WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2022 issue of *CERN Courier.*

The vast range of detector and accelerator technologies on offer, and the need for stronger and international collaboration to build increasingly large and sophisticated facilities, makes modern-day community planning exercises more complex and necessary than ever. Two technology R&D roadmaps released in December set out a path to achieve the goals of the 2020 update of the European strategy for particle physics, focusing on the next generation of facilities after the LHC (p7), while a similar exercise, Snowmass 2021, recently got under way in the US (p43).

As for what physics might lie ahead, exploring the flavour anomalies is an exciting prospect at the proposed Future Circular Collider (p35), while probing the twin mysteries of the cosmic acceleration and the smallness of the electroweak scale is another priority for future experiments (p45).

Also in this first issue of the new year: Borexino neutrinos reveal the secrets of stellar fusion (p24); CERN's beam-transfer lines undergo a revolution in energy efficiency (p39); tackling the neutron-lifetime puzzle from space (p11); low-cost linacs for radiotherapy (p30); top tips on pivoting your career (p49); the latest meeting reports (p19); LHC-experiment results (p15); reviews (p47); miscellanea (p58) and much more.

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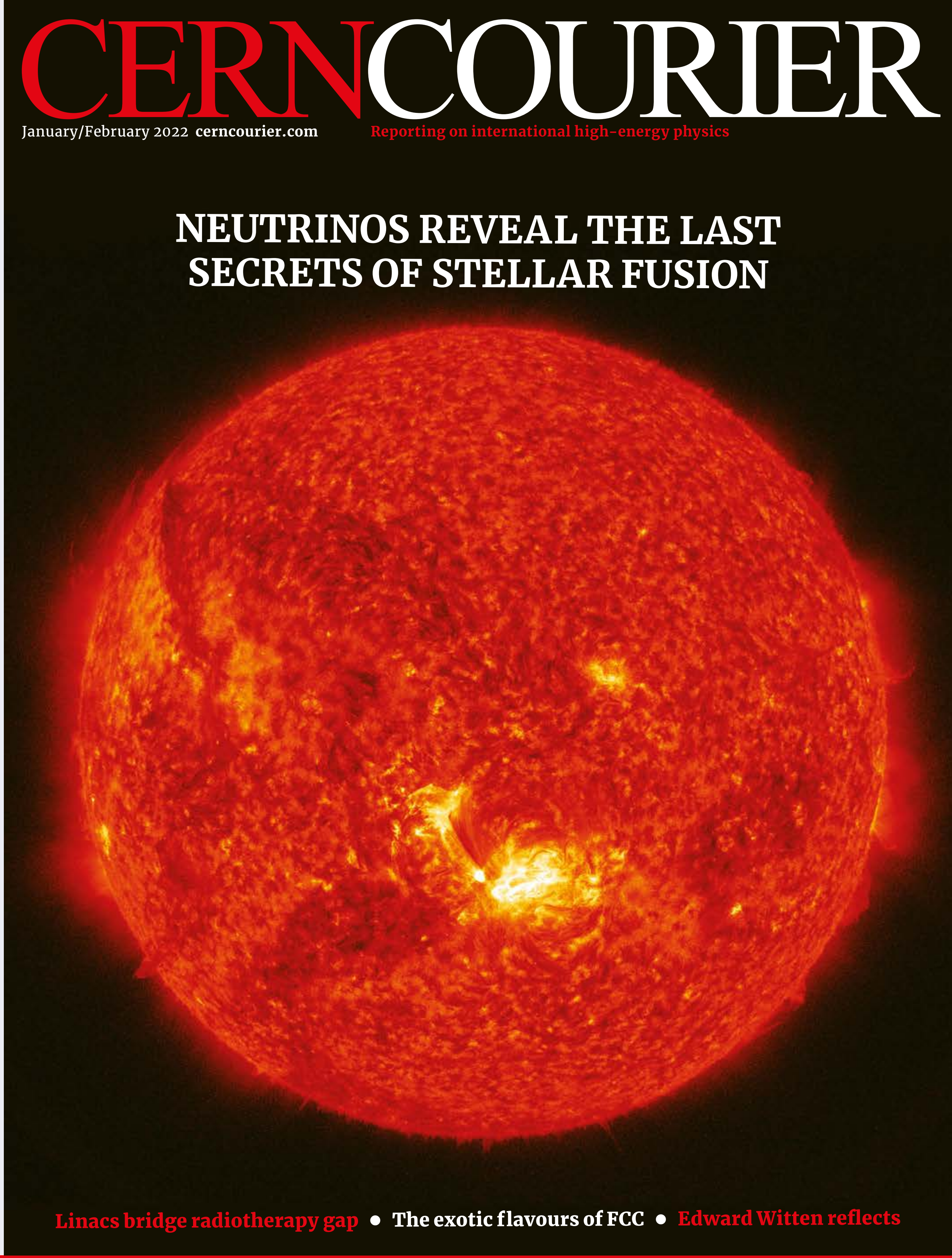

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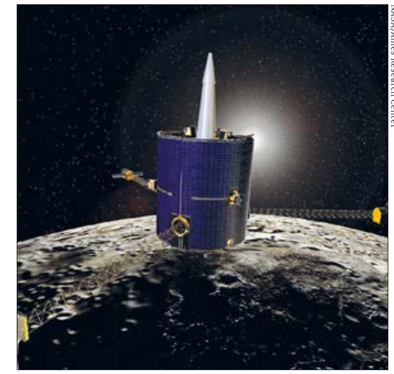

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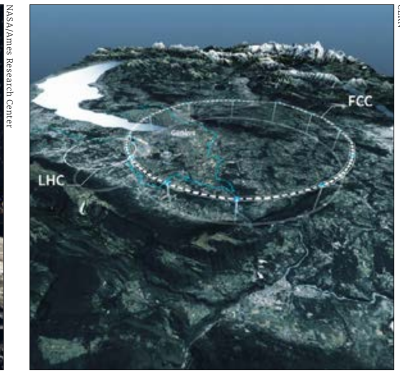

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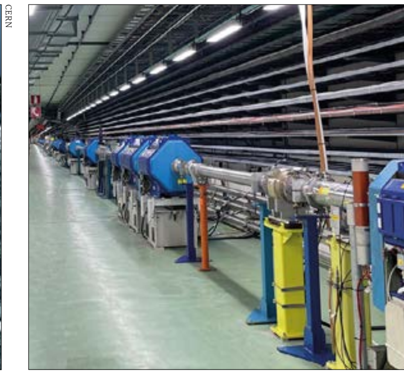

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FROM THE EDITOR

Bringing the future into focus

Matthew Chalmers
Editor

A new year, a look ahead. Two technology R&D roadmaps released in December set out a path to achieve the ambitious goals of the 2020 update of the European strategy for particle physics (ESPPU). One, coordinated by the European Laboratory Directors Group, charts the priorities in accelerator science for the next 5–10 years; the other, by the European Committee for Future Accelerators, covers detector R&D from now to the 2040s. At 250 pages a piece, they reveal the huge potential of new and future technologies to advance the field in the most flexible and efficient manner possible (p7).

The focus is on the next generations of colliders and experiments after the LHC. The highest priority for the next collider is an e^+e^- Higgs factory, for which the technology is relatively mature, although would benefit from further R&D to reduce the environmental impact through higher-efficiency RF systems. For the longer term, the ESPPU recommended that a feasibility study be undertaken for a Future Circular Collider (FCC) colliding protons at the highest possible energies, with a Higgs factory as a possible first stage, acknowledging that such post-Higgs-factory machines will be extremely challenging and require reinforced R&D.

The sheer range of detector and accelerator technologies on the table, and the need for stronger and more coordinated international collaboration to build increasingly large and sophisticated facilities, makes modern-day community planning exercises more complex – and more necessary – than ever. A similar exercise to the ESPPU currently under way in the US, Snowmass 2021, is due to present a scientific vision for the future of particle physics in the US and its international partners in July, including the direction for US participation in the R&D effort for next-generation colliders (p43).

The challenge now is to turn words and will into actions for a healthy and sustainable future

Common to the latest strategic planning exercises in particle physics and related fields is a greater emphasis on the needs of individuals, from better structured and recognised career paths to diversity and inclusion issues. The US Decadal Survey on Astronomy and Astrophysics 2020, published in November 2021, stated that "harsh realities" such as those that led to the Black Lives Matter movement and the inequitable impacts of COVID-19 have led to a renewed conviction to tackle systemic issues of race, gender bias and privilege at a local and global scale. Early-career researchers are more actively involved in the ESPPU and Snowmass processes than they have been in previous editions. And the environmental impact of future facilities is also significantly higher on agendas. The challenge now is to turn words and will into actions for a healthy and sustainable future.

As for what physics might lie ahead, exploring the flavour anomalies is an exciting prospect at FCC (p35). Probing the twin mysteries of the cosmic acceleration and the smallness of the electroweak scale as thoroughly as possible is another priority for future experiments, says Edward Witten (p45).

Also in the issue: Borexino neutrinos reveal the secrets of stellar fusion (p24); CERN's beam-transfer lines undergo a revolution in energy efficiency (p39); tackling the neutron-lifetime puzzle from space (p11); low-cost linacs for radiotherapy in challenging regions (p30); top tips on pivoting your career (p49); the latest meeting reports (p19), LHC-experiment results (p15), reviews (p47), miscellanea (p58) and more.

Journey on *New R&D roadmaps flesh out the ESPPU vision.*

Reporting on international high-energy physics

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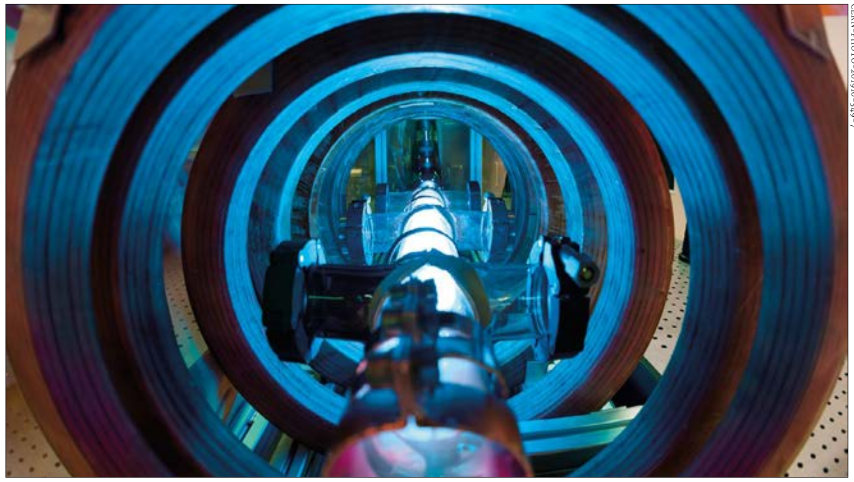
NEWS ANALYSIS

EUROPEAN STRATEGY UPDATE

Roadmaps set a path to post-LHC facilities

In setting out a vision for the post-LHC era, the 2020 update of the European strategy for particle physics (ESPPU) emphasised the need to ramp up detector and accelerator R&D in the near and long term. To this end, the European Committee for Future Accelerators (ECFA) was asked to develop a global detector R&D roadmap, while the CERN Council invited the European Laboratory Directors Group (LDG) to oversee the development of a complementary accelerator R&D roadmap.

After more than a year of efforts involving hundreds of people, and comprising more than 500 pages between them, both roadmaps were completed in December. In addition to putting flesh on the bones of the ESPPU vision, they provide a rich and detailed snapshot of the global state-of-the-art in detector and accelerator technologies.


CERN-PHOTO-201910-349-7

Future-proof detectors

Beyond the successful completion of the high-luminosity LHC, the ESPPU identified an e^+e^- Higgs factory as the highest priority future collider, and tasked CERN to undertake a feasibility study for a hadron collider operating at the highest possible energies with a Higgs factory as a possible first stage. The ESPPU also acknowledged that construction of the next generations of colliders and experiments will be challenging, especially for machines beyond a Higgs factory.

The development of cost-effective detectors that match the precision-physics potential of a Higgs factory is one of four key challenges in implementing the ESPPU vision, states the ECFA roadmap report. The second is to push the limitations in radiation tolerance, rate capabilities and pile-up rejection power to meet the unprecedented requirements of future hadron-collider and fixed-target experiments, while a third is to enhance the sensitivity and affordably expand the scales of both accelerator and non-accelerator experiments searching for rare phenomena. The fourth challenge identified by ECFA is to vigorously expand the technological basis of detectors, maintain a nourishing environment for new ideas and concepts, and attract and train the next generation of instrumentation scientists.

Advanced technologies
The AWAKE plasma-wakefield experiment at CERN is one of a handful of technologies recommended for further study and optimisation.

To address these challenges, ECFA set up a roadmap panel, chaired by Phil Allport of the University of Birmingham, and defined six task forces spanning different instrumentation topics (gaseous, liquid, solid state, particle-identification and photon, quantum, calorimetry) and three cross-cutting task forces (electronics, integration, training), with the most crucial R&D themes identified for each. Tasks are mapped to concrete time scales ranging from the present to beyond 2045, driven by the earliest technically achievable experiment or facility start-dates. The resulting picture reveals the potential synergies between concurrent projects pursued by separate communities, as well as between consecutive projects, which was one of the goals of the exercise, explains ECFA chair Karl Jakobs of the University of Freiburg: "It shows the role of earlier projects as a stepping stone for later ones, opening the possibility to evaluate and to organise R&D efforts in a much broader strategic context and on longer timescales, and allowing us to suggest greater coordination," he says.

Attracting R&D experts and recognising and sustaining their careers is one of 10 general strategic recommendations made by the report. Others include support for infrastructure and facilities, industrial partnerships, software, open science, blue-sky research, and recommendations relating to international coordination and strategic funding programmes. Guided by this roadmap, concludes the report, concerted and "resource-loaded" R&D programmes in innovative instrumentation will transform the ability of present and future generations of researchers to explore and observe nature beyond current limits.

"Ensuring the goals of future collider and non-collider experiments are not compromised by detector readiness calls now for an R&D collaboration programme, similar to that initiated in 1990 to better manage the activities then already underway for the LHC," adds Allport. "These should be focused on addressing their unmet technology requirements through common research projects, exploiting where appropriate developments in industry and synergies with neighbouring disciplines."

Accelerating physics

Although accelerator R&D is necessarily a long-term endeavour, the LDG roadmap focuses on the shorter but crucial timescale of the next five-to-ten years. It concentrates on the five key objectives identified in the ESPPU: further development of high-field superconducting magnets; advanced technologies ▷

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for superconducting and normal-conducting radio-frequency (RF) structures; development and exploitation of laser/plasma-acceleration techniques; studies and developments towards future bright muon beams and muon colliders; and the advancement and exploitation of energy-recovery linear accelerator technology. Expert panels were convened to examine each area, which are at different stages of maturity, and to identify the key R&D objectives.

The high-field-magnets panel supports continued and accelerated progress on both niobium-tin and high-temperature superconductor technology, placing strong emphasis on its inclusion into practical accelerator magnets and warning that final designs may have to reflect a compromise between performance and practicality. The panel for high-gradient RF structures and systems also identified work needed on basic materials and construction techniques, noting significant challenges to improve efficiency. Longer term, it flags a need for automated test, tuning and diagnostic techniques, particularly where large-scale series-production is needed.

In the area of advanced plasma and laser acceleration, the panel focused on rapidly evolving plasma-wakefield and dielectric acceleration technologies. Further developments require reduced emittance and improved efficiency, the ability to accelerate positrons and the combination of accelerating stages in a realistic future collider, the panel concludes, with the goal to produce a statement about the basic feasibility of such a machine by 2026. The panel exploring muon beams and colliders also sets a date of 2026 to demonstrate that further investment is justified, focusing on a 10 TeV collider with a 3 TeV intermediate-scale facility targeted for the 2040s. Finally, having considered several medium-scale projects under way worldwide, the energy-recovery linacs panel identifies reaching the 10 MW power level as the next practical step, and states that future sustainability rests on developing 4.4 K superconducting RF technology for a next-generation e^+e^- collider.

In addition to the technical challenges, states the report, new investment will be needed to support R&D and test facilities. Energy consumption and sustainability are explicitly identified as key considerations in defining R&D priorities and in the design of new machines. Having identified objectives, each panel set out a detailed work plan covering the period to the next ESPPU, with options for a number of different levels of investment. The aim is to allow the R&D to be pushed as rapidly as needed, but in balance with other priorities for the field.

Energy consumption and sustainability are key considerations in defining R&D priorities and in the design of new machines

Like its detector R&D counterpart, the report concludes with 10 concrete recommendations. These include the attraction, training and career management of researchers, observations on the implementation and governance of the programme, environmental sustainability, cooperation between European and international laboratories, and continuity of funding.

"The accelerator R&D roadmap represents the collective view of the accelerator and particle-physics communities on the route to machines beyond the Higgs factories," says Dave Newbold, LDG chair and director of particle physics for STFC in the UK. "We now need to move swiftly forwards with an ambitious, cooperative and international R&D programme – the potential for future scientific discoveries depends on it."

Further reading

ECFA Detector R&D Roadmap Process Group 2021 CERN-ESU-017.

N Mounet (ed.) 2021 European Strategy for Particle Physics – Accelerator R&D Roadmap *CERN Yellow Reports: Monographs* (to be published).

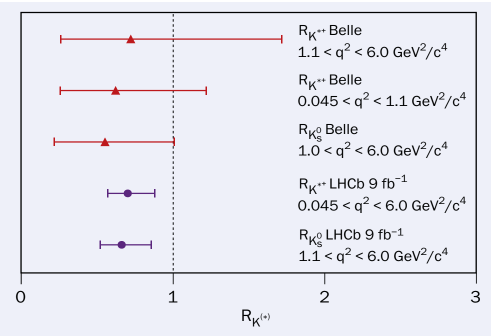
FLAVOUR PHYSICS

LHCb tests lepton universality in new channels

At a seminar at CERN on 19 October, the LHCb collaboration presented new tests of lepton universality in rare B-meson decays. While limited in statistical sensitivity, the results fit an intriguing pattern of recent results in the flavour sector, says the collaboration.

Since 2013, several measurements have hinted at deviations from lepton-flavour universality (LFU), a tenet of the Standard Model (SM) that treats charged leptons, ℓ, as identical apart from their masses. The measurements concern decay processes involving the transition between a bottom and a strange quark $b \rightarrow s\ell^+\ell^-$, which are strongly suppressed by the SM because they involve quantum corrections at the one-loop level (leading to branching fractions of one part in 10^6 or less). A powerful way to probe LFU is therefore to measure the ratio of B-meson decays to muons and electrons, for which the SM prediction, close-to-unity, is theoretically very clean.

In March this year, an LHCb measurement of $R_K = BR(B^+ \rightarrow K^+\mu^+\mu^-)/BR(B^+ \rightarrow K^+e^+e^-)$ based on the full LHC Run 1 and 2 dataset showed a 3.1σ difference from the SM prediction (*CERN Courier* May/June 2021 p17). This followed departures at the level of 2.2–2.5σ in the ratio $R^0_{K^*}$ (which probes $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays) reported by LHCb in 2017. The collaboration has also seen slight deficits in the ratio R_{pK}, and departures from theory in measurements of the angular distribution of final-state particles and of branching fractions in neutral B-meson decays. None of the results is individually significant enough to constitute evidence of new physics. But taken together, say theorists, they point to a coherent pattern (see p35).



Phys. Rev. Lett. **126** 161801 and arXiv:2110.09501

Same sign *Measurements of the ratios of muon to electron decays by LHCb (purple) and previous measurements from Belle (red).*

The latest LHCb analysis clocked the ratio of muons to electrons in the isospin-partner B-decays: $B^0 \rightarrow K^0_S\ell^+\ell^-$ and $B^+ \rightarrow K^{*+}\ell^+\ell^-$. As well as being a first at the LHC, it's the first single-experiment observation of these decays, and the most precise measurement yet of their branching ratios. Being difficult to reconstruct due to the presence of a long-lived K^0_S in the final state, however, the sensitivity of the results is lower than for previous "R_K" analyses. LHCb finds $R_{K^0_S} = 0.66^{+0.2}_{-0.15}$ (stat) $^{+0.02}_{-0.04}$ (syst) and $R_{K^{*+}} = 0.70^{+0.18}_{-0.13}$ (stat) $^{+0.03}_{-0.04}$ (syst), which are consistent with the SM at the level of 1.5 and 1.4σ, respectively.

"What is interesting is that we are seeing a similar deficit of rare muon decays to rare electron decays that we have seen in other LFU tests," said Harry Cliff of the University of Cambridge, who presented the result at CERN on behalf of LHCb. "With many other LFU tests in progress using Run 1 and 2 data, there will be more to come on this puzzle soon. Then we have Run 3, where we expect to really zoom in on the measurements and obtain a detailed understanding."

Further reading

LHCb Collaboration 2021 arXiv:2110.09501.

NEUTRINOS

Evidence fades for a light sterile neutrino

The existence of an eV-scale sterile neutrino looks less likely today than at any time in the past 20 years. Such a particle has long been considered to be the simplest explanation for several related anomalies in neutrino physics, but results released on 27 October by Fermilab's MicroBooNE collaboration disfavour its existence relative to the Standard Model.

"MicroBooNE has made a very comprehensive exploration through multiple types of interactions, and multiple analysis and reconstruction techniques," says co-spokesperson Bonnie Fleming of Yale University. "They all tell us the same thing, and that gives us very high confidence in our results that we are not seeing a hint of a sterile neutrino."

R Hahn/Fermilab

Cross check *The MicroBooNE experiment's liquid-argon time-projection chamber is inserted into its cryostat.*

Identity crisis

Neutrinos suffer from an identity crisis regarding their mass. As a result, the three known flavours morph into each other as phase differences develop between three mass eigenstates. However, well before this model solidified around the turn of the millennium, a measurement by the LSND collaboration at Los Alamos in the US suggested the existence of an additional neutrino that had to be "sterile" with respect to the weak, electromagnetic and strong interactions, and much more massive, given how rapidly the oscillation developed. Since this first hint, the tale of the sterile neutrino has taken multiple twists and turns (*CERN Courier* July/August 2020 p32).

In the mid-1990s, LSND reported seeing a 3.8σ excess of electron antineutrinos in a beam of accelerator-generated muon antineutrinos, but the KARMEN experiment at the Rutherford Appleton Laboratory in the UK failed to reproduce the effect. Evidence for an eV-scale sterile neutrino mounted with the observation of a deficit of electron neutrinos from ^{37}Ar and ^{51}Cr electron-capture decays at Gran Sasso in Italy and at the Baksan Neutrino Observatory in Russia (the "gallium anomaly"), and a reported deficit of electron antineutrinos from nuclear reactors (the "reactor anomaly"). Troublingly, however, long-baseline accelerator neutrino experiments such as MINOS+ do not observe the requisite "disappearance" of muon neutrinos required by the principle of unitarity (*CERN Courier* March/April 2019 p7), and the existence of such a sterile neutrino is also starkly incompatible with current models of cosmology.

But the most compelling single piece of evidence in favour of sterile neutrinos came when the MiniBooNE experiment at Fermilab tried to reproduce the LSND effect. In November 2018, the collaboration reported a 4.5σ excess of electron neutrinos and antineutrinos compared to Standard Model expectations. "That earlier data from MiniBooNE doesn't lie," says former MicroBooNE co-spokesperson Sam Zeller of Fermilab. "There's something really interesting happening that we still need to explain."

Sibling experiment MicroBooNE has now released its first round of tests of the MiniBooNE anomaly. Equipped with a cutting-edge liquid-argon time-projection chamber, the collaboration observed neutrino interactions at the level of individual particle tracks – a key advantage compared to a Cherenkov detector such as MiniBooNE, which could not distinguish electrons from photons. The collaboration has now used half of its available data to probe which particle is the true origin of the anomaly. Earlier this month, MicroBooNE tested the hypothesis that MiniBooNE's excess was actually due to an underestimated single-photon background, perhaps caused by a difficult-to-model rare decay of a Δ resonance (*CERN Courier* November/December 2021 p8). Now, MicroBooNE has tested the hypothesis that the MiniBooNE excess was caused by single electrons, most likely the result of neutrino oscillations via an eV-scale sterile neutrino. Few neutrino physicists foresaw that MicroBooNE would disfavour both hypotheses.

Few neutrino physicists foresaw that MicroBooNE would disfavour both hypotheses

Exotic topologies

The MicroBooNE collaboration will now investigate whether more exotic topologies such as electron–positron pairs could be the source of the MiniBooNE anomaly. Such a final state might suggest the existence of heavier sterile neutrinos, say theorists. "eV-scale sterile neutrinos no longer appear to be experimentally motivated, and never solved any outstanding problems in the Standard Model," says theorist Mikhail Shaposhnikov of EPFL. "But GeV-to-keV-scale sterile neutrinos – so-called Majorana fermions – are well motivated theoretically and do not contradict any existing experiment. They can explain neutrino masses and oscillations, give a dark-matter candidate, and produce a baryon asymmetry in the universe: all problems that the Standard Model is incapable of addressing. Experimental efforts at the intensity frontier should now be concentrated in this direction."

Further reading

MicroBooNE Collab. 2021 arXiv:2110.14065.

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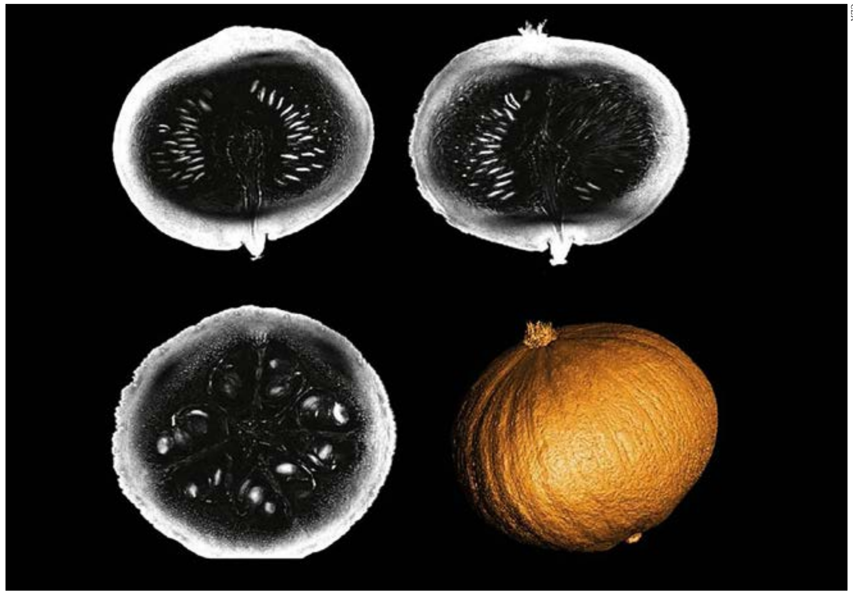
Applications

World's most powerful MRI unveiled

A 132 tonne superconducting magnet has set a new record for magnetic-resonance imaging (MRI), producing a field of 11.7 T inside a 0.9 m diameter and 5 m-long volume. Four-times more powerful than typical hospital devices, the "Iseult" project at CEA-Paris-Saclay paves the way for imaging the brain in unprecedented detail for medical research.

Using a pumpkin as a suitably brain-like subject, the team released its first images in October, validating the system and demonstrating an initial resolution of 400 μm in three dimensions. Other checks and approvals are necessary before the first imaging of human volunteers can begin.

"Thanks to this extraordinary MRI, our researchers are looking forward to studying the anatomical and structural organisation of the brain in greater detail. This work will undoubtedly lead to major clinical applications," said Stanislas Dehaene, director of NeuroSpin, the neuroimaging platform at CEA-Paris-Saclay.



CEA

High resolution *On account of its multiple textures and resemblance to brain tissue, a pumpkin was the natural choice to showcase MRI's capabilities at 11.7 T.*

The magnets that drive tens of thousands of MRI devices worldwide perform the vital task of aligning the magnetic moments of hydrogen atoms. Then, RF pulses are used to momentarily disturb this order in a specific region, after which the atoms are pulled back into equilibrium by the magnetic field, and radiate. The stronger the field, the higher the signal-to-noise ratio, and thus better image resolution.

In addition to being the largest and most powerful MRI magnet ever built, claims the team, the Iseult solenoid (carrying a current of 1.5 kA) also sets a record for the highest ever field achieved using niobium-titanium conductor, the same as is used in the main LHC magnets. With various optimisations, and working with the European Union project Aroma on methodologies for optimal functioning of the new MRI device, a resolution approaching 100 to 200 microns is planned – some 10 times higher than commercial 3 T devices are capable of.

F Rhodes/CEA

Flying the flag *The front face of the high-field niobium-titanium MRI magnet.*

Particle physics know-how

Designed and built over 10 years, Iseult was jointly led by neuroscientists and magnet and MRI specialists at the CEA Institute of Research into the Fundamental Laws of the Universe (IRFU) and the Frédéric Joliot Institute for Life Sciences, along with several industry and academic partnerships in Germany. Although CERN was not directly involved, Iseult's success is anchored in more than four decades of joint developments between CERN and the CEA, explains Anne-Isabelle Etienvre, head of CEA IRFU:

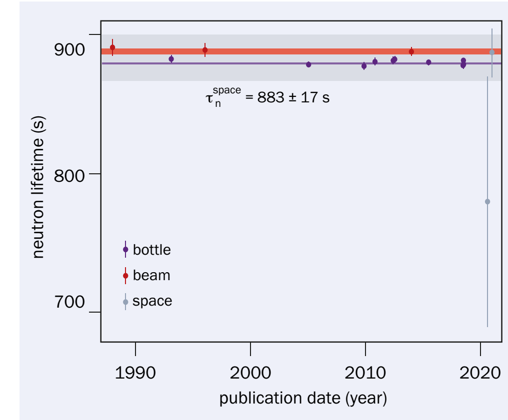
"It is thanks to the know-how developed for particle physics and fusion that MRI experts had the idea to ask us to design and build this unique and challenging magnet for MRI – in particular, CEA has played a major role, together with CERN and other partners, on LHC magnets, the ATLAS toroidal magnets and the CMS solenoid," says Etienvre. "The collaboration between CEA and CERN is still very lively, in particular for advanced magnets for future accelerators."

Astrowatch

Space-based data probe neutron lifetime

The neutron lifetime is key to a range of fields, not least astrophysics and cosmology, where it is used in the modeling of the synthesis of helium and heavier elements in the early universe. Its value, however, is uncertain. In recent years, discrepancies of up to 4σ between measurements of the neutron lifetime using different methods present a puzzle that particle physicists, nuclear physicists and cosmologists are increasingly eager to solve.

A recent experiment with the UCNτ experiment at the Los Alamos Neutron Science Center, which resulted in the most constraining measurement of the lifetime to date, further strengthens the discrepancy. The latest result, achieved using the so called "bottle" method, results in a neutron lifetime of $877.75 \pm 0.28\,(\text{stat})\,^{+0.22}_{-0.16}\,(\text{syst})$ s, whereas measurements using the "beam" method have consistently resulted in longer lifetimes (see figure). While the beam method determines the lifetime by measuring the decay products of the neutron, the bottle method instead stores cold, or thermalised, neutrons for a certain time before counting the remaining ones by direct detection. If not the result of some unknown systematic error, the discrepancy could be a sign of exotic physics whereby the longer lifetime in the beam method stems from an unmeasured second decay channel.



Phys. Rev. C 104 045501

Get in line *Recent measurements of the neutron lifetime using the bottle (purple) and beam (red) methods, along with those from the first and second ever space-based measurements (grey).*

A dedicated instrument on a future lunar mission could bring a crucial third independent tool to tackle the neutron lifetime puzzle

Escape detection

Astrophysics brings a third, independent measurement into play based on the bombardment of galactic cosmic rays on planetary surfaces. This continual process liberates large numbers of high-energy neutrons, some of which escape into space while others approach thermal equilibrium with surface and atmospheric material, a proportion subsequently escaping into space where at some point they will decay. The neutron lifetime can therefore be inferred by counting the neutrons remaining at different distances from their production location, using detectors positioned hundreds to thousands of kilometres above the surface. As the escaped neutron flux depends on a planet's particular elemental composition at depths corresponding to the neutron mean-free path (typically around 10 cm), neutron spectrometers have already been installed on several missions to explore planetary surface compositions.

In 2020, using neutrons produced through interactions of cosmic rays with Venus and Mercury, a team from the Johns Hopkins Applied Physics Laboratory and Durham University demonstrated the feasibility of such a neutron-lifetime measurement. Now, using data from a lunar mission, the same team has provided the first results with uncertainties approaching those coming from lab-based experiments. Importantly, since it also relies on direct detection, the result from space should produce the same lifetime as the bottle experiments.

For this latest study, the researchers used data from NASA's Lunar Prospector taken during several elliptical orbits around the moon in 1998. The orbiter contained two neutron detectors, one with a cadmium shield making it insensitive to slow or thermal neutrons, and one containing a tin shield that allows it to measure thermal as well as higher-energy neutrons. The difference between the two count rates then provides the thermal neutron flux. Combining this with the spacecraft position, the group deduced the thermal neutron flux for different positions and distances towards the Moon and fitted the data against a model that includes the production and propagation of thermal neutrons originating from interactions of cosmic rays with the lunar surface.

Surface studies

The highly detailed models account for neutron production from cosmic-ray interactions with the different elements of the lunar surface, and also for the varying composition of the surface in different regions. For the lifetime measurement, thermal neutrons were used due to their lower velocities (a few km/s), which makes their flux as a function of the distance to the surface (typically several 100 km) more sensitive to their lifetimes. The higher sensitivity comes at the cost of greater model complexity, however. For example, thermal neutrons cannot simply be modeled as traveling in a straight line, but are affected by the lunar gravity, meaning that they not only come directly from the surface but also enter the detector from the back as they perform elliptical orbits.

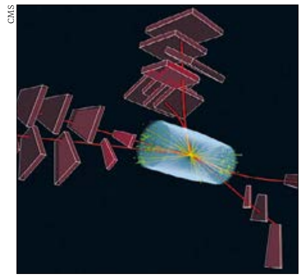
The study found a lifetime of $887 \pm 14\,(\text{stat})\,^{+7}_{-3}\,(\text{syst})$ s. The systematic error stems mainly from uncertainties in the surface composition and its variations as well as a lack of modeling of the temperature variation of the Moon's surface, which affects the thermalisation process, and from uncertainties in the ephermides (location) of the spacecraft. In future dedicated missions, the latter two issues can be mitigated, while knowledge of the surface composition can be improved with additional studies. Indeed, the large statistical error arises from this being a non-dedicated mission where the small data sample used was not even part of the science data of the original mission. The results are therefore highly promising, as they show that a dedicated instrument on a future lunar mission would bring a crucial third independent tool to tackle the neutron lifetime puzzle.

Further reading

J T Wilson et al. 2021 *Phys. Rev. C* **104** 045501.
UCNτ Collab. 2021 *Phys. Rev. Lett.* **127** 162501.

CERNCOURIER
Volume 62 Number 1 January/February 2022

NEWS DIGEST



CMS

A candidate triple-J/ψ event.

Triple treat for CMS

The CMS collaboration has observed three J/ψ particles emerging from a single collision between two protons for the first time, offering a new way to study the evolution of the transverse density of quarks and gluons inside the proton (arXiv:2111.05370). Analysing LHC Run-2 events in which a J/ψ decays into a pair of muons, the team identified five in which three J/ψ particles were produced simultaneously, with a statistical confidence of more than 5σ. The measured cross section is consistent, within the current large uncertainties, with previous measurements of double-J/ψ production but found to be a few times smaller than those derived from other measurements of double-parton scatterings. The larger sample of three-J/ψ events expected in Run 3 will further improve understanding of the internal structure of protons at small scales.

Sympathy for positrons

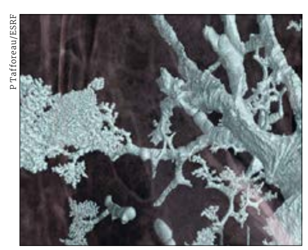
As a constituent of antihydrogen, the only long-lived neutral antimatter bound state that can currently be produced at low energy, the positron is key to high-precision tests of CPT and other fundamental symmetries. Now, the ALPHA collaboration at CERN has demonstrated a way to enhance antihydrogen synthesis by using laser-cooled Be^+ ions to sympathetically cool a plasma of positrons. Reaching a temperature below 7 K, almost a factor of three colder than currently used for antihydrogen formation, the Penning-trap scheme is expected to increase the amount of trapped antihydrogen per mixing attempt by up to a factor of five, paving the way for faster and more precise measurements of antihydrogen (*Nat. Commun.* **12** 6139).

Meet the cool copper collider

A team from SLAC and other institutions has presented a proposal for a linear e^+e^- collider with a "compact" footprint of 8 km (arXiv:2110.15800). Based on recent advances in normal-conducting copper accelerator technology, the new "C^3" (Cool Copper Collider) concept would provide a rapid path to precision Higgs-boson and top-quark measurements as well as a first step towards multi-TeV e^+e^- physics, write the authors. The machine could in principle be located anywhere in the world, they state, and would enable a staged programme at 250 and 550 GeV similar to that proposed for the ILC. The proposal has been submitted to the US Snowmass community planning exercise (p43).

X-rays probe COVID-19 damage

The damage caused by COVID-19 to the smallest blood vessels in the lung has been captured by the ESRF's Extremely Brilliant Source (EBS). Using a new 3D imaging



P Tafforeau/ESRF

The complex vascular system of a COVID-19 victim's lung.

technology called hierarchical phase-contrast tomography to scan a lung from a 54 year-old male COVID-19 victim, researchers from University College London observed how severe COVID-19 infection stops the patient's blood from being properly oxygenated, which was previously hypothesised but not proven (*Nat. Methods* DOI/10.1038/s41592-021-01317-x). The intensity of X-rays from the recently operational EBS – a hybrid multi-bend achromat that reduces the electron beam's horizontal emittance – enables blood vessels 5 μm in diameter to be observed, compared to around 1 mm for a conventional clinical CT scan.

Sphere or rugby ball?

Alternating from spheres to pronounced rugby balls as more neutrons are packed in is no longer the sole preserve of mercury nuclei. Using the ultrasensitive Resonance Ionisation Laser Ion Source at CERN's ISOLDE facility, where the phenomenon was first observed in mercury isotopes 50 years ago, an international team has shown that bismuth isotopes also undergo this dramatic change. The discovery of a second shape-staggering nucleus provides a powerful tool to understand this unusual nuclear-physics effect (*Phys. Rev. Lett.* **127** 192501).

CERN and the environment

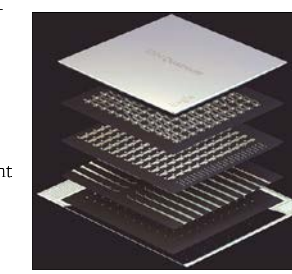
CERN's second public environment report, released on 24 November, highlights several improvements to its environmental footprint. Covering the years 2019–2020, during LS2 when the accelerator complex was not operating, CERN's direct greenhouse-gas emissions were less than half of the amount emitted annually over the previous reporting period, 2017–2018. The report also details the environmental impact of the HL-LHC, currently being prepared, which will enjoy a higher performance and a data-per-unit-of-energy-used ratio. Among other environmental goals, CERN has committed to reducing its direct ("scope 1") greenhouse-gas emissions by 28% by the end of 2024.

KEK to host quantum centre

The KEK laboratory in Japan will host the International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (QUP). Funded by the Japanese Ministry of Education, Culture, Sports, Science and Technology, and directed by Masashi Hazumi of the Institute of Particle and Nuclear Studies, QUP will integrate particle physics and several other fields to develop new systems for measuring quantum fields. The new centre's flagship project will be LiteBIRD, a space mission led by the Japanese space agency which aims to detect the imprint of primordial gravitational waves on the cosmic microwave background.

Qubits fly high

IBM has crossed the 100-qubit barrier with the announcement on 16 November of a quantum processor called Eagle that has 127 qubits – almost twice as many as the company's previous



IBM

IBM's multi-layer "Eagle" processor.

record set by the Hummingbird processor. Using state-of-the-art 3D chip architectures to place control wiring on multiple levels while keeping the qubits on a single layer, the device marks a milestone on the road to the Osprey 433-qubit machine in 2022 and the Condor 1121-qubit machine by 2023, says the firm, and heralds the point in hardware development where quantum circuits cannot be reliably simulated exactly on a classical computer.

CERNCOURIER

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IOP Publishing

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Unrivalled precision on Z invisible width

The LHC was built in the 27 km tunnel originally excavated for LEP, the highest energy electron–positron collider ever built. Designed to study the carriers of the weak force, LEP's greatest legacy is the accuracy with which it pinned down the properties of the Z boson. Among the highlights is the measurement of the Z boson's invisible width and decay branching fraction, which was used to deduce that there are three, and only three, species of light neutrinos that couple to the Z boson. This measurement of the Z-boson invisible width from LEP has remained the most precise for two decades.

In a bid to provide an independent and complementary test of the Standard Model (SM) at a new energy regime, CMS has performed a precise measurement of the Z-boson invisible width – the first of its kind at a hadron collider. The analysis uses the experimental signature of a very energetic jet accompanied by large missing transverse momentum to select events where the Z boson decays predominantly to neutrinos. The invisible width is then extracted from the well-known relationship between the Z-boson coupling to neutrinos and its coupling to muons and electrons.

While the production of a pair of neutrinos occurs through a pure Z interaction, the production of a pair of charged leptons can also occur through a virtual photon. The contribution of virtual photon exchange and the interference between photon and Z-boson exchange are determined to be less than 2% for a dilepton invariant mass range of 71–111 GeV, and was accounted for to allow the collaboration to compare the results directly to the Z's decay to neutrinos.

Figure 1 shows the missing transverse momentum distribution for the three key regions contributing to this measurement: the jets-plus-missing-transverse-momentum region; the dimuon-plus-jets region; and the dielectron-plus-jets region. For the dilepton regions, selected muons and electrons are not included in the calculation of the missing transverse momentum. The dominant background to the jets plus missing transverse momentum region is from a W boson decaying leptonically, and accounts for 35% of the events. Estimating this background with a high accuracy is one of the key aspects of the measurement, and was performed by studying several exclusive regions in data that are designed to be kinematically very similar to the signal region, but statistically independent.

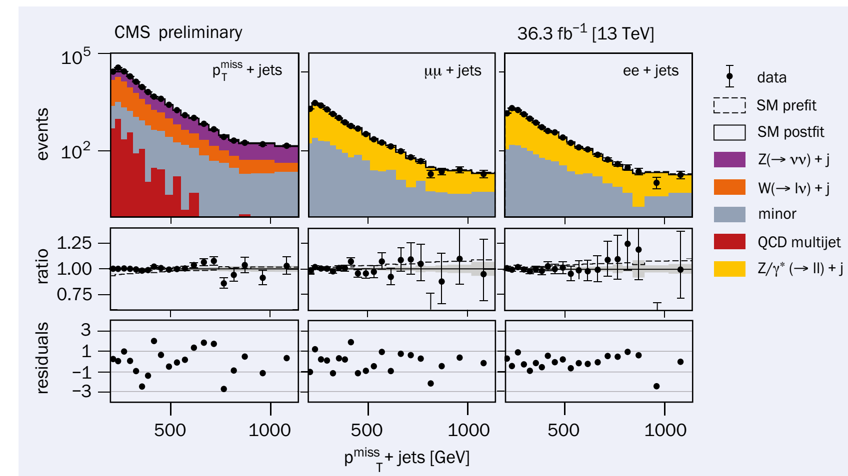

Fig. 1. *Distribution of the missing transverse momentum comparing data (black points) and simulation for the three most important regions used to extract the Z-boson invisible width. In the leptonic regions, selected muons and electrons are not included in the calculation.*

This precise measurement of the Z-boson invisible width is the first of its kind at a hadron collider

The invisible width of the Z boson was extracted from a simultaneous likelihood fit and measured to be 523 ± 3 (stat) ± 16 (syst) MeV. This 3.2% uncertainty in the final result is dominated by systematic uncertainties, with the largest contributions coming from the uncertainty in the efficiencies of selecting muons and electrons. In a fitting tribute to its predecessor and testament to the LHC entering a precision era of physics, this measurement from CMS is competitive with the LEP combined result of 503 ± 16 MeV and is currently the world's most precise single direct measurement.

Further reading

ALEPH Collab. *et al.* 2006 *Phys. Rep.* **427** 257.
CMS Collab. 2021 CMS-PAS-SMP-18-014.

LHCb

Beauty enhances precision of CKM angle γ

The CP-violating angle γ of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix is a benchmark of the Standard Model, since it can be determined from tree-level beauty decays in an entirely data-driven way with negligible theoretical uncertainty. Comparisons between direct and indirect measurements of γ therefore provide a potent test for new physics. Before LHCb began taking data, γ was one of the poorest known constraints of the CKM unitarity triangle, but that is no longer the case.

A chance to observe CP violation in charm mixing

A new result from LHCb marks an important change in strategy, by ▷

including not only results from beauty decays sensitive to γ but additionally exploiting the sensitivity to CP violation and mixing of charm meson (D^0) decays. Mixing in the D^0–$\bar{D}^0$ system proceeds via flavour-changing neutral currents, which may also be affected by contributions from new heavy particles. The process is described by two parameters: the mass difference, x, and width difference, y, between the two charm flavour states (see figure 1).

The latest combination takes the results of more than 20 LHCb beauty and charm measurements to determine $\gamma = (65.4^{+3.8}_{-4.2})°$, which is the most precise measurement from a single experiment (see figure 2). Furthermore, various charm-mixing parameters were determined by combining, for the first time, both the beauty and charm datasets, which results in $x = (0.400^{+0.052}_{-0.053})\%$ and $y = (0.630^{+0.033}_{-0.030})\%$. The latter is a factor-of-two more precise than the current world average, which is entirely due to the new methodology that harnesses additional sensitivity to the charm sector from beauty decays.

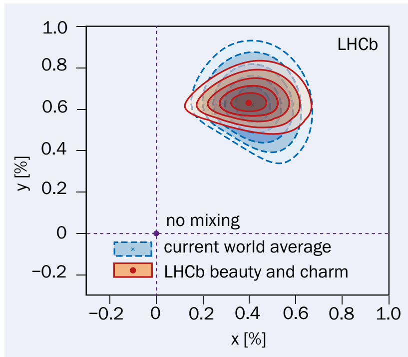

Fig. 1. *New (orange) constraints for the charm mixing parameters x and y compared to the current world average (blue). Contours are drawn from 1–5σ.*

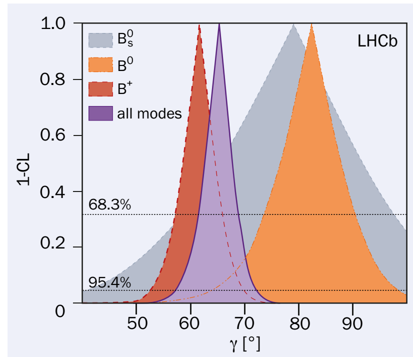

Fig. 2. *The sensitivity to γ with all beauty and charm modes (purple, solid line) compared to those just originating from the individual B-meson initial states.*

This demonstrates that LHCb has already achieved better precision than its original design goals. When the redesigned LHCb detector restarts operations in 2022, the target of sub-degree precision on γ, and the chance to observe CP violation in charm mixing, comes ever closer.

Further reading

LHCb Collab. 2021 arXiv:2110.02350.

ATLAS

Searching for Higgs compositeness

Since the discovery of the Higgs boson at the LHC in 2012, physicists have a more complete understanding of the Standard Model (SM) and the origin of elementary particle mass. However, theoretical questions such as why the Higgs boson is so light remain. An attractive candidate explanation postulates that the Higgs boson is not a fundamental particle, but instead is a composite state of a new, strongly-interacting sector – similar to the pion in ordinary strong interactions. In such composite-Higgs scenarios, new partners of the top and bottom quarks of the SM could be produced and observed at the LHC.

Ordinary SM quarks come in left-handed and right-handed varieties, which behave differently in weak interactions. The hypothetical new quark partners, however, behave the same way in weak interactions, whether they are left- or right-handed. Composite-Higgs models, and several other theories beyond the SM, predict the existence of such "vector-like quarks" (VLQs). Searching for them is therefore an exciting opportunity for the LHC experiments.

If they exist, VLQs could be very heavy, with masses at the TeV scale, and could be produced either singly or in pairs at the LHC. Furthermore, VLQs could decay into regular top or bottom quarks in combination with a W, Z or Higgs boson. This rich phenomenology warrants a varied range of complementary searches to provide optimal coverage.

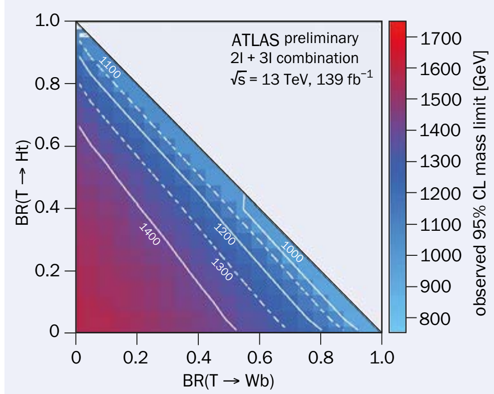

Fig. 1. *The mass range excluded in the search for the pair production of vector-like top quarks as a function of the fraction decaying to a W boson and a bottom quark (x-axis), and the fraction decaying to a Higgs boson and a top quark (y-axis). The redder colours indicate higher masses are excluded, while bluer colours indicate lower masses are excluded.*

The ATLAS collaboration has recently carried out two VLQ searches based on the full Run-2 dataset (139 fb^{-1}) at 13 TeV.

The first analysis targets pair-production of VLQs, focusing on the possibility that most VLQs decay to a Z boson and a top quark. To help identify likely signal events, leptonically decaying Z bosons were tagged in events with pairs of electrons or muons. To maximise the discriminating power between the VLQ signal and the SM background, machine-learning techniques using a deep neural network were employed to identify the hadronic decays of top quarks, Z, W or Higgs bosons, and categorise events into 19 distinct regions.

The second analysis targets the single production of VLQs. While the rate of pair production of VLQs through regular strong interactions only depends on their mass, their single production also depends on their coupling to SM electroweak bosons. As a result, depending on the model under consideration, VLQs heavier than approximately 1 TeV might predominantly be produced singly, and a measurement would therefore uniquely allow insight into this coupling strength.

The analysis was optimised for VLQ decays to top quarks in combination with either a Higgs or a Z boson. Events with a single lepton and multiple jets were selected, and tagging algorithms were used to identify the boosted leptonic ▷ and hadronic decays of top quarks, and the hadronic decays of Higgs and Z bosons. The presence of a forward jet, characteristic of the single VLQ production mode, was used (along with the multiplicity of jets, b-jets and reconstructed boosted objects) to categorise the analysed events into 24 regions.

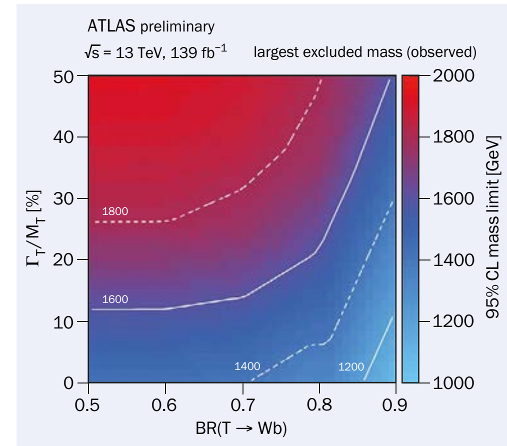

Fig. 2. *The largest excluded mass for the single production of a vector-like top quark for a range of models, depending on the resonance width divided by the mass (y-axis), and the fraction decaying to a W boson and a bottom quark, while keeping the decay fraction to a Higgs or Z boson and a top quark equal (x-axis). Models at the lowest end of this decay fraction constitute vector-like quarks with a SU(2) singlet configuration, to which the analysis is the most sensitive.*

The observations from both analyses are consistent with SM predictions, which allows ATLAS to set the strongest constraints to date on VLQ production. Together, the pair- and single-production analyses exclude VLQs with masses up to 1.6 TeV (see figure 1) and 2.0 TeV (see figure 2), respectively, depending on the assumed model. These two analyses are part of a broader suite of searches for VLQs underway in ATLAS. The combination of these searches will provide the greatest potential for the discovery of VLQs, and ATLAS therefore looks forward to the upcoming Run-3 data.

Further reading

ATLAS Collab. 2021 ATLAS-CONF-2021-024.
ATLAS Collab. 2021 ATLAS-CONF-2021-040.

ALICE

Charm-strange mesons probe hadronisation

The ALICE collaboration has reported a new measurement of the production of D_s^+ mesons, which contain a charm and an anti-strange quark, in Pb–Pb collisions collected in 2018 at a centre-of-mass energy per nucleon pair of 5.02 TeV. The large data sample and the use of machine-learning techniques for the selection of particle candidates led to increased precision on this important quantity.

D-meson measurements probe the interaction between charm quarks and the quark–gluon plasma (QGP) formed in ultra-relativistic heavy-ion collisions. Charm quarks are produced in the early stages of the nucleus–nucleus collision and thus experience the whole system evolution, losing part of their energy via scattering processes and gluon radiation. The presence of the QGP medium also affects the charm-quark hadronisation and, in addition to the fragmentation mechanism, a competing process based on charm-quark recombination with light quarks of the medium might occur. Given that strange quark-antiquark pairs are abundantly produced in the QGP, the recombination mechanism could enhance the yield of D_s^+ mesons in Pb–Pb collisions with respect to that of D^0 mesons, which do not contain strange quarks.

ALICE investigated this possibility using the ratio of the yields of D_s^+ and D^0 mesons. The figure displays the D_s^+/D^0 yield ratio in central (0–10%) Pb–Pb collisions divided by the ratio in pp collisions, showing that the values of the ratio in the $2 < p_T < 8$ GeV/c interval are higher in central Pb–Pb collisions by about 2.3σ. The measured D_s^+/D^0 double ratio also hints at a peak for $p_T \approx 5$–6 GeV/c. Its origin could be related to the different D-meson masses and to the collective radial expansion of the system with a common flow-velocity profile. In addition, the hadronisation via fragmentation becomes dominant at high transverse momenta, and consequently, the values of the D_s^+/D^0 ratio become similar between Pb–Pb and pp collisions.

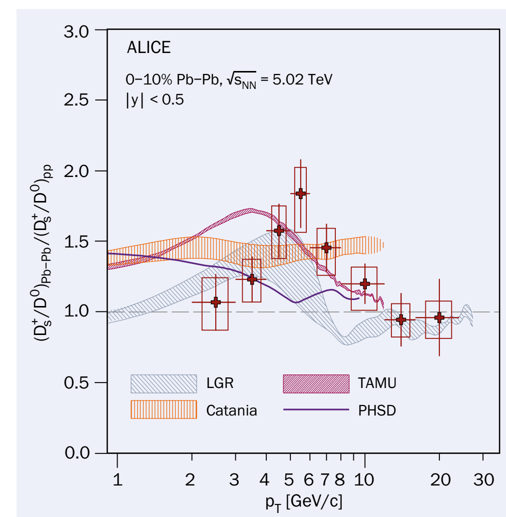

Fig. 1. *The ratio of the p_T-differential production yield of D_s^+ and D^0 mesons in Pb–Pb collisions at 5.02 TeV for the 0–10% centrality interval divided by the ratio measured in pp collisions at the same energy. The measurement is compared to theoretical predictions by the LGR, TAMU, Catania and PHSD models.*

The measurement was compared with theoretical calculations based on charm-quark transport in a hydrodynamically expanding QGP (LGR, TAMU, Catania and PHSD), which implement the strangeness enhancement and the hadronisation of charm quarks via recombination in addition to the fragmentation in the vacuum. The Catania and PHSD models predict a ratio almost flat in p_T, while TAMU and LGR describe the peak at $p_T \approx 3$–5 GeV/c.

Complementary information was obtained by comparing the elliptic flow coefficient v_2 of D_s^+ and non-strange D mesons (D^0, D^+ and D^{*+}) in semi-central (30–50%) Pb–Pb collisions. The D_s^+-meson v_2 is positive in the $2 < p_T < 8$ GeV/c interval with a significance of 6.4σ, and is compatible within uncertainties with that of non-strange D mesons. These features of the data are described by model calculations that include recombination of charm and strange quarks.

The freshly-completed upgrade of the detectors and the harvest of Pb–Pb collision data expected in Run 3 will allow the ALICE collaboration to further improve the measurements, deepening our understanding of the heavy-quark interaction and hadronisation in the QGP.

Further reading

ALICE Collab. 2021 arXiv:2110.10006.

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FIELD NOTES

Reports from events, conferences and meetings

FLAVOUR ANOMALIES WORKSHOP 2021

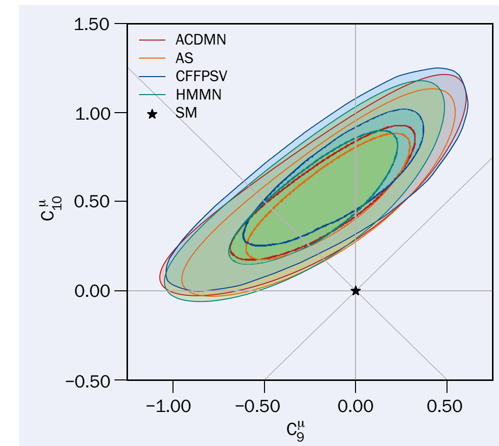
Flavour workshop looks beyond bumps

The inaugural CERN Flavour Anomalies Workshop took place on 20 October as part of the 2021 Implications of LHCb Measurements and Future Prospects meeting. More than 500 experimentalists and theorists met in a hybrid format via Zoom and in person. Discussion centered on the longstanding tensions in B-physics measurements and new project ideas. The workshop was dedicated to the memory of long-time LHCb collaborator Sheldon Stone (Syracuse), who made plentiful contributions to CERN's flavour programme (see p55).

Intriguing patterns

The central topic of the workshop was the b anomalies: a persistent set of tensions between predictions and measurements in a number of semileptonic b-decays that are not as clear as unexpected peaks in invariant mass distributions. Instead, they manifest themselves as modifications to the branching fractions and angular distributions of certain flavour-changing neutral-current (FCNC) b-decays, and they have become more significant over the past decade. The latest LHCb measurement of the ratio R_K of B^+ decays to a kaon and a muon or electron pair differs from the Standard Model (SM) by more than 3σ (*CERN Courier* May/June 2021 p17), and the ratio R_{K^*} of B^0 decays to an excited kaon and a muon or electron pair differs by more than 2σ. LHCb has also seen several departures from theory in measurements of angular distributions at the level of roughly 3σ significance (*CERN Courier* May/June 2020 p10). Finally, and coherent with these FCNC effects, BaBar, Belle and LHCb analyses of charged-current $b \to c\tau^-\bar{\nu}$ decays support lepton-flavour-universality (LFU) violation at a combined significance of roughly 3σ. Though no single measurement is statistically significant, the collective pattern is intriguing (*CERN Courier* May/June 2019 p33).

But how robust are the SM predictions for these observables? Efforts include both theory-only and data-driven approaches for distinguishing genuine signs of beyond-the-SM (BSM) effects from hard-to-understand hadronic effects. A further aim is to understand what type of BSM models could produce the observed effects. Of particular interest was the question of how to incorporate information from high-p_T searches at the LHC experiments. ATLAS and CMS are ramping up their efforts, and their ongoing B-physics programmes will hopefully soon confirm and complement LHCb's results. Both experiments reported on work to address the main bottlenecks: the reconstruction of low-p_T leptons, and trigger challenges foreseen as a result of increased luminosities in Run 3. The complementarity of B physics and direct searches was clear from results such as ATLAS and CMS searches for leptoquarks compatible with the flavour anomalies.



B Capdevila/M Fedele/S Neshatpour/P Stangl

Stunning agreement *Fits to beyond-the-Standard-Model couplings by four of the major fitting groups. Effective-field-theory coefficients C_9^{μ} and C_{10}^{μ} can affect both lepton-flavour universality and the golden decays $B_{s,d} \to \mu^+\mu^-$.*

Discussions centered on the longstanding tensions in B-physics measurements and new project ideas

The workshop saw, for the first time, a joint theory presentation by four of the major $b \to s\ell^+\ell^-$ fitting groups. They showed a stunning agreement in fits to effective-field-theory parameters that register as nonzero in the presence of BSM physics (see figure). The fits use observables that either probe LFU or help to constrain troublesome hadronic uncertainties. The observables include: the now famous R_K, R_{K^*} and R_{pK} (which studies Λ_b^0 baryon decays to a proton, a charged kaon and a pair of muons or electrons), the measurements of which are dominated by LHCb results; and results on the branching fraction for $B_s \to \mu^+\mu^-$ from ATLAS, CMS and LHCb. Though the level of agreement diminishes when other observables and measurements are included, dominantly due to the different theoretical assumptions made by the four groups, all agree that substantial tensions with the SM are unavoidable.

Diverse datasets

New results from LHCb included first measurements (see p8) of the LFU-sensitive ratios $R_{K^{*+}}$ (which concerns $B^+ \to K^{*+}\ell^+\ell^-$ decays) and R_{Ks} (which concerns $B^0 \to K_S^0\ell^+\ell^-$ decays), and new measurements of branching fractions and angular observables for the decay $B_s \to \varphi\mu^+\mu^-$, which is at present hampered by significant theoretical uncertainties. By contrast, many theoretical predictions for $b \to c\tau^-\bar{\nu}$ processes are now more precise than measurements, with the promise of further improvements thanks to dedicated lattice-QCD studies. Larger and more diverse datasets will be needed to reduce the experimental uncertainties.

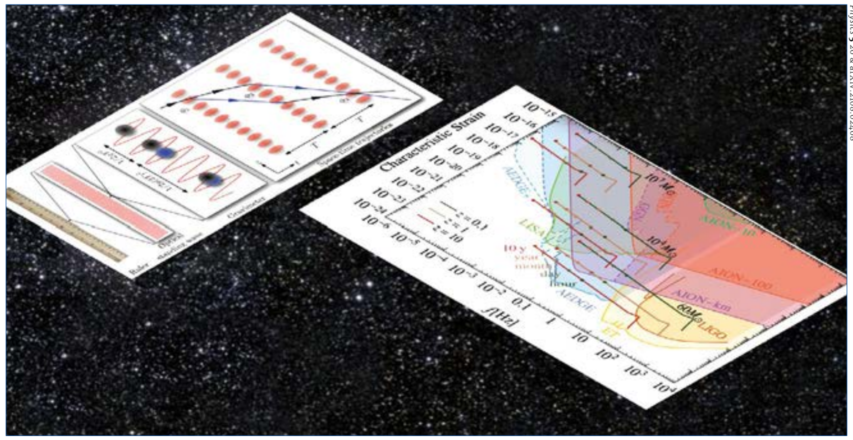
At the start of a new year, it is time to collect our wishes for 2022. The most prevalent of these involve new analysis results from ATLAS, CMS and LHCb on these burning topics, and for a 2022 workshop to happen in person.

Marie-Hélène Schune *IJCLab Paris-Saclay and CNRS/IN2P3,* and **Danny van Dyk** *Technische Universität München.*

Community Workshop on Cold Atoms in Space

The quantum frontier: cold atoms in space

Cold atoms offer exciting prospects for high-precision measurements based on emerging quantum technologies. Terrestrial cold-atom experiments are already widespread, exploring both fundamental phenomena such as quantum phase transitions and applications such as ultra-precise timekeeping. The final quantum frontier is to deploy such systems in space, where the lack of environmental disturbances enables high levels of precision. This was the subject of a workshop supported by the CERN Quantum Technology Initiative, which attracted more than 300 participants online from 23 to 24 September. Following a 2019 workshop triggered by the European Space Agency (ESA)'s Voyage 2050 call for ideas for future experiments in space, the main goal of this workshop was to begin drafting a roadmap for cold atoms in space.



Physics 5 26 & arXiv:2108.02468

Looking up *Prospects for space-borne cold-atom experiments include the detection of gravitational waves, probes of the equivalence principle and searches for dark matter.*

The workshop opened with a presentation by Mike Cruise (University of Birmingham) on ESA's vision for cold-atom R&D for space: considerable efforts will be required to achieve the technical readiness level needed for space missions, but they hold great promise for both fundamental science and practical applications. Several of the cold-atom teams that contributed white papers to the Voyage 2050 call also presented their proposals.

Atomic clocks

Next came a session on atomic clocks, including descriptions of their potential for refining the definitions of SI units, such as the second, and distributing this new time-standard worldwide, and potential applications of atomic clocks to geodesy. Next-generation space-based atomic-clock projects for these and other applications are ongoing in China, the US (Deep Space Atomic Clock) and Europe.

This was followed by a session on Earth observation, featuring the prospects for improved gravimetry using atom interferometry and talks on the programmes of ESA and the European Union. Quantum space gravimetry could contribute to studies of climate change, for example, by measuring the densities of water and ice very accurately and with improved geographical precision.

For fundamental physics, prospects for space-borne cold-atom experiments include studies of wavefunction collapse and Bell correlations in quantum mechanics, probes of the equivalence principle by experiments like STE-QUEST, and searches for dark matter. The proposed AEDGE atom interferometer will search for ultralight dark matter and gravitational waves in the deci-Hertz range, where LIGO/Virgo/KAGRA and the future LISA space observatory are relatively insensitive, and will probe models of dark energy. AEDGE gravitational-wave measurements could be sensitive to first-order phase transitions in the early universe, as occur in many extensions of the Standard Model, as well as to cosmic strings, which could be relics of symmetries broken at higher energies than those accessible to colliders. These examples show that cold-atom experiments in space offer great opportunities to probe the foundations of physics as well as make frontier measurements in astrophysics and cosmology.

Cold-atom experiments in space offer great opportunities to probe the foundations of physics

Several pathfinder experiments are underway. These include projects for terrestrial atom interferometers on scales from 10 m to 1 km, such as the MAGIS project at Fermilab and the AION project in the UK, which both use strontium, and the MIGA project in France and proposed European infrastructure ELGAR, which both use rubidium. Meanwhile, a future stage of AION could be situated in an access shaft at CERN – a possibility that is currently under study, and which could help pave the way towards AEDGE. Pioneering experiments using Bose–Einstein condensates on research rockets and the International Space Station were also presented.

A strong feature of the workshop was a series of breakout sessions to enable discussions among members of the various participating communities (atomic clocks, Earth observation and fundamental science), as well as a group considering general perspectives, which were summarised in a final session. Reports from the breakout sessions will be integrated into a draft roadmap for the development and deployment of cold atoms in space. This will be set out in a white paper to appear by the end of the year and presented to ESA and other European space and funding agencies.

Space readiness

Achieving space readiness for cold-atom experiments will require significant research and development. Nevertheless, the scale of participation in the workshop and the high level of engagement testifies to the enthusiasm in the cold-atom community and prospective user communities for deploying cold atoms in space. The readiness of the different communities to collaborate in drafting a joint roadmap for the pursuit of common technological and scientific goals was striking.

Oliver Buchmueller *Imperial College London,* **Albert De Roeck** *CERN and* **John Ellis** *King's College London.*

50 years of hadron colliders at CERN

Hadron colliders in perspective

From visionary engineer Rolf Widerøe's 1943 patent for colliding beams, to the high-luminosity LHC and its possible successor, the 14 October symposium "50 Years of Hadron Colliders at CERN" offered a feast of physics and history to mark the 50th anniversary of the Intersecting Storage Rings (ISR). Negotiating the ISR's steep learning curve in the 1970s, the ingenious conversion of the Super Proton Synchrotron (SPS) into a proton–antiproton collider (Sp$\bar{p}$S) in the 1980s, and the dramatic approval and switch-on of the LHC in the 1990s and 2000s chart a scientific and technological adventure story, told by its central characters in CERN's main auditorium.

CERN-PHOTO-202110-155-12

Historic *Carlo Rubbia gave the opening talk at the October event.*

Former CERN Director-General (DG) Chris Llewellyn Smith swiftly did away with notions that the ISR was built without a physics goal. Viki Weisskopf (DG at the time) was well aware of the quark model, he said, and urged that the ISR be built to discover quarks. "The basic structure of high-energy collisions was discovered at the ISR, but you don't get credit for it because it is so obvious now," said Llewellyn Smith. Summarising the ISR physics programme, Ugo Amaldi, former DELPHI spokesperson and a pioneer of accelerators for hadron therapy, listed the observation of charmed-hadron production in hadronic interactions, studies of the Drell–Yan process, and measurements of the proton structure function as ISR highlights. He also recalled the frustration at CERN in late 1974 when the J/ψ meson was discovered at Brookhaven and SLAC, remarking that history would have changed dramatically had the ISR detectors also enabled coverage at high transverse momentum.

A beautiful machine

Amaldi sketched the ISR's story in three chapters: a brilliant start followed by a somewhat difficult time, then a very active and interesting programme. Former CERN director for accelerators and technology Steve Myers offered a first-hand account, packed with original hand-drawn plots, of the battles faced and the huge amount learned in getting the first hadron collider up and running. "The ISR was a beautiful machine for experimental physics, but sadly is forgotten in particle physics," he said. "One of the reasons is that we didn't have beam diagnostics, on account of the beam being a coasting beam rather than a bunched beam, which made it really hard to control things during physics operation." Stochastic cooling, a "huge surprise", was the ISR's most important legacy, he said, paving the way for the Sp$\bar{p}$S and beyond.

Former LHC project director Lyn Evans took the baton, describing how the confluence of electroweak theory, the SPS as collider and stochastic cooling led to rapid progress. It started with the Initial Cooling Experiment in 1977–1978, then the Antiproton Accumulator. It would take about 20 hours to produce a bunch dense enough for injection into the Sp$\bar{p}$S, recalled Evans, and several other tricks to battle past the "26 GeV transition, where lots of horrible things" happened. At 04:15 on 10 July 1981, with just him and Carlo Rubbia in the control room, first collisions at 270 GeV at the Sp$\bar{p}$S were declared. Poignantly, Evans ended his presentation "The SPS and LHC machines" there. "The LHC speaks for itself really," he said. "It is a fantastic machine. The road to it has been a long and very bumpy one. It took 18 years before the approval of the LHC and the discovery of the Higgs. But we got there in the end."

The parallel world of hadron-collider experiments was brought to life by Felicitas Pauss, former CERN head of international relations, who recounted her time as a member of the UA1 collaboration at the Sp$\bar{p}$S during the thrilling period of the W and Z discoveries. Jumping to the present day, early-career researchers from the ALICE, ATLAS, CMS and LHCb collaborations brought participants up to date with the progress at the LHC in testing the Standard Model and the rich physics prospects at Run 3 and the HL-LHC.

It seems in hindsight that the LHC was inevitable, but it was anything but

Few presentations at the symposium did not mention Carlo Rubbia, who instigated the conversion of the SPS into a hadron collider and was the prime mover of the LHC, particularly, noted Evans, during the period when the US Superconducting Super Collider was under construction. His opening talk presented a commanding overview of colliders, their many associated Nobel prizes and their applications in wider society. During a brief Q&A at the end of his talk, Rubbia reiterated his support for a muon collider operating as a Higgs factory in the LHC tunnel: "The amount of construction is small, the resources are reasonable, and in my view it is the next thing we should do, as quickly as possible, in order to make sure that the Higgs is really what we think it is."

In a lively and candid presentation about how the LHC got approved, Llewellyn Smith also addressed the question of the next collider, noting it will require the unanimous support of the global particle-physics community, a "reasonable" budget envelope and public support. "It seems in hindsight that the LHC was inevitable, but it was anything but," he said. "I think going to the highest energy is the right way forward for CERN, but no government is going to fund a mega project to reduce error bars – we need to define the physics case."

Following a whirlwind "view from the US", in which Young-Kee Kim of the University of Chicago described the Tevatron and RHIC programmes and collated congratulatory messages from the US Department of Energy and others, CERN DG Fabiola Gianotti rounded off proceedings with a look at the future of the LHC and beyond. She updated participants on the significant upgrade work taking place for the HL-LHC and on the status of the Future Circular Collider feasibility study, a high-priority recommendation of the 2020 update of the European strategy for particle physics which is due to be completed in 2025. "The extraordinary success of the LHC is the result of the vision, creativity and perseverance of the worldwide high-energy physics community and more than 30 years of hard work," the DG stated. "Such a success demonstrates the strength of the community and it's a necessary milestone for future, even more ambitious, projects."

• *Videos from the one-off symposium, which capture the rich interactions between the people who made hadron colliders a reality, are available at: www.youtube.com/c/CERNLectures/playlists.*

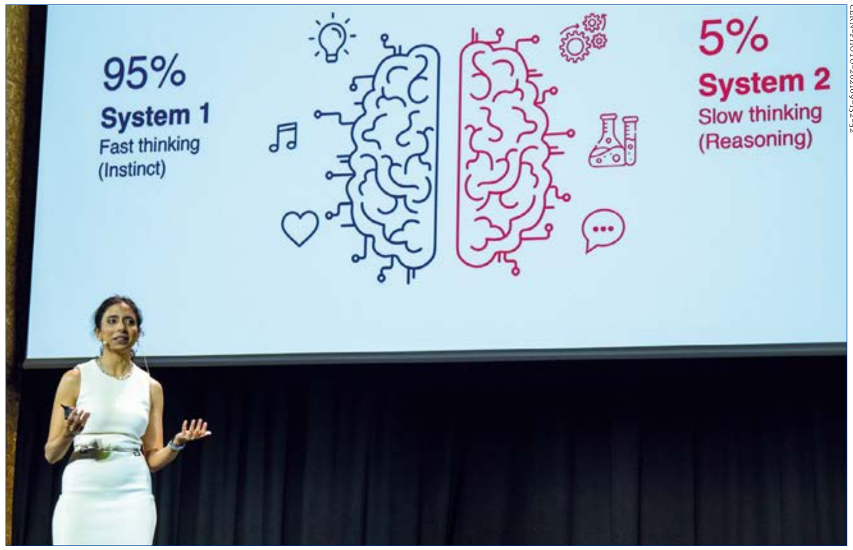
Matthew Chalmers *editor.*

Sparks! Serendipity Forum

Multidisciplinary CERN forum tackles AI

The inaugural Sparks! Serendipity Forum attracted 49 leading computer scientists, policymakers and related experts to CERN from 17 to 18 September for a multidisciplinary science-innovation forum. In this first edition, participants discussed a range of ethical and technical issues related to artificial intelligence (AI), which has deep and developing importance for high-energy physics and its societal applications. The structure of the discussions was designed to stimulate interactions between AI specialists, scientists, philosophers, ethicists and other professionals with an interest in the subject, leading to new insights, dialogue and collaboration between participants.

World-leading cognitive psychologist Daniel Kahneman opened the public part of the event by discussing errors in human decision making, and their impact on AI. He explained that human decision making will always have bias, and therefore be "noisy" in his definition, and asked whether AI could be the solution, pointing out that AI algorithms might not be able to cope with the complexity of decisions that humans have to make. Others speculated as to whether AI could ever achieve the reproducibility of human cognition – and if the focus should shift from searching for a "missing link" to considering how AI research is actually conducted by making the process more regulated and transparent.



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Cerebral *Machine-learning expert Anima Anandkumar of Caltech and NVIDIA speaking in the Globe at CERN on 20 September.*

Introspective AI

Participants discussed both the advantages and challenges associated with designing introspective AI, which is capable of examining its own processes and could be beneficial in making predictions about the future. Participants also questioned, however, whether we should be trying to make AI more self-aware and human-like. Neuroscientist Ed Boyden explored introspection through the lens of neural pathways, and asked whether we can design introspective AI before we understand introspection in brains. Following the introspection theme, philosopher Luisa Damiano addressed the reality versus fiction of "social-embodied" AI – the idea of robots interacting with us in our physical world – arguing that such a possibility would require careful ethical considerations.

AI is already a powerful, and growing, tool for particle physics

Many participants advocated developing so-called "strong" AI technology that can solve problems it has not come across before, in line with specific and targeted goals. Computer scientist Max Welling explored the potential for AI to exceed human intelligence, and suggested that AI can potentially be as creative as humans, although further research is required.

On the subject of ethics, Anja Kaspersen (former director of the UN Office for Disarmament Affairs) asked: who makes the rules? Linking to military, humanitarian and technological affairs, she considered how our experience in dealing with nuclear weapons could help us deal with the development of AI. She said that AI is prone to ethics washing: the process of creating an illusory sense that ethical issues are being appropriately addressed when they are not. Participants agreed that we should seek to avoid polarising the community when considering risks associated with current and future AI, and suggested a more open approach to deal with the challenges faced by AI today and tomorrow. Skype co-founder Jann Tallin identified AI as one of the most worrying existential risks facing society today; the fact that machines do not consider whether their decisions are unethical demands that we consider the constraints of the AI design space within the realm of decision making.

Fruits of labour

The initial outcomes of the Sparks! Serendipity Forum are being written up as a CERN Yellow Report, and at least one paper will be submitted to the journal *Machine Learning Science and Technology*. Time will tell what other fruits of the serendipitous interactions at Sparks! will bring. One thing is certain, however, AI is already a powerful, and growing, tool for particle physics. Without it, the LHC experiments' analyses would have been much more tortuous, as discussed by Jennifer Ngadiuba and Maurizio Pierini (*CERN Courier* September/October 2021 p31)

Future editions of the Sparks! Serendipity Forum will tackle different themes in science and innovation that are relevant to CERN's research. The 2022 event will be built around future health technologies, including the many accelerator, detector and simulation technologies that are offshoots of high-energy-physics research.

Alexia Yiannouli *and* **James Gillies** *CERN.*

Higgs Hunting 2021

Scrutinising the Higgs sector

The 11th Higgs Hunting workshop took place remotely between 20 and 22 September 2021, with more than 300 registered participants engaging in lively discussions about the most recent results in the Higgs sector. ATLAS and CMS presented results based on the full LHC Run-2 dataset (up to 140 fb^{-1}) recorded at 13 TeV. While all results remain compatible with Standard Model expectations, the precision of the measurements benefited from significant reductions in statistical uncertainties, more than three times smaller with the 13 TeV data than in previous LHC results at 7 and 8 TeV. This also brought into sharp relief the role of systematic uncertainties, which in some cases are becoming dominant. The status of theory improvements and phenomenological interpretations, such as those from effective field theory, were also presented.

Highlights included the Higgs pair-production process, which is particularly challenging at the LHC due to its low rate. ATLAS and CMS showed greatly improved sensitivity in various final states, thanks to improvements in analysis techniques. Also shown were results on the scattering of weak vector bosons, a process that is strongly related to the Higgs sector, highlighting large improvements from both the larger datasets and the higher collision energy available in Run 2. Several searches for phenomena beyond the Standard Model – in particular for additional Higgs bosons – were presented. No significant excesses have yet been found.

L Fayard

Virtual look *Some of the speakers at the September workshop.*

The historical talk "The LHC timeline: a personal recollection (1980–2012)" was given by Luciano Maiani, former CERN Director-General, and concluding talks were given by Laura Reina (Florida) and Paolo Meridiani (Rome). A further highlight was the theory talk from Nathaniel Craig, who discussed the progress being made in addressing six open questions. Does the Higgs boson have a size? Does it interact with itself? Does it mediate a Yukawa force? Does it fulfill the naturalness strategy? Does it preserve causality? And does it realise electroweak symmetry?

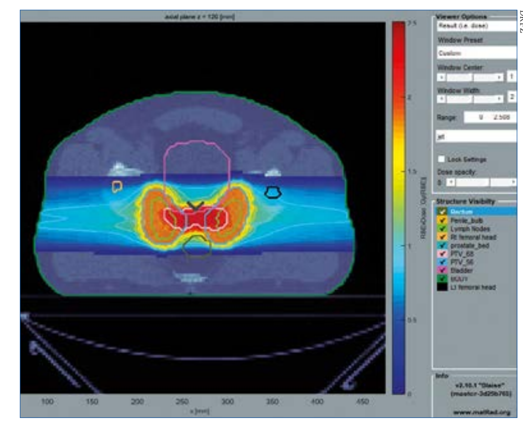
The next Higgs Hunting workshop will be held in Orsay and Paris from 12 to 14 September 2022.

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

Heavy Ion Therapy Masterclass school

Training future experts in the fight against cancer

The leading role of CERN in fundamental research is complemented by its contribution to applications for the benefit of society. A strong example is the Heavy Ion Therapy Masterclass (HITM) school, which took place from 17 to 21 May 2021. Attracting more than 1000 participants from around the world, many of whom were young students and early-stage researchers, the school demonstrated the enormous potential to train the next generation of experts in this vital application. It was the first event of the European Union project HITRIplus (Heavy Ion Therapy Research Integration), in which CERN is a strategic partner along with other research infrastructures, universities, industry partners, the four European heavy-ion therapy centres and the South East European International Institute for Sustainable Technologies (SEEIIST). As part of a broader "hands-on training" project supported by the CERN and Society Foundation with emphasis on capacity building in Southeast Europe, the event was originally planned to be hosted in Sarajevo but was held online due to the pandemic.



DKFZ

Hands on *The "matRad" user interface showing a carbon-therapy treatment plan for a prostate tumour.*

The school's scientific programme highlighted the importance of developments in fundamental research for cancer diagnostics and treatment. Focusing on treatment planning, it covered everything needed to deliver a beam to a tumour target, including the biological response of cancerous and healthy tissues. The Next Ion Medical Machine Study (NIMMS) group delivered many presentations from experts and young researchers, starting from basic concepts to discussions of open points and plans for upgrades. Expert-guided practical sessions were based on the matRad open-source professional toolkit, developed by the German cancer research centre DKFZ for training and research. Several elements of the course were inspired by the International Particle Therapy Masterclasses.

Virtual visits to European heavy-ion therapy centres and research infrastructures were ranked by participants among the most exiting components of the course. There were also plenty of opportunities for participants to interact with experts in dedicated sessions, including a popular session on entrepreneurship by the CERN Knowledge Transfer group. This interactive approach had a big impact on participants, several of which were motivated to pursue careers in related fields and to get actively involved at their home institutes. This future expert workforce will become the backbone for building and operating future heavy-ion therapy and research facilities that are needed to fight cancer worldwide (see p30).

Further support is planned at upcoming HITRIplus schools on clinical and medical aspects, as well as HITRIplus internships, to optimally access existing European heavy-ion therapy centres and contribute to relevant research projects.

Yiota Foka *GSI.*

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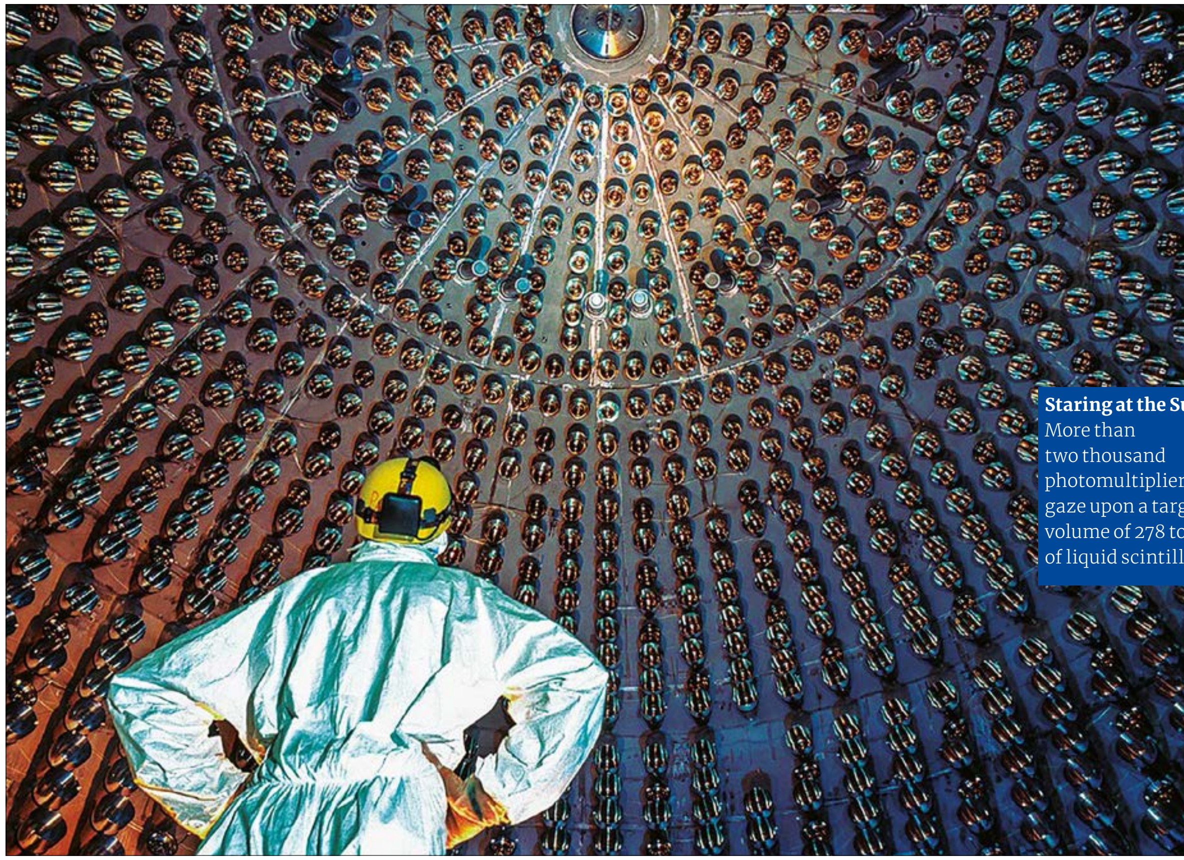


Staring at the Sun More than two thousand photomultipliers gaze upon a target volume of 278 tonnes of liquid scintillator.

HOW THE SUN AND STARS SHINE

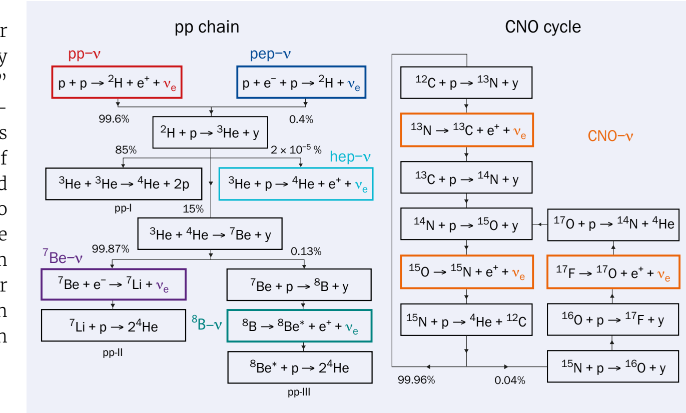
Thanks to its extraordinary radiopurity, Borexino has definitively observed the two main fusion reactions in stars and will soon weigh in on a controversy relating to the birth of the Sun that challenges the basic assumptions of the Solar Standard Model, write Gianpaolo Bellini and Aldo Ianni.

Each second, fusion reactions in the Sun's core fling approximately 60 billion neutrinos onto every square centimetre of the Earth. In the late 1990s, the Borexino experiment at Gran Sasso National Laboratory in Italy was conceived to measure these neutrinos right down to a few tens of keV, where the bulk of the flux lies. The detector's name means "little Borex" and refers to an earlier idea for a large experiment with a boron-loaded liquid scintillator, which was shelved in favour of the present, smaller and more ambitious detector. Rather than studying rare but high-energy ^{8}B neutrinos from a little-followed branch of the proton–proton (pp) fusion chain, Borexino would target the far more numerous but lower energy neutrinos produced in the Sun by electron

THE AUTHORS
Gianpaolo Bellini *Università degli Studi/INFN Milano* and **Aldo Ianni** *INFN at LNGS.*

captures on ^{7}Be (*CERN Courier* October 1998 p12).

Three decades after its conception, Borexino has far exceeded this goal thanks to the exceptional radiopurity of the experimental apparatus (see "Detector design" panel, p26). Special care taken in construction and commissioning has achieved a radiopurity about three orders of magnitude better than predicted, and 10 to 12 orders of magnitude below natural radioactivity. This has allowed the collaboration to probe the entire solar-neutrino spectrum, including not only the pp chain, but also the carbon–nitrogen–oxygen (CNO) cycle. This mechanism plays a minor role in the Sun but becomes important for more massive stars, dominating the energy production and the production of elements heavier than helium in the universe at large.



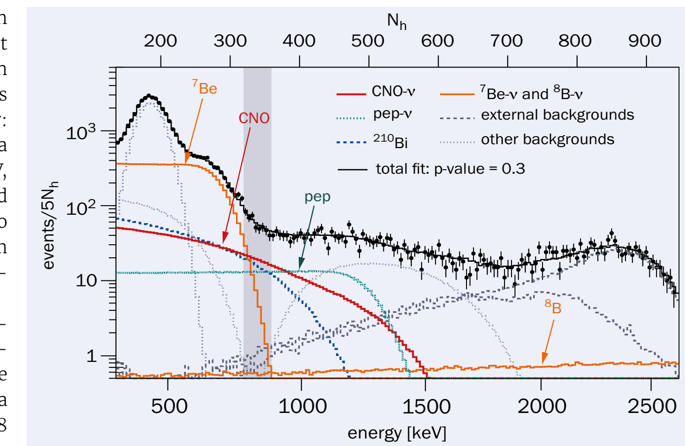
Chain and cycle *The fusion reactions generating the Sun's energy.*

The heart of the Sun

The pp-chain generates 99% of the energy in the Sun: it begins when two protons fuse to produce a deuteron and an electron neutrino – the so-called pp neutrino (see "Chain and cycle" figure). Subsequent reactions produce light elements, such as ^{3}He, ^{4}He, ^{7}Be, ^{7}Li, ^{8}B and more electron neutrinos. In Borexino, the sensitivity to pp neutrinos depends on the amount of ^{14}C in the liquid scintillator: with an end-point energy of 0.156 MeV compared with a maximum visible energy for pp neutrinos of 0.264 MeV, the $^{14}C \rightarrow {}^{14}N + \beta^- + \nu$ beta decay sets the detection threshold and the feasibility of probing pp-neutrinos. The Borexino scintillator was therefore made using petroleum from very old and deep geological layers, to ensure a low content of ^{14}C.

Since data-taking began in 2007, Borexino has measured, for the first time, all the individual fluxes produced in the pp-chain. In 2014 the collaboration made the first definitive observation of pp neutrinos, using a comparison with the predicted energy spectrum. In 2018 the collaboration performed, with the same apparatus, a measurement of all the pp-chain components (pp, ^{7}Be, pep and ^{8}B neutrinos), demonstrating the large-scale energy-generation mechanism in the Sun for the first time (see "Energy spectrum" figure). This spectral fit allowed the collaboration to directly determine the ratio between the interaction rate of ^{3}He + ^{3}He fusions and that of ^{3}He + ^{4}He fusions – a crucial parameter for characterising the pp chain and its energy production.

The simultaneous measurement of pp-chain neutrino fluxes also gave Borexino a unique window onto the famous "vacuum-matter" transition, whereby coherent virtual W-boson interactions with electrons modify neutrino-oscillation probabilities as neutrinos propagate through matter, enhancing the oscillation probability as a function of energy. In 2018 Borexino measured the solar electron-neutrino survival probability, P_{ee}, in the energy range from a few tens of keV up to 15 MeV (see "Survival probability" figure). This was the first direct observation of the transition from a low-energy vacuum regime (P_{ee}~0.55) to a higher energy matter regime where neutrino propagation is dominantly affected by the solar interior (P_{ee}~0.32). The transition was measured by Borexino at the level of 98% confidence.



Energy spectrum *Solar neutrinos and residual backgrounds (not labelled: ^{210}Po, ^{85}Kr and ^{11}C, with ^{14}C lying below the energy range shown) in Borexino, showing a multivariate fit of the energy spectrum (black). The region of greatest sensitivity to CNO neutrinos is highlighted by the grey band. N_h is the total number of photons collected for each event.*

CNO cycle

A different way to burn hydrogen, the CNO cycle, was hypothesised independently by Carl Friedrich von Weizsäcker and Hans Albrecht Bethe between 1937 and 1939. Here, ^{12}C acts as a catalyst, and electron neutrinos are produced by the beta decay of ^{13}N and ^{15}O, with a small contribution from ^{17}F. The maximum energy of CNO neutrinos is about 1.7 MeV. In addition to making an important contribution to the production of elements heavier than helium, this cycle is important for the nucleosynthesis of ^{16}O and ^{17}O. In massive stars it also develops in more complex reactions producing ^{18}F, ^{18}O, ^{19}F, ^{18}Ne and ^{20}Ne.

The sensitivity to CNO neutrinos in Borexino mainly comes from events in the energy range from 0.8 to 1 MeV. In this region, the dominant background comes from ^{210}Bi, which is produced by the slow radioactive decay $^{210}Pb\,(22y) \rightarrow {}^{210}Bi\,(5\,d) + \beta^- + \nu \rightarrow {}^{210}Po\,(138\,d) + \beta^- + \nu \rightarrow {}^{206}Pb\,(stable) + \alpha$.

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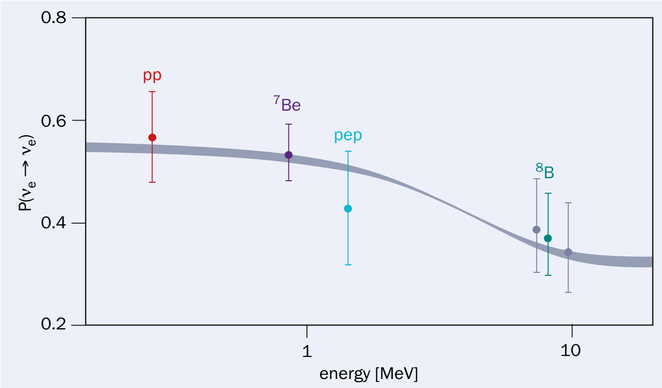


Survival probability *Solar-neutrino measurements from Borexino versus ±1σ predictions for neutrino mixing and propagation (grey curve). As the neutrino energy increases, "matter effects" enhance the oscillation probability.*

The ^{210}Bi activity can be inferred from ^{210}Po, which can be efficiently tagged using pulse-shape discrimination. However, convective currents in the liquid scintillator bring into the central fiducial mass ^{210}Po produced by ^{210}Pb, which is most likely to be embedded on the nylon containment vessel. In order to reduce convection currents, a passive insulation system and a temperature control system were installed in 2016, significantly reducing the effect of seasonal temperature variations.

Thanks to these and other efforts, in 2020 Borexino rejected the null hypothesis of no CNO reactions by more than five standard deviations, providing the first direct proof of the process (*CERN Courier* September/October 2020 p11). The energy production as a fraction of the solar luminosity was measured to be $1^{+0.4}_{-0.3}$%, in agreement with the Solar Standard Model (SSM) prediction of roughly 0.6 ± 0.1% (which assumes the solar surface has a high metallicity – a topic discussed in more detail later). Given that luminosity scales as M^4 and number density as $M^{-2.5}$ for stars between one and 10 solar masses, the CNO cycle is thought to be the most important source of energy in massive hydrogen-burning stars. Borexino has provided the first experimental evidence for this hypothesis.

But, returning to the confines of our solar system, it's important to remember that the SSM is not a closed book. Borexino's results are thus far in agreement with its assumption of a protostar that had a uniform composition throughout its entire volume when fusion began ("zero-age homogeneity"). However, thanks to the ability of neutrinos to peek into the heart of the Sun, the experiment now has the potential to explore this assumption and weigh in on one of the most intriguing controversies in astrophysics.

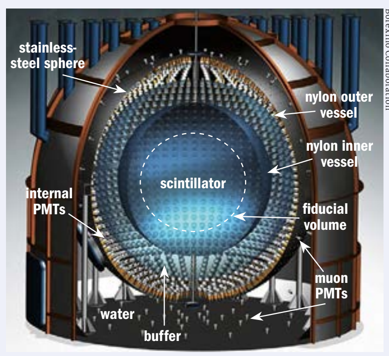
The solar-abundance controversy

As stars evolve, the distribution of elements within them changes thanks to fusion reactions and convection currents. But the composition of the surface is thought to remain very nearly the same as that of the protostar, as it is not hot enough there for fusion to occur. Measuring the abundance of elements on a star's surface therefore gives an idea of the protostar's composition and is a powerful way to constrain the SSM.

Detector design

Like many particle-physics detectors, Borexino has an onion-like design. The innermost layers have the highest radio-purity. The detector's active core consists of 278 tonnes of pseudocumene (C_9H_{12}) scintillator. Into this is dissolved 2,5-diphenyloxazole (PPO) at a concentration of 1.5 grams per litre, which shifts the emission light to 400 nm, where the sensitivity of photomultipliers is peaked. The scintillator is contained within a 125 µm-thick nylon inner vessel (IV) with a 4.5 m radius – made thin to reduce radiation emission from the nylon . In addition, the IV stops radon diffusion towards the core of the detector.

The IV is contained within a 7 m-radius stainless-steel sphere (SSS) that supports 2212 photomultipliers (PMTs) and contains 1000 tonnes of pseudocumene as high-radio-purity shielding liquid against radioactivity from PMTs and the SSS itself. Between the SSS and the IV, a second nylon balloon acts as a barrier preventing radon and its progeny from reaching the scintillator. The SSS is contained in a 2400-tonne tank



Onion design *Borexino is installed underground at Gran Sasso in Italy.*

of highly purified water which, together with Borexino's underground location, shields the detector from environmental radioactivity. The tank boasts a muon detector to tag particles crossing the detector.

When a neutrino interacts in the target volume, energy deposited by the decelerating electron is registered by a handful of PMTs. The neutrino's energy can be obtained from the total charge, and the hit-time distribution is used to infer the location of the event's vertex. Recoiling electrons are used to tag electron neutrinos, and the combination of a positron annihilation and a neutron capture on hydrogen (an inverse beta decay) are used to tag electron antineutrinos.

Due to the impossibility of discriminating individual solar-neutrino events from the backgrounds, the greatest challenge has been the reduction of natural radioactivity to unprecedented levels. In the early 1990s, Borexino developed innovative techniques such as under-vacuum distillation, water extraction, ultrafiltration and nitrogen sparging with ultra-high radiopurity nitrogen to reduce radioactive impurities in the scintillator to 10^{-10} Bq/kg or better. An initial detector called the Counting Test Facility was developed as a means to demonstrate such claims, publishing results for the key uranium, thorium and krypton backgrounds in 1995. Full data taking at Borexino began in 2007.

Currently, the best method to determine the surface abundance of elements heavier than helium ("metallicity") uses measurements of photo-absorption lines. Since 2005, improved hydrodynamic calculations (which are needed to model atomic-line formation, and radiative and collisional processes which contribute to excitation and ionization) indicate a much lower surface metallicity than was previously considered. However, helioseismology observables differ by roughly five standard deviations from SSM predictions that use the new surface metallicity to infer the protostar's composition, when the sound-speed profile, surface–helium abundance and the depth of the convective envelope are taken into account. Helioseismology implies that the zero-age Sun's core was richer in metallicity than the present surface composition, suggesting a violation of zero-age homogeneity and a break with the SSM. This is the solar-abundance controversy, which was discovered in 2005.

One possible explanation is that a late "dilution" of the Sun's convective zone occurred due to a deposition of elements during the formation of the solar system. Were there to have been an accretion of dust and gas from the proto-planetary disc onto the central star during the evolution of the star–planet system, this could have changed the initial metallicity of the surface of the Sun – a hypothesis backed up by recent simulations that show that a metal-poor accretion could produce the present surface metallicity.

As they are an excellent probe of metallicity, CNO neutrinos have an important role to play in settling the solar-abundance controversy. If Borexino were to measure the Sun's present core metallicity, and by running simulations backwards prove that its surface metallicity must have been diluted right from its birth, this would violate one of the basic assumptions of the SSM. Probing solar metallicity using CNO neutrinos is, therefore, of the utmost importance, and Borexino is hard at work on the problem. Initial results favour the high-metallicity hypothesis with a significance of 2.1 standard deviations – a tentative first hint from Borexino that zero-age homogeneity may indeed be false.

The ancient question of why and how the Sun and stars shine finally has a comprehensive answer from Borexino, which has succeeded thanks to the detector's extreme and unprecedented radio-purity – the hard work of hundreds of researchers over almost three decades. ●

Probing solar metallicity using CNO neutrinos is of the utmost importance, and Borexino is hard at work on the problem

Further reading

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LINACS TO NARROW RADIOTHERAPY GAP

A technology initiative launched at CERN to address the lack of radiotherapy in low- and middle-income countries is preparing for its first linear-accelerator prototype, write Deepa Angal-Kalinin, Graeme Burt and Manjit Dosanjh

By 2040, the annual global incidence of cancer is expected to rise by more than 42% from 19.3 million to 27.5 million cases, corresponding to approximately 16.3 million deaths. Shockingly, some 70% of these new cases will be in low- and middle-income countries (LMICs), which lack the healthcare programmes required to effectively manage their cancer burden. While it is estimated that about half of all cancer patients would benefit from radiotherapy (RT) for treatment, there is a significant shortage of RT machines outside high-income countries.

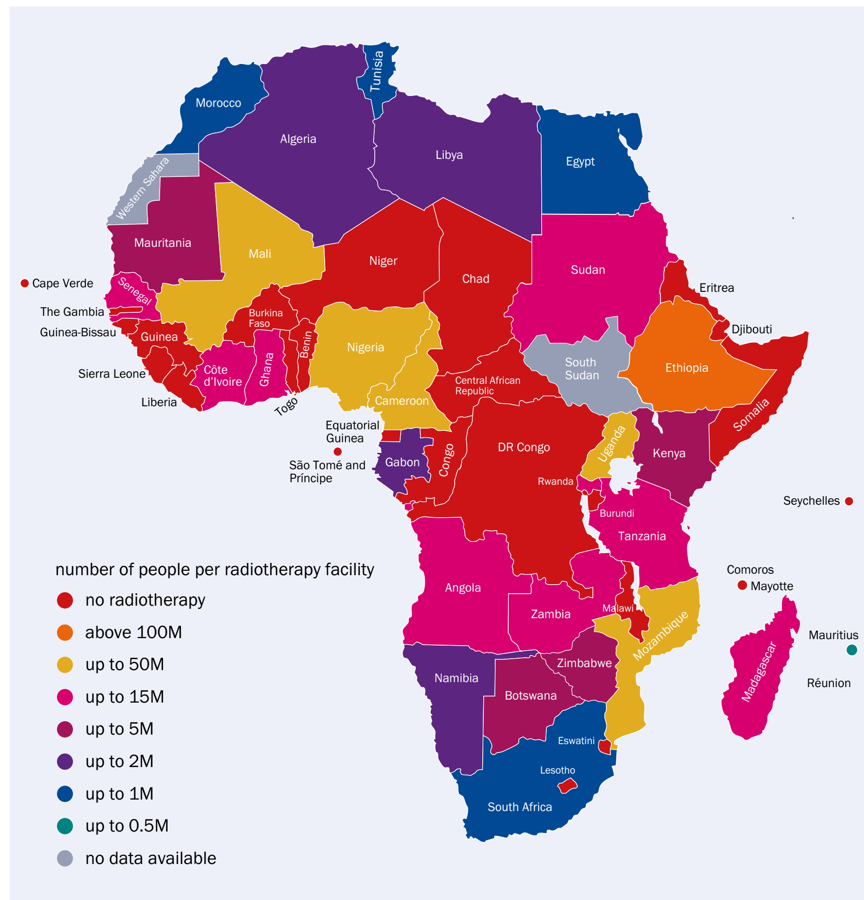
More than 10,000 electron linear accelerators (linacs) are currently used worldwide to treat patients with cancer. But only 10% of patients in low-income and 40% in middle-income countries who need RT have access to it. Patients face long waiting times, are forced to travel to neighbouring regions or face insurmountable expenditure to access treatment. In Africa alone, 27 out of 55 countries have no linac-based RT facilities. In those that do, the ratio of the number of machines to people ranges from one machine to 423,000 people in Mauritius, one machine to almost five million people in Kenya and one machine to more than 100 million people in Ethiopia (see "Out of balance" image). In high-income countries such as the US, Switzerland, Canada and the UK, by contrast, the ratio is one RT machine to 85,000, 102,000, 127,000 and 187,000 people, respectively. To draw another stark comparison, Africa has approximately 380 linacs for a population of 1.2 billion while the US has almost 4000 linacs for a population of 331 million.

Unique challenges

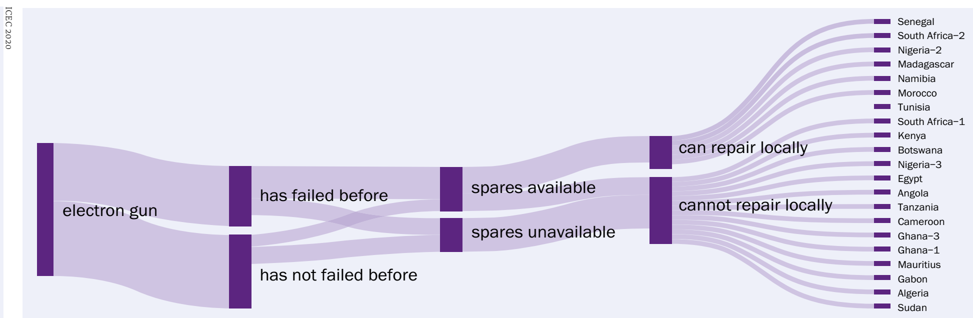
It is estimated that to meet the demand for RT in LMICs over the next two to three decades, the current projected need of 5000 RT machines is likely to become more than 12,000. To put these figures into perspective, Varian, the market leader in RT machines, has a current worldwide installation base of 8496 linacs. While many LMICs provide RT using cobalt-60 machines, linacs offer better dose-delivery parameters and better treatment without the environmental and potential terrorism risks associated with cobalt-60 sources. However, since linacs are more complex and labour-intensive to operate and maintain, their current costs are significantly higher than cobalt-60 machines, both in terms of initial capital costs and annual service contracts. These differences pose unique challenges in LMICs, where macro- and micro-economic conditions can influence the ability of these countries to provide linac-based RT.

In November 2016 CERN hosted a first-of-its-kind workshop, sponsored by the International Cancer Expert Corps (ICEC), to discuss the design characteristics of RT linacs (see "Linac essentials" image) for the challenging environments of LMICs. Leading experts were invited from international organisations, government agencies, research institutes, universities and hospitals, and companies that produce equipment for conventional X-ray and particle therapy (*CERN Courier* March 2017 p31). The following October, CERN hosted a second workshop titled "Innovative, robust and affordable medical linear accelerators for challenging environments", co-sponsored by the ICEC and the UK's Science and Technology Facilities Council, STFC (*CERN Courier* January/February 2018 p35). Additional workshops have taken place in March 2018, hosted by STFC in collaboration with CERN and the ICEC, and in March 2019, hosted by STFC in Gaborone, Botswana (see "Healthy vision" image). These and other efforts have identified substantial opportunities for scientific and technical advancements in the design of the linac and the overall RT system for use in LMICs. In 2019, the ICEC, CERN, STFC and Lancaster University entered into a formal collaboration agreement to continue concerted efforts to develop this RT system.

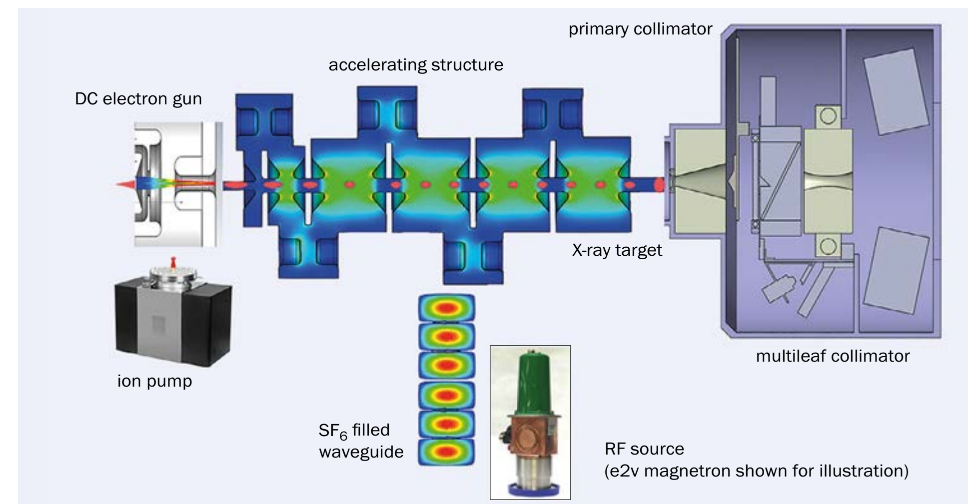
In June 2020, STFC funded a project called ITAR (Innovative Technologies towards building Affordable and equitable global Radiotherapy capacity) in partnership with the ICEC, CERN, Lancaster University, the University of Oxford and Swansea University. ITAR's first phase was aimed at defining the persistent shortfalls in basic infrastructure, equipment and specialist workforce that remain barriers to effective RT delivery in LMICs. Clearly, a linac suitable for these conditions needs to be low-cost, robust and easy to maintain. Before specifying a detailed design, however, it was first essential to assess the challenges and difficulties RT facilities face in LMICs and



Out of balance *The variation in the number of people in African countries who have access to radiotherapy facilities. For comparison, Switzerland has one radiotherapy machine for every 102,000 people. (Source: ICEC)*



Downtime *A Sankey plot revealing the difficulties of operating electron guns in certain low- and middle-income countries.*



Linac essentials *A standard medical linac comprises an electron gun, an accelerating structure, a target and a collimator. Also needed are an RF source to power the linac, a waveguide to transport the power between the linac and the RF source, and a vacuum pump to keep everything under vacuum.*

THE AUTHORS

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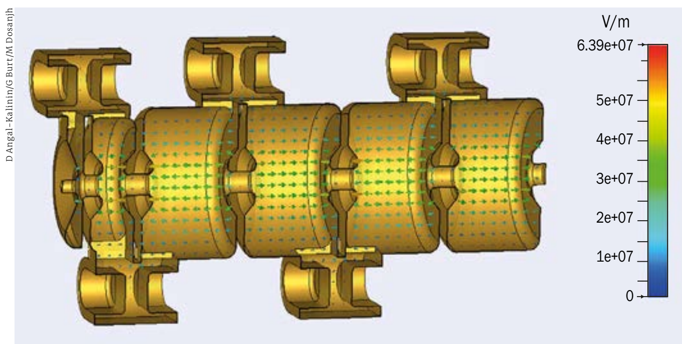
D Wendling

Healthy vision *The participants of the Designing a Robust and Affordable Radiation Therapy Treatment System for Challenging Environments workshop, which was held in Botswana in March 2019.*

D Angal-Kalinin/G Burt/M Dosanjh



Strong coupling *The ITAR linac cavity geometry showing the electric field contour map, with the short first and second cells, and strong coupling to the first cell to increase electron capture.*

in other demanding environments. Published in June 2021, an expansive study of RT facilities in 28 African countries was carried out and compared to western hospitals by the ITAR team to quantitatively and qualitatively assess and compare variables in several domains (see "Downtime" figure). The survey builds on a related 2018 study on the availability of RT services and barriers to providing such services in Botswana and Nigeria, which looked at the equipment maintenance logs of linacs in those countries and selected facilities in the UK.

Surveying the field

The absence of detailed data regarding linac downtime and failure modes makes it difficult to determine the exact impact of the LMIC environment on the performance of current technology. The ongoing ITAR design development and prototyping process identified a need for more information on equipment failures, maintenance and service shortcomings, personnel, training and country-specific healthcare challenges from a much larger representation of LMICs. A further-reaching ITAR survey obtained relevant information for defining design parameters and technological choices based on issues raised at the workshops. They include well-recognised factors such as ease and reliability of operation, machine self-diagnostics and a prominent display of impending or actual faults, ease of maintenance and repair, insensitivity to power interruptions, low power requirement and the consequent reduced heat production.

Based on the information from its surveys, ITAR produced a detailed specification and conceptual design for an RT linac that requires less maintenance, has fewer failures and offers fast repair. Over the next three years, under the umbrella of a larger project called STELLA (Smart Technologies to Extend Lives with Linear Accelerators) launched in June 2020, the project will progress to a prototype development phase at STFC's Daresbury Laboratory.

The design of the electron gun has been optimised to increase beam-capture. This has the dual advantage of reducing both the peak current required from the gun to deliver the requisite dose and "back bombardment". It also allows for simpler replacement of the electron gun's cathode by trained personnel (current designs require replacement of the full electron gun or even the full linac). Electron-beam capture is limited in medical linacs as the pulses from the electron gun are much longer in duration than the radiofrequency (RF) period, meaning electrons are injected at all RF phases. Some phases cause the bunch to be accelerated while others result in electrons being reflected back to the cathode. In typical linacs, less than 50% of electrons reach the target and many electrons reach the target with lower energies. In high-energy accelerators velocity bunching can be used to compress the bunch, however the space is limited in medical linacs and the energy gain per cell is often well in excess of the beam energy. To allow velocity bunching in a medical linac, the first cell needs to operate at a low gradient – such that less space is required to bunch as the average beam velocity is much lower and the deceleration is less than the beam energy. By adjusting the length of the first and second cells, the decelerated electrons can re-accelerate on the next RF cycle and synchronise with the accelerated electrons, capturing nearly all the electrons and transporting them to the target without a low-energy tail. This is achieved using techniques originally developed for the optimisation of klystrons as part of the Compact Linear Collider project at CERN. By adjusting cell-to-cell coupling, it is possible to make all the other cells at a higher gradient similar to a standard medical linac such that the total linac length remains the same (see "Strong coupling" figure).

The electrical power supply in LMICs can often be variable and protection equipment to isolate harmonics between pieces of equipment is not always installed, hence it is critical to consider this when designing the electrical system for RT machines. This in itself is relatively straightforward but is not normally considered as part of a RT machine design.

The failure of multi-leaf collimators (MLCs), which alter the intensity of the radiation so that it conforms to the tumour volume via several individually actuated leaves, is a major linac downtime issue. Designing MLCs that are less prone to failure will play a key role in RT in LMICs, with studies ongoing into ways to simplify the design without compromising on treatment quality.

Building a workforce

Making it simpler to diagnose and repair faults on linacs is another key area that needs improvement. Given the limited technical staff training in some LMICs, when a machine fails it can be challenging for local staff to make repairs. In addition, components that are degrading can be missed by staff, leading to loss of valuable time to order spares. An important component of the STELLA project, led by ICEC, is to enhance existing and establish new twinning programmes that provide mentoring and training to healthcare professionals in LMICs to build workforce capacity and capability in those regions.

The idea to address the need for a novel medical linac for challenging environments was first presented by Norman Coleman, senior scientific advisor to the ICEC, at the 2014 ICTR-PHE meeting in Geneva. This led to the creation of the STELLA project, led by Coleman and ICEC colleagues Nina Wendling and David Pistenmaa, which is now using technology originally developed for high-energy physics to bring this idea closer to reality – an excellent example of the impact of fundamental research on wider society.

The idea of novel medical linacs is an excellent example of the impact of fundamental research on wider society

The next steps are to construct a full linac prototype to verify the higher capture, as well as to improve the ease of maintaining and repairing the machine. Then we need to have the RT machine manufactured for use in LMICs, which will require many practical and commercial challenges to be overcome. The aim of project STELLA to make RT truly accessible to all cancer patients brings to mind a quote from the famous Nigerian novelist Chinua Achebe: "While we do our good works let us not forget that the real solution lies in a world in which charity will have become unnecessary." ●

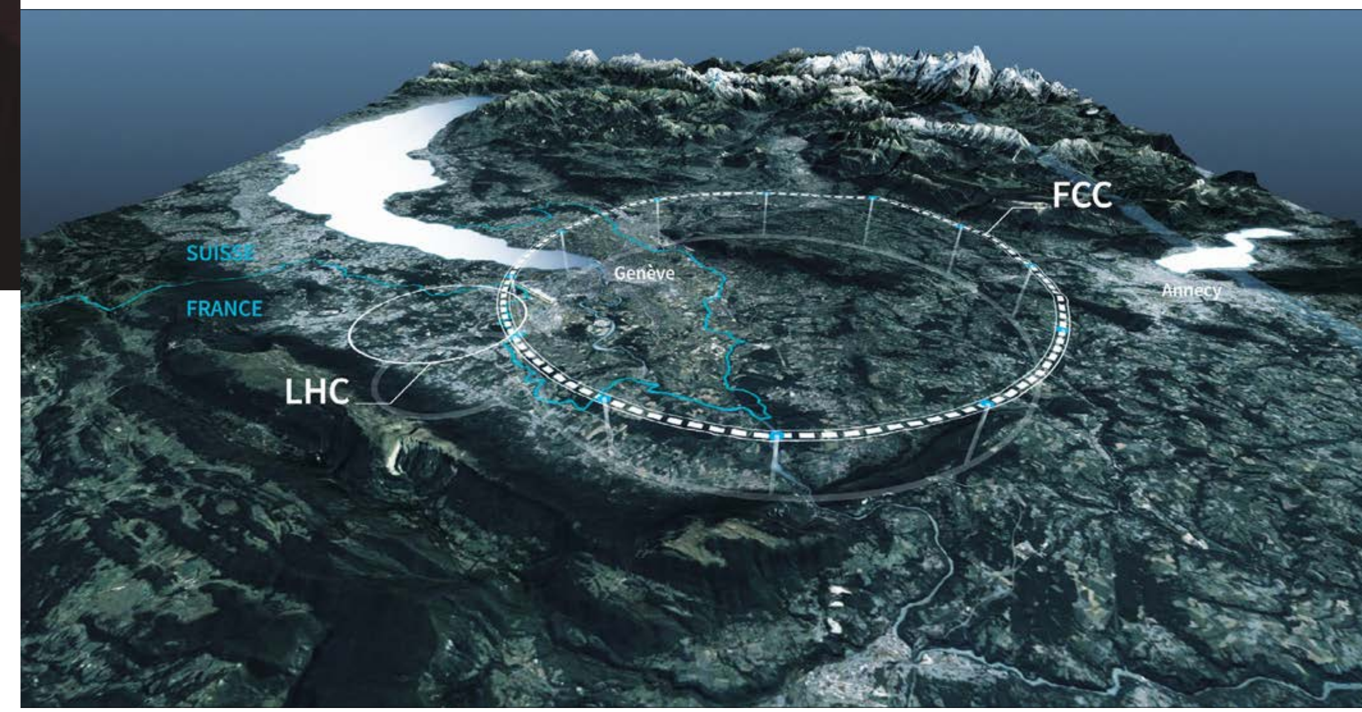
Further reading

dirac.iaea.org (International Atomic Energy Agency: Directory of Radiotherapy Centres)

T A Ige *et al.* 2021 *Clin. Oncol.* **33** e521.

EXOTIC FLAVOURS AT THE FCC

Intriguing hints of deviations from the Standard Model in the flavour sector point towards new physics accessible at a Future Circular Collider, write Andreas Crivellin and John Ellis.

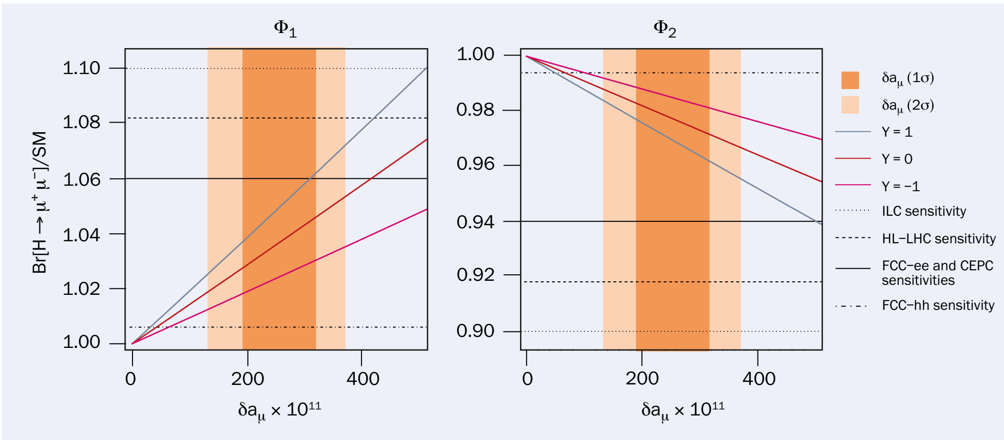


Under study *A possible layout of the Future Circular Collider at CERN, for which a feasibility study is currently under way. (Credit: CERN)*

Half a century after its construction, the Standard Model of particle physics (SM) still reigns supreme as the most accurate mathematical description of the visible matter in the universe and its interactions. It was placed upon its throne by the many precise measurements made at the Large Electron Positron collider (LEP), in particular, and its rule was confirmed by the discovery of the Higgs boson at the Large Hadron Collider (LHC). CERN's LEP/LHC success story, in which a hadron collider provided direct evidence for a new particle (the Higgs boson) whose properties were already partially established at a lepton collider, can serve as a blueprint for physics discoveries at a proposed Future Circular Collider (FCC) operating at CERN after the end of the LHC.

Back in the late 1970s and early 1980s when the LEP/LHC programme was first proposed, the W and Z bosons mediating the weak interactions had not yet been observed, the top quark was considered a possible discovery, and the Higgs boson was regarded as a distant speculation. Precise studies of the W and Z, which were discovered in 1983 at the SPS proton–antiproton collider at CERN, were key items in LEP's physics programme along with direct searches for the top quark, the Higgs boson and possible unknown particles. Even though the LEP experiments did not reveal any new particles beyond the W and Z, the unprecedented precision of its measurements revealed indirect effects (via quantum fluctuations) of the top and the Higgs, thereby providing indirect evidence for the SM

The e^+e^- stage of FCC would reproduce the entire LEP sample of Z bosons within a couple of minutes



Anomalous correlations *The branching ratio of $H \to \mu^+\mu^-$ versus new physics contributions to the anomalous magnetic moment of the muon for two different leptoquark scenarios: Φ_1 yields a constructive effect in $H \to \mu^+\mu^-$, while the one of Φ_2 is destructive such that they can be clearly distinguished at a future collider. Y is a free parameter of the model.*

mechanism of electroweak symmetry breaking. When the top quark was discovered at the Tevatron proton–antiproton collider at Fermilab in 1995, and the Higgs boson at the LHC in 2012, their masses were within the ranges indicated by precision measurements made at lepton colliders.

Nowadays, the hope is that the proposed FCC programme – comprising an electron–positron collider followed by a high-energy proton–proton collider in the same ~100 km tunnel – will repeat the LEP/LHC success story at an even higher level of precision and energy. The e^+e^- FCC stage would reproduce the entire LEP sample of Z bosons within a couple of minutes, yielding around 5×10^{12} Z bosons after four years of operation. In addition to allowing an incredibly accurate determination of the Z-boson's properties, Z decays would also provide unprecedented samples of bottom quarks (1.5×10^{12}) and tau leptons (3×10^{11}). Potential increases in the FCC-ee centre-of-mass energy would also produce unparalleled numbers of W^+W^- and top-antitop pairs, which are important for the global electroweak fit, close to their respective thresholds, as well as more Higgs bosons than promised by other proposed e^+e^- Higgs factories (*CERN Courier* January/February 2021 p23).

Probing beyond the Standard Model

Analyses of FCC-ee data, combined with results from previous experiments at the LHC and elsewhere, would not only push our understanding of the SM to the next level but would also provide powerful indirect probes of possible physics beyond the SM, with sensitivities to masses an order of magnitude greater than those of the LHC. A possible subsequent proton–proton FCC stage (FCC-hh) operating at a centre-of-mass energy of at least 100 TeV would then provide unequalled opportunities to discover this new physics directly, just as the LHC made possible the discovery of the Higgs boson following the indirect hints from high-precision LEP data. Whereas the combination of LEP and the LHC explore the TeV scale both indirectly and directly, the combination of FCC-ee and FCC-hh will carry the search for new physics to 30 TeV and beyond.

However, for this dream scenario to play out, at least one beyond-the-SM particle must exist within FCC's discovery reach. While the existence of dark matter and neutrino masses already prove that the SM cannot be complete (and there is no shortage of theoretical ideas as to what extensions of the SM could account for them), these observations can be explained by new particles within a very wide mass range – possibly well beyond the reach of FCC-hh. Fortunately, intriguing hints for new physics in the flavour sector have accumulated in recent years that point towards beyond-the-SM physics that should be accessible to FCC.

B-decay anomalies

Within the SM, the charged leptons – electrons, muons and taus – all have very similar properties. They interact with the photon as well as the W and Z bosons in the same way, and differ only in their masses, which in the SM are represented as Yukawa couplings to the Higgs boson. It is therefore said that the SM (approximately) respects lepton-flavour universality (LFU), despite the seemingly large differences in charged-lepton lifetimes originating from phase-space effects.

Flavour observables (i.e. processes resulting from rare transitions among the different generations of quarks and leptons), and observables measuring LFU in particular, are especially promising to test the SM because they are strongly suppressed in the SM and thus very sensitive to new physics. In recent years, a coherent pattern of anomalies, all pointing towards the violation of LFU, have emerged (*CERN Courier* May/June 2019 p33). Two classes of fundamental processes giving rise to decays of B mesons – $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$ – show deviations from the SM predictions.

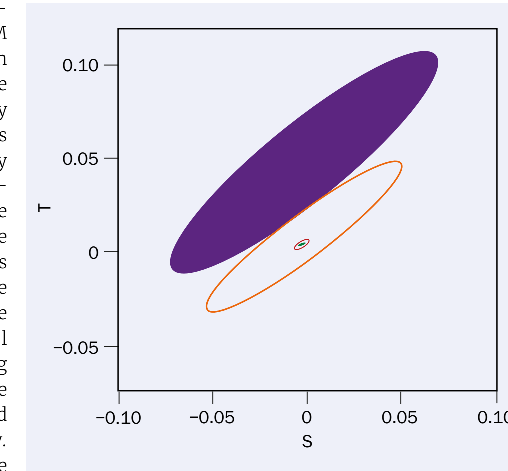
In the flavour-changing neutral-current process $b \to s\ell^+\ell^-$, a heavy bottom quark undergoes a transition to a strange quark and a pair of oppositely-charged leptons, which could be either electrons or muons. The ratios $R_K = Br(B \to K\mu^+\mu^-)/Br(B \to Ke^+e^-)$ and $R_{K^*} = Br(B \to K^*\mu^+\mu^-)/Br(B \to K^*e^+e^-)$, measured most precisely by the LHCb collaboration, are particularly interesting because their SM predictions are very clean. Since the muon and electron masses are negligible compared to the B-meson mass, the ratio of muon to electron decays should be close to unity according to the SM. However, intriguingly, LHCb has observed values significantly lower than one, and recently reported first evidence for LFU violation in R_K (*CERN Courier* May/June 2021 p17). These hints of new physics are supported by measurements of the angular observable P_5' in $B^0 \to K^{*0}\mu^+\mu^-$ decays and the rate of $B_s \to \phi\mu^+\mu^-$ decays (*CERN Courier* May/June 2020 p10). Importantly, all these observations can potentially be explained by the same new-physics interactions and are consistent with all other available measurements of processes involving $b \to s\ell^+\ell^-$ transitions. In fact, global fits of all available $b \to s\ell^+\ell^-$ data find a preference for new physics compared to the SM hypothesis which reeks of a possible discovery.

The second class of anomalies involves the charged-current process $b \to c\tau\nu$, which is already mediated at tree level in the SM. The corresponding B-meson decays therefore have much higher probabilities to occur and thus larger branching ratios. However, the non-negligible tau mass leads to imperfect cancellations of the form factors in the ratio to electron or muon final states, and thus the resulting SM prediction is not as precise as those for R_K and R_{K^*}. The most prominent examples of observables involving $b \to c\tau\nu$ transitions are the ratios $R_D = Br(B \to D\tau\nu_\tau)/Br(B \to D\ell\nu_\ell)$ and $R_{D^*} = Br(B \to D^*\tau\nu_\tau)/Br(B \to D^*\tau\nu_\ell)$. Here, the measurements of Belle, BaBar and LHCb consistently point above the SM predictions, resulting in a combined tension of 3σ. Importantly, as these processes happen quite frequently in the SM, a significant new-physics effect would be required to account for the corresponding anomaly.

With the FCC-ee capable of producing 1.5×10^{12} b quarks, clearly the b anomalies could be further verified within a short period of running, assuming that LHCb, Belle II and possibly other experiments do confirm them. The large data sample would also allow physicists to study complementary modes that bear upon LFU but are more difficult for LHCb to measure, such as other "R" measurements involving neutral kaons (see p8). These measurements would be invaluable for pinning down the mechanism responsible for any violation of lepton universality.

Other possible anomalies

The B anomalies are just one exciting avenue that a "Tera-Z factory" like FCC-ee could explore further. The anomalous magnetic moment of the muon, a_μ, can also be viewed as an exciting hint for new physics in the lepton sector. Predicted by the Dirac equation to have a value exactly equal to two, the physical value of the magnetic moment of the muon is slightly higher due to fluctuations at the quantum level. The very high precision of both the calculation and measurement therefore make it a powerful observable with which to search for new physics. A tension between the measured and predicted value of a_μ has persisted since Brookhaven published its final result in 2006, and was recently strengthened by the muon g-2 experiment at



High precision *Expected uncertainty (1σ) contour for parameters (S, T) describing the effects of new physics on precision electroweak measurements. Present limits from LHC, LEP, Tevatron, SLC and low-energy experiments (purple) are shown compared with HL-LHC expectations (orange) and the FCC-ee with present (red) and ultimate (tiny green ellipse) systematic uncertainties.*

Fermilab, yielding an overall significance of 4.2σ when combined with the earlier Brookhaven data (*CERN Courier* May/June 2021 p7).

Various models have been proposed to explain the g-2 anomaly. They include leptoquarks (scalar or vector particles that carry colour and couple directly to a quark and a lepton that arise in models with extended gauge groups) and supersymmetry. Such leptoquarks could have masses anywhere between the lower LHC limit of 1.5 TeV and about 10 TeV, thus being within the reach of FCC-hh, whereas a supersymmetric explanation would require a couple of new particles with masses of a few hundred GeV, possibly even within reach of FCC-ee. Importantly, any explanation involving heavy new particles would also lead to effects in $Z \to \mu^+\mu^-$, as both observables are sensitive to interactions with sizeable coupling strength to muons. FCC-ee's large Z-boson sample could therefore reveal deviations from the SM predictions at the suggested level. Leptoquarks could also modify the SM prediction for $H \to \mu^+\mu^-$ decay, which will be measured very accurately at FCC-hh (see "Anomalous correlations" figure).

CKM under scrutiny

As the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which describes flavour violation in the quark sector, is unitary, the sum of the squares of the elements in each row and in each column must add up to unity. This unitarity relation can be used to check the consistency of different determinations of CKM elements (within the SM) and thus also to search for new physics. Interestingly, a deficit in the first-row unitarity relation exists at the 3σ level. This can be traced back to the fact that the value of the element V_{ud}, extracted from super-allowed beta decays, is not compatible

For this dream scenario to play out, at least one beyond-the-SM particle must exist within FCC's discovery reach

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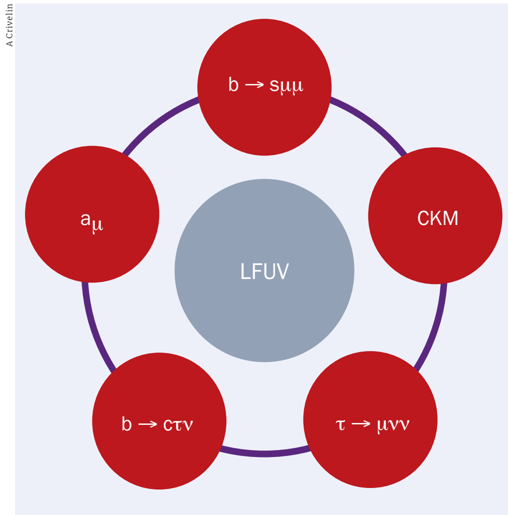

Circling in on new physics *Anomalies spanning heavy-quark decays, the CKM matrix and the anomalous magnetic moment of the muon point to possible violations of lepton-flavour universality (LFUV).*

with the value of V_{us}, determined from kaon and tau decays, given CKM unitarity. Interestingly, this deviation can also be interpreted as a sign of LFU violation, since beta decays involve electrons while the most precise determination of V_{us} comes from decays with final-state muons.

Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample (> 10^{11}) of Z decays to tau leptons.

FCC-ee's extraordinarily large dataset will also enable scrutiny of a long-standing anomaly in the forward-backward asymmetry of $Z \to b\bar{b}$ decays. The LEP measurement of ΔA_{FB}, which arises from the difference between the Z boson couplings to left- and right-handed chiral states with different strengths, lies 2–3σ below the SM prediction. Although not significant, this anomaly may also be linked to new physics entering in $b \to s$ transitions.

Finally, a possible difference in the decay asymmetries of $B \to D^* \mu\nu$ vs $B \to D^* e\nu$ was recently reported by an analysis of Belle data. As in the case of R_K, the SM prediction that the difference between the muon and the electron asymmetries should be zero is very clean and, like R_D and R_{D^*}, this observable points towards new physics in $b \to c$ transitions and could be related via leptoquarks to g–2 of the muon. Once more, the great number of b quarks to be produced at FCC-ee, together with the clean environment of a lepton collider, would allow this observable to be determined with unprecedented accuracy.

Since all these anomalies point, to varying degrees, towards the existence of LFU-violating new physics, it raises the question of whether a common explanation exists? There are several particularly interesting possibilities, including leptoquarks, new scalars and fermions (as arise in supersymmetric extensions of the SM), new vector bosons (W′ and Z′) and new heavy fermions. In the overwhelming majority of such scenarios, a direct discovery of a new particle is possible at FCC-hh. For example, it could discover leptoquarks with masses up to 10 TeV and Z′ bosons with masses up to 40 TeV, covering most of the mass ranges expected in such models.

A return to the Z pole and beyond

The LEP programme was extremely successful in determining the mechanism of electroweak symmetry breaking, in particular by measuring the properties and decays of the Z boson very precisely from a 17 million-strong sample. This allowed for a prediction of a range for the Higgs mass within which it was later discovered at the LHC. The flavour anomalies could lead to a similar situation in the near future. In this case, the roughly 5×10^{12} Z bosons that the FCC-ee is designed to collect would not only be able to test the effects of new particles in precision electroweak observables, but also, via Z decays into bottom quarks and tau leptons, provide a unique testing ground for flavour physics. As noted earlier, FCC-ee's Z-pole run is also envisaged to be the first step in a broader electroweak programme encompassing large statistics at the WW and $t\bar{t}$ thresholds, in addition to its key role as a precision Higgs factory (*CERN Courier* January/February 2021 p29).

Looking much further ahead to the energy frontier, FCC-hh would be able, in the overwhelming number of scenarios motivated by the flavour anomalies, to directly discover a new particle. Furthermore, FCC-hh would allow for a precise determination of rare Higgs decays and the Higgs potential, probing new-physics effects related to this sector, such as leptoquark explanations of the anomalous magnetic moment of the muon.

Pending the outcome of the FCC feasibility study recommended by the 2020 update of the European strategy for particle physics, the hope that the LEP/LHC success story could be repeated by FCC-ee/FCC-hh is well justified. While FCC-ee could be used to indirectly pin down the parameters of the model(s) of new physics explaining the flavour anomalies via precision electroweak and flavour measurements, FCC-hh would be capable of searching for the predicted particles directly. ●

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Further reading

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POWERING FOR A SUSTAINABLE FUTURE

CERN's transfer lines are undergoing significant renovations to make them more energy efficient while delivering high-quality beams reliably to experiments, write Konstantinos Papastergiou and Gilles Le Godec.

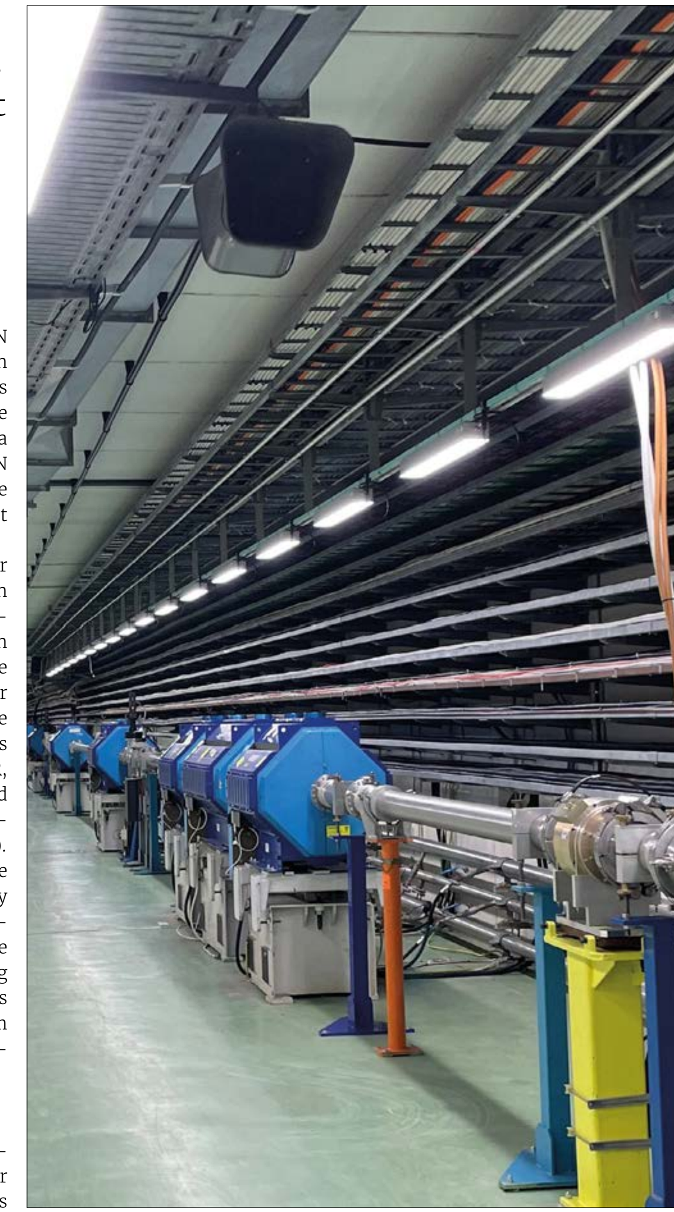
Just over 60 years ago, physicists and engineers at CERN were hard at work trying to tune the world's first proton synchrotron, the PS. It was the first synchrotron of its kind, employing the strong-focusing principle to produce higher-energy beams within a smaller aperture and with a lower construction cost compared to, for example, the CERN synchrocyclotron. Little could physicists in 1959 imagine the maze of technical galleries and tunnels stemming out of the PS ring not many years later.

The first significant expansion to CERN's accelerator complex was prompted by the 1962 discovery of the muon neutrino at the competing Alternating Gradient Synchrotron at Brookhaven National Laboratory in the US. Soon afterwards, CERN embarked on an ambitious programme starting with a new east experimental area, the PS booster and the first hadron collider – the Intersecting Storage Rings (ISR). A major challenge during this expansion was transferring the beam to targets, experiments and the ISR, which required that CERN build transfer lines that could handle different particles, different extraction energy levels and various duty cycles (see "In service" figure, p40).

Transfer lines transport particle beams from one machine to another using powerful magnets. Once fully accelerated, a beam is given an ultra-fast "kick" off its trajectory by a kicker magnet and then guided away from the ring by one or more septum magnets. A series of focusing and defocusing quadrupole magnets contain the beams in the vacuum pipe while bending magnets direct them to their new destination (a target or a subsequent accelerator ring).

Making the connection

The first transfer lines linking two different CERN accelerators were TT1 and TT2, which were originally built for the ISR. The need to handle different particle energies and even different particle charges required continuous adjustment of the magnetic field at every extraction,



Linked up *A section of the 300 m-long TT2 transfer line, which carries beams from the Proton Synchrotron to the majority of CERN's facilities.*

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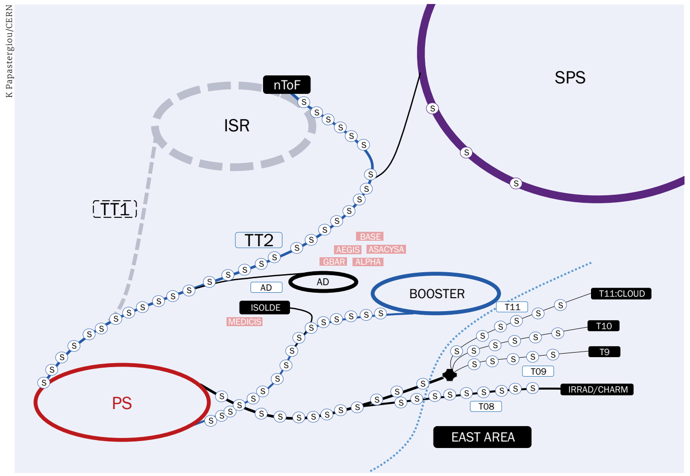
K Papastergiou/CERN



In service *The many CERN facilities and experiments whose transfer lines have been fully renovated during long shutdown 2, also showing the former ISR ring and TT1 line. "S" denotes the locations of the new power converters.*

typically once per second in the PS. One of the early challenges faced was a memory effect in the steel yokes of the magnets: alternating among different field values leaves a remnant field that changes the field density depending on the order of cycles played out before. Initially, complex solutions with secondary field-resetting coils were used. Later, magnetic reset was achieved by applying a predefined field excitation that brings the magnet to a reproducible state prior to the next physics cycle.

Solving the magnetic hysteresis problem was not the only hurdle that engineers faced. Handling rapid injections and extractions through the magnets was also a major challenge for the electronics of the time. The very first powering concept used machine/generator setups with adjustable speeds to modulate the electric current and consequently the field density in the transfer-line magnets. Each transfer line would have its own noisy generation plant that required a control room with specialised personnel (see "Early days" images). Modifying the mission-profile of a magnet to test new physics operations was a heavy and tedious operation.

Towards the end of 1960s, electrical motors in the west PS hall were replaced by the first semiconductor-operated thyristor rectifiers, which transformed the 50 Hz alternating grid voltage to a precisely regulated (to nearly 100 parts per million) current in the beamline magnets. They also occupied a fraction of the space, had lower power losses and were able to operate unsupervised. All of a sudden, transporting different particles with variable energies became possible at the touch of a knob. The timing could not have been better, as CERN prepared itself for the Super Proton Synchrotron (SPS) era, which would see yet more transfer lines added to its accelerator complex.

By the early 1980s the ISR had completed its mission, and the TT1 transfer line was decommissioned together with the storage rings. However, the phenomenal versatility of TT2 has allowed it to continue to extract particles for

CERN 222-1-70

CERN 163-1-64

Early days *The TT2 tunnel linking the PS and the ISR during installation of the beam-transfer magnets (top) and the control room of the PS south generator building (bottom).*

experiments. Today, virtually all user beams, except those for the East Area and ISOLDE, pass through the 300 m-long line. It delivers low-energy 3 GeV beams to "Dump 2" for machine development, 14 GeV beams to the SPS for various experiments in the North Area, 20 GeV beams towards the n_ToF facility, 26 GeV beams to the Antiproton Decelerator, and to the SPS – where protons are accelerated to 450 GeV before being injected into the LHC. While beams traverse TT2 in just over a microsecond, other beamlines, such as those in the East Area, spill particles out of the PS continuously for 450 ms towards the CLOUD experiment and other facilities – a process known as slow extraction.

Energy economy

Transfer lines are heavy users of electrical power, since typically their magnets are powered for long periods compared to the time it takes a beam to pass. During their last year of operation in 2017, for example, the East Area transfer lines accounted for 12% of all energy consumption by CERN's PS/PSB injector complex. The reason for this inefficiency was the non-stop powering of the few dozen magnets used in each transfer line for the necessary focusing, steering and trajectory-correction functions. This old powering system, combined with a solid-yoke magnet structure, did not permit extraction of the magnetic field energy between beam operations.

For reference, a typical bending magnet absorbs the

The East Area magnet circuits powered by the new Sirius converters consume 95% less energy than with the old 1960s rectifiers

S Neagu/Electrotel S.A.

Transformational *Some of the 144 new Sirius power converters and their electrolytic capacitors manufactured by industry and qualified at CERN.*

same energy as a high-performance car accelerating from 0 to 100 km/h, and must do so in a period of 0.5 s every 1.2 s for beams from the PS. To supply and recover all this energy between successive beam operations, powerful converters are required along with laminated steel magnet yokes, all of which became possible with the recent East Area renovation project.

Energy economy was the primary motivation for CERN to adopt the "Sirius" family of regenerative power converters for TT2 and, subsequently, the East Area and Booster transfer lines. While transfer lines typically absorb and return all the magnetic field energy from and to the power grid, the new Sirius power converter allows a more energy-efficient approach by recovering the magnetic field energy locally into electrolytic capacitors for re-use in the next physics cycle. Electrolytic capacitors are the only energy-storage technology that can withstand the approximately 200 million beam transports that a Sirius converter is expected to deliver during its lifetime, and the system employs between 15 and 420 such wine-bottle-sized units according to the magnet size and beam energy to be supplied (see "Transformational" image).

Sirius is also equipped with a front-end unit that can control the energy flow from the grid to match what is required to compensate the thermal losses in the system. By estimating in real time how much of the total energy can be recycled, Sirius has enabled the newly renovated East Area to be powered using only two large-distribution transformers rather than the seven transformers used in the past for the old 1960s thyristor rectifiers. To control the energy flow in the magnets, Sirius uses powerful silicon-based semiconductors that switch on and off 13,000 times per second. By adjusting the "on" time of the switches the average current in and out of the energy-storing units can be controlled with precision, while the high switching frequency allows rapid corrections of the generated voltage and current across the magnet.

The Sirius converters entered operation gradually from September 2020, and at present a total of 500 million magnetic cycles have been completed. Recent measurements made on the first circuits commissioned in the East Area demonstrated an energy consumption 95% lower than compared to the original 1960s figures. But above all, the primary role of Sirius is to provide current and hence magnetic field in transfer-line magnets to a precision of 10 parts per million, which enables excellent reproducibility for the beams coming down the lines. The most recent measurements demonstrated a stability better than 10 ppm during a 24-hour interval.

Unusual engineering model

CERN employs a rather unusual engineering model compared to those in industry. For Sirius, a team of experts and technicians from the electrical power converters group designed, prototyped and validated the power-converter design before issuing international tenders to procure the subsystems, assembly and testing. Engineers therefore have the opportunity to work with their counterparts in member-state industries, often helping them develop new manufacturing methods and skills. Sirius, for example, helped a magnetics-component manufacturer in Germany achieve a record precision in their manufacturing process and to improve their certification procedures for medium-power reactors. Another key partner acquired new knowledge in the manufacturing and testing of inoxidised water-cooling circuits, enabling the firm to expand its project portfolio.

Thanks to the CERN procurement process, Sirius components are built by a multitude of suppliers across Europe. For some, it was their first time working with CERN. For example, the converter-assembly contract was the first major (CHF 12 million) contract won by Romanian industry after the country's accession to CERN five years ago. Other significant contributions were made by German, Dutch,

CERN is looking at testing and implementing new systems that lower its environmental impact today and into the far future

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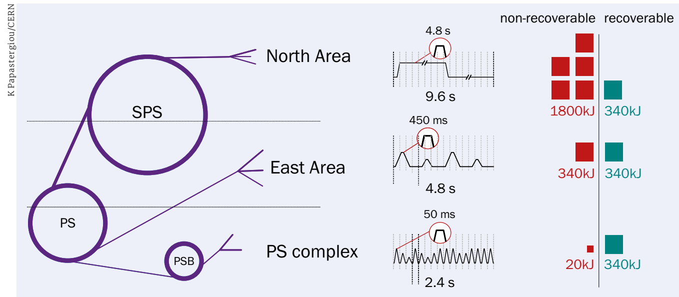

Physics cycles *The amount of thermal loss (red squares) versus recoverable energy (green squares) used by a typical magnet in three different CERN accelerator facilities. The mix of non-recoverable/recoverable energy is a function of the beam extraction time and cycle repetition frequency, also shown.*

French, UK, Danish and Swedish industries. Recent work by the CERN knowledge transfer group resulted in a contract with a Spanish firm that licensed the Sirius design for production for other laboratories, with the profits invested in R&D for future converter families.

Energy recycling tends to yield more impressive energy savings in fast-cycling accelerators and transfer lines, such as those in the PS. However, CERN is planning to deploy similar technologies in other experimental facilities such as the North Area that will undergo a major makeover in the following years. The codename for this new converter project is Polaris – a scalable converter family that can coast through the long extraction plateaus used in the SPS (see "Physics cycles" figure). The primary goal of the renovation, beyond better energy efficiency, is to restore the reliability and provide a 10-fold improvement in the precision of the magnetic field regulation.

Development efforts in the power-converters group do not stop here. The electrification of transportation and the net-zero carbon emission targets of many governments are also driving innovation in power electronics, which CERN might take advantage of. For example, wide bandgap semiconductors exhibit higher reverse-blocking capabilities and faster transitions that could allow switching at a rate of more than 40,000 Hz and therefore help to reduce size, losses and eliminate the audible noise emitted by power conversion altogether.

Another massive opportunity concerns energy storage, with CERN looking closely at the technologies driven by the battery mega-factories that are being built around the world. As part of our mission to provide the next generation of sustainable scientific facilities, as outlined in CERN's recently released second environment report, we are looking at testing and implementing new systems to lower our environmental impact today and into the far future. ●

THE AUTHORS

Konstantinos Papastergiou and **Gilles Le Godec** CERN

OPINION COMMENT

Snowmass promises bright future

We expect to emerge in July with a grand vision for the future of US high-energy physics.

AUTHORS

APS Division of Particles and Fields chair line: **Tao Han** *(2021 chair)*, **Joel Butler** *(2022 chair)*, **R Sekhar Chivukula** *(2023 chair)*, **Young-Kee Kim** *(2020 chair)*, **Priscilla Cushman** *(2019 chair)*

New heights *Snowmass, Colorado, where the final drafting session historically took place.*

Every seven to 10 years, the US high-energy-physics community comes together to re-evaluate and update its vision of the field. These wide-ranging exercises, organised by the American Physical Society (APS)'s Division of Particles and Fields (DPF) since 1982, are now known as the Snowmass Community Studies on account of the final drafting having historically taken place in Snowmass, Colorado. They include all related disciplines that contribute to elementary particle physics and welcome the participation of physicists from outside the US.

Snowmass exists to identify the physics issues that should be addressed and possible approaches to pursuing them, but we do not seek to specify which projects should be carried out. That task is accomplished by a Particle Physics Project Prioritization Panel (P5), a subpanel of the US High Energy Physics Advisory Panel (HEPAP), which uses the Snowmass output to develop programmatic priorities based on specific budget scenarios and provides recommendations to US funding agencies. Snowmass 2013 and the subsequent 2014 P5 roadmap recommended a suite of new projects, including: the HL-LHC upgrade; DUNE/LBNF; a short-baseline neutrino programme; the PIP-II proton source upgrade; the Mu2e experiment; the LSST camera and DESI; the LUX-ZEPLIN and CDMS dark-matter searches; preparation for a new cosmic-microwave-background explorer; and strong investment in R&D for future accelerators. With many of these projects now under construction, it is vital to prepare the next round of compelling US particle-physics initiatives.

In April 2020 we kicked off a new Snowmass study. Initially scheduled to conclude with a workshop at the University of Washington in Seattle in July 2021, the process was paused due to COVID-19. On 24 September, at a virtual "Snowmass Day" meeting, we declared the Snowmass process officially resumed, with the Seattle workshop scheduled for 17 to 26 July.

White papers describing ideas, proposals and projects are due by 15 March for discussion

The Snowmass 2021 study is divided into 10 "frontiers": energy; neutrino physics; rare processes and precision measurements; cosmic; theory; accelerator; instrumentation; computation; underground facilities; and community engagement. Each frontier is led by two or three conveners and is divided into between six and 11 topical groups – with community development, demographics, and diversity and inclusion addressed across all frontiers. A Snowmass early-career organisation has also been formed to assist young physicists in contributing to the process. The whole exercise is overseen by a steering group, which includes the DPF chair line, and international representation is provided by an advisory group chosen by national and regional physics societies.

Informing Snowmass 2021 are many recent results: Higgs-boson properties obtained by ATLAS and CMS; the measurement of the angle θ_{13} in the neutrino mixing matrix; evidence for anomalies in B-meson decays from LHCb; and the tension between Fermilab's measurement of muon g-2 and the Standard Model prediction. These topics will continue to be explored in current experiments. Snowmass 2021 and the latest European strategy update focus on what comes next.

Collider matters

In the Snowmass process, we collect all ideas, whether they are large or small, expensive or less so, require international collaboration or not, and are hosted in the US or elsewhere. One topic of intense interest worldwide is the next generation of colliders, both to study the Higgs boson with sub-percent level precision and to directly search for new phenomena in the multi-TeV regime. The proposed Higgs factories require some final development that could be completed in a few years, which would enable a decision on which machine to build, and the start of negotiations to fund it, as an international project. Machines to explore the multi-TeV terrain require significantly more R&D to develop and industrialise the necessary new technologies. We expect this Snowmass/P5 process to set the direction for US participation in this R&D effort and future construction projects. We also look forward to new experiments and upgrades to existing experiments in neutrino physics, rare decays and astrophysics, along with new R&D initiatives in detectors, computing, accelerators and theory.

White papers describing ideas, proposals and projects are due by 15 March 2022 for discussion at the Seattle meeting, where a draft report will be produced and then submitted to HEPAP and the APS in the fall. With hard work and good will, we expect to emerge from the Snowmass/P5 process with a grand vision for a vibrant US high-energy physics programme over the 10 years starting from 2025 and with a roadmap for large new initiatives that will come to fruition in the 2030s. Please join us and contribute your ideas to shaping our future!

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Witten reflects

Edward Witten has spent almost 50 years at the forefront of theoretical and mathematical physics. Here he describes how the LHC and other recent results have impacted his view on nature, and asks whether naturalness is still a useful guide for the field.

How has the discovery of a Standard Model-like Higgs boson changed your view of nature?
The discovery of a Standard Model-like Higgs boson was a great triumph for renormalisable field theory, and really for simplicity. By the time the LHC was operating, attempts to make the Standard Model (SM) work without an elementary Higgs field – using a dynamical mechanism instead – had become rather convoluted. It turned out that, as far as one can judge from what we have learned so far, the original idea of an elementary Higgs particle was correct. This also means that nature takes advantage of all the possible building blocks of renormalisable field theory – fields of spin 0, 1/2 and 1 – and the flexibility that that allows.

The other key fact is that the Higgs particle has appeared by itself, and without any sign of a mechanism that would account for the smallness of the energy scale of weak interactions compared to the much larger presumed energy scales of gravity, grand unification and cosmic inflation. From the perspective that my generation of particle physicists grew up with (and not only my generation, I would say), this is quite a shock. Of course, we lived through a somewhat similar shock a little over 20 years ago with the discovery that the expansion of the universe is accelerating – something that is most simply interpreted in terms of a very small but positive cosmological constant, the energy density of the vacuum. It seems that the ideas of naturalness that we grew up with are failing us in at least these two cases.

B Lacombe/Breakthrough Prize

Trendsetter *Edward Witten, Charles Simonyi professor at the Institute for Advanced Study, Princeton, on the occasion of the award of the 2012 Breakthrough Prize in Fundamental Physics.*

What about new approaches to the fine-tuning problem such as the relaxion or "Nnaturalness"?
Unfortunately, it has been very hard to find a conventional natural explanation of the dark energy and hierarchy problems. Reluctantly, I think we have to take seriously the anthropic alternative, according to which we live in a universe that has a "landscape"of possibilities, which are realised in different regions of space or maybe in different portions of the quantum mechanical wavefunction, and we inevitably live where we can. I have no idea if this interpretation is correct, but it provides a yardstick against which to measure other proposals. Twenty years ago, I used to find the anthropic interpretation of the universe upsetting, in part because of the difficulty it might present in understanding physics. Over the years I have mellowed. I suppose I reluctantly came to accept that the universe was not created for our convenience in understanding it.

> **It seems that the ideas of naturalness that we grew up with are now failing us**

Which experimental paths should physicists prioritise at this time?
It is extremely important to probe the twin mysteries of the cosmic acceleration and the smallness of the electroweak scale as thoroughly as possible, in order to determine whether we are interpreting the facts correctly and possibly to discover a new layer of structure. In the case of the cosmic acceleration, this means measuring as precisely as we can the parameter w (the ratio of pressure and energy), which equals –1 if the acceleration of the expansion is governed by a simple cosmological constant, but would be greater than –1 in most alternative models. In particle physics, we would like to probe for further structure as precisely as we can both indirectly, for example with precision studies of the Higgs particle, and hopefully directly by going to higher energies than are available at the LHC.

What might be lurking at energies beyond the LHC?
If it is eventually possible to go to higher energies, I can imagine several possible outcomes. It might become rather clear that the traditional idea of naturalness is not the whole story and that we have on our hands a "bare" Higgs particle, without a mechanism that would account for its mass scale. Alternatively, we might find out that the apparent failure of naturalness was an illusion and that additional particles and forces that provide an explanation for the electroweak scale are just beyond our current experimental reach. There is also an intermediate possibility that I find fascinating. This is that the electroweak scale is not natural in the customary sense, but additional particles and forces that would help us understand what is going on exist at an energy not too much above LHC energies. A fascinating theory of this

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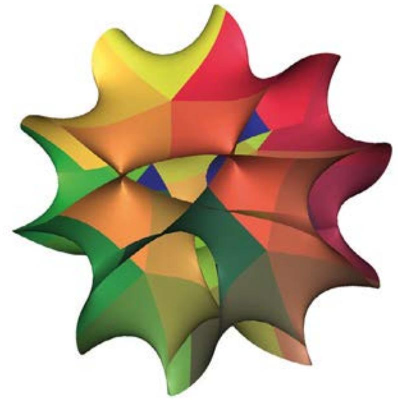
type is the "split supersymmetry" that has been proposed by Nima Arkani-Hamed and others.

There is an obvious catch, however. It is easy enough to say "such-and-such will happen at an energy not too much above LHC energies". But for practical purposes, it makes a world of difference whether this means three times LHC energies, six times LHC energies, 25 times LHC energies, or more. In theories such as split supersymmetry, the clues that we have are not sufficient to enable a real answer. A dream would be to get a concrete clue from experiment about what is the energy scale for new physics beyond the Higgs particle.



A J Hanson

Higher plane *6D Calabi–Yau manifolds, on which the extra dimensions of string theory are conjectured to be "compactified", exhibit powerful symmetries that Witten helped uncover.*

Could the flavour anomalies be one such clue?
There are multiple places that new clues could come from. The possible anomalies in b physics observed at CERN are extremely significant if they hold up. The search for an electric dipole moment of the electron or neutron is also very important and could possibly give a signal of something new happening at energies close to those that we have already probed. Another possibility is the slight reported discrepancy between the magnetic moment of the muon and the SM prediction. Here, I think it is very important to improve the lattice gauge theory estimates of the hadronic contribution to the muon moment, in order to clarify whether the fantastically precise measurements that are now available are really in disagreement with the SM. Of course, there are multiple other places that experiment could pinpoint the next energy scale at which the SM needs to be revised, ranging from precision studies of the Higgs particle to searches for muon decay modes that are absent in the SM.

Which current developments in theory are you most excited about?
The new ideas about gravity and quantum mechanics that go under the rough title "It from qubit" are really exciting. Black-hole thermodynamics was discovered in the 1970s through the work of Jacob Bekenstein, Stephen Hawking and others. These results were fascinating, but for several decades it seemed to me – rightly or wrongly – that this field was evolving only slowly compared to other areas of theoretical physics. In the past decade or so, that is clearly no longer the case. In large part the change has come from thinking about "entropy" as microscopic or fine-grained von Neumann entropy, as opposed to the thermodynamic entropy that Bekenstein and others considered. A formulation in terms of fine-grained entropy has made possible new statements and more general statements which reduce to the traditional ones when thermodynamics is valid. All this has been accelerated by the insights that come from holographic duality between gravity and gauge theory.

How different does the field look today compared to when you entered it?
It is really hard to exaggerate how the field has changed. I started graduate school at Princeton in September 1973. Asymptotic freedom of non-abelian gauge theory had just been discovered a few months earlier by David Gross, Frank Wilczek and David Politzer. This was the last key ingredient that was needed to make possible the SM as we know it today. Since then there has been a revolution in our experimental knowledge of the SM. Several key ingredients (new quarks, leptons and the Higgs particle) were unknown in 1973. Jets in hadronic processes were still in the future, even as an idea, let alone an experimental reality, and almost nothing was known about CP violation or about scaling violations in high-energy hadronic processes, just to mention two areas that developed later in an impressive way.

Not only is our experimental knowledge of the SM so much richer than it was in 1973, but the same is really true of our theoretical understanding as well. Quantum field theory is understood much better today than was the case in 1973. There really is no comparison.

Exploring the string-theory framework has led to a remarkable series of discoveries

Perhaps equally dramatic has been the change in our understanding of cosmology. In 1973, the state of cosmological knowledge could be summarised fairly well in a couple of numbers – notably the cosmic-microwave temperature and the Hubble constant – and of these only the first was measured with any reasonable precision. In the intervening years, cosmology became a precision science and also a much more ambitious science, as cosmologists have learned to grapple with the complex processes of the formation of structure in the universe. In the inhomogeneities of the microwave background, we have observed what appear to be the seeds of structure formation. And the theory of cosmic inflation, which developed starting around 1980, seems to be a real advance over the framework in which cosmology was understood in 1973, though it is certainly still incomplete.

Finally, 50 years ago the gulf between particle physics and gravity seemed unbridgeably wide. There is still a wide gap today. But the emergence in string theory of a sensible framework to study gravity unified with particle forces has changed the picture. This framework has turned out to be very powerful, even if one is not motivated by gravity and one is just searching for new understanding of ordinary quantum field theory. We do not understand today in detail how to unify the forces and obtain the particles and interactions that we see in the real world. But we certainly do have a general idea of how it can work, and this is quite a change from where we were in 1973. Exploring the string-theory framework has led to a remarkable series of discoveries. This well has not run dry, and that is one of the reasons that I am optimistic about the future.

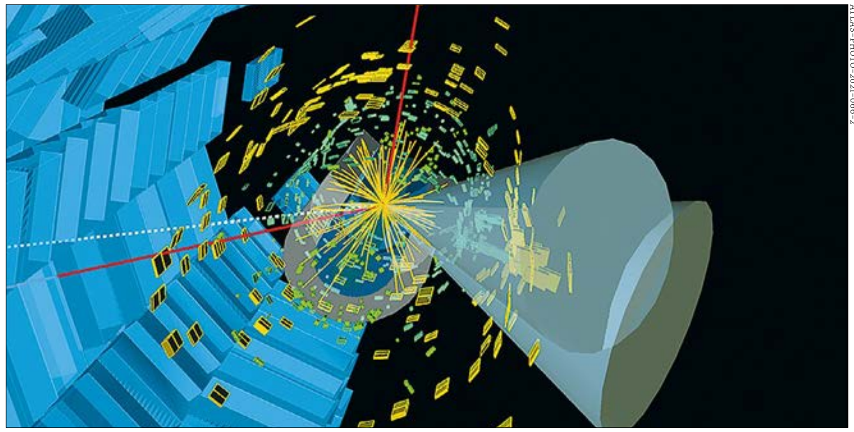
Which of the numerous contributions you have made to particle and mathematical physics are you most proud of?
I am most satisfied with the work that I did in 1994 with Nathan Seiberg on electric-magnetic duality in quantum field theory, and also the work that I did the following year in helping to develop an analogous picture for string theory.

Who knows, maybe I will have the good fortune to do something equally significant again in the future.

Interview by **Matthew Chalmers**.

Ideas not equations

The Ideas of Particle Physics, fourth edition
By J E Dodd and B Gripaios
Cambridge University Press

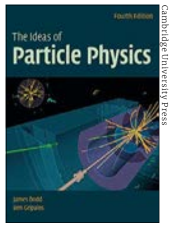


ATLAS-PHOTO-2021-066-2

Unfolding physics *A candidate WWW event in the ATLAS detector.*

When it was first published in 1984, James E Dodd's *The Ideas of Particle Physics* used very little maths, but was full of clear and concise explanations – a strong contrast with the few other reference books that were available at the time. The first edition was written prior to the start of LEP, just after the discovery of the W and Z bosons. The fourth edition, published in 2021, brings it up to date while keeping its signature style.

At the time of my PhD, 30 years ago, Dodd's book was revolutionary and helped me enormously. Over the years I have recommended it to countless students, to complement lectures and internet resources. But I had not looked at the updated versions until now. In keeping with the original, the new edition states explicitly that it is not a textbook: it contains no mathematical derivations, and no complicated formulae are written down. This is not at all to say that it is an easy read – it is not! But Dodd and Ben Gripaios, who joins the original author for this expanded fourth edition, convey the beauty of fundamental physics, and some of the phrases border on poetic: "Viewed picturesquely, it is as if the world of physical reality conducts itself while hovering over an unseen sea of negative-energy electrons."



Cambridge University Press

The second half of the updated book follows on from where the first edition left off. Precision measurements at LEP and the discovery of the gauge bosons and the top quark are all described with the same excitement and eye for beauty as the earlier discoveries. However, the LHC receives fewer words than the World Wide Web, with its almost five-decades-long journey reduced to a couple of milestones. The hunt for the Higgs boson is also glossed over and fails to capture the excitement of the past couple of decades. More problematically, the description of the role the Higgs boson plays in spontaneous symmetry breaking is muddled.

The latter chapters redeem the text by detailing many of the theories that have arisen over the past 30 to 40 years, and how they may address the many remaining questions in fundamental physics. Indeed, while the first edition perhaps gave the impression that there was not much more to learn about the universe, the fourth edition shows how little we understand, and gives good pointers to where we may find answers.

As a tome on the evolutionary nature of particle physics, with concepts rather than mathematics at the forefront, *The Ideas of Particle Physics* remains an excellent book, predominantly aimed at graduate students, as a complement to courses and other reference works.

Dave Barney *CERN.*

Copenhagen
By Michael Frayn
Performed at the ADC theatre, Cambridge, UK

"But why?" asks Margrethe Bohr. Her husband, Niels, replies "Does it matter my love now that we're all three of us dead and gone?" Alongside Werner Heisenberg, the trio look like spirits meeting in an atemporal dimension, maybe the afterlife, under an eerie ring of light. Dominating an almost empty stage, they try to revive what happened on one day in September 1941, when Heisenberg, a prominent figure in Hitler's Uranverein (Uranium Club), travelled to Nazi-occupied Denmark to visit his former mentor, Niels Bohr.

The three actors orbit like electrons in an atom

Why did Heisenberg go to meet Bohr that day? Did he seek an agreement not to develop the bomb in Germany? Was he searching for intelligence on Allied progress? To convince Bohr that there was no German programme? Or to pick Bohr's brain on atomic physics? Or, according to Margrethe, to show off? Perhaps his motives were a superposition of all of these. No one knows what was said. This puzzle has intrigued historians ever since.

Eighty years after that meeting, and 23 since Michael Frayn's masterwork *Copenhagen* premiered at the National Theatre in London, award-winning director Polly Findlay and Emma Howlett in her professional directorial debut have revived a play that contains little action but much physics and food for thought.

Frayn's nonlinear script is based on three possible versions of the same meeting in Copenhagen in 1941, which can be construed as three different scenarios playing out in the many-worlds ▷

interpretation of quantum mechanics. He describes it as the process of rewriting a draft of a paper again and again, trying to unlock more secrets. In the afterlife, the trio's dialogue jumps back and forth in time, adding confusing memories and contradicting hypotheses. Delivered at pace, the narrative explores historical information and their personal stories.

The three characters reflect on how German scientists failed to build the bomb, even though they had the best start; Otto Hahn, Lise Meitner and Fritz Strassmann having discovered nuclear fission in 1939. But Frayn highlights how Hitler's Deutsche Physik was hostile to so-called Jewish physics and key Jewish physicists, including Bohr, who later fled to Los Alamos in the US. Frayn's Heisenberg reveals the disbelief he felt when he learnt about the destruction of Hiroshima on the radio. At the time he was detained in Farm Hall, not far from this theatre in Cambridge in the UK, together with other members of the Uranium Club. Called Operation Epsilon, the bugged hall was used by the Allied forces to try to uncover the state of Nazi scientific progress.

The three actors orbit like electrons in an atom, while the theatre's revolving stage itself spins. Superb acting by Philip Arditti and Malcolm Sinclair elucidates an extraordinary student–mentor relationship between Heisenberg and Bohr. The sceptical Mrs Bohr (Haydn Gwynne) steers the conversation and questions their friendship, cajoling Bohr to speak in plain language. Nevertheless, the use of scientific jargon could leave some non-experts in the audience behind.

Although Heisenberg wrote in his autobiography that "it would be better to stop disturbing the spirits of the past," the private conversation between the two physicists has stirred the interest of the public, journalists and historians for years. In 1956 the journalist Robert Jungk wrote in his debated book, *Brighter than a Thousand Suns*, that Heisenberg wanted to prevent the development of an atomic bomb. This book was also an inspiration for Frayn's play. More recently, in 2001, Bohr's family released some letters that Bohr wrote and never sent to Heisenberg. According to these letters, Bohr was convinced that Heisenberg was building the bomb in Germany.

To this day, the reason for Heisenberg's visit to Copenhagen remains uncertain, or unknowable, like the properties of a quantum particle that's not observed. The audience can only imagine what really happened, while considering all philosophical interpretations of the fragility of the human species.

Letizia Diamante *University of Cambridge.*

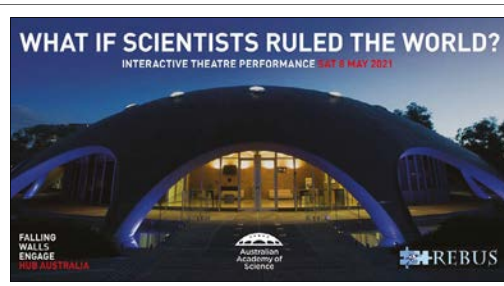

Winchester Today

One day in September *The ghosts of Niels Bohr, Werner Heisenberg and Margrethe Bohr discuss the infamous 1941 meeting in Copenhagen.*

What if scientists ruled the world?

Directed by Ali Clinch and Robin Davidson

The Shine Dome, Canberra



Falling Walls Engage

A chemistry professor invents a novel way to produce chemical compounds, albeit with a small chance of toxicity. A paper is published. A quick chat with a science communicator leads to a hasty press release. But when the media picks up on it, the story is twisted.

What if scientists ruled the world? – a somewhat sensational but thought-provoking title for a play – is an interactive theatre production by the Australian Academy of Science in partnership with Falling Walls Engage. Staged on 8 May at the Shine Dome in Canberra, Australia, a hybrid in-person/online performance explored the ramifications of an ill-considered press release, and provided a welcome opportunity for scientists to reflect on how best to communicate their research. The dynamic exchange of ideas between science experts and laypeople in the audience highlighted the power of words, and how they are used to inform, persuade, deceive or confuse.

After setting the scene, director Ali Clinch invited people participating remotely on Zoom and via a YouTube livestream to guide the actors' actions, helping to advance and reframe the storyline with their ideas, questions and comments. Looking at the same story from different points of view invited the audience to think about the different stakeholders and their responsibility in communicating science. In the first part of the performance, for example, the science communicator talks excitedly about her job with students, but later has to face a crisis that the busy professor is unable or unwilling to deal with. At a critical point in the story, when a town-hall meeting is held to debate the future of a company that employs most of the people in the town, but which probably produced the same toxic chemical, everybody felt part of the performance. The audience could even take the place of an actor, or act in a new role.

The play highlighted the pleasures and tribulations of work at the interface between research and public engagement during euphoric discoveries and crisis moments alike, and has parallels both with the confusion encountered during the early stages of the COVID-19 pandemic and misguided early fears that the LHC could generate a black hole. In an age of fake news, sensationalism and misinformation, the performance adeptly highlighted the complexities and vested interests inherent in science communication today.

Letizia Diamante *University of Cambridge.*

Harnessing the LHC network

The fifth LHC Career Networking event saw former LHC physicists lend their advice on securing a top job outside of the field, reports Connie Potter.


I Kostiuk/LHCb Collaboration

Pivoting *Moderated by Connie Potter, former LHC researchers offer tips to those considering a career move.*

On 15 November, around 260 physicists gathered at CERN (90 in person) to participate in the 2021 LHC Career Networking event, which is aimed at physicists, engineers and others who are considering leaving academia for a career in industry, non-governmental organisations and government. It was the fifth event in a series that was initially limited to attendance only by members of LHC experiments but which, in light of its strong resonance within the community, is now open to all.

Former members of the LHC experiments were invited to share their experiences of working in fields ranging from project management at the Ellen MacArthur Foundation, to consultants like McKinsey and pharmaceutical companies such as Boehringer Ingelheim. They spoke movingly of the difficulties of leaving academia and research, the introspection they experienced to discover the path that was right for them, and the sense of satisfaction and happiness they felt in their new roles.

Adjusting to new environments

Following a supportive welcome from Joachim Mnich, CERN director for research and computing, and Marianna Mazzilli, a member of the ALICE collaboration and chair of the organising committee, the first speaker to take to the stage in the main auditorium was Florian Kruse. Florian was a physicist on the LHCb experiment who, upon leaving CERN, decided to set up his own data-science and AI company called Point 8 – a throwback from many years spent commuting to the LHCb pit at LHC Point 8. His company has grown from three to 20 staff members, some ex-CERN, and continues to expand. Setting the tone for the evening, he talked about what to expect when interacting with industry, how people view CERN physicists and where and how adjustments have to be made to adapt to a new environment – advising participants to "recalibrate your imposter syndrome" and "adjust to other audiences".

Julia Hunt, a former CMS experimentalist, shared a personal insight into her journey out of academia. "I was aiming for a job somewhere near the mountains or the sea, environmental, with less screen time but still using my skills," she said, revealing that she fortuitously came across sailor Ellen MacArthur's TED talk and soon landed the job of project manager at the Ellen MacArthur Foundation.

The field of data science has welcomed numerous former CERN physicists, among them ex-ATLAS members Max Baak and Till Eifert, former CMS and ALICE member Torsten Dahms, ex-CMS member Iasonas Topsis-Giotis and ex-ALICE member Elena Bruna. Max gave a mini-course in bond trading at ING bank, while Iasonas put a positive spin on his long search for a job by saying that each interview or application taught him essential lessons for the next application, eventually landing him a job as a manager at professional services company Ernst & Young in Belgium. In a talk titled "19 years in physics… and then?", Torsten shared the sleepless nights he endured when deliberating whether to continue in a field that had him relocate himself and his family five times in 15 years, ultimately turning down a tenure-track position in 2019.

Elena, who despite having a permanent position left the field in 2018 to become a data scientist at Boehringer Ingelheim, highlighted the differences between physics (where data structures are usually designed in advance and data are largely available) and data science (where the value of data is not always known *a priori*, and tends to be more messy), and indicated areas to highlight on a data-science CV. These include keeping it to a maximum of two pages and emphasising skills and tools, including big-data analysis, machine-learning techniques, Monte Carlo simulations and working in international teams. The topic of CVs came up repeatedly, a key message being that physicists must modify the language used in academic applications because people "outside" just don't understand our terminology.

Two networking breaks, held in person and accompanied by beer, wine and pizza for those who were present and via Zoom breakout rooms for remote participants, were alive with questions and discussion. Former ATLAS member Till Eifert was surrounded by physicists eager to learn more about his role as a specialist consultant with McKinsey in Geneva, speaking passionately about the renewable energy, cancer diagnostics and decarbonisation projects he has worked on. Head of CERN alumni relations Rachel Bray and her team were on hand to answer a multitude of questions about the CERN Alumni programme.

Emphasising the power of such events, speaker Anthony Nardini from entrepreneurial company On Deck cited a 2017 Payscale survey which found that 70–85% of jobs come through networking. Following up from the event on Twitter, he offered takeaways for all career "pivoters": craft and prioritise your guiding principles, such as industry, job function, company stage/size/mission; create a daily information-gathering practice so that you are reading the same newsletters, articles and Twitter feeds as those in your target roles; identify and contact "pathblazers" in your target organisations who understand your background; and do the work to pitch how your unique skillset can help a startup to grow.

All the speakers gave their time and contact details for follow-up questions and advice.

The overall message was that, while the transition out of academia can be hard, CERN's brand recognition in certain fields helps enormously. Use your connections and have confidence!

Connie Potter *CERN.*

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Appointments and awards

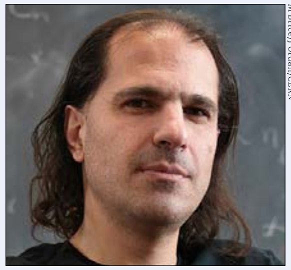
2022 APS awards

The American Physical Society (APS) W K H Panofsky Prize in Experimental Particle Physics has been awarded to Byron G Lundberg and Regina Abby Rameika (Fermilab), Kimio Niwa (Nagoya University) and Vittorio Paolone (University of Pittsburgh) "for the first direct observation of the tau neutrino through its charged-current interactions in an emulsion detector". Lundberg, Rameika (below), Niwa and Paolone were leaders of the DONUT collaboration, which in July 2000 reported evidence of four tau neutrino interactions (with an estimated background of 0.34 events) in a sample of 203

R Hahn

neutrino–nucleus interactions, consistent with the Standard Model expectation. Although earlier experiments had produced convincing indirect evidence for the ν_τ existence, the DONUT/Fermilab result represented the first direct observation.

The 2022 J J Sakurai Prize for Theoretical Particle Physics has been awarded to Nima Arkani-Hamed (Institute for Advanced Study) for the development of transformative new frameworks for physics beyond the Standard Model "with novel experimental signatures, including work on large extra dimensions, the Little Higgs, and more generally for new ideas connected to the origin of the electroweak scale". One of the leading particle phenomenologists of his generation, Arkani-Hamed (pictured top) has argued that the extreme weakness of gravity relative to other forces of nature might be explained by the existence of extra spatial dimensions, and how the structure



M Brice/J Ordan/CERN

of comparatively low-energy physics is constrained within the context of string theory.

In the field of accelerators, the Robert R Wilson Prize has been given to Fermilab's William G Foster and Stephen D Holmes for leadership in developing the modern accelerator complex at Fermilab, enabling the success of the Tevatron and rich programmes in neutrino physics. In 2008, Foster was elected to the US Congress to represent the people of Illinois, while Holmes was director of the PIP-II project when he retired in 2018 after 35 years at Fermilab.

In nuclear theory, the Herman Feshbach Prize was granted to David B Kaplan (University of Washington) for multiple foundational innovations in lattice quantum chromodynamics, effective field theories and nuclear strangeness, and for strategic leadership to broaden participation between nuclear theory and other fields.

Finally, the Henry Primakoff Award for early career researchers goes to ATLAS researcher Benjamin Nachman (below, Lawrence Berkeley National Laboratory) for his innovative use of machine learning to search for new physics in collider data and for the effective communication of these new techniques to the broader physics community.

Dr Max Liu

Distinguished career service

Fermilab director Nigel Lockyer has been honoured with the Distinguished Career Service Award by the US Department of Energy (DOE) "for his dedication and service to the DOE and the US nation". Lockyer has led Fermilab since 2013, during which international projects including the Deep Underground Neutrino Experiment and PIP-II have entered construction. In September, Fermilab announced that Lockyer will be stepping down from the role in spring 2022.

Mustafa prizes

An ATLAS researcher and a leading theorist are among the winners of the 2021 Mustafa prize, which recognises researchers from the Islamic world. Yahya Tayalati (below, Mohammed V University, Rabat) was cited for his contributions to searches for magnetic monopoles and his work on light-by-light scattering, which was observed by ATLAS in 2019, and Cumrun Vafa (Harvard) was recognised for developing a branch of string theory called F-theory. Among other laureates, M Zahid Hasan (Princeton) was cited for his work on Weyl-fermion semimetals and topological insulators. This

Y Tayalati and Hayward photography

year is the first time that the prize has been awarded to researchers in fundamental science, with each recipient winning $500,000.

2021 Otto Hahn prize

Klaus Blaum, director at the Max Planck Institute for Nuclear Physics in Heidelberg, has been awarded the 2021 Otto Hahn Prize for "his pioneering work for broad areas of atomic, nuclear and particle physics, especially for the test of the fundamental forces of nature in the microcosm". Blaum is a former CERN fellow and project leader for mass spectrometry of exotic nuclei at ISOLDE's ISOLTRAP facility. Established in 2005 by the German chemical and physical societies, the €50,000 prize is awarded every two years.

BASE researcher recognised

The 2021 dissertation award of the German Physical Society's SAMOP section (atoms, molecules, quantum optics and plasmas) has been awarded to Peter Micke (below) from the

PTB

national metrology institute Physikalisch-Technische Bundesanstalt. Now a senior research fellow at CERN applying these award-winning methods to precision antiproton measurements at the BASE experiment, Micke was recognised for his dissertation and lecture "Quantum Logic Spectroscopy of Highly Charged Ions", which describes a cutting-edge spectroscopy technique applied for the first time to highly charged ions for novel optical clocks and searches for new physics.

Data-science appointment

The American Family Insurance Data Science Institute at the University of Wisconsin-Madison has appointed ATLAS researcher Kyle Cranmer of New York University as its new director. Created in July 2019, the institute exists "to advance discoveries that benefit society through data science research, the translation of fundamental research into practical applications and collaboration across disciplines". Starting on 1 July 2022, the appointment sees Cranmer return to his alma mater, also joining Wisconsin-Madison's department of physics with an affiliate appointment in statistics.

RECRUITMENT

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Fermilab

PEOPLES FELLOWSHIP 2022 (ASSOCIATE SCIENTIST)

The Fermilab Peoples Fellowship attracts outstanding early-career scientists both to enhance Fermilab's capabilities in accelerator science and related technologies, and to train and develop the scientists who will carry the field forward in the future. Peoples Fellows are entry-level accelerator physicists, specialists in accelerator technologies, and high energy physics post-doctoral researchers who wish to embark on a new career in accelerator physics or technology.

Peoples Fellows have extraordinary latitude in choosing their research activities and are provided significant research support. Current areas of research interest at Fermilab include (but are not limited to): optical stochastic cooling, high intensity proton beams, high intensity neutrino sources, muon storage rings, superconducting magnets, superconducting RF, linear colliders, high luminosity hadron colliders, beam-beam effects and their compensation, accelerator controls and feedback, high power target stations, and computational physics and modeling.

Interested candidates are encouraged to review the qualifications and apply at
https://academicprogramsonline.org/ajo/fellowship/20502

Additional information is available at
http://www.fnal.gov/pub/forphysicists/fellowships/john_peoples/index.html.

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PEOPLE OBITUARIES

Graham Ross 1944–2021

A deep and original thinker

Graham Ross, a distinguished Scottish theorist who worked mainly on fundamental particle physics and its importance for the evolution of the universe, passed away suddenly on 31 October 2021.

Born in Aberdeen in 1944, Graham studied physics at the University of Aberdeen, where he met his future wife Ruth. In 1966 he moved to Durham University where he worked with Alan Martin on traditional aspects of the strong interactions for his PhD. His first postdoctoral position began in 1969 at Rutherford Appleton Laboratory (RAL). It was around the time that interest in gauge theories began to flourish, for which he and Alex Love were among the first to investigate the phenomenology. He continued working on this theme after he moved to CERN in 1974 for a two-year fellowship. Among the papers he wrote there was one in 1976 with John Ellis and Mary Gaillard suggesting how to discover the gluon in three-jet events due to "gluestrahlung" in electron–positron annihilation. This proposal formed the basis of the experimental discovery of the gluon a few years later at DESY.

After CERN, Graham worked for two years at Caltech, where he participated in a proof of the factorisation theorem that underlies the application of perturbative QCD to hard-scattering processes at the LHC. He then returned to the UK, to a consultancy at RAL held jointly with a post at the University of Oxford, where he was appointed lecturer in 1984. Here he applied his expertise on QCD in collaborations with Frank Close, Dick Roberts and also Bob Jaffe, showing how the evolution of valence quark distributions in heavy nuclei are in effect rescaled relative to what is observed in hydrogen and deuterium.

Wadham College

Graham was a pillar of Oxford's particle theory group.

This work hinted at an enhanced freedom of partons in dense nuclei.

In 1992 Graham became a professor at Oxford, where he remained for the rest of his career as a pillar of the theoretical particle-physics group, working on several deep questions and mentoring younger theorists. Among the many fundamental problems he worked on was the hierarchical ratio between the electroweak scale and the Planck or grand-unification scale, suggesting together with Luis Ibañez that it might arise from radiative corrections in a supersymmetric theory. The pair also pioneered the calculation of the electroweak mixing angle in a supersymmetric grand unified theory, obtaining a result in excellent agreement with subsequent measurements at LEP. Graham wrote extensively on the hierarchy of masses of different matter particles, and the mixing pattern of their weak interactions, with Pierre Ramond in particular, and pioneered phenomenological string models of particles and their interactions. In recent years, Graham worked on models of inflation with Chris Hill, his Oxford colleagues and others.

Among his formal recognitions were his election as fellow of the Royal Society in 1991 and his award of the UK Institute of Physics Dirac Medal in 2012. The citation is an apt summary of Graham's talents: "for theoretical work developing both the Standard Model of fundamental particles and forces, and theories beyond the Standard Model, that have led to new insights into the origins and nature of the universe".

Graham had a remarkable ability to think outside the box, and to analyse new ideas critically and systematically. His work was characterised by a combination of deep thought, originality and careful analysis. He was never interested in theoretical speculation or mathematical developments for their own sakes, but as means towards the ultimate end of understanding nature.

Many theoretical physicists are competitive and pursue their ambitions aggressively. But this was not Graham's way. Pursuing his ambitions with persistence and good humour, he was greatly admired as a talented physicist but also universally liked and admired, particularly by the many younger physicists whom he mentored at Oxford. He was a great teacher and an inspiration, not just to his formal students but also his daughters, Gilly and Emma, and latterly his grandchildren, James, Charlie and Wilfie.

John Ellis *King's College London/CERN*, **Frank Close** *and* **Subir Sarkar** *University of Oxford.*

Sheldon Stone 1946–2021

Few equals in heavy-quark physics

Sheldon Stone, who passed away on 6 October, was one of the foremost physicists of his generation. In terms of creativity and productivity he had few equals in heavy-quark physics worldwide. His skills in leadership, physics analysis and instrumentation served our field well.

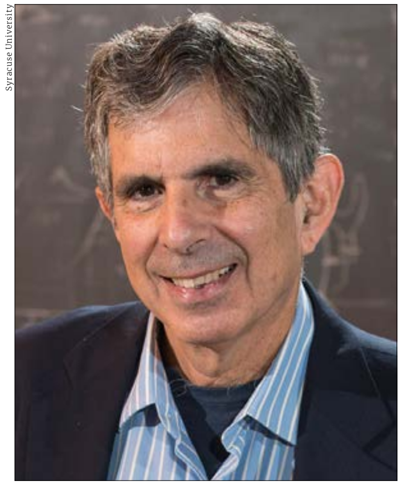
Sheldon had a central role in the success of the CLEO experiment at the Cornell Electron Storage Ring, which over a period of almost 30 years laid the foundations for our current understanding of heavy-flavour physics. He served as both CLEO analysis coordinator and co-spokesperson, and had a leading role in many important discoveries such as the observation of the B^+, B^0 and D_s mesons. In 2000 he was one of the intellectual leaders who proposed to convert CLEO into a charm factory, subsequently leading the measurement of the charm-decay constants f_{D+} and f_{Ds}. These and other measurements demonstrated the applicability of lattice-QCD calculations of hadronic effects in the weak decays of hadrons with a heavy quark with precision of a few percent, thereby enabling similar calculations to be used with confidence to interpret key measurements by other flavour-physics experiments worldwide.

In 2005 Sheldon became a member of the LHCb collaboration, where his and his group's contribution to the physics exploitation of the experiment was second-to-none. Prominent examples include the first measurement of the beauty-production cross-section at the LHC, and a series of publications measuring ▷

CP-violating observables in time-dependent decays of B_s mesons. In 2015 LHCb published the first observation of structures consistent with five-quark resonances – "pentaquarks", which were predicted at the dawn of the quark model but had evaded discovery for more than 50 years until Sheldon and a small team of colleagues uncovered their existence in the LHCb dataset. This result has had an enormous impact on the field of hadron spectroscopy.

Sheldon also led the design and construction of the novel and high-performance detectors underpinning CLEO's outstanding physics output. These include a thallium-doped near-4π caesium-iodide calorimeter (the first application of a precision electromagnetic calorimeter to a general-purpose magnetic spectrometer) and a ring-imaging Cherenkov counter providing four-sigma kaon–pion separation over the full accessible momentum range.

His advocacy of the BTeV project at Fermilab was also vital in making the case for a forward flavour-physics detector at a hadron collider. This led him to be heavily involved in shaping phase one of the LHCb upgrade project, serving as upgrade coordinator for three years during the preparation of the letter of intent, and recently in making innovative proposals for the phase-two upgrade. At the time of his passing, Sheldon was deputy project leader of the upstream tracker, a project that he and his group proposed and led for a decade, and is currently undergoing final assembly. This silicon-strip-based detector will play an essential role in both the triggering and offline event reconstruction from Run 3.


Syracuse University

Sheldon Stone was distinguished professor of physics at Syracuse University.

Exceptionally effective at guiding others both junior and senior, Sheldon was a superb mentor to graduate students and a wonderful person to collaborate with. He was known to have a strong personality. He was direct and honest, and if you won his respect he was a tremendous friend.

Sheldon's contributions to our field were at the highest level, recognised most recently with the American Physical Society Panofsky Prize in 2019. For more than 30 years he also formed a formidable scientific and life partnership with physicist Marina Artuso, who survives him.

His friends and colleagues.

GENNADY ZINOVJEV 1941–2021

A founding member of ALICE

Gennady Zinovjev, a prominent theorist in the field of quantum chromodynamics (QCD) and the physics of strongly-interacting matter, a pioneer in experimental studies of relativistic heavy-ion collisions and a leader of the Ukraine–CERN collaboration, passed away on 19 October 2021 at the age of 80. In a career spanning more than 50 years, Genna, as he was known to most of his friends, made important theoretical contributions to many different topics, ranging from analytical and perturbative QCD to phenomenology, and from hard probes and photons to hadrons and particle chemistry. His scientific activities were concentrated around experimental facilities at CERN and the Joint Institute for Nuclear Research (JINR), Dubna. He was one of the key initiators of the NICA complex at JINR, played a pivotal role in Ukraine becoming an Associate Member State of CERN in 2016 and was one of the founding members of the ALICE collaboration.

Born in 1941 in Birobidzhan (Russian Far East), in 1963, Zinovjev graduated from Dnepropetrovsk State University, a branch of Moscow State University. From 1964 to 1967 he studied at the graduate school of the Laboratory of Theoretical Physics of JINR, after which he spent a year at the Institute of Mathematics and Computer Science of the Academy of Sciences of the Moldavian SSR (Kishinev now Chisinau). He was awarded a PhD in physics and mathematics in 1975 at the Dubna Laboratory of Theoretical Physics and then joined the Kiev Institute for Theoretical Physics (both now the Bogolyubov Institute for Theoretical Physics) of the National Academy of Sciences of Ukraine, firstly as a staff member and then, from 1986, as head of the department of high-energy-density physics. In 2006 he was awarded the Certificate of Honour of the Verkhovna Rada (Parliament) of Ukraine, and in 2008 was awarded the Davydov Prize of the National Academy of Sciences of Ukraine becoming a member of the Academy in 2012.


T Nayak

Gennady Zinovjev pioneered the Ukraine–CERN collaboration.

In the mid-1990s Zinovjev initiated Ukraine's participation in ALICE, and soon started to play a key role in the conception and construction of the Inner Tracking System (ITS), and more generally in the creation of both the ALICE experiment and the collaboration. Overcoming innumerable practical and bureaucratic obstacles, he identified technical and technological expertise within the Ukrainian academic and research environment, and then managed and led the development and fabrication of novel ultra-lightweight electrical substrates for vertex and tracking detectors. These developments, which took place at the Kharkiv Scientific Research Technological Institute of Instrument Engineering, resulted in technologies and components that formed the backbone of the ITS 1 and ITS 2 detectors. He was the deputy chair of the ALICE collaboration board from 2011 to 2013 and also served as a member of the ALICE management board during that time.

Genna was one of those rare people who are equally comfortable with theory, experiment, science, politics and human interactions. He was a passionate scientist, deeply committed to the Ukrainian scientific community. He did not hesitate to make great personal sacrifices to pursue what he considered important for science, his students and colleagues. Equally influential was his prominent role as a teacher and mentor for a steady stream of talent, both experimentalists and theorists. Many of us in the heavy-ion physics community owe him a great deal. We will always remember him for his charismatic personality, great kindness, openness and generosity.

His friends and colleagues in the ALICE collaboration.

JÜRGEN HANS GARLEF KÖRNER 1939–2021

Devoted to baryon phenomenology

Jürgen G Körner, a well-known German theoretical physicist at the Johannes Gutenberg University in Mainz, passed away after a brief illness on 16 July 2021 at the age of 82.

Jürgen was born in Hong Kong in 1939, as the fourth child of a Hamburg merchant's family. After the family returned to Germany in 1949, he attended the secondary school in Blankenese and studied physics at the Technical University of Berlin and the University of Hamburg. He received his PhD from Northwestern University, Illinois, in 1966 under Richard Capps. He then held research positions at Imperial College London, Columbia University, the University of Heidelberg and DESY. He completed his habilitation at the University of Hamburg in 1976.


S Groote

Jürgen Körner in discussion with Carlo Becchi at the 1996 Triangle School on Particle Physics, Prague.

In 1982 Jürgen became a professor of theoretical particle physics at Johannes Gutenberg University, where he remained for the rest of his career. His research interests included the phenomenology of elementary particles, heavy-quark physics, spin physics, radiative corrections and exclusive decay processes. He made pioneering contributions to the heavy-quark effective theory with applications to exclusive hadron decays. He also studied mass and spin effects in inclusive and exclusive processes in the Standard Model, and developed the helicity formalism describing angular distributions in exclusive hadron decays. Jürgen's other notable contributions include the Körner–Pati–Woo theorem providing selection rules for baryon transitions and a relativistic formalism for electromagnetic excitations of nucleon resonances.

Jürgen collaborated with theoretical physicists worldwide and published about 250 papers in leading physics journals, including several influential reviews on the physics of baryons. He also contributed to the development of strong relations between German and Russian particle physicists. Together with colleagues from the Joint Institute for Nuclear Research, Dubna, and leading German and Russian universities he initiated a series of international workshops on problems in heavy-quark physics (Dubna: 1993–2019, Bad Honnef: 1994 and Rostock: 1997).

Jürgen was a cheerful person, attentive to the needs of his colleagues and friends, and always ready to help. He liked to travel and was actively involved in sports, especially football and cycling. Despite various commitments, he always found time for discussions. He cherished good conversations about physics and made a lasting impact on our lives. We will always remember him.

His friends and colleagues worldwide.

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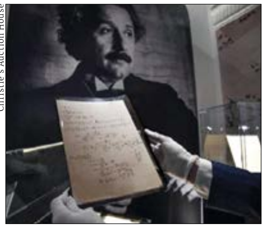
BACKGROUND

Notes and observations from the high-energy physics community

Relativity in demand


Christie's Auction House

Einstein's notes on general relativity fetched a record €11.6 million at auction in Paris on 23 November. The 54-page manuscript was handwritten in 1913 and 1914 in Zurich by Einstein and his colleague and confidant, Swiss engineer Michele Besso. Auction house Christie's said it was thanks to Besso that the manuscript was preserved for posterity.

Degrees of stardom


Haneke Twins

Art Garfunkel has a masters in mathematics education from Columbia. Brian May has a PhD in astrophysics from Imperial. No big deal. Post-punk/dark-rock band Haneke Twins, who have just signed a record deal with The Animal Farm Music in London, have five PhDs between them. The group met through CERN's music club, began writing original material in 2018, and have since released an EP and a mini-LP. Vocalist Paschalis Vichoudis works on the ATLAS level-1 central trigger (L1CT) and the CMS high-granularity calorimeter (HGCAL). Bassist Paul Aspell also works on the HGCAL, and drummer Aimilianos Koulouris on the L1CT. Guitarist Stefanos Leontsinis works on the CMS inner tracker and guitarist Andrés Delannoy on its beam radiation, instrumentation and luminosity system. "Physics may not have made it (yet!) to any of our lyrics, but definitely monopolises the discussions in between the rehearsals," says Paschalis.

Media corner

"Everything is science fiction until someone does it, and then all of a sudden it goes from impossible to inevitable."

Bob Mumgaard, chief executive of Commonwealth Fusion Systems, quoted in *The Wall Street Journal* (1 December) about the firm raising more than $1.8 billion.

"The closer we get to the real world, the fewer tools we have and the less we understand the rules of the game."

Cosmologist **Daniel Baumann** quoted in *Quanta* (10 November) on the fundamental laws.

"Given the power of our new detector and its prime location at CERN, we expect to be able to record more than 10,000 neutrino interactions in the next run of the LHC."

FASER project co-leader **David Casper** discussing the first neutrino candidates detected at the LHC on *Phys.org* (26 November).

"This is an important paper in that it's highlighting part of the ditch-digging of neutrino physics that doesn't make it to the front very often."

Neutrino physicist **Daniel Cherdack** on a recent *Nature* paper questioning our ability to reconstruct incident neutrino energies from lepton–nucleus collisions (*Physics World* 1 December).

From the archive: January/February 1982

What goes around comes around...


CERN 266.11.81

The 40 ton UA5 streamer chamber dangles in the air 50 m below ground as UA2 moves into position in the CERN SPS ring.

Proton–antiproton collisions in the CERN SPS at 540 GeV total energy are the highest collision energies ever reached under controlled conditions. First experiments taking data in the summer were the UA1 calorimeter, the UA5 streamer chamber, and the UA4 'Roman pots'. UA5 was then removed and UA2 was shifted into place, recording its first data in December. A luminosity of 5×10^{27} $cm^{-2}s^{-1}$ was attained towards the end of 1981. Data amassed so far is meagre by high energy physics experiment standards, but copious in cosmic ray terms. Nothing totally unexpected has been seen at 540 GeV, but these are early days.

The project to build a large electron–positron storage ring, LEP, at CERN already had the backing of the twelve CERN Member States, but three votes remained subject to conditions. At a CERN Council meeting in December this 'ad referendum' was lifted by the Netherlands, Norway and Sweden. The LEP project thus has the un-conditional support of all Member States. Meanwhile the LEP project team has continued to work on the optimization of the designs for the machine components and of the location of the underground LEP ring itself.

- Based on text from p3 and p20 of *CERN Courier* January/February 1982.

Compiler's note

"Early days" indeed at the SPS. In January 1983 the discovery of W and Z bosons was announced, earning Rubbia and van der Meer the Nobel Prize in Physics the following year. The discovery gave enormous impetus to LEP, which started operations in the summer of 1989, in parallel with the Stanford Linear Collider at SLAC. Two high-energy electron–positron colliders in service at the same time? A golden age of precision electroweak measurements was underway.

290 T/s

The fastest ramping rate ever achieved for an accelerator magnet, obtained using high-temperature superconductors by a team at Fermilab seeking to develop advanced fast-cycling magnets for the proposed Future Circular Collider and other future facilities (arXiv:2111.06459)

Correction

Advacam, mentioned in the context of CERN's Medipix technology (July/August 2021 p5), is a spinout from the Institute of Experimental and Applied Physics of the Czech Technical University in Prague (IEAP-CTU), not CERN.