high-level-trigger (HLT) stages. HLT1 performs track reconstruction and partial PID to apply inclusive selections, after which the data is stored in a large disk buffer while alignment and calibration tasks run in semi real-time. The final data reduction occurs at the HLT2 level, with exclusive selections based on full offline-quality event reconstruction. Starting from Upgrade I, all HLT1 algorithms are running on a farm of GPUs, which enabled, for the first time at the LHC, track reconstruction to be performed at a rate of 30 MHz. The HLT2 sequence, on the other hand, is run on a farm of CPU servers – a model that would be prohibitively costly for Upgrade II. Given the current evolution of processor performance, the baseline approach for Upgrade II is to perform the reconstruction algorithms of both HLT1 and HLT2 on GPUs. A strong R&D activity is also foreseen to explore alternative co-processors such as FPGAs and new emerging architectures.

The second computing challenge for LHCb Upgrade II derives from detector simulations. A naive extrapolation from the computing needs of the current detector implies that 2.5 million cores will be needed for simulation in Run 5, which is one order of magnitude above what is available with a flat budget assuming a 10% performance increase of processors per year. All experiments in high-energy physics face this challenge, motivating a vigorous R&D programme across the community to improve the processing time of simulation tools such as GEANT4, both by exploiting co-processors and by parametrising the detector response with machine-learning algorithms.



A Cerri/University of Sussex

On the up *Bandwidth of data analysed in real-time versus the start date of various high-energy physics experiments.*

Intimately linked with digital technologies today are energy consumption and efficiency. Already in Run 3, the GPU-based HLT1 is up to 30% more energy-efficient than the originally planned CPU-based version. The data centre is designed for the highest energy-efficiency, resulting in a power usage that compares favourably with other large computing centres. Also for Upgrade II, special focus will be placed on designing efficient code and fully exploiting efficient technologies, as well as designing a compact data acquisition system and optimally using the data centre.

A flavour of the future

The LHC is a remarkable machine that has already made a paradigm-shifting discovery with the observation of the Higgs boson. Exploration of the flavour-physics domain, which is a complementary but equally powerful way to search for new particles in high-energy collisions, is essential to pursue the next major milestone. The proposed LHCb Upgrade II detector will be able to accomplish this by exploring energy scales well beyond those reachable by direct searches. The proposal has received strong support from the 2020 update of the European strategy for particle physics, and the framework technical design report was positively reviewed by the LHC experiments committee. The challenges of performing precision flavour physics in the very harsh conditions of the HL-LHC are daunting, triggering a vast R&D programme at the forefront of technology. The goal of the LHCb teams is to begin construction of all detector components in the next few years, ready to install the new detector at the time of Long Shutdown 4. ●

Further reading

LHCb Collab. 2021 CERN-LHCC-2021-012.
LHCb Collab. 2018 CERN-LHCC-2018-027.

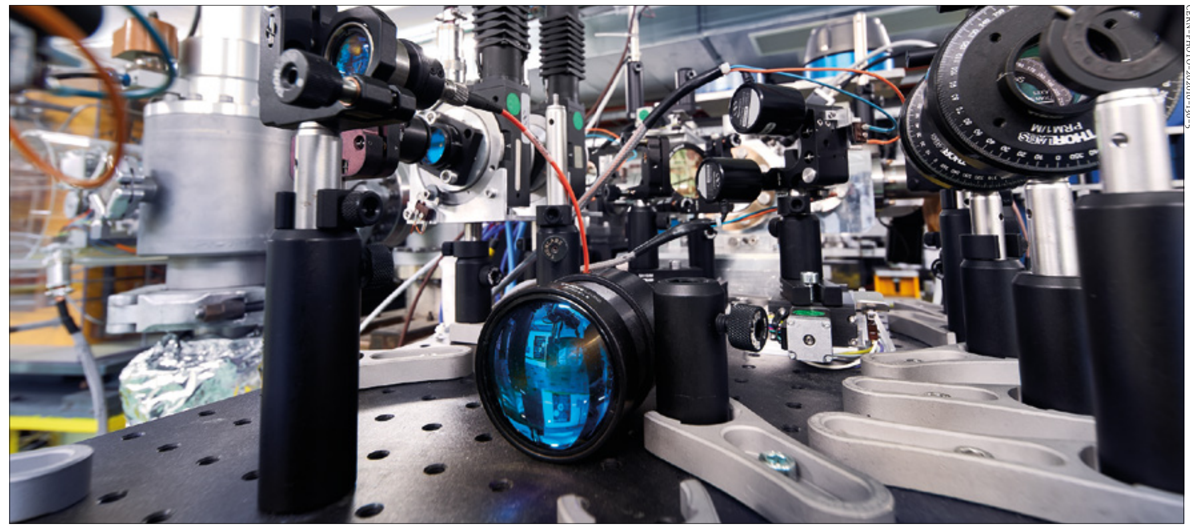
CLEAR HIGHLIGHTS AND GOALS

Built in response to the low availability of test-beam facilities in Europe, the CERN Linear Accelerator for Research (CLEAR) serves as a unique facility for R&D towards accelerator technologies for science and society. Luke Dyks and Roberto Corsini present highlights and future activities.

Particle accelerators have revolutionised our understanding of nature at the smallest scales, and continue to do so with facilities such as the LHC at CERN. Surprisingly, however, the number of accelerators used for fundamental research represents a mere fraction of the 50,000 or so accelerators currently in operation worldwide. Around two thirds of these are employed in industry, for example in chip manufacturing, while the rest are used for medical purposes, in particular radiotherapy. While many of these devices are available "off-the-shelf", accelerator R&D in particle physics remains the principal driver of innovative, next-generation accelerators for applications further afield.

The CERN Linear Electron Accelerator for Research (CLEAR) is a prominent example. Launched in August 2017 (*CERN Courier* November 2017 p8), CLEAR is a user facility developed from the former CTF3 project which existed to test technologies for the Compact Linear Collider (CLIC) – a proposed e^+e^- collider at CERN that would follow the LHC. During the past five years, beams with a wide range of parameters have been provided to groups from more than 30 institutions across more than 10 nations.

CLEAR was proposed as a response to the low availability of test-beam facilities in Europe. In particular, there was very little time available to users on accelerators with electron beams with an energy of a few hundred MeV, as these tend to be used in dedicated X-ray light-source and other specialist facilities. CLEAR therefore serves as a unique facility to perform R&D towards a wide range of accelerator-based technologies in this energy range. Independent of CERN's other accelerator installations, CLEAR has been able to provide beams for around 35 weeks per year since 2018, as well as during long shutdowns, and even managing successful operation during the COVID-19 pandemic.



In focus *An optical table used to direct a laser used as part of an experiment to measure bunch length using electro-optical techniques.*

Access all areas *Inspecting beamline equipment to ensure that CLEAR continues to operate efficiently.*

In position *The installation of novel microbeam position monitors on the in-air test station prior to a beam test in 2020.*

Flexible physics

As a relatively small facility, CLEAR operates in a flexible fashion. Operators can vary the range of beams available with relative ease by tailoring many different parameters, such as the bunch charge, length and energy, for each user. There is regular weekly access to the machine and, thanks to the low levels of radioactivity, it is possible to gain access to the facility several times per day to adjust experimental setups if needed. Along with CLEAR's location at the heart of CERN, the facility has attracted an eager stream of users from day one.

Among the first was a team from the European Space Agency working in collaboration with the Radiation to Electronics (R2E) group at CERN. The users irradiated electronic components for the JUICE (Jupiter Icy Moons Explorer) mission with 200 MeV electron beams. Their experiments demonstrated that high-energy electrons trapped in the strong magnetic fields around Jupiter could induce faults, so-called single event upsets, in the craft's electronics, leading to the development and validation of components with the appropriate radiation-hardness. The initial experiment has been built upon by the R2E group to investigate the effect of electron beams on electronics.

As the daughter of CTF3, CLEAR has continued to be used to test the key technological developments necessary for CLIC. There are two prototype CLIC accelerating structures in the facility's beamline. Originally installed to test CLIC's unique two-beam acceleration scheme, the structures have been used to study short-range "wakefield kicks" that can deflect the beam away from the planned path and reduce the luminosity of a linear collider. Additionally, prototypes of the high-resolution cavity beam position monitors, which are vital to measure and control the CLIC beam, have been tested, showing promising initial results.

One of the main activities at CLEAR concerns the development and testing of beam instrumentation. Here, the flexibility and the large beam-parameter range provided by the facility, together with easy access, especially in its dedicated in-air test station, have proven to be very effective. CLEAR covers all phases of the development of novel beam diagnostics devices, from the initial exploration of a concept or physical mechanism to the first prototyping and to the testing of the final instrument adapted for use in an operational accelerator. Examples are beam-loss monitors based on optical fibres, and beam-position and bunch-length monitors based on Cherenkov diffraction radiation under development by the beam instrumentation group at CERN.

CLEAR has attracted an eager stream of users from day one

Advanced accelerator R&D

There is a strong collaboration between CLEAR and the Advanced Wakefield Experiment (AWAKE), a facility at CERN used to investigate proton-driven plasma wakefield acceleration. In this scheme, which promises higher acceleration gradients than conventional radio-frequency accelerator technology and thus more compact accelerators, charged particles such as electrons are accelerated by forcing them to "surf" atop a longitudinal plasma wave that contains regions of positive and negative charges. Several beam diagnostics for the AWAKE beamline were first tested and optimised at CLEAR. A second phase of the AWAKE project, presently being commissioned for operation in 2026, requires a new source of electron beams to provide shorter, higher quality beams. Before its final installation in AWAKE, it is proposed to use this source to increase the range of beam parameters available at CLEAR.

Further research into compact, plasma-based accelerators has been undertaken at CLEAR thanks to the installation of an active plasma lens on the beamline. Such lenses use gases ionised by very high electric currents to provide focusing for beams many orders of magnitude stronger than can be achieved with conventional magnets. Previous work on active plasma lenses had shown that the focusing

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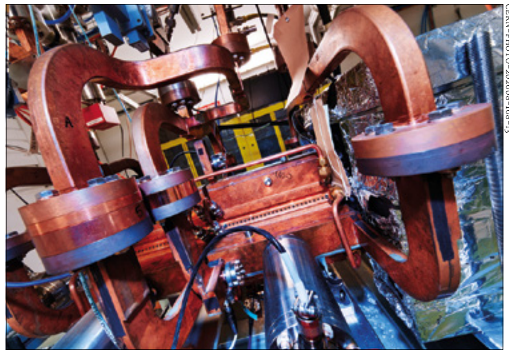


In a flash *Advances in high-gradient accelerator technology for projects such as CLIC have opened up the possibility of using very high-energy electrons to perform FLASH radiotherapy.*

force was nonlinear and reduced the beam quality. However, experiments performed at CLEAR showed, for the first time, that by simply swapping the commonly used helium gas for a heavier gas like argon, a linear magnetic field could be produced and focusing could be achieved without reducing the beam quality (*CERN Courier* December 2018 p8).

Plasma acceleration is not the only novel accelerator technology that has been studied at CLEAR over the past five years. The significant potential of using accelerators to produce intense beams of radiation in the THz frequency range has also been demonstrated. Such light, on the boundary between microwaves and infrared, is difficult to produce, but has a variety of different uses ranging from imaging and security scanning to the control of materials at the quantum level. Compact linear accelerator-based sources of THz light could potentially be advantageous to other sources as they tend to produce significantly higher photon fluxes. By using long trains of ultrashort, sub-ps bunches, it was shown at CLEAR that THz radiation can be generated through coherent transition radiation in thin metal foils, through coherent Cherenkov radiation, and through coherent "Smith–Purcell" radiation in periodic gratings. The peak power emitted in experiments at CLEAR was around 0.1 MW. However, simulations have shown that with relatively minor reductions in the length of the electron bunches it will be possible to generate a peak power of more than 100 MW.

FLASH forward

Advances in high-gradient accelerator technology for projects like CLIC (*CERN Courier* April 2018 p32) have led to a surge of interest in using electron beams with energies between 50–250 MeV to perform radiotherapy, which is one of the key tools used in the treatment of cancer. The use of so-called very-high energy electron (VHEE) beams could provide advantages over existing treatment types. Of particular interest is using VHEE beams to perform radiotherapy at ultra-high dose rates, which could potentially generate the so-called FLASH effect in patients. Here, tumour cells are killed while sparing the surrounding healthy tissues, with the potential to significantly improve treatment outcomes.

So far, CLEAR has been the only facility in the world studying VHEE radiotherapy and FLASH with 200 MeV electron beams. As such, there has been a large increase in beam-time requests in this field. Initial tests performed by researchers from the University of Manchester demonstrated that, unlike other types of radiotherapy beams, VHEE beams are relatively insensitive to inhomogeneities in tissue that typically result in less targeted treatment. The team, along with another from the University of Strathclyde, also looked at how focused VHEE beams could be used to further target doses inside a patient by mimicking the Bragg peak seen in proton radiotherapy. Experiments with the University Hospital of Lausanne to try to demonstrate whether the FLASH effect can be induced with VHEE beams are ongoing (*CERN Courier* January/February 2023 p8).

Even if the FLASH effect can be produced in the lab, there are issues that need to be overcome to bring it to the clinic. Chief among them is the development of novel dosimetric methods. As CLEAR and other facilities have shown, conventional real-time dosimetric methods do not work at ultra-high dose rates. Ionisation chambers, the main pillar of conventional radiotherapy dosimetry, were shown to have very nonlinear behaviour at such dose rates, and recombination times that were too long. Due to this, CLEAR has been involved in the testing of modified ionisation chambers as well as other more innovative detector technologies from the world of particle physics for use in a future FLASH facility.

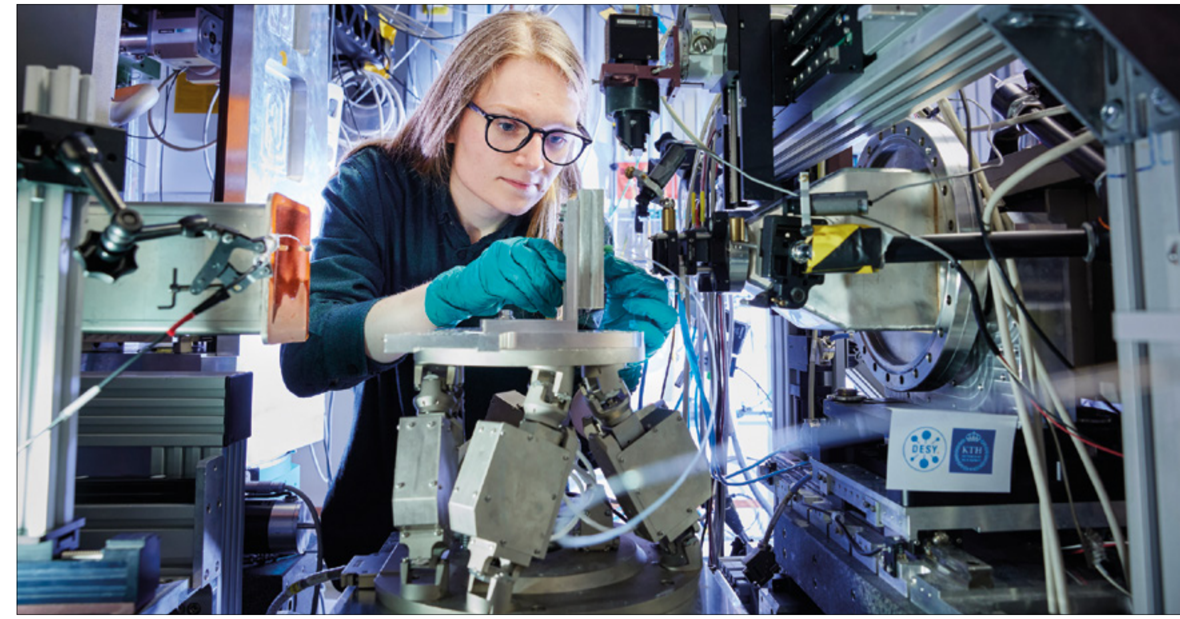
Numerous masters and doctoral students have spent time performing experiments at CLEAR

High impact

As well as being a test-bed for new technologies and experiments, CLEAR has provided an excellent training infrastructure for the next generation of physicists and engineers. Numerous masters and doctoral students have spent a large portion of their time performing experiments at CLEAR either as one-time users or long-term collaborators. Additionally, CLEAR is used for practical accelerator training for the Joint Universities Accelerator School.

As in all aspects of life, the COVID-19 pandemic placed significant strain on the facility. The planned beam schedule for 2020 and beyond had to be scrapped as beam operation was halted during the first lockdown and external users were barred from travelling. However, through the hard work of the team, CLEAR was able to recover and run at almost full capacity within weeks. Several internal CERN users, many of whom were unable to travel to external facilities, were able to use CLEAR during this period to continue their research. Furthermore, CLEAR was involved in CERN's own response to the pandemic by undertaking sterilisation tests of personal protective equipment.

Test-beam facilities such as CLEAR are vital for developing future physics technology, and the impact that such a small facility has been able to produce in just a few years is impressive. A variety of different experiments from several different fields of research have been performed, with many more that are not mentioned in this article. Unfortunately for the world of high-energy physics, the aforementioned shortage of accelerator test facilities has not gone away. CLEAR will continue to play its role in helping provide test beams, with operations due to continue until at least 2025 and perhaps long after. There is an exciting physics programme lined up for the next few years, featuring many experiments similar to those that have already been performed but also many that are new, to ensure that accelerator technology continues to benefit both science and society. ●



At your service *DESY scientists and engineers ensure industrial users make the most of their beam time at the PETRA III synchrotron source, offering services that include feasibility studies, sample preparation, execution of measurements, as well as analysis of experimental data.*

DESY'S INNOVATION ECOSYSTEM DELIVERS IMPACT FOR INDUSTRY

Djamschid Safi explains how the DESY laboratory in Germany is helping Europe's technology and manufacturing companies to fast-track the development of innovative products, services and applications.

Collaboration, applied research services and innovation networks: these are the reference points of an evolving business development strategy that's building bridges between DESY's large-scale research infrastructure and end-users across European industry. The goal is to open up the laboratory's mission in basic science to support technology innovation for economic and societal impact.

As a German national laboratory rooted in physics, and one of the world's leading accelerator research centres, DESY's scientific endeavours are organised along four main coordinates: particle physics, photon science, astroparticle physics and the accelerator physics division. Those parallel lines of enquiry, pursued jointly with regional and international partners, make DESY a magnet for more than 3000 guest scientists from over 40 countries every year.

In the same way, the laboratory is a coveted research partner for industry and business, with its experimental facilities offering a unique addition to the R&D pipeline of some of Europe's small and medium-sized enterprises as well as established technology companies.

Industry collaboration with DESY spans applied R&D and innovation initiatives across topics such as compact next-generation accelerator technologies, advanced laser systems for quality control in semiconductor-chip

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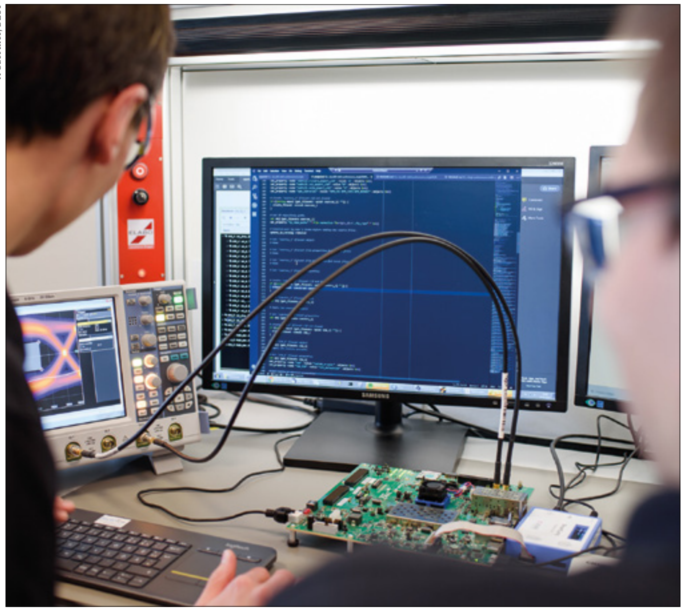


A Gaertner, DESY

Setting the standard *DESY's MicroTCA Technology Lab supports industry partners and customers with hardware, firmware and software development, as well as product testing and technical consultancy. The dedicated laboratory space is open to prospective end-users interested in applying the MicroTCA.4 electronics standard for novel applications in research and industry.*

production, and the 3D printing of custom resins to create parts for use in ultrahigh-vacuum environments. While such cooperative efforts often involve established companies from many different industries, partners from academic science play an equally significant role – and typically with start-up or technology-transfer ambitions as part of the mix.

This is the case for an envisaged spin-off project in which scientists from the University of Hamburg and DESY are working together on a portable liquid biopsy device for medical diagnostics applications (for example, in cancer screening and treatment evaluation). Reciprocity is key to such projects: university researchers bring their background in nanoanalytics, while DESY physicists contribute knowledge and expertise on the development of advanced detector technologies for particle-physics experiments. As a result, a prototype test station for high-sensitivity *in situ* analysis is now in the works, with the interaction of the nanochannels and the detector in the test device representing a significant R&D challenge in terms of precision mechanics (while the DESY team also provides expertise in pattern recognition to accelerate the readout of test results).

Elsewhere, DESY's MicroTCA Technology Lab (TechLab) represents a prominent case study in direct industry collaboration, fostering the uptake of the MicroTCA.4 open electronics standard for applications in research and industry. Originally developed for the telecommunications market, the standard was subsequently adapted by DESY and its network of industrial partners – among them NAT (Germany), Struck (Germany) and CAENels (Italy) – for deployment within particle accelerator control systems (enabling precision measurements of many analogue signals with simultaneous high-performance digital processing in a single controller).

As such, MicroTCA.4 provides a core enabling technology in the control systems of the European X-ray Free Electron Laser (European XFEL), which runs over a 3.4 km span from DESY's Hamburg location to the main European XFEL campus in the town of Schenefeld. Another bespoke application of the standard is to be found in the ground-based control centre of the Laser Interferometer Space Antenna (LISA), a future space-based gravitational wave detector jointly developed by NASA and the European Space Agency.

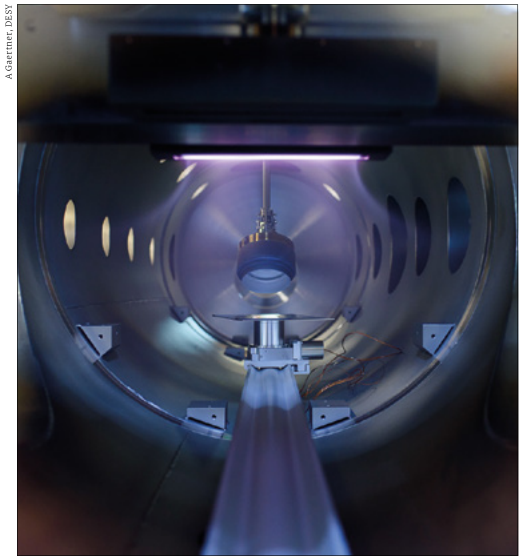
Underpinning this technology transfer is a parallel emphasis on education. This is the reason why TechLab, which sits as part of the business development office at DESY, offers a programme of annual workshops and seminars for current and prospective users of MicroTCA.4. The long-term vision, moreover, is to develop a commercially self-sustaining TechLab spin-off based on the development and dissemination of MicroTCA into new applications and markets.

Industry services

One of the principal drivers of industrial engagement with DESY is the laboratory's PETRA III synchrotron light source (comprising a 2.3 km-circumference storage ring and 25 experimental beamlines). This high-brilliance X-ray facility is exploited by academic and industrial scientists to shed light on the structure and behaviour of matter at the atomic and molecular level across a range of disciplines – from clean-energy technologies to drug development and healthcare, from structural biology and nanotech to food and agricultural sciences.

Operationally, DESY photon scientists and engineers ensure that industrial users are in a position to maximise the return on their PETRA III beam time, offering a portfolio of services that includes feasibility studies, sample preparation, execution of measurements, as well as downstream analysis of experimental data. Industry customers can request proprietary access to PETRA III via the business development office (under a non-disclosure agreement if necessary), while clients do not even need to come to DESY themselves, with options for a mail-in sample service or even remote access studies in certain circumstances. Publication is not required under this access model, though discounted fees are available to industry users willing to publish a "success story" or scientific paper in partnership with DESY.

Alongside the proprietary route, companies are able to access PETRA III beam time through academic partners. This pathway is free of charge and based on research proposals with strong scientific or socioeconomic impact (established via a competitive review process), with a requirement that results are subsequently published in the formal scientific literature. Notwithstanding the possibilities offered by DESY itself, the laboratory's on-campus partners – namely the Helmholtz Centre Hereon and the European Molecular Biology Laboratory (EMBL) – use



A Gaertner, DESY

Quality assurance *Thin-film deposition is part of the service offering to industry users at DESY, opening up unique coating tasks that are not otherwise commercially accessible. The laboratory's magnetron-sputtering deposition systems (shown above) enable functional thin-film development as well as complex multilayer coatings on small and medium-sized planar and 3D objects.*

A Gaertner/DESY

Take your pick *Industry scientists do not even need to go to DESY to access PETRA III beam time, with options for a mail-in sample service or even remote studies in certain circumstances.*

PETRA III to deliver dedicated services that help industry customers address diverse problems in applied R&D.

The German biotech company BioNTech is a case in point. Best known for its successful mRNA vaccine against SARS-Cov-2 infections, BioNTech conducted a programme of X-ray scattering experiments at EMBL's PETRA III beamline P12. The results of these investigations are now helping the company's scientists to better package mRNA within nanoparticles for experimental vaccines and drugs. Along an altogether different R&D track, PETRA III has helped industry users gain novel insights into the inner life of conventional AAA batteries – studies that could ultimately lead to products with significantly extended lifetimes. Using non-invasive X-ray diffraction computer tomography, applied under time-resolved conditions, the studies revealed aspects of the battery ageing process by examining phase transformations in the electrodes and electrolyte during charging and discharge.

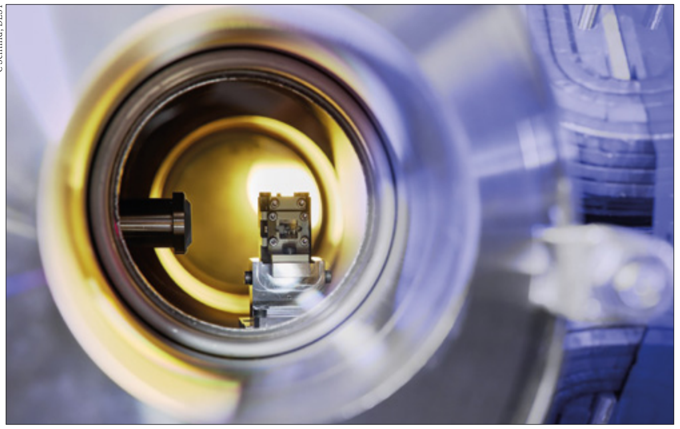
Building an ecosystem

While access to DESY's experimental facilities represents a game-changer for many industry customers, the realisation of new commercial products and technologies does not happen in a vacuum. Innovators, for their part, need specialist resources and expert networks to bring their ideas to life – whether that's in the form of direct investment, strategic consultancy, business and entrepreneurship education, or access to state-of-the-art laboratories and workshops for prototyping, testing, metrology and early-stage product qualification.

DESY is single-minded in its support for this wider "innovation ecosystem", with a range of complementary initiatives to encourage knowledge exchange and collaboration among early-career scientists, entrepreneurs and senior managers and engineers in established technology companies. The DESY start-up office, for example, offers new technology businesses access to a range of services, including management consultancy, business-plan development and networking opportunities with potential suppliers and customers. There's also the Start-up Labs Bahrenfeld, an innovation centre and technology incubator on the DESY Hamburg campus that provides laboratory and office space to young technology companies. The incubator's current portfolio of 16 start-ups reflects DESY's pre-eminence in lasers, detectors and enabling photonic technologies, with seven of the companies also targeting applications in the life sciences.

A more focused initiative is the DESY Startup School, which provides scientists with the core competencies for running their own scientific service companies (intermediary providers of analytical research services to help industry make greater use of large-scale science facilities like DESY). Longer term, the DESY Innovation Factory is set to open in 2025, creating an ambitious vehicle for the commercial development of novel ideas in advanced materials and the life sciences, while fostering cooperation between the research community and technology companies in various growth phases. There will be two locations, one on the DESY campus and one in the nearby innovation and technology park Vorhornweg.

DESY photon scientists and engineers ensure that industrial users are in a position to maximise the return on their PETRA III beam time



C Schmid, DESY

Think small, win big *A laser plasma subsystem under vacuum.*

Opportunities galore

If the network effects of DESY's innovation ecosystem are a key enabler of technology transfer and industry engagement, so too is the relentless evolution of the laboratory's accelerator R&D programme. Consider the rapid advances in compact plasma-based accelerators, offering field strengths in the GV/m regime and the prospect of a paradigm shift to a new generation of user-friendly particle accelerators – even potentially "bringing the accelerator to the problem" for specific applications. With a dedicated team working on the miniaturisation of particle accelerators, DESY is intent on maturing plasma technologies for its core areas of expertise in particle physics and photon science while simultaneously targeting medical and industrial use-cases from the outset.

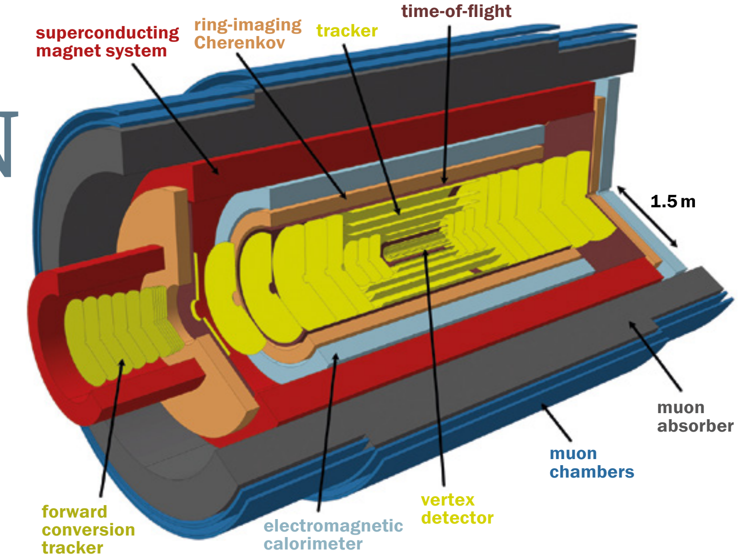
Meanwhile, plans are taking shape for PETRA IV and conversion of the PETRA storage ring into an ultralow-emittance synchrotron source. By generating beams of hard X-rays with unprecedented coherence properties that can be focused down to the nm regime, PETRA IV will provide scientists and engineers with the ultimate 3D process microscope for all manner of industry-relevant problems – whether that's addressing individual organelles in living cells, following metabolic pathways with elemental and molecular specificity, or observing correlations in functional materials over mm length scales and under working conditions.

Fundamental science never stops at DESY. Neither, it seems, do the downstream opportunities for industrial collaboration and technology innovation. ●

● This article originally appeared in the 2022 *CERN Courier In Focus* issue on *Big Science and Industry*.

ALICE 3: A HEAVY-ION DETECTOR FOR THE 2030s

Jochen Klein and Marco van Leeuwen describe the physics motivation, detector concept and projected performance of a next-generation heavy-ion programme for LHC Runs 5 and 6.



Brand new *ALICE 3 is built around a high-resolution tracker with a specialised vertex detector within the beam pipe, housed in a superconducting solenoidal magnet and complemented by several detectors for particle identification: a time-of-flight detector, a ring imaging Cherenkov detector and a muon identifier. An electromagnetic calorimeter provides photon detection and a forward conversion tracker allows the measurement of ultra-soft photons in the forward direction. (Credit: ALICE)*

The ALICE experiment at the LHC was conceived to study the properties of the quark–gluon plasma (QGP), the state of matter prevailing a few microseconds after the Big Bang. Collisions between large nuclei in the LHC produce matter at temperatures of about 3×10^{12} K, sufficiently high to liberate quarks and gluons, and thus to study the deconfined QGP state in the laboratory. The heavy-ion programme at LHC Runs 1 and 2 has already enabled the ALICE collaboration to study the formation of the QGP, its collective expansion and its properties, using for example the interactions of heavy quarks and high-energy partons with the QGP. ALICE 3 builds on these discoveries to reach the next level of understanding.

One of the most striking discoveries at the LHC is that J/ψ mesons not only "melt" in the QGP but can also be regenerated from charm quarks produced in independent hard scatterings. The LHC programme has also shown that the energy loss of partons propagating through the plasma depends on their mass. Furthermore, collective behaviour and enhanced strange-baryon production have been observed in selected proton–proton collisions in which large numbers of particles are produced, signalling that high densities may be reached in such collisions.

During Long Shutdown 2, a major upgrade of the ALICE detector (ALICE 2) was completed on budget and in time for the start of Run 3 in 2022. Together with improvements in the LHC itself, the experiment will profit from a factor-50 higher Pb–Pb collision rate and also provide a better pointing resolution. This will bring qualitative improvements for the entire physics programme, in particular for the detection of heavy-flavour hadrons and thermal di-electron radiation. However, several important questions – for example concerning the mechanisms leading to thermal equilibrium and the formation of hadrons in the QGP – will remain open even after Runs 3 and 4. To address these, the collaboration is pursuing next-generation technologies to build a new detector with a significantly larger rapidity coverage and excellent pointing resolution and particle identification (see "Brand new" figure above). A letter of intent for ALICE 3, to be installed in 2033/2034 (Long Shutdown 4) and operated during Runs 5 and 6 (starting in 2035), was submitted to the LHC experiments committee in 2021 and led to a positive evaluation by the extended review panel in March 2022.

Behind the curtain of hadronisation

In heavy-ion collisions at the LHC, a large amount of energy is deposited in a small volume, forming a QGP. The plasma immediately starts expanding and cooling down, eventually reaching a temperature at which hadrons are formed. Although hadrons formed at the boundary of this phase transition carry information about the expansion of the plasma, they do not inform us directly about the temperature and other properties of the hot plasma phase of the collision before hadronisation takes place. Photons and di-lepton pairs, which are produced as thermal radiation in electromagnetic processes and do not participate in the strong interaction, allow us to look behind the curtain of hadronisation. However, measurements of photon and dilepton emission are challenging due to the large background from electromagnetic decays of light hadrons and weak decays of heavy-flavour hadrons.

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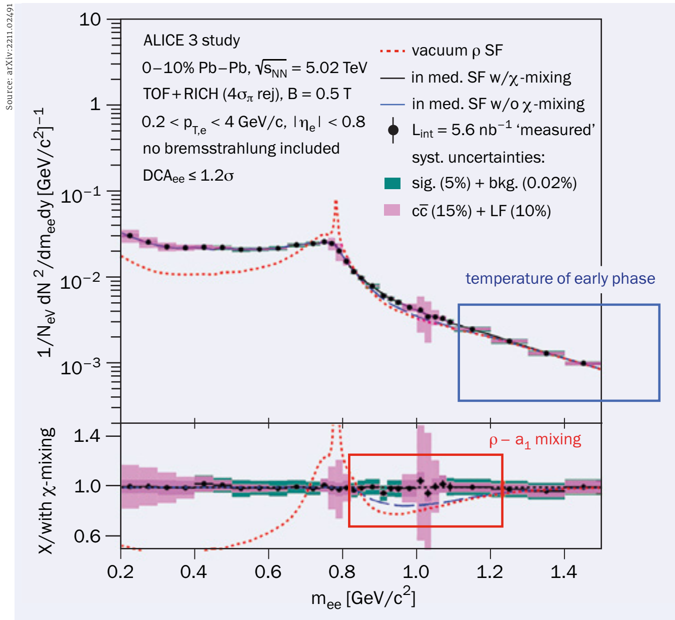
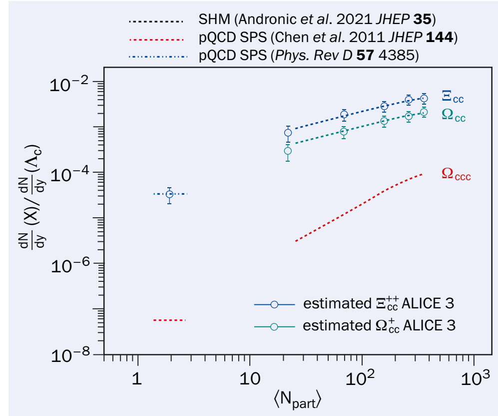


Taking the temperature *The expected invariant-mass distribution of electron–positron pairs in Pb–Pb collisions at the LHC, with coloured bands indicating the projected systematic uncertainties for ALICE 3. The slope of the spectrum above the ρ peak gives access to the plasma temperature. In the absence of ρ and a_1 mixing for chiral-symmetry restoration, a depletion appears in the intermediate mass range.*



Multi-charm production *Expected production yields of double and triple charmed hadrons normalised to the Λ_c yield as a function of the number of participation nucleons, from pp (N_{part} = 2) to central Pb–Pb (N_{part} = 416). Statistical thermal models predict an enhancement by several orders of magnitude for central Pb–Pb collisions. The data points indicate the measurements that could be performed with ALICE 3.*

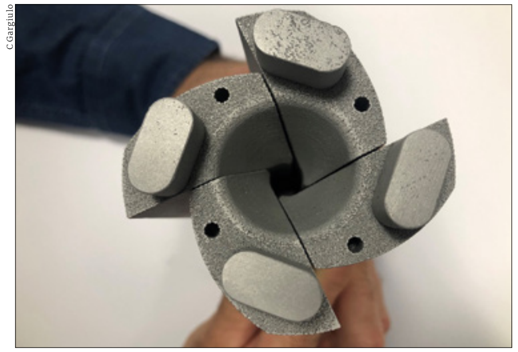
One of the goals of the current ALICE 2 upgrades is to enable the first measurements of the thermal emission of electron–positron pairs (from virtual photons), and thus to determine the average temperature of the system before the formation of hadrons, during Runs 3 and 4. To further understand the evolution of temperature with time, larger data samples and excellent background rejection are needed. The early-stage temperature is determined from the exponential slope of the mass distribution above the ρ resonance, i.e. pair masses larger than 1.2 GeV/c^2 (see "Taking the temperature" figure, upper panel). ALICE 3 would be able to explore the time dependence of the temperature before hadronisation using more differential measurements, e.g. of the azimuthal asymmetry of di-electron emission and of the slope of the mass spectrum as a function of transverse momentum.

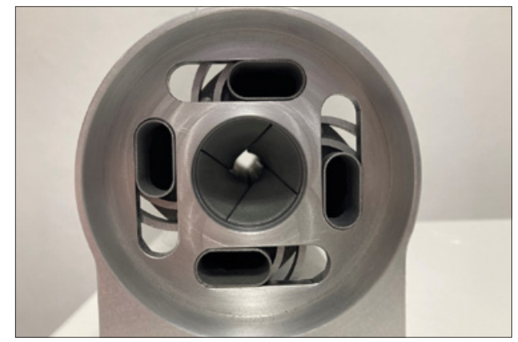
The di-electron mass spectrum also carries unique information about the mechanism of chiral symmetry breaking – a fundamental quantum-chromodynamics (QCD) effect that generates most of the hadron mass. At the phase transition to the QGP, chiral symmetry is restored and quarks and gluons are deconfined. One of the predicted signals of this transition is mixing between the ρ and a_1 vector-meson states, which gives the di-electron invariant mass spectrum a characteristic exponential shape in the mass range above the ρ meson peak (0.8–1.1 GeV/c^2). Only the excellent electron identification and rejection of electrons from heavy-flavour decays possible with ALICE 3 can give physicists experimental access to this effect (see "Taking the temperature" figure, lower panel).

Another important goal of the ALICE physics programme is to understand how energetic quarks and gluons interact with the QGP and eventually thermalise and form a plasma that behaves as a fluid with very low internal friction. The thermalisation process and the properties of the QGP are governed by low-momentum interactions between quarks and gluons, which cannot be calculated using perturbative techniques. Experimental input is therefore important to understand these phenomena and to link them to fundamental QCD.

Heavy quarks

The heavy charm and beauty quarks are of particular interest because their interactions with the plasma can be calculated using lattice-QCD techniques with good theoretical control. Heavy quarks and antiquarks are mostly produced as back-to-back pairs in hard scatterings in the early phase of the collision. Subsequent interactions between the quarks and the plasma change the angle between the quark and antiquark. In addition, the "drag" from the plasma leads to an asymmetry in the overall azimuthal distributions of heavy quarks (elliptic flow) with respect to the reaction plane. The size of these effects is a measure of the strength of the interactions with the plasma. Since quark flavour is conserved in interactions in the plasma, measurements of hadrons containing heavy quarks, such as the D meson and Λ_c baryon, are directly sensitive to the interactions between heavy quarks and the plasma. While the increase in statistics and the improved spatial resolution of ALICE 2 will already allow us to measure the production of charm baryons, measurements of azimuthal correlations of charm–hadron pairs are needed to directly address how they interact with the plasma. These will only become possible with the precision, statistics and acceptance of ALICE 3.





Close encounters *Model of a novel design for a retractable tracker. The four segments can be rotated to bring the tracker sensors closer to the beam pipe.*

Next-gen tracking *An engineering model of ITS 3, demonstrating the mechanical stability of three bent wafers supported by only carbon foam wedges.*

Heavier beauty quarks are expected to take longer to thermalise and therefore lose less information through their interactions with the QGP. Therefore, systematic measurements of transverse-momentum distributions and azimuthal asymmetries of beauty mesons and baryons in heavy-ion collisions are essential to map out the interactions of heavy-flavour quarks with the QGP and to understand the mechanisms that drive the system towards thermal equilibrium.

To understand how hadrons emerge from the QGP, those containing multiple heavy quarks are of particular interest because they can only be formed from quarks that were produced in separate hard-scattering processes. If full thermal equilibrium is reached in Pb–Pb collisions, the production rates of such states are expected to be enhanced by up to three orders of magnitude with respect to pp collisions. This implies enormous sensitivity to the probability for combining independently produced quarks during hadronisation and to the degree of thermalisation. At ALICE 3, the precision with which multi-charm baryon yields can be measured is enhanced (see "Multi-charm production" figure).

In addition to precision measurements of di-electrons and heavy-flavour hadrons, ALICE 3 will allow us to investigate many more aspects of the QGP. These include fluctuations of conserved quantum numbers, such as flavour and baryon number, which are sensitive to the nature of the deconfinement phase transition of QCD. ALICE 3 will also aim to answer questions in hadron physics, for example by searching for the existence of nuclei containing charm baryons (analogous to strange baryons in hypernuclei) and by studying the interaction potentials between unstable hadrons, which may elucidate the structure of exotic hadronic states that have recently been discovered in electron–positron collisions and in hadronic collisions at the LHC. In addition, ALICE 3 will use ultra-peripheral collisions to study the structure of resonances such as the ρ′ and to look for new fundamental particles, such as axion-like particles and dark photons. A dedicated detector system is foreseen to study very low-energy photon production, which can be used to test "soft theorems" that link the production of very soft photons in a collision to the hadronic final state.

Pushing the experimental limits

To pursue this ambitious physics programme, ALICE 3 is designed to be a compact, large-acceptance tracking and particle-identification detector with excellent pointing resolution as well as high readout rates. The main tracking information is provided by an all-silicon tracker in a magnetic field provided by a superconducting magnet system, complemented by a dedicated vertex detector that will have to be retractable to provide the required aperture for the LHC at injection energy. To achieve the ultimate pointing resolution, the first hits must be detected as close as possible to the interaction point (5 mm at the highest energy) and the amount of material in front of it be kept to a minimum. The inner tracking layers will also enable so-called strangeness tracking – the direct detection of strange baryons before they decay – to improve the pointing resolution and suppress combinatorial background, for example in the measurement of multi-charm baryon decays.

First feasibility studies of the mechanical design and the integration with the LHC for the vertex tracker have been conducted and engineering models have been produced to demonstrate the concept and explore production techniques for the components (see "Close encounters" image). The detection layers are to be constructed from

ALICE 3 is a compact, large-acceptance tracking and particle-identification detector with excellent pointing resolution as well as high readout rates

bent, wafer-scale pixel sensors. The development of the next generation of CMOS pixel sensors in 65 nm technology with higher radiation tolerance and improved spatial resolution has already started in the context of the ITS 3 project in ALICE, which will be an important milestone on the way to ALICE 3 (see "Next-gen tracking" image). The outer tracker, which has to cover the cylindrical volume to a radius of 80 cm over a total length of ±4 m, will also use CMOS pixel sensors. These will be integrated into larger modules for an effective instrumentation of about 60 m² while minimising the material used for mechanical support and services. The foreseen material budget for the tracker is 1% of a radiation length per layer for the outer tracker, and only 0.05% per layer for the vertex tracker.

For particle identification, five different detector systems are foreseen: a silicon-based time-of-flight system and a ring-imaging Cherenkov (RICH) detector that provide hadron and electron identification over a broad momentum range, a muon identifier starting from a transverse momentum of about 1.5 GeV/c, an electromagnetic calorimeter for photon detection and identification, and a forward tracker to reconstruct photons at very low momentum from their conversions to electron–positron pairs. For the time-of-flight system, the main R&D line aims at the integration of a gain layer in monolithic CMOS sensors to achieve the required time resolution of at least 20 ps (alternatively, low-gain avalanche diodes with external readout circuitry can be used). The calorimeter is based on a combination of lead-sampling and lead-tungstate segments, both of which would be read out by commercially available silicon photomultipliers (SiPMs). For the detection layers of the muon identifier, both resistive plate chambers and scintillating bars are being considered. Finally, for the RICH design, the R&D goal is to integrate the digital readout circuitry in SiPMs to enable efficient detection of photons in the visible range.

ALICE 3 provides a roadmap for an exciting heavy-ion physics programme in Runs 5 and 6

ALICE 3 provides a roadmap for an exciting heavy-ion physics programme, along with the other three large LHC experiments, in Runs 5 and 6. An R&D programme for the coming years is being set up to establish the technologies and enable the preparation of technical design reports in 2026/2027. These developments not only constitute an important contribution to the full physics exploitation of the LHC, but are of strategic interest for future particle detectors and will benefit the particle and nuclear physics community at large. ●

Further reading

ALICE Collab. 2022 arXiv:2211.04384.
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P M Hohler and R Rapp 2014 *Phys. Lett. B* **731** 103.

OPINION VIEWPOINT

Physics is about principles, not particles

We should all renew the enthusiasm that built the LHC, be outspoken about the profound ideas we explore, and embrace the journey that the discovery of the Higgs boson has opened, says Veronica Sanz.

Shutterstock/Mgraphics

Boldly go *The spirit of basic research is to follow those paths with unknown destinations.*

University of Sussex

Veronica Sanz *is a theorist at Universitat de Valencia and the University of Sussex.*

Last year marked the 10th anniversary of the discovery of the Higgs particle. Ten years is a short lapse of time when we consider the profound implications of this discovery. Breakthroughs in science mark a leap in understanding, and their ripples may extend for decades and even centuries. Take Kirchhoffs' blackbody proposal more than 150 years ago: a theoretical construction, an academic exercise that opened the path towards a quantum revolution, the implications of which we are still trying to understand today.

Imagine now the vast network of paths opened by ideas, such as emission theory, that led to no fruition despite their originality. Was pursuing these useful, or a waste of resources? Scientists would answer that the spirit of basic research is precisely to follow those paths with unknown destinations; it's how humanity reached the level of knowledge that sustains modern life. As particle physicists, as long as the aim is to answer nature's outstanding mysteries, the path is worth following. The Higgs-boson discovery is the latest triumph of this approach and, as for the quantum revolution, we are still working hard to make sense of it.

Particle discoveries are milestones in the history of our field, but they signify something more profound: the realisation of a new principle in nature. Naively, it may seem that the Higgs discovery marked the end of our quest to understand the TeV scale. The opposite is true. The behaviour of the Higgs boson, in the form it was initially proposed, does not make sense at a quantum level. As a fundamental scalar, it experiences quantum effects that grow with their energy, doggedly pushing its mass towards the Planck scale. The Higgs discovery solidified the idea that gauge symmetries could be hidden, spontaneously broken by the vacuum. But it did not provide an explanation of how this mechanism makes sense with a fundamental scalar sensitive to mysterious phenomena such as quantum gravity.

Now comes the hard part. From the plethora of ideas proposed during the past decades to make sense of the Higgs boson – supersymmetry being the most prominent – most physicists predicted that it would have an entourage of companion particles with electroweak or even strong couplings. Arguments of naturalness, that these companions should be close-by to prevent troublesome fine-tunings of nature, led to the expectation that discoveries would follow or even precede that of the Higgs. Ten years on, this wish has not been fulfilled. Instead, we are faced with a cold reality that can lead us to sway between attitudes of nihilism and hubris, especially when it comes to the question of whether particle physics has a future beyond the Higgs. Although these extremes do not apply to everyone, they are understandable reactions to viewing our field next to those with more immediate applications, or to the personal disappointment of a lifelong career devoted to ideas that were not chosen by nature.

The no-lose theorem we enjoyed when planning the LHC was an exception to the rules of basic research

Such despondence is not useful. Remember that the no-lose theorem we enjoyed when planning the LHC, i.e. the certainty that we would find something new, Higgs boson or not, at the TeV scale, was an exception to the rules of basic research. Currently, there is no no-lose theorem for the LHC, or for any future collider. But this is precisely the inherent premise of any exploration worth doing. After the incredible success we have had, we need to refocus and unify our discourse. We face the uncertainty of searching in the dark, with the hope that we will initiate the path to a breakthrough, still aware of the small likelihood that this actually happens.

Those hopes are shared by wider society, which understands the importance of exploring big questions. From searching for exoplanets that may support life to understanding the human mind, few people assume these paths will lead to immediate results. The challenge for our field is to work out a coherent message that can enthuse people. Without straying far from collider physics, we could notice that there is a different type of conversation going on in the search for dark matter. Here, there is no no-lose theorem either, and despite the current exclusion of most vanilla scenarios, there is excitement and cohesion, which are effectively communicated. As for our critics, they should be openly confronted and viewed as an opportunity to build stronger arguments.

We have powerful arguments to keep delving into the smallest scales, with the unknown nature of dark matter, neutrinos and the matter–antimatter asymmetry the most well-known examples. As a field, we need to renew the excitement that led us where we are, from the shock of watching alpha particles bounce back from a thin gold sheet, to building a colossus like the LHC. We should be outspoken about our ambition to know the true face of nature and the profound ideas we explore, and embrace the new path that the Higgs discovery has opened.

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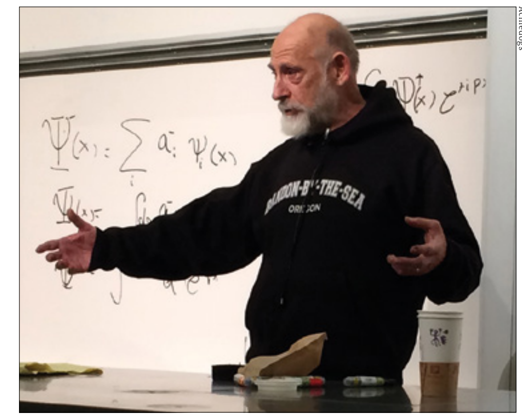
OPINION
INTERVIEW

Lost in the landscape

20 years ago Leonard Susskind coined the term "landscape" to describe the vast set of possible string-theory solutions. He describes what led to this picture, the hopes for string theory today, and how emerging connections between quantum mechanics and gravity are transforming our views about a fundamental theory.

What is string theory?
I take a view that a lot of my colleagues will not be too happy with. String theory is a very precise mathematical structure, so precise that many mathematicians have won Fields medals by making contributions that were string-theory motivated. It's supersymmetric. It exists in flat or anti-de Sitter space (that is, a space–time with a negative curvature in the absence of matter or energy). And although we may not understand it fully at present, there does appear to be an exact mathematical structure there. I call that string theory with a capital "S", and I can tell you with 100% confidence that we don't live in that world. And then there's string theory with a small "s" – you might call it string-inspired theory, or think of it as expanding the boundaries of this very precise theory in ways that we don't know how to at present. We don't know with any precision how to expand the boundaries into non-supersymmetric string theory or de Sitter space, for example, so we make guesses. The string landscape is one such guess. It's not based on absolutely precise capital-S string theory, but on some conjectures about what this expanded small-s string theory might be. I guess my prejudice is that some expanded version of string theory is probably the right theory to describe particle physics. But it's an expanded version, it's not supersymmetric. Everything we do in anti-de-Sitter-space string theory is based on the assumption of absolute perfect supersymmetry. Without that, the models we investigate are rather speculative.

How has the lack of supersymmetric discoveries at the LHC impacted your thinking?
All of the string theories we know about with any precision are exactly supersymmetric. So if supersymmetry is broken at the weak scale or beyond, it doesn't help because we're still facing a world that is not exactly supersymmetric. This only gets worse as we find out that supersymmetry doesn't seem to even govern the world at the weak scale. It doesn't even seem to govern it at the TeV scale. But that, I think, is secondary. The first primary fact is that the world is not exactly supersymmetric and string theory with a capital S is. So where are we? Who knows! But it's exciting to be in a situation where there is confusion. Anything that can be said about how string theory can be precisely expanded beyond the supersymmetric bounds would be very interesting.



Master of strings *Leonard Susskind, Felix Bloch professor of physics at Stanford University, pictured lecturing in 2013, is one of the founders of string theory.*

What led you to coin the string theory "landscape" in 2003?
A variety of things, among them the work of other people, in particular Polchinski and Bousso, who conjectured that string theories have a huge number of solutions and possible behaviours. This was a consequence, later articulated in a 2003 paper abbreviated "KKLT" after its authors, of the innumerable (initial estimates put it at more than 10^{500}) different ways the additional dimensions of string theory can be hidden or "compactified". Each solution has different properties, coupling constants, particle spectra and so forth. And they describe different kinds of universes. This was something of a shock and a surprise; not that string theory has many solutions, but that the numbers of these possibilities could be so enormous, and that among those possibilities were worlds with parameters, in particular the cosmological constant, which formed a *discretuum* as opposed to a continuum. From one point of view that's troubling because some of us, me less than others, had hoped there was some kind of uniqueness to the solutions of string theory. Maybe there was a small number of solutions and among them we would find the world that we live in, but instead we found this huge number of possibilities in which almost anything could be found. On the other hand, we knew that the parameters of our world are unusual, exceptional, fine-tuned – not generic, but very special. And if the string landscape could say that there would be solutions containing the peculiar numbers that we face in physics, that was interesting. Another motivation came from cosmology: we knew on the basis of cosmic-microwave-background experiments and other things that the portion of the universe we see is very flat, implying that it is only a small part of the total. Together with the peculiar fine-tunings of the numbers in physics, it all fitted a pattern: the spectrum of possibilities would not only be large, but the spectrum of things we could find in the much bigger universe that would be implied by inflation and the flatness of the universe might just include all of these various possibilities.

So that's how anthropic reasoning entered the picture?
All this fits together well with the anthropic principle – the idea that

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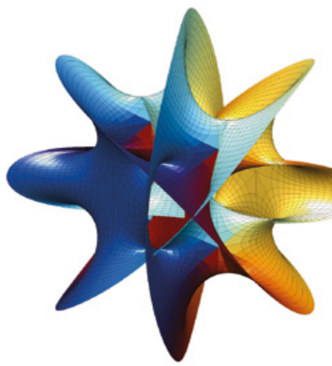
the patterns of coupling constants and particle spectra were conditioned on our own existence. Weinberg was very influential in putting forward the idea that the anthropic principle might explain a lot of things. But at that time, and probably still now, many people hated the idea. It's a speculation or conjecture that the world works this way. The one thing I learned over the course of my career is not to underestimate the potential for surprises. Surprises will happen, patterns that look like they fit together so nicely turn out to be just an illusion. This could happen here, but at the moment I would say the best explanation for the patterns we see in cosmology and particle physics is a very diverse landscape of possibilities and an extremely large universe – a multiverse, if you like – that somehow manifests all of these possibilities in different places. Is it possible that it's wrong? Oh yes! We might just discover that this very logical, compelling set of arguments is not technically right and we have to go in some other direction. Witten, who had negative thoughts about the anthropic idea, eventually gave up and accepted that it seems to be the best possibility. And I think that's probably true for a lot of other people. But it can't have the ultimate influence that a real theory with quantitative predictions can have. At present it's a set of ideas that fit together and are somewhat compelling, but unfortunately nobody really knows how to use this in a technical way to be able to precisely confirm it. That hasn't changed in 20 years. In the meantime, theoretical physicists have gone off in the important direction of quantum gravity and holography.

What do you mean by holography in the string-theory context?
Holography predates the idea of the landscape. It was based on Bekenstein's observation that the entropy of a black hole is proportional to the area of the horizon and not the volume of the black hole. It conjectures that the 3D world of ordinary experience is an image of reality coded on a distant 2D surface. A few years after the holographic principle was first conjectured, two precise versions of it were discovered; so called M(atrix) theory in 1996 and Maldacena's "AdS/CFT" correspondence in 1997. The latter has been especially informative. It holds that there is a holographic duality between anti-de Sitter space formulated in terms of string theory, and quantum field theories that are similar to those that describe elementary particles. I don't think string theory and holography are inconsistent with each other. String theory is a quantum theory that contains gravity, and all quantum mechanical gravity theories have to be holographic. String theory and holographic theory could well be the same thing.

One of the things that troubles me about the standard model of cosmology, with inflation and a positive cosmological constant, is that the world, or at least the portion of it that we see, is de Sitter space. We do not have a good quantum understanding of de Sitter space. If we ultimately learn that de Sitter space is impossible, that would be very interesting. We are in a situation now that is similar to 20 years ago, where very little progress has been made in the quantum foundations of cosmology and in particular in the so-called measurement problem, where we don't know how to use these ideas quantitatively to make predictions.



Curled up *String theory requires additional, microscopic dimensions that are compactified using Calabi–Yau manifolds. The innumerable possible ways of doing so produce a vast "landscape" of possible string-theory solutions. (Credit: Z Zhang)*

What does the measurement problem have to do with it?
The usual methodology of physics, in particular quantum mechanics, is to imagine systems that are outside the systems we are studying. We call these systems observers, apparatuses or measuring devices, and we sort of divide the world into those measuring devices and the things we're interested in. But it's quite clear that in the world of cosmology/de Sitter space/eternal inflation, that we're all part of the same thing. And I think that's partly why we are having trouble understanding the quantum mechanics of these things. In AdS/CFT, it's perfectly logical to think about observers outside the system or observers on the boundary. But in de Sitter space there is no boundary; there's only everything that's inside the de Sitter space. And we don't really understand the foundations or the methodology of how to think about a quantum world from the inside. What we're really lacking is the kind of precise examples we have in the context of anti-de Sitter space, which we can analyse. This is something I've been looking for, as have many others including Witten, without much success. So that's the downside: we don't know very much.

What about the upsides?
The upside is that almost anything we learn will be a large fraction of what we know. So there's potential for great developments by simply understanding a few things about the quantum mechanics of de Sitter space. When I talk about this to some of my young friends, they say that de Sitter space is too hard. They are afraid of it. People have been burned over the years by trying to understand inflation, eternal inflation, de Sitter space, etc, so it's much safer to work on anti-de Sitter space. My answer to that is: yes, you're right, but it's also true that a huge amount is known about anti-de Sitter space and it's hard to find new things that haven't been said before, whereas in de Sitter space the opposite is true. We will see, or at least the young people will see. I am getting to the point where it is hard to absorb new ideas.

Almost anything we learn will be a large fraction of what we know

To what extent can the "swampland" programme constrain the landscape?
The swampland is a good idea. It's the idea that you can write down all sorts of naive semi-classical theories with practically infinite options, but that the consistency with quantum mechanics constrains the things that are possible, and those that violate the constraints are called the swampland. For example, the idea that there can't be exact global symmetries in a quantum theory of gravity, so any theory you write down that has gravity and has a global symmetry in it, without having a corresponding gauge symmetry, will be in the swampland. The weak-gravity conjecture, which enables you to say something about the relative strengths of gauge forces and gravity acting on certain particles, is another good idea. It's good to try to separate those things you can write down from a semi-classical point of view and those that are constrained by whatever the principles of quantum gravity are. The detailed example of the cosmological constant I am much less impressed by. The argument seems to be: let's put a constraint on parameters in cosmology so that we can put de Sitter space in the swampland. But the world looks very much like de Sitter space, so I don't understand the argument and I suspect people are wrong here.

What have been the most important and/or surprising physics results in your career?
I had one big negative surprise, as did much of the community. This was a while ago when the idea of "technicolour" – a dynamical way to break electroweak symmetry via new gauge interactions – turned out to be wrong. Everybody I knew was absolutely convinced that technicolour was right, and it wasn't. I was surprised and shocked. As for positive surprises, I think it's the whole collection of ideas called "it from qubit". This has shown us that quantum mechanics and gravity are much more closely entangled with each other than we ever thought, and that the apparent difficulty in unifying them was because they were already unified; so to separate and then try to put them back together using the quantisation technique was wrong. Quantum mechanics and gravity are so closely related that in some sense they're almost the same thing. I think that's the message from the past 20 – and in particular the past 10 – years of it-from-qubit physics, which has largely been dominated by people like Maldacena and a whole group of younger physicists. This intimate connection between entanglement and spatial structure – the whole holographic and "ER equals EPR" ideas – is very bold. It has given people the ability to understand Hawking radiation, among other things, which I find extremely exciting. But as I said, and this is not always stated, in order to have real confidence in the results, it all ultimately rests on the assumption of theories that have exact supersymmetry.

What are the near-term prospects to empirically test these ideas?
One extremely interesting idea is "quantum gravity in the lab" – the idea that it is possible to construct systems, for example a large sphere of material engineered to support surface excitations that look like conformal field theory, and then to see if that system describes a bulk world with gravity. There are already signs that this is true. For example, the recent claim, involving Google, that two entangled quantum computers have been used to send information through the analogue of a wormhole shows how the methods of gravity can influence the way quantum communication is viewed. It's a sign that quantum mechanics and gravity are not so different.

Do you have a view about which collider should follow the LHC?
You know, I haven't done real particle physics for a long time. Colliders fall into two categories: high-precision e^+e^- colliders and high-energy proton–proton ones. So the question is: do we need a precision Higgs factory at the TeV scale or do we want to search for new phenomena at higher energies? My prejudice is the latter. I've always been a "slam 'em together and see what comes out" sort of physicist. Analysing high-precision data is always more clouded. But I sure wouldn't like anyone to take my advice on this too seriously.

Interview by **Kristiane Bernhard-Novotny** *associate editor.*

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OPINION REVIEWS

A powerful eye opener into the world of AI

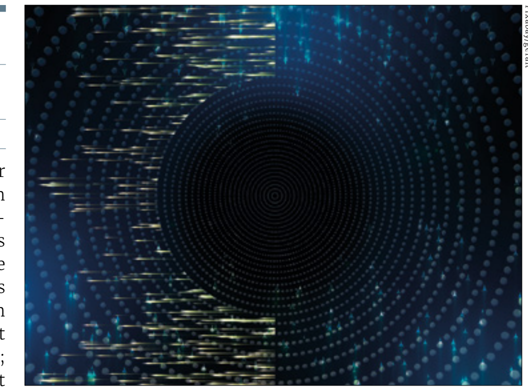
Artificial Intelligence for High Energy Physics

By Paolo Calafiura, David Rousseau, Kazuhiro Terao

World Scientific

The appearance of the word "for" rather than "in" in the title of this collection raises the bar from an academic description to a primer. It is neither the book's length (more than 800 pages), nor the fact that the author list resembles a who's who in artificial intelligence (AI) research carried out in high-energy physics that makes this book live up to its premise; it is the careful crafting of its content and structure.

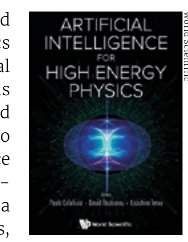
Artificial intelligence is not new to our field. On the contrary, some of the concepts and algorithms have been pioneered in high-energy physics. *Artificial Intelligence for High Energy Physics* credits this as well as reaching into very recent AI research. It covers topics ranging from unsupervised machine-learning techniques in clustering to workhorse tools such as boosted decision trees in analyses, and from recent applications of AI in event reconstruction to simulations at the boundary where AI can help us to understand physics.



Pixabay/geralt

Connections *Machine learning has entered every aspect of data analysis in high-energy physics.*

Each chapter follows a similar structure: after setting the broader context, a short theoretical introduction into the tools (and, where possible, the available software) is given, which is then applied and adapted to a high-energy physics problem. The ratio of in-depth theoretical background to AI concepts and the focus on applications is well balanced, and underlines the work of the editors, who avoided duplication and cross-reference individual chapters and topics. The editors and authors have not only created a selection of high-quality review articles, but a coherent and remarkably good read. Takeaway messages in the chapter for distributed training and optimisation stand out, and one might wish that this concept found more resonance throughout the book.



World Scientific

Sometimes, the book can be used as a glossary, which helps to bridge the gaps that seem to exist simply because high-energy physicists and data scientists use different names for similar or even identical things. While the book can certainly be used as a guide for a physicist in AI, an AI researcher with the necessary physics knowledge may not be served quite so well.

In an ideal world, each chapter would have a reference dataset to allow the reader to follow the stated problems and learn through building and exercising the described pipelines. This, however, would turn the book from a primer into a textbook for AI in high-energy physics. To be fair, wherever possible the authors of the chapters have used and referred to publicly available datasets, and one chapter is devoted to the issue of arranging a community data competition, such as the TrackML challenge in 2018.

As for the most important question – have I learned something new? – the answer is a resounding "yes". While none of the broad topics and their application to high-energy physics will come as a surprise to those who have been following the field in recent years, there are neat projects and detailed applications showcased in this book. Furthermore, reading about a familiar topic in someone else's words can be a powerful eye opener.

Andreas Salzburger *CERN.*

The Sketchbook and the Collider

Forum Exposition Bonlieu, Annecy, France, 30 September to 23 October 2022

"Reality is not what it seems: Drawing links between fine art and particle physics" was the title of the art–science exhibit set up by the Laboratoire d'Annecy de Physique des Particules (LAPP) on the occasion of the 2022 Fête de la Science. The installation was part of an ongoing collaboration between UK fine artist Ian Andrews and ATLAS physicist Kostas Nikolopoulos called "The Sketchbook and the Collider", which was initiated in 2018 while Andrews was an artist in residence at the University of Birmingham. The project takes viewers on a journey where the artist's sketchbook and the experimental physicist's collider can both be seen as arenas where the invisible is made visible, "sometimes violently", by bringing elements together and examining the traces of hidden interactions. It also comprises performative pieces that involve "live" drawing and the cooperation, participation and interaction of artists, scientists and members of the public.

I Andrews

The invisible made visible *An installation at the exhibition.*

"About 900 visitors spanning all ages, professions and cultural backgrounds engaged and interacted with the exhibition, either attracted by the arts and the science, or caught by surprise on their way to Lake Annecy, in a very special Higgs and LHC celebration year," said organiser Claire Adam-Bourdarios of LAPP.

Claire Adam-Bourdarios *LAPP Annecy.*

Unconventional music @ CERN

CERN Globe, 19 October 2022

Honouring the 100th anniversary of Einstein's Nobel prize, the Swedish embassy in Bern collaborated with CERN for an event connecting science and music, held at the CERN Globe of Science and Innovation on 19 October. The event was originally planned for 2021 but was postponed due to the pandemic.

Brian Foster (University of Oxford) talked about Einstein's love for music and playing the violin, which was underlined with many photos showing Einstein with some of the well-known violinists of the time. Around the period Einstein was awarded the Nobel prize, Russian engineer Lev Termen invented the theremin, consisting of two antennae and played without physical contact. This caught Einstein's attention and it is said that he even played the theremin himself once.

Delving further into the unconventional, LHC physicists performed Domenico Vicinanza's (GEANT and Anglia Ruskin University) "Sonification of the LHC", for which the physicist-turned composer mapped data recorded by the LHC experiments between 2010 and 2013 into music. First performed in 2014 on the occasion of CERN's 60th anniversary, Vicinanza's piece is intended as a metaphor for scientific cooperation, in which different voices and perspectives can reach the same goal only by playing together.

CERN

Photoelectric *Physicists and musicians celebrated the centenary of Einstein's Nobel prize by fusing tradition and modernism.*

There followed the debut of an even more unconventional piece of music by The Stone Martens – a Swiss and Swedish "noise collaboration" improvised by Henrik Rylander and Roland Bucher. By sending the output of his theremin through guitar-effects pedals, Rylander created a unique sound. Together with Bucher's self-made "noise table", with which he sampled acoustic instruments and everyday objects, the duo created a captivating, otherworldly sound collage that was well received by the 160-strong audience. The event closed with an unconventional Bach concerto for two violins in which these unique sounds were fused with traditional instruments. Anyone interested in experiencing the music for themselves can find a recorded version at https://indico.cern.ch/event/1199556/.

Kristiane Bernhard-Novotny *associate editor.*

How to find your feet in industry

The 2022 LHC Career Networking Event explored the diverse career paths on offer to physicists considering life outside academia. Shaun Roe reports.

S Celani

Insightful *Speaker Albert Puig Navarro described his journey from LHCb to Geneva-based firm Proton.*

The sixth annual LHC Career Networking Event, which took place at CERN on 21 November 2022, attracted more than 200 scientists and engineers (half in person) seeking to explore careers beyond CERN. Seven former members of the LHC-experiment collaborations and representatives from CERN's knowledge transfer group discussed their experiences, good and bad, upon transitioning to the diverse employment world outside particle physics. Lively Q&A sessions and panel discussions enabled the audience to voice their questions and concerns.

While the motivations for leaving academia expressed by the speakers differed according to their personal stories, common themes emerged. The long time-scales of experimental physics coupled with job instability and the glacial pace of funding cycles for new projects, for example, sometimes led to demotivation, whereas the speakers found that industry had exciting shorter-term projects to explore. Several speakers sought a better work–life balance in subjects they could enthuse about, having previously experienced a sense of stagnation. Another factor related to that balance was the better ratio between salary and performance, and hours worked.

Case studies

Caterina Deplano, formerly an ALICE experimentalist, and Giorgia Rauco, ex-CMS, described the personal constraints that led them to search for a job in the local area, and showed that this need not be a limiting factor. Both assessed their skills frankly and opted for further training in their target sectors: education and data science, respectively. Deplano's path to teaching in Geneva led her to go back and study for four years, improving her French-language skills while obtaining a Swiss teaching qualification. The reward was apparent in the enthusiasm with which she talked about her students and her chosen career. Rauco explained how she came to contemplate life outside academia and talked participants through the application process, emphasising that finding the "right" employment fit had meant many months of work with frequent disappointments, the memory of which was erased by the final acceptance letter. Both speakers gave links to valuable resources for training and further education, and Rauco offered some top-tips for prospective transitioners: be excited for what is coming next, start as soon as possible if you are thinking about changing and don't feel guilty about your choice.

Maria Elena Stramaglia, formerly ATLAS, described the anguish of deciding whether to stay in academia or go to industry, and her frank assessment of transferable skills weighed up against personal desires and her own work–life balance. Her decision to join Hitachi Energy was based on the right mix of personal and technical motivation, she said. In moving from LHCb to data science and management, Albert Puig Navarro joined a newly established department at Proton (the developers of ProtonMail, which was founded by former ATLAS members; *CERN Courier* September/October 2019 p53), in which he ended up being responsible for hiring a mix of data scientists, engineers and operations managers, conducting more than 200 interviews in the process. He discussed the pitfalls of over-confidence, the rather different requirements of the industrial sector, and the shift in motivations between pure science and industry. Cécile Deterre, a former ATLAS physicist now working on technology for sustainable fish farming, focussed on CV-writing for industrial job applications, during which she emphasised transferable skills and how to make your technical experience more accessible to future employers.

With one foot still firmly in particle physics, Alex Winkler, formerly CMS, joined a company that makes X-ray detectors for medical, security and industrial applications; in a serendipitous exception among the speakers, he described how he was head-hunted while contemplating life beyond CERN, and mentioned the novel pressures implicit in working in a for-profit environment. Massimo Marino, ex-ATLAS, gave a lively talk about his experiences in a number of diverse environments: Apple, the World Economic Forum and the medical energy industries, to name a few. Diverting along the way to write a series of books, his talk covered the personal challenges and expectations in different roles and environments over a long career.

Throughout the evening, which culminated in a panel session, participants had the opportunity to quiz the speakers about their sectors and the personal decisions and processes that led them there. Head of CERN Alumni Relations Rachel Bray also explained how the Alumni Network can help facilitate contact between current CERN members and their predecessors who have left the field. The interest shown by the audience and the detailed testimonials of the speakers demonstrated that this event remains a vital source of information and encouragement for those considering a career transition.

Shaun Roe *CERN.*

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Appointments and awards

New head at IRFU
Experimental nuclear physicist Franck Sabatié is the new director of the French CEA Institute for Research into the Fundamental Laws of the Universe (IRFU), beginning in September 2022. He succeeds particle-physicist Anne-Isabelle Etienvre, a former French delegate to the CERN Council and now cabinet member of the French ministry for higher education and research. After completing his PhD at

CEA in 1998, Sabatié worked on nucleon-structure experiments at Jefferson Lab, returning to the CEA in 2000 and becoming head of the nuclear physics department in 2016. "We are truly in a golden age of experimental physics in the full spectrum of IRFU's activities," he says. "In the next 10–15 years, the HL-LHC will have accumulated a large amount of data, the DUNE experiment will have started, the Electron–Ion Collider will see its first collisions, in addition to a wealth of data from the James Webb and other research satellites to be launched this year. Closer to home, GANIL with SPIRAL2 and soon FAIR will profoundly change the landscape of nuclear physics."

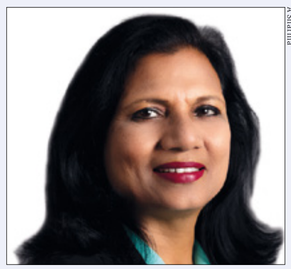
DPG 2023 awards
Due to be presented in March, the 2023 awards of the German Physical Society (DPG) recognise the contributions of several high-energy physicists. The Max Planck medal for accomplishments in theoretical physics goes to Rashid Sunyaev (above right; MPI/IAS) in recognition of his numerous contributions to relativistic astrophysics and cosmology, in particular for the prediction,

together with his doctoral supervisor Yakov Zeldovich, of experimentally observed changes in the spectrum of cosmic microwave background radiation due to photons passing through galaxy clusters. The Max Born prize, granted jointly by the UK Institute of Physics and the DPG, is awarded to experimentalist and current DUNE co-spokesperson Stefan Söldner-Rembold (University of Manchester) for his outstanding contributions to neutrino and high-energy collider physics. The Hertha Sponer prize, established in honour of one of the first women in Germany to gain a doctorate and teach physics at university level, has been awarded to Adinda de Wit (below; University of Zurich),

co-convener of the CMS Higgs group, for her contributions to the observation of the Yukawa coupling between the Higgs boson and b quarks, and to Belina von Krosigk (University of Hamburg) for her fundamental contributions to direct dark-matter searches.

Cosmology research wins
Diego Blas (Universitat Autònoma de Barcelona) and Alexander Jenkins (UCL) have won the second prize of the 2022 Buchalter award for cosmology in recognition of their work "Bridging the μHz gap in the gravitational-wave landscape with binary resonance" (arXiv:2107.04601). The third prize, to Daniel Figueroa *et al.* for their paper "'Stairway to Heaven' – Spectroscopy of Particle Couplings with Gravitational Waves (arXiv:2202.05805), also recognised cutting-edge research at the boundary between particle and gravitational-wave physics.

India honours overseas role
Archana Sharma (CERN), a senior CMS physicist and head of relations between CERN and other international organisations, has been awarded India's



highest honour for non-resident Indian citizens, the Pravasi Bharatiya Samman Award, for her contribution to science and technology. In a first, Sharma was exceptionally employed in 2001 by CERN as an Indian national. Currently head of the engagement office in CMS and until recently project leader of the CMS muon gas electron multiplier group, she formally engages with India via programmes including SAHEPI (South Asia High Energy Physics Instrumentation) and SASEP (South Asia Science Education Program), and also spearheaded the educational programme Quarknet India.

2023 UK Blavatnik prize
Cosmologist Clare Burrage (University of Nottingham) has been named one of three winners of the 2023 UK Blavatnik Prize for Young Scientists, gaining £100,000 of "unrestricted funding". Currently exploring ways to study dark energy using atom interferometry, in 2016 she

co-proposed a method to hunt for dark energy at the LHC – an idea which was tested by ATLAS in 2018 (*CERN Courier* January/February 2019 p12).

First Hernandez-Garcia award
In recognition of his long-lasting efforts to promote accelerator physics in Mexico, Carlos Hernandez-Garcia (JLab) is the first recipient of a prize named in his honour. With no research accelerators yet available in Mexico, Hernandez-Garcia led an effort to bring undergraduate students from universities in Mexico to JLab for a 10-week summer study programme, which has so far enabled more than a dozen young scientists to pursue careers in particle and accelerator physics around the world.

Giudice elected fellow
The Accademia dei Lincei of Italy has elected Gian Giudice, head of the CERN theoretical physics department (below right with Giorgio Parisi, left, at the ceremony in Rome on 11 November), as a fellow for his contributions to beyond-the-Standard Model physics and their

applications to the history of the early universe. His contributions to scientific committees for reviewing the status of present and future particle colliders worldwide were also recognised.

RECRUITMENT

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PEOPLE OBITUARIES

LARS BRINK 1943–2022

A paragon of scientific humility

It is with great sadness that we learnt of the passing of Lars Brink on 29 October 2022 at the age of 78. Lars Brink was an emeritus professor at Chalmers University Göteborg, Sweden and a member of the Royal Swedish Academy. He started his career as a fellow in the CERN theory group (1971–1973), which was followed by a stay at Caltech as a scientific associate (1976–1977). In subsequent years he was a frequent visitor at CERN, Caltech and ITP Santa Barbara, before becoming a full professor of theoretical physics at Chalmers in 1986, which under his guidance became an internationally leading centre for string theory and supersymmetric field theories.

Lars held numerous other appointments, in particular as a member and chairperson on the board of NORDITA, the International Center for Fundamental Physics in Moscow, and later as the chairperson of the advisory board of the Solvay Foundation in Brussels. Since 2004 he was an external scientific member of the Max Planck Institute for Gravitational Physics in Golm. During his numerous travels Lars was welcomed by many leading institutions all over the world. He also engaged in many types of community service, such as the coordination of the European Union network "Superstring Theory" since 2000. Most importantly, he served on the Nobel Committee for physics many years, and as its chairperson for the 2013 Nobel Prize in Physics awarded to François Englert and Peter Higgs.

Lars was a world-class theoretical physicist, with many pioneering contributions, especially to the development of supergravity and superstring theory, as well as many other topics. One of his earliest contributions was a beautiful derivation of the critical dimension of the bosonic string (with

Chalmers University of Technology

Lars Brink was a world-class theoretical physicist who served on the Nobel Committee for physics.

Holger Bech Nielsen), obtained by evaluating the formally divergent sum over zero-point energies of the infinitely many string oscillators; this derivation is now considered a standard textbook result. In 1976, with Paolo Di Vecchia and Paul Howe, he presented the first construction of the locally supersymmetric world-sheet Lagrangian for superstrings (also derived by Stanley Deser and Bruno Zumino) which now serves as the basis for the quantisation of the superstring and higher loop calculations in the Polyakov approach. His seminal 1977 work with Joel Scherk and John Schwarz on the construction of maximal ($N = 4$) supersymmetric Yang–Mills theory in four dimensions laid the very foundation for key developments of modern string theory and the AdS/CFT correspondence that came to dominate string-theory research only much later. Independently of Stanley Mandelstam, he proved the UV finiteness of the $N = 4$ theory in the light-cone gauge in 1983, together with Olof Lindgren and Bengt Nilsson – another groundbreaking result. Equally influential is his work with Michael Green and John Schwarz on deriving supergravity theories as limits of string amplitudes. More recently, he devoted much effort to a reformulation of $N = 8$ supergravity in light-cone super-space (with Sudarshan Ananth and Pierre Ramond). His last project before his death was a reevaluation and pedagogical presentation of Yoichiro Nambu's seminal early papers (with Ramond).

Lars received numerous honours during his long career. In spite of these achievements he remained a kind, modest and most approachable person. Among our many fondly remembered encounters we especially recall his visit to Potsdam in August 2013, when he revived an old tradition by inviting the Nobel Committee to a special retreat for its final deliberations. The concluding discussions of the committee thus took place in Einstein's summer house in Caputh. Of course, we were all curious for any hints from the predictably tight-lipped Swedes in advance of the official Nobel announcement, but in the end the only useful information we got out of Lars was that the committee had crossed the street for lunch to eat mushroom soup in a local restaurant!

He leaves behind his wife Åsa, and their daughters Jenny and Maria with their families, to whom we express our sincere condolences. We will remember Lars Brink as a paragon of scientific humility and honesty, and we miss a great friend and human being.

Hermann Nicolai *director emeritus at Max Planck Institute for Gravitational Physics, Potsdam.*

KURT GOTTFRIED 1929–2022

The epitome of a concerned scientist

Kurt Gottfried, professor emeritus at Cornell University and co-founder of the Union of Concerned Scientists (UCS), passed away on 25 August 2022 at the age of 93. Throughout his career, he encouraged fellow scientists to hold their leaders to account on topics ranging from nuclear arms control to human rights and scientific integrity.

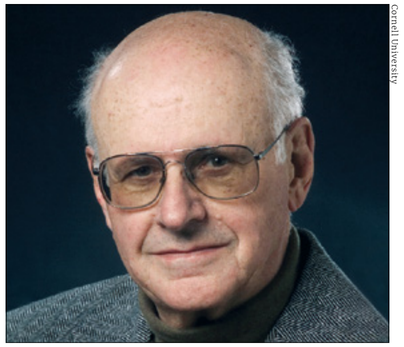
Gottfried was born in Vienna, Austria in 1929, fleeing the country with his family when he was nine years old after their home was raided on Kristallnacht, and eventually immigrating to Montreal, Canada. He graduated from McGill University, earned a PhD in theoretical physics from MIT in 1955 and was a junior fellow at Harvard. In 1964 he became a physics professor at Cornell and remained affiliated with the university until his death. He also served on the senior staff of CERN, as a chair of the division of particles and fields of the American Physical Society, and as a member of the American Academy of Arts and Sciences, and the Council on Foreign Relations.

Well known for his work in high-energy theoretical physics and the foundations of quantum mechanics, Gottfried worked with David Jackson in the 1960s on the production and decay of unstable resonances in hadronic collisions using the density-matrix approach. He proposed the Gottfried sum rule for deep inelastic scattering and is also known for his work in the 1970s on charmonium. Along with Tung-Mow Yan, he authored the classic work *Quantum Mechanics: Fundamentals*, originally published in 1966.

In 1969, deeply concerned about what he saw as the growing threat to civilisation from the unchecked exploitation of scientific knowl- ▷

edge for military purposes, Gottfried co-founded UCS with his friend and future Nobel laureate Henry Kendall. His many years of leadership and guidance helped expand the scope of the organisation's work from research on nuclear power and weaponry, to climate change, agriculture, transportation and renewable energy. Even in retirement, Gottfried continued to advise UCS scientists on policy and strategy, and to inspire the organisation with his passionate sense of urgency about its work.

In the 1980s, working with Hans Bethe and Richard Garwin, Gottfried drew attention and acclaim to UCS by demonstrating the infeasibility of the "Star Wars" missile defence programme. He authored numerous scholarly articles on missile defence, space weapons, nuclear weapons and cooperative security, and reached an even wider audience with his articles and op-eds on these topics. He also authored or co-authored three books – *The Fallacy of Star Wars* (1984), *Crisis Stability and Nuclear War* (1988) and *Reforging European Security: From Confrontation to Cooperation* (1990) – and contributed chapters to several others.


Kurt Gottfried co-founded the Union of Concerned Scientists in 1969.

Throughout his life, Gottfried also used his standing to advocate for the free practice of science. In addition to his work with UCS, he was deeply engaged in campaigns in support of scientists in the former Soviet Union and South America who were imprisoned for expressing views in conflict with the dogmas of authoritarian rulers. In 2016, citing his long and distinguished career as a "civic scientist", the American Association for the Advancement of Science awarded Gottfried its Scientific Freedom and Responsibility Award.

As current UCS board chair Anne Kapuscinski noted, Kurt was the epitome of a concerned scientist and an inspiration to all of us. We will miss his passion, kindness, dedication and integrity, and we will strive to honour his lifelong dedication to building a safer world.

Seth Shulman *Union of Concerned Scientists.*

Nicola Najib Khuri 1933–2022

From the Riemann hypothesis to Regge poles

Renowned high-energy theorist Nicola Najib Khuri died on 4 August 2022 in New York City. Born in 1933 in Beirut, Lebanon he was the eldest of four siblings and a precocious student. He graduated from the American University of Beirut (AUB) in 1952 at the age of 19, then travelled to the US for his graduate studies in physics. He received his MA and PhD from Princeton University and was a fellow of Princeton's Institute for Advanced Study. While in graduate school, he met Elizabeth Tyson, the love of his life and wife of over 60 years. Upon receiving his doctorate in 1957, Nicola returned to Lebanon and joined the faculty at AUB. In 1964 he went back to the US and accepted a position at The Rockefeller University, New York, where he founded a lab and remained for the rest of his career.


Nicola Khuri contributed to the mathematical foundations of elementary-particle collisions.

Nicola was a leading authority on the use of mathematics in high-energy theoretical physics. At Rockefeller, his research focused on the mathematical description of elementary-particle collisions. Among his most notable achievements were the introduction of a new method to study the Riemann hypothesis, one of the last unsolved problems in mathematics, and the foundation of the field of potential scattering theory, which led to the development of important concepts such as Regge poles and strings.

In addition to his post at Rockefeller, he held visiting appointments and consulting roles at CERN, Stanford University, Columbia University, Lawrence Livermore National Laboratory, Brookhaven National Laboratory and Los Alamos National Laboratory. He was also a member of the panel on national security and arms control of the Carnegie Endowment for International Peace and a fellow of the American Physical Society.

Nicola and Liz, along with their two children, built a beautiful life in New York. Their homes had a revolving door for friends, family, colleagues and mentees who came from far and wide to hear Nicola's remarkable stories, take in his sage advice, and enjoy his timeless, occasionally risqué jokes. A true cosmopolitan, he relished the vibrancy and possibility of New York. When not at home, he could be found ordering mezze for the table at one of his favourite Lebanese restaurants, exploring his interest in international politics at the Council on Foreign Relations, or making a toast at the Century Association. He retained an enduring love for, and a fundamental commitment to, Lebanon. He was a passionate supporter of his alma mater, a mentor to generations of young scientists from the Middle East, and was instrumental in establishing the university's Center for Advanced Mathematical Sciences, among many other contributions.

There are many things we will miss about Nicola: his character; the way he commanded a room; his childlike sense of humour; the happy gleam in his eye when he told a story from his adventurous life; and his sneaky determination in old age to satisfy a lifelong appetite for good wine, good cheese and excellent chocolate over the protests of doctors, caregivers and his daughter, Suzanne. Above all, we will miss the way he treated others.

Nicholas Seshadri *adapted from text originally published by Legacy Remembers.*

Meenakshi Narain 1964–2023

Championing diversity in physics

Experimental particle physicist Meenakshi Narain, an inspirational leader and champion of diversity, died unexpectedly on 1 January 2023 in Providence, RI. Considered by many as a "force of nature", Meenakshi's impact on the physics community has left an indelible mark.

Meenakshi grew up in Gorakhpur, India and emigrated to the US in 1984 for graduate school at SUNY Stony Brook. Her PhD thesis, based on data taken by the CUSB-II detector at CESR, utilised inclusive photon spectra from upsilon decays for both spectroscopy measurements and searches for exotic particles, including the Higgs boson. In 1991 Meenakshi joined Fermilab as a postdoc on the DØ experiment, where she was a principal player in the 1995 discovery of the top quark, leading a group searching for top anti-top pair production in the dilepton channel. Over the next decade, as a Fermilab Wilson Fellow and a faculty member at Boston University, she made seminal contributions to measurements of top-quark pair and single-top production, as well as to the top-quark mass, width and couplings.

In 2007, upon joining the faculty at Brown University, Meenakshi joined the CMS experiment at the LHC. In addition to pioneering a number of exotic searches for high-mass resonances, new heavy gauge bosons and top-quark partners, she continued to make innovative contributions to precision top-quark measurements. Her foundational work on b- and c-quark identification also paved the way for Higgs boson searches and measurements. As a leader of the CMS upgrade studies group, Meenakshi coordinated physics studies for several CMS technical design reports for the High-Luminosity LHC upgrade, and an impressive number of results for the CERN yellow reports. She was also a key contributor to the US CMS outer tracker upgrade.

The tutorials and workshops Meenakshi organised as co-coordinator of the LHC Physics Center (LPC) were pivotal in advancing the careers of many young scientists, whom she cared about deeply. As chair of the US CMS collaboration board, she was a passionate advocate for the LHC research programme. She created an inclusive, supportive community that participated in movements such as Black Lives Matter, and tackled numerous challenges imposed by the COVID-19 pandemic.


Meenakshi Narain was a strong voice for women and under-represented minorities in physics.

A strong voice for women and under-represented minorities in physics, Meenakshi was the founding co-chair of the CMS diversity office and the driving force behind the CMS task force on diversity and inclusion and the CMS women's forum. She mentored a large group of students, post-docs and scientists from diverse backgrounds, and created PURSUE – an internship programme that provides summer research opportunities at CMS to students from minority-serving institutions.

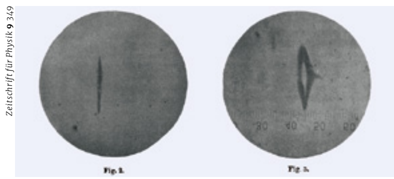
Meenakshi's illustrious career has been recognised via numerous accolades and positions of responsibility. She is remembered for her recent co-leadership of the Snowmass energy-frontier study, her service on HEPAP and her new appointment to the P5 subpanel, in addition to her new position as the first woman to chair the physics department at Brown. She will be remembered as a brilliant scientist, a beloved mentor and an inspiring leader who made the world a better, more equitable and inclusive place.

Her colleagues and friends.

BACKGROUND

Notes and observations from the high-energy physics community

A new spin on Stern–Gerlach



Zeitschrift für Physik 9 349

Photographic plates after exposure to a silver-atom beam in an inhomogeneous magnetic field (right) and with the field switched off (left).

It took only a century and a Twitter conversation to translate Walther Gerlach and Otto Stern's famous 1922 paper, which showed that the spatial orientation of angular momentum is quantised, from its original German into English. While preparing a lecture, theoretical cosmologist Chanda Prescod-Weinstein (University of New Hampshire) realised that an English version of the seminal four-page work does not exist, and took to social media to remonstrate. Within days, particle theorist and hobby historian Martin Bauer (University of Durham) had hooked up with Phillip Helbig (formerly University of Liège) to put things to rights. "Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld" – which described the splitting of a silver-atom beam in an inhomogeneous magnetic field in two directions in line with the inhomogeneity – put the new quantum theory on solid ground, and can now be enjoyed in an even greater number of words: arXiv:2301.11343 (submitted to *EPJ H*).

Declining disruptiveness

Despite the exponential growth of knowledge in science and technology, papers and patents are increasingly less likely to break with the past in ways that push us in new directions, according to an analysis of 45 million papers and 3.9 million patents over the past 60 years. Reconciling the patterns with the 'shoulders of giants' view, the authors link this decline in disruptiveness, which holds universally across fields, to a narrowing in the use of previous knowledge. While the observed declines are unlikely to be driven by changes in the quality of published science, they conclude, it may reflect a fundamental shift in the nature of science and technology (*Nature* **613** 138).

Media corner

"For the first time ever, we kind of have a time-travelling machine going in both directions."
Sonja Franke-Arnold commenting on quantum time-flip circuits in *Quanta* (27 January).

"Millions of dark-matter particles pass through the Earth every second. It is not something we want to study far away, in another galaxy, for pure knowledge."
Irene Bolognino talking to *Cosmos* (20 January) about the upcoming SABRE South experiment in Australia.

"I was so excited in 1980 about the idea of grand unification, and that now looks small compared to the possibilities ahead."
Michael Turner discussing "where is physics headed?" in the *New York Times* (24 January).

"Maintaining scientific collaboration is top priority, as a great way of bringing nations together to solve humankind's problems."
John Ellis in a *Guardian* article (15 January) addressing the impact of the Russian invasion of Ukraine on the LHC-experiment collaborations.

From the archive: March/April 1983

Fast Work

CERN 265.1.83

At a CERN press conference on 25 January 1983 are (left to right), Carlo Rubbia (UA1 spokesman), Simon van der Meer (inventor of stochastic cooling, which made the CERN antiproton project possible), CERN Director-General Herwig Schopper (showing a typical UA1 event, featured on the January/February CERN Courier cover), Erwin Gabathuler (CERN research director) and Pierre Darriulat (UA2 spokesman).

Excitement was high at CERN during January, when results emerged from the recent proton–antiproton collision run at the SPS ring. The UA1 and UA2 experiments unearthed a handful of events suggestive of the long sought Ws, carriers of the weak force. After preliminary information at the Rome Topical Workshop, 12 January, fuller information was given in packed CERN seminars on 20 and 21 January, when Carlo Rubbia (for UA1) and Luigi Di Leila (for UA2) took the audiences through the brilliant analyses of the complex data emerging from collisions at the highest man-made energies.

One of the most impressive aspects of the initial evidence for Ws was how fast it emerged from the mass of collected data, underlined by Leon Lederman in his conclusion at the Rome workshop. The 1982 proton–antiproton run finished on 6 December when UA1 and UA2 had each been exposed to some 10^9 collisions. By 12 January 1983 the experimenters had enjoyed Christmas and combed their data for decays of charged W bosons into an electron and neutrino, lone high transverse momentum electrons 'balanced' by missing energy. Only a very small fraction of the extremely complex events is of immediate interest, and judicious triggering greatly assists the subsequent data handling and extraction of physics results.

● Based on text on pp 43, 44 and 82 of *CERN Courier* March and April 1983.

Compiler's note

The superb achievements of high-energy physics accelerator engineers and detector builders are clearly in evidence, including technology transfers to radio- and nuclear-therapy, whereas the vast amount of state-of-the-art computing and data handling goes on largely below the horizon. Take up of the best-known 'soft' spin-off, the World Wide Web, benefitted from the global distribution of the research community and was underpinned by the spirit of CERN's 1953 Convention that ensured work carried out there "shall be published or otherwise made generally available".

53 as

The shortest electron pulse to date, produced via optical field emission of electron pulses from a tungsten nanotip, opens new prospects for research and applications at the interface of attosecond physics and nano-optics (*Nature* 613 662)

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Advertisement

Where pressure prevails

PAS

The PAS pressure transducer, made by Hofheim-based automation specialists KOBOLD Messring GmbH, enables the precise monitoring of absolute pressure and overpressure. The devices, which are available with different measuring ranges between –1 to 1.5 bar and 0 to 800 bar, can be used for a multitude of applications.

At the heart of this robust and long-term stable measuring instrument is a piezoresistive absolute pressure sensor. It is accurate to within 0.075% of the calibrated measuring range and can withstand process temperatures between –30°C and +100°C. Appropriate connecting pieces make it easy and quick to install, and an extensive range of industry-standard accessories is available to adapt the device to each application, including various types of diaphragm seal, which can be connected both directly and via a capillary line, depending on the application.

A tried-and-tested, industry-quality microprocessor provides a host of setting options and comprehensive system monitoring. The microprocessor controls the sensors, memories, A/D-converters and current. It also compares and compensates the input and output values. The measuring instrument has a 4–20 mA analogue output with two conductors. The settings and communication with the automation systems can be administered via the HART protocol, and the device has a clear, freely configurable, built-in LED display.

The protection class is IP 67, and versions with ATEX Ex d and Ex i certifications are available.

Differences in control

High flexibility and reliability are important characteristics of the PAD differential pressure transducer made by KOBOLD Messring GmbH. This reliable measuring instrument is equally as suited to recording absolute and differential pressure as it is to measuring filling levels and flow rates. A multitude of measuring ranges, from –1 to more than 400 bar and the overpressure models up to 800 bar, provide solutions for a wide range of applications.

The membrane that is in contact with the media during the process is made of proven, hard-wearing materials (stainless steel, Hastelloy C, tantalum or Monel) and can withstand process temperatures of up to 120°C. Special multi-level connecting flanges make it possible to install the pressure transducer vertically without separate fitting pieces or different mounting plates.

The protection class is IP 67 and ATEX approval is available.

The measuring process is monitored and evaluated using a high-quality microprocessor. This includes the automatic compensation of ambient temperature and process variables, sensor calibration and zero-point adjustment, filtering and damping, continual self-diagnosis and adjustment, as well as data transfer and LCD display. The analogue and frequency output relays the measurement values, and operation and integration in automation systems can also take place using the HART protocol.

PAD

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