WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2020 issue of *CERN Courier*.

This issue's cover feature (p36) describes recent results from CERN's ISOLDE facility, where researchers are probing the extremities of the nuclear landscape to complete our understanding of the nuclear interaction. Advanced laser and trapping techniques developed over many years at ISOLDE are also bringing new ways to test physics beyond the Standard Model.

This autumn CERN launches its quantum technology initiative (p47) – part of a fast-growing interdisciplinary effort taking place worldwide to develop quantum computing, communication, sensing and other devices that promise to underpin a "second quantum revolution" (p49).

Sticking with CERN science, we report on new tetraquark discoveries by LHCb (p25), NA62's evidence for an ultra-rare kaon decay (p9), the first signs of Higgs–muon coupling (p7), and how the Higgs boson has so far delivered three fundamental discoveries (p41). Also, don't miss our special feature on careers from the CERN Alumni Network (p56).

Elsewhere in this issue: the European Spallation Source nears completion (p29); neutrinos prove rare solar-fusion process (p11); how particles attract Nobel prizes (p70); reports from ICHEP and Neutrino 2020 (p19); news in brief (p13); reviews (p53), and more.

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EDITOR: MATTHEW CHALMERS, CERN
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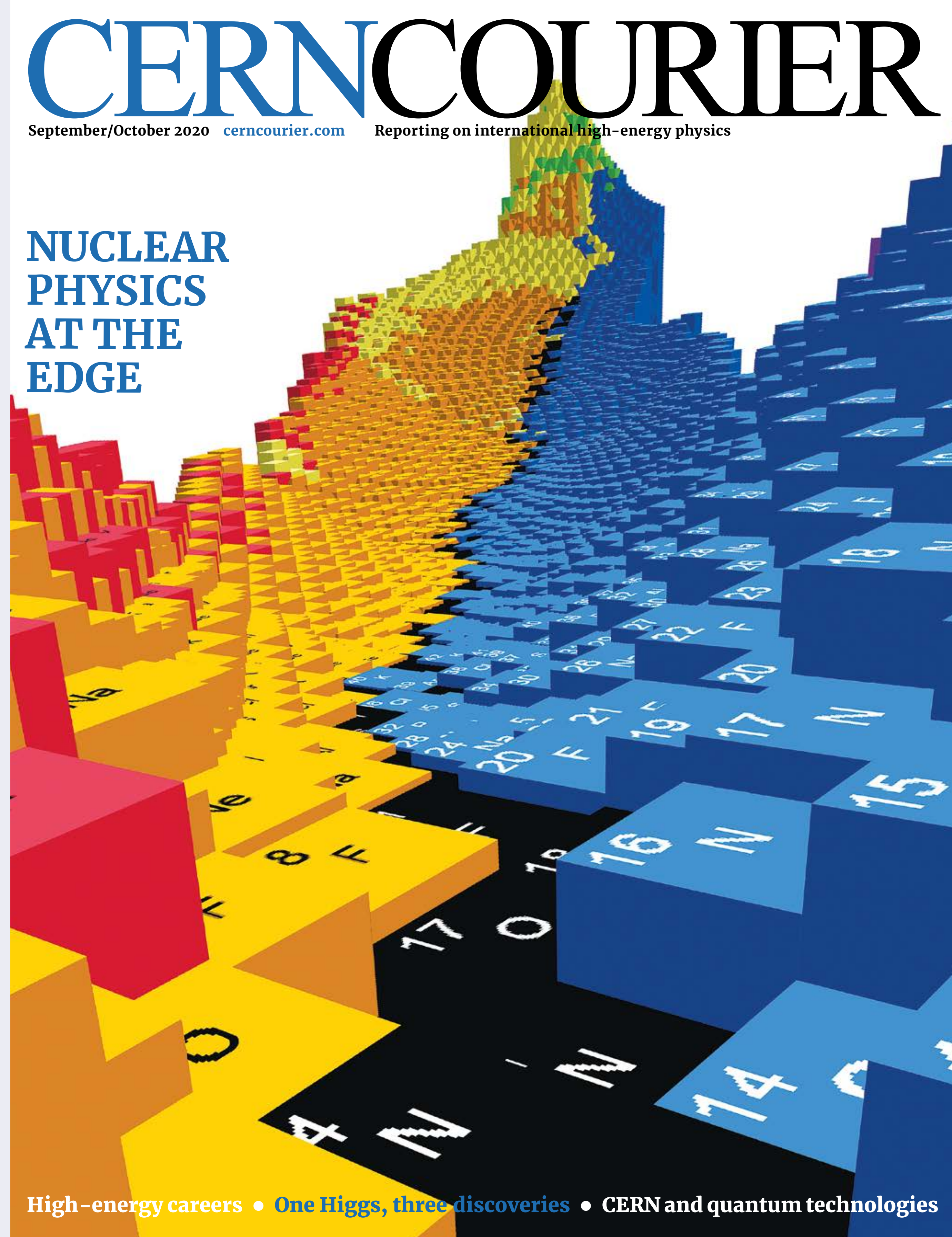

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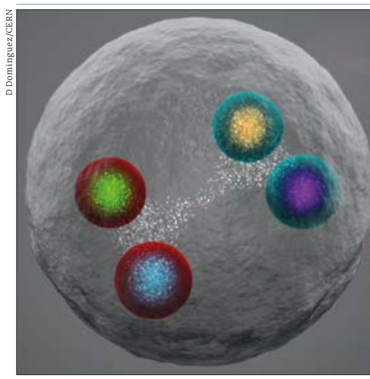

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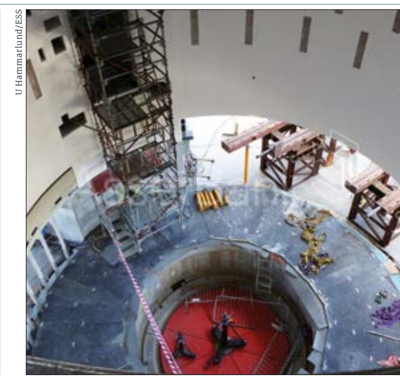

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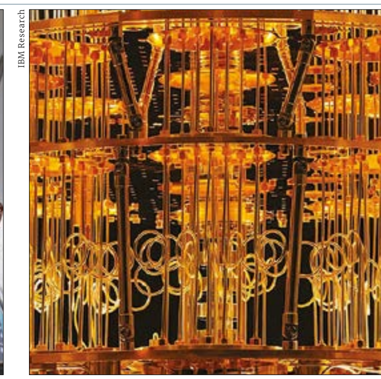

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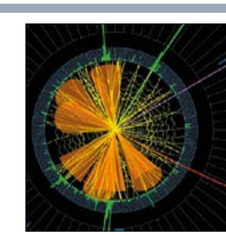

CMS-PHO-EVENTS-2019-002-2

OPINION

DEPARTMENTS

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FROM THE EDITOR

ISOLDE: shaping the nuclear landscape

Matthew Chalmers
Editor

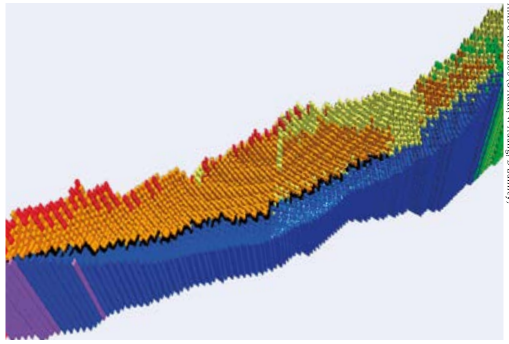
After 100 years of expanding and exploring the chart of the nuclides (cover image) physicists are still without a complete understanding of nuclear interactions. An early picture of the nucleus was of an incompressible liquid drop. Systematic surveys of the nuclear chart later revealed that protons and neutrons arrange themselves in quantum orbits or shells, with certain "magic" numbers of nucleons resulting in greater stability. Reconciling the drop and shell models has been a longstanding quest, but a lack of predictive power has required further exploration of the nuclear chart to reveal clues.

By continuing to innovate in the production and purification of the most exotic species, CERN's ISOLDE facility leads the charge in probing the extremities of the nuclear landscape (see p36). Understanding nuclear structure relies on measurements of the mass and radii of nuclei, made possible by precision laser and trapping techniques developed at ISOLDE over many years, which have been adopted by facilities worldwide. The farther experimenters venture from the valley of stability, the more surprises they find – the most dramatic being the erosion of the stabilising magic of closed nuclear shells, which gives way to nuclei in contorted dis-equilibrium.

ISOLDE's ability to produce the most exotic nuclides is also stimulating developments in theory, in particular ab-initio techniques, derived using chiral effective field theory that respects the symmetries of QCD. Recently, precision laser and mass spectroscopy have brought radioactive molecules within its grasp – offering a new way to detect possible electric dipole moments that would point to new physics. In its sixth decade, ISOLDE continues to innovate and evolve.

CERN's science is a strong theme of this issue

CERN's science is a strong theme of this issue, with recent results from LHCb reinvigorating the tetraquark debate (p25), NA62 establishing evidence for an ultra-rare kaon decay (p9), and the LHC experiments reporting the first indications of couplings of the Higgs boson to a second-generation fermion (p7 and p41). Our special feature on the CERN Alumni Network (p56), meanwhile, highlights the high value placed by employers on skills gained from training in high-energy physics.



AMDC-NUCLEUS (G Audi, W Huang, D Lunney)

Onwards and outwards *Nuclear mass excess versus proton and neutron number. Colours show decay mode (stable nuclides in black).*

Quantum future

This autumn, CERN launches its quantum technology initiative (p47). New quantum computing, communication and sensing devices that harness properties such as entanglement promise to underpin a "second quantum revolution", following the information and communication technology that resulted from the birth of quantum mechanics in the 20th century. Several major national programmes are already under way, with the US recently announcing more than $500M for five quantum-science institutes at its national laboratories (p13). Though relatively new to the game, CERN has significant experience in many of the relevant domains and provides valuable use-cases, particularly in quantum computing.

As our interview (p49) explores, it is too early to tell how quantum technologies will impact society – just as nobody in the 1950s could have predicted that billions of transistors would be packed into our pockets today. But it is clear that high-energy physics stands to benefit from new computing, sensing and other quantum-technology applications, and that labs like CERN have the potential to make a real impact.

Reporting on international high-energy physics

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CERN

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Editor Matthew Chalmers
Associate editor Mark Rayner
Archive contributor Peggie Rimmer
Astrowatch contributor Merlin Kole
E-mail cern.courier@cern.ch

Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Laboratory correspondents
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Temple Circus, Temple Way, Bristol BS1 6HG, UK
Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Tom Houlden
Recruitment sales Chris Thomas
Advertisement production Katie Graham
Marketing and circulation Laura Gillham

Advertising
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NEWS ANALYSIS

Higgs boson

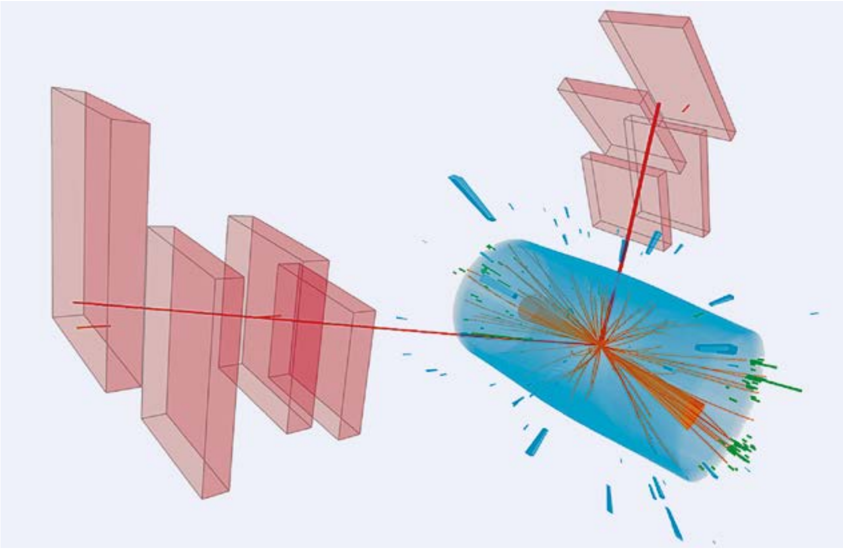
Turning the screw on H → μμ

The first evidence for the coupling of the Higgs boson to a second-generation fermion, the muon, has been reported at the LHC. At the 40th International Conference on High Energy Physics, held from 28 July to 6 August (see p19), CMS reported a 3σ excess of H → μμ decay candidates compared to the expected sample under the hypothesis of no coupling between the Higgs boson and the muon. A similar analysis by the ATLAS collaboration yielded a 2σ excess for the coupling.

The latest measurements of the Higgs boson by ATLAS and CMS follow 5σ observations of its coupling to the tau lepton in 2015 and to the top and bottom quarks in 2018, all of which are third-generation fermions. Its couplings to W and Z bosons have also been established at 5σ confidence. Within present experimental accuracy, all couplings between the Higgs boson and other Standard Model particles correspond to the strength of interaction that would give the particles their observed masses, according to the Brout–Englert–Higgs mechanism. In this model, the particles acquire mass through spontaneous symmetry breaking; the W and Z as a result of a local gauge symmetry and the fermions, such as the muon, as a result of Yukawa couplings to the Higgs field – a novel type of interaction among fundamental particles that is not derived from a symmetry principle (see p41). Any deviation from the expected couplings would imply that the Higgs sector is more complicated than this minimal scenario.

Couplings to lighter particles are expected to be proportionately smaller and more difficult to observe. The decay to two muons, H → μμ, is expected to occur with a branching fraction of just one in 5000 Higgs-boson decays, and is overwhelmed by backgrounds from the Drell–Yan process.

The new ATLAS and CMS analyses, which deploy the entire 13 TeV Run-2 data set, include events where the Higgs boson was produced according to four topologies: gluon fusion, which accounts for the creation of 87% of the Higgs bosons observed at the LHC; vector-boson fusion; the production of a Higgs boson in association with a weak vector boson; and its production in association with a top quark–antiquark pair. Uniquely, CMS simulated the background to the vector-boson-fusion signal rather than fitting it from data – a procedure that would have incurred additional statistical uncertainty – resulting in the topology contributing roughly equal statistical power compared to gluon fusion.



New topology *A CMS candidate for Higgs-boson production via vector-boson fusion and its decay into two muons (red lines).*

Machine learning

"The first evidence in CMS was reached thanks to the excellent performance of our muon and tracking systems, and an improved signal/background discrimination with machine-learning techniques," says Andrea Rizzi, CMS physics co-coordinator.

The new results sharpen the question of why there is a hierarchy of particle masses

The signature for the decay is a small excess of events near a muon-pair invariant mass of 125 GeV – the mass of a Higgs boson. CMS reports an overall signal strength of 1.2 ± 0.4, while ATLAS finds a signal strength of 1.2 ± 0.6, with the uncertainties dominated by their statistical component. "Both measurements are compatible with the Standard Model," says ATLAS physics coordinator Klaus Mönig. "Assuming the H → μμ coupling predicted by the Standard Model, and extrapolating the current results, the combined sensitivity could get near the observation threshold of 5σ at the end of Run 3, from 2022 to 2024."

If there is only a single Higgs field, it should provide the masses for all the Standard-Model particles, but there may be additional Higgs fields that could make contributions to their masses. The new results therefore reduce the scope available to such multi-Higgs models, and sharpen the question of why there is a hierarchy of particle masses, says John Ellis of King's College London. "Why is the Higgs coupling to the muon so different from its coupling to the tau lepton, whereas the couplings of the W boson to tau leptons and muons are equal to within a couple of percent? The more we learn about the Higgs, the more mysterious it seems!"

Further reading

ATLAS Collab. 2020 arXiv.org:2007.07830.
CMS Collab. 2020 CMS-PAS-HIG-19-006.

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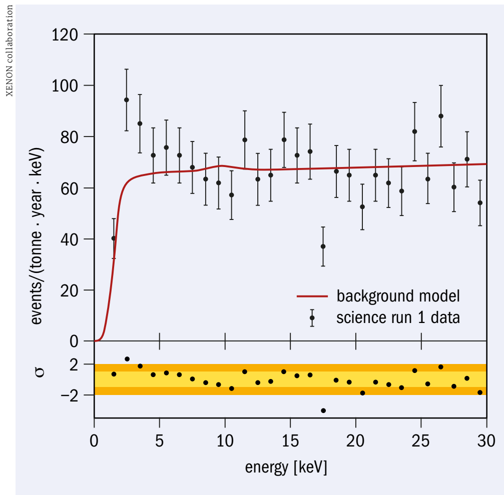
Dark matter

Researchers grapple with XENON1T excess

An intriguing low-energy excess of background events recorded by the XENON1T detector at Gran Sasso National Laboratory in Italy has sparked a series of preprints speculating on its underlying cause, ranging from unexpected background sources to phenomena beyond the Standard Model. On 17 June the XENON collaboration, which searches for excess nuclear recoils in a one-tonne liquid-xenon time-projection chamber (TPC), reported an unexpected excess of events at energies of a few keV. Though acknowledging that the excess could be due to a difficult-to-constrain tritium background, the collaboration says that solar axions and solar neutrinos with a Majorana nature, both of which would signal physics beyond the Standard Model, are credible explanations for the approximately 3σ effect.



XENON collaboration

Threshold events *XENON1T data from scientific run 1, from February 2017 to February 2018, show an excess of low-energy electronic recoils above the background model.*

World-leading limits

The XENON collaboration has been in pursuit of WIMPs, a leading cold-dark-matter candidate, since 2005 with a programme of 10 kg, 100 kg and now 1 tonne liquid-xenon TPCs. Particles scattering in the liquid xenon create both scintillation light and ionisation electrons; the latter drift upwards in an electric field towards a gaseous phase where electroluminescence amplifies the charge signal into a light signal. XENON1T derives its world-leading limit on WIMPs – the strictest 90% confidence limit being a cross-section of $4.1\times10^{-47}\,cm^2$ for WIMPs with a mass of 30 GeV – from the very low rate of nuclear recoils observed by XENON1T from February 2017 to February 2018.

A surprise was in store, however, in the same data set, which also revealed 285 electronic recoils at the lower end of XENON1T's energy acceptance, from 1 to 7 keV, over the expected background of 232 ± 15. The sole background-modelling explanation for the excess that the collaboration has not been able to rule out is a minute concentration of tritium in the liquid xenon. Though cryogenic distillation plus running the liquid xenon through a getter is expected to remove any tritium below the level that would be relevant, there is not yet any instrument sensitive enough to directly detect such a trace amount, says the collaboration.

One explanation proposed by the team is solar axions, which, should they exist, would be produced by the Sun at energies consistent with the XENON1T excess. According to this hypothesis, the axions would be detected via the "axioelectric" effect, an axion analogue of the photoelectric effect. Though a good fit phenomenologically, and like tritium favoured over the background-only hypothesis at approximately 3σ, the solar-axion explanation is disfavoured by astrophysical constraints. For example, it would lead to a significant extra energy loss in stars.

> **If the XENON1T signal is indeed an axion, IAXO will find it within the first hours of running**

Axion helioscopes such as the CERN Axion Solar Telescope (CAST) experiment will help in testing the hypothesis. "It is not impossible to have an axion model that shows up in XENON but not in CAST, but CAST already constrains part of the axion interpretation of the XENON signal," says CAST deputy spokesperson Igor Garcia Irastorza of the University of Zaragoza. Its successor, the International Axion Observatory (IAXO), which is set to begin data taking in 2024, will have improved sensitivity. "If the XENON1T signal is indeed an axion, IAXO will find it within the first hours of running," says Garcia Irastorza.

A second new-physics explanation cited for XENON1T's low-energy excess is an enhanced rate of solar neutrinos interacting in the detector. In the Standard Model, neutrinos have a negligibly small magnetic moment, however, should they be Majorana rather than Dirac fermions, and identical to their antiparticles, their magnetic moment should be larger, and proportional to their mass, though still not detectable. New physics could, however, enhance the magnetic moment further, leading to a larger interaction cross section at low energies and an excess of low-energy electron recoils. XENON1T fits indicate that solar Majorana neutrinos with an enhanced magnetic moment are also favoured over the background-only hypothesis at the level of 3σ.

Flurry of activity

The community has quickly chimed in with additional ideas, with more than 100 papers citing XENON1T's findings appearing on the arXiv preprint server since the result was released. One possibility is a heavy dark-matter particle that annihilates or decays to a second, much lighter, "boosted dark-matter" particle that could scatter on electrons via some new interaction, notes CERN theorist Joachim Kopp. Another class of dark-matter model that has been proposed, he says, is "inelastic dark matter", where dark-matter particles down-scatter in the detector into another dark-matter state just a few keV below the original one, with the liberated energy then seen in the detector. "An explanation I like a lot is in terms of dark photons," he says.

The XENON collaboration is soon to start taking data with a new detector, XENONnT. With three times the fiducial volume of XENON1T and a factor six reduction in backgrounds, explains XENON spokesperson Elena Aprile of Columbia University in New York, XENONnT should be able to verify or refute the signal within a few months of data taking. "I am especially intrigued by the possibility to detect axions produced in the Sun," she says. "Who needs the WIMP if we can have the axion?"

Further reading

E Aprile *et al.* 2020 arXiv.org:2006.09721.

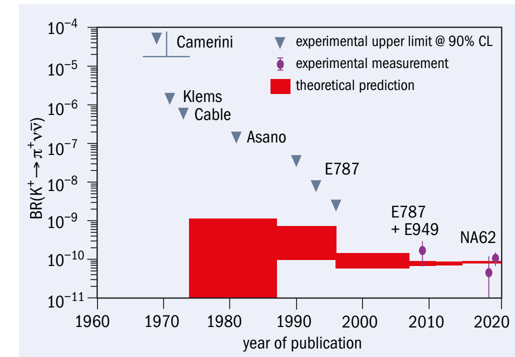
Rare decays

Double digits for ultra-rare kaon decay

CERN's NA62 collaboration has presented its latest progress in the search for $K^+\rightarrow\pi^+\nu\bar{\nu}$ – a "golden decay" with exceptional sensitivity to physics beyond the Standard Model (SM). The new analysis provides the strongest evidence yet for the existence of this ultra-rare process, at 3.5σ significance. "After several years of a very challenging analysis, battling 10 orders of magnitude of background over the signal, we are proud to have achieved the first statistically significant evidence for a process that has great sensitivity to new physics," says lead analyst Giuseppe Ruggiero of Lancaster University, who presented the result on 5 August during the International Conference on High-Energy Physics (see p19).

A flavour-changing, neutral-current process, $K^+\rightarrow\pi^+\nu\bar{\nu}$ is highly suppressed in the SM, with contributions from Z-penguin and box diagrams with W, top quark and charm exchanges. It is also very "clean" theoretically, since the low-energy hadronic matrix elements are just those of the quark currents between the hadronic states.

NA62 observes the 6% of positively charged kaons that are produced when 450 GeV protons from the Super Proton Synchrotron strike a beryllium target. The analysis is challenging because of the tiny branching fraction and the presence of a neutrino pair in the final state. Pioneering the technique of observing kaon decays in flight, the collaboration measures the kinematics of both the initial kaon and the final-state pion to isolate the kinematic signature of $K^+\rightarrow\pi^+\nu\bar{\nu}$, before then suppressing other decay modes by a further eight orders of magnitude using particle-identification techniques.



NA62 collaboration

Convergence *Theoretical predictions and experimental measurements of the $K^+\rightarrow\pi^+\nu\bar{\nu}$ branching fraction.*

The collaboration's new result, which includes the full dataset collected until 2018, adds a further 17 events to its previous analysis, wherein three events observed in 2016 and 2017 yielded an estimated branching fraction of 47^{+72}_{-47} decays per trillion. The measured branching fraction of 110^{+40}_{-35} per trillion is in agreement with the SM prediction of 84 ± 10 per trillion.

The NA62 result is expected to soon be complemented by a measurement of the related CP-violating $K_L\rightarrow\pi^0\nu\bar{\nu}$ decay by the KOTO collaboration at the J-PARC research facility in Tokai, Japan. This even rarer process has a predicted SM branching fraction of just 34 ± 6 per trillion. KOTO's 2015 data yielded no event candidates and a 90% confidence upper limit on the branching fraction of 3.0 per billion, but the collaboration is now finalising its results from the 2016–2018 run, and plans to improve its sensitivity to less than 0.1 per billion by increasing the beam intensity and upgrading the KOTO detectors.

As experimental uncertainties are expected to approach the theoretical precision in coming years, explains theorist Andrzej Buras of the Institute for Advanced Study in Garching, Germany, $K^+\rightarrow\pi^+\nu\bar{\nu}$ and $K_L\rightarrow\pi^0\nu\bar{\nu}$ decays can probe scales as high as a few hundred TeV – beyond the reach of most B-meson decays. "$K^+\rightarrow\pi^+\nu\bar{\nu}$ is most sensitive to hypothetical Z′ gauge bosons, vector-like quark models, supersymmetry and some leptoquark models," he says. "LHCb studies of $K_S\rightarrow\mu^+\mu^-$ and Belle II studies of $B\rightarrow K(K^*)\nu\bar{\nu}$ will also have a part to play, allowing a global analysis to test not only the concept of minimal flavour violation, but also probe new CP-violating phases and right-handed currents."

Theorists expect to reach an accuracy of 5% on the predicted $K^+\rightarrow\pi^+\nu$ branching ratio towards the end of the decade. In the same period, the NA62 team is seeking to hone its resolution from the current 30% down to 10%. The collaboration will resume data taking in 2021, following upgrades to both beam and detector taking place during the ongoing second long shutdown of CERN's accelerator complex. "The horizon of a new-physics programme with a sensitivity to decay rates well below the 10^{-11} level is now in sight," says NA62 spokesperson Cristina Lazzeroni of the University of Birmingham, UK.

Further reading

NA62 Collab. 2020 arXiv:2007.08218.

Policy

UK report shows impact of CERN membership

The benefits of CERN membership go well beyond science and technology, confirms a study commissioned by the UK's Science and Technology Facilities Council (STFC). The report "Evaluation of the benefits that the UK has derived from CERN", published on 6 August, finds that around 500 UK firms have benefitted from supplying goods and services to CERN during the past decade, bringing in £183.3M in revenue. An additional £33.4M was awarded to UK firms for CERN experiments ▷

HV Wooding

Profit *An electroplating plant at UK engineering firm HV Wooding, which is one of 500 UK companies to have benefitted from supplying goods and services to CERN during the past decade.*

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and from the CERN pension fund, while a further £1B in turnover and £110M in profit is estimated to have resulted from knock-on effects for UK companies after working with CERN.

Over the same 10-year period, 1000 or so individuals who have participated in CERN's various employment schemes have received training estimated to be worth more than £4.9M. The knowledge and skills gained via working at CERN are deployed across sectors including IT and software, engineering, manufacturing, financial services and health, the report notes, with young UK researchers who have engaged with CERN estimated to earn 12% more across their careers (corresponding to an extra £489M in additional wages in the past 10 years).

Each year an average of 12,000 school students and other members of the public visit CERN in person; 220,000 visit CERN's website; and 40,000 interact with its social media. More than 1000 teachers have attended CERN's national teacher programme in the past decade, who go on to teach an estimated 175,000 school students within three months of their visit. A survey of 673 physics undergraduates in eight UK universities revealed that 95% were attracted to study science because of activities in particle physics, with more than 50% saying they were inspired by the discovery of the Higgs boson.

In terms of science diplomacy, the report acknowledges that CERN provides a platform for the UK to engage more widely in global initiatives and international networks, spilling over to favourable perceptions of its members and greater engagement in science, technology and beyond. "Fundamental research requires long-term engagement; international collaboration makes this essential pooling of efforts possible, and the report provides a promising testimony for the future of CERN membership," said Charlotte Warakaulle, CERN director of international relations.

Carried out by consulting firm Technopolis, the study also quantified the scientific benefits of CERN membership. Over the past decade, more than 20,000 scientific papers with a UK author have cited one of the 40,000 papers based directly on CERN research published in the past 20 years. The report estimates that the production of knowledge can be valued at more than £495M, before even considering the impact of the advances that this research may underpin. Bibliometric analyses also show that CERN research underpins many of the UK's most influential physics papers.

Being part of one of the biggest international scientific collaborations on the planet places the UK at the frontier of discovery science

The new report supports previous studies into the benefits of CERN membership. In particular, a recent study of the impact of the High Luminosity LHC conducted by economists at the University of Milan concluded that the quantifiable return to society is well in excess to the project's costs (*CERN Courier* September 2018 p51).

The UK is one of CERN's founding members, and currently contributes £144M per year to the CERN budget (representing 16% of Member State subscriptions) via the STFC. "Being part of one of the biggest international scientific collaborations on the planet places the UK at the frontier of discovery science, which in turn helps to inspire the next generation to study physics and other STEM subjects," says STFC executive chair Mark Thomson. "This is of huge value to the UK – and for the first time this report goes some way to quantify this."

CERN

Estonia joins CERN

S Hertzog/CERN

Online first *Estonia's prime minister Jüri Ratas and CERN Director-General Fabiola Gianotti at the signing ceremony which, due to the COVID-19 pandemic, took place via a live feed between Tallinn and Geneva – a first in CERN's 66-year history.*

On 19 June the prime minister of Estonia, Jüri Ratas, and CERN Director-General, Fabiola Gianotti, signed an agreement admitting Estonia as an associate member state in the pre-stage to membership of CERN. The agreement will enter into force once CERN has been informed by the Estonian authorities that all the necessary approval processes have been finalised.

"With Estonia becoming an associate member, Estonia and CERN will have the opportunity to expand their collaboration in, and increase their mutual benefit from, scientific and technological development as well as education and training activities," said CERN Director-General Fabiola Gianotti. "We are looking forward to strengthening our ties further."

After joining the CMS experiment in 1997, Estonia became an active member of the CERN community. Between 2004 and 2016 new collaboration frameworks gradually boosted scientific and technical co-operation. Today, Estonia is represented by 25 scientists at CERN, comprising an active group of theorists, researchers involved in R&D for the Compact Linear Collider project, a CMS team involved in data analysis and the Worldwide LHC Computing Grid, and another team taking part in the TOTEM experiment.

CERN's associate member states are entitled to participate in meetings of the CERN Council, Finance Committee and Scientific Policy Committee. Their nationals are eligible for staff positions and fellowships, and their industries are entitled to bid for CERN contracts.

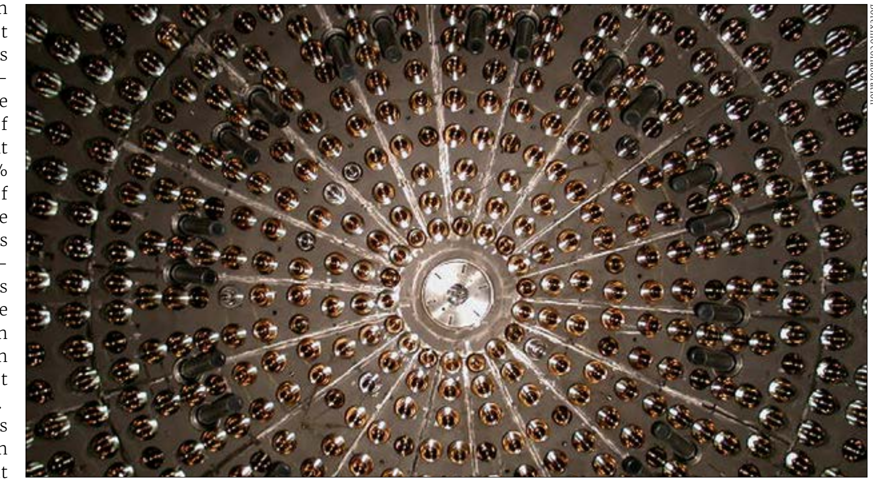
"As an associate member, many important opportunities open up for Estonian entrepreneurs, scientists and researchers to work together on innovation and R&D, which will greatly benefit Estonia's business sector and the economy as a whole," said Jüri Ratas, Estonia's prime minister, at the signing ceremony. "Becoming an associate member is the next big step for Estonia to deepen its co-operation with CERN before becoming a full member."

ASTROWATCH

Neutrinos confirm rare solar-fusion process

Despite being our closest star, much remains to be learned about the exact nature of the Sun and how it produces its energy. Two different fusion processes are thought to be at play in the majority of stars: the direct fusion of hydrogen into helium, which is thought to be responsible for approximately 99% of the Sun's energy; and the fusion of hydrogen into helium via the six-stage carbon–nitrogen–oxygen (CNO) process (see CNO cycle diagram). Although theorised in the 1930s, direct proof of this fusion process was missing. Now, the international Borexino collaboration directly detected neutrinos produced in the CNO cycle, providing the first direct proof of this important fusion process.

The Borexino detector uses 278 tonnes of liquid scintillator held in a nylon balloon deep under the mountains at Gran Sasso National Laboratory in Italy to detect extremely rare interactions between the scintillator and solar neutrinos. In 2012 the experiment detected neutrinos from the main solar fusion process. Now, one year before the end of its scheduled operations, the Borexino team has fully probed the solar energy production.

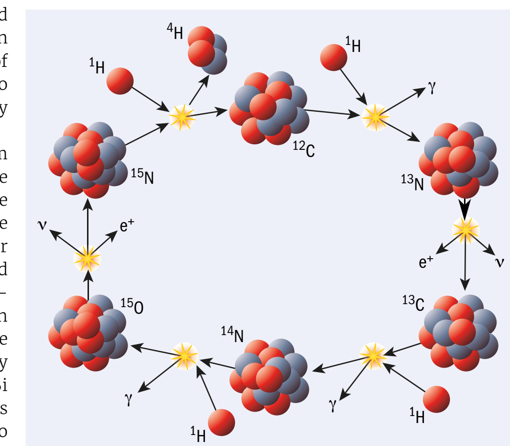


Borexino collaboration

Solar focus *Borexino's 2200 photomultipliers detect scintillation light generated by electron/positron recoils induced by sub-MeV neutrinos.*

Despite minimising backgrounds from cosmic rays, trace amounts of radioactive nuclei that leak into the active volume of Borexino produce a background of the same magnitude as the sought-after signal. The most important background for the CNO analysis was ^{210}Bi, a product of ^{210}Pb of which trace amounts can diffuse into the scintillator from the nylon balloon surface. Since the energy spectrum of the beta-decay of ^{210}Bi resembles that induced by neutrinos produced in the CNO process, the key to detecting CNO neutrinos was to directly measure the ^{210}Bi-induced background. This was made possible by delving into the fluid dynamics of the liquid scintillator.

The ^{210}Bi in Borexino's scintillator produces ^{210}Po, which undergoes alpha decay with a half-life of 134 days. As the alpha decay is relatively easy to identify, the team used ^{210}Po decays to deduce the number of ^{210}Bi decays in the detector. However, as the different isotopes move around in the liquid it cannot be guaranteed that the ^{210}Bi distribution is equal to ^{210}Po unless the flow in the detector is well understood. To overcome this, the collaboration had to reduce the flow of the scintillator material by stabilising the temperature, both through insulation and direct temperature regulation. After the ^{210}Po decay distribution inside the detector was found to be stable over times exceeding its half-life, an area with low ^{210}Po activity was identified and used to measure the CNO neutrinos with a well-understood and relatively low background.



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CNO cycle *A proton is absorbed by a carbon nucleus, followed by a nuclear decay, then a second and third absorption of a proton, followed by another decay, the absorption of a fourth proton and finally a decay into a carbon nucleus, a helium nucleus and the release of around 25 MeV of energy.*

The spectral measurements performed of the CNO cycle exclude a non-detection with a statistical significance of more than five sigma. The solar-neutrino interaction rate ($7.2^{+3.0}_{-1.7}$ counts per day per 100 tonnes of target, at 68% confidence) furthermore agrees with models which predict that 1% of the energy produced in the Sun comes from the CNO process. Additionally, the results shine light on the density of elements other than hydrogen and helium – the metallicity – of the Sun's core, which in recent years has been debated to potentially differ from that on the solar surface. The Borexino results indicate that the density is likely similar, although more precise measurements with future detectors are required to confirm this.

The groundbreaking Borexino study, which required not only some of the most precise techniques used in particle physics but also complex fluid-dynamics simulations, provides a first probe into the processes at the cores of stars. Although it has now been proved that the CNO process is responsible for only a fraction of the Sun's energy, for heavier and therefore hotter stars it is predicted to be the dominant fusion process, making future high-precision studies important to understand the evolution of the universe in general.

Further reading

Borexino Collab. 2020 arXiv:2006.15115.

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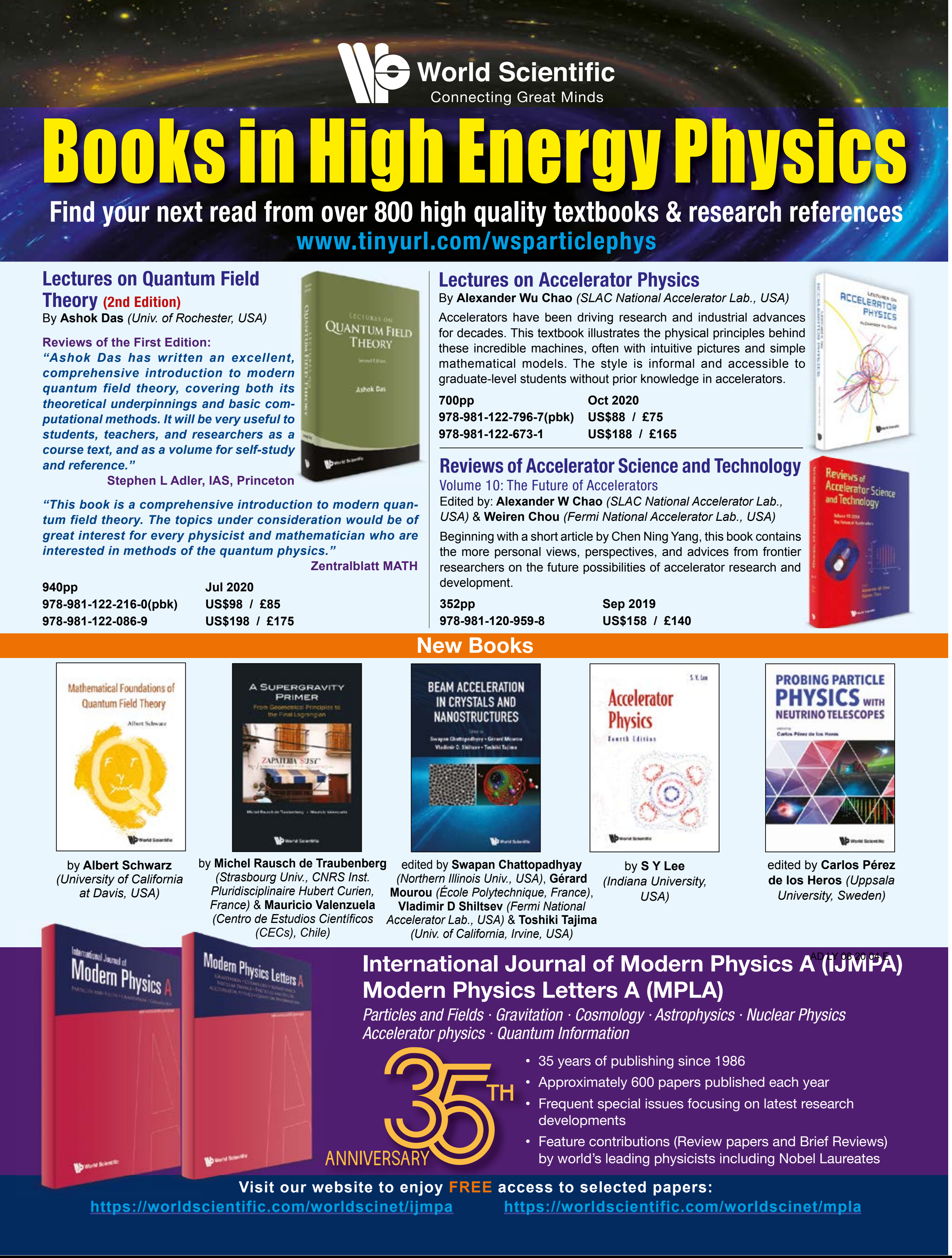


NEWS DIGEST

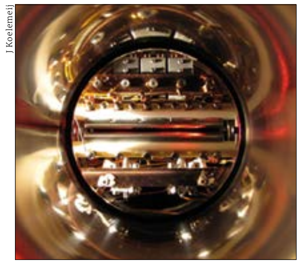
R Hahn

Alex Romanenko (Fermilab) with a qubit based on RF-cavity technology.

US invests in quantum technology
Following a competitive peer-review process, the US Department of Energy has funded new quantum-technology centres at five national laboratories: Argonne, Berkeley, Brookhaven, Fermilab and Oak Ridge. Each lab will receive a $115 million investment over five years plus contributions from industrial partners. The successful proposals include bids to use accelerator technology in quantum computing, by using superconducting radio-frequency cavities to make niobium qubits. Earlier this year, such Fermilab cavities broke the world record for qubit coherence, achieving stability over a period of seconds (*Phys. Rev. Applied* **13** 034032). The five labs will also develop quantum-sensor technology for use in applications including dark-matter searches. In June, CERN also launched a quantum-technology initiative (see p47).

High-performance collaboration
On 22 July, CERN and the Square Kilometer Array (SKA) signed an agreement to co-operate with European networking and data-management organisations GÉANT and PRACE on the development of high-performance computing in high-energy physics and astronomy. Analysing the data sets generated by the High-Luminosity LHC at CERN and the SKA radio-telescopes planned for Australia and South Africa will depend upon "exascale" supercomputers, capable of 10^{18} operations per second, which are expected to emerge in the next few years (*CERN Courier* April 2018 p39).

Brilliant synchrotron begins
Following a 20-month shutdown, the European Synchrotron Radiation Facility (ESRF), in Grenoble, France, is back in action with users now able to carry out experiments using a brand new fourth-generation high-energy synchrotron light source, the Extremely Brilliant Source (EBS). The new machine will provide users across a wide range of disciplines with an X-ray brilliance and coherence 100 times greater than ESRF's previous storage ring. It is based on the hybrid multi-bend achromat – with seven, as opposed to two, bending magnets per cell, reducing the horizontal emittance (*CERN Courier* December 2018 p17).



J Koelemeij

The ion trap used to measure the proton–electron mass ratio.

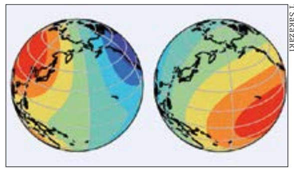
Proton slimmed down
A new precision laser spectroscopy measurement of the proton–electron mass ratio using trapped HD^+ ions supports other recent indications that the proton is less massive than previously thought (10.1126/science.abao453). In the last few years, traditional Penning-trap measurements (e.g. *Phys. Rev. Lett.* **119** 033001) have weighed in at around 300 parts per trillion (ppt) and three standard deviations lighter than the previously accepted mass. The new measurement, obtained by researchers in the Netherlands and France, deployed a pair of narrowly detuned counter-propagating lasers to eliminate error due to the Doppler effect and achieve an unprecedented precision of 21 ppt. The proton's mass discrepancy is the latest in a series of oddities observed in recent years, including the converging proton-radius puzzle and the long-standing proton spin crisis (*CERN Courier* May/June 2019 p38).

Muon-collider study initiated
A new international design study for a future muon collider began in July, following the recommendations of the 2020 update of the European strategy for particle physics (*CERN Courier* July/August 2020 p7). Initiated by the Large European Laboratory Directors Group, which exists to maximise co-operation in the planning, preparation and execution of future projects, the study will initially be hosted at CERN, and carried out in collaboration with international partners. Institutes can join by expressing their intent to collaborate via a Memorandum of Understanding. The goal of the study is to evaluate the feasibility of both the accelerator and its physics experiments (*CERN Courier* May/June 2020 p41). CERN's Daniel Schulte has been appointed as interim project leader.

KEK reclaims luminosity record
A new record for the highest luminosity at a particle collider has been set by SuperKEKB at Japan's KEK laboratory. On 15 June, electron–positron collisions at the 3 km-circumference machine reached an instantaneous luminosity of $2.22\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$ — surpassing the LHC's record of $2.14\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$ set with proton–proton collisions in 2018. SuperKEKB is an upgrade of the KEKB B-factory, which held the luminosity record of $2.11\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$ for almost 10 years until the LHC edged past it. SuperKEKB's new record was achieved thanks to a novel "nano-beam" scheme that squeezes the vertical height of the beams at the collision point to about 220 nm.

Simplifying sums
A team led by Pierpaolo Mastrolia (Padova) and Sebastian Mizera (Princeton) has published a new exposition of their 2017 idea for using techniques in algebraic geometry to circumvent some of the challenges relevant to computing multi-loop Feynman amplitudes. The approach uses "twisted cohomology", a mathematical theory previously only applied to string theory, to tame the algebraic complexity inherent to multi-loop computations. Their new paper provides further evidence that the technique could be used in the future to perform calculations for the LHC that are out of the reach of conventional techniques (arXiv:2008.04823).

Laplace vindicated
Two centuries ago, Pierre-Simon Laplace modelled the effect of the Moon's gravity on a thin fluid coating a smooth sphere, and deduced that continent-sized pressure waves would periodically sweep across the planet at hundreds of kilometres per hour.



T Sakazaki

Resonant modes can be randomly excited in the atmosphere.

Takatoshi Sakazaki (Kyoto) and Kevin Hamilton (Hawaii) have now analysed 38 years of atmospheric data to prove him correct (*J. Atmos. Sci.* 2020 **77** 2519). Sakazaki and Hamilton observed the ringing of randomly excited global-scale resonant modes in precise accord with those hypothesised by Laplace. With periods as short as two hours, the new excitations complete the experimental picture first hinted at by the observation of the fundamental two-hemisphere mode in the 1980s.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

The LHC as a photon collider

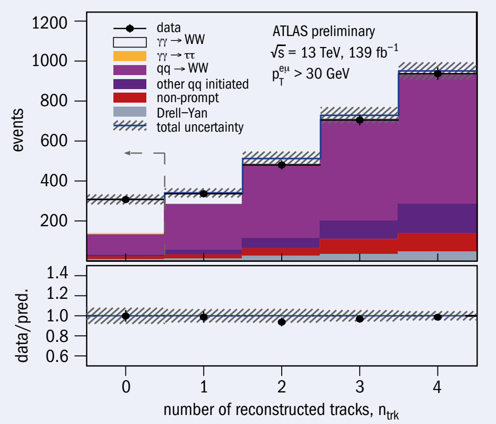


Fig. 1. *To isolate a sample of $\gamma\gamma \rightarrow WW$ interactions, events with no additional reconstructed charged-particle tracks in the vicinity of the electron–muon pair ($n_{trk} = 0$) are selected.*

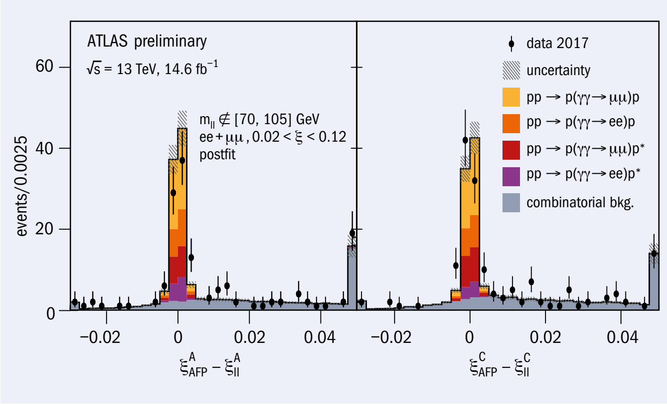


Fig. 2. *A sample of $\gamma\gamma \rightarrow \ell\ell$ events can be isolated by observing a scattered proton in the AFP spectrometer. Here, the proton energy loss measured in the AFP installed either side (A and C) of the collision point (ξ_{AFP}, dimensionless) is shown to agree with that predicted from measurements of the lepton pair in the main detector ($\xi_{\ell\ell}$).*

Protons accelerated by the LHC generate a large flux of quasi-real high-energy photons that can interact to produce particles at the electroweak scale. Using the LHC as a photon collider, the ATLAS collaboration recently announced a set of landmark results, among which is the first observation the photo-production of W-boson pairs.

As it proceeds via trilinear and quartic gauge-boson vertices involving two W bosons and either one or two photons, the production of a pair of W bosons from two photons ($\gamma\gamma \rightarrow WW$) tests a long-standing prediction of the Standard Model (SM). This process is extremely rare but predicted precisely by electroweak theory, such that any observed deviation would suggest that new physics is at play. The measurement relies on the large 139 fb^{-1} dataset of proton–proton collisions recorded by ATLAS in LHC Run 2.

Protons usually remain intact or are excited into a higher energy state in photon collisions, with the products of any subsequent decay not reaching the innermost components of the ATLAS detector. In these cases, the electron and muon decaying from the W bosons – an event topology chosen to avoid the high background for same-flavour lepton pairs – are the only particles detected in the vicinity. However, if charged particles arise from nearby proton–proton collisions, the clean $\gamma\gamma \rightarrow WW$ signal can be missed. The main background is W boson pairs produced in head-on proton–proton collisions where particles from the breakup of the protons are not detected due to imperfect detector coverage or reconstruction (figure 1). A total of 127 background events are predicted compared to 307 events observed in data. This signal excess corresponds to a statistical significance of 8.4 standard deviations. This establishes the existence of light transforming into particles with weak-scale masses – a remarkable and previously unobserved phenomenon.

Precisely testing SM predictions of photon collisions requires accurate knowledge of the rate protons remain intact relative to those that break apart. This is challenging to predict theoretically and probing these rates unambiguously requires directly detecting the intact protons. The ATLAS Forward Proton (AFP) spectrometer is becoming increasingly indispensable for this task. Among the newest additions to the ATLAS experiment, and located a few millimetres from the beam 210 metres either

Observing $\gamma\gamma \rightarrow WW$ and scattered protons in $\gamma\gamma \rightarrow \ell\ell$ interactions are long-awaited milestones

side of the collision point, the AFP can detect protons that have been scattered in photon–photon collisions but which have nevertheless been focused by the LHC's magnets. Its pioneering results so far analyse a standard-candle process where a proton is scattered in photon collisions that produce electron or muon pairs ($\gamma\gamma \rightarrow \ell\ell$). For these signals, the measured proton energy loss is equal to that predicted from the lepton pairs measured in the main ATLAS detector (figure 2). ATLAS reported 180 events with a proton having matched kinematics to the lepton pair with an expected background of about 20 events. This corresponds to a significance exceeding nine standard deviations for both lepton flavours, establishing the presence of the signal and the successful operation of the AFP spectrometer in high-luminosity data. The detectors were sufficiently well understood to measure the cross sections of these processes.

Observing $\gamma\gamma \rightarrow WW$ and scattered protons in $\gamma\gamma \rightarrow \ell\ell$ interactions are long-awaited milestones in an emerging experimental programme studying photon collisions. These complement recent heavy-ion results where ATLAS measured muon pairs from photon ▷

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collisions and the kinematic properties of light-by-light scattering – a very rare process predicted by quantum electrodynamics. Interestingly, the latter was also used to search for the axion-like particles predicted by certain extensions of the SM.

The techniques developed to study $\gamma\gamma \to WW$ and $\gamma\gamma \to \ell\ell$ interactions lay the groundwork for future, more detailed tests of the SM. Further results using the AFP spectrometer can improve theoretical understanding of photon collisions that will also benefit future measurements of $\gamma\gamma \to WW$ production. These landmark experimental feats will only become more interesting with the increased dataset of Run 3 and the High-Luminosity LHC.

Further reading

ATLAS Collab. 2020 ATLAS-CONF-2020-038.
ATLAS Collab. 2020 ATLAS-CONF-2020-041.
ATLAS Collab. 2020 CERN-EP-2020-135.
ATLAS Collab. 2020 CERN-EP-2020-138.

CMS

CMS reaffirms exotic nature of the X(3872)

Exotic charmonium-like states are a very active field of study at the LHC. These states have atypical properties such as non-zero electric charges and strong decays that violate isospin symmetry. The exotic X(3872) charmonium state discovered by the Belle collaboration in 2003 displays such isospin-violating strong decays and has a natural width of about 1 MeV, which is unexpectedly narrow for a state with mass very close to the $D^{*0}\bar{D}^0$ threshold.

Several theoretical interpretations of the internal structure of these charmonium-like states have been proposed to explain their peculiar properties. To choose the most adequate model for each state, we must continue studying their properties and improving the determination of their parameters. As for the X(3872), although it is inconsistent with the predicted conventional charmonium states and does not have a definite isospin, its production partially resembles that of ordinary charmonium states such as ψ(2S) or χ_{c1}(1P). One of the ways to evaluate the degree of similarity between X(3872) and ψ(2S) is to compare their production rates in exclusive b-hadron decays. In the case of ψ(2S), which is a conventional charmonium state, the branching fractions of the decays $B^0_s \to \psi(2S)\phi$, $B^+ \to \psi(2S)K^+$, and $B^0 \to \psi(2S)K^0$, are approximately equal to each other. Recent CMS measurements of the corresponding rates for decays to X(3872) show differences, however, which may provide a clue to the nature of this exotic charmonium-like state.

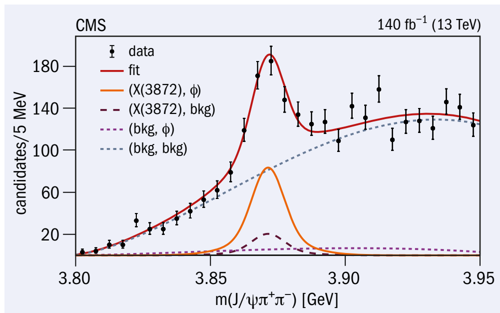

Fig. 1. *The reconstructed invariant mass distribution of $X(3872) \to J/\psi\pi^+\pi^-$ for $B^0_s \to X(3872)\phi$ candidates.*

Recently the CMS collaboration observed the decay $B^0_s \to X(3872)\phi$ for the first time, with a significance exceeding five standard deviations. The X(3872) is reconstructed via its decay to $J/\psi\pi^+\pi^-$, followed by a decay of the J/ψ meson into a pair of muons, and of the ϕ meson to a pair of charged kaons (figure 1).

At a simple Feynman-diagram level, this decay is a close analogue to the $B^+ \to X(3872)K^+$ and $B^0 \to X(3872)K^0$ decays that have previously been observed. The ratio of the branching fractions of this new B^0_s decay to that of the B^+ decay is significantly below unity at 0.48 ± 0.10, while a similar ratio for the decays involving ψ(2S) is consistent with unity. This is not expected from naive "spectator-quark" considerations, based on a simple tree-level diagram, and assuming X(3872) is a pure charmonium state. The measured ratio also happens to be consistent with the analogous ratio for the $B^0 \to X(3872)K^0$ to $B^+ \to X(3872)K^+$ decays, though the latter ratio has not yet been measured with high accuracy. The results suggest that spectator quarks behave differently in the B^+ and $B^0_{(s)}$ two-body decays into X(3872) and a light meson. In a recent theoretical paper, former CERN Director-General Luciano Maiani and collaborators pointed out that the new CMS measurement can naturally be explained by a tetraquark model of X(3872), which describes this exotic particle as a bound state of a diquark (charm and up quarks) and its anti-diquark.

Further studies of X(3872) are now important in order to gain a deeper understanding of its exotic properties and uncover its mysterious nature. The results may have interesting consequences for our understanding of quantum chromodynamics.

Further reading

CMS Collab. 2020 arXiv:2005.04764.
L Maiani, A D Polosa and V Riquer 2020 arXiv:2005.08764.

ALICE

J/ψ polarisation differs in lead collisions

Polarisation studies represent a valuable tool for the study of the properties of quark–gluon plasma

Quarkonia, the bound states of charm and anti-charm or bottom and anti-bottom quarks, are an important tool to test our knowledge of quantum chromodynamics (QCD). At the LHC, the study of quarkonia polarisations offers a valuable new window onto how heavy quarks bind together in such states. Understanding quarkonium polarisation has already proven to be difficult at lower energies, however, and measurements at the LHC pose significant further challenges.

ALICE measures quarkonia spin orientations with respect to a chosen axis via a measurement of the anisotropy in the angular distribution of the decay products. The angular distribution is parametrised in terms of the polarisation parameters, λ_θ, λ_ϕ and $\lambda_{\theta\phi}$, where θ and ϕ are the polar and azimuthal emission angles. If all of them are null, no polarisation is present, whereas ($\lambda_\theta = 1$, $\lambda_\phi = 0$, $\lambda_{\theta\phi} = 0$) and ($\lambda_\theta = -1$, $\lambda_\phi = 0$, $\lambda_{\theta\phi} = 0$) indicate a polarisation of the spin in the transverse and longitudinal directions, respectively.

In pp collisions, polarisation has been mainly used to investigate the J/ψ production mechanism. Reproducing the small values of polarisation parameter λ_θ observed at the LHC is a challenge for many theoretical models. Until recently, no corresponding results were available for nucleus–nucleus collisions, and in this domain polarisation studies represent a valuable tool for the study of the properties of quark–gluon plasma (QGP). The formation of this deconfined, strongly interacting medium impacts differently on the various quarkonium resonances, inducing a larger suppression on the less bound excited states ▷

ψ(2S) and χ_c, and modifying their feed-down fractions into the ground state, J/ψ. This effect may lead to a variation of the overall polarisation values since different charmonium states are expected to be produced with different polarisations. In addition, the recombination of uncorrelated heavy-quark pairs inside the QGP gives rise to an extra source of J/ψ, which can further modify the overall polarisation with respect to pp collisions.

The ALICE experiment has recently made the first measurements of the J/ψ and ϒ(1S) polarisation in Pb–Pb collisions. The data correspond to a centre-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV, and the rapidity range $2.5 < y < 4$. The measurements were carried out in the dimuon decay channel, and results were obtained in two different reference frames, helicity and Collins–Soper, each of them with its own definition of the quantisation axis. In the helicity frame, the quarkonium momentum direction in the laboratory is chosen, while the bisector of the angle formed by the two colliding beams boosted in the quarkonium rest frame is used in the Collins–Soper frame. The J/ψ polarisation parameters, evaluated in three p_T bins covering the range between 2 and 10 GeV, are close to zero, but with a maximum positive deviation for λ_θ (corresponding to a transverse polarisation) of 2σ for $2 < p_T < 4$ GeV in the helicity reference frame. Interestingly, the corresponding LHCb pp result for prompt J/ψ at $\sqrt{s_{NN}} = 7$ TeV instead shows a small but significant longitudinal polarisation.

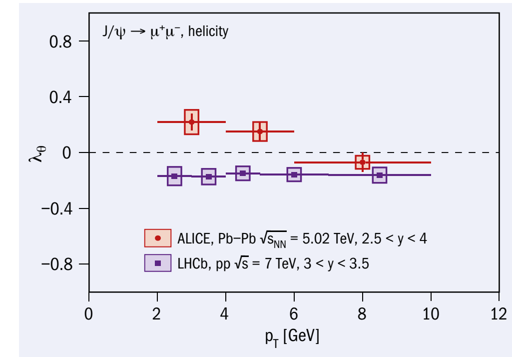

Fig. 1. *Inclusive J/ψ polarisation parameters as a function of transverse momentum for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are compared to proton–proton collisions observed by LHCb for prompt J/ψ at $\sqrt{s} = 7$ TeV* (Eur. Phys. J. C 2013 **73** 2631).

The observation of a significant difference between J/ψ polarisation results in pp and Pb–Pb collisions motivates further experimental and theoretical studies, with the main goal of connecting this observable with the known suppression and regeneration mechanisms in heavy-ion collisions. For the rarer ϒ(1S), a bound state of a bottom and an anti-bottom quark, the inclusive polarisation parameters were found to be compatible with zero within sizeable uncertainties. A higher precision and momentum-differential measurement will be enabled by the ten-fold larger Pb–Pb luminosity expected in Run 3 of the LHC.

Further reading

ALICE Collab. 2020 arXiv:2005.11128.

LHCb

LHCb explores dark-sector confinement

The possibility that dark-matter particles may interact via an unknown force, felt only feebly by Standard Model (SM) particles, has motivated substantial efforts to search for dark forces. The force-carrying particle for such hypothesised interactions is often referred to as a dark photon, in analogy with the ordinary photon that mediates the electromagnetic interaction.

In the minimal dark-photon scenario, the dark photon does not couple directly to SM particles; however, quantum-mechanical mixing between the photon and dark-photon fields can generate a small interaction, providing a portal through which dark photons may be produced and through which they might decay into visible final states.

While the minimal dark-photon model is both compelling and simple, it is not the only viable dark-sector scenario. Many other well-motivated dark-sector models exist, and some of these would have avoided detection in all previous experimental searches. Fully exploring the space of dark sectors is vital given the lack of signals observed thus far in the simplest scenarios. For example, so-called hidden-valley (HV) scenarios that exhibit confinement in the dark sector, similar to how the strong nuclear force confines SM quarks, would produce a high multiplicity of light hidden hadrons from showering processes in a similar way to jet production in the SM. These hidden hadrons would typically decay displaced from the proton–proton collision, thus failing the criteria employed in previous dark-photon searches to suppress backgrounds due to heavy-flavour quarks. Therefore, it is desirable to perform experimental searches for dark sectors that are less model dependent, by not focusing solely on the minimal dark-photon scenario.

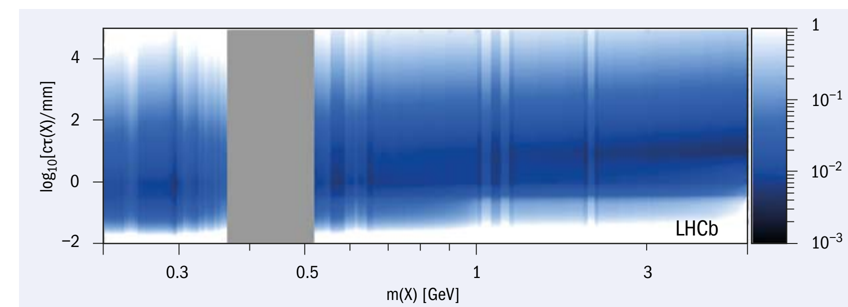

Fig. 1. *90% confidence upper limits on the kinetic mixing strength between photons and composite hidden-valley bosons, X (colour scale), for a scenario that exhibits confinement, as a function of mass and proper decay length. The grey box was vetoed due to a large doubly misidentified K_S background.*

Using its Run-2 data sample, LHCb recently performed searches for both short-lived and long-lived exotic bosons that decay into the dimuon final state. These searches explored the invariant mass range from near the dimuon threshold up to 60 GeV. None of the searches found evidence for a signal and exclusion limits were placed on the $X \to \mu^+\mu^-$ cross sections, each with minimal model dependence.

For many types of dark-sector models, these limits are the most stringent to date. This is especially true for the HV scenario (see figure), for which LHCb has placed the first such constraints on physically relevant HV mixing strengths in this mass range.

These results demonstrate the unique sensitivity of the LHCb experiment to dark sectors. Looking forward to Run 3, the trigger will be upgraded, greatly increasing the efficiency to low-mass dark sectors, and the luminosity will be higher. Taken together, these improvements will further expand LHCb's world-leading dark-sector programme.

Further reading

LHCb Collab. 2020 arXiv:2007.03923.

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ADVERTISING FEATURE

EPICS integration of the ESS accelerator cryoplant

The European Spallation Source (ESS) will be the world's most powerful pulsed neutron source to provide a means for multidisciplinary research in areas such as materials science, life sciences, energy, environmental technology, cultural heritage and fundamental physics. ESS plans the first experiments for 2023 with the commencement of the user programme. Ivana Mustać Kostevc describes how it was possible to adapt an industrial solution for a cryogenic plant (cryoplant) to the custom requirements of the ESS EPICS environment.

Example of a cryoplant, courtesy of Linde Kryotechnik AG.

The proton linear accelerator of ESS will contain three cryogenic refrigeration/liquefaction plants and an extensive cryogenic distribution system. The accelerator cryoplant (ACCP), which is currently in the phase of commissioning, is the largest of the ESS cryoplants. Its primary purpose is to cool the superconducting RF cavities to a temperature of 2 K via saturated He-II baths through several cryomodules. Apart from that, a forced flow of 4.5 K helium is supplied in a second circuit to cool the RF power couplers, and a third circuit provides helium at around 40 K to cool the thermal radiation shields. The ACCP provides cooling for all three of these circuits.

The two main ACCP subsystems are the warm compressor station and the coldbox. The warm compressor station consists of three oil-lubricated compressor skids with a bulk oil removal system and oil and gas filters, a final oil removal system and a gas management panel consisting of valves and pipe terminals for the process control. There is a single coldbox with a number of heat exchangers, expansion turbines, a cold compressor system, adsorbers, filters, electrical heaters and other equipment.

Many manual and remote valves will be installed for different purposes, for example to isolate specific loops, to protect the system against loss of oil or helium and safety valves to protect the system against overpressure. Measuring points necessary for operation and protection of the equipment include points for helium mass flow and water flow, position of all control valves, limit switches for manual valves, oil-level, oil and helium, impurity, helium, water, and oil temperatures. These measurements, and control over the devices mentioned above, are exposed to the operators by the ESS control system.

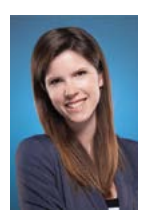
Supervision of all functions of the ACCP control system, including substantial technical safety requirements and deterministic sequence programmes, is carried out by a Siemens Step 7- 400 PLC. All relevant control points are collected and processed by the PLC and distributed and exposed to the operator via a dedicated IOC running EPICS. The interface between the PLC and the IOC is implemented through the s7plc EPICS driver, which is based on the Siemens send/receive protocol.

The EPICS database covers the input and output of all relevant control points and additional functionalities such as the communication logic with the PLC, recovery of set-points after a system shut down and locking access to a single workstation. Data from the PLC to the IOC is stored and recovered by the PLC while IOC setpoints are stored on the IOC. The EPICS database provides the option to either initialize all data to their last values on the IOC, or to copy their respective readbacks from the PLC.

Since the ACCP is a large and complicated system, we structured its graphical user interface hierarchically. At the top level, a process diagram of the whole system provides a quick overview of the cryoplant's most critical measuring points. Due to the complexity of the ACCP control system, we automated as much as possible. Appropriate Python scripts parse the PLC variables and all relevant information to create the EPICS database and configuration files for services such as the alarm handler and archiving service. The latter ensures that all services are up to date with the EPICS database.

For the screen design we used templates, wherever possible.

A large and complex system like a cryoplant is always customised by an experienced supplier. However, when considering an extensive facility such as ESS, all systems must be integrated into the central control system similarly – employing the same technologies that are used for other subsystems. The latter is vital for operators and becomes a necessity when considering maintenance throughout the system's lifecycle. In ESS's case, Cosylab put particular emphasis on managing device configuration in the cryoplant as the latter changes during development and testing. The final product was the functioning "missing link" between the industrial solution of the cryoplant manufacturer and the custom requirements of ESS's control system – the EPICS environment.



ABOUT THE AUTHOR

Ivana Mustać Kostevc started working at Cosylab in 2015. She holds a PhD in physics with a topic in elementary particle physics. She is a senior team leader in the Scientific Services department and an expert in designing EPICS-based control systems. Kostevc was the technical lead on the EPICS integration project for the ESS ACCP. Her hobbies are dancing and cycling. e-mail ivana.mustac@cosylab.com

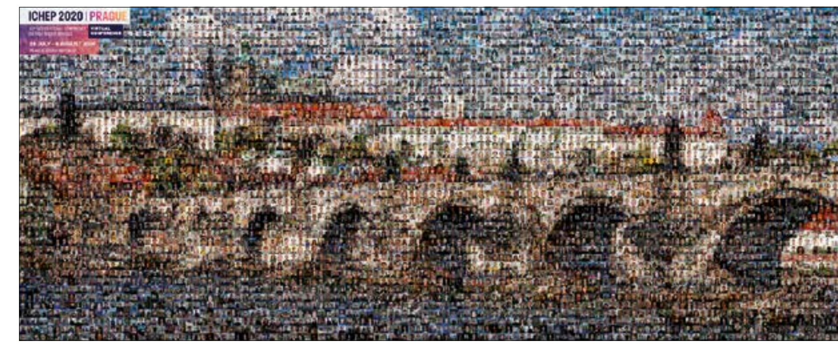
FIELD NOTES

Reports from events, conferences and meetings

INTERNATIONAL CONFERENCE OF HIGH ENERGY PHYSICS

ICHEP's online success

Originally set to take place in Prague, the International Conference of High Energy Physics (ICHEP) took place virtually from 28 July to 6 August. Running a major biennial meeting virtually was always going to be extremely difficult, but the local organisers rose to the challenge by embracing technologies such as Zoom and YouTube. To allow global participation, the conference was spread over eight days rather than the usual six, with presentations compressed into five-hour slots that were streamed twice: first as a live "premiere" and later as recorded "replay" sessions, for the benefit of participants in different time zones.



ICHEP 2020

Building bridges *A photo-collage of ICHEP delegates mapped to the Charles Bridge – a Prague landmark that has facilitated trade between eastern and western Europe since the 15th century.*

This was the first ICHEP meeting since the publication of the update of the European strategy for particle physics, which presented an ambitious vision for the future of CERN. Though VIP-guest Peter Gabriel – rock star and human-rights advocate – may not have been aware of this when delivering his opening remarks, his urging that delegates speak up for science and engage with politicians resonated with the physicists virtually present.

Many scientific highlights were covered at ICHEP and it is only possible to scratch the surface here. The results from all four major LHC experiments were particularly impressive and the collective progress in understanding the properties of neutrinos shows no sign of slowing down.

Higgs physics

ATLAS and CMS presented the first evidence for the decay of the Higgs boson into a pair of muons (two and three standard deviations, respectively, see p7). Combined, the results provide strong evidence for the coupling of the Higgs boson to the muon, with the strength of the coupling consistent with that predicted in the Standard Model. Prior to these new results, the Higgs had only been observed to couple to the much heavier third-generation fermions and the W and Z gauge bosons. The measurements also provide further evidence for the linearity of the Higgs coupling, now over four orders of magnitude (from the muon to top quark), indicating the universality of the Standard-Model Higgs boson as the mechanism through which all Standard Model particles acquire mass. These are highly non-trivial statements.

ATLAS also presented a combined measurement of the Higgs signal strength, which describes a common scaling of the expected Higgs-boson yields in all processes, of 1.06 ± 0.07. In this measurement, the experimental and theoretical uncertainties are now roughly equal, emphasising the ever-increasing importance of theoretical developments in keeping up with the experimental progress; a feature that will ultimately determine the precision that will be reached by the LHC and high-luminosity LHC (HL-LHC) Higgs physics programmes.

More generally, the precision we are seeing from the ATLAS and CMS Run 2 proton–proton data is truly impressive, and an exciting indication of what is to come as the integrated luminosity accumulated by the experiments ramps up, and then ramps up again in the HL-LHC era. One interesting new example was the first observation of WW production from photon–photon collisions, where the photons are radiated from the incoming proton beams (see p15). This is a neat measurement that demonstrates the breadth of physics accessible at the LHC.

Overall, the range and Standard Model measurements presented at ICHEP 2020 by ATLAS and CMS were truly impressive and we should not forget that it is still relatively early in the LHC programme. In parallel, direct searches for new phenomena, such as supersymmetry and the "unexpected", continues apace. Results from direct searches at the energy frontier were covered in numerous parallel session presentations. The current status was summarised succinctly by Paris Sphicas (Athens) in his conference summary talk: "Looked for a lot of possible new things. Nothing has turned up yet. Still looking intensively."

The collective progress in understanding the properties of neutrinos shows no sign of slowing down

Flavour physics

Over the last few years, a number of deviations from theoretical predictions have been observed in B-meson decays to final states with leptons. Discrepancies have been observed in ratios of decays to different lepton species, and in the angular distributions of decay products (*CERN Courier* May/June 2020 p10). Taken alone, each of these discrepancies are not particularly significant, but collectively they may be telling us something new about nature. At ICHEP 2020, the LHCb experiment presented their recently published results on the angular analysis in $B^0 \to K^{*0} \mu^+\mu^-$. The overall picture remains unchanged. The full analysis of the LHCb Run-2 data set, including updated measurements of the relative rates of the muon and electron decay ▷

modes (R_K and R_{K^*}), is eagerly awaited.

The search for rare kaon decays continues to attract interest. One of the most impressive results presented at ICHEP was the recent observation by NA62 of the extremely rare kaon decay, $K^+ \to \pi^+ \nu\bar{\nu}$. Occurring only once in every 10 billion decays, this is an incredibly challenging measurement and the new NA62 result is the first statistically significant observation of this decay, based on just 17 events (see p9). Whilst the observed rate is consistent with the Standard Model expectation, its observation opens up a new future avenue for exploring the possible effects of new physics.

The search for rare kaon decays continues to attract interest

Neutrino physics

Neutrino physics continues to be one of the most active areas of research in particle physics (*CERN Courier* July/August 2020 p32), so it was not surprising that the neutrino parallel sessions were the best attended of the conference. This is a particularly interesting time, with long-baseline neutrino oscillation experiments becoming sensitive to the neutrino mass ordering, and beginning to provide constraints on CP violation. Updates were presented by the NOvA experiment in the USA and the T2K experiment in Japan. Both experiments favour the normal-ordering hypothesis, although not definitively, and there is currently a slight tension between the CP violation results from the two experiments. It is worth noting that the combined interpretation of the two experiments is quite complex. The NOvA and T2K collaborations are working on a combined analysis to clarify the situation.

There were also a number of presentations on the next generation of long-baseline neutrino oscillation experiments, DUNE in the US and Hyper-Kamiokande in Japan, which aim to make the definitive discovery of CP violation in the neutrino sector. In the context of DUNE, the progress with liquid-argon time-projection-chamber (LArTPC) detector technology is impressive. It was particularly pleasing to see a number of physics results from MicroBooNE at Fermilab, and the single-phase DUNE detector prototype at CERN, that are based on the automatic reconstruction of LArTPC images – a longstanding challenge.

Virtual success

A vast range of high-qualify scientific research was covered in the 800 parallel session presentations and summarised in the 44 plenary talks at ICHEP 2020. The quality of the presentations was high, and speakers coped well with the challenge of pre-recording talks. The "replay" sessions worked extremely well too – an innovation that is likely to persist in the post-COVID world. About 3000 people registered for the meeting, which is more than double the previous two events. It was particularly pleasing to learn that almost 2500 connected to the parallel sessions.

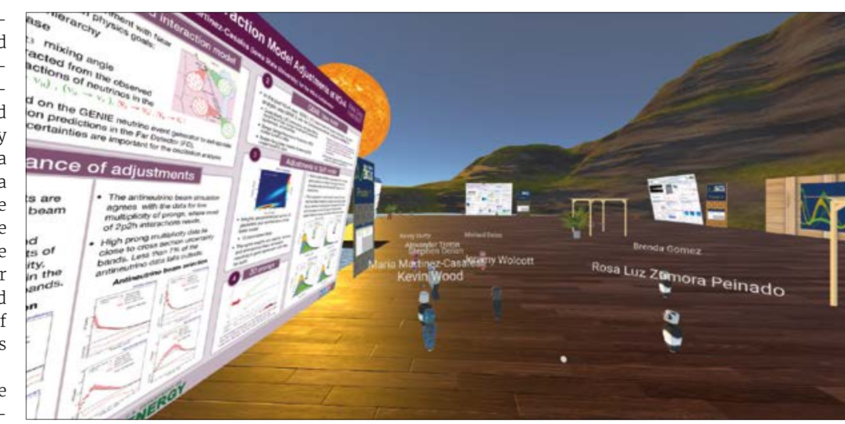
Despite the many successes, we all missed the opportunity to meet colleagues in person; it is often the informal discussions over coffee or in restaurants and bars that generate new ideas and, importantly, lead to new collaborations. Whilst virtual conferences are likely to remain a feature in the post-COVID world, they will not replace in-person events.

Mark Thomson *STFC and the University of Cambridge.*

NEUTRINO 2020

Neutrino 2020 zooms into virtual reality

More than 4000 people from every continent, including Antarctica, participated from 22 June to 2 July in the XXIX International Conference on Neutrino Physics and Astrophysics, which was hosted online by Fermilab and the University of Minnesota. Originally planned as a five-day in-person June meeting at a large hotel in Chicago city centre, the organisers quickly pivoted in March, due to COVID-19, to an online programme with eight half days over two weeks, four poster sessions with both web-based and virtual-reality displays, and the use of the Slack platform for speaker questions and ongoing discussions.



M Del Tutto/Fermilab

Neutrino 2020 avatars *The conference's poster session took place in virtual reality.*

A highlight of the conference was the first observation of solar CNO neutrinos by the Borexino collaboration, which operates a 280 tonne liquid-scintillator detector in Italy's Gran Sasso Laboratory. Dominant in stars more than 1.3 times the mass of the Sun, the CNO cycle accounts for about 1% of the Sun's energy and generates a difficult-to-detect neutrino flux similar to backgrounds due to decays in the detector of ^{210}Bi and its daughter nucleus ^{210}Po. Gioacchino Ranucci (INFN, Milano) explained that the spectral fit to the observed data returns only the sum of CNO and ^{210}Bi neutrinos. "The quest for CNO is turned into the quest for ^{210}Bi through ^{210}Po," he emphasised. "With this outcome, Borexino has completely unravelled the two processes powering the Sun – the pp chain and the CNO cycle." The final data analysis yielded a 5.1σ statistic against a hypothesis of no CNO neutrinos, and a CNO flux at the Earth of $7.0^{+2.9}_{-1.9} \times 10^8\,cm^{-2}\,s^{-1}$ (see p11).

Another highlight from Gran Sasso was the report from the Gerda collaboration on the search for neutrino-less double beta decay. If observed, this process would confirm the long-suspected Majorana rather than Dirac-fermion nature of neutrinos – a beyond the Standard Model feature with intriguing implications for why the neutrino mass is so small. Since Neutrino 2018, Gerda has nearly doubled its Phase 2 exposure and added a liquid-argon veto and a ▷

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new detector string. The now complete Phase 2 result is a 90% confidence level half-life of $>1.8\times10^{26}$ years according to a frequentist analysis, or $>1.4\times10^{26}$ years, according to a Bayesian analysis with additional prior assumptions. Talks describing a half-dozen other double-beta-decay experiments displayed the high level of interest in this field.

A highlight of the conference was the first observation of solar CNO neutrinos

Sterile neutrinos

Searches for additional "sterile" neutrinos with no Standard Model gauge interactions were also featured. Takasumi Maruyama (KEK) described the liquid-scintillator JSNS^2 experiment as a direct test of the controversial LSND experiment result, first reported about 25 years ago. JSNS^2 collected its first data during the three weeks before Neutrino 2020. Adrien Hourlier (MIT) reported on the now complete analysis of data from MiniBooNE that was collected during the past 17 years. Combining neutrino and anti-neutrino modes, MiniBooNE reports a 4.8σ excess. Hourlier presented soon-to-be published detailed distributions that the collaboration hopes "will guide theorists to explain our data". Minerba Betancourt (Fermilab) then described the Fermilab Short-Baseline Neutrino (SBN) programme, which will use three detectors to obtain a definitive result on neutrino oscillations for an LSND and MiniBooNE-like ratio of oscillation distance to energy of ~1 m/MeV. The beam neutrino energy peaks at 700 MeV. A new liquid-argon near detector (SBND) will be placed 110 m from the target. The existing MicroBooNE is located at 470 m and the ICARUS Detector, moved from Gran Sasso, is installed at 600 m. Thomas Carroll (Wisconsin) reported on sterile-neutrino limits by muon disappearance determined by the now completed long-baseline MINOS/MINOS+ collaboration. These limits are in tension with the appearance data from both LSND and MiniBooNE when analysed as evidence for sterile neutrinos.

Two talks described the world's 200 km-scale neutrino-oscillation experiments, NOvA and T2K. The degeneracy of mass difference, mixing angle, hierarchy and possible CP violation make interpretation of these experiments' results quite complex. Interestingly, there is mild tension, albeit only at the 1σ level, between the NOvA and T2K results regarding leptonic CP conservation and the neutrino mass hierarchy. The two collaborations are now working together on a combined analysis. Several talks discussed future initiatives. Lia Merminga (Fermilab) reported on LBNF and PIP-II, which will result in a new neutrino beam from Fermilab to the Sanford Laboratory in South Dakota for the DUNE experiment. Combined, these two projects will result in a beam power of 2.4 MW, more than three times the intensity of the current NuMI beam. Michael Mooney (Colorado State) reported on the enormous progress of the DUNE project with two successful prototype detectors operating at CERN and pre-excavation work progressing at Sanford Laboratory. Complementary to the liquid-argon technology of DUNE is the recently approved Hyper-Kamiokande water-Cherenkov detector, which was described by Masaki Ishitsuka (Tokyo University of Science). Hyper-K will have a total mass of 260 kilotonne and 8.4 times the fiducial volume of the current Super-Kamiokande detector.

While much of Neutrino 2020 was modelled after the usual features of an in-person conference, the virtual reality (VR) poster presentation was novel and unique. Marco Del Tutto (Fermilab) created multiple virtual "rooms" for five posters each, along with additional rooms for topical discussions, sightseeing in Chicago and visiting Fermilab. The most enabling feature of the VR was that the software facilitated dialogue between participants whose avatars could move around the space and speak with one another. For example, if a group of avatars clustered around a poster, the participants could discuss the poster as a group. The VR feature attracted 3409 participants. The VR was also supplemented by two-minute videos from presenters, which enabled 5800 YouTube views and 60,600 web displays.

Exciting physics

In the closing remarks, the organisers acknowledged the challenges of an online conference, but also emphasised the strengths of this novel approach. The exciting physics of Neutrino 2020 was made available to an extensive and diverse audience, including many scientists who would not have been able to attend an in-person conference because of funding, visas, family concerns or other issues. About 60% of participants were students or post-docs and the conference reached participants from 67 countries. The Slack discussions and posts on social media indicated widespread praise that the online format worked as well as it did. Some aspects of Neutrino 2020 may well affect the planning and organisation of future in-person and online conferences.

Steve Brice *and* **Sam Zeller** *Fermilab, and* **Marvin Marshak** *University of Minnesota.*

TERASCALE SUMMER SCHOOL

Terascale summer school goes global

In a new venture by physicists at DESY, the first Terascale Summer School took place online from 23 July to 12 August, providing more than 160 undergraduate students from more than 30 countries with an engaging introduction to the world of particle and astroparticle physics. Following a wide-ranging three weeks of teaching, an impromptu fortnight-long online tutorial, which only concluded yesterday, focused on strong interactions and Monte Carlo techniques, allowing students to deepen their knowledge through practical exercises.

International appeal
Forced online by the pandemic, the summer school drew particularly high participation from Cuba, Egypt, India, Malaysia and Russia.

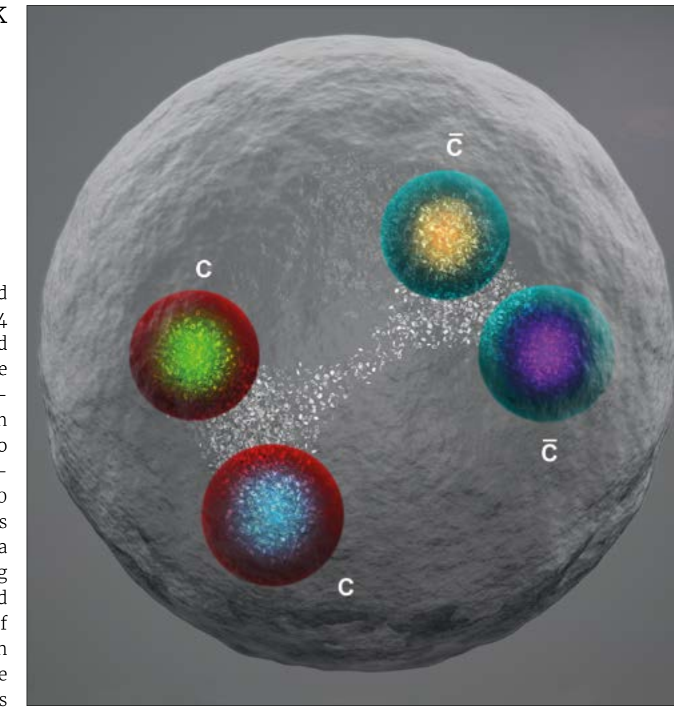
As the school had been forced online due to the ongoing pandemic, the organisers settled upon a reduced programme with just one or two 45 minutes lectures per day. Active moderation was key, with students typing questions in the chat box, and the moderator interrupting the lecturer when appropriate to give the participants a chance to speak up. This format conferred upon less brash participants a more comfortable way to ask questions, several students noted. When one brave pioneer had broken the ice, queries flowed every few minutes – a resonance effect characterised by a lively, stimulating and relaxed atmosphere that boosted concentration levels.

With its global reach and breathing space for students to explore concepts independently, Terascale 2020's compact online format may merit consideration during less extraordinary times too.

Olaf Behnke *DESY Hamburg.*

TETRAQUARKS BACK IN THE SPOTLIGHT

A hidden-double-charm tetraquark observed recently by the LHCb collaboration has reinvigorated the debate over whether tetraquarks are loosely bound pairs of mesons or tightly bound pairs of diquarks.



D Dominguez/CERN

Diquark dilemma *An artist's impression of a hidden-double-charm tetraquark. In the pictured model, a pair of colour-charged diquarks are bound together by the exchange of gluons.*

The existence of particles with fractional charges and fractional baryon numbers was a hard sell in 1964 when Gell-Mann and Zweig independently proposed the quark model. Physicists remained sceptical until the discovery of the J/ψ meson 10 years later. Heavier than anything previously seen and extremely narrow, with a width of just 0.1 MeV and a mass of 3097 MeV, the J/ψ pointed to the existence of a new quark with its own quantum number. This confirmed Glashow, Iliopoulos and Maiani's 1970 hypothesis, which they cooked up to explain peculiarities in rare kaon decays. Any doubt as to the existence of a charm–anticharm system was eliminated by observing narrow excitations of the J/ψ, which lined up as expected in non-relativistic quantum mechanics. The spectrum of charmonium mesons soon became populated by states with widths up to hundreds of MeV as their masses surpassed the threshold for decaying to a pair of "open-charm" mesons with a single charm quark each.

Hadron spectroscopy continues to be a rich area of fundamental exploration today, with results from collider experiments over the past two decades revealing the existence of multi-quark states more exotic than the familiar mesons and baryons (*CERN Courier* April 2017 p31). The LHCb experiment at CERN is at the forefront of this work. Now, a structure in the J/ψ-pair mass spectrum consistent with a tetraquark state made up of two charm quarks and two charm antiquarks has been observed by the collaboration. With doubly hidden charm, the new $cc\bar{c}\bar{c}$ state is the most significant evidence so far for the existence of tightly bound tetraquarks composed of a pair of colour-charged "diquarks", and sheds light on a difficult-to-model regime of quantum chromodynamics (QCD).

Multi-quark states

Gell-Mann and Zweig both acknowledged that the symmetries which led to the quark hypothesis allowed for more complicated quark configurations than just mesons ($q\bar{q}$) and baryons (qqq). Tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$) and hexaquarks ($qqq\bar{q}\bar{q}\bar{q}$ or $qqqqqq$) were all suggested. In the early 1970s, a deepening understanding of the dynamics of strong interactions brought about by QCD only furthered the motivation for seeking new multi-quark states. QCD not only predicted attractive forces between a quark and an antiquark, and between three quarks, but also between two quarks.

The attraction between two quarks can easily be proven when they are close together and the strong coupling constant is small enough to allow perturbative calculations. Similar interactions also likely occur in the non-perturbative regime. Such systems, known as diquarks, have the colour charge of an antiquark. (For example, red and blue combine to make an anti-green diquark.) As coloured objects, they can be confined in hadrons by partnering with other coloured constituents. A diquark can attract a quark to create a simple baryon. Alternatively, a diquark

THE AUTHORS
Marco Pappagallo *INFN and University of Bari*, **Liupan An** *INFN Sezione di Firenze and* **Tomasz Skwarnicki** *Syracuse University.*

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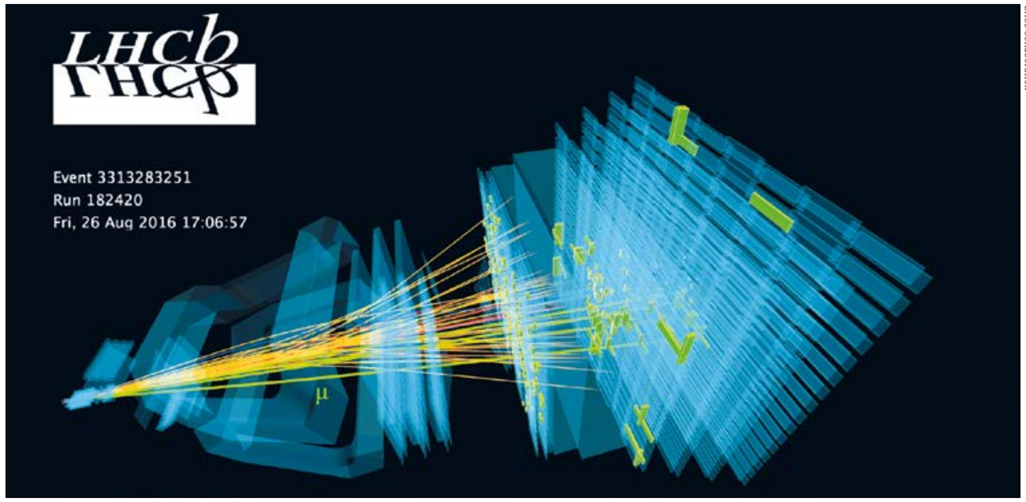


LHCb Collaboration

Four muons *A J/ψ-pair candidate event in the LHCb detector, in which both mesons decayed into a pair of muons (green lines). LHCb observed a resonance in the invariant mass of such events, which is indicative of a hidden-double-charm tetraquark.*

and an antidiquark can attract each other to create a tetraquark. As a result of their direct colour couplings, such compact tetraquarks can have binding energies of several hundreds of MeV.

Compact two-diquark tetraquarks stand in stark contrast to the alternative "molecular" model for tetraquarks, which was named by loose analogy with the exchange of electrons between atoms in molecules. In this picture, the tetraquark is arranged as a pair of mesons that attract each other by exchanging colour-neutral objects, such as light mesons and glueballs – an idea first proposed in 1935 by Hideki Yukawa, in the context of interactions between nucleons. Such exchanges only provide a binding energy of a few MeV per nucleon.

Molecular tetraquarks are therefore expected to be only loosely bound, with masses near the sum of the masses of their constituent mesons, however they could have rather narrow widths if their mass lies below the "fall-apart" threshold. As such states are most likely to be created without angular momentum between the mesons, the spin-parity combinations available to them are highly restricted. In contrast, a rich spectrum of radial and angular momentum excitations between the coloured constituents is predicted for diquark tetraquarks. The widths of these states could be large, as they can easily fall apart into lighter hadrons, with their binding energy transformed into a light quark–antiquark pair.

Unfortunately, it is difficult to rigorously apply QCD in the confining regime of multi-quark states. It is therefore up to experiments to discover which multi-quark states actually exist in nature. There have been some hints of tetraquark states built out of light quarks, though without definite proof. This is largely because additional light quark pairs can easily be created in the decay process of simple mesons and baryons, and the highly relativistic nature of such states makes model predictions for their excitations unreliable. Hidden charm states have proved helpful again, however, as the charmonium spectrum and the properties of such states are well predicted.

Experiments to the fore

Molecular tetraquark proposals were fuelled in 2003 by the unexpected discovery by the Belle collaboration, at the KEKB electron–positron collider in Tsukuba, Japan, of a new narrow state, right at the sum of the masses of a charmed-meson pair. Unlike other charmonium states near its mass, the state is surprisingly narrow, with a width of the order of just 1 MeV. Originally named X(3872), it is now conventionally referred to as $\chi_{c1}(3872)$, reflecting its nature as a possible triplet P-wave state with hidden charm and one unit of total angular momentum. Despite subsequent results from collider experiments around the world, there is no consensus about its exact nature, as it variously exhibits features of simple charmonium or a loosely bound molecule.

Stronger evidence for the loose meson–meson binding of multi-quark states was provided by observations in 2013 of a hidden-charm tetraquark candidate $Z_c(3900)$ by the BES III collaboration at the BEPC II electron–positron collider in Beijing, China, and by Belle, and of the $Z_c(4020)$, also by BES III. Since they have electrically charged forms, they cannot be counted as charmonium states. They are both relatively narrow states near meson–meson thresholds for open charm, with widths of the order of tens of MeV. They are definitely tetraquarks, though it is still a moot point if they are genuinely bound states or merely manifestations of non-binding hadron–hadron forces that manifest in complicated forms. The molecular interpretation had also been reinforced in 2012 by Belle's observations of the hidden-beauty $Z_b(10610)$ and $Z_b(10650)$ tetraquarks. These states also have relatively narrow widths of the order of tens of MeV and masses near the threshold for falling apart, in this case to "open-beauty" mesons.

Pentaquark observations have also weighed in on the debate. Last year's observation of three narrow hidden-charm pentaquarks by the LHCb collaboration, with widths below tens of MeV and masses close to the charm meson–baryon threshold (*CERN Courier* May/June 2019 p15), also points to loose hadron–hadron binding, in this case between a meson and a baryon.

It is up to experiments to discover which multi-quark states actually exist in nature

Bucking the trend

Yukawa-style bindings cannot, however, explain a large number of broader tetraquark-like structures with hidden charm, with widths of hundreds of MeV, which are not near any hadron–hadron threshold. Such states include the charged $Z_c(4430)$ observed by Belle in 2008 and later confirmed by LHCb in 2014, and a family of states that decay to a $J/\psi\,\phi$ final state, including X(4140) and X(4274), which were observed by the CDF collaboration at Fermilab in 2009 and later by CMS and LHCb at CERN. These states could be either manifestations of diquark interactions or kinematic effects near the fall-apart threshold. No single simple model can account for all of them.

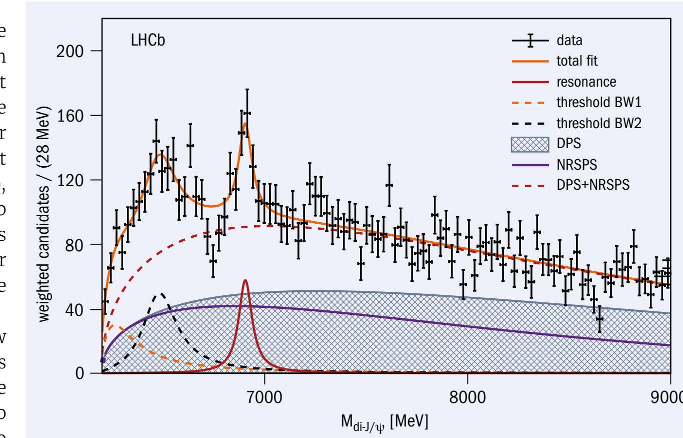
Reaching states with hidden double charm ($cc\bar{c}\bar{c}$) now promises new insights into multi-quark dynamics, as all the quarks are non-relativistic. Furthermore, there is no known mechanism for two charmonium mesons to be loosely bound, according to a molecular model, as no light valence quarks are available to be exchanged. Compact diquark-type tetraquarks have been predicted for such quark combinations, but it is not clear whether they might lead to experimentally detectable signatures – the tetraquarks could be too broad or their production rate too small. While collisions at the LHC provide enough energy to simultaneously produce pairs of charm–anticharm quark combinations, getting them close enough together to form diquarks is a tall order. Additionally, while observations of beauty–charm mesons such as B_c and doubly charmed baryons such as Ξ_{cc} showed that LHCb has reached the sensitivity to detect the interactions of two heavy quarks, it was unclear until recently if the interactions of diquark-model tetraquarks could be detected. The observation, reported in July, by LHCb, of a highly significant J/ψ-pair mass structure is therefore an exciting moment for the study of multi-quark dynamics.

Introducing the X(6900)

Exploiting the full data set collected from 2011 to 2018, LHCb investigated the J/ψ-pair invariant mass spectrum, where J/ψ meson candidates are reconstructed from the dimuon decay mode. A narrow peaking structure at 6900 MeV and a broader structure at approximately twice the J/ψ mass threshold was observed. The structure of X(6900) is consistent with the signature of a resonance (see figure), suggesting a four-charm-quark state.

While the peaking X(6900) structure is close to the $\chi_{c0}\chi_{c1}$ meson-pair threshold, its width, of the order of a hundred MeV, seems too large to fit into the loose-binding scheme, wherein decay modes other than the "fall-apart" topology are expected to be strongly suppressed, and in any case, there is no known loose binding mechanism between two charmonium states. Charmonium-pair re-scattering effects are also disfavoured due to the requirements of such interactions. This observation is therefore the most intriguing experimental indication so far for hadrons made out of diquarks.

It is less clear if the observed structure is made of one state, or several that may or may not interfere with each other. There is no information on the spin-parity of the observed structure. Neither do we yet know if mass structures also appear in the invariant mass spectra of other charmonium or doubly charmed baryon pairs.



LHCb Collaboration

Di-J/ψ bump *The X(6900) structure (solid red curve) observed in the J/ψ-pair mass spectrum.*

The first LHCb upgrade is currently in progress and data taking will recommence at the beginning of LHC Run 3 in 2022, with a second upgrade phase planned to collect a much larger data set by 2030. The ATLAS and CMS experiments have highly performing muon detectors too, and could also make significant contributions to the study of the new X(6900) structure, with both existing and future data. A key contribution may also be made by Belle's successor, Belle II, currently in its start-up phase, which observes electron–positron collisions at the SuperKEKB collider at energies above the observed J/ψ-pair mass structure. It is unclear, however, if the collision energy, luminosity and electromagnetic production cross sections will be high enough to achieve the required sensitivity.

Research is already moving forward quickly, with further evidence for diquark tetraquarks coming from an even more recent discovery by LHCb of two "X(2900)" states with widths between 57 and 110 MeV. As they decay to a D^+K^- final state, they are both openly charming and openly strange. Their most likely composition is that of a $(cs)(\bar{u}\bar{d})$ diquark tetraquark. While the X(2900) states decay strongly, similar heavy–light diquark systems, such as $(cc)(\bar{u}\bar{d})$, $(bc)(\bar{u}\bar{d})$ and $(bb)(\bar{u}\bar{d})$, have been studied theoretically, resulting in varying degrees of confidence that some may be stable with respect to strong interactions, and instead decay weakly, with measurable lifetimes. Hunting for such states is an exciting prospect for the upgraded LHCb experiment.

LHCb's new tetraquark observations have once again thrown open the debate on the nature of multi-quark states. With the theory still mired in non-perturbative calculations, experimental observations will be decisive in leading the development of this subject. The community is waiting eagerly to see if other experiments confirm the LHCb observation, and shed light on its nature. ●

Further reading

LHCb Collaboration 2020 arXiv:2006.16957.
LHCb Collaboration 2020 arXiv:2009.00025.
LHCb Collaboration 2020 arXiv:2009.00026.

This observation is the most intriguing experimental indication so far for hadrons made out of diquarks

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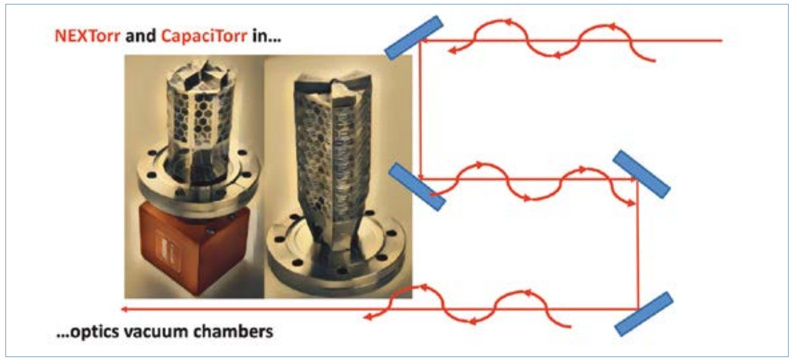

Vacuum engineers and scientists have long known that even if a sample material is initially clean and handled with ultrahigh-vacuum (UHV) standards, a carbon contamination layer will deposit and grow on the material's surface after placing it in a high vacuum (HV) or UHV chamber. This condition is also true for the optics vacuum chambers found in particle accelerators and synchrotron beamlines. For the optics vacuum chambers, this situation is worsened by X-ray irradiation, which can result in a one to two orders of magnitude pressure increase and high yield of carbon contaminants. The effects of carbon contamination on the X-ray optics can significantly reduce the X-ray transmission downstream to the experimental stations, and as next-generation synchrotrons usher in X-ray brightness increases of two to three orders of magnitude, it is critical to minimize these losses from carbon contamination.

Multiple studies have shown that carbon contamination develops on X-ray optics and reduces the transmission of photons near the carbon K edge, around 285 eV, as well as at higher energies around 1000 eV. As early as the 1980s, this carbon contamination layer was shown to cause intensity modulations in X-ray absorption spectra that closely resembled those above the carbon K edge in bulk crystalline graphite. These results suggested the formation of graphitic carbon contamination even under UHV conditions. Carbon contamination is not only experimentally detected; it is also visually evident after a few months to a year of beamline operation. It will usually appear as a black line where the X-rays strike the optics.

Read the full paper online.

SAES Group S.p.A
Web www.saesgroup.com

On track *An aerial view of the European Spallation Source (ESS) construction site in Lund, Sweden, on 28 May 2020. (Credit: P Nordeng/ESS)*

ESS UNDER CONSTRUCTION

The European Spallation Source (ESS) will provide neutron beams 100 times brighter than those from reactor sources, enabling new research into material properties and fundamental physics.

Just a few years after the discovery of the neutron by James Chadwick in 1932, investigations into the properties of neutrons by Fermi and others revealed the strong energy dependence of the neutron's interactions with matter. This knowledge enabled the development of sustainable neutron production by fission, opening the era of atomic energy. The first nuclear-fission reactors in the 1940s were also equipped with the capacity for materials irradiation, and some provided low-energy (thermal) neutron beams of sufficient intensity for studies of atomic and molecular structure. Despite the high cost of investment in nuclear-research reactors, neutron science flourished to become a mainstay among large-scale facilities for materials research around the world.

The electrical neutrality of neutrons allows them to probe deep into matter in a non-destructive manner, where they scatter off atomic nuclei to reveal important information about atomic and molecular structure and dynamics. Neutrons also carry a magnetic moment. This property, combined with their absence of electric charge, make neutrons uniquely sensitive to magnetism at an atomic level. On the downside, the absence of electric charge means that neutron-scattering cross sections are much weaker than they are for X-rays and electrons, making neutron flux a limiting factor in the power of this method for scientific research.

Throughout the 1950s and 1960s, incremental advances in the power of nuclear-research reactors and improvements in moderator design provided increasing fluxes of thermal neutrons. In Europe these developments culminated in the construction of the 57 MW high-flux reactor (HFR) at the Institut Laue-Langevin (ILL) in Grenoble, France, with a compact core containing 9 kg of highly enriched uranium enabling neutron beams with energies from around 50 μeV

THE AUTHORS
Håkan Danared, **Shane Kennedy** *and* **Mats Lindroos**
European Spallation Source, Sweden.

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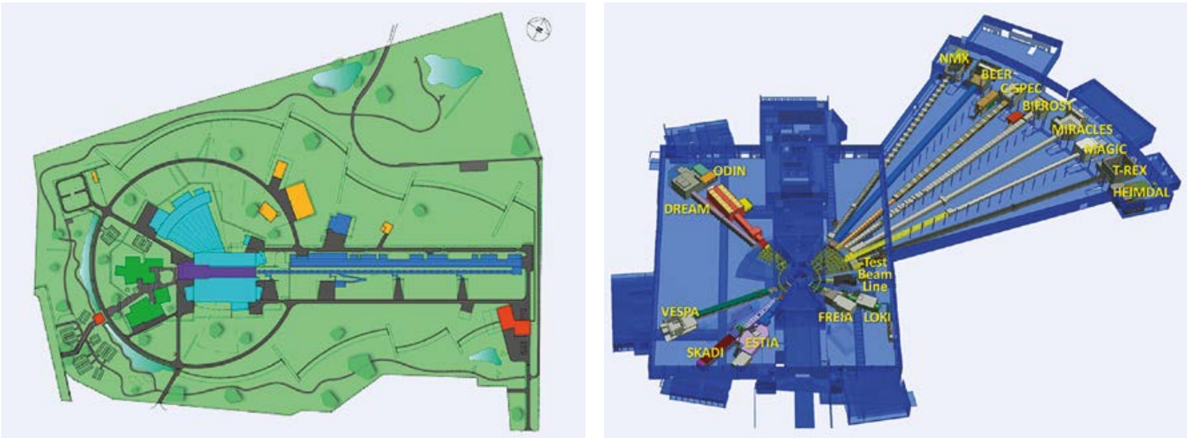

ESS

ESS from above *Left: the ESS site layout, showing accelerator buildings (dark blue), target (violet), instrument halls (light blue), offices and labs (green) and auxiliary buildings (red and yellow). Right: the positions of the first 15 neutron instruments: diffractometers for hard-matter structure determination (DREAM, HEIMDAL and MAGIC), macromolecular crystallography (NMX) and engineering studies (BEER); small-angle scattering instruments for the study of large-scale structures (LOKI and SKADI); reflectometers for the study of surfaces and interfaces (ESTIA and FREIA); spectrometers for the study of atomic and molecular dynamics (BIFROST, C-SPEC, MIRACLES, T-REX and VESPA); and a neutron imaging station (ODIN).*

to 500 meV. When the HFR came into operation in 1972, however, it was clear that nuclear-fission reactors were already approaching their limit in terms of steady-state neutron flux (roughly 1.5×10^{15} neutrons per cm^2 per second).

In an effort to maintain pace with advances in other methods for materials research, such as synchrotron X-ray facilities and electron microscopy, accelerator-based neutron sources were established in the 1980s in the US (IPNS and LANSCE), Japan (KENS) and the UK (ISIS). Spallation has long been hailed as the method with the potential to push through to far greater neutron fluxes, and hence to provide a basis for continued growth of neutron science. However, after nearly 50 years of operation, and with 10 more modern medium- to high-flux neutron sources (including five spallation sources) in operation around the world, the HFR is still the benchmark source for neutron-beam research. Of the spallation sources, the most powerful (SNS at Oak Ridge National Laboratory in the US and J-PARC in Japan) have now been in operation for more than a decade. SNS has reached its design power of 1.4 MW, and J-PARC is planning for tests at 1 MW. At these power levels the sources are competitive with ILL for leading-edge research. It has long been known that the establishment of a new high-flux spallation neutron facility is needed if European science is to avoid a severe shortage in access to neutron science in the coming years (*CERN Courier* May/June 2020 p49).

Spallation has long been hailed as the method with the potential to push through to far greater neutron fluxes

Unprecedented performance

The European Spallation Source (ESS), with a budget of €1.8 billion (2013 figures), is a next-generation high-flux neutron source that is currently entering its final construction phase. Fed by a 5 MW proton linac, and fitted with the most compact neutron moderator and matched neutron transport systems, at full power the brightness of the ESS neutron beams is predicted to exceed the HFR by more than two orders of magnitude.

The idea for the ESS was advanced in the early 1990s. The decision in 2009 to locate it in Lund, Sweden, led to the establishment of an organisation to build and operate the facility (ESS AB) in 2010. Ground-breaking took place in 2014, and today construction is in full swing, with first science expected in 2023 and full user operation in 2026. The ESS is organised as a European Research Infrastructure Consortium (ERIC) and at present has 13 member states: Czech Republic, Denmark, Estonia, France, Germany, Hungary, Italy, Norway, Poland, Spain, Sweden, Switzerland and the UK. Sweden and Denmark are the host countries, providing nearly half of the budget for the construction phase. Around 70% of the funding from the non-host countries is in the form of in-kind contributions, meaning that the countries are delivering components, personnel or other support services to the facility rather than cash.

The unprecedented brightness of ESS neutrons will enable smaller samples, faster measurements and more complex experiments than what is possible at existing neutron sources. This will inevitably lead to discoveries across a wide range of scientific disciplines, from condensed-matter physics, solid-state chemistry and materials sciences, to life sciences, medicine and cultural heritage. A wide range of industrial applications in polymer science and engineering are also anticipated, while new avenues in fundamental physics will be opened (see "Fundamental physics at the ESS" panel).

From the start, the ESS has been driven by the neutron-scattering community, with strong involvement from all the leading neutron-science facilities around Europe. To maximise its scientific potential, a reference set of 22 instrument concepts was developed from which 15 instruments covering a wide range of applications were selected for construction. The suite includes three diffractometers for hard-matter structure determination, a diffractometer for macromolecular crystallography, two small-angle scattering instruments for the study of large-scale structures, two reflectometers for the study of surfaces and interfaces, five spectrometers for the study of atomic and molecular dynamics over an energy range from a few μeV to several hundred meV, a diffractometer for engineering studies and a neutron imaging station (see "ESS layout" figure). Given that the ESS target system has the capacity for two neutron moderators and that the beam extraction system allows viewing of each moderator by up to 42 beam ports, there is the potential for many more neutron instruments without major investment in the basic infrastructure. The ESS source also has a unique time structure, with far longer pulses than existing pulsed sources, and an innovative bi-spectral neutron moderator, which allows a high degree of flexibility in the choice of neutron energy.

ESS

Monolith *The 6000-tonne target station monolith, consisting of concrete and steel shielding, will surround the target wheel, moderator, cooling systems and beam extraction system.*

U Hammarlund/ESS

Cool view *A section of the cryogenic system for the 600 m-long linear accelerator.*

Accelerator and target

Most of the existing spallation neutron sources use a linear accelerator to accelerate protons to high energies. The particles are stored in an accumulator ring and are then extracted in a short pulse (typically a few microseconds in length) to a heavy-metal spallation target such as tungsten or mercury, which have a high neutron yield. A notable exception is SINQ at PSI, which uses a cyclotron that produces a continuous beam.

ESS has a linear accelerator but no accumulator ring, and it will thus have far longer proton pulses of 2.86 ms.

Fundamental physics at the ESS

The ESS will offer a multitude of opportunities for fundamental physics with neutrons, neutrinos and potentially other secondary particles from additional target stations. While neutron brightness and pulse time structure are key parameters for neutron scattering (the main focus of ESS experiments), the total intensity is more important for many fundamental-physics experiments.

A cold neutron-beam facility for particle physics called ANNI is proposed to allow precision measurements of the beta decay, hadronic weak interactions and electromagnetic properties of the neutron. ANNI will improve the accuracy of measurements of neutron beta decay by an order of magnitude. Experiments will probe a broad range of new-physics models at mass scales from 1 to 100 TeV, far beyond the threshold of direct particle production at accelerators, and resolve the tiny effects of hadronic weak interactions, enabling quantitative tests of the non-perturbative limit of quantum chromodynamics.

Another collaboration is proposing a two-stage experiment at the ESS to search for baryon-number violation. The first stage, HIBEAM, will look for evidence for sterile neutrinos. As a second stage, NNBAR could be installed at the large beam port, with the purpose to search for oscillations between neutrons and anti-neutrons. Observing such a transition would show that the baryon number is violated by two units and that matter containing neutrons is unstable, potentially shedding light on the observed baryon asymmetry of the universe.

A design study, financed through the European Commission's Horizon 2020 programme, is also under way for the ESS Neutrino Super Beam (ESSνSB) project. This ambitious project would see an accumulator ring and a separate neutrino target added to the ESS facility, with the aim of sending neutrinos to a large underground detector in mid-Sweden, 400–500 km from the ESS. Here, the neutrinos would be detected at their second oscillation maximum, giving the highest sensitivity for discovery and/or measurement of the leptonic CP-violating phase. An accumulator ring and the resulting short proton pulses needed by ESSνSB would open up for other kinds of fundamental physics as well as for new perspectives in neutron scattering, and muon storage rings.

Finally, a proposal has been submitted to ESS concerning coherent neutrino–nucleus scattering (CEνNS). The high proton beam power together with the 2 GeV proton energy will provide a 10 times higher neutrino flux from the spallation target than previously obtained for CEνNS. Measured for the first time by the COHERENT collaboration in 2017 at ORNL's Spallation Neutron Source, CEνNS offers a new way to probe the properties of the neutrino including searches for sterile neutrinos and a neutrino magnetic moment, and could help reduce the mass of neutrino detectors.

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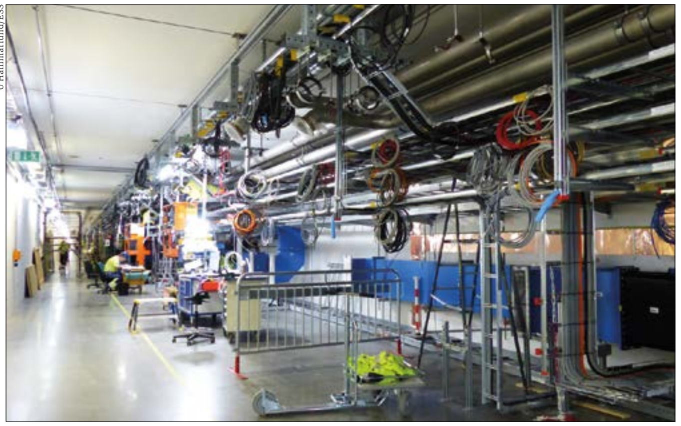
Cabling *Installation of part of the 5 MW proton linac.*


Quad control *A linac warm unit, which will be positioned between all the cryomodules inside the tunnel.*

This characteristic, combined with the 14 Hz repetition rate of the ESS accelerator, is a key advantage of the ESS for studies of condensed matter, because it allows good energy resolution and broad dynamic range. The result is a source with unprecedented flexibility to be optimised for studies from condensed-matter physics and solid-state chemistry, to polymers and the biological sciences with applications to medical research, industrial materials and cultural heritage. The ESS concept is also of major benefit for experiments in fundamental physics, where the total integrated flux is a main figure of merit.

The high neutron flux at ESS is possible because it will be driven by the world's most powerful particle accelerator, in terms of MW of beam on target. It will have a proton beam of 62.5 mA accelerated to 2 GeV, with most of the energy gain coming from superconducting radio-frequency cavities cooled to 2 K. Together with its long pulse structure, this gives 5 MW average power and 125 MW of peak power. For proton energies around a few GeV, the neutron production is nearly proportional to the beam power, so the ratio between beam current and beam energy is to a large extent the result of a cost optimisation, while the pulse structure is set by requirements from neutron science.

The ESS will be driven by the world's most powerful particle accelerator, in terms of MW of beam on target

The neutrons are produced by spallation when the high-energy protons hit the rotating tungsten target. The 2.5 m-diameter target wheel consists of 36 sectors of tungsten blocks inside a stainless-steel disk. It is cooled by helium gas, and it rotates at approximately 0.4 Hz, such that successive beam pulses hit adjacent sectors to allow adequate heat dissipation and limiting radiation damage. The neutrons enter moderator–reflector systems above or below the target wheel. The unique ESS "butterfly" moderator design consists of interpenetrating vessels of water and parahydrogen, and allows viewing of either or both vessels from a 120° wide array of beam ports on either side. The moderator is only 3 cm high, ensuring the highest possible brightness. Thus each instrument is fed by an intense mix of thermal (room temperature) and cold (20 K) neutrons that is optimised to its scientific requirements. The neutrons are transported to the instruments through neutron-reflecting guides that are up to 165 m long. Neutron optics are quite challenging, due to the weak cross-sections, which makes the technology for transporting neutrons sophisticated. The guides consist of optically flat glass or metal channels coated with many thin alternating layers of nickel and titanium, in a sequence designed to enhance the critical angle for reflection. The optical properties of the guides allow for broad spectrum focusing to maximise intensity for varying sample sizes, typically in the range from a few mm^3 to several cm^3.

Under construction

Construction of the ESS has been growing in intensity since it began in 2014. The infrastructure part was organised differently compared to other scientific large-scale research facilities. A partnering collaboration agreement was set up with the main contractor (Skanska), with separate agreements for the design and target cost settled at the beginning of different stages of the construction to make it a shared interest to build the facility within budget and schedule.

Today, all the accelerator buildings have been handed over from the contractor to ESS. The ion source, where the protons are produced from hydrogen gas, was delivered from INFN in Catania at the end of 2017. After installation, testing and commissioning to nominal beam parameters, the ion source was inaugurated by the Swedish king and the Italian president in November 2018. Since then, the radio-frequency quadrupole and other accelerator components have been put into position in the accelerator tunnel, and the first prototype cryomodule has been cooled to 2 K. There is intense installation activity in the accelerator, where 5 km of radio-frequency waveguides are being mounted, 6000 welds of cooling-water pipes performed and 25,000 cables being pulled. The target building is under construction, and has reached its full height of 31 m. The large target vacuum vessel is due to arrive from in-kind partner ESS Bilbao in Spain later this year, and the target wheel in early 2021.

The handover of buildings for the neutron instruments started in September 2019, with the hall of the long instruments along with the buildings housing associated laboratories and workshops. While basic infrastructure such as the neutron bunker and radiation shielding for the neutron guides are provided by ESS in Lund, European partner laboratories are heavily involved in the design and construction of the neutron instruments and the sample-environment equipment. ESS has developed its own detector and chopper technologies for the neutron instruments, and these are being deployed for a number of the instruments currently under construction. In parallel, the ESS Data Management and Software Centre, located in Copenhagen, Denmark, is managing the development of instrument control, data management and visualisation and analysis systems. During full operation, the ESS will produce scientific data at a rate of around 10 PB per year, while the complexity of the data-handling requirements for the different instruments and the need for real-time visualisation and processing add additional challenges.

The major upcoming milestones for the ESS project are beam-on-target, when first neutrons are produced, and first-science, when the first neutron-scattering experiments take place. According to current schedules, these milestones will be reached in October 2022 and July 2023, respectively. Although beam power at the first-science milestone is expected to be around 100 kW, performance simulations indicate that the quality of results from first experiments will still have a high impact with the user community. The initiation of an open user programme, with three or more of the neutron instruments beginning operation, is expected in 2024, with further instruments becoming available for operation in 2025. When the construction phase ends in late 2025, ESS is expected to be operating at 2 MW, and all 15 neutron instruments will be in operation or ready for hot-commissioning.

The ESS has been funded to provide a service to the scientific community for leading-edge research into materials properties. Every year, up to 3000 researchers from all over the world are expected to carry out around 1000 experiments there. Innovation in the design of the accelerator, the target system and its moderators, and in the key neutron technologies of the neutron instruments (neutron guides, detectors and choppers), ensure that the ESS will establish itself at the vanguard of scientific discovery and development well into the 21st century. Furthermore, provision has been made for the expansion of the ESS to provide a platform for leading-edge research into fundamental physics and as yet unidentified fields of research. ●

Every year, up to 3000 researchers from all over the world are expected to carry out around 1000 experiments

Further reading

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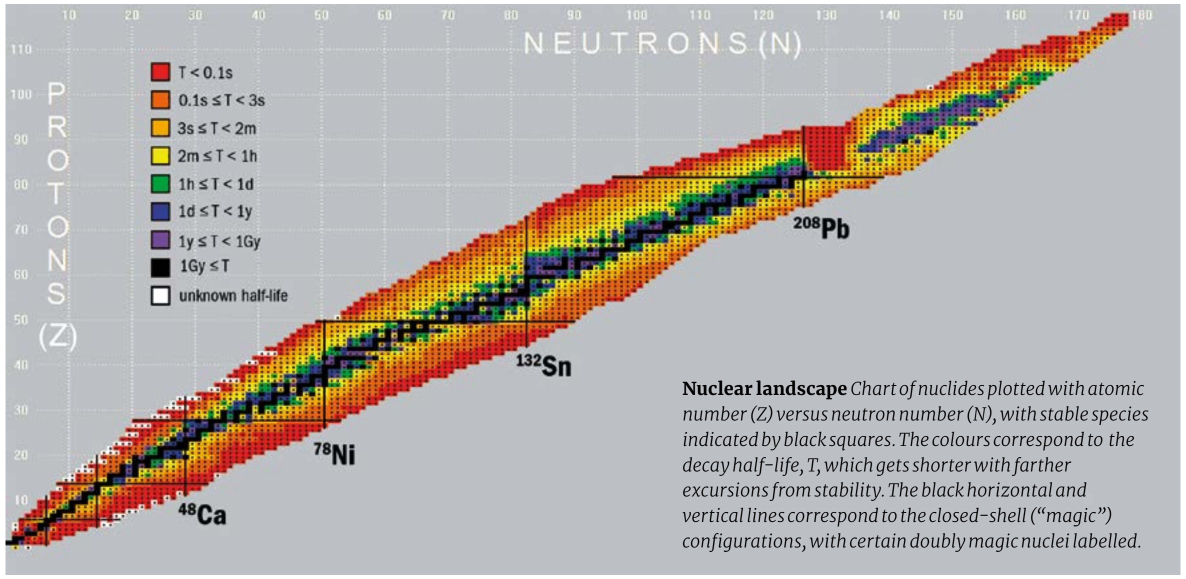
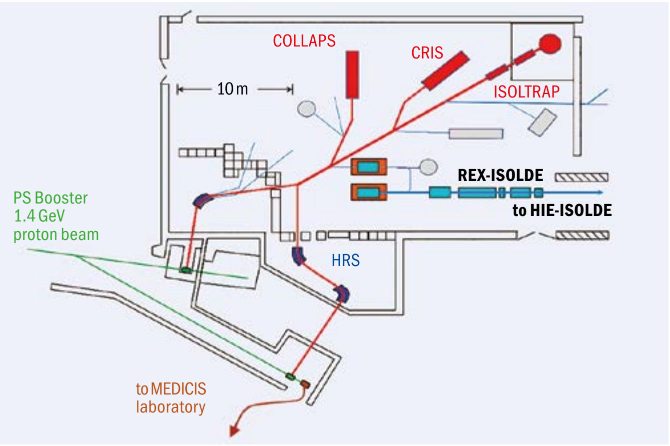
EXPLORING NUCLEI AT THE LIMITS

Recent studies of exotic nuclides using traps and lasers at CERN's ISOLDE facility are not only helping researchers understand nuclear structure, explain David Lunney and Gerda Neyens, but also offer new ways to look for physics beyond the Standard Model.



Nuclear landscape *Chart of nuclides plotted with atomic number (Z) versus neutron number (N), with stable species indicated by black squares. The colours correspond to the decay half-life, T, which gets shorter with farther excursions from stability. The black horizontal and vertical lines correspond to the closed-shell ("magic") configurations, with certain doubly magic nuclei labelled.*



ISOLDE from above *Laser and trap experiments (red) in the low-energy section of ISOLDE (the REX-ISOLDE post-accelerator and the recent HIE-ISOLDE project produce radioactive ion beams of higher energies). A target behind that of the high-resolution separator (HRS) can be parasitically irradiated and then moved with robots to the MEDICIS facility to extract long-lived radioisotopes for medical research.*

Understanding how the strong interaction binds the ingredients of atomic nuclei is the central quest of nuclear physics. Since the 1960s CERN's ISOLDE facility has been at the forefront of this quest, producing the most extreme nuclear systems for examination of their basic characteristic properties.

A chemical element is defined by the number of protons in its nucleus, with the number of neutrons defining its isotopes. Apart from a few interesting exceptions, all elements in nature have at least one stable isotope. These form the so-called valley of stability in the nuclear chart of atomic number versus neutron number (see "Nuclear landscape" figure). Adding or removing neutrons disturbs the nuclear equilibrium and creates isotopes that are generally radioactive; the greater the proton–neutron imbalance, the faster the radioactive decay.

The mass of a nucleus reveals its binding energy, which reflects the interplay of all forces at work within the nucleus from the strong, weak and electromagnetic interactions. Indications of sudden changes in the nuclear shape, when adding neutrons, are often revealed first indirectly as a sudden change in the mass, and can then be probed in detail by measurements of the charge radius and electromagnetic moments. Such diagnosis – performed by ion-trapping and laser-spectroscopy experiments on short-lived (from a few milliseconds upwards) isotopes – provides the first vital signs concerning the nature of nuclides with extreme proton-to-neutron ratios.

Recent mass-spectrometry measurements and high-precision measurements of nuclear moments and radii at ISOLDE demonstrate the rapid progress being made in understanding the stubborn mysteries of the nucleus. ISOLDE's state-of-the-art laser-spectroscopy tools are also opening an era where molecular radioisotopes can be used as sensitive probes for physics beyond the Standard Model.

Tools of the trade

Progress in understanding the nucleus has gone hand in hand with the advancement of new techniques. Mass measurements of stable nuclei pioneered by Francis Aston nearly a century ago revealed a near-constant binding energy per nucleon. This pointed to a characteristic saturation of the nuclear force, which underlies the liquid-drop model and led to the semi-empirical mass formula for the nucleus developed by Bethe and von Weizsäcker. With the advent of particle accelerators in the 1930s, more isotopic mass data became available from reactions and decays, bringing new surprises. In particular, comparisons with the liquid drop revealed conspicuous peaks at certain so-called "magic" numbers (8, 20, 28, 50, 82, 126), analogous to the high atomic-ionisation potentials of the closed electron-shell noble-gas elements. These findings inspired the nuclear-shell model, developed by Maria Goeppert-Mayer and Hans Jensen, which is still used as an important benchmark today. The difference with the atomic system is that the force that governs the nuclear shells is poorly understood. This is because nucleons are themselves composite particles that interact through the complex interplay of three fundamental forces, rather than the single electromagnetic force governing atomic structure. The most important question in nuclear physics today is to describe these closed shells from fundamental principles (e.g. the strong interaction between quarks and gluons inside nucleons), to understand why shell structure erodes and how new shells arise far from stability.

A key to reaching a deeper understanding of nuclear structure is the ability to measure the size and shape of nuclei. This was made possible using the precision technique of laser spectroscopy, which was pioneered with tremendous success at ISOLDE in the late 1970s. While increased binding energy is a tell-tale sign of a deforming nucleus, it gives no specific information concerning nuclear size or shape. Closed-shell configurations tend to favour spherical nuclei, but since these are rather rare, a particularly important feature of nuclei is their deformation. Inspecting electromagnetic moments derived from the measured atomic hyperfine structure and the change in charge radii derived from its isotopic shift provides detailed information about nuclear shapes and deformation, beautifully complementing mass measurements.

During the past half-century, nuclear science at ISOLDE has expanded beyond fundamental studies to applications involving radioactive tracers in materials (including biomaterials) and the fabrication of isotopes for medicine (with the MEDICIS facility). But the bulk of the ISOLDE physics programme, around 70%, is still devoted to the elucidation of nuclear structure and the properties of fundamental interactions. These studies are carried out through nuclear reactions, by decay spectroscopy, or by measuring the basic global properties – mass and size – of the most exotic species possible.

Half a century of history

The fabrication of extreme nuclear systems requires a driver accelerator of considerable energy, and CERN's expertise here has been instrumental. After many years receiving proton beams from a 600 MeV synchrocyclotron (the SC, now a museum piece at CERN), ISOLDE now lies just off the beam line to the Proton Synchrotron (PS), receiving 1.4 GeV beam pulses from the PS Booster (see "ISOLDE from above" figure). ISOLDE in fact receives typically 50% of the pulses in the so-called super-cycle that links the intricate complex of CERN's injectors for the LHC.

The heart of ISOLDE is a cylindrical target that can contain various different materials. The stable nuclei in the target are dissociated by the proton impact and form exotic combinations of protons and neutrons. Heating the target (up to 2000 degrees) helps these fleeting nuclides to escape into an ionisation chamber, in which they form 1^+ ions that are electrostatically accelerated to around 50 keV. Isotopes of one particular mass are selected using one of two available mass separators, and subsequently delivered to the experiments through more than a dozen beamlines. A similar number of permanent experimental setups are operated by several small international collaborations. Each year, more than 40 experiments are performed at ISOLDE by more than 500 users. More than 900 users from 26 European and 17 non-European countries around the world are registered as members of the ISOLDE collaboration.

ISOLDE sets the global standard for the production of exotic nuclear species at low energies, producing beams that

THE AUTHORS
David Lunney *IN2P3/CNRS U. Paris-Saclay and*
Gerda Neyens *CERN and KU Leuven.*

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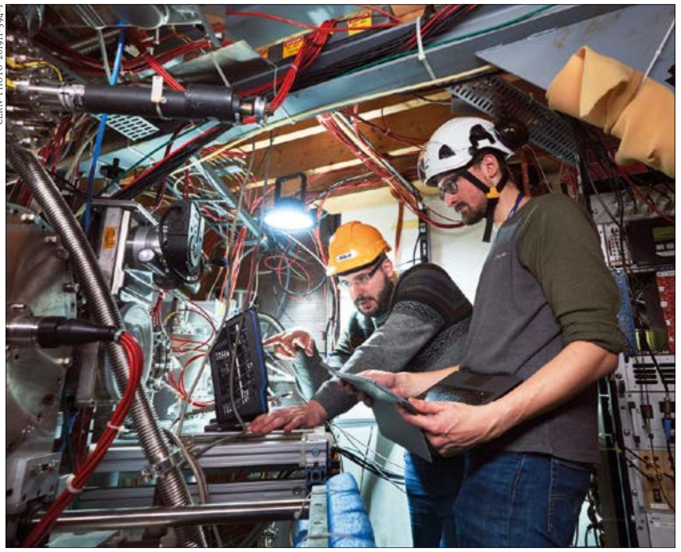

ISOLTRAPpers *CERN fellow Maxime Mougeot and PhD student Lukas Nies (University of Greifswald) tuning ISOLDE's high-precision mass spectrometer in 2019.*

R Stevens/KU Leuven

CRIS collaborators *CERN research fellow Ronald Garcia Ruiz with former PhD students Adam Vernon (Manchester) and Agi Koszorus (KU Leuven), with ISOLDE group leader Gerda Neyens (standing, centre) at the Collinear Resonance Ionization Spectroscopy (CRIS) experiment, photographed in 2018.*

are particularly amenable to study using precision lasers and traps developed for atomic physics. Hence, ISOLDE is complementary to higher energy, heavy-ion facilities such as the Radioactive Isotope Beam Factory (RIBF) at RIKEN in Japan, the future Facility for Rare Isotope Beams (FRIB) in the US, and the Facility for Antiproton and Ion Research (FAIR/GSI) in Europe. These installations produce even more exotic nuclides by fragmenting heavy GeV projectiles on a thin target, and are more suitable for studying high-energy reactions such as breakup and knock-out. Since 2001, ISOLDE has also driven low-energy nuclear-reaction studies by installing a post-accelerator that enables exotic nuclides to be delivered at MeV energies for the study of more subtle nuclear reactions, such as Coulomb excitation and transfer. Post-accelerated radioactive beams have superior optical quality compared to the GeV beams from fragment separators so that the radioactive beams accelerated in the REX and more recent HIE-ISOLDE superconducting linacs enable tailored reactions to reveal novel aspects of nuclear structure.

ISOLDE's state-of-the art experimental facilities have evolved from more than 50 years of innovation from a dedicated and close-knit community, which is continuously expanding and also includes material scientists and biochemists. The pioneering experiments concerning binding energies, charge radii and moments were all performed at CERN during the 1970s. This work, spearheaded by the Orsay group of the late Robert Klapisch, saw the first use of on-line mass separation for the identification of many new exotic species, such as ^{31}Na. This particular success led to the first precision mass measurements in 1975 that hinted at the surprising disappearance of the N = 20 shell closure, eight neutrons heavier than the stable nucleus ^{23}Na. In collaboration with atomic physicists at Orsay, Klapisch's team also performed the first laser spectroscopy of ^{31}Na in 1978, revealing the unexpected large size of this exotic isotope. To reach heavier nuclides, a mass spectrometer with higher resolution was required, so the work naturally continued at the expanding ISOLDE facility in the early 1980s.

Meanwhile, another pioneering experiment was initiated by the group of the late Ernst-Wilhelm Otten. After having developed the use of optical pumping with spectral lamps in Mainz to measure charge radii, Otten's group exploited ISOLDE's first offerings of neutron-deficient Hg isotopes and discovered the unique feature of shape-staggering in 1972. Through continued technical improvements, the Mainz group established the collinear laser spectroscopy (COLLAPS) programme at ISOLDE in 1979, with results on barium and ytterbium isotopes. When tunable lasers and ion traps became available in the early 1980s, the era of high-precision measurements of radii and masses began. These atomic-physics inventions have revolutionised the study of isotopes far from stability and the initial experimental set-ups are still in use today thanks to continuous upgrades and the introduction of new measurement methods. Most of these developments have been exported to other radioactive beam facilities around the world.

Mass measurements with ISOLTRAP

ISOLTRAP is one of the longest established experiments at ISOLDE. Installed in 1985 by the group of Hans-Jürgen Kluge from Mainz, it was the first Penning trap on-line at a radioactive beam facility, spawning a new era of mass spectrometry. The mass is determined from the cyclotron frequency of the trapped ion, and bringing the technique on line required significant and continuous development, notably with buffer-gas cooling techniques for ion manipulation. Today, ISOLTRAP is composed of four ion traps, each of which has a specific function for preparing the ion of interest to be weighed.

Since the first results on caesium, published in 1987, ISOLTRAP has measured the masses of more than 500 species spanning the entire nuclear chart. The most recent results, published this year by Vladimir Manea (Paris-Saclay), Jonas Karthein (Heidelberg) and colleagues, concern the strength of the N = 82 shell closure below the magic (Z = 50) ^{132}Sn from the masses of (Z = 48) ^{132,130}Cd. The team found that the binding energy only two protons below the closed shell was much less than what was predicted by global microscopic models, stimulating new ab-initio calculations based on a nucleon–nucleon interaction derived from QCD through chiral effective-field theory. These calculations were previously available for lighter systems but are now, for the first time, feasible in the region just south-east of ^{132}Sn, which is of particular interest for the rapid neutron-capture process creating elements in merging neutron stars.

The other iconic doubly magic nucleus ^{78}Ni (Z = 28, N = 50) is not yet available at ISOLDE due to the refractory nature of nickel, which slows its release from the thick target so that it decays on the way out. However, the production of copper – just one proton above – is so good that CERN's Andree Welker and his colleagues at ISOLTRAP were recently able to probe the N = 50 shell by measuring the mass of its nuclear neighbour ^{79}Cu, finding it to be consistent with that of the doubly magic ^{78}Ni nucleus. Masses from large-scale shell-model calculations were in excellent agreement with the observed copper masses, indicating the preservation of the N = 50 shell strength but with some deformation energy creeping in to help. Complementary observables from laser spectroscopy helped to tell the full story, with results on moments and radii from the COLLAPS and the more recent Collinear Resonance Ionization Spectroscopy (CRIS) experiments adding an interesting twist.

Laser spectroscopy with COLLAPS and CRIS

Quantum electrodynamics provides its predictions of atomic energy levels mostly by assuming the nucleus is point-like and infinitely heavy. However, the nucleus indeed has a finite mass as well as non-zero charge and current distributions, which impact the fine structure. Thus, complementary to the high-energy scattering experiments used to probe nuclear sizes, the energy levels of orbiting electrons offer a marvellous probe of the electric and magnetic properties of the nucleus. This fact is exploited by the elegant technique of laser spectroscopy, a fruitful marriage of atomic and nuclear physics realised by the COLLAPS collaboration since the late 1970s. COLLAPS uses tunable continuous-wave lasers for high-precision studies of exotic nuclear radii and moments, and similar setups are now running at other facilities, such as Jyvaskyla in Finland, TRIUMF in Canada and NSCL-MSU in the US.

A recent highlight from COLLAPS, obtained this year by Simon Kaufmann of TU Darmstadt and co-workers, is the measurement of the charge radius of the exotic, semi-magic isotope ^{68}Ni. Such medium-mass exotic nuclei are now in reach of the modern ab-initio chiral effective-field theories, which reveal a strong correlation between the nuclear charge radius and its dipole polarisability. With both measured for ^{68}Ni, the data provide a stringent benchmark for theory, and allow researchers to constrain the point-neutron radius and the neutron skin of ^{68}Ni. The latter, in turn, is related to the nuclear equation-of-state, which plays a key role in supernova explosions and compact-object mergers, such as the recent neutron-star merger GW170817.

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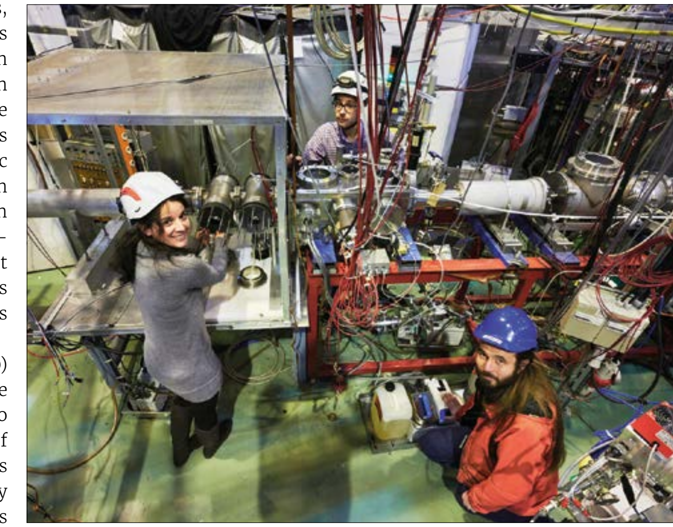

COLLAPS view *Liss Vasquez Rodriguez (Heidelberg), Tassos Kanellakopoulos (KU Leuven) and Mark Bissell (Manchester) at ISOLDE's Collinear Laser Spectroscopy experiment, COLLAPS, in 2019.*

Building on pioneering work by COLLAPS, the collinear laser beamline, CRIS, was constructed at ISOLDE 10 years ago by a collaboration between the groups of Manchester and KU Leuven. In CRIS, a bunched atom beam is overlapped with two or three pulsed laser beams that are resonantly laser-ionised via a particular hyperfine transition. These ions are then deflected from the remaining background atoms and counted in quasi background-free conditions. CRIS has dramatically improved the sensitivity of the collinear laser spectroscopy method so that beams containing just a few tens of ions per second can now be studied with the same resolution as the optical technique of COLLAPS.

Ruben de Groote of KU Leuven and co-workers recently used CRIS to study the moments and charge radii of the copper isotopes up to ^{78}Cu, providing critical information on the wave function and shape of these exotic neighbours, and insight on the doubly magic nature of ^{78}Ni. Both the ISOLTRAP and CRIS results provide a consistent picture of fragile equilibrium in ^{78}Ni, where the failing strength of the proton and neutron shell closures is shored up with binding energy brought by slight deformation.

These precision measurements in new regions of the nuclear chart bring complementary observables that must be coherently described by global theoretical approaches. They have stimulated and guided the development of new ab-initio results, which now allow the properties of extreme nuclear matter to be predicted. While ISOLDE cannot produce absolutely all nuclides on the chart (for example, the super-heavy elements), precision tests in other, key regions provide confidence in the global-model predictions in regions unreachable by experiment.

Most of the developments have been exported to other radioactive beam facilities around the world

Searches for new physics

By combining the ISOLDE expertise in radioisotope production with the mass spectrometry feats of ISOLTRAP and the laser spectroscopy prowess from the CRIS and

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RILIS (Resonant Ionization Laser Ion Source) teams, a new era for fundamental physics research has opened up. It is centred on the ability of ISOLDE to produce short-lived radioactive molecules composed of heavy pear-shaped nuclei, in which a putative electric dipole moment (EDM) would be amplified to offer a sensitive test of time-reversal and other fundamental symmetries. Molecules of radium fluoride (RaF) are predicted to be the most sensitive probes for such precision studies: the heavy mass and octupole-deformed (pear shape) of some radium isotopes, immersed in the large electric field induced by the molecular RaF environment, makes these molecules very sensitive probes for symmetry-violation effects, such as the existence of an EDM. However, these precision studies require laser cooling of the RaF molecules, and since all isotopes of Ra are radioactive, the molecular spectroscopy of RaF was only known theoretically.

This year, for the very first time, an ISOLDE collaboration led by CRIS collaborator Ronald Garcia Ruiz at CERN was able to produce, identify and study the spectroscopy of RaF molecules, containing different long-lived radioisotopes of radium. Specific Ra isotopes were chosen because of their octupole nature, as revealed by experiments at the REX- and HIE-ISOLDE accelerators in 2013 and 2020. The measured molecular excitation spectral properties provide clear evidence for an efficient laser-cooling scheme, providing the first step towards precision studies.

A new era for fundamental physics research has opened up

Many interesting new-physics opportunities will open up using different kinds of radioactive molecules tuned for sensitivity to specific symmetry violation aspects to test the Standard Model, but also with potential impact in nuclear physics (for example, enhanced sensitivity to specific moments), chemistry and astrophysics. This will also require dedicated experimental set-ups, combining lasers with traps. The CRIS collaboration is preparing these new set-ups, and the ability to produce RaF and other radioactive molecules is also under investigation at other facilities, including TRIUMF and the low-energy branch at FRIB. More than 50 years after its breakthrough beginning, ISOLDE continues to forge new paths both in applied and fundamental research. ●

Further reading

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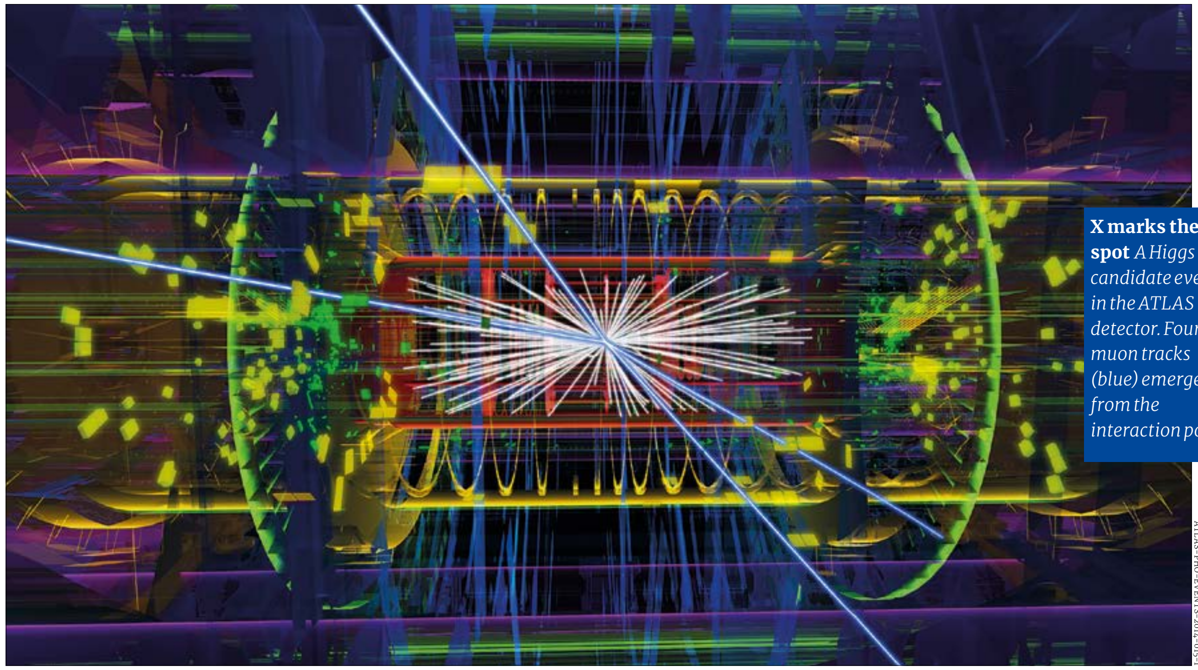
ONE HIGGS, THREE DISCOVERIES



ATLAS-PHO-EVENTS-2016-015-1

X marks the spot *A Higgs candidate event in the ATLAS detector. Four muon tracks (blue) emerge from the interaction point.*

The ATLAS and CMS collaborations have not only discovered a new particle, argues Yosef Nir, but also laid bare the underpinnings of electroweak interactions and uncovered the first evidence for a new type of fundamental interaction – one not related to a known symmetry of nature.

The discovery of the Higgs boson in 2012 was the culmination of almost five decades of research, beginning in 1964 with the theoretical proposal of the Brout–Englert–Higgs (BEH) mechanism. This discovery was monumental, but was itself just a beginning, and research into the properties of the Higgs boson and the BEH mechanism, which has unique significance for the dynamics of the Standard Model, stretches the horizons of even the most ambitious future-collider proposal. Despite this, the ATLAS and CMS collaborations have already made three major discoveries relating to the Higgs boson. These are the jewels in the crown of LHC research so far: an elementary spin-zero particle, the mechanism that makes the weak interaction short range, and the mechanism that gives the third-generation fermions their masses. They can be related to three distinct classes of measurements: the decay of the Higgs boson into two photons, and its production from and decays into the weak force carriers and third-generation fermions, respectively.

Until 2012, the list of elementary particles could be divided into just two broad classes: spin-1/2 matter particles (fermions) and spin-1 force carriers (vector bosons), with a spin-2 force carrier (the graviton) pencilled in by most theorists to mediate the gravitational force. The first jewel in the LHC's crown is the discovery of an elementary spin-0 particle – the first and only particle of this type to have been discovered. The question of the spin of the Higgs boson is intrinsically linked to the dominant discovery mode in 2012: the decay into two photons. Conservation laws insist that only a spin-0 or spin-2 particle

THE AUTHOR
Yosef Nir
Weizmann Institute of Science, Israel.

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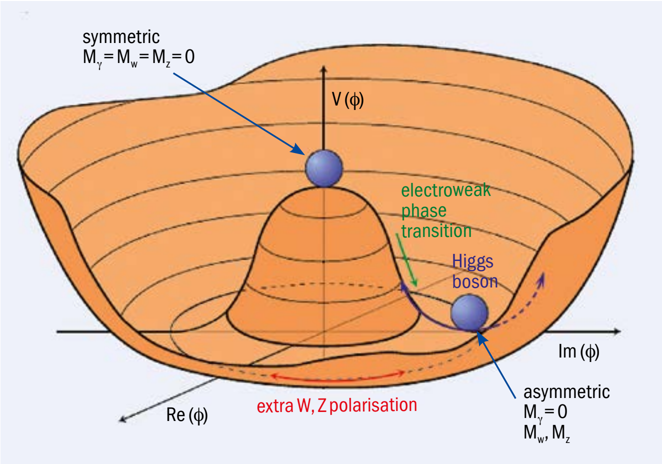
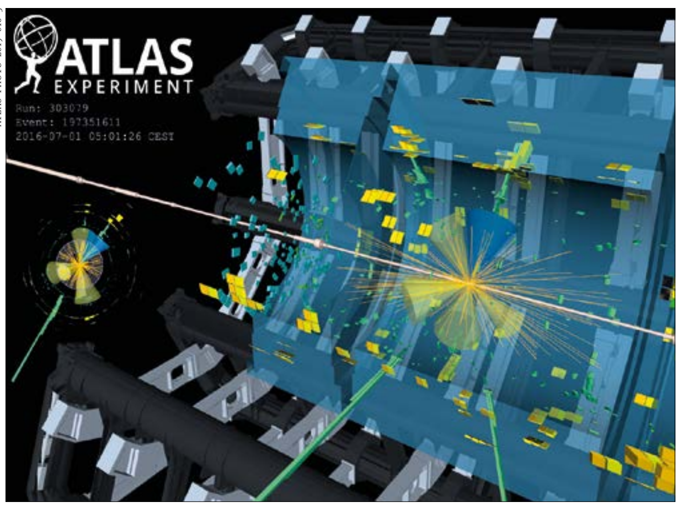


Broken symmetry *The energy stored in the Higgs field, as a function of its value. If we look at it from far away, we realise that the Higgs potential is symmetric. However, a local observer sitting in the rim of the potential, at the vacuum state, will not experience a symmetric world. Thus, the theory is symmetric, but the ground state is not. In the Higgs mechanism, the rotational degree of freedom along the rim becomes the longitudinal polarisation of the W and Z bosons, which thereby acquire mass.*

ATLAS-PHOTO-2019-016-3



Two photons *A 2016 ATLAS candidate for the decay of a Higgs boson into two photons (green) in the ATLAS detector. Only a spin-0 or spin-2 particle can decay this way.*

can decay into two photons.

To decide between the two spin options, a more complex study than just measuring decay rates was needed. The spin of the parent particle affects the angular distributions of the daughter particles of Higgs-boson decays. Studies began immediately within ATLAS and CMS, showing unambiguously that the newly discovered particle was spin-0. The ways in which this particle is produced and the ways in which it decays call for its identification with the only particle that was predicted by the Standard Model of particle physics that had not been observed by 2012 – the Higgs boson. The field related to this particle is the BEH field.

The next question was whether this new particle is elementary or composite. If the Higgs boson is actually a composite spin-0 particle, then there should be a whole series of new composite particles with different quantum numbers – in particular, spin-1 particles whose mass scale is roughly inversely proportional to the distance scale that characterises their internal structure.

One can test the question of whether the Higgs boson is elementary or composite in three ways. Firstly: indirectly. The virtual effects of these heavy spin-1 particles would modify the properties of the W and Z bosons. Part of the legacy of the LEP experiments, which operated at CERN between 1989 and 2000, and the SLD experiment, which operated in SLAC between 1992 and 1998, is a large class of precision measurements of these properties. The other two ways are pursued by the LHC experiments: the direct search for the new spin-1 particles, and precision measurements of properties of the Higgs boson itself, such as its couplings to electroweak vector-boson pairs, which would differ if it were composite. No such composite excitations have been discovered to date, and the Higgs boson shows no signs of internal structure down to a scale of 10^{-19} m – some four orders of magnitude smaller than the proton.

A second jewel

The electromagnetic and strong interactions are mediated by massless mediators – the photon and the gluon. Consequently, they are long-range, though colour confinement – the phenomenon that quarks and gluons cannot be isolated – renders the long-range effects of the strong interaction unobservable. By contrast, weak interactions are mediated by massive mediators – the W and Z bosons – with masses of the order of 100 times larger than that of the proton. As a result, the weak force is exponentially suppressed at distances larger than 10^{-18} m.

A common feature of the electromagnetic, strong and weak forces is that their mediators are all spin-1. This type of interaction is very special. By assuming that nature has certain gauge symmetries, our current quantum field theories can predict the existence of these types of interactions, and many of their features. There are numerous predictions stemming from these symmetries that have been successfully tested by experiments, such as the identical couplings between gluons and quarks of all flavours, the fact that photons don't interact with each other, and the structure of higher-order corrections, for example the running of coupling constants and the anomalous magnetic moment of the electron and the muon. Yet, as the mass term in the Lagrangian isn't invariant under gauge transformations, gauge symmetry predicts, at least naively, that the spin-1 force carriers should be massless. So, while the symmetries that predict the electromagnetic and strong interactions also explain why their force carriers are massless, the symmetry principle that predicts the weak interaction is challenged by the experimental fact that its force carriers are massive.

This conundrum has a possible solution if a symmetry is respected by the quantum field theory but not by the ground state of the universe (see "Broken symmetry" image). The theory's predictions will then be different from those that would follow if the ground state were also symmetric. One way in which the symmetry can be broken is if there is a scalar field that does not vanish in the ground state. This is the case for the Higgs potential, which, unlike a purely parabolic potential, does not have rotational symmetry around its ground state. The weak-force carriers are affected by their interaction with the BEH field, and this interaction slows them down. Moving at speeds slower than the speed of light – the consequence of interacting with the BEH field in the ground state – is equivalent to having non-zero masses, making weak interactions short range. These insights also transformed our understanding of the early universe. Following the Glashow–Weinberg–Salam breakthrough shortly after the BEH proposal, the Standard Model presents a universe in which the ground state transitioned from zero to non-zero due to the spontaneous breaking of electroweak symmetry – a cosmological event that took place when the universe was about 10^{-11} seconds old.

A BEH field different from zero in the ground state of the universe has important observational and experimental consequences. For example, if the symmetry were unbroken, a process where a single Higgs particle decays into a pair of Z bosons would be forbidden. But, once the ground state of the universe breaks the symmetry – the BEH field is non-zero – this process is allowed to occur. (Strictly speaking, the Higgs boson cannot decay into two Z bosons because the sum of their masses is larger than the mass of the Higgs boson, however, the Higgs boson can decay into a real Z boson and a virtual one that produces a pair of fermions.) Similarly, the symmetry would not allow a single Higgs-boson production from Z-boson fusion. But, once the ground state of the universe breaks the symmetry, the latter process is also allowed to occur.

An asymmetric ground state costs the theory none of its predictive power. The strength of the interaction of the Z boson with the BEH field, measured by the mass it gains from this interaction, is closely related to the strength of the interaction of the Z boson with the Higgs particle, measured by the rate at which the Higgs boson decays into two Z bosons, or by the rate at which it is produced by Z-boson fusion. This relation is commonly expressed as the ratio μ_{ZZ^*} between the measured and the predicted rates: if the field related to the newly discovered spin-0 particle is indeed responsible for the mass of the Z boson, then $\mu_{ZZ^*} = 1$.

The rate of the Higgs decay into two Z bosons was first measured with 5σ significance by the ATLAS and CMS experiments in 2016. Its current value is $\mu_{ZZ^*} \approx 1.2 \pm 0.1$. The rate at which the Higgs boson decays into a pair of W bosons was measured in the same year. Its current value of $\mu_{WW^*} \approx 1.2 \pm 0.1$ also corresponds to the strength of interaction that would give the W boson its mass. Finally, the experiments measured the rate at which a single Higgs boson is produced in vector-boson fusion to be $\mu_{VBF} \approx 1.2 \pm 0.2$. Thus, ATLAS and CMS have established a new law of nature: the force carriers of the weak interaction gain their masses via their interactions with the everywhere-present BEH field. The strength of this interaction is precisely the right size to limit the effects of the weak interaction to distances shorter than 10^{-18} metres.

ATLAS and CMS have established a new law of nature

Third generation, third jewel

The third jewel in the crown of the LHC is the explanation for how the tau-lepton and the top and bottom quarks – members of the third, heaviest fermion family – gain their masses. The same electroweak symmetry that predicts that

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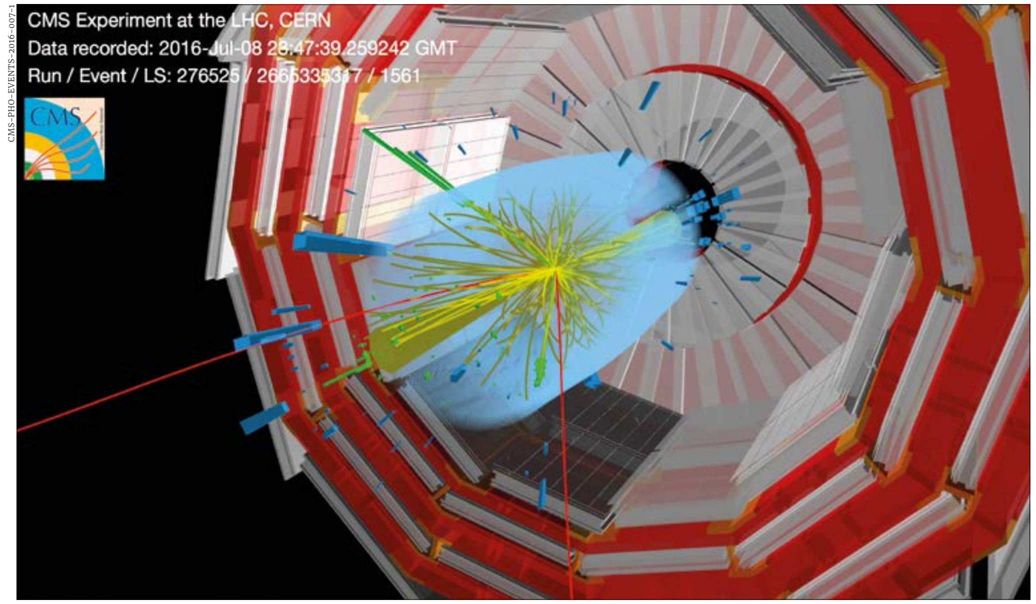

Vector-boson fusion *A candidate event for the production of a Higgs boson in the CMS detector in 2016, showing two high-energy electrons (green), two high-energy muons (red) and two-high energy jets (yellow cones). The cross section for this process is in agreement with the hypothesis that the force carriers of the weak interaction gain their masses via their interactions with the everywhere-present BEH field.*

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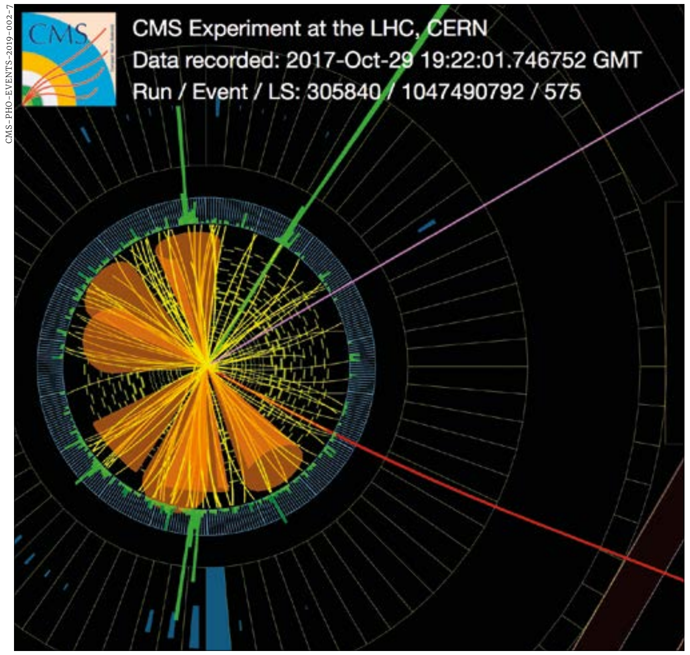

Yukawa evidence *The LHC uncovered the first Yukawa interactions – spin-0 mediated forces that are not predicted by symmetry principles. This 2017 event in CMS is evidence for the production of a Higgs boson in association with a pair of top quarks. An electron is shown in green, a muon in red, and missing energy in pink.*

the weak-force carriers should be massless also predicts that all 12 spin-1/2 matter particles known to us should also be massless. Experiments have shown, however, that all the matter particles are massive, with the one possible exception of the lightest neutrino. The fact that this symmetry is broken in the ground state of the universe also opens the door to the possibility that matter particles gain masses. But via what mechanism? For the ground state of the BEH field to slow down the fermions as well as the W and Z bosons, a new type of interaction has to exist: an interaction with a spin-0 mediator – the Higgs boson itself. Discovering a Higgs–boson decay into a pair of fermions would mean the discovery of this new type of spin-0 mediated interaction, which was first proposed in a different context by Hideki Yukawa in the 1930s.

Yukawa interactions are fundamentally different from the interactions through which the W and Z bosons get their mass because they are not deduced from a symmetry principle. Another difference, in contrast not only to weak, but also to strong and electromagnetic interactions, is that the interaction strength is not quantised. However, the strength of the interaction of a matter particle with the BEH field, measured by the mass it gains from this interaction, is still closely related to the strength of the Yukawa interaction of that matter particle with the Higgs boson, measured by the rate at which the Higgs boson decays into two such fermions. Once again, if the field that gives the matter particles their masses is indeed the one related to the newly discovered spin-0 particle, then the measured decay rate of the Higgs particle to fermion pairs should give a value of unity to the corresponding μ-ratio.

The three heaviest spin-1/2 particles – the top quark, the bottom quark and the tau lepton – are expected to have the strongest couplings to the Higgs boson, and consequently the largest rates of Yukawa interactions with it. The first Yukawa interaction to be measured, with the significance in both the ATLAS and CMS analyses rising to 5σ in 2015, concerned the decay of a Higgs boson into a tau lepton–antilepton pair. The current decay rate is $\mu_{\tau^+\tau^-} \approx 1.15 \pm 0.15$, which, within present experimental accuracy, corresponds to the strength of interaction that would give the tau lepton its mass. The rate of Higgs-boson decays into the bottom quark–antiquark pair was measured by ATLAS and CMS three years later. The current value is $\mu_{b\bar{b}} \approx 1.04 \pm 0.13$. Within present experimental accuracy, this corresponds to the strength of interaction that would give the bottom quark its mass.

In the case of the top quark, the Higgs boson has a vanishingly tiny decay rate into a top–antitop pair, because the mass of each is individually larger than that of a Higgs boson, and both would have to be produced virtually. To extract the strength of the Higgs–top interaction, experiments instead measure the rate at which this trio of particles is produced. The rate of the production of a Higgs boson together with a top quark–antiquark pair was measured by the ATLAS and CMS experiments in 2018. The current value is $\mu_{t\bar{t}h} \approx 1.3 \pm 0.2$. Within present experimental accuracy, this value corresponds to the strength of interaction that would give the top quark its mass. (The remaining third-generation particle, a neutrino, is at least 12 orders of magnitude lighter than the top quark, and is suspected to derive its mass via a different mechanism, which is unlikely to be tested experimentally in the near future.)

ATLAS and CMS have therefore discovered a new fact about nature: the third-generation charged particles – the tau lepton, the bottom quark and the top quark – also gain their masses via their interaction with the everywhere-present BEH field. This is also the discovery of the new and rather special Yukawa interactions among elementary particles, which are mediated by a spin-0 force carrier, the Higgs boson.

The path forward

Answering questions about nature's fundamental workings almost always leads to new questions. The discovery of the Higgs boson has already been the source of at least two. Firstly, the value of the Higgs boson's mass suggests the possibility that our universe is likely in an unstable state. In the extremely distant future, a transition to an entirely different universe with a different ground state could occur. Should this remain true as precision improves, not only is there nothing special about Earth, nor the solar system, nor even Milky Way galaxy, but the fundamental structure of the universe is itself only temporary. What's more, the lightness of the mass of the Higgs boson compared to both the Planck scale (above which quantum-gravity effects become significant) and the "seesaw scale" (below which new particles, beyond those of the Standard Model, are predicted to exist), poses a challenge to the basic framework that we use to formulate the laws of nature. In quantum field theory, cancellations between tree-level and higher order loop-diagram contributions to the mass of the Standard Model Higgs boson are huge, and require extreme fine-tuning, perhaps by as many as 32 orders of magnitude, between seemingly unrelated constants of nature. Various ideas of how to restore "naturalness", such as supersymmetry and Higgs compositeness, have been suggested, but the LHC experiments have not uncovered any of the TeV-scale particles predicted by these models and are ruling out ever-increasing swathes of parameter space for the models.

The potential of the LHC to discover new facts about nature and the universe is far from saturated. There are at least two additional, big open questions that are guaranteed to be answered, at least in part, by the LHC experiments. First is the understanding of the mechanism that gives second-generation particles – in particular the muon and the charm quark – their masses. That may be the same mechanism as the one that has been shown to give the third-generation fermions masses, or it may be different (for the latest progress, see p7). Second is the question of what happened at the electroweak phase transition in the early universe? It may have been a smooth crossover, where the value of the BEH field changed from zero to its present value continuously and uniformly in space, as predicted by the combination of the Standard Model of particle physics and the Big Bang model, or it may have been a first-order phase transition, where bubbles with a finite value of the BEH field nucleated within the surrounding plasma. A first-order phase transition could open the door to a new mechanism to explain the matter–antimatter imbalance in the universe. These deep questions depend on a new chapter of Higgs research concerning the self-interaction of the Higgs boson, which will be carried forward by a future collider.

Beyond constituting amazing intellectual and technological achievements, the LHC experiments have already made a series of profound discoveries about nature. The existence of a spin-0 particle whose non-zero force field is responsible for both the short range of weak interactions and, in a distinct way, the masses of spin-1/2 particles, represents three major discoveries. That theorists have long speculated on these new laws of nature ideas must not diminish the significance of establishing them experimentally. These three jewels in the crown of LHC research, the first steps in the exploration of Higgs physics, begin a trek to some of the most significant open questions in particle physics and cosmology. ●

The potential of the LHC to discover new facts about nature and the universe is far from saturated

Further reading

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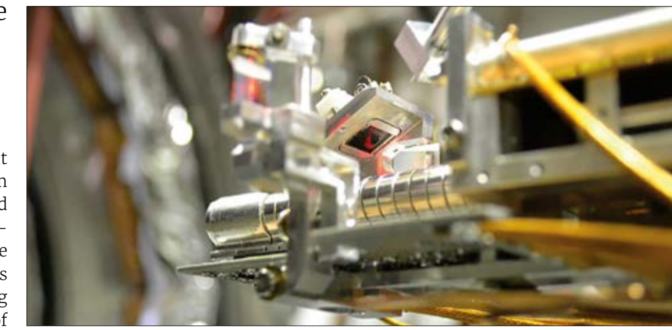
OPINION VIEWPOINT

CERN and quantum technologies

CERN's new quantum technology initiative has the potential to enrich and expand its challenging research programme, says Alberto Di Meglio.

CERN

Alberto Di Meglio *is coordinator of the CERN quantum technology initiative and head of CERN openlab.*



CERN-PHOTO-201804-080-2

QT inroads *CERN's AEGIS experiment is able to explore the multi-particle entangled nature of photons from positronium annihilation, and is one of several examples of existing CERN research with relevance to quantum technologies.*

Quantum technologies, which exploit inherent phenomena of quantum mechanics such as superposition and entanglement, have the potential to transform science and society over the next five to 10 years. This is sometimes described as the second quantum revolution, following the first that included the introduction of devices such as lasers and transistors over the past half century. Quantum technologies (QTs) require resources that are not mainstream today. During the past couple of years, dedicated support for R&D in QTs has become part of national and international research agendas, with several major initiatives underway worldwide. The time had come for CERN to engage more formally with such activities.

Following a first workshop on quantum computing in high-energy physics organised by CERN openlab in November 2018 (*CERN Courier* December 2018 p41), best-effort initiatives, events and joint pilot projects have been set up at CERN to explore the interest of the community in quantum technologies (in particular quantum computing), as well as possible synergies with other research fields. In June, CERN management announced the CERN quantum technology initiative. CERN is in the unique position of having in one place the diverse set of skills and technologies – including software, computing and data science, theory, sensors, cryogenics, electronics and material science – necessary for a multidisciplinary endeavour like QT. CERN also has compelling use cases that create ideal conditions to compare classic and quantum approaches to certain applications, and has a rich network of academic and industry relations working in unique collaborations such as CERN openlab.

Quantum technologies have the potential to transform science and society over the next five to 10 years

Today, QT is organised into four main domains. One is computing, where quantum phenomena such as superposition are used to speed up certain classes of computational problems beyond the limits achievable with classical systems. A second is quantum sensing and metrology, which exploits the high sensitivity of coherent quantum systems to design new classes of precision detectors and measurement devices. The third, quantum communication, whereby single or entangled photons and their quantum states are used to implement secure communication protocols across fibre-optic networks, or quantum memory devices able to store quantum states. The fourth domain is quantum theory, simulation and information processing, where well-controlled quantum systems are used to simulate or reproduce the behaviour of different, less accessible, many-body quantum phenomena, and relations between quantum phenomena and gravitation can be explored – a topic at the heart of CERN's theoretical research programme. There is much overlap between these four domains, for example quantum sensors and networks can be brought together to create potentially very precise, large-scale detector systems.

Over the next three years, the quantum technology initiative will assess the potential impact of QTs on CERN and high-energy physics on the timescale of the HL-LHC and beyond. After establishing governance and operational instruments, the initiative will work to define concrete R&D objectives in the four main QT areas by the end of this year. It will also develop an international education and training programme in collaboration with leading experts, universities and industry, and identify mechanisms for knowledge sharing within the CERN Member States, the high-energy physics community, other scientific research communities and society at large. Graduate students will be selected in time for the first projects to begin in early 2021.

Joint initiatives

A number of joint collaborations are already being created across the high-energy physics community and CERN is involved in several pilot investigation projects with leading academic and research centres. On the industry side, through CERN openlab, CERN is already collaborating on quantum-related technologies with CQC, Google, IBM and Intel. The CERN quantum technology initiative will continue to forge links with industry and collaborate with the main national quantum initiatives worldwide.

By taking part in this rapidly growing field, CERN not only has much to offer, but also stands to benefit directly from it. For example, QTs have strong potential in supporting the design of new sophisticated types of detectors, or in tackling the computing workloads of the physics experiments more efficiently. The CERN quantum technology initiative, by helping structure and coordinate activities with our community and the many international public and private initiatives, is a vital step to prepare for this exciting future.

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Lessons in leadership

The best leaders are those who don't want to be leaders per se, says experimentalist Ian Shipsey, who started out in kaon physics before taking up prominent positions in CLEO, the LHC experiments, the Vera Rubin Observatory and, most recently, quantum technologies.

What drew you to particle physics?

Ever since I was an undergraduate, I wanted to know why there was a lot more matter in the universe than antimatter – an asymmetry that permits us to exist. My thesis was on CP violation in the kaon system as part of the NA31 experiment at CERN. I had the opportunity to help build a muon detector and we found the first evidence that matter and antimatter behave differently as they disintegrate; subsequently established with greater significance by NA48 and by KTeV at Fermilab. NA31 was a wonderfully nurturing environment with many brilliant physicists. Like many European students at that time, I was strongly encouraged to head to the US for post-PhD finishing school and decided to join the CLEO experiment at the Cornell Electron Storage Ring (CESR) – for two reasons: first, CLEO studied beauty quarks, which were expected to have much larger CP violating effects than kaons; and second because I had fallen in love with a student (now my wife, Daniela Bortoletto) working on CLEO whom I had met at CERN. CLEO was another astonishingly nurturing environment. I joined Purdue University as an assistant professor just a couple of years after arriving in the US.


University of Oxford

Positive outlook *Ian Shipsey is head of the physics department at the University of Oxford.*

How did you make the transition to the LHC experiments?

While I'd help build the CLEO muon spectrometer and worked on analyses, there was an expectation to work on a far-future project as well. I set up a fledgling research group to develop micro pattern gas detectors (MPGDs) for the SDC collaboration at the Superconducting Super Collider (SSC). Fairly quickly we concluded that silicon microstrip and pixel detectors were a better technology choice for this application, but then, in 1993, the SSC was cancelled and a lot of people went towards the LHC. I was invited to join ATLAS due to my MPGD expertise, but I decided to focus on CLEO and the surety of great physics results, which were needed to win tenure. Shortly afterwards, with CLEO colleagues, I received a large grant to build a silicon vertex detector for CLEO III, which was commissioned successfully in 2000. Almost immediately I and my group were invited to join CMS to help build the forward silicon pixel detector. After the pixel detector was installed I was asked to co-lead the LHC Physics Center (LPC) at Fermilab. Then the LHC began operation and I moved to CERN, serving also as the co-convener of the CMS quarkonia working group. The atmosphere at CERN was electric and analysing those first LHC data was one of the most exciting moments of my career. CMS has been a wonderful, supportive environment in which to learn and grow as a physicist. Then, in 2013, I took up a position at Oxford, which is a founding member of ATLAS. I joined ATLAS in 2016 and brought with me experience with muons, silicon and data analysis. It's very exciting to be part of ATLAS and the collaboration has been very welcoming.

NA31 was a wonderfully nurturing environment with many brilliant physicists

What attracted you to work on the Vera C Rubin Observatory?

The Rubin Observatory is a ground-based 8.4 m, 10 square-degree field-of-view telescope that will see more of the universe at optical wavelengths in its first month of operation than all previous telescopes combined. Scheduled to start in late 2022, (but delayed by COVID-19 situation), it will revolutionise astronomical observations by conducting the Legacy Survey of Space and Time – an optical survey of faint astronomical objects across the entire sky every three nights, enabling precision dark-energy measurements, studies of dark matter and opening a movie-like window on objects that change or move on rapid timescales. I have been a member since 2007, when I was asked to help out in the pitch to the US Department of Energy (DOE) to participate in the project. The scope of particle physics was broadening and the US national laboratories engaged in particle physics had significant capabilities, for example in silicon detector construction, that were an excellent match to the technical challenges of building the Rubin Observatory's 3 Gigapixel CCD camera. We met healthy

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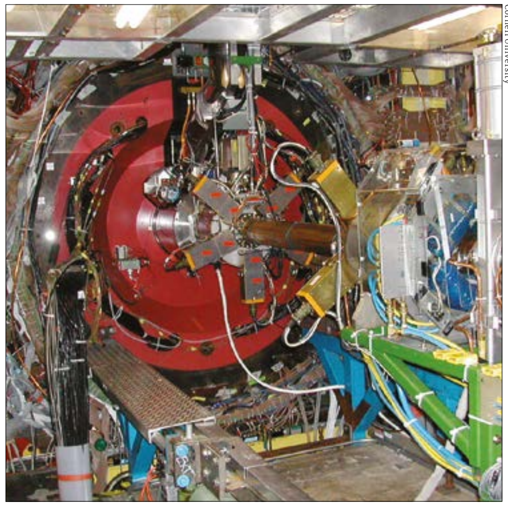
scepticism at DOE, given the completely unknown nature of dark energy. From a science perspective we found two lines of argument were useful. First, the job of particle physicists is to understand the fundamental nature of energy, matter, space and time, and in so doing to understand the origin, evolution and fate of the universe. Second, by analogy to the Higgs field and Higgs boson, the cosmological observations are consistent with dark energy being a scalar field, which if correct implies an associated scalar particle. The pitch was successful and the DOE approved funding for the construction of the CCD camera. Soon after arriving at Oxford I was asked to help make the case for UK participation in the project. Like everyone else in the Rubin Observatory community, I am eagerly anticipating first data.

Did you plan to enter scientific management?
I had no plan to be involved in scientific management of any kind! At around the time I joined CMS a few of us had been developing the idea to transform CLEO and CESR into a machine that would preferentially produce charm quarks rather than beauty quarks to test ultra-precise lattice-QCD predictions used by B-physics experiments to extract CKM matrix elements. When getting the idea funded I became the public face of the experiment, and around that time I was also elected by the collaboration to be co-spokesperson. As CLEO entered its twilight phase, the success of the LPC led to me being elected chairperson of the CMS collaboration board in 2012. I was also elected chair of the APS division of particles and fields. Moving back to Europe I was elected head of the Oxford particle-physics group in 2014 and I was elected head of the physics department in 2018. Throughout this entire period, leadership roles have occupied about 50% of my working day, which has meant that to get research done I tend to be connected to my laptop until the early hours on most days. Fortunately, five to six hours of sleep each night is sufficient. I have also been blessed with wonderful colleagues, students, postdocs, and administrative support. In my opinion the best leaders are those people who don't want to be leaders per se, and I think I was selected for this reason. Particle physics is a team effort, quite distinct to the way an army or a corporation is organised. Our leaders are not generals or CEOs, but colleagues called to serve for a time before returning to the rank and file.


Cornell University

Sense of beauty *Shipsey first rose to management positions in the CLEO experiment at the Cornell Electron Storage Ring.*

Our leaders are not generals or CEOs, but colleagues called to serve for a time before returning to the rank and file

How did you wind up leading the quantum-sensor programme for the UK's Quantum Technologies initiative?
In 2017 the DOE invited me and a colleague to articulate the case for quantum sensing in particle physics. We co-organised a workshop bringing together many disparate communities from which an influential whitepaper (arXiv.org:1803.11306) emerged and contributed to the creation of a new DOE-funded quantum-sensing programme in 2018. I then conducted a similar activity in the UK at the invitation of the Science and Technology Facilities Council (STFC), bringing together the particle-physics and particle-astrophysics community with the atomic, molecular and optical and condensed-matter communities to form a Quantum Sensing for Fundamental Physics (QSFP) consortium, targeting strategic UK government funding to support interdisciplinary research. STFC announced around £40M for the programme in September 2019 and a call for proposals led to the identification of seven projects for funding, for which an official announcement is imminent. I am a member of one of them: AION (the Atom Interferometer Observatory Network).

What is driving current interest in quantum technologies?
The birth of quantum mechanics nearly 100 years ago has led to the information and communication technology that is now central to modern civilisation – sometimes referred to as the first quantum revolution. But none of the existing technologies use any of the iconic characteristics of quantum mechanics such as the uncertainty principle, superposition states, macroscopic quantum interference, or two-particle quantum entanglement. Second-generation quantum technology that exploits these phenomena is just coming online. Most well-known is quantum computing, which exhibits extraordinary capabilities and is steadily entering the scientific and corporate marketplaces. As humankind harnesses the characteristics of quantum mechanics and gains mastery over them we will witness the second quantum revolution that will transform our society in as profound a way as the first quantum revolution did. It is no different to the transistor in the 1950s: if people told you back then that transistors could change your life, no one would have believed you; now we have a billion of them in a smart phone. So we can start to harness (crudely) phenomena such as entanglement and the promise is that over the next 20–30 years we can put this technology in your phone. We can't even begin to think what that would enable because it's beyond our imagination. Think quantum internet, quantum liquid crystals and quantum artificial neural networks.

What do quantum technologies offer high-energy physics?
A revolution in the theory and tools of quantum mechanics has produced new sensitive measurement techniques that allow measurements to be made near the intrinsic noise limits imposed by the uncertainty principle, as well as enabling new capabilities in sensitivity, resolution and robustness. This can now be harnessed to accelerate searches for new physics including, for example, dark matter, hidden dark sectors and electric dipole moments. For decades, one way that we've hunted for dark-matter particles is with large detectors via nuclear recoils, but the allowable mass ranges from 10^{-22} eV to the Planck scale, which demands

new detection technologies. Related fields that will also be impacted by quantum sensing are gravitational wave cosmology, astrophysics and fundamental tests of quantum mechanics. Quantum computing, along with traditional high-performance computing and advances in machine learning and artificial intelligence, will be absolutely necessary to analyse HL-LHC data. Quantum communication is also key to this.

What can high-energy physics contribute to quantum technologies?
Bringing the unique resources and expertise of the particle-physics community to bear on the development of quantum sensors will lead to rapid technology advances. For example, Fermilab develop high-Q superconducting RF cavities. Some searches for ultra-light dark matter use these. Additionally, they provide a high-coherence environment for qubits used as detectors, isolating them from a noisy environment. CERN, as the premier particle-physics laboratory in the world, will also find ways to contribute. In quantum sensing, CERN can help with its deep shafts potentially suited to atom interferometry. Several fledgling efforts exist, and collaboration can be enhanced by structures and funding and a world lab that brings people together from a wide range of disciplines.

How has becoming profoundly deaf at the age of 29 affected your career?
I was eight-months married and had just been appointed assistant professor when suddenly I fell very ill and was diagnosed with a rare cancer of the blood and bone marrow called acute myeloid leukemia, which few people at that time survived. I underwent intense chemotherapy, which weakened my immune system and caused me to fall into a coma. The hair cells in my cochlea were destroyed as a result of the antibiotics that were medically necessary to keep me safe until my own immune system had returned, rendering me permanently deaf. I was taught to lip read but I didn't learn to sign because in general physics is not a culture where it is used. I also didn't develop deaf speak. However, without hearing it was a slow process to communicate. There was immense support from my colleagues at Cornell and Persis Drell, who is now Provost at Stanford, was essential in taking it to the next level because she suggested she write down what people said. Others quickly followed suit, allowing me to communicate instantly for the first time. In 2003 I had a cochlear implant installed. When I couldn't hear, I was treated completely like everyone else. I didn't sense any discrimination.

It taught me to be positive and to believe in myself and in life. Belief is important in everything we do both as individuals and as scientific institutions. Believing a 100 km circumference future circular collider is possible is a prerequisite for it to happen – and I believe!

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

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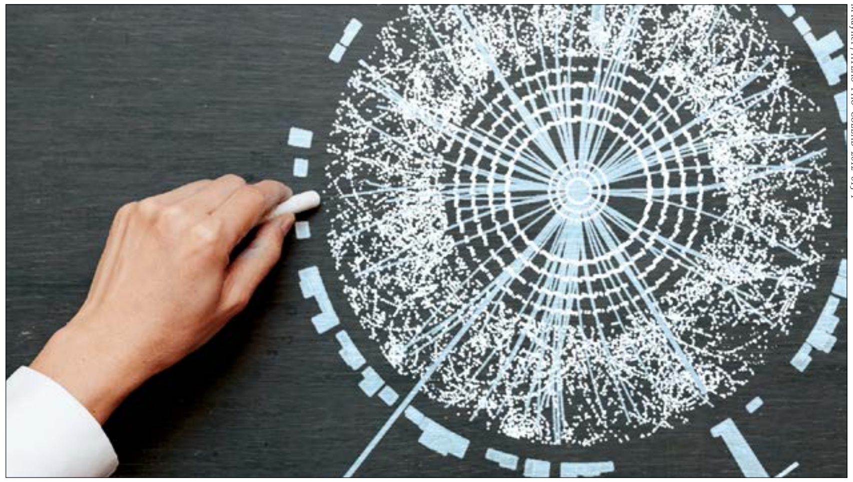
OPINION REVIEWS

An intuitive approach to teaching

Elementary Particle Physics: An Intuitive Introduction
By Andrew Larkoski
Cambridge University Press

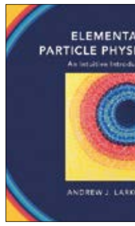

M Rayner / ATLAS-PHO-COLLAB-2012-013-1

Brain food *A particularly attractive feature of Larkoski's writing is his use of intuitive and conceptual discussions, writes our reviewer.*

This elementary textbook, suitable for either advanced undergraduate or introductory postgraduate courses, is a gem. Its author, Andrew Larkoski, is a phenomenologist with expertise in QCD, and a visiting professor at Reed College. It is worth mentioning that Reed College is also home to David J Griffiths, who is the author of several successful textbooks, including his well-known *Introduction to Elementary Particles* (Wiley, 2nd edition, 2008). Larkoski's book has a similar scope to Griffiths' and certainly lives up to its legacy.

Larkoski begins with an introduction to special relativity and the standard preliminaries to particle physics, such as the Dirac equation, Fermi's golden rule and a very accessible introduction to group theory. The book also features a superb 30-page chapter on experimental concepts and statistics – an excellent resource for any student starting a particle-physics project for the first time. The main menu follows: matrix element and cross-section calculations for QED, QCD and weak interactions. The book includes a nice introduction to electroweak unification, the basics of flavour physics, neutrino oscillations, and an accessible discussion on parton evolution and jets. The latter will be particularly useful for students of LHC physics. The book closes with an insightful chapter on open problems in particle physics.

A very nice collection of unsolved exercises will serve as an invaluable resource for lecturers. Many refer to processes currently being studied at the LHC and



other projects. The book's modernity is also evident through mentions throughout the text on the latest results in dark matter and neutrino physics, and a discussion on how the Higgs boson discovery was made.

A particularly attractive feature of Larkoski's writing is his use of intuitive and conceptual discussions: dimensional analysis is used often in calculations to get an idea of what we expect; analogies are drawn between Feynman diagrams and electrical circuits; connections between space curvature and quantum chromodynamics are pointed out, just to mention some of the very many examples you can find in the book.

One point that the lecturers should be aware of is that Larkoski employs the Weyl basis of Dirac γ-matrices, whereas Griffiths, Thomson (*Modern Particle Physics*, Cambridge, 2013), Halzen and Martin (*Quarks and Leptons*, Wiley, 1984), and other popular textbooks that currently form the backbone of many university courses, use the Dirac basis. As a result, both equations and Feynman rules look different, and care will be required when multiple textbooks are used in the same course. In general, Larkoski is closer to Thomson and Griffiths, as it does not include the wide range of calculations of Halzen and Martin, which is slightly more advanced.

Larkoski's new book will certainly find its way among the most popular particle-physics textbooks. Its clear and intuitive presentation will doubtlessly deepen the understanding of students who read it, and inspire lecturers to a more conceptual approach to teaching.

Nikolaos Rompotis *University of Liverpool.*

Accelerator Radiation Physics for Personnel and Environmental Protection
By J Donald Cossairt and Matthew Quinn
CRC Press

Don Cossairt and Matthew Quinn's recently published book summarises both basic concepts of the propagation of particles through matter and fundamental aspects of protecting personnel and environments against prompt radiation and radioactivity. It constitutes a compact and comprehensive compendium for radiation-protection professionals working at accelerators. The book's content originates in a course taught by Cossairt, a longstanding and recently retired radiation expert at Fermilab, at numerous sessions ▷

A compact and comprehensive compendium for radiation-protection professionals

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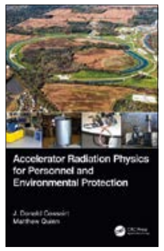
of the US Particle Accelerator School (USPAS) since the early 1990s. It is also available as a Fermilab report, which has stood the test of time as one of the standard health-physics handbooks for accelerator facilities for more than 20 years. Quinn, the book's co-author, is the laboratory's radiation-physics department manager.



The book begins with a short overview of the physical and radiological quantities relevant for radiation-protection assessments, and briefly sketches the mechanisms for energy loss and scattering during particle transport in matter. The introductory part concludes with chapters on the Boltzmann equation, which in this context describes the transport of particles through matter, and its solution using Monte Carlo methods. The following chapters illustrate the radiation fields that are induced by the interactions of electron, hadron and ion beams with beamline components. The tools described in these chapters are parametrised equations and handy rules-of-thumb. Graphs of representative particle spectra and yields serve for back-of-the-envelope calculations and describe the fundamental characteristics of radiation fields.

Practical questions

The second half of the book deals with the practical questions encountered in everyday radiation-protection assessments, such as the selection of the most efficient shielding material for a given radiation field, the energy spectra to be expected outside of the shielding, where personnel might be present, and lists of the radiologically relevant nuclides that are typically produced around accelerators. It also provides a compact introduction to activation at accelerators. The final chapter gives a comprehensive overview of the radiation-protection instrumentation traditionally used at accelerators, helping the reader to select the most appropriate detector for a given radiation field.

Some topics have evolved since the time when the material upon which the book is based was written. For example, the rules-of-thumb presented in the text are nowadays mostly used for cross-checking results obtained with much more powerful and user-friendly Monte Carlo transport programs. The reader will not, however, find information on the use and limitations of such codes. For example, the chapter on aspects of radiation dose attenuation through passage ways and ducts as well as environmental doses due to prompt radiation ("skyshine") gives only analytical formulae, while assessments are nowadays more readily and accurately obtained with Monte Carlo simulations. There is a risk, however, that such codes will be treated as a "black box", and their results blindly believed. In this regard, the book gives many tools necessary for obtaining rough but valuable estimates for setting up simulations and cross-checking results.

Stefan Roesler *CERN.*

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PEOPLE CAREERS
ALUMNI SPECIAL

Growing the high-energy network

While most CERN alumni remain in research, stories from those who choose other professional avenues demonstrate the high value placed by employers on skills acquired in high-energy physics.

C Smith/CERN

Thumbs up *Barbara Warmbein, Miguel Anjo, Paulo Pinto, Marzena Lapka, Hugo França, Michael Eppard, Ana Sousa e Silva and Pedro Alexandre Loureiro at the CERN Alumni "First Collisions" event in February 2018.*

Since its launch in June 2017, the CERN Alumni Network has attracted more than 6300 members located in more than 100 countries. Predominantly a young network, with the majority of its members aged between 25 and 39, CERN alumni range between their early 20s up to those who are over 75. After a professional experience at CERN, be it as a user of the lab, as an associate, a student, a fellow or a staff member, our alumni venture into diverse careers in many different fields, such as computer software, information technology and services, mechanical or industrial engineering, electric/electronic manufacturing, financial services and management consulting.

The network was established to enable our alumni to maintain an institutional link with the organisation, as well as to demonstrate the positive impact of a professional CERN experience on society. Though most CERN alumni remain in high-energy physics research or closely related fields, those who wish to use their skills elsewhere, especially early-career members, will find active support in the Alumni Network.

The alumni.cern platform (also available as an app on Android and iOS) provides members with access to an exclusive and powerful network that can be leveraged as required, whether at the start of a career or later when the desire to give back to CERN is there. The platform facilitates different groups, including regional groups, interest groups (such as entrepreneurship and finance) and groups for managing the alumni of the CERN scientific collaborations. Events and selected news articles are also posted on the alumni.cern platform, and members can also benefit from messaging.

A key appeal of the platform is its jobs board, where both alumni and companies can post job opportunities free of charge. Since its launch more than 500 opportunities have been posted with 260 applications submitted directly via the platform, mostly in fields such as engineering, software engineering and data science. Several CERN alumni have found their next position thanks to the network, either directly via job postings or through networking events.

A notable success has been a series of "Moving out of Academia" networking events that showcase sectors into which CERN alumni migrate. Over the course of one afternoon, around half a dozen alumni are invited to share their experiences in a specific sector. Events devoted to finance, industrial engineering, big data, entrepreneurship and, most recently, medical technologies, have proved a great success. The alumni provide candid and pragmatic advice about working within a specific field, how to market oneself and discuss the additional skills that are advisable to enter a certain sector. These events attract more than 100 in-person participants and many more via webcast.

The Office for Alumni Relations has recently launched its first global CERN alumni survey to understand the community better and identify problems it can help to solve. The survey results will soon be shared with registered members, helping us to continue to build a vibrant and supportive network for the future.

Rachel Bray *Office for CERN Alumni Relations.*

Markus Pflitsch
Founder and CEO of Terra Quantum

Markus joined CERN as a summer student in 1996, working on the OPAL experiment at LEP. Eager to tackle other professional challenges, upon graduating he accepted an internship with the Boston Consulting Group. "On my first day I found myself surrounded by Harvard MBAs in sleek suits, wondering what we would have in common," he says. "I think there are two very clear reasons why companies are so keen to employ people from CERN. Number one, you develop extremely strong and structured analytical skills, and this is coupled with the second reason: a CERN experience provides you with a deep passion to perform."

In 2001 Markus returned to Germany as director of corporate development with Deutsche Bank. He enjoyed a meteoric rise in the world of finance, moving to UniCredit/HypoVereinsbank as managing director in 2005, and then to Landesbank Baden-Württemberg (LBBW), first as head of corporate development and subsequently CEO of LBBW Immobilien GmbH. The global financial crisis in 2009 led him to pursue a more entrepreneurial role, and he moved into marketing, becoming CFO and managing director of Avantgarde. After six successful years he sought some major life changes, taking three months off and discovering a passion for hiking. In 2018 Markus founded Terra Quantum to develop quantum computing. He describes it as his proudest career achievement to date, taking him back to his lifelong interest in quantum physics. "CERN gave me so much!" he says. "Recently I brought 70 entrepreneurs to CERN and they were blown away by their visit. Not only were they impressed that CERN is seeking answers to the most profound and relevant questions, but the sheer scale of project management of such a gigantic endeavour left them in complete awe."

Maria Carmen Morodo Testa
Launch range programmatic support officer at ESA

After completing her studies as a telecommunications engineer at the Polytechnic University in Barcelona, Carmen joined a multinational company in the agro-food sector specialising in automation and control systems, whilst studying for an MBA. On the university walls she spotted an advert for a staff position at CERN, which corresponded almost word for word to the position she held at the time, but in a completely different sector: CERN's cooling and ventilation group. "So, why not?" she thought. "At CERN, I discovered the importance of being open to different paths and different ways of thinking." In 2004, five years in to her position and with a "reasonable prospect" but no confirmation of a permanent contract, she began to think about the future. "I decided that it would be either CERN or a sister international organisation that would also give me the opportunity to take ownership of my work and shape it." She sent a single application for an open position in the launcher department of the European Space Agency (ESA), and was successful. "I didn't know of course if I was making a good choice and I was afraid of closing doors. But, my interest was already piqued by the launchers!" Carmen joined ESA at an exciting time, when Ariane 5 was preparing for flight. She trained on the job, largely thanks to a "work-meeting" technique that allows small teams to be fast and share knowledge and experience effectively on a specific objective, and is currently working on the Ariane 6 design project. "I do not hesitate to change positions at ESA, taking into account my technical interests, without giving too much importance to opportunities for hierarchical promotion."

Alessandro Pasta
General manager at Diagramma

In 1987, then 18 year-old Alessandro was selected to take part in a physics school hosted by the Weizmann Institute of Science in Israel. His mentor Eilam Gross sparked a passion for particle physics, and Alessandro arrived at CERN in 1991 as a summer student working on micro strip gas avalanche chambers for a detector to be installed in the DELPHI experiment at LEP. His contract was extended to enable him to complete his work, and he returned to CERN in 1992 to work on DELPHI. After three glorious years, his Swiss scholarship was replaced by an Italian one with a much lower salary. A desire to buy a house and start a family forced him to consider other avenues, drawing on his hobby of computer programming. "I had a number of ongoing consultancies with external companies so I switched my hobby for my job and physics became my hobby!" Alessandro returned to Italy in 1995 as a freelance software developer designing antennas. In 1999 he joined Milan software company Diagramma, and transitioned from telecommunications to car insurance – where he was tasked with developing tools to enable customers to enter their data online and obtain the best tariff. "Nowadays, this is quite commonplace, but at the time such software did not exist," he says. Alessandro is now general manager of Diagramma, which is developing AI algorithms to increase the efficiency of its products. He values his particle-physics experience more than ever: "It wasn't enough to know the physics and think logically, I also had to think differently, laterally one could say. I learnt how to solve problems using an innovative approach. Having worked at CERN, I know how multi-talented these people are and I am very keen to employ such talent in my company."

Stephen Turner
Electrical/electronic engineer at STFC

Following a Master's degree in electrical and electronic engineering at the University of Plymouth in the UK, Stephen started working for the UK Science and Technology Facilities Council (STFC), where he sought a three-month placement as part of their graduate scheme. Having contacted an STFC scientist with CERN links "who knew someone, who also knew someone" at CERN – a scientist supporting the Beamline for Schools competition – Stephen secured his placement in the autumn of 2017. As a member of the support-scientists team, his role was to help characterise the detectors and prepare the experimental area for the students, enabling him to combine his passion for education and outreach with technical experience, where he would gain precious knowledge that could be put to use in his current role at the ISIS neutron and muon source at the Rutherford Appleton Laboratory. "My experience at CERN provided me with the bigger picture of how such user facilities are run," he says. Whilst at Plymouth, Stephen was also involved in Engineers Without Borders UK, which works with non-governmental organisations in developing countries on projects including water sanitation and hygiene, building techniques and clean energy. Although he now has a full time job, Stephen is still an active volunteer, and his interests in public engagement and international development brought him back to CERN in 2018 to share knowledge on target manufacturing and testing with the CERN mechanical and materials engineering group. "Lots of variety, public engagement and outreach were part of the job's remit and it has kept its promises, he says. "There are not many companies that can offer this!"

John Murray
Private investor and synthetic-biology consultant

John arrived at CERN in 1985 as a PhD student on the L3 experiment at LEP. Every day was a new experience, he says. "My absolute favourite thing was spending time with the summer students, out on the patio of Restaurant 1 in the evenings, just chatting. Everyone was so curious and knowledgeable." Despite the fulfilment of his experience, he decided to pursue a career in finance, reckoning it was a game he could "win". He found his first job on Wall Street thanks to a book he had read about option pricing, realising that the equations were similar to those of quantum field theory, only easier. His employer, First Boston, soon gave him responsibility for investing the firm's capital, and by the late 1990s he was a hedge-fund manager at Goldman Sachs. Realising that the investment world was about to go digital, he started his own company, building computer models that could predict market inefficiencies and designing trading strategies. "Finance textbooks said these sorts of things were impossible, but they were all written before the markets went digital," he says. In recent years, John has turned his attention to synthetic biology, where he invests in and advises start-up companies. Biology is following a similar path to finance 30 years ago, he says, and the pace of progress is going to accelerate as the field becomes more quantitative. In 2018 John offered to co-found the New York group of the CERN Alumni Network. "I loved the time I spent at CERN and the energy of its people. In setting up the New York group, I want to recreate that atmosphere. I also hope to help young alumni at the beginning of their careers. I hope we can help our younger members avoid making the same mistakes we did!"

Anne Richards
CEO at a private finance services company

Anne came to CERN as a summer student in 1984 and fell in love with the international environment, leading her to apply for a fellowship where she worked on software and electronics for LEP. At the end of the fellowship, she was faced with a choice. "I was surrounded by these awesomely brilliant, completely focused physicists who were willing to dedicate their lives to fundamental research. And much as I loved to be amongst them and was proud of my equipment being installed in the accelerator, I didn't feel I had the same passion they did. I was still seeking something else." She returned to the UK and joined a technology consultancy firm in Cambridge where she had the opportunity to run a variety of different small-scale projects. "I really enjoyed that variety, I think that was what I was seeking," she says. "Now I know that at CERN there are varied jobs one person can do, but at that time perhaps I wasn't mature enough to realise that." Today, she works in investment and finance, and has actively sought out roles that allow her to travel and work with people from different places. But a return visit to CERN in 2011 added another career dimension. "A fantastically positive change had happened in my lifetime: the appreciation of the importance of science by wider society. It was time to think how to capitalise on this and help society become more engaged directly with us." The answer was the CERN & Society Foundation, of which Anne was appointed chair and that has seen CERN proactively engage with society, leading to the future Science Gateway project dedicated to education and outreach. "When we started the foundation in 2014 we did not know how incredibly successful it was going to be. The major part of this success comes from the interest and engagement we have had from alumni."

Bartosz Niemczura
Software engineer, Facebook

Bartosz graduated with a Master's degree in computer science from AGH University of Science and Technology in 2012. The following year he became a CERN technical student working on databases in CERN's IT department. It was his first professional experience, and he was immediately captivated by the field of data security. Deciding to enter into a career in the area, he then applied for positions elsewhere, leading to a six-month research internship at IBM Zurich, participating in the Great Minds Programme. "My project focused on big-data analysis, an activity very closely related to my CERN project. I probably wouldn't have been selected for the internship if I hadn't had the CERN experience," he explains. "It's not just about the experience, but also the CERN reputation and prestige." Working in a global environment with more than 20 international students was also extremely valuable. Since 2015 Bartosz has been working as a software engineer for Facebook's product security team in Silicon Valley. "Despite the culture being slightly different at Facebook compared to CERN, I still apply the same approach I learnt at CERN," he says. "Having learnt to communicate with people from other countries, this is highly useful for me in my current position as I now find it easier to make connections. It's important not to close yourself off in your office. Go out and talk to people, those who have lots of experience, or who are working on something different from you, ask questions, make connections!"

Maaike Limper
Data engineering and web portal specialist at Swiss Global Services

Following a PhD on ATLAS, Maaike became a CERN openlab fellow in 2012. There was a lot to learn in moving from physics to IT, she says. "You need to understand how technology actually works: how it stores your data as bytes on the disk or how your computations can optimise the CPU usage." Until last year, Maaike was head of aviation surface performance at Inmarsat, investigating solutions to allow aircraft passengers to have a reliable internet connection. One of her challenges was to put data from all the systems involved in passenger internet connectivity, such as ground control, satellites and aircraft together and understand where outages were experienced and why." As a particle physicist, by contrast, Maaike was dealing with "very specific issues and no longer felt challenged". She also didn't warm to the ruthless competition she encountered, especially when the first LHC data were being collected and the normal collaborative spirit was slightly set aside. In her new career, which recently saw her join Swiss Global Services as a data-engineering specialist, she feels she is the expert. "I like the fact that I am constantly kept busy, challenged and, sometimes, very much stressed!" However, her particle-physics training had a useful impact on her career. "At CERN, we are very good at developing our own tools and we don't just expect there to be a ready-made product on the market." And Maaike is proud that the detector she worked on sits at the centre of the ATLAS experiment. "I was there, checking that each optical cable was producing the right sound once connected and that everything was working as expected. So actually, yes, a little piece of my heart is there, deep inside ATLAS."

Panayotis Spentzouris
Head of Fermilab's Quantum Science Program

Panayotis's affiliation with CERN began in 1986 as an associate physicist working on a prototype of a detector for the DELPHI experiment at LEP. He moved to the US in 1990 and started a PhD, continuing his research at Fermilab, first as a Columbia University postdoc and then a junior staff scientist. Of his time at CERN he recalls the challenging experience of working for a multi-institutional, multicultural and multinational collaboration of many people of different cultures. "I remember it being a great experience with exposure to many wonderful things from machine shops to computers and scientific collaborations. It was also whilst at CERN that my first ever paper was published, when DELPHI started taking data, around 1990 I think – I was absolutely thrilled. Even though, somewhere in the middle of my career, I ended up doing a lot of computational physics, CERN is where I began my career as an experimentalist and I am always grateful for that." He did not want to leave fundamental research, and today Panayotis is a senior scientist at Fermilab. In 2014 he was head of Fermilab's scientific computing division and since 2018 has led Fermilab's Quantum Science Program, which includes simulation of quantum field theories, teleportation experiments and applying qubit technologies to quantum sensors in high-energy physics experiments. Shortly afterwards, he presented the Fermilab programme to CERN openlab's "Quantum computing for high-energy physics" event. "Coming back to CERN was actually strange, because everything had changed so much that I needed to follow signs to find my way to the cafeteria!" He would also like to see Fermilab establish an alumni network of its own. "It is good to have a sense of community, especially during difficult times when you need your community to stand up in support of your organisation."

Cynthia Keppel
Professor, Hampton University

Having attended a small liberal arts college in the US where the focus was on philosophy, Thia found herself a bit frustrated. "We would discuss deep questions at length in class, and I would think:' Can't we test something?' Physics seemed to be a place where people were striving to provide concrete answers to big questions, so I looked for summer internships in physics, and to my surprise I got one." She wound up working with a group of plasma physicists who wanted an "artsy" person to make a movie visualising the solar magnetic flux cycle. "I liked learning the physics, I liked being sent off on my own, and it turned out I even liked the programming." She went on to do a PhD in nuclear physics at SLAC and continued her research at JLab where, one night, while working late on a scintillating fibre-type particle detector, she realised that a colleague in the lab across from her was building the same type of detector – but for a project in medical instrumentation. They started to collaborate, and a few years later Thia founded the Center for Advanced Medical Instrumentation at Hampton University. More than a dozen patented technologies later, they were contacted by Hampton University's president about proton therapy and realised that they had the know-how to build their own proton-therapy centre, which ended up being one of the largest in the world. "Having directed the centre from the start, Thia preferred the period of building, instrumenting and commissioning the facility over that of clinical operations. So she decided to set up a consulting company, which has so far helped to start 16 proton-therapy centres. "I think that my discourse-based philosophy education has been a help in learning to express ideas clearly and succinctly to people," she says. "If you're going to irradiate people, you must explain carefully and well why that's a beneficial thing. Once you're used to explaining things in plain language to potential patients or the public, you can give the same talk in a boardroom."

• *This final case study is based on an article in* APS Careers 2020, *produced in conjunction with* Physics World. *All other articles and images are drawn from the CERN Alumni Network.*

Appointments and awards

Yeck to lead EIC
Brookhaven National Laboratory (BNL) has appointed Jim Yeck as the project director for the Electron–Ion Collider (EIC), which will open new vistas on

the properties and dynamics of quarks and gluons (*CERN Courier* October 2018 p31). Yeck has held leading roles in BNL's Relativistic Heavy Ion Collider and National Synchrotron Light Source II, the US hardware contribution to the LHC project, and the IceCube neutrino observatory (*CERN Courier* June 2014 p27). He was also former director general of the European Spallation Source. Yeck will head a newly created EIC directorate at BNL, working in partnership with Jefferson Laboratory and others. The EIC is scheduled to begin operations at BNL at the end of the decade.

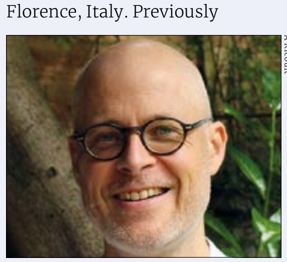
Brüning takes hi-lumi helm
CERN's Oliver Brüning has succeeded Lucio Rossi, who retires this year, as project leader for the High-Luminosity LHC (HL-LHC). Brüning, who completed his PhD on particle dynamics at HERA, joined CERN in 1995 one year after the LHC was approved. He has been at the forefront of accelerator and beam physics ever since, being one of the initial six machine coordinators during the LHC start-up and leading the LHC

full-energy exploitation study from 2015–2019. Among the next significant steps for the HL-LHC are the testing of the first triplet quadrupole prototype, and the RF-dipole crab cavities in the SPS.

Sette continues at ESRF
After more than 11 years as the director-general of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, Francesco Sette's term has been extended to 2025. Having joined ESRF in 1991, Sette was at the

forefront of the effort to develop a new generation of inelastic X-ray scattering beam lines, before becoming director of research in 2001. The announcement comes at a pivotal time for the ESRF, as the European facility begins user operations of its brand new Extremely Brilliant Source (see p13).

New LHCb spokesperson
Chris Parkes of the University of Manchester, UK, became spokesperson of the LHCb collaboration on 1 July for a period of three years, taking over from Giovanni Passaleva of the National Institute for Nuclear Physics in Florence, Italy. Previously



deputy LHCb spokesperson, Parkes has been a member of the collaboration for more than 20 years. He was one of the instigators of the current and future LHCb upgrades, and has worked extensively on physics studies involving the charm quark and the experiment's VELO detector.

2020 Guido Altarelli awards
This year's Guido Altarelli awards, which recognise exceptional achievement by young scientists in the field of deep inelastic scattering (DIS), and related topics, have been presented to Pier Francesco Monni (CERN; top) and Philip Ilten (University of Birmingham; below). Monni was recognised for his pioneering contributions to the

theory and phenomenology of multi-scale QCD resummation, and Ilten, a member of the LHCb collaboration, for his exceptional contributions to bridging the gap between experiment and phenomenology in QCD and proton structure. The ceremony took place during a LHCb collaboration meeting in June.

IUPAP Young Scientist Prize
The International Union of Pure and Applied Physics (IUPAP) has awarded its Young Scientist Prize for 2020 to two early-career researchers working in high-energy physics. CMS member Marco Lucchini of Princeton University (left) was recognised "For his pioneering

work in the development of fast crystal sensors for the precision timing of charged particles, while Benjamin Safdi (University of Michigan; right) was honoured "For groundbreaking theoretical contributions to the search for dark matter, in particular the development of innovative techniques to search for axion dark matter, and to separate dark matter signals from astrophysical backgrounds". The award was presented during the 2020 International Conference of High Energy Physics (see p19).

CMS thesis award
Marcel Rieger (RWTH Aachen University) has been presented with the 2019 CMS Thesis Award, with a thesis exploring "ttH" production – the process by which a Higgs boson is created in high-energy particle collisions in combination with two top quarks. The annual award is given to the best PhD of the year, based on originality, importance and clarity, and Rieger's contribution to the first observation of ttH production in 2018 made him stand out among the 25 other nominees.

LHCb honours young researchers
In June, the LHCb collaboration announced the recipients of its 2020 PhD Thesis and Early Career Scientist Awards. Thesis awards were presented to Philippe D'Argent of Heidelberg University and Laurent Dufour of Nikhef/Groningen University, while early-career prizes were granted to Carlos Abellan Beteta (Zurich), Claudia Bertella (CERN), Daniel Campora (Nikhef), Nadim Conti (INFN, Milan), Edgar Lemos Cid (Santiago de Compostela), Olli Lupton (Warwick), Mark Smith (Imperial College) and Dorothea vom Bruch (LPNHE, Paris).

RECRUITMENT

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PEOPLE OBITUARIES

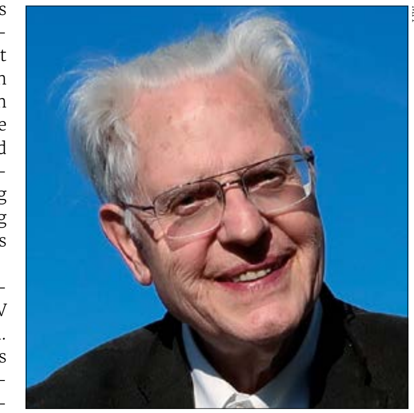
Ulrich Becker 1938–2020

A master of detectors and hardware

Ulrich J Becker, a major contributor to LEP's L3 experiment and the Alpha Magnetic Spectrometer (AMS), passed away on 10 March at the age of 81. Born in Dortmund, Germany, on 17 December 1938 – the day that nuclear fission was discovered in Berlin – as a young man he was adept as an electrician, coal miner and even in steel smelting. More drawn to physics, he studied at the University of Marburg and obtained his PhD in Hamburg, focusing on the photo-production and leptonic decays of vector mesons.

In late 1965 Becker met Sam Ting, who admitted him to his group at DESY using the 6 GeV synchrotron to measure the size of the electron. It was a complementary match: Becker was a dogged researcher with detector and hardware acumen, and Ting was a master in scientific organisation and politics. In 1970 Becker joined the MIT faculty, where he found mentors including Victor Weisskopf and Martin Deutsch. He was promoted to associate professor in 1973, and the following year he began designing a precision spectrometer for Brookhaven National Laboratory. He joined a group led by Ting that used the spectrometer to search for heavy particles produced when protons were smashed into a fixed target of beryllium. Instead, the team recorded an unexpected bump in the data corresponding to the production of a heavy particle with a lifetime that was about a thousand times longer than predicted.

Meanwhile, MIT alumnus Burton Richter was reviewing data from Stanford Linear Accelerator Laboratory when he too found what looked like a long-lived heavy resonance. Ting flew to Stanford in November and he and Richter quickly organised a lab seminar. They presented their discovery of the J/ψ particle, a bound state of a charm quark and antiquark, on 11 November 1974, sparking rapid changes in high-energy physics. Ting and Richter shared the 1976 Nobel Prize in Physics for the J/ψ discovery. If only one of the groups, MIT, had discovered the particle, it is likely that Becker would also have shared in the prize.



Ulrich Becker was a long-time collaborator with Sam Ting.

Made a full professor at MIT in 1977, Becker developed several other major instruments that were the catalyst for discoveries. His large-area drift chamber would provide large acceptance coverage for experiments, and his drift tube enabled physicists to measure particles near the interaction point. Those developments led Becker to design and build the huge muon detectors for the MARK-J experiment at DESY, which resulted in the discovery of the three-jet pattern from gluon production. Becker then led hundreds of colleagues in designing the muon detector for the L3 experiment at LEP.

In 1993 Becker started to work with MIT's team on building AMS – another Ting project that was born when he and Becker were on a coffee break while working on L3. Becker then went on to help design the transition radiation detector for AMS-02, which has so far collected more than 150 billion cosmic-ray events from its position on the International Space Station.

Becker was a mentor to many great physicists. He also made important contributions to advancing international collaboration in high-energy physics, for example involving China. In 2013 he transitioned to emeritus status at MIT, but still he came in every day to mentor students. At the age of 81 he even picked up Python to continue his craft. His friendly approach and deep understanding of physics made him a superb teacher, even if his style was highly individual.

Our community has lost an excellent researcher and teacher, and a wonderful colleague and human being.

His friends and colleagues at MIT.

Claude Détraz 1938–2020

A true visionary

Claude Détraz was born on 20 March 1938 in Albi, in the south of France. He graduated from the École Normale Supérieure and began his research career at CNRS in 1962, studying atomic nuclei. Détraz then joined the Institut de Physique Nucléaire d'Orsay, founded by Irène and Frédéric Joliot Curie, which has recently been merged with its neighbouring laboratories in Orsay to form the Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab).

At CERN's Proton Synchrotron (PS), in collaboration with Robert Klapisch's team, he contributed to the discovery of the first evidence of deformation in exotic nuclei at a shell closure. Drawing on these results, he became convinced that the beams at the Grand Accélérateur National d'Ions Lourds (GANIL) laboratory in Caen could also become a unique tool in this field.

As director of GANIL from 1982 to 1990, he launched several research projects on exotic nuclei. The legacy of these projects is still with us today and will continue into the future. Détraz was one of the main founders of NuPECC (the Nuclear Physics European Collaboration Committee) and was its first chair from 1989 ▷

Claude Détraz was CERN research director from 1999–2003.

to 1992, cementing its position as the main coordinating committee for nuclear physics in Europe.

In 1991 Détraz became a technical adviser in the office of the French minister for research, Hubert Curien. Through his involvement with decision-making bodies at all levels in France, Détraz made a major contribution to ensuring that the LHC project was approved in 1994. For example, he played a key role in Curien's appointment as president of the CERN Council, a position from which he was able to exert a major influence in the final phases of the decision. As director of IN2P3 at CNRS from 1992 to 1998, he helped to provide the impetus, first with Robert Aymar and then with Catherine Cesarsky of the CEA, to France's wholehearted participation in the LHC adventure.

Détraz made a major contribution to ensuring that the LHC project was approved in 1994

In 1999 Luciano Maiani, CERN Director-General at that time, appointed Détraz as director of research, jointly with Roger Cashmore, until 2003. This was a period filled with important events for CERN, including the shutdown of LEP, the excavation of new caverns for the LHC and the start of a project to send neutrinos from CERN to the underground laboratory at Gran Sasso, to which Claude contributed substantially.

Throughout his career Détraz promoted and supported interaction between scientific disciplines. As a nuclear physicist he established strong links with particle physics. He was also one of the architects of the emergence of astroparticle physics, and received multiple honours both in France and abroad.

Détraz was a great scientist and a true visionary, who played a major role in nuclear and particle physics in France and Europe. As well as being a brilliant scientist and occupying several high-level positions, Claude was a true "Enlightenment man" of great culture and finesse. He was a shining light of our generation.

Michel Spiro *former president of the CERN Council.*

John Flanagan 1964–2020

Accelerating physics at KEK

Accelerator physicist John Flanagan, who made important contributions to beam instrumentation for the KEKB and SuperKEKB projects in Japan, passed away on 13 March.

John grew up in The Valley of Vermont, graduating from Harvard University in 1987 with a degree in physics, astronomy and astrophysics. After working for a few years at software companies and at the Space Sciences Laboratory at Berkeley, he attended graduate school in physics at the University of Hawai'i at Manoa in 1992 and joined the Super-Kamkiokande experiment in Japan at an early stage. John took the first data-taking shift on the experiment in 1996, and the following year completed his thesis on the first observation of atmospheric neutrino oscillations at Super-Kamkiokande, supervised by John Learned. He then became a research fellow in the KEK accelerator division where his talent was quickly recognised. He was appointed as an assistant professor in 1999, an associate professor in 2008 and promoted to full professor in 2016.

John was well known for his immense contributions to the KEKB and SuperKEKB projects. His work on the photoelectron instability, monitoring of the beam size via synchrotron light and X-rays, and feedback systems played a key role in KEKB's achievement of the world's highest luminosity at an electron–positron accelerator. He is most celebrated for his outstanding work on the synchrotron radiation (SR) light monitor using interferometry, which allows real-time measurement of micron-level beam sizes. For SuperKEKB, he greatly improved the SR monitor by using a diamond mirror; this eliminated the systematics from thermal expansion of the mirror that had plagued the SR monitoring system in KEKB.


M Masuzawa

John Flanagan made immense contributions to the KEKB and SuperKEKB projects.

John also led work on the remediation of the electron-cloud effect, in particular concerning the onset of the electron-cloud blowup and its relation to the head-tail instability, which has been quite visible in the global accelerator community. In addition to being one of the key accelerator problems for KEKB and SuperKEKB, the solution to the electron-cloud problem will also benefit the future International Linear Collider, where it is needed for successful operation of the damping rings.

His beam-monitoring work played a key role in KEKB's achievement of the world's highest luminosity at an electron–positron accelerator

Finally, he developed an innovative X-ray beam profile monitoring technique by adapting techniques from X-ray astronomy and using innovative high-speed electronics. In the near future, an upgraded version of this X-ray monitor will be used to realise John's dream of bunch-by-bunch measurements of small vertical beam sizes.

In addition to his fluent command of Japanese and understanding of Japanese manners, John was a modest and kind person who was beloved by his colleagues in the KEK accelerator division and by those on the Belle and Belle II experiments. He was also known for his activities on gender-equality issues, including participation in the Japanese Physical Society taskforces and committees as well as serving as an instructor at the Rikejo science camp for high-school girls.

We will all remember John with the greatest of respect, as a splendid person, an innovative scientist and someone who we are very proud to have had the opportunity to work with.

His friends and colleagues.

Henri Laporte 1928–2020

Leading the construction of LEP

Henri Laporte, who led the civil-engineering work for the Large Electron Positron collider (LEP) at CERN, passed away on 18 May. Built in the 1980s, LEP was the biggest construction project for fundamental research ever undertaken and included the construction of the 27 km-circumference tunnel that now houses the LHC.

A native of Sète in the south of France, Laporte graduated from the École Polytechnique and École des Ponts et Chaussées, and began his career in marine engineering in the early 1950s. He was appointed as chief engineer, first for the construction of the port of Oran and then the Toulon naval base, before moving to French Polynesia in 1963 to preside over the extension of the Port of Papeete. In 1967 he was recruited by CERN to lead the technical services and buildings division.

Known for his relentless work ethic, expertise and authority, Laporte joined LEP at the start of the 1980s and was given responsibility for the hugely ambitious civil-engineering project by project leader Emilio Picasso. Before excavation could begin, however, CERN had to get the local authorities on board as the tunnel would pass underneath about 10 Swiss and French communes, and nine sites would be built on the surface. Under Robert Lévy-Mandel, who was in charge of the impact study, dozens of consultation meetings were held. Laporte shone on these occasions thanks to his oratory and interpersonal skills.


CERN

Henri Laporte, photographed in 2017.

The flagship construction project began in 1983 with the excavation of 18 shafts, followed by the excavation of the tunnel itself. Three tunnel-boring machines were required to dig out 23 km's worth of earth under the plain. Explosives were used to excavate the section of the tunnel below the Jura mountains due to fears that a geological incident could halt the progress of the machines. And such an incident did indeed occur in 1986, when high-pressure inflows of water flooded the tunnel, causing delays to the project. Laporte's expertise and leadership were decisive in the response to this incident and throughout the project as a whole. It was a regular occurrence for him to arrive on site any time of day or night to study damage and take urgent decisions. In 1988 the tunnel was finally completed.

But the main tunnel represented less than half the total excavation work, as the ring is punctuated with access shafts, caverns and service tunnels. In addition, around 80 buildings were built on the surface. Jean-Luc Baldy, who managed the surface work, and Michel Mayoud, who was in charge of the crucial work of the surveyors, remember the trust that Laporte placed in them, giving them considerable room for manoeuvre.

Once the construction work had been completed, CERN became entangled in protracted legal proceedings involving the consortium of companies that had carried out the work. Laporte spent several years working with the CERN legal service, once more demonstrating his trademark persistence. At the arbitration tribunal, Laporte distinguished himself not only for his technical knowledge, but also his talent as an actor and his humour. He retired in 1993 and devoted himself to numerous intellectual and artistic pursuits.

Henri Laporte was a man of great curiosity and was highly knowledgeable in many fields. He will be remembered as a charismatic man, with a firm hand and great tenacity, but also someone who exuded a contagious joviality and always showed compassion towards his colleagues.

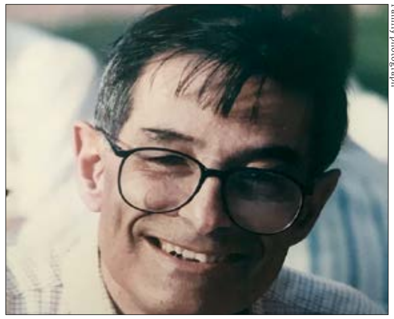
His friends and colleagues.

George Trilling 1930–2020

An exemplary leader

George Trilling passed away in Berkeley, California, on 30 April at the age of 89. Born in Poland, he completed his PhD at Caltech in 1955 and two years later joined the University of Michigan. In 1960 he joined the faculty at the University of California, Berkeley and the scientific staff at what is now called the Lawrence Berkeley National Laboratory (LBNL). He followed Don Glaser, whose invention of the bubble chamber provided a new way to view particle interactions, and teamed up with Gerson Goldhaber.

The Trilling–Goldhaber group used bubble chambers developed at Berkeley to study K-meson interactions. In the early 1970s the group joined SLAC colleagues led by Burt Richter and Martin Perl to build the Mark-I detector for the SPEAR electron–positron collider. The Mark-I collaboration went on to discover the J/ψ resonance, charmed particles and the tau lepton. Beginning in the 1980s, the group continued their collaboration with SLAC to construct the Mark-II detector, which was first installed at SPEAR, and later moved to the higher energy PEP collider, where it enabled the measurement of the lifetime of the B meson among other important results.


Family photograph

George Trilling was instrumental in securing US participation in the LHC.

George was a key figure in the many US studies in the 1980s that led to the successful proposal for the Superconducting Super Collider (SSC). He served on the SSC board of overseers and helped foster the early SSC design phase at LBNL. He initiated and led the Solenoidal Detector Collaboration, the first major experiment approved for the SSC in 1990. Despite retiring in 1994, he was instrumental in helping to organise and negotiate the US participation in the LHC.

Throughout his career, George was asked to take on important leadership roles. At the age of 38 he became chair of the UC Berkeley physics department. From 1984 to 1987 he was director of the physics division at LBNL, where he guided a major evolution towards precision semiconductor detectors – still a dominant theme at the lab today. Work on pixel detectors for the SSC, custom ASIC design, the Microsystems Lab and the CDF silicon vertex detector all began under his leadership. The Berkeley group is now a major participant in the ATLAS collaboration at the LHC.

A member of the National Academy of Sciences, in 2001 George served as president of the American Physical Society. He also chaired innumerable national panels, committees and task forces. We shall miss him greatly.

Abe Seiden *UC Santa Cruz*; **Bob Cahn**, **Gil Gilchriese** *and* **Jim Siegrist** *DOE*.

BACKGROUND

Notes and observations from the high-energy physics community

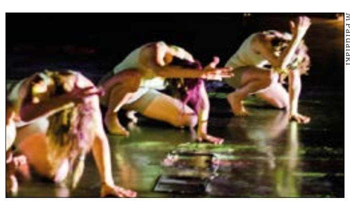
Particles mean prizes


Nobel Foundation

Just five research areas account for more than half of Nobel prizes, even though they publish only 10% of papers, reveals a study by social scientists John Ioannidis, Ioana-Alina Cristea and Kevin Boyack (*PLOS ONE* 15(7):e0234612). The trio mapped the number of Nobel prizes in medicine, physics and chemistry between 1995 and 2017 to 114 fields of science, finding that particle physics came top with 14%, followed by cell biology (12%), atomic physics (11%), neuroscience (10%) and molecular chemistry (5%).

Particle-physics prize-winners in the period studied include: Perl and Reines (1995) for the discovery of the tau lepton and the detection of the neutrino; 't Hooft and Veltman (1999) for contributions to electroweak theory; Davis and Koshiba (2002) for the detection of cosmic neutrinos; Gross, Politzer and Wilczek (2004) for asymptotic freedom; Nambu, Kobayashi and Maskawa (2008) for work on spontaneous symmetry breaking and quark mixing; Englert and Higgs (2013) for the Brout–Englert–Higgs mechanism; and Kajita and McDonald (2015) for the discovery of neutrino oscillations. The team also chose to class Mather and Smoot's 2006 prize relating to the cosmic microwave background, Perlmutter, Schmidt and Riess's 2011 award for the discovery of the accelerating expansion of the universe, and Weiss, Barish and Thorne's 2017 gong for the observation of gravitational waves as particle-physics research.

Neutrino *passoire*


M Pardalaki

Muses *Neutrino Passoire will open in Annecy, France, on 12 October.*

According to Hesiod, writing in the seventh-century BCE, Zeus and Mnemosyne gave birth to nine Muses who inspire the world's artists. Judging from recent arts–sciences collaborations (e.g. *CERN Courier* 2020 July/August p62), the sisters may have a hitherto unknown sibling: the neutrino.

The latest oeuvre by choreographer Mairi Pardalaki and particle physicist Kostas Nikolopoulos of the University of Birmingham explores how neutrinos originate in the Sun and pass through our bodies undisturbed. This gave Pardalaki the idea that the human body is not a fortress, but a colander. "*Le neutrino vois des passoires partout*," she narrates ("The neutrino sees colanders everywhere"), as two dancers, arms aloft and entwined in a single red elastane shift, revolve on stage, before abruptly injecting karaoke snippets from Ella Fitzgerald's timeless collaboration with Louis Armstrong into the performance. The dance is also intended to be an allegory for the cross-border movement of people. "Both particle physicists and artists try to make something that's invisible, visible," observes Nikolopoulos. "What we call the creative process in art is just what we call research in science."

From the archive: September/October 1980

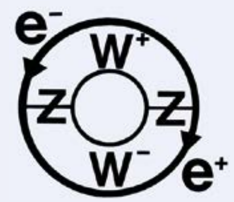
Pioneers ...


CERN 77.595

At the control console during commissioning are (left to right) Roy Billinge, who led the construction, Eifionydd Jones and Simon Van der Meer.

The 'hot news' at the XI International Conference on High Energy Accelerators, held at CERN from 7–11 July, was the spectacular first operation of the CERN Antiproton Accumulator (see image, right). The AA ring, one of the most demanding ever built, was completed in less than two years.

At the 66th Session of the CERN Council on 27 June, the project for a large electron–positron storage ring (LEP) was formally presented as Europe's next major high-energy physics research facility. By using CERN's existing proton accelerators in the injection scheme (PS and SPS), Council agreed that the project can be considered as an extension of CERN facilities, to simplify authorization in a number of Member States with 'Phase 1' – 50 GeV per beam and four experimental halls – being financed within existing budget levels for a cost of 900 million Swiss francs over eight years.



The symbol used at Uppsala to convey what the 'International Conference on Experimentation at LEP' was all about.

From 16–20 June some 350 physicists gathered at the University of Uppsala, Sweden, to take a first look at the challenges of LEP's experiments. For data collection and analysis, the way to go looked to be distributed rather than monolithic, with many computers dedicated to specific tasks. Establishing standards throughout the data-handling system would ease the participation of small groups.

● Based on *CERN Courier* September 1980 p235, p255; October 1980 p292.

Compiler's note

During the 1980s, standard data-acquisition hardware, CAMAC and FASTBUS, became widespread in the field, with brave attempts to define and adopt standards for the associated software. Distributed computing was commonplace in LEP experiments and across the community, increasing the acceptance of networking that culminated in the invention of the Web at CERN in 1989, contemporary with LEP start-up.

$142^{+28}_{-16}\,M_\odot$

The most massive black-hole merger yet observed by the LIGO and Virgo detectors. Announced on 2 September, the merger is the first clear detection of an intermediate-mass black hole – an object thought too large to result from such inspiral events.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