Welcome to the digital edition of the July/August 2023 issue of CERN Courier.

Dealing with 1000 proton–proton collisions per bunch crossing is just one of the challenges in designing a detector for the Future Circular Collider (FCC), describes our cover feature (p30). Meanwhile, FCC Week 2023 projected a strong sense of momentum amongst the community toward this visionary proposed facility (p5), a feasibility study for which is in full swing. In line with the way astronomers and other fields of fundamental exploration view their tools, the FCC would be better branded as an international particle “observatory” than a collider, argues this issue’s Viewpoint (p45).

This issue also describes how the discovery of neutral currents at CERN 50 years ago put the nascent Standard Model on solid ground (p35), asks whether the 5σ rule is still the best criterion for discoveries in particle physics (p24), gets up close with event displays (p41) and explores the wonderful world of welding in CERN’s workshops (p51).

Unique measurements of thorium isomers at ISOLDE advance a nuclear clock (p7), CERN shares its expertise in vacuum and materials for gravitational-wave observatories (p18), record precision on key CP-violation observables by LHCb (p8), an interview with physicist and YouTuber Don Lincoln (p47), and much more inside.

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The Circular Collider (FCC) is the most compelling project for CERN’s future. We need to work together to make it happen. Not this magazine’s words, but those of CERN Director-General Fabiola Gianotti during the opening session of the ninth FCC Week in London on 5 June. The event was a timely opportunity to review the recent progress of the FCC Feasibility Study, for which a mid-term review is due to be submitted to the CERN Council later this year, and project a strong sense of momentum among the 500 participants.

The FCC is a proposed 900-cm circumference post-LHC research infrastructure offering an electron–positron collider (FCC-ee) as a first stage followed by a hadron collider (FCC-hh). The former offers the highest luminosities of all proposed Higgs and electroweak factories, while the latter (a conical detector for which features on the cover of this issue, see p30) would increase the direct discovery reach by almost a factor of 10 compared to the LHC. The technology for FCC-ee is mature and construction could proceed in parallel to HL-LHC operations, enabling physics exploitation to start in 2024–2026. A circular collider such as the FCC also offers four experimental points, which provides scientific robustness and the possibility of building specialised detectors to maximise the physics reach – as at the LHC. Moreover, noted Gianotti, with at least four experiments potentially on offer, the FCC is the only facility proposed that is commensurate with the size of the CERN community.

The 2020 European strategy update cited an electron–positron Higgs factory as the highest-priority next collider, and recommended that Europe, together with its international partners, investigate the feasibility of a future hadron collider at CERN with an energy of at least 100 TeV and with an electron–positron Higgs and electroweak factory as a possible first stage. It is now clear that putting FCC-ee first would not only minimise the time between colliders, but spread the cost of the more expensive FCC-hh over a longer period and allow two decades of R&D towards affordable high-field magnets, possibly based on high-temperature superconductors.

It is also becoming well established that large research infrastructures such as the LHC, and potentially the FCC, return more to society than they cost. Among numerous highlights of FCC Week were quantitative studies demonstrating the socio-economic benefits of collider facilities, and results from surveys which show that most people are prepared to pay more for fundamental research than they currently do via taxes. One of the challenges with a project as vast and complex as the FCC, however, is to communicate its many evolving facets, including within the community. The upcoming mid-term review therefore offers an ideal chance to update physicists across the field on the significant work that has taken place towards the physics case, technology, costs, energy consumption and many other key aspects of the visionary FCC project.

Should the FCC go ahead, eventually it will need a new name. As this issue’s Viewpoint argues, this brings an opportunity to refresh colliders as “observatories” in line with other facilities of fundamental exploration (p6). This issue also marks 50 years since the discovery of neutral currents at CERN (p35), asks whether the 50 rule is still the best criterion for discoveries in particle physics (p24), and gets up close with event displays (p41). ISOLDE advances a nuclear clock (p97), LHCb sets record precision on CP-violation (p48), CERN Shares its expertise for gravitational-wave observatories (p38), careers (p93), news digest (p29), and much more inside.
The observation at CERN’s ISOLDE facility of a long-sought decay of the thorium-229 nucleus marks a key step towards a clock that could surpass today’s most precise atomic timekeepers. Publishing the results in Nature, an international team has used ISOLDE’s unique facilities to measure, for the first time, the radiative decay of the metastable state of thorium-229m, opening a path to direct laser-manipulation of a nuclear state to build a new generation of nuclear clocks.

Today’s best atomic clocks, based on periodic transitions between two electronic states of an atom such as caesium or aluminium held in an optical lattice, achieve a relative systematic frequency uncertainty below 1 x 10^-17, meaning they won’t lose or gain a second over about 30 billion years. Nuclear clocks would exploit the periodic transition between two states in the vastly smaller atomic nucleus, which couple less strongly to electromagnetic fields and hence are less vulnerable to external perturbations. In addition to offering a more precise timepiece, nuclear clocks could test the constancy of fundamental parameters such as the fine structure or strong-coupling constants, and enable searches for a “light” dark matter (CERN Courier September/October 2022 p32).

Higher precision

In 2003 Ekkehard Peik and Christian Tammin of Physikalisch-Technische Bundesanstalt in Germany proposed a nuclear clock based on the transition between the ground state of the thorium-229 nucleus and its first, higher-energy state. The advantage of the 229mTh isomer compared to almost all other nuclear species is its unusually low excitation level (~8 eV), which in principle allows direct laser manipulation. Despite much effort, researchers have not succeeded until now in observing the radiative decay – which is the inverse process of direct laser excitation – of 229mTh to its ground state. This allows, among other things, the isomer’s energy to be determined to higher precision.

A novel technique based on vacuum-ultraviolet spectroscopy, lead author Sandro Kraemer of KU Leuven and co-workers used ISOLDE to generate an isomeric beam with atomic mass number A=229, following the decay chain 229Fr → 229Ra → 229Ac → 229Th/229mTh. A fraction of 229Ac decays to the metastable excited state of 229Th, the isomer 229mTh. To achieve this, the team incorporated the produced 229Ac into six separate crystals of calcium fluoride and magnesium fluoride at different thicknesses. They measured the radiation emitted when the isomer relaxes to its ground state using an ultraviolet spectrometer, determining the wavelength of the observed light to be 148.7 nm. This corresponds to an energy of 8.38 eV, seven times more precise than the previous best measurements.

“ISOLDE is currently one of only two facilities in the world that can produce actinium-229 isotopes in sufficient amounts and purity,” says Kraemer. “By incorporating these isotopes in calcium fluoride or magnesium fluoride crystals, we produced many more isomeric thorium-229 nuclei and increased our chances of observing their radiative decay.”

The team’s novel approach of producing thorium-229 nuclei also made it possible to determine the lifetime of the isomer in the magnesium fluoride crystal, which helps to predict the precision of a thorium-229 nuclear clock based on this solid-state system. The result A (16.1 ± 2.5 min) indicates that a clock precision which is competitive with that of today’s most precise atomic clocks is attainable, while also being four orders of magnitude more sensitive to a number of effects beyond the Standard Model. “Solid-state systems such as magnesium fluoride crystals are one of two possible settings in which to build a future thorium-229 nuclear clock,” says the team’s spokesperson, Piet Van Dopper of KU Leuven. “Our study marks a crucial step in this direction, and it will ease the development of lasers with which to drive the periodic transition that would make such a clock tick.”

Further reading
**CP violation**

LHCb sets record precision on CP violation

At a CERN seminar on 13 June, the LHCb collaboration reported the world’s most precise measurement of CP violation in B mesons. Based on the full LHCb dataset collected during LHC Runs 1 and 2, the collaboration presented the world’s most precise measurement of CP violation, present in B mesons. This is defined to have unit length, while the other two sides and three angles must be inferred via measurements of certain hadron decays. If the measurements do not provide a consistent description of the triangle, it would hint that something is amiss in the SM.

The measurement of sin^2β, which determines the angle β in the unitarity triangle, is more difficult than a hadron collider than it is an e+e- collider. However, the large data samples available at the LHC and the optimised design of the LHCb experiment have enabled a measurement that is twice as precise as the previous best result from Belle. The LHCb team used decays of mesons to J/ψ K, which can proceed directly or by first oscillating into their antimat- ter partners. The interference between the amplitudes for the two decay paths results in a time-dependent asymmetry between the decay-time distributions of the B^+ and B^- amplitudes.

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Based on an analysis of B^± → J/ψ K decay, LHCb also presented the world’s best measurement of CP violation, which reflects a similar role in B^± meson decays as sin^2β in B^- decays. For B^- mesons, a B^- may decay directly or oscillate into a B^- and then CP violation causes these decays to proceed at slightly different rates, manifesting itself as a non-zero value of sin^2β due to the inter-ference between mixing and decay. This predicted value of sin^2β is about 0.107, but new physics effects, even if also small, could change its value significantly.

A detailed study of the angular distribution of B^- decay products using the two data samples enabled LHCb to measure this decay-time-dependent CP asymmetry α = 0.09 ± 0.005 ± 0.005.

**Higgs boson**

ATLAS and CMS find first evidence for H → Zγ

The discovery of the Higgs boson in 2012 unleashed a detailed programme of measurements by the ATLAS and CMS Collaborations. Now, two teams have confirmed that its couplings are consistent with those predicted by the Standard Model (SM). However, the Higgs boson decay channels have such small predicted branching fractions that they have not yet been observed. Involv- ing higher order loops, these channels also provide indirect clues about physics beyond the SM. ATLAS and CMS have now teamed up to report the first evidence of the decay H → Zγ, presenting the combined result in the Large Hadron Collider (LHC) conference in Belgrade in May.

The SM predicts that approximately 0.1% of Higgs bosons produced at the LHC will decay in this way, but some theories beyond the SM predict a different decay rate. Examples include models in which the Higgs boson is a neutral scalar of different origin, or a composite state. Different branching fractions are also expected for mod- els with additional colourless charged scalars, leptons or vector bosons that couple to the Higgs boson, due to their contributions via loop corrections.

To access the GFFs, the team measured the threshold cross section of exclusive J/ψ photoproduction at different ener-gies by forcing photons with energies between 1 and 3 GeV through a hydrogen target. Gluons do not provide such an enhancement and to access the hydrogen, the team proposed to use the photoproduction cross section of exclusive J/ψ photoproduction at different ener-gies by forcing photons with energies between 1 and 3 GeV through a hydrogen target. Gluons do not provide such an enhancement and to access the hydrogen, the team proposed to use the photoproduction cross section at different energies. The selection criteria for H → Zγ events are shown in the left panel of the figure, demonstrating the success of the cut-off procedure. The analysis revealed a scalar proton radius of 0.6 fm, which is substan-tially larger than both the charge radius (0.8 fm) and the proton mass radius (0.7 fm). This led the team to propose that the proton structure consists of three distinct regions: an inner core that makes up most of the mass radius and is dominated by the proton gluonic field structure, followed by the charge radius resulting from the relativistic motion of quarks, all enclosed by a larger confining scalar gluon density.

**Quantum chromodynamics**

Proton structure consists of three distinct regions

Researchers at Jefferson lab in the US have gained a deeper understanding of the role of gluons in providing mass to visible matter. Based on measurements of the photoproduction of J/ψ particles, the findings suggest that the proton’s structure has three distinct regions, with an inner core driven by gluonic interactions comprising most of the mass radius. Although the charge and spin of the protons have been extensively studied for decades, relatively little is known about its mass distribution. This is because gluons, which despite being massless provide a substantial contribution to the proton’s mass, are neutral and thus cannot be studied directly using elec-romagnetic probes. The Jefferson team instead used the gluonic gravitational form factors (GFFs) to directly study gluonic magnetic form factors, which provide information about a proton’s charge and magnetisation distributions, the GFFs (technically the matrix elements of momentum’s energy–momentum ten-soe) encode the mechanical properties of the proton with its rigidity, pressure and shear distributions.

To access the GFFs, the team measured the threshold cross section of exclusive J/ψ photoproduction at different ener-gies by forcing photons with energies between 1 and 3 GeV through a hydrogen target. Gluons do not provide such an enhancement and to access the hydrogen, the team proposed to use the photoproduction cross section of exclusive J/ψ photoproduction at different energies. The selection criteria for H → Zγ events are shown in the left panel of the figure, demonstrating the success of the cut-off procedure. The analysis revealed a scalar proton radius of 0.6 fm, which is substan-tially larger than both the charge radius (0.8 fm) and the proton mass radius (0.7 fm). This led the team to propose that the proton structure consists of three distinct regions: an inner core that makes up most of the mass radius and is dominated by the proton gluonic field structure, followed by the charge radius resulting from the relativistic motion of quarks, all enclosed by a larger confining scalar gluon density. **Better together** Candidate events from ATLAS (left) and CMS (right) for a Higgs boson decaying into Zbosons and a photon, with the Zboson decaying into muons or taus (red), combined data that was collected during the second run of the LHC in 2015–2018 to significantly increase the statistical precision and reach of their searches. This collaborative effort resulted in the first evidence of the Higgs boson in a proton and a photon, with a statistical significance of 3.4σ. The measured signal rate relative to the SM prediction was found to be 2.2 ± 0.5 in agreement with the theoretical expec-tation from the SM.

The existence of new particles could have very significant effects on rare processes of the Standard Model. With the ongoing third run of the LHC and the future High-Luminos-ity LHC, we will be able to improve the precision of this test and probe ever larger Higgs boson masses.

**Further reading**

**NEWS ANALYSIS**

**CERN Neutrino Platform**

**A new TPC for T2K upgrade**

In the latest milestone for the CERN Neutrino Platform, a key element of the near detector for the T2K (Tokai to Kamioka) neutrino experiment in Japan – the near detector for the T2K (Tolai to Kamioka) neutrino experiment in Japan – is now fully operational and taking cosmic data at CERN. T2K detects a neutrino beam at two sites: a near-detector complex close to the neutrino production point and Super-Kamiokande 300 km downstream.

The upgraded ND280 is also expected to serve as a near detector of the next generation long-baseline neutrino oscillation experiment Hyper-Kamiokande. Meanwhile, R&D and testing for the prototype detectors for the DUNE experiment at the Long Baseline Neutrino Facility at Fermilab/SURF in the US is entering its final stages.

**Eastbound bound**

**Detail of one of the time projection chambers (TPCs) of the ND280 detector, which is a key element of the upgraded T2K experiment in Japan.**

**Atmospheric Neutrinos**

**The exact origin of the high-energy cosmic rays that bombard Earth remains one of the most important open questions in astrophysics. Since their discovery more than a century ago, a multitude of potential sources, both galactic and extra-galactic, have been proposed. Examples of proposed galactic sources, which are theorised to be responsible for cosmic rays with energies below the PeV range, are supernova remnants and pulsars, while blazars and gamma-ray bursts are two of many potential sources theorised to be responsible for the cosmic-ray flux at higher energies.**

**The upgraded T2K setup consists of three detectors: the far detector, the near detector, and the far detector upgrade. The far detector is located at the experimental site of the Tokai–Kamioka neutrino experiment, while the near detector is situated in a building close to the far detector. The far detector upgrade includes a new system of cosmic-ray muon detectors, which are crucial to reduce systematic uncertainties.**

**Further reading**


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The MACHINA accelerators.

Restoring arts
CERN and INFN have teamed up to build a compact, transportable accelerator for the analysis of artworks. Based on a radical frequency quadrupole accelerator cavity designed at CERN, the Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis (MACHINA) will make use of iso-beam analysis (IBA) to scan samples of cultural heritage pieces. IBA probes surface composition and material structure via spectroscopy of the emitted radiation when beams strike atoms in the sample. But most machines are fixed at one location, ruling out scans of fragile or immovable art pieces such as frescoes. Following intensive testing, the 1m-long accelerator will eventually be transferred to the Opificio delle Pietre Dure in Florence to become part of their regular diagnostic activities (Kendimont Lincel, Science Fische & Naturali 34, 477).

Surfing plasma curves
Plasma–wakefield accelerators, which impart energy to electrons by making them “surf” on plasma waves generated by a high-power laser or other beam, promise compact, high-gradient particle accelerators. But to reach beam energies and qualities comparable to those of conventional accelerators, multiple plasma stages are required – in which the challenge is to keep the particle bunch and the plasma wave in sync, and to maintain sufficient laser intensity to drive plasma oscillations across the successive stages. By directing a laser into a curved plasma channel to create an unbroken path for the particles, Xinhue Zhu and colleagues from the Shanghai Jiao Tong University have demonstrated that the transverse oscillation of the laser beam can be mitigated, and that the stably guided laser pulse accelerates electrons along the curved channel to a maximum energy of 0.716 GeV. The approach thus exhibits good potential for seamless multistage laser wakefield acceleration, says the team (Phys. Rev. Lett. 120 255001).

Al spots baby planet
Inspired by analysis techniques used at the CMS experiment, a team has used machine-learning algorithms to hunt for planets forming in protoplanetary disks. Too small to be detected by standard “transit” methods, whereby an exoplanet periodically reduces the brightness of a distant star as it orbits, such protoplanets can be detected via the non-Keplerian motion they induce in the disk. Using data from the ALMA telescope, Jason Ferry of the University of Georgia and co-workers applied an object-agnostic classification algorithm to the protoplanetary disk HD 14266. The algorithm identified non-Keplerian motion implying the presence of a planet roughly five times the mass of Jupiter, which had previously been missed based on visual analysis. The researchers validated their findings using hydrodynamic simulations to recreate the disk’s kinematic structure (ApJ 947 60).

Start of ALPS II experiment
The experiment that searches for so-called “light shining through walls” experiment – the Any Light Particle Search (ALPS-II) at DESY – began its hunt for such an object. ALPS-II is a new generation of direct searches for axion-like particles (ALPs), which are predicted by the Standard Model to have weak interactions. If ALPs exist, they could be converted into photons, allowing them to be detected by a detector placed in a magnetic field. The DESY detector is a compact free-electron laser (SFEL) that has been built in Japan and will soon be positioned in a strong magnetic field to test for the existence of ALPs. ALPS-II is a collaboration between DESY, the Max Planck Institutes in Hamburg and Mainz, and the University of Tokyo. The experiment will search for ALPs by measuring the time it takes for a light pulse to travel between two detectors placed in a strong magnetic field. If ALPs are detected, they could be used to explain the dark matter content of the universe.

LHC’s former outer tracker
Still in good shape, the LHCb collaboration agreed to hand it over to another experiment with related physics goals: the Axion & Antiproton Search (AAPS). AAPS aims to search for axions, which are predicted by some theories of particle physics to have weak interactions. If axions exist, they could be converted into photons, allowing them to be detected by a detector placed in a magnetic field. The AAPS detector is a compact free-electron laser (SFEL) that has been built in Japan and will soon be positioned in a strong magnetic field to test for the existence of axions. AAPS is a collaboration between DESY, the Max Planck Institutes in Hamburg and Mainz, and the University of Tokyo. The experiment will search for axions by measuring the time it takes for a light pulse to travel between two detectors placed in a strong magnetic field. If axions are detected, they could be used to explain the dark matter content of the universe.

FEXLA on photosynthesis
Studies at the Linacs: Coherent Light Source (CLS) at SLAC and the SPring-8 Angstrom Compact free-electron laser (SACLA) in Japan have captured the first time in atomic detail what happens in the final moments leading up to the release of breathable oxygen during photosynthesis. By exciting samples from cyanobacteria with optical light and then probing them with ultrafast X-ray pulses, the team observed the atomic structure of a subsystem that facilitates a series of chemical reactions that split apart water molecules to release molecular oxygen, revealing an intermediate reaction step. Published in Nature, the results not only shed light on how nature has optimised this fundamental process for life on Earth, but might offer inspiration for the development of water-splitting technologies to produce solar fuels, according to an accompanying “News and Views” article (Nature 617 629).

Circling on dark matter
Infrasound lensing can provide information about the type of dark matter (DM) present in distant galaxies, according to an international study. Specifically, multiply lensed images of background galaxies can reveal whether the foreground lensing galaxy inhabits a particle-like (as for Weakly Interacting Massive Particles) or wave-like (due to quantum interference between axion-like particles) DM halo. Using HiZ00 – a gravatar first observed by the Hubble Space Telescope in 2002, as a test case the team showed that wave-like DM is able to reproduce all aspects of the system whereas discreet DM models often fail. The growing success of the former in reproducing astrophysical observations tilt the balance toward new physics involving axions, says the team (arXiv:2304.08989).
New physics may come at us in unexpected ways that may be completely hidden from conventional search methods. One unique example of this is the narrowly spaced, semi-periodic spectra of heavy gravitons predicted by the clockwork gravity model. Similar to models with extra dimensions, the clockwork model addresses the hierarchy problem between the weak and Planck scales, but by bringing the fundamental higher dimensional Planck scale down to accessible energies. The mass spectrum of the resulting graviton tower in the clockwork model is described by two parameters: $k$, a mass parameter that determines the onset of the tower, and $M_5$, the five-dimensional reduced Planck mass that controls the overall cross-section of the tower’s spectrum.

At the LHC, these gravitons would be observed via their decay into two light Standard Model particles. However, conventional bump/tail hunts are largely insensitive to this type of signal, particularly when its cross section is small. A recent ATLAS analysis approaches the problem from a completely new angle by exploiting the underlying approximate periodicity feature of the two-particle invariant mass spectrum. Graviton decays with dielectron or diphoton final states are an ideal test-bed for this search due to the excellent mass resolution of the ATLAS detector. After convolving the mass spectrum of the graviton tower with the ATLAS detector resolution corresponding to these final states, it resembles a wave-packet propagating in space as a pulse of plane-wave superposition with a finite momenta range. This implies that a transformation exploiting the periodic nature of the signal may be helpful.

Signal shape is given without realistic statistical fluctuations. The tiny “bumps” or the shape’s integral over the falling shape of the background cannot be detected with conventional bump/tail-hunting methods. Instead, for the first time, a continuous wavelet transformation is applied to the mass distribution. The problem is therefore transformed to the “scalogram” space, i.e. the mass versus scale (or inverse frequency) space, as shown in figure 1 (left). The large red area at high scales (low frequencies) represents the falling shape of the background, while the signal from figure 1 now appears as a clear, distinct local “blob” above $m_{\gamma\gamma}$ and at low scales (high frequencies). With realistic statistical fluctuations and uncertainties, these distinct “blobs” may partially wash out, as shown in figure 2 (left). To construct this effect, the signal shape was generated using an autoencoder neural-network. A statistical test based on the two networks’ scores is derived to check the compatibility of a given scalogram with the background-only hypothesis. A recent ATLAS analysis approaches the problem from a completely new angle by exploiting the underlying approximate periodicity feature of the two-particle invariant mass spectrum. Graviton decays with dielectron or diphoton final states are an ideal test-bed for this search due to the excellent mass resolution of the ATLAS detector. After convolving the mass spectrum of the graviton tower with the ATLAS detector resolution corresponding to these final states, it resembles a wave-packet propagating in space as a pulse of plane-wave superposition with a finite momenta range. This implies that a transformation exploiting the periodic nature of the signal may be helpful.

Fig. 1. The measured diphoton invariant mass distribution (grey), respective background-only fit parametrisation (red), analytical clockwork signal with $k=500\,\text{GeV}$ and $M_5=50,000\,\text{GeV}$, close to the sensitivity limit (green), and the background-plus-signal parametrisation (blue).

Fig. 2. The scalograms resulting from the continuous wavelet transformation of the blue line of figure 1 in the scale-versus-mass space without (left) and with (right) realistic fluctuations. The localised blob at low scales (high frequencies) corresponds to the signal contribution, while the solid continuum at high scales (low frequencies) corresponds to the falling background shape.
Charm production in proton–proton collisions

A crucial missing piece in our understanding of quantum chromodynamics (QCD) is a complete description of hadronisation in hard scattering processes with a large momentum transfer, which has now been investigated by the LHCb collaboration in proton–proton (p+p) collisions. While perturbative QCD describes systems, providing crucial information of a deconfined medium in small collisions would strongly indicate the formation of a quark–gluon plasma (QGP), which affects the behaviour of particles traversing the medium. In particular, hadronisation hadrons can be affected, modifying the relative abundance of hadrons compared to p+p collisions. Several models predict an enhanced strange–quark production. Thus an abundance of strange hadrons is seen as a signature of QGP formation.

The role that QGP may play in p+p collisions is currently unclear. Some models predict the formation of “QGP droplets”, which could partially induce the same behaviour, albeit less pronounced, as in p+p collisions. In addition, in p+p interactions, “cold nuclear matter effects” are also present that can mimic the behaviour caused by QGP or other hadronisation hadrons. In particular, strange–quark enhancement in p+p collisions would strongly indicate the formation of a deconfined medium in small collisions, providing valuable information about QGP properties and formation once the CMS effects are under control.

The LHCb collaboration recently analysed p+p data for QGP effects with the twofold purpose of searching for strangeness enhancement and providing a precise understanding of the CMS effects. This search was performed by measuring the production ratio of the strange baryon Σ to the strangeless baryon Λ using an earlier p+p sample. LHCb has also studied the ratios of the DD′ and D′D′ cross sections and corresponding ratios in different rapidity regions. While the ratios show little enhancement within the statistical uncertainty, a large asymmetry is observed in the forward–backward production. This strongly indicates CMS effects and provides detailed constraints on models of nuclear parton distribution functions and hadron production in a wide range of Bjorken-x (0–30%).

A strong suppression is observed for the Dmesons, giving insight into the nature of the CMS effects involved. An explanation via additional final-state effects is challenged by the ratio data, that are well described by models not including them. The production ratios of Σ, DD′ and D′D′ measured as a function of p+p collisions confirm these findings. All these studies will profit from the increased statistics and precision in p+p collisions that are expected from future LHC runs.

Further reading

- LHCb-CONF-2023-086, arXiv:2305.05426
- LHCb-CONF-2023-087, arXiv:2305.06752
- LHCb-CONF-2023-088, arXiv:2305.06753

Inclusive photon production at forward rapidities

The primary goal of high-energy heavy-ion physics is the study of a new state of nuclear matter, quark–gluon plasma, a strongly interacting, deconfined and colourless medium. The study of proton–proton (p+p) and p+Pb reactions provides inputs for the understanding of collisions at the LHC and provides a baseline for the interpretation of results from heavy-ion collisions. The study of p+p collisions also helps researchers understand the effects of cold nuclear matter on the production of final-state particles. Global observables, such as the number of produced particles (particle multiplicities) and their distribution in pseudorapidity (η), provide key information about particle–production mechanisms in these collisions. 

The pseudorapidity density distributions of inclusive photons from Monte Carlo event generators, compared with charged-particle measurement in p+p collisions (left), and different charged-particle multiplicity classes (right).

Using LHC Run 2 data, the p+p data show evidence for the production of high-pt γs in p+p collisions. The analysis of γ production in p+p collisions at the LHC is performed using a fast and highly efficient photon detector called the PHOS (Pb-Pb) detector. The PHOS detector is designed to detect photons with a high efficiency and a high signal-to-background ratio.

- LHCb-CONF-2023-086, arXiv:2305.05426
- LHCb-CONF-2023-087, arXiv:2305.06752
- LHCb-CONF-2023-088, arXiv:2305.06753

Novel search for inelastic dark matter

As dark matter (DM) search experiments increasingly constrain minimal models, more complex models have been suggested, featuring a rich “dark sector” with additional particle states and often involving forcing conditions typically set by Standard Model (SM) particles. Novel dark matter candidates are typically connected by a “portal” that can be experimentally probed. A crucial missing piece in our understanding of quantum chromodynamics (QCD) is a complete description of hadronisation in hard scattering processes with a large momentum transfer, which has now been investigated by the CMS collaboration in proton–proton (p+p) collisions. While perturbative QCD describes systems, providing crucial information of a deconfined medium in small collisions would strongly indicate the formation of a quark–gluon plasma (QGP), which affects the behaviour of particles traversing the medium. In particular, hadronisation hadrons can be affected, modifying the relative abundance of hadrons compared to p+p collisions.

The role that QGP may play in p+p collisions is currently unclear. Some models predict the formation of “QGP droplets”, which could partially induce the same behaviour, albeit less pronounced, as in p+p collisions. In addition, in p+p interactions, “cold nuclear matter effects” are also present that can mimic the behaviour caused by QGP or other hadronisation hadrons. In particular, strange–quark enhancement in p+p collisions would strongly indicate the formation of a deconfined medium in small collisions, providing valuable information about QGP properties and formation once the CMS effects are under control.

The LHCb collaboration recently analysed p+p data for QGP effects with the twofold purpose of searching for strangeness enhancement and providing a precise understanding of the CMS effects. This search was performed by measuring the production ratio of the strange baryon Σ to the strangeless baryon Λ using an earlier p+p sample. LHCb has also studied the ratios of the DD′ and D′D′ cross sections and corresponding ratios in different rapidity regions. While the ratios show little enhancement within the statistical uncertainty, a large asymmetry is observed in the forward–backward production. This strongly indicates CMS effects and provides detailed constraints on models of nuclear parton distribution functions and hadron production in a wide range of Bjorken-x (0–30%).

A strong suppression is observed for the Dmesons, giving insight into the nature of the CMS effects involved. An explanation via additional final-state effects is challenged by the ratio data, that are well described by models not including them. The production ratios of Σ, DD′ and D′D′ measured as a function of p+p collisions confirm these findings. All these studies will profit from the increased statistics and precision in p+p collisions that are expected from future LHC runs.

Further reading

- LHCb-CONF-2023-086, arXiv:2305.05426
- LHCb-CONF-2023-087, arXiv:2305.06752
- LHCb-CONF-2023-088, arXiv:2305.06753
The next generation of GWs would represent the largest ultrahigh vacuum systems ever built.
**FIELD NOTES**

**Moriond Electroweak 2023**

**An overall harvest of new results**

The 57th Rencontres de Moriond conference on electroweak and unified theories, which took place from 18 to 23 March, saw more than 150 physicists meet in La Thuile, Italy, for 100 talks covering the latest results in experiment and theory. These encompassed complementary approaches to some of the most pressing problems in particle physics and cosmology, and were actively debated in a stimulating atmosphere.

**Neutrinos first**

Neutrinos provide a unique window onto the only new physics so far seen beyond the Standard Model (SM). Their measured mass differences and mixing parameters provide a consistent picture, suggesting a new scale potentially at 10^{-14} GeV. However, the absolute neutrino–mass scale and the determination, via neutrinoless double beta decay, of whether neutrinos are Majorana particles, are missing. All of fundamental importance are the mass-squared ordering, atmospheric mixing, and the measurement of leptonic CP-violation. All these questions were addressed by new experimental results presented at the conference for the first time.

The KATRIN collaboration reported an absolute upper limit on the electron-neutrino mass of 600 meV. By analysing the tritium-decay spectrum, the team excluded rapid oscillations between electron and potential sterile neutrinos and set a limit on the electron neutrino number density below 200 meV/c^2. The KamiLo-Zen, CUPID-Mo and Majorana Demonstrator experiments showed results on neutrinoless double-beta decay searches in different systems (CERN Courier May/June 2023 p11), and the long-baseline neutrino oscillation anomaly was further confirmed by the best-estimate, whose data are also consistent with a simple sterile-neutrino oscillation pattern. The PROSPECT reactor–reactor experiment excluded sterile neutrino oscillations as its main explanation for the gallium anomaly. Finally, a peaking anomaly in the range 5–7.3 mu or 0.0 or 0.0 at 90% confidence was reported by the NOvA collaboration, although the DISC-conserving values of 0.0 or 0.0 could not be excluded with 90% confidence. NOvA provided the first evidence for the antinu-
**Cold atoms for nuclear physics**

On 13 and 14 March CERN hosted an international workshop on atom interferometry and the prospects for future large-scale experiments employing this quantum-sensing technique. The workshop had some 300 registered participants, of whom about half participated in person. As outlined in a keynote introduction by Mark Kasevich (Stanford), one of the pioneers of the field, this quantum sensing technology holds great promise for making ultra-sensitive measurements in fundamental physics.

Like light interferometry, atom interferometry involves measuring interference patterns, but between atomic wavepackets rather than light waves. Measurements of gravitational waves by atom interferometers can have coherent waves of ultralight bosonic dark matter and standard model (SM) particles could induce an observable shift in the interference phase, as could the passage of gravitational waves.

Atom interferometry is therefore a well-established concept that can provide exceptionally high sensitivity, for example to inertial/gravitational effects. Experimental designs take advantage of features used by state-of-the-art atomic clocks in combination with established techniques for building inertial sensors.

This makes atom interferometry an ideal candidate to hunt for physics beyond the SM, such as waves of ultra-light bosonic dark matter, or to measure gravitational waves in a frequency range (around 1 Hz) that is inaccessible to laser interference experiments on Earth, such as LIGO, Virgo and KAGRA, or to the space-borne experiment LISA. As discussed during the workshop, measurements of gravitational waves in this frequency range could reveal mergers of black holes with masses intermediate between those accessible to laser interferometers, casting light on the formation of the supermassive black holes known to inhabit the centres of galaxies.

Atom interferometer experiments can also explore the limits of quantum mechanics and its interface with gravity, for example by measuring a gravitational analogue of the Aharonov–Bohm effect.

Although the potential of atom interferometers for fundamental scientific measurements was the principal focus of the meeting, it was emphasised that technologies based on the same principles also have wide-ranging practical applications. These include gravimetry, geodesy, navigation, time-keeping and Earth observation from space, providing, for example, a novel and sensitive technique for monitoring the effects of climate change through measurements of Earth’s gravitational field.

Several large atom interferometers with a length of m or already exist, for example at Stanford University, or are planned, for example in Hannover (VLBI4), Wuhan and at the University of Oxford (AION). However, many of the proposed physics measurements require next-generation setups with a length of 100 m, and such experiments are under construction at Fermilab (MAiDI), in France (MISHA) and in China (ZSKA). The Atomic Interferometry (Shanghai and Network and AION) collaboration is evaluating possible sites in the UK and at CERN. In this context, a recent conceptual feasibility study supported by the CERN Physics Beyond Colliders study group concluded that a deep shift at Point 4 of the LHC is a promising location for an atom interferometer with a vertical baseline of over 100 m. The March workshop provided a forum for discussing such projects, their current status, future plans and prospective sensitivities.

Looking further ahead, participants discussed the prospects for one-micron km-scale atom interferometers, which would provide the maximal sensitivity possible with a terrestrial experiment to search for ultra-light dark matter and gravitational waves. It was agreed that the global community in particular would benefit from such projects, due to the critical technological advances and developments resulting from their realisation.

A highlight of the workshop was a poster session that provided an opportunity for 30 early-career researchers to present their ideas and current work on projects exploiting the quantum properties of cold atoms and related topics. The liveliness of the session showed how this interdisciplinary field at the boundaries between atomic physics, particle physics, astrophysics and cosmology is inspiring the next generation of researchers. These researchers will form the core of the team that will lead atom interferometers to their full potential.

**MMAP 2020**

**A carnival of ideas in Kolkata**

A one-of-a-kind conference (MMAP) Macrocosmos, Microcosmos, Accelerator and Philosophy 2020 was held in May last year in Kolkata, India, attracting 200 participants in person and remotely. An unusual format for an international conference, it combined the voyage from the microcosms of elementary particles to the macrocosms of our universe up to the horizon and beyond with accelerator physics and philosophy through the medium of poetry and songs, as inspired by the Indian poet Rabindranath Tagore and the creative grace Satyajit Ray.

The first presentation was by Roger Penrose, who talked about black holes, singularities and conformal cyclic cosmology. He discussed the cosmology of dark matter and dark energy, and inspired participants with the fascinating idea of one going over to another extremely close with no beginning or end of time and space. Larry McLerran’s talk “Quarkyonic matter and neutron stars” provided an intuitive understanding of the origin of the equation of state of neutron stars at a very high density, followed by Dinesh Srivastava’s talk “Bandyopadhyay’s talk on unlocking the mysteries of neutron stars.” Jean-Paul Blaizot talked about the emergence of hydrodynamics in expanding quark-gluon plasma, whereas Edward Shuryak discussed the role of spherelam expansions and baryogenesis in the cosmological electroweak phase transition. Subir Sarkar’s talk “Testing the cosmological principle” was provocative, as usual, and Sunil Mukhi and Amita Sinha described the prospects for string theory. Sumit Soma, Chandana Bhattacharya, Nabanta Naskar and Arup Bandyopadhyay discussed the low- and medium-energy physics possible using cyclotrons at Kolkata.

Moving to extreme nuclear matter, Barbara Lacka talked about experimental studies of transport in dense gluon matter, Jürgen Schukraft, Federico Antinori, Tapan Nayak, Bedangadas Mohanty and Subhrajyoti Chattopadhyay spoke on signatures for the early-universe quark-gluon plasma and described the experimental programme of the ALICE experiment at the LHC, while Pratishna Saha focussed on the electromagnetic signatures of quark-gluon plasma.

Amanda Cooper-Sarkar emphasised the role of parton distribution functions in searches for new physics at colliders such as the LHC. Shoji Nagamiya introduced the physics prospects of the J-PARC facility in Japan, Paolo Giubellino described the evolution of the latest FAIR accelerator at GSI, and Horst Sticker discussed how to observe strangelets using fluctuation techniques. In his presentation on the history of CERN, former Director-General Rolf Heuer talked about the marvel of large-scale collaboration capturing the thrill of a big discovery.

The MMAP 2020 conference witnessed a carnival of ideas, a mixture of low- to high-energy physics on the one hand and the cosmology of the creation of the universe on the other.

Bikash Sinha VECC Kolkata

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FIVE SIGMA REVISITED

Louis Lyons traces the origins of the “five sigma” criterion in particle physics, and asks whether it remains a relevant marker for claiming the discovery of new physics.

The standard criterion for claiming a discovery in particle physics is that the observed effect should have the equivalent of a five standard-deviation (5σ) discrepancy with already known physics, i.e. the Standard Model (SM). This means that the chance of observing such an effect or larger should be at most 3 × 10^−5, assuming it is merely a statistical fluctuation. The probability of correctly guessing whether a coin will fall heads or tails is 50%. This says that a five-sigma effect is the same as the probability of being wrong eight or nine times (5.5%). A small p-value indicates a tension between the theory and the observation. The p-value analysis often looks for peaks in mass spectra, which could be the sign of a new particle. An example is shown in the “Higgs signals” figure (p26), which contains data from CMS used to discover the Higgs boson (Atlas has similar data). Where the local p-value of an observed effect is the chance of a statistical fluctuation being at least as large as the observed one at its specific location, more relevant is a global p-value corresponding to a fluctuation anywhere in the analysis, which has a higher probability and hence reduces the significance. The local p-values corresponding to the data in “Higgs signals” are shown in the figure “p-values” (p26).

A new physics example highlighting the difference between local and global p-values was provided by an archaeologist who noticed that a direction defined by two of the large stones at the Stonehenge monument pointed at a specific ancient monument in France. He calculated that the probability of this was very small, assuming that the placement of the stones was random (local p-value), and hence that this pointed to the similarity of the old age that “extraordinary claims require extraordinary evidence”. Since these factors vary from one analysis to another, one can argue that it is unreasonable to use the same discovery criterion everywhere.

There are other relevant aspects of the discovery procedure. Searches for new physics can be just tests for consistency with the SM, or they can search for which of two competing hypotheses (“just SM” or “SM plus new physics”) provides a better fit to the data. The threshold of probability is the “Bayesian prior probability of the model”. This is an example of the probability of an event A, assuming that B is true, not in general expected, the probability of B, given A. Thus the probability of an amurderer eating toast for breakfast may be 60%, but the probability of someone who eats toast for breakfast becoming an amurderer is thankfully much smaller (about one in a million). In general, our belief in the plausibility of a model for a particular version of new physics is much smaller than for the SM, being an example of the old adage that “extraordinary claims require extraordinary evidence”. Since these factors vary from one analysis to another, one can argue that it is unreasonable to use the same discovery criterion everywhere.

In summary, the five-sigma criterion is not unreasonable to regard 5σ as a discovery, but 4.9σ as not.

Discoveries in progress

A useful exercise is to review a few examples that might be (or might have been) discoveries. The CMS and ATLAS observation of events involving four-top quarks. From the similarity of the heroic work of the physicists involved, these analyses have interesting contrasts with the Higgs boson discovery. First, the Higgs discovery involved clear mass peaks, while the four-top events simply caused an enhancement of events in the relevant region of phase space (see “Four-top figures”). Then, the four-top production is just a verification of an SM prediction and indeed it would have been more of a surprise if the measured rate had been zero. So this is just an observation of an expected process, rather than a new discovery. Indeed, both preprints used the word “observation” rather than “discovery”. Finally, although 5σ was the required criterion for discovering the Higgs boson, surely a lower level of significance would have been sufficient for the observation of four-top events.

The degree of model dependence is a continuous spectrum rather than a binary choice. It is unreasonable to regard 5σ as a discovery, but 4.9σ as not.
FEATURE STATISTICS

Four tops

Histogram of the output from a graph neural network (GNN) comparing ATLAS data with the predicted distribution expected for various backgrounds (as specified on the figure) and from the four-top signal (red). The GNN was trained to distinguish between the signal and backgrounds. The agreement between two data and prediction is clearly much improved by the inclusion of the four-top signal.

Measurement of the moment: The anomalous magnetic moment of the muon, defined as $\mu - 2\mu$, where $\mu$ is the magnetic moment in units of its Bohr magneton, the value $\mu = 2$ corresponds to the prediction using Dirac theory, but there are many higher order corrections. The figure shows an earlier measurement at Brookhaven (BNL g-2) and the more recent result from Fermilab (FLAS g-2) as well as their combination (Blue band). The green band is the theoretical prediction, which is 1.4 × 10⁻⁵ (translating to 5.6 standard deviations, to be compared with 4.2 standard deviations observed). The red band is the experimental average of all measurements, which reduces the discrepancy, but only slightly. A subsequent measurement by ATLAS disagreed with the CDF result; the CMS determination of $m_H$ is awaited with interest.

Nuanced approach

It is worth noting that the muon g-2, flavour and $m_H$, discrepancies concern tests of the SM predictions, rather than direct observation of a new particle or its interactions. Independent confirmations of the observations and the theoretical calculations would be desirable.

One of the high hopes for further running of the LHC is that it will result in the “discovery” of Higgs pair production. But surely there is no reason to require a 5σ discrepancy with the SM in order to make such a claim? After all, the Higgs boson is known to exist, its mass is known and there is no big surprise in observing its pair-production rate being consistent with the SM prediction. “Confirmation” would be a better word than “discovery” for this process. In fact, we would be real discovery if the di-Higgs production rate was found to be significantly above or below the SM prediction. A similar argument could be applied to the searches for single-top–quark production at hadron colliders, and decays such as $W → τν$ or $B → τν$. This should not be taken to imply that LHC running can be stopped once a suitable lower level of significance is reached. Clearly there will be interest in using more data to study di-Higgs production in greater detail.

Our hope for the future is that the current 5σ criterion will be replaced by a more nuanced approach for what qualifies as a discovery. This would include just quoting the observed and expected p-values; whether the analysis is dominated by systematic uncertainties or statistical ones; the look–elsewhere effect; whether the analysis is robust; the degree of surprise; etc. This may mean leaving it for future measurements to determine who deserves the credit for a discovery. It may need a group of respected physicists (e.g. the directors of large labs) to make decisions as to whether a given result merits being considered a discovery or needs further verification. Hopefully we will have several of these interesting decisions to make in the toe–toe–distant future.

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<th>Current</th>
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<tr>
<td>70-200 MeV</td>
<td>High current proton beams for neutron production and delivery*</td>
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<td>3–90 MeV</td>
<td>For Proton Therapy*</td>
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<tr>
<td>1–15 MeV</td>
<td>Proton only, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
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<td>Proton or alpha/deuteron/proton, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
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<td>30 MeV</td>
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<td>35–70 MeV</td>
<td>Proton only or alpha/deuteron/proton systems, capable of high current up to 1000 Micro Amps, for medical radioisotopes</td>
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*Patent Pending

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EXTREME DETECTOR DESIGN FOR A FUTURE CIRCULAR COLLIDER

A pileup of 1000 proton–proton collisions per bunch–crossing, highly boosted objects and radiation levels up to $10^{18}$ hadrons per cm$^2$ are just some of the challenges in extracting physics from a next–generation hadron collider to follow the LHC. Martin Aleksa, Werner Riegler and Michele Selvaggi digest the conceptual design report for a general–purpose experiment at the Future Circular Collider.

The Future Circular Collider (FCC) is the most powerful post–LHC experimental infrastructure proposed to address key open questions in particle physics. Under study for almost a decade, it envisions an electron–positron collider phase, FCC–ee, followed by a proton–proton collider in the same 91 km–circumference tunnel at CERN. The hadron collider, FCC–hh, would operate at a centre–of–mass energy of 100 TeV, extending the energy frontier by almost an order of magnitude compared to the LHC, and provide an integrated luminosity a factor of 5–10 larger. The mass reach for direct discovery at FCC–hh will reach several tens of TeV and allow, for example, the production of new particles whose existence could be indirectly exposed by precision measurements at FCC–ee.

At the time of the kickoff meeting for the FCC study in 2014, the physics potential and the requirements for detectors at a 100 TeV collider were already heavily debated. These discussions were eventually channelled into a working group that provided the input to the 2020 update of the European strategy for particle physics and recently concluded with a detailed writeup in a 300–page CERN Yellow Report. To focus the effort, it was decided to study one reference detector that is capable of fully exploiting the FCC–hh physics potential. At first glance it resembles a super CMS detector with two LHCb detectors attached (see “Grand designs” image). A detailed detector performance study followed, allowing a very efficient study of the key physics capabilities.

The first detector challenge at FCC–hh is related to the luminosity, which is expected to reach $1\times10^{34}$ cm$^{-2}$s$^{-1}$. This is six times larger than the HL–LHC luminosity and 30 times larger than the nominal LHC luminosity. Because the FCC will operate beams with a 25 ns bunch spacing, the so–called pile–up (the number of pp collisions per bunch crossing) scales by approximately the same factor. This results in almost 1000 simultaneous pp collisions, requiring a highly granular detector. Evidently, the assignment of tracks to their respective vertices in this environment is a formidable task. The plan to collect an integrated pp luminosity of 30 ab$^{-1}$ brings the radiation hardness requirements for the first...
layers of the tracking detector close to 10^10 hadrons/cm^2, which is around 100 times more than the requirement for the HL-LHC. Still, the tracker volume with such high radiation load is not excessively large. From a radial distance of around 30 cm outwards, radiation levels are already close to those expected for the HL-LHC, thus the silicon technology for these detector regions is already available. The high radiation levels also need very radiation-hard calorimetry, making a liquid-argon calorimeter the first choice for the electromagnetic calorimeter and forward regions of the hadron calorimeter. The energy deposit in the very forward regions will be very low per unit of rapidity and it will be an interesting task to keep cryogenic liquids cold in such an environment. Thanks to the large shielding effect of the calorimeters, which have to be quite thick to contain the highest energy particles, the radiation levels in the muon system are not too different from those at the HL-LHC. So the technology needed for this system is available.

Looking forward
As an example of the 7 TeV, important SM particles such as the Higgs boson are abundantly produced in the very forward region. The forward acceptance of FCC-hh detectors therefore has to be much larger than at the LHC detectors. ATLAS and CMS used different concepts for momentum resolution of pseudo-rapidity (a measure of the angle between the track and beamline) of around η = 2.5, whereas at FCC-hh this will have to be extended to η = 4 (see “Far reaching” figure). Since this is not achievable with a central solenoid alone, a forward magnet system is assumed on either side of the detector. Whether the optimum forward magnets are solenoids or dipole systems still has to be studied and will depend on the requirements for momentum resolution in the very forward region. Forward solenoids have been considered that extend the precision of momentum measurements by one additional unit of rapidity. A silicon tracking system with a radius of 1.6 m and a total length of 30 m provides a momentum resolution of around 0.6% for low-momentum particles, 2% at 1 TeV and 20% at 30 TeV (see “Forward momentum” figure). To detect at least 90% of the very forward jets that accompany a Higgs boson in vector-boson-fusion production, the tracker acceptance has to be extended up to η = 6. At the LHC such an acceptance is already achieved up to η = 4. The total tracker surface of around 400 m^2 at FCC-hh is “just” a factor two larger than the HL-LHC trackers, and the total number of channels (16.5 billion) is around eight times larger.

Higgs self-coupling
The precision of the Higgs self-coupling measurement at FCC-hh can be achieved by a new method: the combination of the self-coupling measurement with the total Higgs width measurement. The latter has been known for some time, but the total Higgs width measurement is not as precise as needed for the FCC-hh project, and it is subject to uncontrolled systematic uncertainties. The combination of the two methods will provide a stringent test of the Higgs self-coupling and improve the confidence level in the predicted Higgs width.

LHC versus FCC-hh

**Forward momentum resolution versus pseudorapidity** η for the FCC-hh reference detector for given transverse momentum p_T. If dipole magnets instead of solenoids are used in the forward region, the momentum resolution can be significantly improved (dashed lines).

**Liquid argon** A cross section through the liquid–argon electromagnetic calorimeter using inclined absorber plates and highly granular readout boards (top), and measurements of the electrical properties of a readout electrode prototype for such a calorimeter at CERN (bottom).

The FCC-hh reference detector will result in about 250 TB/s of data for calorimetry and the muon system, about to times more than the ATLAS and CMS HL-LHC scenario. There is no doubt that it will be possible to digitise and read this data at the full bunch-crossing rate for these detector systems. The question remains whether the data rate of almost 250 TB/s from the tracker can also be read out at the full bunch-crossing rate or whether calorimeter, muon and possible coarse tracker information need to be used for a first-level trigger decision, reducing the tracker readout rate to the few MHz level, without the loss of important physics. Even if the optical link technology for full tracker readout were available and affordable, sufficient radiation hardness of devices and infrastructure constraints from power and cooling services are prohibitive with current technology calling for R&D on low-power radiation-hard optical links.

**Benchmarks physics** The potential of FCC-hh in the realm of precision Higgs and electroweak physics, high mass reach and dark-matter searches offers an unprecedented opportunity to address fundamental unknowns about our universe. The performance requirements for the FCC-hh baseline detector have been defined through a set of benchmark physics processes, selected among the key ingredients of the physics programme. The detector’s increased acceptance compared to the LHC detectors, and the higher energy of FCC-hh collisions, will allow physicists to uniquely improve the
Detailed studies have shown that it should be possible to build a detector that can fully exploit the physics potential of such a machine.

In terms of dark-matter searches, FCC-hh has immense potential – particularly for probing scenarios of weakly interacting massive particles such as higgsinos and winos (see “Dark matters” figure). Electroweak multiplets are typically elusive, especially in hadron collisions, due to their small abundances and large masses (needed to explain the relic abundance of dark matter in our universe). Their nearly degenerate mass spectrum produces an elusive final state in the form of so-called “disappearing tracks”. Thanks to the dense coverage of the FCC-hh detector tracking system, a general-purpose FCC-hh experiment could detect these particle decays directly, covering the full mass range expected for this type of dark matter.

A detector at a 100 TeV hadron collider is clearly a challenging project. But detailed studies have shown that it should be possible to build a detector that can fully exploit the physics potential of such a machine, providing we invest in the necessary detector R&D. Experience with the Phase-II upgrades of the LHC detectors for the HL-LHC, developments for further exploitation of the LHC and detector R&D for future Higgs factories will be important stepping stones in this endeavour.

Further reading

The neutrino had barely been known for two years when CERN’s illustrious neutrino programme got under way. As early as 1958, the 600 MeV Synchro­cyclotron enabled the first observation of the decay of a charged pion into an electron and a neutrino – a key piece in the puzzle of weak interactions. Dedicated neutrino–beam experiments began a couple of years later when the Proton Synchrotron (PS) entered operation, rivalled by activities at Brookhaven’s higher-energy Alternating Gradient Synchrotron in the US. Producing the neutrino beam was relatively straightforward: make a proton beam from the target, put the target in the right place, and they discovered that neutrinos when they decay, then use an iron shielding to filter the remaining hadrons, such that only neutrinos and muons remain. Ensuring that a new generation of particle detectors would enable the study of neutrino–beam interactions proved a tougher challenge.

CERN began with two small, 1-m-long heavy-liquid bubble chambers that used proton beams which struck an internal target inside the PS, hoping to see at least one neutrino event per day. It was nowhere near that. Unfortunately the target configuration had made the beams about 10 times less intense than expected, and in 1961 CERN’s nascent neutrino programme came to a halt. “It was a big disappointment,” recalls Don Cundy, who was a young scientist at CERN at the time. “Then, several months later, Brookhaven did the same experiment but this time they put the target in the right place, and they discovered that there were two neutrinos – the muon neutrino (νμ) and the electron neutrino (νe) – a great discovery for which Lederman, Schwartz and Steinberger received the Nobel prize some 25 years later.”

Despite this setback, CERN Director-General Victor Weisskopf, along with his science director Gilberto Bernardini and the CERN team, decided to embark on an even more ambitious setup. Employing Simon van der Meer’s recently proposed “magnetic horn” – a high-current, pulsed focusing device placed around the target – and placing the target

**Spotted** The first candidate leptonic neutrino-current event. In the image a muon anti-neutrino (unseen) coming from the right interacts with an electron that leaves the horizontal track as it moves to the left and radiates photons, which in turn create electron–positron pairs. The neutrino continues to the left (unseen) without having produced a muon.
In an external beam pipe increased the neutrino flux by about two orders of magnitude. In 1965 this opened a new series of neutrino experiments at CERN. They began with a heavy-liquid bubble chamber containing around 500 kg of freon and a single-pion production. With Simon van der Meer’s invention of the magnetic horn, the production of precise and focused particle beams for neutrino experiments became possible.

The first observation of neutrino interactions was a discovery of neutral-current (NC) processes, the most sensitive way to look for NCs was the decay of a K\(^+\) meson into two muons or two electrons but that had a very low branching ratio, so if NCs existed it would be at a very small level. The first thing on the list for Gargamelle was in fact looking at the structure of the nucleus, to measure the total cross section and to investigate the quark model. Setting priorities

After the discovery of the neutrino in 1956 by Reines and Cowan (CERN Courier July/August 2016 p7), the weak interaction became a focus of nuclear research. The unification of the electromagnetic and weak interactions by Salam, Glashow and Weinberg set new limits on electron–neutrino and single-pion neutral-current (NC) processes, the search for actual NC events made it onto the list. However, it only placed eighth out of 10 science goals. That is quite understandable, comments Cundy: “People thought that the most sensitive way to look for NCs was the decay of a K\(^+\) meson into two muons or two electrons but that had a very low branching ratio, so if NCs existed it would be at a very small level. The first thing on the list for Gargamelle was in fact looking at the structure of the nucleus, to measure the total cross section and to investigate the quark model.”

Eyes down Working on the pilot model of a scannable table for Gargamelle in 1966 was Anita Borkoška, who was looking for “interesting events” among the many recorded tracks.

In 1967 Gargamelle moved to the PS and in 1970 the detector was receiving a beam of muon neutrinos from the PS. The Gargamelle collaboration consisted of researchers from seven European institutes: Aachen, Brussels, CERN, École Polytechnique Paris, Milan, LAL, Orsay and University College London. In 1969 the collaboration had made a list of physics priorities. Following the results of CERN’s Heavy Liquid Bubble Chamber, which set new limits on neutrino–electron scattering and single-pion-neutral-current (NC) processes, the search for actual NC events made it onto the list. However, it only placed eighth out of 10 science goals. That is quite understandable, comments Cundy: “People thought that the most sensitive way to look for NCs was the decay of a K\(^+\) meson into two muons or two electrons but that had a very low branching ratio, so if NCs existed it would be at a very small level. The first thing on the list for Gargamelle was in fact looking at the structure of the nucleus, to measure the total cross section and to investigate the quark model.”

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when the first leptonic event was found in December 1972 we were convinced that NCs existed,” says Gargamelle member Donatella Cavalli from the University of Milan. “It was just one event but with very low background, so a lot of effort was put into the search for hadronic NC events and in the full understanding of the background. I was the youngest in my group and I remember spending the evenings with my colleagues scanning the films on special projectors, which allowed us to see the eight views of the chamber. I proudly remember my travels to Paris, London and Brussels, taking the photographs of the candidate events found in Milan to be checked with colleagues from other groups.”

At a CERN seminar on 19 July 1973, Paul Musset, who was one of the principal investigators, presented Gargamelle’s evidence for NCs based on both the leptonic and hadronic analyses. Results from the former had been published in a short paper received by Physics Letters two weeks earlier, while the paper on the hadronic events, which reported on the actual observation and hence confirmation of neutral currents, was received on 23 July. In August 1973 Gerald Myatt of University College London, now at the University of Oxford, presented the results at the Electron–Photon conference. The papers were published in the same issue of the journal on 3 September. So many physicists doubted them. “It was generally believed that Gargamelle made a mistake,” says Myatt. “There was only one event, a tiny track really, and very low background. Still, it was not seen as conclusive evidence.” Among the critical voices were T D Lee, who was utterly unpersuaded, and Jack Steinberger, which the energy of the proton was doubled and a small chamber that the Gargamelle result would be wrong. The difficulty was to demonstrate that the hadronic NC signal was not due to background from neutral hadrons. “A lot of work and many different checks were done, from calculations to a full Monte Carlo simulation to a comparison between spatial distributions of charge- and neutral-current events,” explains Cavalli. “We were really happy when we published the first results from hadronic and leptonic NCs after all background checks, because we were confident in our results.” Initially the Gargamelle results were confirmed by the independent HPWF (Harvard–Pennsylvania–Wisconsin–Fermilab) experiment at Fermilab. Unfortunately, a problem with the HPWF setup led to their paper being rewritten, and a new analysis presented in November 1973 showed no sign of NCs. It was not until the following year that the modified HPWF apparatus and other experiments confirmed Gargamelle’s findings. Additionally, the collaboration managed to tick off number two on its list of physics priorities: deep-inelastic scattering and scaling. Confirming earlier results from SLAC which showed that the proton is made of point-like constituents, Gargamelle-data were crucial in proving that these constituents (quarks) have charges of +1/3 and −1/3. For neutral currents, the icing on the cake came 10 years after Gargamelle’s discovery with the direct discovery of the Z (and W) bosons at the Spp–S collider in 1983. The next milestone for CERN in understanding weak interactions came in 1990 with the precise measurement of the decay width of the Z boson at LEP, which showed that there are three and no more light neutrinos.

Legacy of a giantess

In 1977 Gargamelle was moved from the PS to the newly installed Super Proton Synchrotron (SPS). The following year, however, metal fatigue caused the chamber to crack and the experiment was decommissioned. Some of the collaboration members — including Cundy and Myatt — went to work on the nearby Big European
FEATURE NEUTRINOS

Testing the future The Neutrino Platform at CERN’s North Area is a unique detector R&D facility and currently hosts the ProtoDUNE (red cryostats).

Bubble Chamber. Also hocked up to the SPS for neutrino studies at that time were CDHS (CERN–Dortmund–Heidelberg–Saclay, officially denoted WAs) led by Steinberger, and Klaus Winter’s CHARM experiment. Operating for eight years, these large detectors collected millions of events that enabled precision studies on the structure of the charged and neutral currents as well as the structure of nucleons and the first evidence for QCD via scaling violations.

The third type

The completion of the CHARM programme in 1991 marked the end of neutrino operations at CERN for the first time in almost 30 years. But not for long. Experimental activities restarted with the search for neutrino oscillations, driven by the idea that neutrinos were an important component of dark matter in the universe. Consequently, two similarly styled short-baseline neutrino–beam experiments – CHORUS and NOMAD – were built. These next-generation detectors, which took data from 1993 to 1997 and from 1995 to 1998, respectively, joined others around the world to look for interactions of the third neutrino type, the ντ, and to search for neutrino oscillations, i.e., the change in neutrino flavour as they propagate, which was proposed in the 1990s and confirmed in 1998 by the SNO and Super-Kamiokande experiments in Canada and Japan. In 2000 the DONUT experiment at Fermilab reported the first direct evidence for ντ interactions.

CERN’s neutrino programme entered a hiatus until July 2006, when the SP8 began firing an intense beam of muon neutrinos 732 km through Earth to two huge detectors – ICARUS and OPERA – located underground at Gran Sasso National Laboratory in Italy. Designed to make precision measurements of neutrino oscillations, the CERN Neutrino to Gran Sasso (CNGS) programme observed the oscillation of muon neutrinos into tau neutrinos and was completed in 2012.

As the CERN neutrino-beam programme was wound down, a brand-new initiative to support fundamental neutrino research began. “The initial idea for a ‘neutrino platform’ at CERN was to do a short-baseline neutrino experiment involving ICARUS to check the LSND anomaly, and another to test prototypes for ‘LBNO’, which would have been a European long-baseline neutrino oscillation experiment sending beams from CERN to Phylakopi in Finland to investigate the oscillation,” says Dario Autiero, who has been involved in CERN’s neutrino programme since the beginning of the 1980s. “The former was later decided to take place at Fermilab, while for the latter the European and US visions for long-baseline experiments found a consensus for what is now DUNE (the Deep Underground Neutrino Experiment) in the US.”

A unique facility

Officially launched in 2013 in scope of the update to the European strategy for particle physics, the CERN Neutrino Platform serves as a unique R&D facility for next-generation long-baseline neutrino experiments. Its most prominent project is the design, construction and testing of prototype detectors for DUNE, which will see a neutrino beam from Fermilab sent 1300 km to the SURF laboratory in Europe. One of the Neutrino Platform’s early successes was the refurbishment of the ICARUS detector, which is now taking data at Fermilab’s short-baseline neutrino programme. The platform is also developing key technologies for the near detector for the Tokai-to-Kamikawa (T2K) neutrino factory in Japan (see p11), and has a dedicated theory working group aimed at strengthening the connections between CERN and the worldwide neutrino community. Independently, the NA64 experiment at the SP8 is contributing to a better understanding of neutrino–nucleon cross sections for DUNE and T2K data.

More than 60 years after first putting the neutrino to work, CERN’s neutrino programme continues to evolve. In April 2023 a new experiment at the LHC, called FASER made the first observation of neutrinos produced at a collider. Together with another new experiment, SNAP-HIC, FASER will enable the study of neutrinos in a new energy range and compare the production rate of all three types of neutrinos to further test the Standard Model.

As for Gargamelle, today, it lies next to BEBC and other retired colleagues in the garden of Square van Hove behind CERN’s main entrance. Not many can still retell the story of the discovery of neutral currents, but those who can share the story with delight “It was very tiny that first track from the electron, one in hundreds of thousands of pictures,” says Myatt. “Yet it justified André Lagarrigue’s vision of the large heavy-liquid bubble chamber as an ideal detector of neutrinos, combining large mass with a very finely detailed picture of the interaction. There can be no doubt that it was these features that enabled Gargamelle to make one of the most significant discoveries in the history of CERN.”

Kobold continues to design and develop quality measuring and analytical instrument products, and have now launched their compact flow meter, the MIM with even more versatile features. With factories within the Kobold Group experiencing well over one hundred years of trading, Kobold has an enviable and extensive wealth of technical knowledge and experience to draw upon when developing new products. At the concept stage, Kobold will often draw upon the experience of their international sales offices to establish a framework of practical features and functionality, and thus produce an instrument which is suitable and compliant for an international market place. This indeed was the process for MIM.

More than 60 years after first putting the neutrino to work, CERN’s neutrino programme continues to evolve

From the MIM concept Kobold have produced a high quality and versatile compact flow meter for measuring conductive liquids, ensuring suitability for a wide range of industrial applications. Heavy duty construction in stainless steel provides a clean and robust instrument module. The design of the 90° step indexable TFT display screen is clever, yet simple and robust, ensuring suitability for multi-directional flow applications, programmable from the touch screen. A nice feature of the TFT display screen is that it can be used by operators wearing gloves. Unlike some of the TFT screens on the market using inclination sensors for screen position, the MIM screen remains clear and stable in use, a reminder of Kobold’s instinctive preference for simplified practical functionality and reliable service.

Innovative design and quality have become hallmarks of all Kobold manufactured products but refreshingly, during their concept stage Kobold are clearly applying focus to practical ease of functionality and to some extent, resisting the trend wand temptation to incorporate unnecessary features and over complicated software.

Typically with an electromagnetic flow meter there are no moving parts in the measuring device and this can be a key advantage in many industrial applications. In principle the induced voltage is picked up by two sensing electrodes which are in contact with the measuring agent and sent to the measuring amplifier. The flow rate will be calculated based on the cross sectional area of the pipe. A key advantage of this measuring principle is that the measurement is not dependent on the process liquid and its material properties such as density, viscosity and temperature, however, be mindful that the flowing media must have a minimum conductivity.
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**EVENT DISPLAYS IN MOTION**

Ever-increasing luminosity, advances in computing and the creativity of the LHC experiments are driving event displays to new levels of sophistication for physics and outreach activities, finds Kristiane Bernhard-Novotny.

The first event displays in particle physics were direct images of traces left by particles when they interacted with gases or liquids. The oldest event display of an elementary particle, published in Charles Wilson’s Nobel lecture from 1927 and taken between 1912 and 1913, showed a trajectory of an electron. It was a trail made by small droplets caused by the interaction between an electron coming from cosmic rays and gas molecules in a cloud chamber, the trajectory being bent due to the electrostatic field (see “First light” figure). Bubble chambers, which work in a similar way to cloud chambers but are filled with liquid rather than gas, were key in proving the existence of neutral currents 50 years ago (see p35), along with many other important results. In both cases a particle crossing the detector triggered a camera that took photographs of the trajectories.

Georges Charpak’s invention of the multi-wire proportional chamber in 1968, which made it possible to distinguish single tracks electronically, paved the way for three-dimensional (3D) event displays. With 40 drift chambers, and computers able to process the large amounts of data produced by the UA1 detector at the SppS, it was possible to display the tracks of decaying W and Z bosons along the beam axis, aiding their 1983 discovery (see “Inside events” figure, top, p42).

**Design guidelines**

With the advent of LEP and the availability of more powerful computers and reconstruction software, physicists knew that the amount of data would increase to the point where displaying all of it would make pictures incomprehensible. In 1995 members of the ALEPH collaboration released guidelines – implemented in a programme called Dali, which emphasised the role of the tracking system. The remaining issue of superimposed detector layers was mitigated by showing a cross-section of the detector in the same event display (see “Inside events” figure, middle). Together with a colour palette that helped distinguish the different objects, such as jets, from one other, these design principles prevailed into the LHC era.

The LHC not only took data acquisition, software and...
This is especially important after long shutdowns or the annual year-end technical stops. Largely based on the software used to create event displays at LEP, each of the four main LHC experiments developed their own tools, tailored to their specific analysis software (see “LHC returns” figure). The detector geometry is loaded into the software, followed by the event data, if the detector layout doesn’t change, the geometry is not recreated. As at LEP, both fish-eye and wire-frame images are used. Thanks to better rendering software and hardware developments, such as more powerful CPUs and GPUs, wire-frame images are becoming ever more realistic (see “LHC returns” figure). Computing developments and additional cleanup due to increased collisions have motivated more advanced event displays. Driven by the enthusiasm of individual physicists, and in time for the start of the LHC Run 3 on run in October 2022, ALICE experimentalists have begun to use software that renders each event to give a more realistic and crispier view (see “Picture perfect” image, p41). In particular, in lead-lead collisions at 5.36 TeV per nucleon pair measured with ALICE, the fully reconstructed tracks are plotted to achieve the most efficient visualisation. ATLAS also uses both fish-eye and wire-frame views. Their current event-display framework, Virtual Point 1 (VP1), creates interactive 3D event displays and integrates the detector geometry to draw a selected set of particle passages through the detector. As with the other experiments, different parts of the detector can be added or removed, resulting in a sliced view. Similarly, CMS visualises their events using in-house software known as Fireworks, while LHCb has moved from a traditional view using Panoramix software to a 3D one using software based on ROOT TVE. 

In addition, ATLAS, CMS and ALICE have developed virtual-reality views. For instance, allows data to be expected in a format that is used for videos and 3D images. This enables both physicists and the public to fully immerse themselves in the detector. CMS physicists created a first virtual-reality version during a hackathon, which took place at CERN in 2016 and integrated this feature with small modifications in another application to create ATLAS’s augmented-reality application “More than ALICE”, which is intended for visitors, overlays the description of detectors and even event displays, and works on mobile devices. Phoenix rising to streamlines the work on event displays at CERN, developers in the LHC experiments joined forces and published a visualisation whitepaper in 2017 to identify challenges and possible solutions. As a result it was decided to create an experiment-agnostic event display, later named Phoenix. “When we realised the overlap of what we are doing across many different experiments, we decided to develop a flexible framework, where we can share effort and leverage our individual expertise, and where users don’t need to install any special software,” says main developer Edward Mayou of ATLAS. While experimental-specific frameworks are closely tied to the experiments’ data format and visualise all incoming data, experiment-agnostic frameworks only deal with a simplified version of the detectors and a subset of the event data. This makes them lightweight and fast, and requires an extra processing step as the experimental data need to be put into a generic format and thus lose some detail. Furthermore, not every experiment has the symmetric layout of ATLAS and CMS. This applies to LHCb, for instance. Phoenix initially supported the geometry and event-display formats for LHCb and ATLAS, but those for CMS were added soon after and now FCC has joined. The platform had its first test in 2018 with the TrackML computing challenge using a Furiosa High-Luminosity LHC (HL-LHC) detector created with Phoenix. The main reason to launch this challenge was to find new machine-learning algorithms that can deal with the unprecedented increase in data collection and pile-up in detectors expected during the HL-LHC runs, and at proposed future colliders.

Painting outreach Following the discovery of the Higgs boson in particular, outreach has become another major pillar of event displays. Visually pleasing images and videos of particle collisions, which help in the communication of results, are tailor made for today’s era of social media and high-bandwidth internet connections. “We created a special event display for the LHCb master class,” mentions LHCb’s Ben Courty. “We show the students what an event looks like from the detector to the particle tracks.” CMS’s VP1 application is web-based and primarily used for outreach and CMS masterclasses, and has also been extended with a virtual-reality application. “When I started to work on event displays around 2007, the graphics were already good but ran in dedicated applications,” says CMS’s Tim McCauley. “For me, the big change is that you can now use all these things on the web. You can access them easily on your mobile phone or your laptop without needing to be an expert on the specific software.” Being available via a browser means that Phoenix is a versatile tool for outreach as well as physics. In cases or regions where the necessary bandwidth to create event displays is sparse, pre-created events can be used to highlight the main physics objects and to display the detector as clearly as possible. Another new way to experience a collision and to immerse fully into an event is to wear virtual-reality goggles. An even older and more experiment-agnostic framework than Phoenix using virtual-reality experiences exists at CERN, and is aptly called TVB (Total Event Display). Formerly used to show event displays in the LHC interactive tunnel as well as in the Microcosm exhibition, it is now used at the CERN Globe and the new Science Gateway centre. There, visitors will be able to play a game called “proton football”, where the collision energy depends on the “kick”. The players give their protons “This game shows that event displays are the best of both worlds,” explains developer Joao Pequeno of CERN. “They inspire children to learn more about physics by simply playing a soccer game, and they help physicists to debug their detectors.”


Following the discovery of the Higgs boson in particular, outreach has become another major pillar of event displays.
Future colliders are particle observatories

Colliders are not just searches for new physics; they are general-purpose observatories of fundamental processes on the smallest scales. We need to start thinking of them as such, says Twong You. In no other field of science is the promise of revolutionary discovery the only standard by which future proposals are held. Yet in particle physics—a narrative persists that the current lack of new physics beyond the Standard Model (SM) is putting the future of the field in doubt. This pessimism is misguided.

Take cosmology and astrophysics. These are fundamental sciences whose aim is nothing more than to better understand the objects within their remit. Telescopes and other instruments point at the universe at large, observing to ever higher precision, farther than ever before, in new, previously inaccessible regimes. The Gaia, JWST and LIGO instruments, which cost between $3–10 billion each, had clear scientific cases: to simply do better science. Not once in ESA’s list of Gaia science objectives is dark matter or dark energy mentioned. Gaia’s scientific potential is fulfilled not by the promise of new physics discoveries but by improving precision astrometry, uncovering unknown astrophysical objects and testing further the standard cosmological model. JWST is a success if it makes sharper observations and peers further than ever, regardless of whether it discovers new types of exotic phenomena or sees the same objects as before but better. LIGO was not considered a failure for having discovered gravitational-wave signals in agreement with Einstein’s general theory of relativity; nor is the future of gravitational-wave observatories in doubt as a consequence.

Particle physics is pushing the boundaries of our understanding in the other direction—looking inwards rather than outwards. The discovery of the Higgs boson, like that of gravitational waves, opens an entirely new window for probing our universe. Its agreement with the SM until now does nothing to diminish the need for future Higgs observatories. New particle processes are continually being unfolded, from the long-predicted quantum scattering of light by light to complex interactions involving multiple bosons or fermions, most recently in the spectacular observation of four top quarks by ATLAS and CMS. Moreover, unlike cosmology and astrophysics, particle physics can do much more than observe. It is an experimental sciences in the truest sense: set up the initial conditions, repeat the experiment, then analyse what comes out. The ability to directly manipulate the elementary building blocks of our world both complements and works symbiotically with astrophysical and cosmological observations. We need eyes open on the universe to make progress; blinding one eye will not make the other sharper.

A better name can help
In this spirit, the CERN Future Circular Collider (FCC) is a bold and ambitious proposal for ensuring another thrilling century of particle physics. As a multi-generational project, it would be our era’s cathedral to knowledge and wonder about the universe. However, the FCC cannot always remain a future collider if it ever becomes reality. When it comes to be renamed, the CERN International Particle Physics Observer would be more apt. This better reflects the role of colliders as a general-purpose tool to good science. The International Particle Physics Observer will cost around $10 billion for a high-precision observatory, starting in the 2040s. A high-energy observatory would then follow in the 2070s. Is it worth it? Should we not be more concerned with climate change? Both questions must be put in the context of other areas of government spending and the value of fundamental physics. For example, an Olympic Games funded by a single nation, for a month’s worth of entertainment, costs about $10 billion. The same price tag shared across multiple countries, to uncover fundamental knowledge that stands for all time, is a bargain by comparison. Furthermore, studies have shown that the economic return of investment in CERN outweighs the cost. We get back more than we put in.

The value of the enterprise itself belies the society in myriad indirect ways, which does not place it at odds with practical issues such as climate change. On the contrary, a new generation of particle physics experiments stimulating cutting-edge engineering, technology, computing and data analysis, while fostering international collaboration and inspiring popular culture, creates the right conditions for tackling other problems. Particle physics helps humankind prosper in the long run, and has already played an indispensable role in creating our modern world.

Building an International Particle Observatory is a win-win proposition. It pays for itself, contributes to a better society, improves our understanding of the universe by orders of magnitude, and advances our voyage of exploration into the unknown. We just need to shift our narrative to one that emphasises the tremendous range of fundamental science to be done. A better name can help.
Physicist by day, YouTuber by night

Appearing in robes, alongside pets and sliced into parallel dimensions, Don Lincoln is a well-known face of Fermilab’s outreach. He tells the Courier how he manages to combine physics and outreach, and why more physicists should take up the challenge.

What got you into physics?
I have always been interested in what one might call existential questions: those that were originally theological or philosophical, but are now science, such as “why are things the way they are?” When I was young, for me it was a toss-up: do I go into particle physics or cosmology? At the time, experimental cosmology was less developed, so it made sense to go towards particle physics.

What has been your research focus?
When I was a graduate student in college, I was intrigued by the idea of quantum mechanical spin. I didn’t understand spin and I still don’t. It’s a perplexing and non-intuitive concept. It turned out the university I went to was working on it. When I got there, however, I ended up doing a fixed-target jet-photoproduction experiment. My thesis experiment was small, but it was a wonderful training ground because I was able to do everything. I built the experiment, wrote the data acquisition and all of the analysis software. Then I got back on track with the big questions, as colliders with the highest energies were the way to go. Back then it was the Tevatron and I joined D0. When the LHC came online it was an opportunity to transition to CMS.

Why and when did you decide to get into communication?
It has to do with my family background. Many physicists come from families where one or both parents are already from the field. But I come from an academically impoverished, blue-collar background, so I had no direct mentors for physics. However, I was able to read popular books from the generation before me, by figures such as Carl Sagan, Isaac Asimov or George Gamow. They guided me into science. I’m essentially paying that back. I feel it’s sort of my duty because I have some skill at it and because I expect that there is some young person in some small town who is in a similar position as I was in, who doesn’t know that they want to be a scientist. And, frankly, I enjoy it. I am also worried about the antiscience sentiment I see in society, from the antivaccine movement to climate-change denial to 5G radiation fears. If scientists do not speak up, the antiscience voices are the only ones that will be heard. And if public policy is based on these irrational fears, the damage to society can be severe.

How did you start doing YouTube videos?
I had got to a point in my career where I was fairly established, and I could credibly think of other things. When you’re young, you are urged to focus entirely on research, because if you don’t, it could harm your research career. I had already been writing for Fermilab Today and I kept suggesting doing videos, as YouTube was becoming a thing. After a couple of years one of thevideographers said, “You know, Don, you’re actually pretty good at explaining this stuff. We should do a video.” My first video came out a year before the Higgs discovery, in July 2011. It was on the Higgs boson. When the video came out, a few of the bigger science outlets picked it up and during the build-up to the Higgs excitement it got more and more views. By now it has more than three million clicks, which for a science channel is a lot. We do serious science in our videos, but there is also some light-heartedness in them.

Do you try to make the videos funny?
This has more to do with me not taking anything seriously. I have found that irreverent humour can be disarming. People like to be entertained when they are learning. For example, one video was about “What was the real origin of mass?” Most people think that the Higgs boson is giving mass, but it’s really QCD. It’s the energy stored inside nucleons. In any event, in this video I start out with a joke about going into a Catholic church. The Higgs boson tries to say “I’m losing my faith,” and the priest replies: “You can’t leave the church. Without you how can we have mass?” For a lot of YouTube channels, viewership is not just about the material. It’s about the viewer liking the presenter. I’d say people who like our channel
**OPINION INTERVIEW**

appreciate the combination of reliable science facts, but also subscribe for the humour. If a viewer doesn’t like a guy who does terrible dad jokes, they just go to another channel.

During the Covid-19 pandemic your videos switched to “Subatomic stories.” How do they differ?

Most of my videos are done in a studio on green screen so that we can put visuals in the background, but that was not possible during the lockdown. We then did a set up in my living room. I had an old DSLR camera and a recorder, and would record the video and the audio, then send the files to my videographer, Ian Krass, who does all the magic. Our usual videos don’t have a real story arc, they are just a series of topics. With “Subatomic stories” we began to film in my basement in a green-screen studio I built. We’ve returned to the Fermilab studio, but the basement one is waiting should the need arise.

You are quite the public face of Fermilab. How does this relationship work?

It’s working wonderfully! I have no complaints. I can’t say that was always true in the past, because when you’re young, you’re advised to focus on your research, it was like that for me. But the time there was some hostility towards science communicators. If you did outreach, you weren’t really considered a serious scientist, and that’s still true to a degree, although it is getting better. For me, it got to the point where people were just used to me doing it, and they thought I was doing it professionally but also in his personal life. Stories include those by Halstein Hagen, a fellow in the CERN theory department, who describes the determination and perseverance he had in mountainieng. S Lokanathan worked with Jack as a graduate student in the early years in Berkeley, and remained in contact with him, including later on when he became a professor in Jaipur. Jacques Lebrun covers the ALEPH period, and Vera Lauth the earlier kaon experiments at CERN. Italo Spiezia has a fascinating function at the University of Cergy-Pontoise. And a good science story can rekindle anyone’s sense of child-like wonder.

**OPINION REVIEWS**

A tribute to a great physicist

Memorial Volume for Jack Steinberger

Edited by Julia Steinberger, Weimin Wu and KK Phua

World Scientific

This book was written on the occasion of the 50th anniversary of the birth of Jack Steinberger. Edited by Jack’s daughter, Julia Steinberger and his former colleague, Weimin Wu and KK Phua, it is a tribute to the important role that Jack played in particle physics at CERN and elsewhere, and also highlights many aspects of his life outside physics.

The book begins with a nice introduction by his granddaughter, herself a well-known scientist. She describes Jack’s family life, his hobbies, interests and passions, and engagement, such as with the Pugwash conference series. The introduction is followed by a number of short essays by former friends and colleagues. The first is a transcript of an interview with Jack by Swapan Chatterpady in 2007. It contains recollections of Jack’s time at Fermilab, with his PhD supervisor Enrico Fermi, and concludes with his connections with Germany later in life.

Drive and leadership

The next essays highlight the essential impact that Jack had in all the experiments he participated in, mostly as spokesperson, and underline his original ideas, drive and leadership, not just professionally but also in his personal life. Stories include those by Halstein Hagen, a fellow in the CERN theory department, who describes the determination and perseverance he had in mountainieng. S Lokanathan worked with Jack as a graduate student in the early years in Berkeley, and remained in contact with him, including later on when he became a professor in Jaipur. Jacques Lebrun covers the ALEPH period, and Vera Lauth the earlier kaon experiments at CERN. Italo Spiezia has a fascinating function at the University of Cergy-Pontoise. And a good science story can rekindle anyone’s sense of child-like wonder.

Interview by Sanje Fenkart.
Quantum Mechanics: 
A Mathematical Introduction

By Andrew Larkoski
Cambridge University Press

Andrew Larkoski seems to be an author with the ability to write something interesting about topics for which a lot has already been written. His previous book, Elementary Particle Physics (2020, CUP), was noted for its very intuitive style of presentation, which is not easy to find in other particle-physics textbooks (CERN Courier July/August 2021 p55). With his new book on quantum mechanics, the author continues in this manner. It is a textbook for advanced undergraduate students covering most of the subjects that an introduction to the topic usually includes.

Despite the subtitle “a mathematical introduction”, there is no more maths than in any other textbook at this level. The book is concise in length, which means that the author has had to carefully choose the areas that are beyond the standard quantum-mechanics material covered in most undergraduate courses. Larkoski’s choices are probably informed by his background in quantum field theory, so path integral formalism features strongly. Perhaps the price for keeping the book short is that there are topics, such as identical particles or Fermi’s golden rule, that are not covered.

Some readers will find the book’s style of delaying a mathematical introduction unnecessary and may prefer a more direct approach to the topic, which might also be related to the duration of the teaching period at university. I would not agree with such an assessment. Taking the time to build a basis early on helps tremendously with understanding quantum mechanics later on in a course – an approach that it is hoped will find its way to more classrooms in the near future.

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Nicholas Rompotis
University of Liverpool

A soft spot for heavy metal

Welding engineer Audrey Vichard describes the rewards of building high-quality, lasting components for experiments at CERN and beyond.

Welding is the technique of fusing two materials, often metals, by heating them in multiple points, creating a seamless union. Mastery of the materials involved, meticulous caution and remarkable steadiness are integral elements to a proficient welder’s skillset. The ability to adjust to various situations, such as mechanised or manual welding, is also essential. Audrey Vichard’s role as a welding engineer in CERN’s mechanical and materials engineering group (MME) encompasses comprehensive technical guidance in the realm of welding. She evaluates methodologies, improves the welding process, develops innovative solutions, and ensures compliance with global standards and procedures. This amalgamation of tasks allows for the effective execution of complex projects for CERN’s accelerators and experiments. “It is kind of art,” says Audrey. “Years of training are required to achieve high-quality welds.”

Audrey is one of the newest additions to the MME group, which supplies specific engineering solutions combining mechanical design, fabrication and material sciences for accelerator components and physics detectors to the CERN community. She joined the forming and welding section as a fellow in January 2023, having previously studied metallurgy in the engineering school at Polytech Nantes in France. “While in school, I did an internship in Toulon, where they build submarine for the army. I was in a group with a welder, who passed on his passion for welding to me – especially when applied in demanding applications.”

Extreme conditions

What sets welding at CERN apart are the variety of materials used and the environments the finished parts have to withstand. Radioactivity, high pressure in ultra-high vacuum and cryogenic temperatures are all factors to which the materials are exposed. Stainless steel is the most frequently used material, says Audrey, but rarer ones like niobium also come into play. “You don’t really find niobium for welding outside CERN – it is very specific, so it’s interesting and challenging to study niobium welds. To keep the purity of this material in particular, we have to apply a special vacuum welding process using an electron beam.” The same is true for titanium, which is a material of choice for its low density and high mechanical properties. It is currently under study for the next-generation HL-LHC beam dump. Whether it’s steel, titanium, copper, niobium or aluminium, each material has a unique metallurgical behavior that will greatly influence the welding process. To meet the exacting conditions over the lifetime of the components, the welding parameters are developed consequently, and rigorous control of the quality and traceability are essential.

“Although it is the job of the physicist at CERN to come up with the innovative machines they need to push knowledge further, it is an interesting exchange to learn from each other, butting heads between ideal objects and industrial realities,” explains Audrey. “It is a matter of adaptation. The physicists come here and explain what they need and then we see if it’s feasible with our machines. First, we can adapt the design of material, and the physicists are usually quite open to the change.”

“Touring the main CERN workshop – which was one of CERN’s first buildings and has been in service since 1957 – Audrey is one of the few women present. “We are a handful of women graduating as International Welding Engineers (IWE). I am proud to be part of the greater scientific community and to promote my job in this domain, historically dominated by men.”

In the main workshop at CERN, Audrey is along with her colleagues, a member of the welding experts’ team. “My daily task is to support welding activities for current fabrication projects at CERN-wide. On a typical day, I can go from performance visual inspections of welds in the workshop to overseeing the welding quality, advising the CERN community according to the most recent standards, participating in large R&D projects and, as a welding expert, advising the CERN community in areas such as the framework of the pressure equipment directive.”

Together with colleagues from CERN’s vacuum, surfaces and coatings group (TE-VSC), and MME, Audrey is currently working on R&D for the Einstein Telescope – a proposal for a new generation gravitational-wave observatory in Europe. It is a new collaboration between CERN, Nikhef and the INFN to design the telescope’s colossal vacuum system – the largest ever attempted (see p58). To undertake this task, the collaboration is initially investigating different materials to find the best candidate combining ultra-high vacuum compatibility, weldability and cost efficiency. So far, a fully prototyped beam pipe has been finished using stainless steel and another in production with common steel, the third is yet to be done. The next step will then be to go from the current 3 m-long prototype to a 5 m version, which will take about a year and a half. Audrey’s task is to work with the welders to optimise the welding parameters and ultimately provide a robust industrial solution to manufacture this giant vacuum chamber. “The design is unusual, it has not been used in any industrial application, at least not at this quality. I am very excited to work on the Einstein Telescope. Gravitational waves have always interested me, and it is great to be part of the next big experiment at such an early stage.”

Sanje Fenkart editorial assistant.

Metallising expert Audrey Vichard next to a prototype vacuum tube for the Einstein Telescope.

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People & careers

Appointments and awards

Change of director at BNL

Theorist JoAnne Hewett has been appointed director of Brookhaven National Laboratory (BNL), succeeding Doon Gibbs, who led BNL for nearly a decade. A longstanding professor of particle and astrophysics at SLAC/Stanford, she will also hold the title of professor at Stony Brook University. In 1994, Hewett joined the SLAC faculty as the first female member and has taken many leadership roles, including head of the theoretical physics group. As BNL’s first female director, she will oversee more than 2800 personnel working on accelerators, particle and nuclear physics, as the lab prepares for the construction of the Electron-IonCollider as well as the Science and User Support Center. “I can’t think of a better time to join such a vibrant laboratory, given all of the exciting projects ahead...that will help define the lab’s future.”

Lockyer leads CLASSE

On 1 May Nigel Lockyer became director of the Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE). He previously served as director of the TRIUMF laboratory from 2007–2013 and of Fermilab from 2013–2022. CLASSE comprises around 300 researchers and more than 30 graduate students, many of whom work on the CMS experiment at the LHC. Lockyer, whose research background includes heavy-quark physics and accelerator science, said: “Cornell has an esteemed tradition of accelerator-based research collaborators to continue working with CLASSE faculty, staff, students and CLASSE’s research collaborators to continue this tradition.”

2023 EPS-HEPP prizes

The European Physical Society (EPS) has awarded this year’s High-Energy and Particle Physics (HEPP) Prize to Cecilia Jafelde (below; Lund University) “for the discovery of an invariant measure of Q violation in both quark and lepton sectors” and to the members of the Daya Bay and RENO collaborations “for the observation of short-baseine reactor electron–antineutrino disappearance, providing the first determination of the neutrino mixing angle θ13.” The 2023 EPS–HEPP Outreach Prize for a combination of science communication activities, most notably for the “Science & Cocktails” event series. All prizes will be awarded during the EPS Conference on High Energy Physics in Hamburg from 21–25 August.

2023 Gruber Cosmology Prize

Richard Ellis (University College London) has been awarded the 2023 Gruber Cosmology Prize for his numerous contributions in the fields of galaxy evolution, the onset of cosmic dawn and reionisation in the high-redshift universe, and the detection of the earliest galaxies via the Hubble ultra deep-field study. The prize comes with an award of $500,000 and will be presented by the Gruber Foundation in July 2023 during “Shedding New Light on the First Billion Years of the Universe” conference in Marseille, France.

Rising talent at ISOLDE

Kara Lynch (CERN–ISOLDE/Roskilde University, Denmark) has been granted a 2023 Rising Talents award from the L’Oréal–UNESCO Woman in Science UK & Ireland programme, which aims to support women in engineering, physical sciences, life sciences, mathematics, computer sciences and sustainable development with grants. Lynch, currently a postdoc at the University of Manchester in the nuclear physics group, did her PhD jointly with CERN’s doctoral programme in 2013, where she worked with the new CRIS technology department.

Guido Altarelli Award 2023

The Guido Altarelli Award, named after the late CERN theorist who made seminal contributions to QCD, recognises exceptional achievements from young scientists in the field of deep inelastic scattering and related subjects. The eighth edition of the prize, presented on 27 March during the DIS2023 workshop hosted by Michigan State University, recognised CMS experimentalist Adilina de Wit (University of Zurich, above right) for her achievements in understanding the nature of the Higgs boson and theorist Yong Zhan (Argonne National Laboratory, above left) for fundamental contributions to ab initio calculations of parton distributions in lattice QCD.

Spanish King honours TE head

On 22 March CERN technology department head José Miguel Jiménez Carvajal received the Orden de Isabel la Católica from Spain’s minister for foreign affairs in the name of His Majesty The King of Spain Felipe VI. The award is given for extraordinary achievements of a civil nature that benefit the Spanish nation or favour relations and cooperation with the rest of the international community. After obtaining his PhD from CEA, Paris–Saclay and the University of Clermont–Ferrand, Jiménez Carvajal spent a short career in technology transfer and then went to work on LEP at CERN in 1994. In 2002 he was appointed section head of the vacuum group and in 2008 he was promoted to head of vacuum, surfaces and coating. Since 2014, he has led the CERN technology department.

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The future is in laser technologies

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In our team we therefore have the following positions available:

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- Laser Physicist
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- Opto-mechanics
- X-ray Scientist
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- Safety Engineer
- Optical Engineer
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Do you have a desire to work in a unique international environment communicating the latest progress in particle physics?

You will join the International Relations Sector (IRS), Education, Communications and Outreach Group (ECO) that is responsible for generating public engagement with CERN’s activities and with fundamental research, fostering community-building and raising awareness of CERN’s societal impact. The group is composed of professionals covering all its activities: writers, media officers, graphic and web designers, social media specialists, education specialists, exhibition developers, photographers and video editors, as well as event organizers.

CERN Courier is the international magazine for high-energy physics, established in 1959, with an estimated 100,000 readers of its print and online versions worldwide. Published six times per year, the magazine also has a regularly updated website, social media channels, webinars and supplementary “In focus” editions.

Reporting to the editor-in-chief, the successful candidate will be expected to take on significant editorial responsibility and to play a leading role in developing the title’s print and online presence.

Functions

As an editor of the Courier, you will:

- Work closely with the editor-in-chief to produce the CERN Courier and develop its strategic direction;
- Liaise with the CERN and global high-energy physics communities to keep the magazine at the forefront of experimental and theoretical particle physics, astroparticle physics, cosmology and gravitational-wave research;
- Commission and edit expert-authored feature articles;
- Write news, features and other articles;
- Carry out picture research, fact check, proofread;
- Carry out picture research, fact check, proofread;
- Manage @CERNcourier social media accounts;
- Work daily and remotely with the Courier’s publishing partner;
- Contribute to projects and work with teams across the CERN-IR-ECO group;
- Supervise and mentor junior members of the team.

Qualifications

Master’s degree or PhD or equivalent relevant experience in the field of particle physics or a closely related subject.

Experience

Essential:

- Research in particle physics or a closely related subject;
- Proven experience in an editorial/communications role;
- Experience in managing multiple tasks and meeting strict deadlines.

Desirable:

- Proven editorial experience on a science magazine;
- Experience of managing social media channels;
- Graphic design & web development skills.

Technical competencies

- Strategic communications planning;
- Stakeholder relationship management;
- Training needs analysis;
- Internal communications;
- Social media

Behavioural competencies

- Demonstrating Accountability: taking responsibility for own actions and decisions; Working conscientiously and reliably, delivering on promises;
- Managing Self: working well autonomously; taking on activities and tasks without prompting; Maintaining a positive outlook even in difficult situations; demonstrating resilience and persistence in response to setbacks and adversity; Taking initiative beyond regular tasks and making things happen;
- Achieving Results: following through on new ideas and innovations; planning and implementing application; Having a structured and organised approach towards work; being able to set priorities and plan tasks with results in mind;
- Communicating Effectively: successfully changing other people’s opinions by persuasive arguments; Utilising effective negotiation techniques to achieve long-term results acceptable to all parties involved;
- Solving Problems: recognizing what is essential; discriminating between important and peripheral information and being able to see the whole picture; Seeking and integrating other points of view when tackling an issue; consulting experts in the field and undertaking benchmarking.

Language skills

Exceptional written and spoken English; ability to understand and speak French or a willingness to acquire such skills quickly.

Eligibility and closing date

Diversity has been an integral part of CERN’s mission since its foundation and is an established value of the Organization. Employing a diverse workforce is central to our success. We welcome applications from all Member States and Associate Member States.

This vacancy will be filled as soon as possible, and applications should normally reach us no later than 02.08.2023.

Employment Conditions

Contract type: Limited duration contract (5 years). Subject to certain conditions, holders of limited-duration contracts may apply for an indefinite position.

Job grade: 6–7

Job reference: IR-ECO CE-2023-85-LD

How to apply

Instructions can be found under the relevant job reference on CERN’s careers pages, https://careers.cern.alljobs.
Giorgio Brianti 1930–2023

Steering CERN to success

Giorgio Brianti, a pillar of CERN throughout his 46-year career, passed away on 6 April. He played a major role in the success of LEP and other projects, and his legacy lives on across the whole of the accelerator complex.

Giorgio began his engineering studies at the University of Parma and continued them for three years in Bologna, where he obtained his laurea degree in 1954. Driven by a taste for research, he learned, thanks to his thesis advisor, that Edvardo Amaldi was setting up an international organisation in Geneva called CERN, and was invited to meet him in Rome in June 1954. In his autobiography—written for his family and friends—Giorgio describes this meeting as follows: “Edvardo Amaldi received me very warmly and, after various discussions, he told me: ‘you can go home: you will receive a letter of appointment from Geneva soon.’ I thus had the privilege of participating in one of the most important intellectual adventures in Europe, and perhaps the world, which had just a century has made CERN “the” world laboratory for particle physics.”

Giorgio had boundless ambition for John Adams, who had been recruited by Amaldi earlier, aged just 34. He was assigned to the magnet group and, after participating in the design of the main bending magnets for the Proton Synchrotron, was sent by Amaldi to CERN for three years to supervise the construction of 100 magnets made by the leading Italian company in the sector, Ansaldo. Upon his return, he was entrusted with the control group and in 1964, was appointed head of the synchrotrons division. After only four years he was asked to create a new division: the synchrotron—the rooster—in charge of injecting protons into the PS and significantly increasing its capacity during these years, under his leadership new technologies were developed and the first prototypes of high-field superconducting magnets were created. The construction programme for the LHC was preliminarily approved in 1994, under Director-General Chris Llewellyn Smith. In 1996, one year after Giorgio’s retirement, the final approval was granted. Giorgio continued to work. In particular, in 1999 he agreed to chair the advisory committee of the Proton Linear Machine Study, a working group established within CERN aimed at designing and developing a new synchrotron for medical purposes for the treatment of radio-resistant tumours with carbon ion beams. The first centre was built in Italy, in Pavia, by the Italian Foundation National Centre for Oncological Hadrontherapy. Giorgio was also an active member of the editorial board of the book Technology Meets Research, which celebrated 60 years of interaction at CERN between technology and society.

Giorgio has left us not only an intellectual but also a spiritual legacy. He was a man of great moral rigour, with a strong and contemplative Christian faith, determined to achieve his goals with a mindful and patient process. He was very attached to his family and friends. His intelligence, kindness and generosity shone through his eyes and—despite his reserved character—he touched the lives of everyone he met.

His colleagues and friends

Stanley DeSer 1931–2023

At a tireless apostle of astroparticles

Theoretical physicist Stanley DeSer, a co-inventor of supergravity, passed away in Pasadena, California, on 19 November 2022. Stanley was born in middle-class Jewish parents in Brooklyn, then in Poland. In 1939 the family emigrated first to Palestine and then to France. After the Second World War broke out they fled to the US via Portugal (they were one of the families saved by Aristides de Sousa Mendes), eventually settling in Brooklyn. Stanley graduated Summa Cum Laude from Brooklyn College in 1949, and received his PhD at Harvard in 1957 under the supervision of Julian Schwinger. After postdocs at the Institute for Advanced Study in Princeton, NJ (1953–1955) and the Niels Bohr Institute in Copenhagen (1955–1957), and a lecturership at Harvard University (1957–1958), he joined the faculty of the physics department at Brandeis in 1958, where he remained until he joined the French–Italian European Geographical Observatory, coordinating projects related to the detection of gravitational waves with the LIGO and Virgo interferometers. This was a turning point in Stanley’s scientific career. He was an important member of the scientific community. As Rainer Weiss, who shared the Nobel Prize in Physics for the observation of gravitational waves, related, he played an important role in convincing the National Science Foundation to fund the LIGO gravitational-wave detector. He was a fellow of the National Academy of Sciences (NAS) and the American Academy of Arts and Sciences, a foreign member of the Royal Society and the Turin Academy of Sciences; he was awarded the Daniel Heineman Prize in Mathematical Physics and the Einstein Medal, along with the Cugir, Hofstadter, and Fulbright awards, and held honorary doctorates from Stockholm University and the Chalmers Institute of Technology. In memory with his wisdom and ready wit; emails and talks in which every sentence had a hidden meaning and were packed with allusions and jokes, his delight and skill in acquiring languages; a love of travel, and a deep appreciation for art and literature. Stanley was preceded in death by his wife, the artist Edith DeSer (daughter of Iskra Yosef and his daughter Eva. He leaves behind three daughters – retired linguis Toni DeSer; theatre director Abigai DeSer; and atmospheric sci- entist (and fellow NAS member) Clara DeSer – and four grandchildren, Ursula, Oscar, Louise and Simon.

Albinon Lawrence Brandeis University.

Stanley DeSer 1931–2023

At a tireless apostle of astroparticles

Stanley DeSer, who shaped the field of astroparticle physics in Europe, died on 27 November 2022. He had just become professor emeritus of Université Paris Cité and was preparing his return to the Americas. With the support of the European Commission, he created ASPERA, followed by the Astroparticle Physics European Consortium, which today gathers about 20 European countries. He was also involved in interdisciplin ary research projects, mainly in the field of geosciences. He was co-director of the Laboratory of Earth Physics from 2013 to 2018 and at the forefront of a microwave- er project to be installed on the Moon.

Stavros Katzanavas, who shaped the field of astroparticle physics in Europe, died on 27 November 2022. He had just become professor emeritus of Université Paris Cité and was preparing his return to the Americas. With the support of the European Commission, he created ASPERA, followed by the Astroparticle Physics European Consortium, which today gathers about 20 European countries. He was also involved in interdisciplinary research projects, mainly in the field of geosciences. He was co-director of the Laboratory of Earth Physics from 2013 to 2018 and at the forefront of a microwave-er project to be installed on the Moon.
First stone for DESYUM

On 31 May DESY laid the cornerstone for DESYUM – a new visitor centre comprising a large auditorium, cafeteria, offices and a lively multimedia exhibition. Due to open in May 2025, the energy-efficient, six-storey, €28.7 million facility will also house DESY’s guests’ welcome services, press office and technology-transfer department. A striped façade made from anodised aluminium is inspired by the shape of high precision tracking detectors, while curves and circles in the floorplan and on the roof terrace channel the shapes of DESY’s accelerators. “The DESYUM will be DESY’s shop window to the world,” said Helmut Doetch, chairman of the DESY board of directors (pictured left, with Hamburg science senator Katharina Fugebank, DESY’s administrative director Christian Harringa and architect Matthias Latzke).

Invited speakers at the event included former CERN fellows Kitty C. Liao, who founded Ideabatic Ltd to tackle last-mile vaccine-cold chain services, press office and technology-transfer department. A striped façade made from anodised aluminium is inspired by the shape of high precision tracking detectors, while curves and circles in the floorplan and on the roof terrace channel the shapes of DESY’s accelerators. “The DESYUM will be DESY’s shop window to the world,” said Helmut Doetch, chairman of the DESY board of directors (pictured left, with Hamburg science senator Katharina Fugebank, DESY’s administrative director Christian Harringa and architect Matthias Latzke).

Alumni Network turns six

On 9 June the CERN Alumni Network hosted a special online event to celebrate its sixth anniversary. Created in 2017 to nurture and strengthen the bonds between CERN and its alumni from all categories, including students, users, fellows, associates and staff members, the network now has more than 8800 members worldwide.

Invited speakers at the event included former CERN fellows Kitty C. Liao, who founded Ideabatic Ltd to tackle last-mile vaccine-cold chain services, and Patrick Glauner, now an AI professor. “This event once again highlights how an experience at CERN serves as a transformative experience for many of our alumni and students,” said head of alumni relations Rachel Bray, pictured left, hosting the livestream from the CERN Neutrino Platform.

Media corner

“Tears and champagne. It was wonderful.”

Günter Hasinger, former science senator at ESA, talking to DER Standard (31 May) about the search for dark matter.

“In experiments like this, the whole world works against you.”

Vishvish Sudhir of MIT discussing the Archimedes experiment in Sardinia, a testbed for the Einstein Telescope, which aims to “weigh” vacuum (Scientific American 1 May).

“That’s not a physical particle. I even bet a crate of champagne, unfortunately I lost.”

Sam Ting, 1976 Nobel Prize winner, when discussing the Archimedes experiment in Sardinia, a testbed for the Einstein Telescope, which aims to “weigh” vacuum (Scientific American 1 May).

“Counterintuitive property of these anyons is that they are not really physical, they don’t care what they’re made of...”

Hans-Jörg Döring of quantum-computing firm Quantumurn on its reported creation of a quasiparticle called an anyon (New Scientist 9 May).

“We will increase the precision of the measurements by a factor of 100, and the energy by a factor of 10. We may be able to see the genetic diseases of the Higgs boson.”

CERN’s Patrick Janot compares the physics reach of the Future Circular Collider to microscope (Radio France 4 May).

The largest separation between two entangled trapped-ionic qubits ever achieved, by researchers in Austria, suggests that trapped ions could be used to create quantum networks (Phys. Rev. Lett. 130 050803)
Move your VME board to your desk!

The μ-Crate is a mains-powered desktop device integrating a low-noise cooling vents system. The desktop form factor can be optionally converted into a 19" rack thanks to the included metal brackets.

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