WELCOME

CERN Courier – digital edition

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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EDITOR: MATTHEW CHALMERS, CERN
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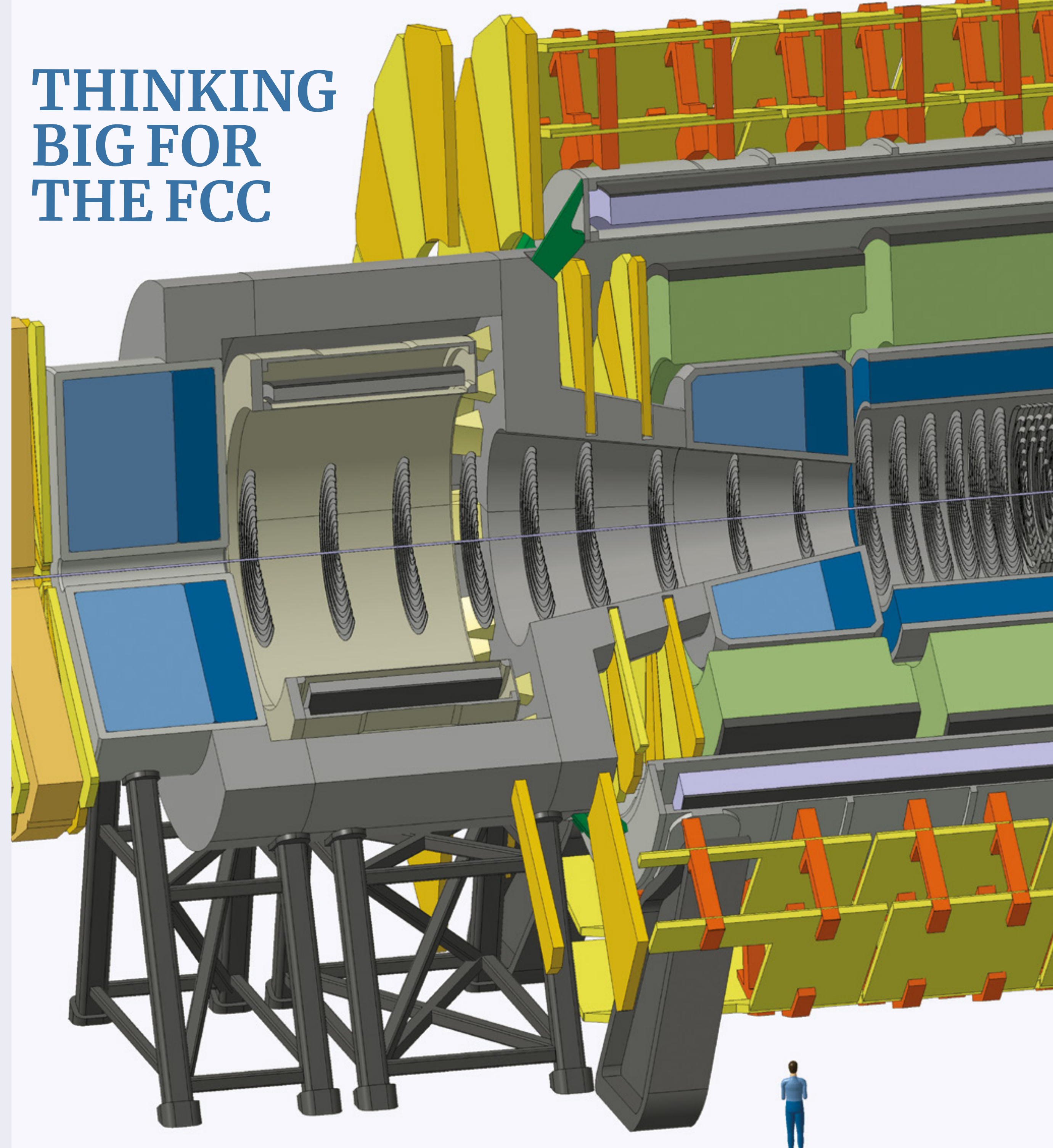
CERNCOURIER
July/August 2023 cerncourier.com Reporting on international high-energy physics

THINKING BIG FOR THE FCC



Five sigma revisited • Neutral currents at 50 • Colliders as observatories

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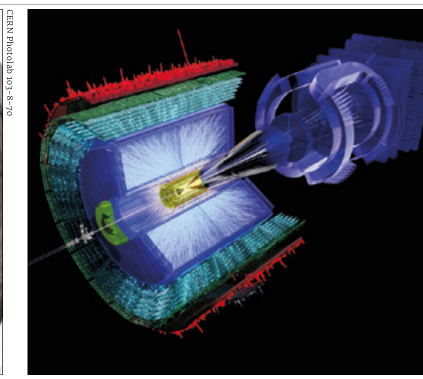
Gargantuan *50 years ago the Gargamelle experiment at CERN discovered neutral currents.* **35**



Striking *The LHC experiments are taking the iconic event display into new territory.* **41**

Fusing skills *Welding engineer Audrey Vichard on working at CERN.* **51**

FROM THE EDITOR

Future Circular Collider picks up the pace

Matthew Chalmers
Editor

The Future 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 projected a strong sense of momentum among the 500 participants.

The FCC is a proposed 91 km-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 conceptual 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 operation, enabling physics exploitation to start in 2045–2048. 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.

One of the challenges with a project as vast and complex as the FCC is to communicate its many evolving facets

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

FCC collab.

Future facing *Almost half of FCC Week participants were under 40.*

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 rebrand colliders as "observatories" in line with other fields of fundamental exploration (p45).

This issue also marks 50 years since the discovery of neutral currents at CERN (p35), asks whether the 5σ 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 (p7), LHCb sets record precision on CP-violation (p8), CERN shares its expertise for gravitational-wave observatories (p18), careers (p51), news digest (p13), and much more inside.

Reporting on international high-energy physics

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CERN
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Editor Matthew Chalmers
Associate editor Kristiane Bernhard-Novotny
Editorial assistant Sanje Fenkart
Astrowatch contributor Merlin Kole
Archive contributor Peggie Rimmer

E-mail cern.courier@cern.ch

Advisory board Gianluigi Arduini, Philippe Bloch, Roger Forty, Peter Jenni, Joachim Kopp, Christine Sutton

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
DESY Laboratory Till Mundzeck
Fermilab Kurt Riesselmann
Forschungszentrum Jülich Markus Buescher
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UK STFC Stephanie Hills
SLAC National Accelerator Laboratory Melinda Lee
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

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Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Curtis Zimmermann
Recruitment sales Chris Thomas

Advertisement production Katie Graham
Marketing and circulation Laura Gillham, Alison Gardiner

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

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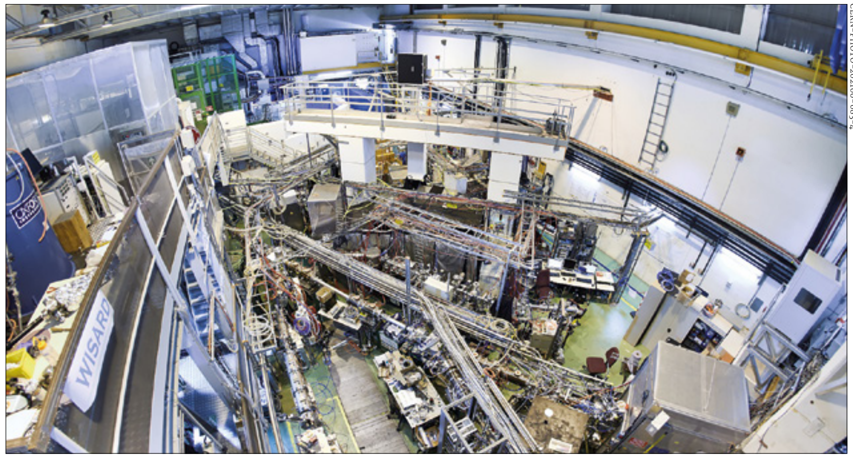
NEWS ANALYSIS

ISOLDE

Counting half-lives to a nuclear clock

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 outperform 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.



On time *The view from above the ISOLDE facility, showing the different beamlines leading to the experiments.*

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 1×10^{-18}, 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 ultralight dark matter (*CERN Courier* September/October 2022 p32).

Higher precision

In 2003 Ekkehard Peik and Christian Tamm 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 ^{229m}Th 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 ^{229m}Th to its ground state. This allows, among other things, the isomer's energy to be determined to higher precision.

> Our study marks a crucial step in the development of lasers that would make such a clock tick

In 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 ^{229}Fr → ^{229}Ra → ^{229}Ac → ^{229}Th/^{229m}Th. A fraction of ^{229}Ac decays to the metastable, excited state of ^{229}Th, the isomer ^{229m}Th. To achieve this, the team incorporated the produced ^{229}Ac into six separate crystals of calcium flouride and magnesium flouride 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 8.338 ± 0.024 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 (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 Duppen 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

S Kraemer *et al.* 2023 *Nature* **617** 706.

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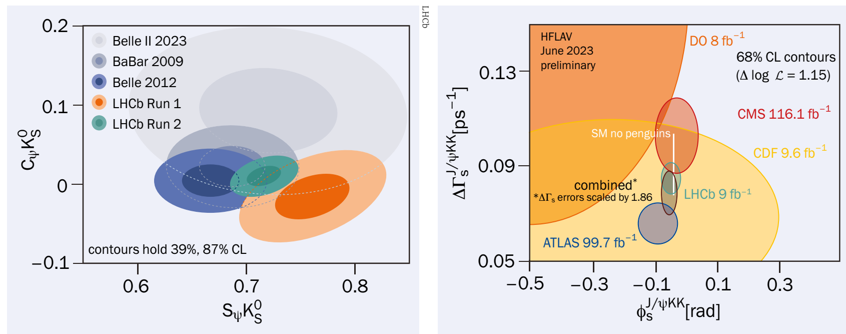
CP VIOLATION

LHCb sets record precision on CP violation

At a CERN seminar on 13 June, the LHCb collaboration presented the world's most precise measurements of two key parameters relating to CP violation. Based on the full LHCb dataset collected during LHC Runs 1 and 2, the first concerns the observable sin2β while the second concerns the CP-violating phase ϕ_s – both of which are highly sensitive to potential new-physics contributions.

CP violation was first observed in 1964 in kaon mixing, and confirmed among B mesons in 2001 by the e^+e^- B-factory experiments BaBar and Belle. The latter enabled the first measurements of sin2β and were a vital confirmation of the Standard Model (SM). In the SM, CP violation arises due to a complex phase in the Cabibbo–Kobayashi–Maskawa mixing matrix, which, being unitary, defines a triangle in the complex plane: one side 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 sin2β, which determines the angle β in the unitarity triangle, is more difficult at a hadron collider than it is at 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 B^0 mesons to $J/\psi K^0_S$, which can proceed either directly or by first oscillating into their antimatter partners. The interference between the amplitudes for the two decay paths results in a time-dependent asymmetry between the decay-time distributions



Spot on *Comparison of sin2β (left, plotted in terms of the amplitudes S and C) and ϕ_s (right) measurements from different experiments, showing the improvements from LHCb's latest results (green).*

of the B^0 and $\overline{B^0}$. The amplitude of the oscillation, and thus the magnitude of CP violation present, is a measurement of sin2β for which LHCb finds a value of 0.716 ± 0.013 ± 0.008, in agreement with predictions.

Based on an analysis of $B^0_s \to J/\psi K^+K^-$ decays, LHCb also presented the world's best measurement of the CP-violating phase ϕ_s, which plays a similar role in B^0_s meson decays as sin2β does in B^0 decays. As for B^0 mesons, a B^0_s may decay directly or oscillate into a $\overline{B^0_s}$ and then decay. CP violation causes these decays to proceed at slightly different rates, manifesting itself as a non-zero value of ϕ_s due to the interference between mixing and decay. The predicted value of ϕ_s is about −0.037 rad, but new-physics effects, even if also small, could change its value significantly.

A detailed study of the angular distribution of B^0_s decay products using the Run 1 and 2 data samples enabled LHCb to measure this decay-time-dependent CP asymmetry ϕ_s = −0.039 ± 0.022 ± 0.006 rad. Representing the most precise single measurement to date, it is consistent with previous measurements and with the SM expectation. The precision measurement of ϕ_s is one of LHCb's most important goals, said co-presenter Vukan Jevtic (TU Dortmund): "Together with sin2β, the new LHCb result marks an important advance in the quest to understand the nature and origin of CP violation."

With both results currently limited by statistics, the collaboration is looking forward to data from the current and future LHC runs. "In Run 3 LHCb will collect a larger data sample taking advantage of the new upgraded LHCb detector," concluded co-presenter Peilian Li (CERN). "This will allow even higher precision and therefore the possibility to detect, through these key quantities, the manifestation of new-physics effects."

Further reading

LHCb Collab. 2023 LHCb-PAPER-2023-013.
LHCb Collab. 2023 LHCb-PAPER-2023-016.

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 ATLAS and CMS which have confirmed that its couplings are consistent with those predicted by the Standard Model (SM). However, several Higgs-boson decay channels have such small predicted branching fractions that they have not yet been observed. Involving higher order loops, these channels also provide indirect probes of possible 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 at the Large Hadron Collider Physics conference in Belgrade in May.

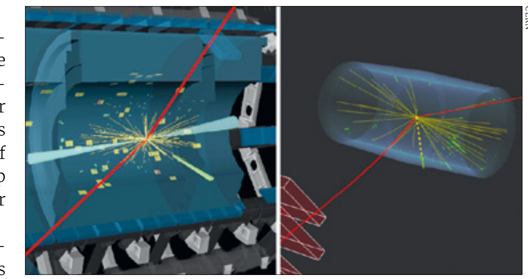
We have made a step forward towards unravelling yet another riddle of the Higgs boson

The SM predicts that approximately 0.15% 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 where the Higgs boson is a neutral scalar of different origin, or a composite state. Different branching fractions are also expected for models with additional colourless charged scalars, leptons or vector bosons that couple to the Higgs boson, due to their contributions via loop corrections.

"Each particle has a special relationship with the Higgs boson, making the search for rare Higgs decays a high priority," says ATLAS physics coordinator Pamela Ferrari. "Through a meticulous combination of the individual results of ATLAS and CMS, we have made a step forward towards unravelling yet another riddle of the Higgs boson."

Previously, ATLAS and CMS independently conducted extensive searches for H → Zγ. Both used the decay of a Z boson into pairs of electrons or muons, which occur in about 6.6% of cases, to identify H → Zγ events. In these searches, the collision events associated with this decay would be identified as a narrow peak over a smooth background of events.

In the new study, ATLAS and CMS 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 decay into a Z boson 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 ± 0.7, in agreement with the theoretical expectation from the SM.



Better together *Candidate events from ATLAS (left) and CMS (right) for a Higgs boson decaying into a Z boson and a photon, with the Z boson decaying into a pair of muons (red).*

"The existence of new particles could have very significant effects on rare Higgs decay modes," says CMS physics coordinator Florencia Canelli. "This study is a powerful test of the Standard Model. With the ongoing third run of the LHC and the future High-Luminosity LHC, we will be able to improve the precision of this test and probe ever rarer Higgs decays."

Further reading

ATLAS Collab. 2023 ATLAS-CONF-2023-025.
CMS Collab. 2023 CMS PAS HIG-23-002.

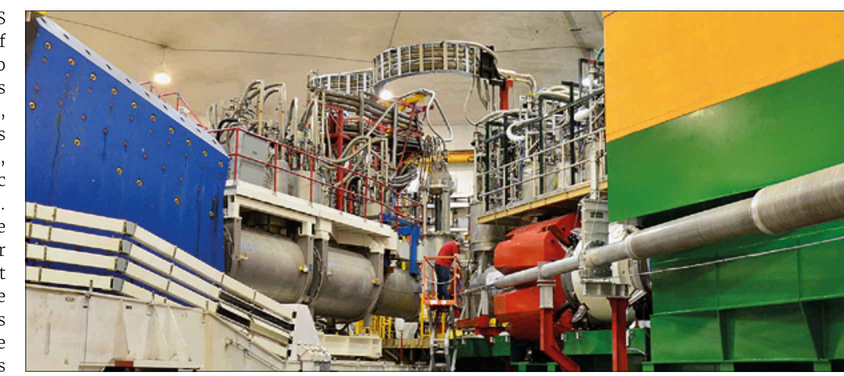
QUANTUM CHROMODYNAMICS

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 making up most of its mass.

Although the charge and spin of the proton have been extensively studied for decades, relatively little is known about its mass distribution. This is because gluons, which despite being massless provide a sizeable contribution to the proton's mass, are neutral and thus cannot be studied directly using electromagnetic probes. The Jefferson team instead used the gluonic gravitational form factors (GFFs). Similar to electromagnetic form factors, which provide information about a hadron's charge and magnetisation distributions, the GFFs (technically the matrix elements of the proton's energy–momentum tensor) encode the mechanical properties of the proton such as its mass, density, pressure and shear distributions.

To access the GFFs, the team measured the threshold cross section of exclusive J/ψ photoproduction at different energies by forcing photons with energies between 9.1 and 10.6 GeV to interact with a liquid- hydrogen target. Gluons dominate the production of J/ψ at small momentum transfer since J/ψ mesons do not share any valence quarks with the proton. Due to the J/ψ's vector quantum numbers, this process can occur at certain energies by gluons in scalar (dilaton-like) and tensor (graviton-like) states. The researchers fed their cross-section results into QCD models describing the gluonic GFFs and extracted the parameters defining the GFFs, enabling them to deduce one mass radius and one scalar radius.



New perspective *The JLab spectrometers used to detect the decay products of the elastically photoproduced J/ψ.*

The analysis revealed a scalar proton radius of 1 fm, which is substantially larger than both the charge radius (around 0.85 fm) and the proton mass radius (0.75 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 tensor gluonic field structure, followed by the charge radius resulting from the relativistic motion of quarks, all enveloped in a larger confining scalar gluon density.

"Given that the proton's scalar gluon radius is the largest, we need to understand how this converts to our understanding of the gluonic structure of nuclei. For example, what would the scalar radius of ⁴He be compared to its charge radius?" says study leader Zein-Eddine Meziani of Argonne National Laboratory. The team plans to extend its studies to include the J/ψ muon final-state decay, doubling the statistics of the current measurement, and to extract the gluon pressure distribution. "It is hard to say much right now, but this is a field in its infancy and the direct role of gluons in nuclei is not well understood," adds Meziani. "We need a new generation of high-precision J/ψ experiments to get a better picture."

Further reading

B Duran *et al.* 2023 *Nature* **615** 813.

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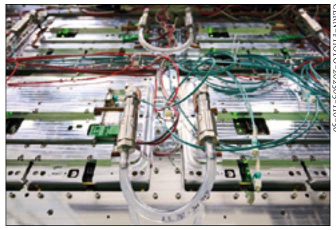
CERN NEUTRINO PLATFORM

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 – a state-of-the-art time projection chamber (TPC) – 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 away. The ND280 detector is one of the near detectors necessary to characterise the beam before the neutrinos oscillate and to measure interaction cross sections, both of which are crucial to reduce systematic uncertainties.



Eastward 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.*

To improve the latter further, the T2K collaboration decided in 2016 to upgrade ND280 with a novel scintillator tracker, two TPCs and a time-of-flight system. This upgrade, in combination with an increase in neutrino beam power from the current 500 kW to 1.3 MW, will increase the statistics by a factor of about four and reduce the systematic uncertainties from 6% to 4%. 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.

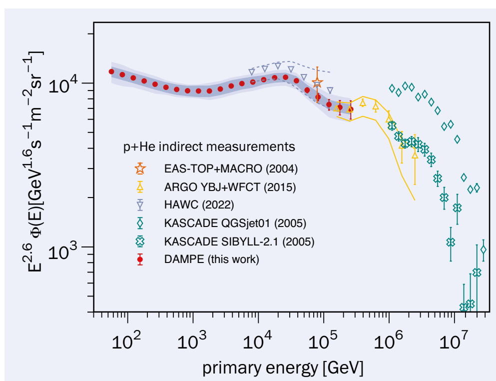
ASTROWATCH

DAMPE confirms cosmic-ray complexity

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.

When identifying the origin of astrophysical photons, one can use their direction. However, for cosmic rays this is not as straightforward due to the impact of galactic and extra-galactic magnetic fields on their direction. To identify the origin of cosmic rays, researchers therefore almost fully rely on information embedded in their energy spectra. When assuming just acceleration within shock regions of extreme astrophysical objects, the galactic cosmic-ray spectrum should follow a simple, single power law with an index between –2.6 and –2.7. However, thanks to measurements by a range of dedicated instruments including AMS, ATIC, CALET, CREAM and HAWC, we know the spectrum to be more complex. Furthermore, different types of cosmic rays, such as protons, and the nuclei of helium or oxygen, have all been shown to exhibit different spectral features with breaks at different energies.

New measurements by the space-based Chinese–European Dark Matter Particle Explorer (DAMPE) provide detailed insights into the various spectral breaks in the combined proton and helium spectra. Clear hints of spectral breaks were already shown previously by various balloon and space-based experiments at low energies (below 1 TeV), and by ground-based air-shower detectors at high energies (> TeV). However, in the region where space-based measurements start to suffer from a lack of statistics, ground-based instruments suffer from a low sensitivity, resulting in relatively large uncertainties. Furthermore, the completely different way in which space- and ground-based instruments measure the energy (directly in the former, and via air-shower reconstruction in the latter) made it important to make measurements that clearly connect the two. DAMPE has now produced detailed spectra in the 46 GeV to 316 TeV energy range, thereby filling most of the gap. The results confirm both a spectral hardening around 100 GeV and a subsequent spectral softening around 10 TeV, which connects well with a second spectral bump previously observed by ARGO-YBJ+WFCT at an energy of several hundred TeV (see figure).



Spectral features *The energy spectrum of the cosmic-ray proton and helium flux as measured by DAMPE (red) compared to various results from ground-based experiments.*

The complex spectral features of high-energy cosmic rays can be explained in various ways. One possibility is through the presence of different types of cosmic-ray sources in our galaxy; one population produces cosmic rays with energies up to PeV, while a second only produces cosmic rays with energies up to tens of TeV, for example. A second possibility is that the spectral features are a result of a nearby single source from which we observe the cosmic rays directly before they become diffused in the galactic magnetic field. Examples of such a nearby source could be the Geminga pulsar, or the young supernova remnant Vela.

In the near future, novel data and analysis methods will likely allow researchers to distinguish between these two theories. One important source of this data is the LHAASO experiment in China, which is currently taking detailed measurements of cosmic rays in the 100 TeV to EeV range. Furthermore, thanks to ever-increasing statistics, the anisotropy of the arrival direction of the cosmic rays will also become a method to compare different models, in particular to identify nearby sources. The important link between direct and indirect measurements presented in this work thereby paves the way to connecting the large amounts of upcoming data to the theories on the origins of cosmic rays.

Further reading

DAMPE Collab. 2023 arXiv:2304.00137.
C Yue *et al.* 2020 *Front. Phys.* **15** 24601.

NEWS DIGEST


CERN

The MACHINA accelerator.

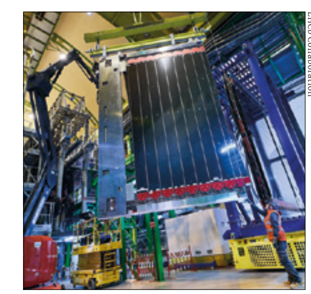
Restoring arts
CERN and INFN have teamed up to build a compact, transportable accelerator for the analysis of artworks. Based on a radio-frequency quadrupole accelerator cavity designed at CERN, the Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis (MACHINA) will make use of ion-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 1 m-long accelerator will eventually be transferred to the Opificio delle Pietre Dure in Florence to become part of their regular diagnostic activities (*Rendiconti Lincei. Scienze Fisiche e Naturali* **34** 427).

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, Xinzhe 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 0.7 GeV. The approach thus exhibits good potential for seamless multistage laser wakefield acceleration, says the team (*Phys. Rev. Lett.* **130** 215001).

AI 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 Terry 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 time 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 world's most sensitive "light shining through walls" experiment – the Any Light Particle Search (ALPS-II) at DESY – began its hunt for axion-like particles on 23 May. Due to achieve full sensitivity in the second half of 2023, the experiment sends a high-intensity laser through a 120 m-long optical resonator enclosed by 12 5.3 T dipole magnets from the former HERA collider. If a photon were to be converted into an axion in the strong magnetic field, the axion could pass through the opaque wall at the end of the line of magnets, whereupon it would enter another magnetic track that could cause it to be converted into a photon. The probability of such a process is very small, says spokesperson Axel Lindner. "Even if we don't find any light particles with ALPS, the experiment will shift the exclusion limits for ultra-light particles by a factor of 1000."

From Point 8 to PANDA
During Long Shutdown 2, many detector systems in the LHC experiments were upgraded or replaced, among them LHCb's $5\times6\,m^2$ straw tube-based outer tracker. Since the detector is still in good shape, the LHCb collaboration agreed to hand it over to another experiment with related physics goals: the Antiproton Anihilation Experiment at Darmstadt (PANDA), under construction at GSI's Facility for Antiproton and Ion Research (FAIR). PANDA will carry out basic research on the weak and strong forces, and explore exotic states of matter such as pentaquarks. Due to be dispatched from CERN in early July, the outer tracker could also be implemented at other FAIR experiments.


LHCb Collaboration

LHCb's former outer tracker.

XFELs on photosynthesis
Studies at the Linac Coherent Light Source (LCLS) at SLAC and the SPring-8 Angstrom Compact free electron laser (SACLA) in Japan have captured for 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
Gravitational 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 HS 0810+2554, a quasar 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 invoking axions, says the team (arXiv:2304.09895).

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Probing for periodic signals

New physics may come at us in unexpected ways that may be completely hidden to 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, not by stabilising the weak scale (as in supersymmetry, for example), 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 testbed for this search due to the excellent energy 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 (like the representation of a free particle 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.

Figure 1 shows how a particularly faint clockwork signal would emerge in ATLAS for the diphoton final state. It is compared with the data and the background-only fit obtained from an earlier (full Run 2) ATLAS search for resonances with the same final state. As an illustration, the signal shape is given without realistic statistical fluctuations. The tiny "bumps" or the shape's integral over the falling 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 2 (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 $m_{\gamma\gamma} = k$ and at low scales (high frequencies).

With realistic statistical fluctuations and uncertainties, these distinct "blobs" may partially wash out, as shown in figure 2 (right). To counteract this effect, the analysis uses multiple background-only and background-plus-signal scalograms to train a binary convolutional neural-network classifier. This network is very powerful in distinguishing between scalograms belonging to the two classes, but it is also model-specific. Therefore, another search for possible periodic signals is performed independently from the clockwork model hypothesis. This is done in an "anomaly detection" mode using an autoencoder neural-network.

Since the autoencoder is trained on multiple background-only scalograms (unlabelled data) to learn the features of the background (unsupervised learning), it can predict the compatibility of a given scalogram with the background-only hypothesis. A statistical test based on the two networks' scores is derived to check the data compatibility with the background-only or the background+signal hypotheses.

Applying these novel procedures to the dielectron and diphoton full Run 2 data, ATLAS sees no significant deviation from the background-only hypothesis in either the clockwork-model search or in the model-independent one. The strongest exclusion contours to date are placed in the clockwork parameter space, pushing the sensitivity to beyond 11 TeV in M_5. Despite the large systematic uncertainties in the background model, these do not exhibit any periodic structure in the mass space and their impact is naturally reduced when transforming to the scalogram space. The sensitivity of this analysis is therefore mostly limited by statistics and is expected to improve with the full Run 3 dataset.

The strongest exclusion contours to date are placed in the clockwork parameter space

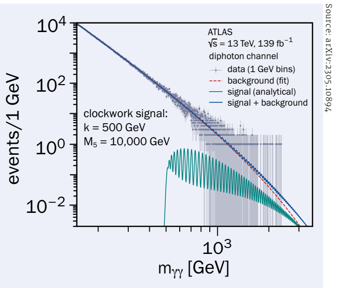


Fig. 1. *The measured diphoton invariant mass distribution (grey), respective background-only fit parametrisation (red), analytical clockwork signal with k = 500 GeV and M_5 = 10,000 GeV, close to the sensitivity limit (green), and the background-plus-signal parametrisation (blue).*

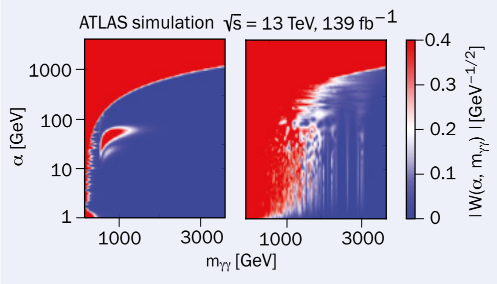


Fig. 2. *The scalograms resulting from the continuous wavelet transformation of the blue line of figure 1 in the scale-versus-mass space without (left) and with (right) realistic fluctuations. The localised blob at low scales (high frequencies) corresponds to the signal contribution, while the solid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

Further reading

ATLAS Collab. 2023 arXiv:2305.10894.
G F Giudice *et al.* 2018 *JHEP* **6** 009.

LHCb

Charm production in proton–lead 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–lead (pPb) collisions. While perturbative QCD describes reasonably well the transverse momentum (p_T) dependence of heavy-quark production in proton–proton (pp) collisions, the situation is different in heavy-ion collisions due to the formation of quark–gluon plasma (QGP), which affects the behaviour of particles traversing the medium. In particular, hadronisation can be affected, modifying the relative abundance of hadrons compared to pp collisions. Several models predict an enhanced strange-quark production. Thus an abundance of strange baryons is seen as a signature of QGP formation.

The role that QGP may play in pPb collisions is currently unclear. Some models predict the formation of "QGP droplets", which could partially induce the same behaviour, albeit less pronounced, as in PbPb collisions. In addition, in pPb interactions, "cold nuclear matter" (CNM) effects are also present that can mimic the behaviour caused by QGP but via different mechanisms. For all these reasons, a strangeness enhancement in pPb collisions would strongly indicate the formation of a deconfined medium in small systems, providing crucial information about QGP properties and formation once the CNM effects are under control.

The LHCb collaboration recently analysed pPb data for QGP effects with the twofold purpose of searching for strangeness enhancement and providing a precise understanding of the CNM effects. This search was performed by measuring the production ratio of the strange baryon Ξ_c^+, which has never been observed in pPb collisions before, to the strangeless baryon Λ_c^+. Using an earlier pPb sample, LHCb has also studied the ratios of the D_s^+, D^+ and D^0, the first being measured for the first time down to zero p_T in the forward region, precisely addressing CNM effects. All measurements are performed differentially in p_T and the rapidity of the produced particle, and compared to the latest theory predictions. The Ξ_c^+ cross section has been measured for the first time in pPb collisions, giving strong indications on the factorisation scale μ_0 of the theory model. This result allows to set the absolute scale of the theoretical computations in terms of strangeness production, a trend confirmed with even higher precision by comparing the measurement to the Λ_c^+ production-cross section evaluated in the same decay mode. Moreover, the ratio is roughly constant as a function of p_T and behaves in the same way at positive (pPb) and negative (Pbp) rapidities (see figure 1). The measurement is consistent with models incorporating initial-state effects due to gluon-shadowing in nuclei, suggesting that QGP formation and the resulting strangeness enhancement have little or no effect on Ξ_c^+ production in pPb collisions.

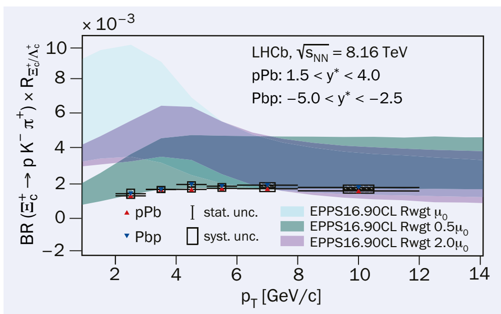


Fig. 1. *Production ratio of prompt Ξ_c^+ to Λ_c^+ baryons times the branching ratio for $\Xi_c^+ \to pK^-\pi^+$.*

This interpretation is confirmed by the measurement of the D_s^+, D^+ and D^0 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 CNM effects and provides detailed constraints on models of nuclear parton distribution functions and hadron production in a very wide range of Bjorken-x (10^{-2} – 10^{-5}). A strong suppression is observed for the D mesons, giving insight into the nature of the CNM effects involved. An explanation via additional final-state effects is challenged by the Ξ_c^+ data that are well described by models not including them. The production ratios of Ξ_c^+, D_s^+, D^+ and D^0 measured as a function of p_T in pPb collisions confirm these findings. All these studies will profit from the increased statistics in pPb collisions that are expected from future LHC runs.

Further reading

LHCb Collab. 2023 arXiv: 2305.06711.
LHCb Collab. 2023 LHCb-PAPER-2023-006.

CMS

A novel search for inelastic dark matter

As dark matter (DM) search experiments increasingly constrain minimal models, more complex ones have gained importance, featuring a rich "dark sector" with additional particle states and often involving forces that cannot be directly felt by Standard Model (SM) particles. Nevertheless, the SM and dark sector are typically connected by a "portal" that can be experimentally probed.

The CMS collaboration recently presented the first dedicated collider search for inelastic dark matter (IDM) using the LHC Run 2 dataset. In IDM models, a small Majorana mass component is combined with a Dirac fermion field corresponding to the DM and added to the SM Lagrangian, resulting in two new DM mass eigenstates with a predominantly off-diagonal (inelastic) coupling and a small mass splitting. In addition, a dark photon (a gauge boson similar to the ordinary photon) serves as the portal to the SM. This means that at the LHC, the lighter (χ_1) and heavier (χ_2) DM states are simultaneously produced via a dark photon (A′). While the lighter state is stable and escapes the detector, the heavier one can travel a macroscopic distance before decaying to the lighter one and a pair of muons, which are produced away from the collision point.

This process can be probed by exploiting a striking signature: a pair of almost collinear, low-momentum and displaced muons from the χ_2 decay; significant missing transverse momentum (MET) from the χ_1; and an initial-state radiation jet that can be used for trigger purposes. The MET–dimuon system recoils against the high-momentum jet, so that the muons and MET are also almost collinear. This unique topology presents challenges, including the reconstruction of the displaced muons. This problem was addressed by using a dedicated reconstruction algorithm, which remains efficient even for muons produced several metres away from the collision point (figure 1, left).

The first dedicated collider search for IDM using the full dataset collected during LHC Run 2

After applying event-selection criteria targeting the expected IDM signal, the number of events is compared to the data-driven background prediction: no excess is observed. Upper limits are set on the product of the $pp \to A' \to \chi_2\chi_1$ production cross-section and the branching fraction of the $\chi_2 \to \chi_1\mu^+\mu^-$ decay; they are shown in figure 1 (right) for a scenario with 10% mass splitting between the χ_1 and χ_2 states. The y variable is roughly proportional to the interaction strength between the SM and the DM sector. Values of $y > 10^{-7}$ to 10^{-9} are excluded for masses between 3 and 80 GeV, when assuming that the fine structure constant has the same value in the dark sector and in the SM.

CMS physicists are looking forward to probing more complex and well-motivated DM models with novel and creative uses of the existing detector.

Further reading

CMS Collab. 2023 arXiv:2305.11649.

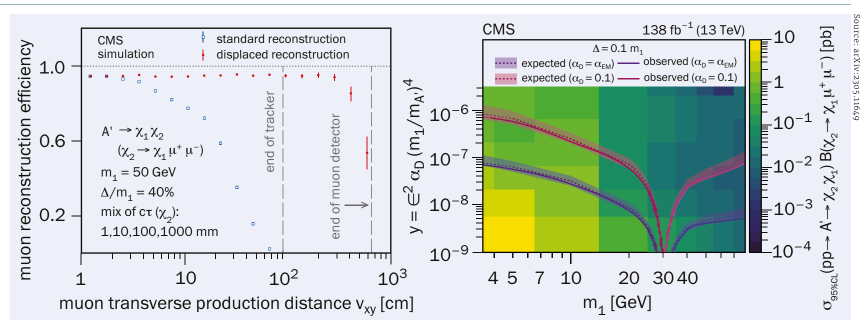


Fig. 1. *Left: the efficiency of the displaced muon reconstruction algorithm (red) remains high for large displacements from the collision point, so that dimuons can be identified, even if produced outside the tracker volume. Right: two-dimensional observed limits on the product of IDM production cross-section and χ_2 decay branching fraction as a function of the χ_1 mass and y, for a 10% mass splitting scenario and $m_{A'} = 3m_1$. The solid (dashed) lines denote the observed (expected) exclusion regions at 95% CL, with 68% uncertainty bands. Regions above the line are excluded depending on the choice of fine-structure constant in the dark sector (α_D).*

ALICE

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 thermalised system of quarks and gluons. The study of proton–proton (pp) and proton–nucleus (pA) collisions provides the baseline for the interpretation of results from heavy-ion collisions. The study of pA 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 multiplicity) and their distribution in pseudorapidity (η), provide key information about particle-production mechanisms in these collisions. The total multiplicity is mostly determined by soft interactions, i.e. processes with small momentum transfer, which cannot be calculated using perturbative techniques and are instead modelled using non-perturbative phenomenological descriptions. For example, the distribution of the number of produced particles can be used to disentangle relative contributions to particle production from hard and soft processes using a two-component model.

ALICE has recently completed the measurement of the multiplicity and pseudorapidity density distributions of inclusive photons at forward rapidity, spanning the range $\eta = 2.3$ to 3.9, by using the photon multiplicity detector (PMD) in pp, pPb and Pbp collisions at a centre-of-mass energy of 5.02 TeV per nucleon pair using LHC Run 1 and 2 data. Since photons mostly originate from decays of neutral pions, this result complements existing measurements of charged-particle production. A comparative study of charged particles and inclusive photons can reveal possible similarities and differences in the underlying production mechanisms for charged and neutral particles.

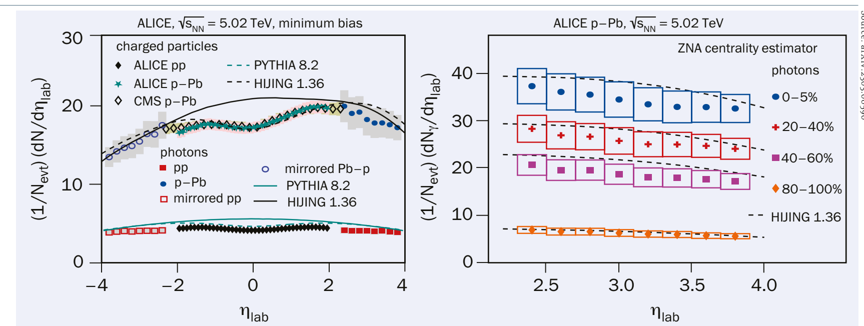


Fig. 1. *The pseudorapidity density distributions of inclusive photons and predictions from Monte Carlo event generators compared with charged-particle measurements at midrapidity in pp, pPb and Pbp collisions (left), and for different multiplicity classes (right).*

The PMD uses the preshower technique, where a three-radiation-length-thick lead converter is sandwiched between two planes comprising an array of 184,320 gas-filled proportional counters. Photons are distinguished from hadrons in the PMD's preshower plane by applying suitable thresholds on the number of detector cells and the energy deposited in reconstructed clusters.

The measured distributions are corrected for instrumental effects using a Bayesian unfolding method. This is the first time that the dependence of the inclusive photon production on the number of nucleons participating in the pPb collision and its scaling behaviour has been studied at the LHC.

Figure 1 (left) compares the pseudorapidity density distribution of inclusive photons in minimum bias pp, pPb and Pbp collisions measured at forward rapidity to that of charged particles at midrapidity. The pseudorapidity distribution of inclusive photons at forward rapidity smoothly matches that of charged particles at midrapidity, indicating that the production mechanisms for charged and neutral pions are similar. Figure 1 (right) shows the pseudorapidity density distribution of inclusive photons in pPb collisions for different multiplicity classes as estimated using the energy deposited in the zero-degree calorimeter (ZNA) at beam rapidity. The multiplicity in the most central collisions reaches values twice as large as those in minimum bias events. The data and model agree within one sigma of the measurement uncertainties.

These results of inclusive photon production in pp, pPb and Pbp collisions provide valuable input for the development of theoretical models and Monte Carlo event generators, and help to establish the baseline measurements for the interpretation of PbPb collision data.

Further reading

ALICE Collab. 2023 arXiv:2303.00590.

FIELD NOTES

Reports from events, conferences and meetings

Beampipes for Gravitational Wave Telescopes 2023

Beampipe know-how for GW observatories

C Hervet

Beam me up *Participants of the March workshop dedicated to vacuum and materials technologies for next-generation gravitational-wave telescopes.*

The direct detection of gravitational waves (GWs) in 2015 opened a new window to the universe, allowing researchers to study the cosmos by merging data from multiple sources. There are currently four gravitational wave telescopes (GWTs) in operation: LIGO at two sites in the US, Virgo in Italy, KAGRA in Japan and GEO600 in Germany. Discussions are ongoing to establish an additional site in India. The detection of GWs is based on Michelson laser interferometry with Fabry–Perot cavities, which reveals the expansion and contraction of space at the level of ten-thousandths of the size of an atomic nucleus, i.e. 10^{-19} m. Despite the extremely low strain that needs to be detected, an average of one GW is measured per week of measurement by studying and minimising all possible noise sources, including seismic vibration and residual gas scattering. The latter is reduced by placing the interferometer in a pipe where ultrahigh vacuum is generated. In the case of Virgo, the vacuum inside the two perpendicular 3 km-long arms of the interferometer is lower than 10^{-9} mbar.

Next generation

While current facilities are being operated and upgraded, the GW community is also focusing on a new generation of GWTs that will provide even better sensitivity. This would be achieved by longer interferometer arms, together with a drastic reduction in noise that might require cryogenic cooling of the mirrors. The two leading studies are the Einstein Telescope (ET) in Europe and the Cosmic Explorer (CE) in the US. The total length of the vacuum vessels envisaged for the ET and CE interferometers is 120 and 160 km, respectively, with a tube diameter of 1 to 1.2 m. The required operational pressures are typical of those needed for modern accelerators (i.e. in the region of 10^{-10} mbar for hydrogen and even lower for other gas species). The next generation of GWTs would therefore represent the largest ultrahigh vacuum systems ever built.

Producing these pressures is not difficult as the current vacuum systems of GWT interferometers have a comparable degree of vacuum. Instead, the challenge is cost. Indeed, if the previous-generation solutions were adopted, then the vacuum pipe system would amount to half the estimated cost of the CE and almost one third of the ET, with underground civil engineering the dominant amount. Reducing the cost of vacuum systems requires the development of different technical approaches with respect to previous-generation facilities. Developing cheaper technologies is also a key subject for future accelerators and a synergy in terms of manufacturing methods, surface treatments and installation procedures is already visible.

Within an official framework between CERN and the lead institutes of the ET study – Nikhef in the Netherlands and INFN in Italy – CERN's TE-VSC and EN-MME groups are sharing their expertise in vacuum, materials, manufacturing and surface treatments with the GW community. The activity began in September 2022 and is expected to conclude at the end of 2025 with a technical design report and full test of a vacuum-vessel pilot sector. During the "Beampipes for Gravitational Wave Telescopes 2023" workshop, held at CERN from 27 to 29 March, 85 specialists from different communities encompassing accelerator and GW technologies, and firms that focus on steel production, pipe manufacturing and vacuum equipment, gathered to discuss the latest progress. The event followed a similar one hosted by LIGO Livingston in 2019 that gave important directions for research topics.

In a series of introductory contributions, the basic theoretical elements regarding vacuum requirements and the status of CE and ET studies were presented, highlighting initiatives in vacuum and material technologies in Europe and the US. The detailed description of current GWT vacuum systems provided a starting point for the presentations of ongoing developments. To conduct an effective cost analysis and reduction, the entire process must be taken into account – including raw-material production and treatment, manufacturing, surface treatment, logistics, installation and commissioning in the tunnel. Additionally, the interfaces with the experimental areas and other services such as civil engineering, electrical distribution and ventilation are essential to assess the impact of technological choices for the vacuum pipes.

The selection criteria for the structural materials of the pipe were discussed, with steel currently being the material of choice. Ferritic steels would contribute to a significant cost reduction compared to austenitic steel, which is currently used in accelerators, because they do not contain nickel. Furthermore, thanks to their body-centred cubic crystallographic structure, ferritic steels have a much lower residual hydrogen content – the first enemy for the attainment of ultrahigh vacuum – and thus do not require expensive solid-state degassing treatments. The cheapest ferritic steels are "mild steels", which are common materials in gas pipelines after treatment to fight corrosion. Ferritic stainless steels, which contain more than 12% in weight of dissolved chromium, are also being studied for GWT applications. While first results are encouraging, the magnetic properties of these materials must be considered to avoid anomalous transmission of electromagnetic signals and of the induced mechanical vibrations.

Four solutions regarding the design and manufacture of the pipes and their support system were discussed at the workshop. ▷

The baseline is a 3 to 4 mm-thick tube similar to the ones operational in Virgo and LIGO, with some modifications to cope with the new tunnel environment and stricter sensitivity requirements. Another is a 1 to 1.5 mm-thick corrugated vessel that does not require reinforcement and expansion bellows. Designs based on double-wall pipes were also discussed, with the inner wall being thin and easy to heat and the external wall performing the structural role. An insulation vacuum would be generated between the two walls without the cleanliness and pressure requirements imposed on the laser beam vacuum. The forces acting on the inner wall during pressure transients would be minimised by opening axial movement valves, which are not yet fully designed. Finally, a gas-pipeline solution was also considered, which would be produced by a half-inch-thick wall made of mild steel. The main advantage of this solution is its relatively low cost, as it is a standard approach used in the oil and gas industry. However, corrosion protection and ultrahigh vacuum needs would require surface treatment on both sides of the pipe walls. These treatments are currently under consideration. For all types of design, the integration of optical baffles (which provide an intermittent reduction in the pipe aperture to block scattered photons) is a matter of intense study, with options for position, material, surface treatment and installation reported. The transfer of vibrations from the tunnel structure to the baffle is also a hot topic.

The manufacturing of the pipes directly from metal coils and their surface treatment can be carried out at supplier facilities or directly at the installation site. The former approach would reduce the cost of infrastructure and manpower, while the latter would reduce transport costs and provide an additional degree of freedom to the global logistics as the storage area would be minimised. The study of *in situ* production was brought to its limit in a conceptual study of a process that, from a coil, could deliver pipes as long as desired directly into the underground areas: the metal coil arrives in the tunnel, and then is installed in a dedicated machine that unrolls the coil and welds the metallic sheet to form the pipe to any length.

> **The next generation of GWTs would represent the largest ultrahigh vacuum systems ever built**

These topics will undergo further development in the near future, and the results will be incorporated into a comprehensive technical design report. This will include a detailed cost optimisation and will be validated in a pilot sector at CERN. With just under two and a half years of the project remaining, its success will demand a substantial effort and resolute motivation. The optimism instilled by the enthusiasm and collaborative approach demonstrated by all participants at the workshop is therefore highly encouraging.

Ana Teresa Fontela *and* **Paolo Chiggiato** *CERN.*

Magnificent CEvNS 2023

Magnificent CEvNS in Munich

A Wex

Hands on *An ideal stage for young scientists at the fifth Magnificent CEvNS workshop hosted by the Carl Friedrich von Siemens Foundation.*

Coherent elastic neutrino–nucleus scattering (CEvNS) is a new neutrino-detection channel with the potential to test the Standard Model (SM) at low-momentum transfer and to search for new physics beyond the SM (BSM). It also has applications in nuclear physics, such as measurements of nuclear form factors, and the detection of solar and supernova neutrinos. In the SM, neutrinos interact with the nucleus as a whole, enhancing the cross section by approximately the neutron number squared. However, detection is challenging as the observable is the tiny recoil of the nucleus, which has an energy ranging from sub-keV to a few tens of keV depending on the nucleus and neutrino source. Several decades after its prediction, CEvNS was measured for the first time in 2017 by the COHERENT experiment (*CERN Courier* October 2017 p8) and the field has grown rapidly since.

The aims of the Magnificent CEvNS workshop, named after the Hollywood Western, are to bring together the broad community of researchers working on CEvNS and promote student engagement and connection among experimentalists, theorists and phenomenologists in this new field. The first workshop was held in 2018 in Chicago, and the most recent in Munich from 22 to 24 March with 96 participants.

Examining CEvNS opens a multitude of promising ways to look for BSM interactions. Improved limits on generalised neutrino interactions, new light mediators and sterile neutrinos derived from the complete COHERENT dataset were presented. These data enable the nuclear radius to be probed in a new way. More physics potential was highlighted in talks showing limits on the Weinberg angle and dark matter (axion-like particles). Notable advances by reactor experiments include new limits on CEvNS on germanium by the CONUS and NuGen experiments, which disagree with the previously published Dresden-II results.

The talks underlined the large experimental effort toward a complete mapping of the neutron and energy dependence of the CEvNS cross section. The observation of CEvNS on CsI and Ar by the COHERENT experiment will be complemented with future measurements on targets ranging from light (sodium) to heavy (tungsten) elements in COHERENT and new facilities such as NUCLEUS and Ricochet. Precision will be achieved by increasing statistics in CEvNS events with larger target masses, lower detection thresholds and increased neutrino flux. Reducing systematic effects by characterising backgrounds and detector responses is also critical. The growing precision will trigger studies on BSM physics in the near future, complementing high-energy experimental efforts.

A half-day satellite workshop "Into the Blue Sky" was dedicated to new ideas related to the CEvNS community. These included measurements of neutrino-induced fission, and detector concepts based on latent damage to the crystalline structure of minerals and superconducting crystals. The workshop was followed by a school organised by the Collaborative Research Center "Neutrinos and Dark Matter in Astro- and Particle Physics" at TU Munich from 27 to 29 March. Six lectures covered the fundamentals of low-energy neutrino physics with a focus on CEvNS, backgrounds, neutrino sources and detectors. The 40 participants then applied this knowledge by creating a fictional micro-CEvNS experiment.

Half a century since it was proposed theoretically, the physics accessible with CEvNS is proving to be extensive. The next Magnificent CEvNS workshop will take place next year at a new location and the participants are looking forward to further exploration of the CEvNS frontier.

Janina Hakenmüller *Duke University,* **Diane M Markoff** *North Carolina Central University,* **Victoria Wagner** *TU Munich.*

Moriond Electroweak 2023

An extraordinary harvest of new results

The 57th Rencontres de Moriond conference on electroweak interactions and unified theories, which took place from 18 to 25 March, saw more than 150 physicists meet in La Thuile, Italy. Over 100 talks covering the latest results in experiment and theory, and providing complementary approaches to some of the most pressing problems in particle physics and cosmology, were actively debated in a stimulating atmosphere.

L Fayard

Stimulating atmosphere *More than 150 physicists met in person.*

L Fayard

Experiment meets theory *Marumi Kado and Stephen King.*

Neutrinos first

Neutrinos provide a unique window on the only new physics so far seen beyond the Standard Model (BSM). Their measured mass differences and mixing parameters provide a consistent picture, suggesting a new scale potentially at 10^{15} GeV. However, the absolute neutrino-mass scale and the determination, via neutrinoless double beta decay, of whether neutrinos are Majorana particles, are missing. Also 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, which were presented for the first time.

The KATRIN collaboration reported an absolute upper limit on the electron-neutrino mass of 800 meV. By analysing the tritium-decay spectrum, the team excluded rapid oscillations between electron and potential sterile neutrinos and set a limit on cosmic neutrino local over-densities. The KamLAND-Zen, CUPID-Mo and Majorana Demonstrator experiments showed results on neutrinoless double-beta decay searches in different systems (*CERN Courier* May/June 2023 p9), the latter also reporting bounds on models for wave-function collapse.

The long-baseline ν_μ oscillation experiments NOvA and T2K presented a very consistent picture of the neutrino mixing (PMNS) framework, with a slight preference for the normal ordering and the exclusion of CP-conserving values of δ_{CP} of 0 or π at 90% confidence. NOvA provided the first evidence for electron antineutrino appearance and a first long-baseline measurement of $\sin^2\theta_{23}$, agreeing very well with reactor-neutrino data. IceCube's DeepCore extension also yielded stunning atmospheric neutrino-oscillation results comparable with Super-Kamiokande and long-baseline experiment sensitivities. All experiments strongly support the three neutrino-flavour paradigm.

Longstanding neutrino anomalies were discussed in detail. The sterile-neutrino explanation for the reactor-antineutrino deficit is incompatible with short-baseline data; the LSND and MiniBooNE short-baseline low-energy excesses were revisited in light of new backgrounds; and the long-standing gallium anomaly was further cemented by the BEST experiment, whose observations are also incompatible with a simple sterile-neutrino oscillation pattern. The PROSPECT reactor-neutrino experiment excluded sterile neutrino oscillations as an explanation for the gallium anomaly. Finally, a peaking anomaly in the range 5–7 MeV was observed by several experiments (including RENO, Daya Bay, NEOS, Chooz and PROSPECT), which cannot be easily explained. Instead, nuclear models were discussed in detail and these should be looked at carefully. Finally, the results of CONUS set limits on light vector mediators and the neutrino magnetic moment.

On the theory side, leptogenesis is possible for any right-handed neutrino masses above 0.1 GeV, which, if light enough, can be probed by proposed and existing experiments at CERN. Neutrino experiments such as COHERENT were analysed in the framework of SM effective field theory.

The IceCube collaboration also showed splendid multi-messenger results from high- and ultrahigh-energy neutrino observations and underlined its ability to probe the SM with neutrinos that have travelled cosmic distances. These neutrinos are expected to be even mixtures of the three neutrino species; any deviation would be a clear sign of new physics. The cosmic-neutrino data also highlighted the missing data in neutrino-nucleon interactions in the range of a few 100 GeV to 10 TeV. Furthermore, the birth of collider neutrino physics was presented, with the new LHC experiment FASER reporting the first observation of neutrinos from proton–proton collisions (*CERN Courier* May/June 2023 p9). Overall the three-neutrino paradigm is standing tall, with some anomalies that still need to be clarified, in particular the BEST gallium anomaly.

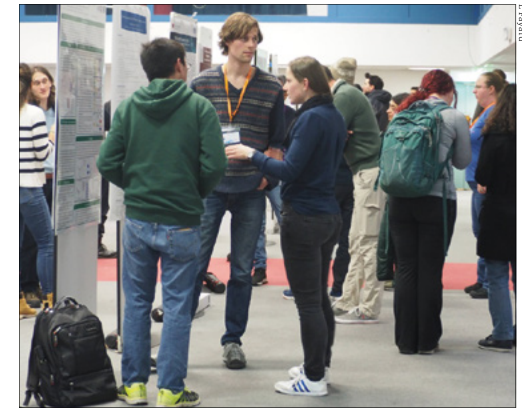
Heavy flavours

From a theoretical point of view, neutrino and heavy-quark physics are two sides of the same coin: they provide information related to the flavour problem, masses and mixings. The fact that fermion mass hierarchies arise from Yukawa couplings in the SM does not make it more satisfactory. Anomalies in semileptonic B decays have raised numerous speculations, in particular that the flavour scale might be at the TeV scale, motivating models involving a Z′ gauge boson or a scalar or vector leptoquark from a twin Pati–Salam theory of flavour.

Recent LHCb results have shed new light on the issue. The collaboration discussed its recent reanalysis of the R(K) and $R(K^*)$ ratios, which now agree with the SM (*CERN Courier* January/February 2023 p7), and presented a plethora of new results. These included new measurement of $R(D^*)$ with fully hadronic τ decays and a new combined measurement of R(D) and $R(D^*)$ (*CERN Courier* May/June 2023 p15), new results in the $\bar{b} \to \bar{s}s\bar{s}$ transition in the $\phi\phi$ channel showing no signs of CP violation (*CERN Courier* May/June 2023 p17), and a new measurement of the CKM angle γ in the $B^\pm \to D[K^\mp\pi^\pm\pi^\mp\pi^\pm]h^\pm$ $(h = \pi, K)$ channel (*CERN Courier* January/February 2023 p13). ▷

The LHC experiments presented results of various rare-decay and new-resonance searches, for example the ambitious search for the extremely rare decay of a D meson into two muons, the observation by CMS of the η decay to four muons, and the search for states (including possible tetraquarks) decaying to di-charmonium.

A highlight was Belle II's strong contribution in all areas of heavy-flavour physics, including: measurements of $b \to s$ transitions, including a fully inclusive measurement; several time-dependent CP-violation observables, which yield precisions on the CKM parameter $\sin 2\beta$ on a par with the current world's best measurements; new input to the $|V_{ub}|$ and $|V_{cb}|$ puzzle, with an exclusive measurement in the golden $B \to \pi l \nu$ mode; and an inclusive measurement of the $B \to D^* l \nu$ decay. In addition, Belle II presented its first and already world's most precise tau-mass measurement, with only approximately half the luminosity accumulated by the Belle experiment. Finally, KOTO collaborators updated participants on their search for the extremely rare process $K_L \to \pi^0 \nu\bar{\nu}$, for which a sensitivity close to the expected SM branching fraction of 3×10^{-11} should ultimately be reached.



L Fayard

Fresh approach *Young researchers presenting their work during the Moriond gravitation conference sessions, which were held in parallel.*

New physics

Also in the quark sector, the latest measurements and prospects of the neutron electric dipole moment were presented, providing strong constraints on new-physics scenarios at high-energy scales.

Lattice-QCD studies have progressed remarkably in recent years, with hadronic contributions to muon g-2 being more or less under control – more so in the case of light-by-light contributions, which agree well with other results, and less so regarding the hadronic vacuum polarisation. For the latter, errors are being driven down by the BMW collaboration, which seems to lead to more consistency with experiment. However, the BMW results are not yet fully confirmed either by other lattice groups or by experiment, with recent VEPP data disagreeing with previous experiments. Higher precision from lattice calculations has also led to the so-called Cabibbo anomaly reported at Moriond, whereby the unitarity of the first row of the CKM matrix seems to be violated by 2.7σ. If confirmed, this could be a signal for new physics.

A variety of dark-matter candidates were discussed, including: primordial black holes with improved limits using hydrogen astronomy; weakly interacting massive particles (WIMPs) from new electroweak fermion multiplets with heavier masses; heavy singlet dilaton-like scalars; keV neutrinos from an inverse seesaw model; axions or axion-like particles with an extended window of masses arising from non-standard cosmology; and ultralight dark matter such as dark photons. An interesting proposal for axion detectors that can double up as high-frequency gravitational wave detectors was also discussed.

The results show how the LHC has already exceeded expectations in precision and sensitivity since the start of operations

The XENONnT (*CERN Courier* May/June 2023 p15) and LZ collaborations also presented their latest results. Along with the xenon-based PandaX experiment, they are now exploring new territory at low WIMP–nucleon cross sections. These very low cross sections motivate further searches for dark photons or axion-like particles. A flurry of results of searches for dark-sector particles at the LHC, Belle II, Babar, NA62 (*CERN Courier* May/June 2023 p11), BES and the PADME experiments were shown. Theories of new heavy particles were also discussed, ranging from an analysis of the minimal supersymmetric SM, which showed that gluinos of 1 TeV and stop squarks of 500 GeV could still have escaped detection, to theories of two Higgs-doublet models plus a Higgs singlet, which might be responsible for the 95 GeV diphoton events, and the observation that vector-like fermions have the right properties to avoid a metastable universe.

The LHC experiments continue to leave no stone unturned in their searches for new phenomena, placing important limits on their presence up to the few-TeV scale. With 20 times more data, the High-Luminosity LHC (HL-LHC) will provide valuable opportunities to significantly increase the search domain and discovery potential.

The LHC experiments also presented a series of new results based on W- and Z-boson production. CMS showed a measurement of the τ polarisation (*CERN Courier* March/April 2023 p15), which can be directly translated in terms of a measurement of the weak mixing angle with a precision of approximately 10% (close to that reached by e^+e^- experiments). CMS also presented a measurement of the invisible Z-boson width that is more precise than the direct measurements at LEP, while ATLAS showed a precise measurement of the Z-boson transverse momentum differential cross section, leading to the most precise measurement of α_S. ATLAS also presented a new W-boson mass measurement with an improved precision of 16 MeV, thus increasing the existing tension with CDF's 2022 measurement (*CERN Courier* May/June 2023 p10).

Striking progress

Equally highlighting the remarkable progress made at the precision frontier, ATLAS and CMS showed results for more complex and rare processes. Both experiments reported the observation of four-top-quark production and ATLAS observed two new tri-boson production processes, WZγ and W$\gamma\gamma$. ATLAS also presented a new measurement of W-boson production in association with a top-quark pair, which is a key background to numerous important processes.

These results show how the LHC has already exceeded expectations in precision and sensitivity since the start of operations. An outstanding example is the search for di-Higgs production by ATLAS and CMS, a cornerstone of the HL-LHC physics programme to constrain the Higgs boson trilinear self-coupling. Once combined, the experiments should reach the sensitivity for observing this process. Another example is the race to reach sensitivity to the Higgs-boson decays to charm quarks, where new deep-learning techniques are making significant progress. To further improve the expected precision at the HL-LHC, intermediate goals at Run 3 are extremely important. Both collaborations presented new results on measurements of Z-boson, top-quark and Higgs-boson production with LHC Run 3 data taken in 2022.

This year's Moriond conference showed an extraordinary harvest of new results, giving participants an opportunity to take stock on the open questions and see the remarkable progress made since last year.

Marumi Kado *Max Planck Institute, Munich* and **Stephen King** *University of Southampton.*

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TERRESTRIAL VERY-LONG-BASELINE ATOM INTERFEROMETRY WORKSHOP

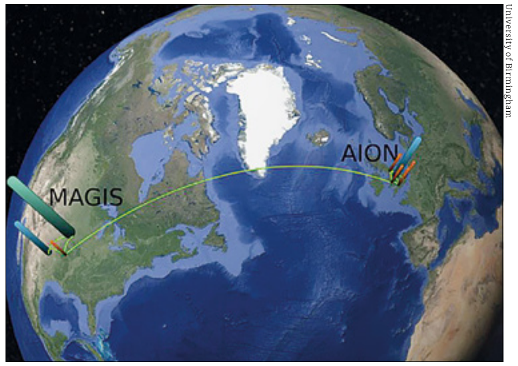
Cold atoms for new physics

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 introductory colloquium 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 wave packets rather than light waves. Interactions between 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 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 ultralight 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 the upcoming 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 10 m already exist, for example at Stanford University, or are planned, for example in Hanover (VLBAI), 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 (MAGIS), in France (MIGA) and in China (ZAIGA). The Atomic Interferometric Observatory and Network (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 shaft 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.



University of Birmingham

Global reach *A network of MAGIS and AION very-long-baseline atom interferometers would detect gravitational waves and search for dark matter.*

Looking further ahead, participants discussed the prospects for one or more km-scale atom interferometers, which would provide the maximal sensitivity possible with a terrestrial experiment to search for ultralight dark matter and gravitational waves. It was agreed that the global community interested in such experiments would work together towards establishing an informal proto-collaboration that could develop the science case for such facilities, provide a forum for exchanging ideas how to develop the necessary technological advances and develop a roadmap for 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 may form the core of the team that will lead atom interferometers to their full potential.

John Ellis *King's College London* and **Oliver Buchmüller** *Imperial College London.*

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 microcosmos of elementary particles to the macrocosmos 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 giant Satyajit Ray.

From the microcosmos to the macrocosmos

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 aeon going over to another aeon endlessly 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 very high density, followed by Debadesh Bandyopadhyay's talk on unlocking the mysteries of neutron stars. Jean-Paul Blaziot talked about the emergence of hydrodynamics in expanding quark–gluon plasma, whereas Edward Shuryak discussed the role of sphaleron explosions and baryogenesis in the cosmological electroweak phase transition. Subir Sarkar's talk "Testing the cosmological principle" was provocative, as usual, and Sunil Mukhi and Aninda Sinha described the prospects for string theory. Sumit Som, Chandana Bhattacharya, Nabanita Naskar and Arup Bandyopadhyay discussed the low- and medium-energy physics possible using cyclotrons at Kolkata.

VECC

Time and space *Bikash Sinha introducing a talk by Roger Penrose at MMAP 2020, which was held in May 2022.*

Moving to extreme nuclear matter, Barbara Jacak talked about experimental studies of transport in dense gluon matter. Jurgen Schukraft, Federico Antinori, Tapan Nayak, Bedangadas Mohanty and Subhasis Chattopadhyay spoke on signatures for the early-universe quark–gluon plasma and described the experimental programme of the ALICE experiment at the LHC, and Dinesh Srivastava 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 presented the physics prospects of the J-PARC facility in Japan, Paolo Giubellino described the evolution of the latest FAIR accelerator at GSI, and Horst Stöcker discussed how to observe strangelets using fluctuation tools. In his presentation on the history of CERN, former Director-General Rolf Heuer talked about the marvels of large-scale collaboration capturing the thrill of a big discovery.

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

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.

Disentanglement *A Jackson Pollock-inspired artwork makes one want to discover whether the pattern is random, created by a computer, or contains evidence of something new.*

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^{-7}, assuming it is merely a statistical fluctuation, which corresponds to the probability of correctly guessing whether a coin will fall down heads or tails for each of 22 tosses. Statisticians claim that it is crazy to believe probability distributions so far into their tails, especially when systematic uncertainties are involved; particle physicists still hope that they provide some measure of the level of (dis)agreement between data and theory. But what is the origin of this convention, and does it remain a relevant marker for claiming the discovery of new physics?

There are several reasons why the stringent 5σ rule is used in particle physics. The first is that it provides some degree of protection against falsely claiming the observation of a discrepancy with the SM. There have been numerous 3σ and 4σ effects in the past that have gone away when more data was collected. A relatively recent example was an excess of diphoton events at an energy of 750 GeV seen in both the ATLAS and CMS data of 2015, but which was absent in the larger data samples of 2016.

Systematic errors provide another reason, since such effects are more difficult to assess than statistical uncertainties and may be underestimated. Thus in a systematics-dominated scenario, if our estimate is a factor of two too small, a more mundane 3σ fluctuation could incorrectly be inflated to an apparently exciting 6σ effect. A potentially more serious problem is a source of systematics that has not even been considered by the analysts, the so-called "unknown unknowns".

Know your p-values

Another reason underlying the 5σ criterion is the look-elsewhere effect, which involves the "p-values" for the observed effect. These are defined as the probability of a statistical fluctuation causing a result to be as extreme as the one observed, or more so, assuming some null hypothesis. For example, in tossing an unbiased coin 10 times, and observing eight of them to be tails when we bet on each of them being heads, it is the probability of being wrong eight or nine or 10 times (5.5%). A small p-value indicates a tension between the theory and the observation.

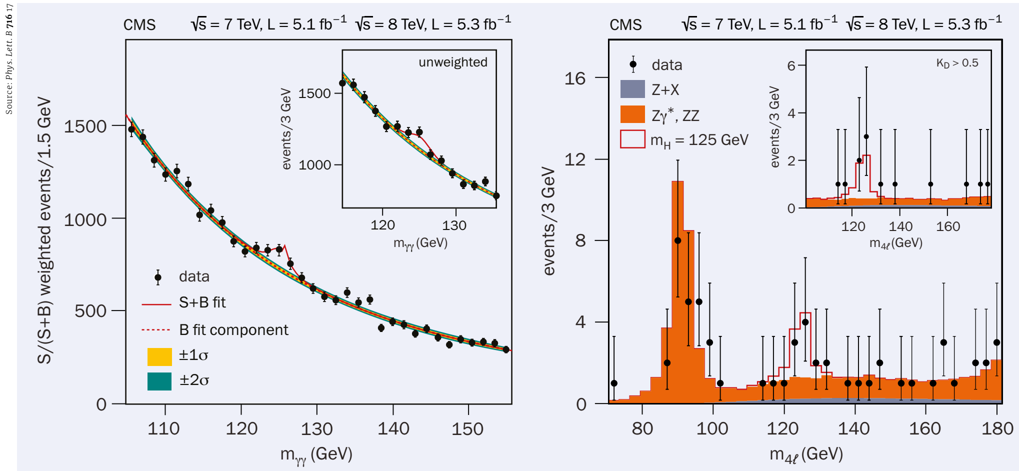
Particle-physics analyses often look for peaks in mass spectra, which could be the sign of a new particle. An example is shown in the "Higgs signals" figure (p25), which contains data from CMS used to discover the Higgs boson (ATLAS has similar data). Whereas the local p-value of an observed effect is 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 non-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 favoured the hypothesis that Stonehenge was designed to point in that way. However, the chance that one of the directions, defined by any pair of stones, was pointing at an ancient monument anywhere in the world (global p-value) is above 50%.

Current practice for model-dependent searches in particle physics, however, is to apply the 5σ criterion to the local p-value, as was done in the search for the Higgs boson. One reason for this is that there is no unique definition of "elsewhere"; if you are a graduate student, it may be just your own analysis, while for CERN's Director-General, "anywhere in any analysis carried out with data from CERN" may be more appropriate. Another is that model-independent searches involving machine-learning techniques are capable of being sensitive to a wide variety of possible new effects, and it is hard to estimate what their look-elsewhere factor should be. Clearly, in quoting global p-values it is essential to specify your interpretation of elsewhere.

THE AUTHOR

Louis Lyons *Imperial College London and University of Oxford.*



Higgs signals *The mass spectrum of possible Higgs-boson decays to a pair of photons (left), showing a peak at around 125 GeV above a smoothly falling background, from the CMS Higgs discovery paper. On the right is a similar histogram for a Higgs boson decaying via a pair of Z bosons to four leptons. The peak at around 90 GeV is due to decays of single Z bosons, and is irrelevant, whereas a small excess at 125 GeV is due to Higgs decays. Although involving only a few events, the excess is significant because the background (orange) here is very small. The expected contribution from the SM Higgs at 125 GeV is shown as the red histogram. ATLAS has very similar data. By now the experiments have about 10 times more data, so the peaks are much more visible.*

It is unreasonable to regard 5.1σ as a discovery, but 4.9σ as not

A fourth factor behind the 5σ rule is plausibility. The likelihood of an observation is the probability of the data, given the model. To convert this to the more interesting probability of the model, given the data, requires 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 being the same as the probability of B, given A. Thus the probability of a murderer eating toast for breakfast may be 60%, but the probability of someone who eats toast for breakfast being a murderer is thankfully much smaller (about one in a million). In general, our belief in the plausibility in a model for a particular version of new physics is much smaller than for the SM, thus 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.

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 see which of two competing hypotheses ("just SM" or "SM plus new physics") provides a better fit to the data. The former are known as goodness-of-fit tests and may involve χ^2, Kolmogorov–Smirnov or similar tests; the latter are hypothesis tests, often using the likelihood ratio. They are sometimes referred to as model-independent and model-dependent, respectively, each having its own advantages and limitations. However, the degree of model dependence is a continuous spectrum rather than a binary choice.

It is unreasonable to regard 5.1σ as a discovery, but 4.9σ as not. Also, should we regard the one with better observed accuracy or better expected accuracy as the preferred result? Blind analyses are recommended, in that this removes the possibility of the analyser adjusting selections to influence the significance of the observed effect. Some non-blind searches have such a large and indeterminate look-elsewhere effect that they can only be regarded as hints of new physics, to be confirmed by future independent data. Theory calculations also have uncertainties, due for example to parameters in the model or difficulties with numerical predictions.

Discoveries in progress

A useful exercise is to review a few examples that might be (or might have been) discoveries. A recent example involves the ATLAS and CMS observation of events involving four-top quarks. Apart 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 tops" figure). 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 use 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.

Going back further in time, an experiment in 1979 claimed to observe free quarks by measuring the electrical

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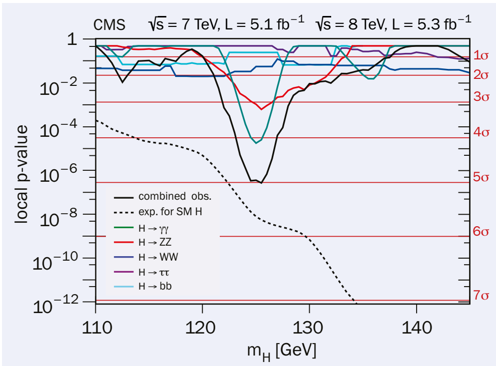
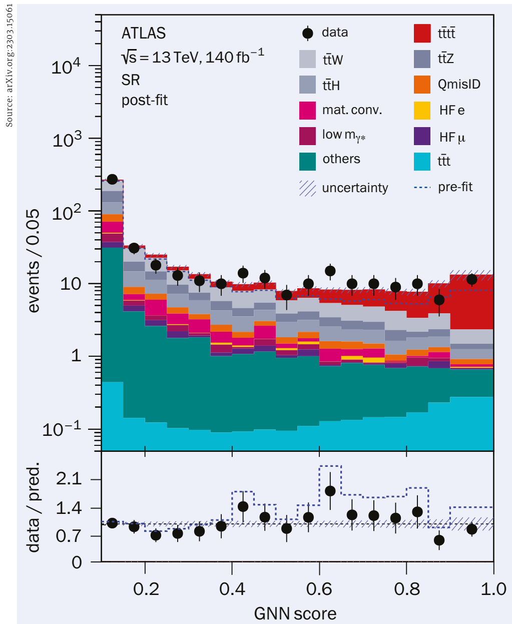


p-values *The local p-values for each of five possible decay modes of a Higgs boson as functions of its assumed mass, and for the combination of these modes (black). The green and red curves correspond to the mass plots shown in the figure "Higgs signals", respectively; the peaks in the number of events correspond to the dips in the p-values, as larger peaks have a smaller probability of being random fluctuations of the SM background. It is seen that the local p-value of the combined data reaches down to 3×10^{-7} (translating to 5σ) at a mass value of about 125 GeV.*

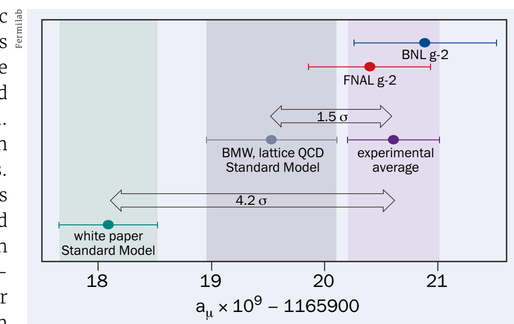


Four tops *Histogram of the output from a graph neural network (GNN) comparing ATLAS data with the predicted distribution expected for various backgrounds (as specified on the figure) and from the four-top signal (red). The GNN was trained to distinguish between the signal and backgrounds. The agreement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

charge of small spheres levitated in an oscillating electric field; several gave multiples of 1/3, which was regarded as a signature of single quarks. Luis Alvarez noted that the raw results required sizeable corrections and suggested that a blind analysis should be performed on future data. The net result was that no further papers were published on this work. This demonstrates the value of blind analyses.

A second historical example is precision measurements at the Large Electron Positron collider (LEP). Compared with the predictions of the SM, including the then-known particles, deviations were observed in the many measurements made by the four LEP experiments. A much better fit to the data was achieved by including corrections from the (at that time hypothesised) top quark and Higgs boson, which enabled approximate mass ranges to be derived for them. However, it is now accepted that the discoveries of the top quark and the Higgs boson were subsequently made by their direct observations at the Tevatron and at the LHC, rather than by their virtual effects at LEP.

The muon magnetic moment is a more contemporary case. This quantity has been measured and also predicted to incredible precision, but a discrepancy between the two values exists at around the 4σ level, which could be an indication of contributions from virtual new particles. The experiment essentially measures just this one quantity, so there is no look-elsewhere effect. However, even if this discrepancy persists in new data, it will be difficult to tell if it is due to the theory or experiment being wrong, or whether it requires the existence of new, virtual particles. Also, the nature of such virtual particles could remain obscure. Furthermore, a recent calculation using lattice gauge theory of the "vacuum hadronic polarisation" contribution to the predicted value of the magnetic moment brings it closer to the observed value (see "Measurement of the moment"



Measurement of the moment *The anomalous magnetic moment of the muon a_μ is defined as $(g_\mu - 2)/2$, where g_μ is the magnetic moment in units of its Bohr magneton; the value g = 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 (FNAL g-2) as well as their combination (lilac band). The green band is the theoretical prediction, which is 4.2σ away. Recent lattice-gauge-theory calculations from the Budapest–Marseille–Wuppertal (BMW) group result in the grey band, where the discrepancy with experiment is now only 1.5σ.*

figure). Clearly it will be worth watching how this develops.

The so-called flavour anomalies are another topical example. The LHCb experiment has observed several anomalous results in the decays of B mesons, especially those involving transitions of a b quark to an s quark and a lepton pair. It is not yet clear whether these could be evidence for some real discrepancies with the SM prediction (i.e. evidence for new physics), or simply and more mundanely an underestimate of the systematics. The magnitude of the look-elsewhere effect is hard to estimate, so independent confirmation of the observed effects would be helpful. Indeed, the most recent result from LHCb for the R(K) parameter, published in December 2022, is much more consistent with the SM. It appears that the original result was affected by an overlooked background source. Repeated measurements by other experiments are eagerly awaited.

A surprise last year was the new result by the CDF collaboration at the former Tevatron collider at Fermilab, which finished collecting data many years ago, on the mass of the W boson (m_W), which disagreed with the SM prediction by 7σ. It is of course more reasonable to use the weighted average of all m_W measurements, which reduces the discrepancy, but only slightly. A subsequent measurement by ATLAS disagreed with the CDF result; the CMS determination of m_W is awaited with interest.

Nuanced approach

It is worth noting that the muon g-2, flavour and m_W 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 big 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 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, it would be a 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 $H\rightarrow\mu\mu$ or $B_s\rightarrow\mu\mu$. 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 not-too-distant future. ●

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

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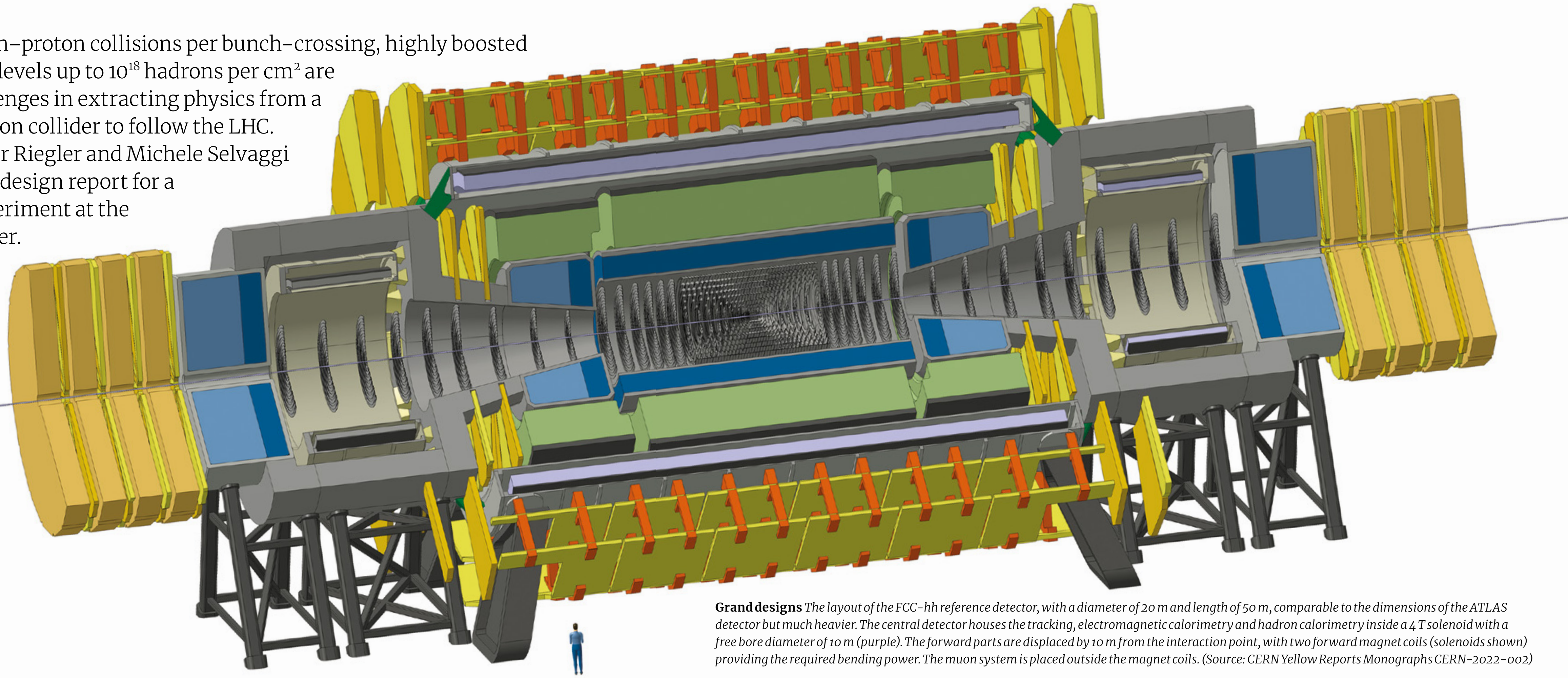
EXTREME DETECTOR DESIGN FOR A FUTURE CIRCULAR COLLIDER

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.



Grand designs *The layout of the FCC-hh reference detector, with a diameter of 20 m and length of 50 m, comparable to the dimensions of the ATLAS detector but much heavier. The central detector houses the tracking, electromagnetic calorimetry and hadron calorimetry inside a 4 T solenoid with a free bore diameter of 10 m (purple). The forward parts are displaced by 10 m from the interaction point, with two forward magnet coils (solenoids shown) providing the required bending power. The muon system is placed outside the magnet coils. (Source: CERN Yellow Reports Monographs CERN-2022-002)*

THE AUTHORS

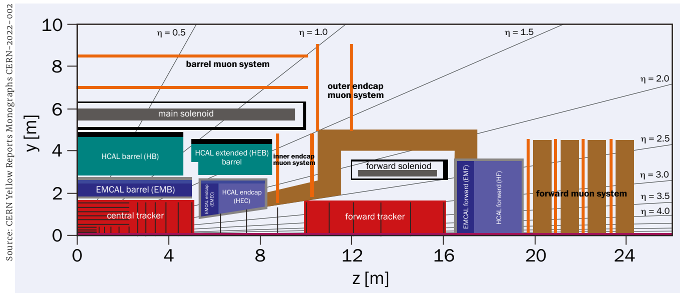
Martin Aleksa, Werner Riegler *and* **Michele Selvaggi** *CERN.*

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.

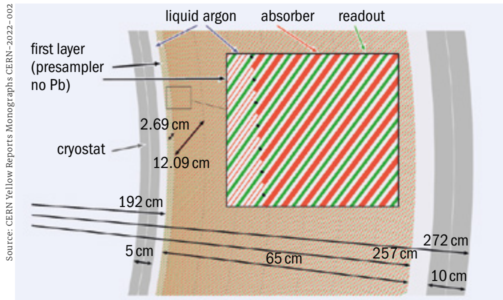
At the time of the kickoff meeting for the FCC study in 2014, the physics potential and the requirements for detectors at a 100 TeV collider were already heavily debated. These discussions were eventually channelled into a working group that provided the input to the 2020 update of the European strategy 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.

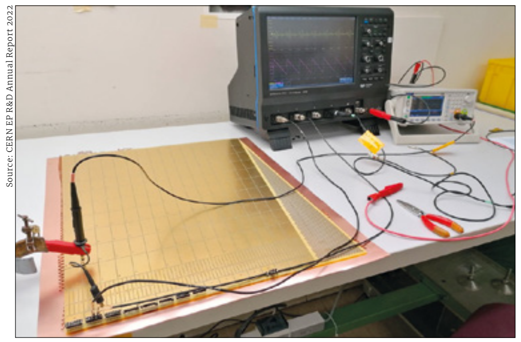
The first detector challenge at FCC-hh is related to the luminosity, which is expected to reach $3\times10^{35}\,cm^{-2}s^{-1}$. This is six times larger than the HL-LHC luminosity and 30 times larger than the nominal LHC luminosity. Because the FCC will operate beams with a 25 ns bunch spacing, the 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

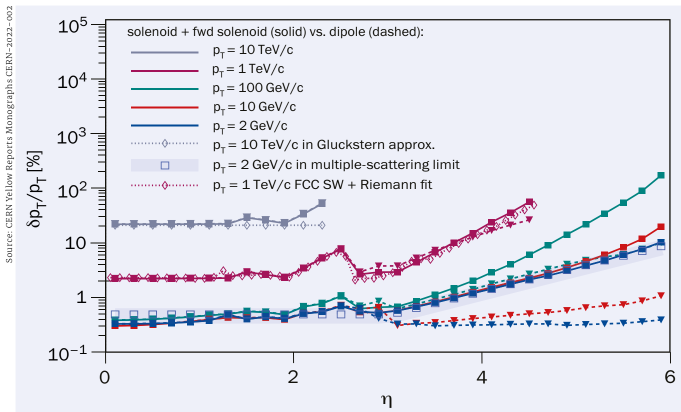


Far reaching *The longitudinal cross-section of the FCC-hh reference detector, showing the pseudorapidity values, η, covered by the various subdetectors.*





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).*



Forward momentum *Momentum resolution versus pseudorapidity, η, for the FCC-hh reference detector for a 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).*

layers of the tracking detector close to 10^{18} hadrons/cm², 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.

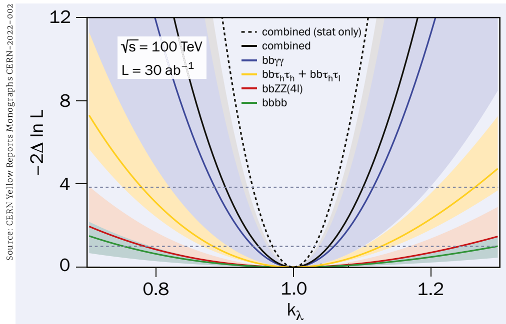
The high radiation levels also need very radiation-hard calorimetry, making a liquid-argon calorimeter the first choice for the electromagnetic calorimeter and forward regions of the hadron calorimeter. The energy deposit in the very forward regions will be 4 kW per unit of rapidity and it will be an 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

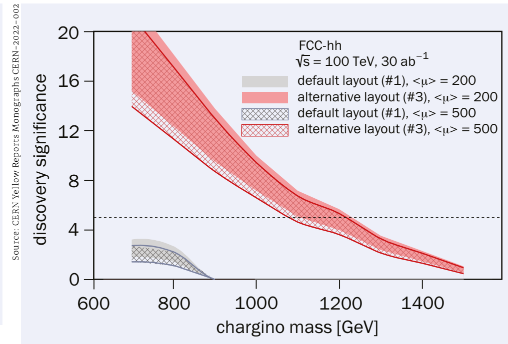
At an energy of 100 TeV, important SM particles such as the Higgs boson are abundantly produced in the very forward region. The forward acceptance of FCC-hh detectors therefore has to be much larger than at the LHC detectors. ATLAS and CMS enable momentum measurements up to pseudorapidities (a measure 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 dipoles 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 10 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 m² 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.

It is evident that the FCC-hh reference detector is more challenging than the LHC detectors, but not at all out of reach. The diameter and length are similar to those of the ATLAS detector. The tracker and calorimeters are housed inside a large superconducting solenoid 10 m in diameter, providing a magnetic field of 4 T. For comparison, CMS uses a solenoid with the same field and an inner diameter of 6 m. This difference does not seem large at first sight, but of course the stored energy (13 GJ) is about five times larger than the CMS coil, which needs very careful design



Higgs self-coupling *The precision of the Higgs self-coupling measurement at FCC-hh (in terms of the expected negative log–likelihood scan as a function of the trilinear self-coupling modifier) in all channels, and their combination. The dashed line represents the sensitivity obtained including statistical uncertainties only; the solid line corresponds to the inclusion of systematic uncertainties.*



Dark matters *The expected discovery significance for higgsino dark-matter models as a function of mass, after an FCC-hh integrated luminosity of 30 ab⁻¹. The grey (red) bands show the significance using a default (alternative) event layout. The difference between the solid and hatched bands corresponds to the different pile-up conditions.*

The potential of FCC-hh offers an unprecedented opportunity to address fundamental unknowns about our universe

of the quench protection system.

For the FCC-hh calorimeters, the major challenge, besides the high radiation dose, is the required energy resolution and particle identification in the high pile-up environment. The key to achieve the required performance is therefore a highly segmented calorimeter. The need for longitudinal segmentation calls for a solution different from the "accordion" geometry employed by ATLAS. Flat lead/steel absorbers that are inclined by 50 degrees with respect to the radial direction are interleaved with liquid-argon gaps and straight electrodes with high-voltage and signal pads (see "Liquid argon" figure). The readout of these pads on the back of the calorimeter is then possible thanks to the use of multi-layer electrodes fabricated as straight printed circuit boards. This idea has already been successfully prototyped within the CERN EP detector R&D programme.

The considerations for a muon system for the reference detector are quite different compared to the LHC experiments. When the detectors for the LHC were originally conceived in the late 1980s, it was not clear whether precise tracking in the vicinity of the collision point was possible in this unprecedented radiation environment. Silicon detectors were excessively expensive and gas detectors were at the limit of applicability. For the LHC detectors, a very large emphasis was therefore put on muon systems with good stand-alone performance, specifically for the ATLAS detector, which is able to provide a robust measurement of, for example, the decay of a Higgs particle into four muons, with the muon system alone.

Thanks to the formidable advancement of silicon-sensor technology, which has led to full silicon trackers capable of dealing with around 140 simultaneous pp collisions every 25 ns at the HL-LHC, standalone performance is no longer a stringent requirement. The muon systems for FCC-hh can therefore fully rely on the silicon trackers, assuming just two muon stations outside the coil that measure the exit point and the angle of the muons. The muon track provides muon identification, the muon angle provides a coarse momentum measurement for triggering and the track position provides improved muon momentum measurement when combined with the inner tracker.

The major difference between an FCC-hh detector and CMS is that there is no yoke for the return flux of the solenoid, as the cost would be excessive and its only purpose to shield the magnetic field towards the cavern. The baseline design assumes the cavern infrastructure can be built to be compatible with this stray field. Infrastructure that is sensitive to the magnetic field will be placed in the service cavern 50 m from the solenoid, where the stray field is sufficiently low.

The high granularity and acceptance of the FCC-hh reference detector will result in about 250 TB/s of data for calorimetry and the muon system, about 10 times more than the ATLAS and CMS HL-LHC scenarios. There is no doubt that it will be possible to digitise and read this data volume at the full bunch-crossing rate for these detector systems. The question remains whether the data rate of almost 2500 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 realms 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

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precision of measurements of Higgs-boson properties for a whole spectrum of production and decay processes complementary to those accessible at the FCC-ee. This includes measurements of rare processes such as Higgs pair-production, which provides a direct measure of the Higgs self-coupling – a crucial parameter for understanding the stability of the vacuum and the nature of the electroweak phase transition in the early universe – with a precision of 3 to 7% (see "Higgs self-coupling" figure).

Moreover, thanks to the extremely large Higgs-production rates, FCC-hh offers the potential to measure rare decay modes in a novel boosted kinematic regime well beyond what is currently studied at the LHC. These include the decay to second-generation fermions, muons, which can be measured to a precision of 1%. The Higgs branching fraction to invisible states can be probed to a value of 10^{-4}, allowing the parameter space for dark matter to be further constrained. The much higher centre-of-mass energy of FCC-hh, meanwhile, significantly extends the mass reach for discovering new particles. The potential for detecting heavy resonances decaying into di-muons and di-electrons extends to 40 TeV, while for coloured resonances like excited quarks the reach extends to 45 TeV, thus extending the current limit by almost an order of magnitude. In the context of supersymmetry, FCC-hh will be capable of probing stop squarks with masses up to 10 TeV, also well beyond the reach of the LHC.

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 weak interactions 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.

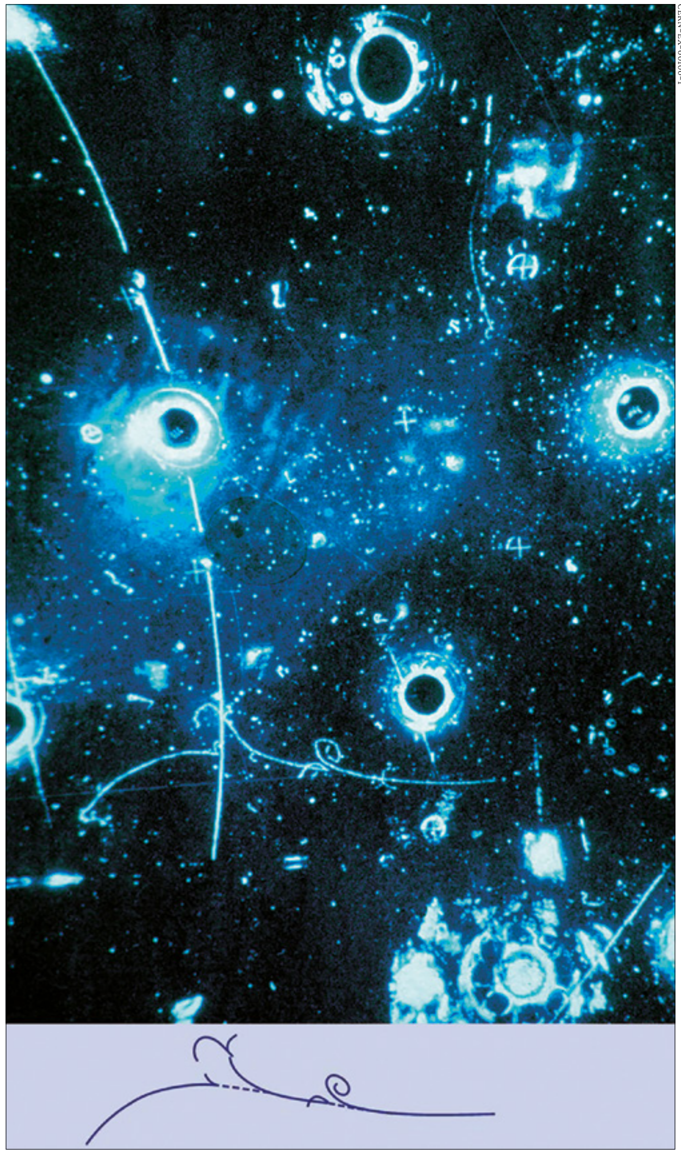
A detector at a 100 TeV hadron collider is clearly a challenging project. But detailed studies have shown that it should be possible to build a detector that can fully exploit the physics potential of such a machine, provided we invest in the necessary detector R&D. Experience with the Phase-II upgrades 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

M Mangano and W Riegler (Eds.) 2022 CERN Yellow Reports: Monographs CERN-2022-002.

CERN'S NEUTRINO ODYSSEY

Fifty years ago, neutrino beams traversing the Gargamelle bubble chamber revealed the existence of the neutral current and put the electroweak Standard Model on solid ground. Sanje Fenkart describes Gargamelle's feat and the lasting impact on CERN's neutrino programme.



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Spotted *The first candidate leptonic neutral-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.*

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 PS hit an internal target to produce pions and kaons, let them fly some distance during which they can produce 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 (ν_μ) and the electron neutrino (ν_e) – 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

THE AUTHOR
Sanje Fenkart
CERN.

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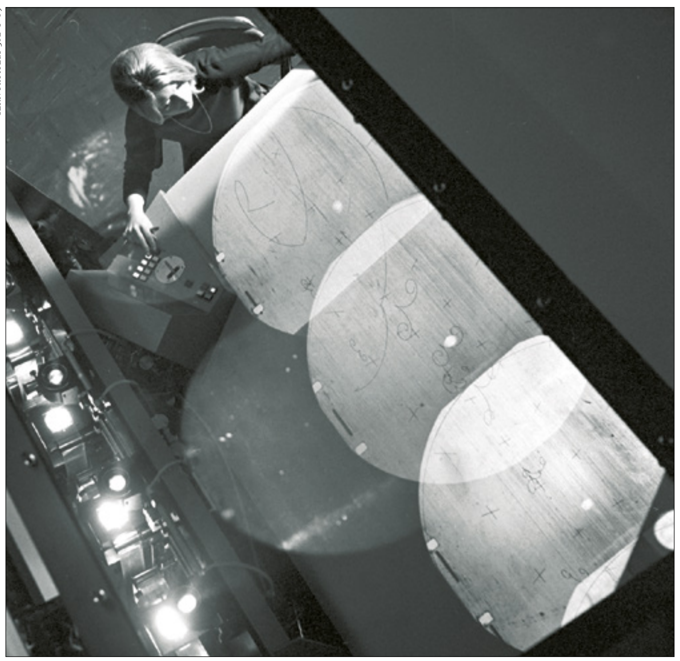
Find your focus *With Simon van der Meer's invention of the magnetic horn, the production of precise and focused particle beams for neutrino experiments became possible.*

CERN PhotoLab 302-1-69



Eyes down *Working on the pilot model of a scanning table for Gargamelle in 1969 was Anita Bjorkebo, who was looking for "interesting events" among the many recorded tracks.*

in an external beam pipe increased the neutrino flux by about two orders of magnitude. In 1963 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 spark-chamber detector weighing several tonnes, for which first results were presented at a conference in Siena that year. The bubble-chamber results were particularly impressive, recalls Cundy: "Even though the number of events was of the order of a few hundred, you could do a lot of physics: measure the elastic form factor of the nucleon, single pion production, the total cross section, search for intermediate weak bosons and give limits on neutral-current processes." It was at that conference that André Lagarrigue of Orsay urged that bubble chambers were the way forward for neutrino physics, and proposed to build the biggest chamber possible: Gargamelle, named after a giantess from a fictional renaissance story.

Construction in France of the much larger Gargamelle chamber, 4.8 m long and containing 18 tonnes of freon, was quick, and by the end of 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^0 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 nucleon, 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 p17), the weak interaction became a focus of nuclear research. The unification of the electromagnetic and weak interactions by Salam, Glashow and Weinberg a decade later motivated experiments to look for the electroweak carriers: the W boson, which mediates charged-current interactions, and the Z boson associated with neutral currents. While the former were known to exist by means of β decay, the latter were barely thought of. Neutral currents started to become interesting in 1971, after Martinus Veltman and Gerard 't Hooft proved the renormalisability of the electroweak theory.

By that time, Gargamelle was running at full speed. Analysing the photographs that were taken every time the PS was pulsed to look for interesting tracks were CERN personnel (at the time often referred to as "scanning girls") who essentially performed the role of a modern level-1 trigger. Interactions were divided into different classes depending on the number of particles involved (muons, hadrons, electron–positron pairs, even one or more isolated protons as well as isolated electrons and positrons). The leptonic NC process ($\nu_\mu + e^- \rightarrow \nu_\mu + e^-$) would give an event that consisted of a single energetic electron. Since the background was very low, it would be the smoking gun for NCs. However, the cross-section was also very low, with only one to nine events expected from the electroweak calculations. The energetic hadronic NC event ($\nu_\mu + N \rightarrow \nu_\mu + X$, with the respective process involving antiparticles if the reaction was triggered by an antineutrino beam) would consist only of several hadrons, in fact just like events produced by incoming high-energy neutrons.

Ecole Polytechnique Paris

Iconic *Visionary and founding father of Gargamelle, André Lagarrigue was the driving force behind the collaboration, which ultimately led to the discovery of neutral currents at CERN.*

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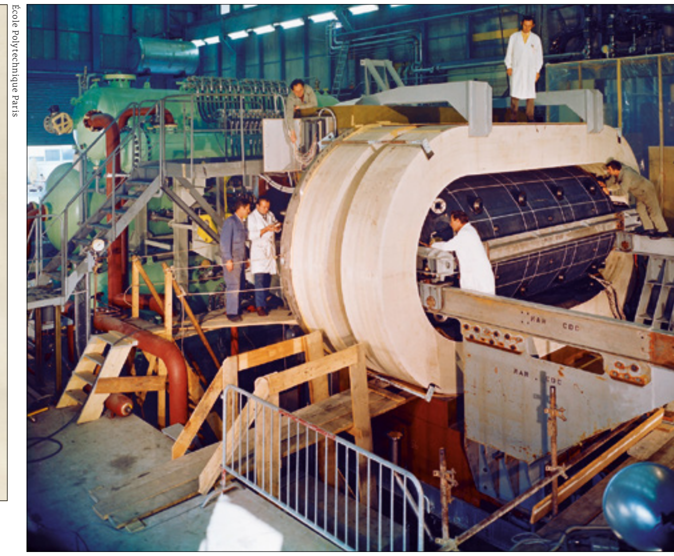

Creating the giantess *The Gargamelle bubble chamber being assembled in the neutrino-beam area of the Proton Synchrotron in 1970.*

"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 observe 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. Yet 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 unimpressed, and Jack Steinberger, who went as far as to bet half his wine cellar 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 +2/3 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 Sp$\bar{p}$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

Gargamelle data were crucial in proving that quarks have charges of +2/3 and –1/3

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

Bubble Chamber. Also hooked up to the SPS for neutrino studies at that time were CDHS (CERN–Dortmund–Heidelberg–Saclay, officially denoted WA1) 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 halt 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 1994 to 1997 and from 1995 to 1998, respectively, joined others around the world to look for interactions of the third neutrino type, the ν_τ, and to search for neutrino oscillations, i.e. the change in neutrino flavour as they propagate, which was proposed in the 1950s 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 ν_τ interactions.

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

CERN's neutrino programme entered a hiatus until July 2006, when the SPS 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 Neutrinos 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 Pyhäsalmi 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 Dakota. 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-Kamioka (T2K) neutrino facility in Japan (see p10), and has a dedicated theory working group aimed at strengthening the connections between CERN and the worldwide neutrino community. Independently, the NA61 experiment at the SPS 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, SND@LHC, 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.

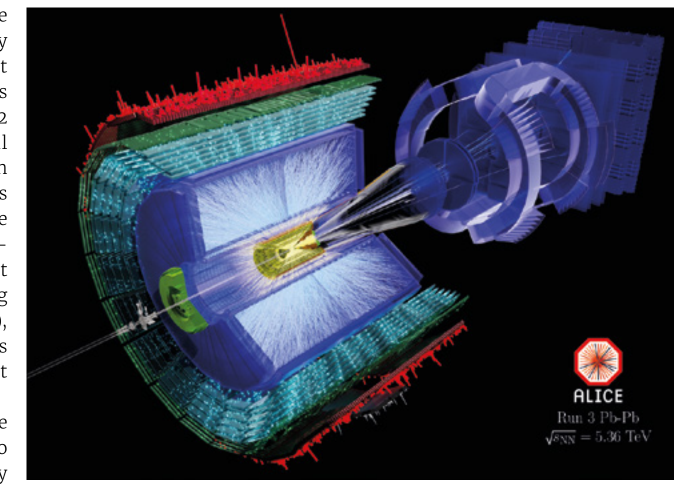
As for Gargamelle, today it lies next to BEBC and other retired colleagues in the garden of Square van Hove behind CERN's main entrance. Not many can still retell the story of the discovery of neutral currents, but those who can share the story with delight "It was very tiny that first track from the 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." ●

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 Sp$\bar{p}$S, 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).



Picture perfect *Today's event displays provide extremely crisp and detailed views of the physics processes in detectors.*

First light *The image of an electron track in a cloud chamber that is widely considered to be the first ever event display.*

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 succeeded Megatek – to make event displays as easy to understand as possible, and the same principles apply today. To make them better match human perception, two different layouts were proposed: the wire-frame technique and the fish-eye transformation. The former shows detector elements via a rendering of their shape, resulting in a 3D impression (see "Inside events" figure, left). However, the wire-frame pictures needed to be simplified when too many trajectories and detector layers were available. This gave rise to the fish-eye view, or projection in x versus y, 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

THE AUTHOR
Kristiane Bernhard-Novotny *associate editor.*

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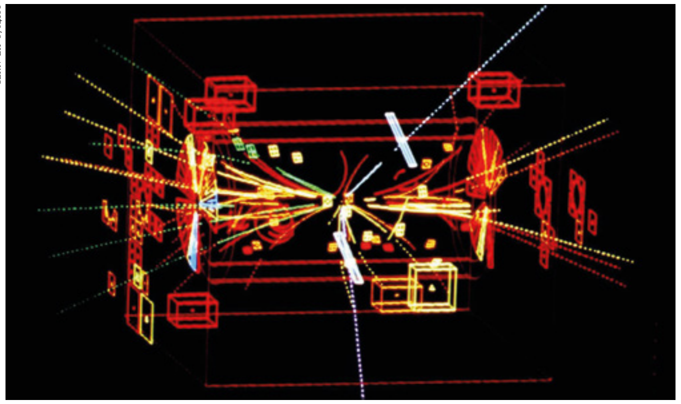
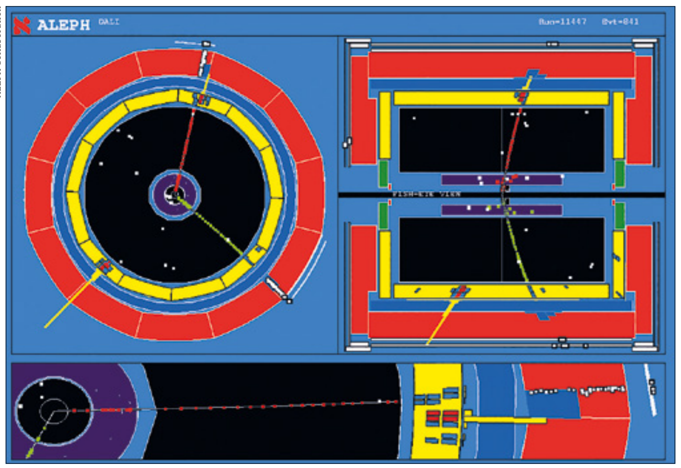


ALEPH Collaboration



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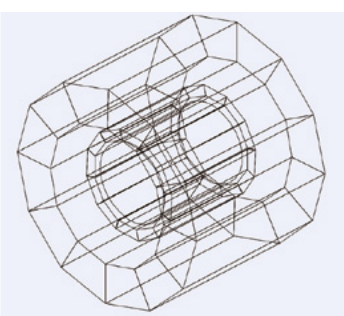


Inside events *(Top) The UA1 event display of the first Z boson that was detected, taken using drift chambers. Calorimeter hits are also shown in the display, which was created using the "Megatek" system. (Middle) The iconic event display design used at the ALEPH experiment, showing the fish-eye view that is still in use today. (Left) The wire-frame technique used during the LEP era.*

analysis algorithms to a new level, but also event displays. In a similar vein to LEP, the displays used to be more of a debugging tool for the experiments to visualise events and see how the reconstruction software and detector work. In this case, a static image of the event is created and sent to the control room in real time, which is then examined by experts for anomalies, for example due to incorrect cabling. "Visualising the data is really powerful and shows you how beautiful the experiment can be, but also the brutal truth because it can tell you something that does not work as expected," says ALICE's David Dobrigkeit Chinellato. "This is especially important after long shutdowns or the annual year-end-technical stops."

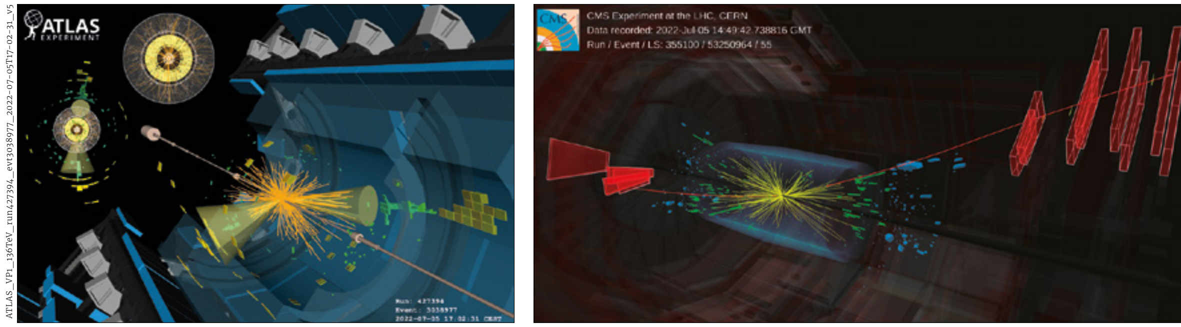
Largely based on the software used to create event displays at LEP, each of the four main LHC experiments developed their own tools, tailored to their specific analysis software (see "LHC returns" figure). The detector geometry is loaded into the software, followed by the event data; if the detector 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 pileup 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 ion run in October 2022, ALICE experimentalists have began to use software that renders each event to give it a more realistic and crisper 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 TEve.

In addition, ATLAS, CMS and ALICE have developed virtual-reality views. VP1, for instance, allows data to be exported 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 their application used for outreach. ALICE'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

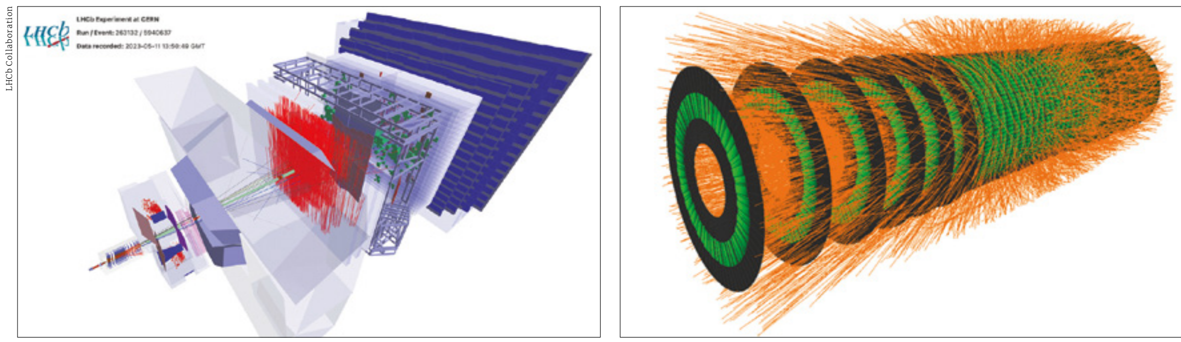
To streamline the work on event displays at CERN, developers in the LHC experiments joined forces and published a visualisation whitepaper in 2017 to identify challenges and possible solutions. As a result it was decided to create an experiment-agnostic event display, later named Phoenix. "When we realised the overlap of what we are doing across many different experiments, we decided to develop a flexible browser-based 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 Moyse of ATLAS. While experiment-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



CMS-PHO-EVENTS-2022-030-4

LHC returns *Event displays of the first LHC Run 3 collisions using the ATLAS VP1 (left) and CMS iSpy (right) display systems.*

LHCb Collaboration



TrackML

Into the future *Event displays from LHCb (left) and the simulated HL-LHC detector for the TrackML challenge made using Phoenix (right).*

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 fictious 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 Couturier. "We show the students what an event looks like from the detector to the particle tracks." CMS's iSpy 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 Tom 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 TEV (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 Pequenao 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

Further reading

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H Drevermann *et al.* 1995 CERN-ECP-95-25.

C T R Wilson 1927 "On the cloud method of making visible ions and the tracks of ionizing particles", Nobel Lecture.

OPINION
VIEWPOINT

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 Tevong You.

iStock/Petrovich9

Looking inwards *Symbiotic with cosmology and astrophysics, particle physics is pushing the boundaries of our understanding in the other direction.*

Branco Weiss Fellowship

Tevong You *is an assistant professor in theoretical physics at King's College London.*

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 $1–10 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 more of the known astrophysical objects and testing further the standard cosmological model. JWST is a success if it makes sharper observations and peers out farther 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.

Gaia, JWST and LIGO had clear scientific cases: to simply do better science

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 a future Higgs observatory. Higgs aside, new elementary particle processes are continually being unveiled, 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 more than observe. It is an experimental science 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 all 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 thriving 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 Observatory would be more apt. This better reflects the role of colliders as general-purpose tools to do good science.

The International Particle Observatory 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 over decades, to uncover fundamental knowledge that stands for all time, is a pittance 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 benefits 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 humanity 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, so colliders with the highest energies were the way to go. Back then it was the Tevatron and I joined DØ. 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 false narratives, the damage to society can be severe.

R Hahn/Fermilab

Best of both worlds *Physicist and science communicator Don Lincoln combines research with outreach activities.*

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 the videographers 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

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 with a plan. I organised it as a sort of self-contained course, beginning with basic things, like the Standard Model, weak force, strong force, etc. Towards the end, we introduced more diverse, current research topics and a few esoteric theoretical ideas. Later, after Subatomic stories, I continued 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. At 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 tolerated it. As long as it didn't bother my research, I could do this on my time. Some people bowl, some people knit, some people hike. I made videos. As I started becoming more successful, the laboratory started embracing the effort and even encouraged me to spend some of my work day on it. I was glad because in the same way that we encourage certain scientists to specialise in AI or computational skills or detector skills, I think that we as a field need to cultivate and encourage those scientists who are good at communicating our work. The bottom line is that I am very happy with the lab. I would like to see other laboratories encourage at least a small subset of scientists, those who are enthusiastic about outreach, to give them the time and the resources to do it, because there's a huge payoff.

D Lincoln

Distance learning *For more than a decade, Don Lincoln has communicated the vast science of particle physics to large audiences on YouTube.*

> **Scientists doing outreach create goodwill, which can lead to better funding for research-focused scientists**

What are your favourite and least favourite things about doing outreach?
I think I'm making an impact. For instance, I've had graduate students or even postdocs ask me to autograph a book saying, "I went into physics because I read this book." Occasionally I'm recognised in public, but the viewership numbers tell the story. If a video does poorly, it will get 50,000 viewers. And a good video, or maybe just a lucky one, can get millions. The message is getting out. As for the least favourite part, lately it is coming up with ideas. I've covered nearly every (hot) topic, so now I am thinking of revisiting early topics in a new way.

What would be your message to physicists who don't have time or see the need for science communication?
Let's start with the second type, who don't see the value of it. I would like to remind them that essentially, in any country, if you want to do research, your funding comes from taxpayers. They work hard for their money and they certainly don't want to pay taxes, so if you want to ask them to support this thing that you're interested in, you need to convince them that it's important and interesting. For those who don't have time, I'm empathetic. Depending on your supervisor, doing science communication can harm a young career. However, in that case I think that the community should at least support a small group of people who do outreach. If nothing else, the scientists doing outreach create goodwill, which can lead to better funding for research-focused scientists.

Where do you see particle physics headed and the role of outreach?
The problem is that the Standard Model works well, but not perfectly. Consequently, we need to look for anomalies both at the LHC and with other precision experiments. I imagine that the next decade will resemble what we are doing now. I think it would be of very high value if we could spend some money on thinking about how to make stronger magnets and advanced acceleration technologies, because that's the only way we're going to get a very large increase in energy. The scientists know what to do. We are developing the techniques and technologies needed to move forward. On the communication side, we just need to remind the public that the questions particle physicists and cosmologists are trying to answer are timeless. They're the questions many children ask. It's a fascinating universe out there and a good science story can rekindle anyone's sense of child-like wonder.

Interview by **Sanje Fenkart**.

A tribute to a great physicist

Memorial Volume for Jack Steinberger

Edited by Julia Steinberger, Weimin Wu and KK Phua

World Scientific


Robert W Kelley/The LIFE Picture Collection, via Getty Images

Giant *Jack Steinberger, who died in 2020 aged 99, was an experimental particle physicist of the highest order.*

This book was written on the occasion of the 100th anniversary of the birth of Jack Steinberger. Edited by Jack's daughter Julia Steinberger and his former colleagues 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, 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 Chattopadhyay in 2017. 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 Hallstein Høgåsen, a fellow in the CERN theory department, who describes the determination and perseverance he had in mountaineering. S Lokanathan worked with Jack as a graduate student in the early 1950s in Nevis Labs and remained in contact with him, including later on when he became a professor in Jaipur. Jacques Lefrançois covers the ALEPH period, and Vera Luth the earlier kaon experiments at CERN. Italo Mannelli comments on both the early times when Jack visited Bologna to work with Marcello Conversi and Giampietro Puppi, and then turns to his work at the NA31 experiment on direct CP violation in the K^0 system.

Gigi Rolandi emphasises the important role that Jack played in the design and construction of the ALEPH time projection chamber. Another good essay is by David N Schwartz, the son of Mel Schwartz who shared the Nobel prize with Jack and Leon Lederman. When David was born, Jack was Mel Schwartz's thesis supervisor. As Jack was a friend of the Schwartz family, they were in regular contact all along. David describes how his father and Jack worked together and how, together with Leon Lederman, they started the famous muon neutrino experiment in 1959. As David Schwartz later became involved in arms control for the US in Geneva, he kept in contact with Jack, who had always been very passionate about arms control. David also remembers the great respect that Jack had for his thesis supervisor Enrico Fermi. The final essay is by Weimin Wu, one of the first Chinese physicists to join the international high-energy physics research community. Weimin started to work on ALEPH in 1979 and has remained a friend of the family since. He describes not only the important role that Jack played as a professor, mentor and role model, but also for establishing the link between ALEPH and the Chinese high-energy physics community.

World Scientific

All these essays describe the enormous qualities of Jack as a physicist and as a leader. But they also highlight his social and human strengths. The reader gets a good feeling of Jack's interests and hobbies outside of physics, such as music, climbing, skiing and sailing. Many of the essays are also accompanied by photographs, covering all parts of his life, and they are free from formulae or complicated physics explanations.

For those who want to go deeper into the physics that Jack was involved with, the second part of the book consists of a selection of his most important and representative publications, chosen and introduced by Dieter Schlatter. The first two papers from the 1950s deal with neutral meson production by photons and a possible detection of parity non-conservation in hyperon decays. They are followed by the Nobel prize-winning paper "Possible Detection of High-Energy Neutrino Interactions and the Existence of Two Kinds of Neutrinos" from 1962, three papers on CP violation in kaon decays at CERN (including first evidence for direct CP violation by NA31), then five important publications from the CDHS neutrino experiment (officially referred to as WA1) on inclusive neutrino and anti-neutrino interactions, charged-current structure functions, gluon distributions and more. Of course, the list would not be complete without a few papers from his last experiment, ALEPH, including the seminal one on the determination of the number of light neutrino species – a beautiful follow-up of Jack's earlier discovery that there are at least two types of neutrinos.

This agreeable and interesting book will primarily appeal to those who have met or known Jack. But others, including younger physicists, will read the book with pleasure as it gives a good impression of how physics and physicists functioned over the past 70 years. It is therefore highly recommended.

Lau Gatignon *Lancaster University and CERN.*

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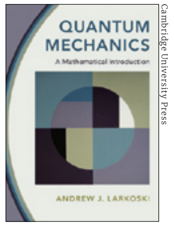
Quantum Mechanics: A Mathematical Introduction

By Andrew Larkoski

Cambridge University Press



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 reason for the title is presumably not the mathematical content, but the presentation style. A standard quantum-mechanics textbook usually starts with postulating Schrödinger's equation and then proceeds immediately to applications on physical systems. For example, the very popular *Introduction to Quantum Mechanics* by Griffiths and Schroeter (2018, CUP) introduces Schrödinger's equation on the first page and, after some discussion on its meaning and basic computational techniques, the first application on the infinite square well appears on page 31. Larkoski aims to build an intuitive mathematical foundation before introducing Schrödinger's equation. Hilbert spaces are discussed in the context of linear algebra as an abstract complex vector space. Indeed, space is given at the very beginning for ideas, such as the relation between the derivative and a translation, that are useful for more advanced applications of quantum mechanics, for example in field theory, but which seldom appear in quantum-mechanics textbooks so early. Schrödinger's equation does not appear until page 58, and the first application in a system (which, as usual, is the infinite square well) appears only on page 89.

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, since 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.

Nikolaos 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.

S Fenkart

Melting point *Engineer Audrey Vichard next to a prototype vacuum tube for the Einstein Telescope.*

Welding is the technique of fusing two materials, often metals, by heating them to their melting 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's a 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 provides 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 submarines 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 to 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 behaviour that will greatly influence the welding process. To meet the strict operating 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 physicists 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, juggling 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. If not, we can adapt the design or 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 CERN-wide. On a typical day, I can go from performing 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 proposed next-generation gravitational-wave observatory in Europe. It is part of a new collaboration between CERN, Nikhef and the INFN to design the telescope's colossal vacuum system – the largest ever attempted (see p18). 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, one fully prototyped beampipe has been finished using stainless steel and another is in production with common steel; the third is yet to be done. The next main step will then be to go from the current 3 m-long prototype to a 50 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.*

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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–Ion Collider 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 history of accelerator-based science, discovery and innovation, and I look forward to 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 Jarlskog (below; Lund University) "for the discovery of an invariant measure of CP violation in both quark and lepton sectors" and to the members of the Daya Bay and RENO collaborations "for the observation of short-baseline reactor electron–antineutrino disappearance, providing the first determination of the neutrino mixing angle θ_{13}". The 2023

Giuseppe and Vanna Cocconi Prize is awarded to the SDSS/BOSS/eBOSS collaborations "for their outstanding contributions to observational cosmology", which includes the use of baryon acoustic oscillations to help constrain the Hubble constant, neutrino masses and dark energy. The 2023 Gribov Medal is awarded to Netta Engelhardt (MIT) "for her ground-breaking contributions to the understanding of quantum information in gravity and black-hole physics". Recognising her contribution to the construction of the ATLAS inner tracker, the development of novel track and

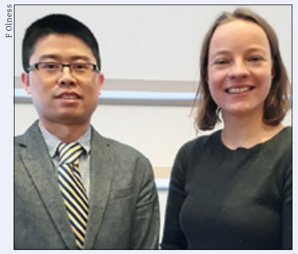
vertex reconstruction algorithms, and searches for di-Higgs production, Valentina Cairo (above; ATLAS/CERN) receives the 2023 Young Experimental Particle Physics prize. Finally, theorist Jácome Armas (University of Amsterdam) is the recipient of the EPS–HEPP Outreach Prize for a combination of science 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/University of Manchester) has been granted a 2023 Rising Talents award from the L'Oreal–UNESCO Women 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 instrument at the ISOLDE facility.

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 Adinda de Wit (University of Zurich, above right) for her achievements in understanding the nature of the Higgs boson and theorist Yong Zhao (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 by 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.

RECRUITMENT

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PEOPLE OBITUARIES

Giorgio Brianti 1930–2023

Steering CERN to success

Giorgio Brianti, a pillar of CERN throughout his 40-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 Edoardo 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: "Edoardo Amaldi received me very warmly and, after various discussions, he said to 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 in half a century has made CERN 'the' world laboratory for particle physics."

Giorgio had boundless admiration for John Adams, who had been recruited by Amaldi a year 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 Adams to Genoa 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 synchrocyclotron division. After only four years he was asked to create a new division to build a very innovative synchrotron – the Booster – capable of injecting protons into the PS and significantly increasing the intensity of the accelerated current. Adams – who had been appointed Director-General of the new CERN-Lab II to construct the 400 GeV Super Proton Synchrotron (SPS) – also entrusted

Giorgio Brianti (right) with Director-General John Adams in 1979.

Giorgio with designing and building the experimental areas and their beam lines. The 40th anniversary of their inauguration was celebrated with him in 2018 and the current fixed-target experimental programme profits to this day from his foresight.

In January 1979 Giorgio was made head of the SPS division, but only two years later he was called to the role of technical director by the newly appointed Director-General Herwig Schopper. As Giorgio writes: "The main objectives of the mandate were to build the LEP ... and to complete the SPS proton–antiproton programme, a very risky enterprise, but whose success in 1982 and 1983 was decisive for the future of CERN." The enormous technical work required to transform the SPS into a proton–antiproton collider that went on to discover the W and Z bosons took place in parallel with the construction of LEP and the launch of the LHC project, to which Giorgio personally devoted himself beginning in 1982.

The LHC occupied Giorgio for nearly 15 years, starting from almost nothing. As he writes: "It was initially a quasi-clandestine activity to avoid possible reactions from the delegates of the Member States, who would not have understood an initiative parallel to that of the LEP."

The LHC received a significant boost from Carlo Rubbia, who became Director-General in 1989 and appointed Giorgio as director of future accelerators. While LEP was operating at full 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, of course! In particular, in 1996 he agreed to chair the advisory committee of the Proton Ion Medical 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 fundamental science.

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 but mindful not to hurt others. He was very attached to his family and friends. His intelligence, kindness and generosity shone through his eyes and – despite his reserved character – touched the lives of everyone he met.

His colleagues and friends.

Stanley Deser 1931–2023

A towering figure in theoretical physics

Theoretical physicist Stanley Deser, a co-inventor of supergravity, passed away in Pasadena, California, on 21 April.

Stanley was born to middle-class Jewish parents in Rovno, then in Poland. In 1935 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 1953 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 lectureship at Harvard University (1957–1958), he joined the faculty of the physics department at Brandeis in 1958, where he remained until he retired in 2005. After moving to Pasadena, he remained an emeritus professor at Brandeis, and continued to publish physics papers until this year (as well as his autobiography, *Forks in the Road*, in 2021). ▷

Stanley was a towering figure in theoretical high-energy physics, classical gravity and quantum gravity. His work cuts through mathematical complexity with deep physical insight. His first signature work, the Arnowitt–Deser–Misner (ADM) formalism, gave a Hamiltonian initial-value formalism for general relativity. This work is the foundation of precise calculations in inflationary cosmology, needed to match cosmic microwave background observations; and in numerical relativity calculations needed to interpret the results of gravitational-wave experiments. He leaves behind a lifetime of work in theoretical physics that remains foundational, including co-inventing supergravity (contemporaneously with Ferrara, Freedman and van Nieuwenhuizen) and formulating the dynamics of the superstring with Zumino; showing that general theories with massive gravity are inconsistent; and developing topologically massive gauge theories and gravity with Jackiw and Templeton.

Stanley was an important member of the scientific community. As Rainer Weiss, who shared the 2017 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

Stanley Deser will be remembered for his wisdom and ready wit.

of the National Academy of Sciences (NAS) and the American Academy of Arts and Sciences; a foreign member of the Royal Society and the Torino Academy of Sciences; he was awarded the Dannie Heineman Prize in Mathematical Physics and the Einstein Medal, along with the Guggenheim and Fulbright awards; and held honorary doctorates from Stockholm University and the Chalmers Institute of Technology.

Stanley will be remembered for his wisdom and ready wit; emails and talks in which every sentence had multiple meanings 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 Elsbeth Deser (daughter of Oskar Klein), and his daughter Eva. He leaves behind three daughters – retired linguist Toni Deser; theatre director Abigail Deser; and atmospheric scientist (and fellow NAS member) Clara Deser – and four grandchildren, Ursula, Oscar, Louise and Simon.

Albion Lawrence *Brandeis University.*

Stavros Katsanevas 1953–2022

A tireless apostle of astroparticles

Stavros Katsanevas, 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 Astroparticle and Cosmology (APC) laboratory.

Born in Athens in 1953, Stavros pursued physics at the University of Athens. In 1979 he obtained his speciality doctorate from École polytechnique in Paris. He obtained his PhD at Athens in 1985, and later became an associate professor there (1989–1996). From 1979 to 1982 he spent three years as a postdoc at Fermilab. He also worked at CERN, as a research fellow (1983–1986), research associate (1991–1992) and corresponding fellow (1996). He was then appointed professor at the University Claude Bernard Lyon 1, and in 2004 became a professor at the University Paris VII Denis Diderot (now Université Paris Cité).

From 2002 to 2012 Stavros was deputy scientific director of IN2P3, during which he steered the institute to a leading position in astroparticle physics. He was particularly active in the emerging field of multi-messenger astronomy and in instrumentation. In this context, he played a key role in the creation of the APC laboratory in Paris, of which he was director from 2014 to 2017. Until his death, he led the French–Italian European Gravitational Observatory consortium, coordinating projects related to the detection of gravitational waves with the Virgo observatory.

Stavros's scientific career was extremely rich, as evidenced by hundreds of publications on topics related to research collaborations, experimental techniques, or the conception and design of new research infrastructures. At CERN, he distinguished himself by developing software for simulating particle interactions, which later became a standard used at LEP. He also played an essential role in federating teams in several large international collaborative projects. One example is his involvement in the OPERA experiment at Gran Sasso laboratory; another is his leading role in the development of underwater neutrino telescopes, starting

Stavros Katsanevas' many contributions ranged from astroparticle physics to art in science.

with the NESTOR project, which led to ANTARES and KM3NeT.

Over the past 15 years, Stavros played a central role in defining a global strategy in astroparticle physics. 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 Excellence UnivEarthS from 2014 to 2018 and at the forefront of a seismometer project to be installed on the Moon.

Stavros was keen to promote science to a wide audience. Since 2015, he was a member of the jury for the Daniel and Nina Carasso Foundation, and in 2019 he organised an exhibition "The Rhythm of Space" at the museo della Grafica in Pisa. He was also coordinator of the European Horizon 2020 project REINFORCE, which intends to support more than 100,000 citizens to increase their awareness of and attitude towards science.

Stavros was driven by an inexhaustible desire to contribute to the advancement of science by serving, stimulating and animating the community. Steeped in philosophy, literature and poetry, he was also remarkably kind and generous. His thought, his vision, his driving force, will continue to accompany his.

Antoine Kouchner *director APC,*
Sotiris Loucatos *and* **Rosy Nikolaidou**
APC and Irfu, CEA Saclay.

CERNCOURIER

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BACKGROUND

Notes and observations from the high-energy physics community

First stone for DESYUM


© Lopez Gonzalez/DESY

CERN isn't the only particle-physics lab upping its offering to visitors. On 31 May DESY laid the cornerstone for DESYUM – a new visitor centre comprising a large atrium, 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 Dosch, chairman of the DESY board of directors (pictured left, with Hamburg science senator Katharina Fegebank, DESY's administrative director Christian Harringa and architect Matthias Latzke).

Alumni Network turns six


CERN

On 8 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 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 issues, and Patrick Glauner, now an AI professor. "This event once again highlighted how an experience at CERN serves as a transformative springboard for one's career," said head of alumni relations Rachel Bray, pictured (left) hosting the livestream from the CERN Neutrino Platform.

Media corner

"I was convinced that once the LHC goes online, we would find dark-matter particles. I even bet a crate of champagne, unfortunately I lost."
Günther Hasinger, former science director at ESA, talking to *Der Standard* (31 May) about the search for dark matter.

"In experiments like this, the whole world works against you."
Vivishek Sudhir of MIT discussing the Archimedes experiment in Sardinia, a testbed for the Einstein Telescope, which aims to "weigh" vacuum (*Scientific American* 1 May).

"A counterintuitive property of these anyons is that they are not really physical, they don't care what they're made of… They're just about information and entanglement."
Henrik Dreyer of quantum-computing firm Quantinuum 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 microscopy (*Radio France* 4 May).

From the archive: July/August 1983

From Galileo to the Z° … and beyond


R Pecoraro

The recent San Remo 'Science for Peace' meeting commemorated the 150th anniversary of the birth of Alfred B. Nobel.

On 3 May an impressive array of eminent scientists gathered in San Remo at the 'Science for Peace' meeting, one of six international nuclear physics symposia organized by Nino Zichichi.

CERN's observation of a first Z° candidate, announced by Director General Herwig Schopper, was greeted with praise from Sheldon Glashow, one of the theoreticians whose ideas appeared vindicated, and from I.I. Rabi who helped motivate the creation of the European laboratory over 30 [now 70] years ago. Simon van der Meer explained stochastic cooling, which turned the dream of antiproton physics into reality, making the crucial experiments possible.

Sam Ting's report of key ideas behind experiments on photons, leptons, quarks and gluons turned thoughts towards big machines being built, planned or imagined. Glashow wondered whether we needed another Einstein rather than new accelerators, but in Viki Weisskopf's view, new accelerators will be built because spending on fundamental research is a great feature of our civilization.

And on to Rome, for a symposium marking the 350th anniversary of Galileo's famous 'Dialogues'. Pope John Paul II greeted 33 Nobel Laureates and about 200 scientists in the Barberini Palace room where Galileo often visited his friend, who later came into conflict with him as Pope Urban VII. John Paul II reiterated his hope that dispelling past misunderstandings will lead to fruitful concord between science and faith.

● Based on text on pp217–218 of *CERN Courier* July/August 1983.

Compiler's note

The elusive Higgs boson appeared in 2012 at the 27 km Large Hadron Collider, one of the big machines that was built. Now the spending and limelight are shared with giant leaps forward, or rather backwards, in astrophysics. The James Webb Space Telescope (JWST), being larger than the Hubble Telescope, detects longer wavelengths, highly red-shifted by the expansion of the universe. In April 2022 the faintest and furthest galaxies ever observed were seen by the JWST when they were about a quarter of a billion years 'old' and 30 billion light-years from Earth. Closer to home, in October 2022 the brightest gamma-ray burst on record, GRB 221009A, was seen sweeping through Earth from a supernova remnant about 2.4 billion light-years away. A month later, the most energetic, cosmic explosion detected to date – and ongoing – was from AT2021lwx, 8 billion light-years away. Watch that space!

230 m

The largest separation between two entangled trapped-ion qubits ever achieved, by researchers in Austria, suggests that trapped ions could be used to create quantum networks (*Phys. Rev. Lett.* 130 050803)