WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2021 issue of *CERN Courier*.

As data volumes surge, deep learning is becoming increasingly important in particle physics. This special edition on artificial intelligence (AI) captures two new trends: using "unsupervised" deep learning to spot anomalous events, and designing AI that can "think not link". Community-organised data challenges are leading the way (p27) and deep learning could even be used in the level-one triggers of LHC experiments (p31). To keep up with the cutting edge of AI research, physicists are reaching out to computer science and industry (p36): the latest developments could help explore theory space (p51) and build trust in AI to do more of the heavy lifting throughout the analysis chain (p49). We also explore recent thinking that an ordered simplicity may emerge from the complexity of deep learning in a similar way to statistical mechanics and quantum field theory (p39).

Elsewhere in the issue: a tribute to Steven Weinberg (p65); a SciFi upgrade for LHCb (p43); reports from the summer conferences (p19); the most stable tetraquark yet (p7); quantum gravity in the Vatican (p59); anisotropies point to cosmic-ray origins (p11); and much more.

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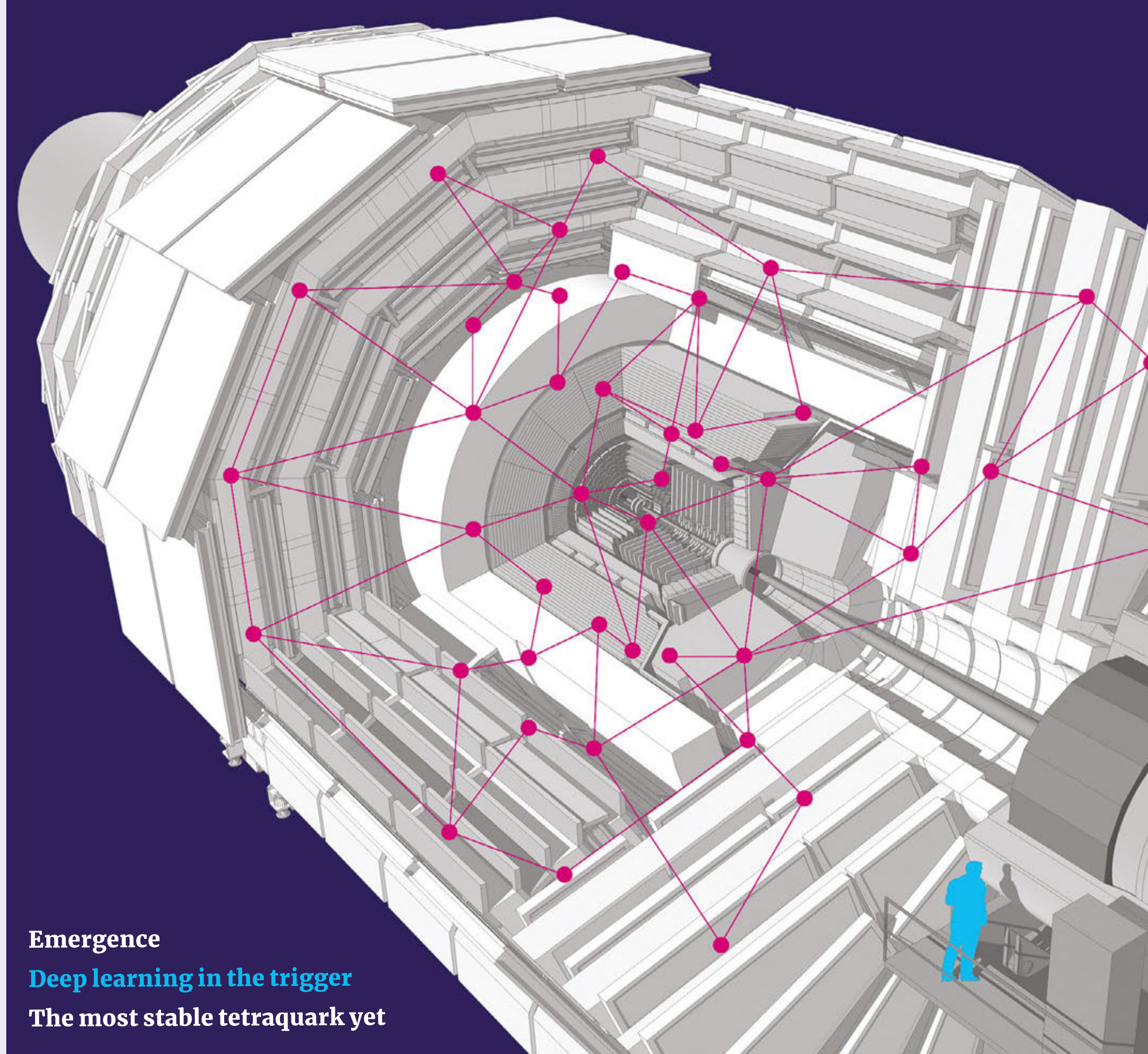
ARTIFICIAL INTELLIGENCE



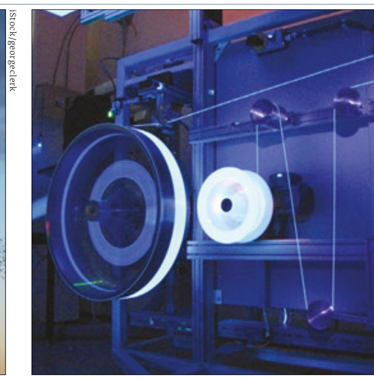
Emergence
Deep learning in the trigger
The most stable tetraquark yet

IN THIS ISSUE

Volume 61 Number 5 September/October 2021

AI leaders *Experts weigh in on what's next in the world of artificial intelligence.* **36**

Order in complexity *A surprising link between theoretical physics and AI research.* **39**



SciFi upgrade *LHCb prepares for a luminous future.* **43**

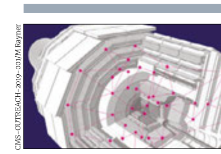
NEWS

PEOPLE

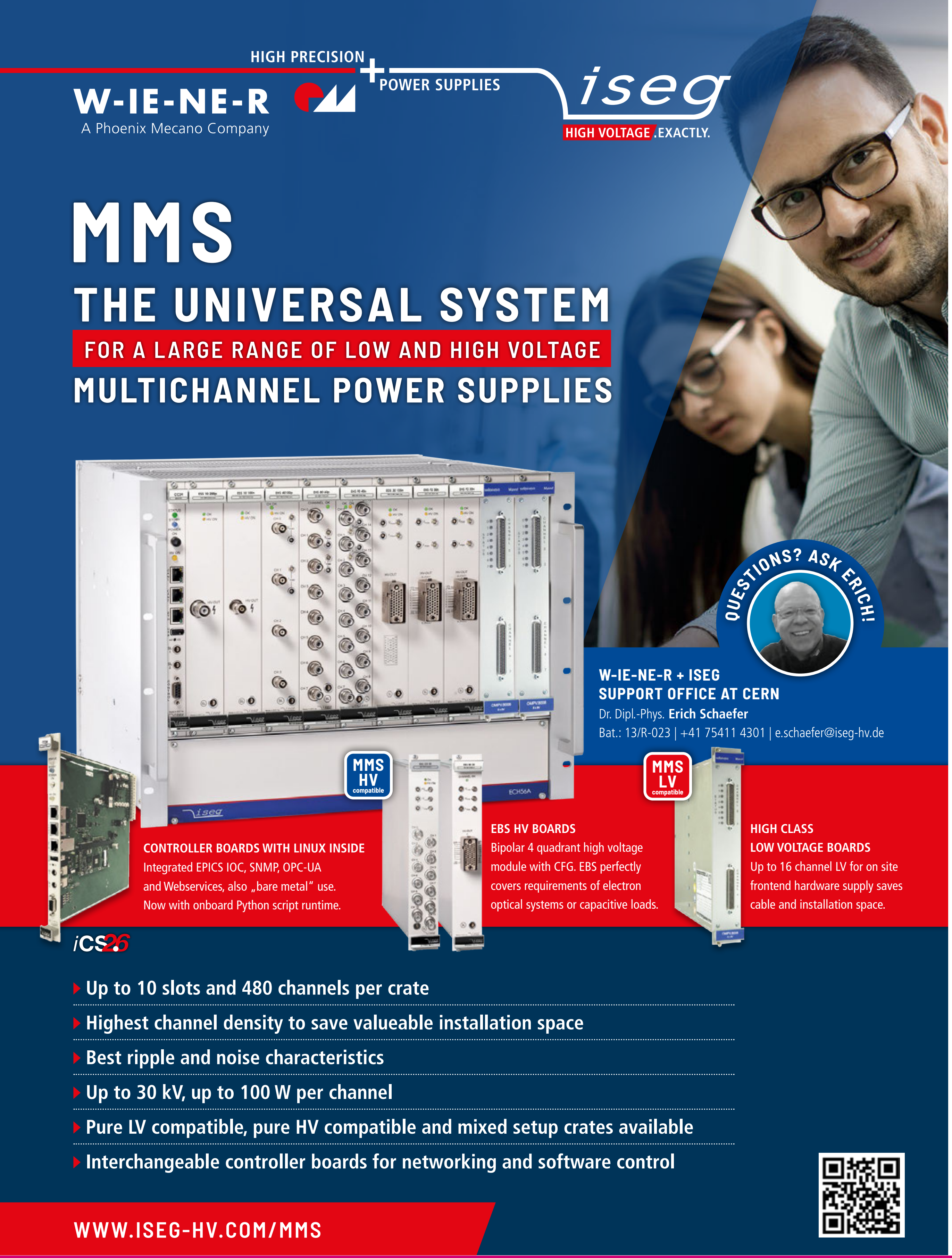
FEATURES

OPINION

DEPARTMENTS



On the cover: *How deep learning could help find new physics at the LHC.* **31**



FROM THE EDITOR

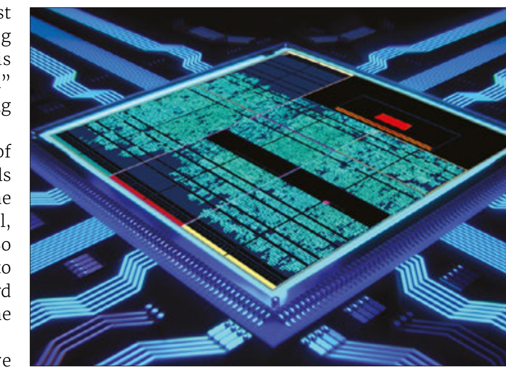
New trends in AI for particle physics

Mark Rayner
Deputy editor

Deep learning has transformed the world over the past decade. As data volumes surge, it is also growing in importance in high-energy physics (HEP). This special edition captures two new trends: using "unsupervised" learning to boost creativity in theory building, and designing artificial intelligence (AI) that can "think not link".

Most deep learning is "supervised". Layer upon layer of artificial neurons operate on data, abstracting electrical signals into particles and jets, and then event topologies, until the data are compressed into a single label: the Standard Model, or whichever flavour of new physics you are searching for. So far, the stack of new-physics labels has never come close to discovery significance, and yet the deficiencies in the Standard Model are there for all to see. What if we're looking for the wrong new physics?

This situation calls for unsupervised learning, where you don't need to tell the machine what to look for. Just one unsupervised analysis has been published so far, and community-organised data challenges are leading the way (p27). But supervised triggering algorithms mean that LHC analysers are already looking at a stacked deck of data adapted to the needs of the most popular theories. To unlock the full power of unsupervised learning, it must be unleashed on the full 40 MHz data flow in the level-one triggers (p31). Readers who want to get involved can take part in a new data challenge launched at the ML4Jets conference in July – you have a year to submit your algorithms.



40 MHz *A data challenge to design artificial intelligence for the level-one trigger has begun.*

We need to design AI that thinks like a physicist if we are to trust it to do more of the heavy lifting in particle physics

Think not link

At their core, deep-learning algorithms are association machines, with limited intelligence. Today, AI research is dominated by the question of how to think rather than link. To make sure HEP is part of the conversation, CERN has invited 50 world leaders on AI to the inaugural Sparks! Serendipity Forum in September (p36). AI initiatives are springing up elsewhere too, with Jesse Thaler recently taking the helm at the new Institute for Artificial Intelligence and Fundamental Interactions in the US. He argues that we need to design AI that thinks like a physicist if we are to trust it to do more and more of the heavy lifting in particle physics (p49).

But with all its inscrutable complexity, is AI really a suitable tool for fundamental science? A recent current of opinion (for example, J Halverson *et al.* 2021 *Mach. Learn.: Sci. Technol.* **2** 035002) asserts that deep learning may actually exhibit emergent simplicity in a similar way to statistical mechanics and quantum field theory, whose laws are not fundamental but emerge from complexity via a process of data compression. To explore this fascinating link to AI research, we asked Erik Verlinde to size up the Standard Model, gravity and intelligence as candidates for future explanation as emergent phenomena (p39).

Elsewhere in this issue: a tribute to Steven Weinberg (p65); a SciFi upgrade for LHCb (p43); anisotropies point to cosmic-ray origins (p11); the most stable tetraquark yet (p7); reports from the summer conferences (p19); Hubble tension questioned (p53); quantum gravity in the Vatican (p59); the flavour anomalies stick around (p15); and much more.

Reporting on international high-energy physics

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NEWS ANALYSIS

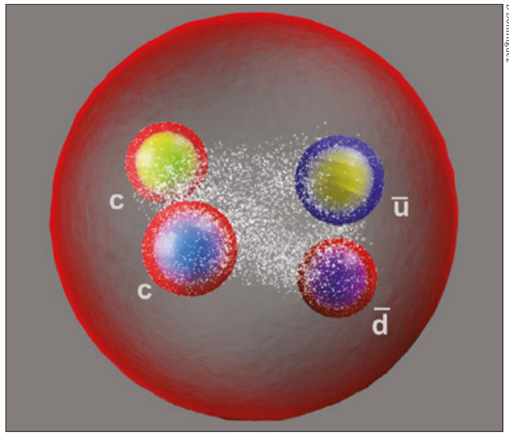
Hadron spectroscopy

New tetraquark a whisker away from stability

All the exotic hadrons that have been observed so far decay rapidly via the strong interaction. The $cc\bar{u}\bar{d}$ tetraquark (T_{cc}^{+}) just discovered by the LHCb collaboration is no exception. However, it is the longest-lived state yet, and reinforces expectations that its beautiful cousin, $bb\bar{u}\bar{d}$, will be stable with respect to the strong interaction when its peak emerges in future data.

"We have discovered a $cc\bar{u}\bar{d}$ tetraquark with a mass just below the $D^{*+}D^{0}$ threshold which, according to most models, indicates that it is a bound state," says LHCb analyst Ivan Polyakov (Syracuse University). "It still decays to D mesons via the strong interaction, but much less intensively than other exotic hadrons."

Most of the exotic hadronic states discovered in the past 20 years or so are $c\bar{c}q\bar{q}$ tetraquarks or $c\bar{c}qqq$ pentaquarks, where q represents an up, down or strange quark. A year ago LHCb also discovered a hidden-double-charm $c\bar{c}c\bar{c}$ tetraquark, X(6900) (*CERN Courier* September/October 2020 p25), and two open-charm $cs\bar{u}\bar{d}$ tetraquarks, $X_0(2900)$ and $X_1(2900)$. The new $cc\bar{u}\bar{d}$ state, announced at the European Physical Society conference on high-energy physics in July to have been observed with a significance substantially in excess of five standard deviations, is the first exotic hadronic state with so-called double open heavy flavour – in this case, two charm quarks unaccompanied by antiparticles of the same flavour.



D Dominguez

Jumbled together *T_{cc}^{+} could be a compact cc diquark tightly bound by gluons to much lighter up and down antiquarks.*

Prime candidate

Tetraquark states with two heavy quarks and two light antiquarks have been the prime candidates for stable exotic hadronic states since the 1980s. LHCb's discovery, four years ago, of the Ξ_{cc}^{++} (ccu) baryon allowed QCD phenomenologists to firmly predict the existence of a stable $bb\bar{u}\bar{d}$ tetraquark, however the stability of a potential $cc\bar{u}\bar{d}$ state remained unclear. Predictions of the mass of the $cc\bar{u}\bar{d}$ state varied substantially, from 250 MeV below to 200 MeV above the $D^{*+}D^{0}$ mass threshold, say the team. Astoundingly, its observation by LHCb reveals that it is a mere 273 ± 61 keV below the threshold – a bound state, then, but with the threshold for strong decays to $D^{*+}D^{0}$ lying within the observed resonance's narrow width of 410 ± 165 keV, prescribed by the uncertainty principle. The T_{cc}^{+} tetraquark can therefore decay via the strong interaction, but strikingly slowly. By contrast, most exotic hadronic states have widths from tens to several hundreds of MeV.

"Such closeness to the threshold is not very common in heavy-hadron spectroscopy," says analyst Vanya Belyaev (Kurchatov Institute/ITEP). "Until now, the only similar closeness was observed for the enigmatic $\chi_{c1}(3872)$ state, whose mass coincides with the $D^{*0}\bar{D}^{0}$ threshold with a precision of about 120 keV." As it is wider, however, it is not yet known whether the $\chi_{c1}(3872)$ is below or above threshold (*CERN Courier* July/August 2020 p18).

"The surprising proximity of T_{cc}^{+} and $\chi_{c1}(3872)$ to the $D^{*}D$ thresholds must have deep reasoning," adds analyst Mikhail Mikhasenko (ORIGINS, Munich). "I am fascinated by the idea that, roughly speaking, a strong coupling to a decay channel might attract the bare mass of the hadron. Tremendous progress in lattice QCD over the past 10 years gives us hope that we will discover the answer soon."

The cause of this attraction, says Mikhasenko, could be linked to a "quantum admixture" of two models that vie to explain the structure of the new tetraquark: it could be a D^{*+} and a D^{0} meson, bound by the exchange of colour-neutral objects such as light mesons, or a colour-charged cc "diquark" tightly bound via gluon exchange to up and down antiquarks (see "Jumbled together" figure). Diquarks are a frequently employed mathematical construct in low-energy quantum chromodynamics (QCD): if two heavy quarks are sufficiently close together, QCD becomes perturbative, and they may be shown to attract each other and exhibit effective anti-colour charge. For example, a red–green cc diquark would have a wavefunction similar to an anti-blue anti-quark, and could pair up with a blue quark to form a baryon – or, hypothetically, a blue anti-diquark, to form a colour-neutral tetraquark.

"The question is if the D and D^{*} are more or less separated, jumbled together to such a degree that all quarks are intertwined in a compact object, or something in between," says Polyakov. "The first scenario resembles a relatively large ~4 fm deuteron, whereas the second can be compared to a relatively compact ~2 fm alpha particle."

The new T_{cc}^{+} tetraquark is an enticing target for further study. Its narrow decay into a $D^{0}D^{0}\pi^{+}$ final state – the virtual D^{*+} decays promptly into $D^{0}\pi^{+}$ – includes no particles that are difficult to detect, leading to a better precision on its mass than for existing measurements of charmed baryons. This, in turn, can provide a stringent test for existing theoretical models and could potentially probe previously unreachable QCD effects, says the team. And, if detected, its beautiful cousin would be an even bigger boon.

"Observing a tightly bound exotic hadron that would be stable with respect to the strong interaction would be a cornerstone in understanding QCD at the scale of hadrons," says Polyakov. "The $bb\bar{u}\bar{d}$, which is believed to satisfy this requirement, is produced rarely and is out of reach of the current luminosity of the LHC. However, it may become accessible in LHC Run 3 or at the High-Luminosity LHC." In the meantime, there is no shortage of work in hadron spectroscopy, jokes Belyaev. "We definitely have more peaks than researchers!"

Further reading

LHCb Collab. 2021 LHCb-PAPER-2021-031.

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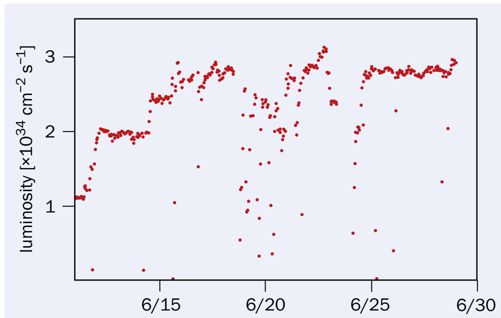
Accelerator physics

SuperKEKB raises the bar

On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan set a new world record for peak luminosity, reaching $3.1\times10^{34}\,cm^{-2}s^{-1}$ in the Belle II detector. Until last year, the luminosity record stood at $2.1\times10^{34}\,cm^{-2}s^{-1}$, shared by the former KEKB accelerator and the LHC. In the summer of 2020, however, SuperKEKB/Belle II surpassed this value with a peak luminosity of $2.4\times10^{34}\,cm^{-2}s^{-1}$ (*CERN Courier* September/October 2020 p13).

In physics operation since 2019, SuperKEKB is an innovative nano-beam, asymmetric-energy accelerator complex that collides 7 GeV electrons with 4 GeV positrons, sitting mostly on or near the ϒ(4S) resonance (*CERN Courier* September 2016 p32). It uses a large crossing angle and strong focusing at the interaction point ($\beta_y^* = 1\,mm$), and has implemented a crab-waist scheme to stabilise beam–beam blowup using carefully tuned sextupole magnets on either side of the interaction point. These innovations have enabled the SuperKEKB team to attain record luminosities with rather modest beam currents: 0.8 A in the low-energy positron ring and 0.7 A in the high-energy electron ring – a product of beam currents 3.5 times smaller than were used at KEKB when its record luminosity was achieved.



Record rates *Instantaneous luminosities recorded in the Belle II detector in June.*

The team is making impressive progress towards a target luminosity of $6.5\times10^{35}\,cm^{-2}s^{-1}$

SuperKEKB/Belle II is also reaching super-B-factory-level performance in integrated luminosity, achieving the highest values collected in a day ($1.96\,fb^{-1}$), in a week ($12\,fb^{-1}$) and in a month ($40\,fb^{-1}$). These are about 40% higher than the old records of KEKB/Belle and about twice the level of SLAC's PEP-II/BaBar, which completed operations more than a decade ago.

"Despite the challenges brought by the COVID-19 pandemic and necessary social-distancing protocols, the SuperKEKB team is making impressive progress towards an eventual target luminosity of $6.5\times10^{35}\,cm^{-2}s^{-1}$," says Belle II physicist Tom Browder of the University of Hawai'i. "The improving performance of SuperKEKB should enable Belle II to collect a large data sample to clarify the intriguing and potentially ground-breaking anomalies in the flavour sector, constrain the dark sector, and search for new physics."

Education and outreach

Science Gateway under construction

On 21 June, officials and journalists gathered at CERN to mark "first stone" for Science Gateway, CERN's new flagship project for science education and outreach. Due to open in 2023, Science Gateway will increase CERN's capacity to welcome visitors of all ages from near and afar. Hundreds of thousands of people per year will have the opportunity to engage with CERN's discoveries and technology, guided by the people who make it possible.

The project has environmental sustainability at its core. Designed by renowned architect Renzo Piano, the carbon-neutral building will bridge the Route de Meyrin and be surrounded by a freshly planted 400-tree forest. Its five linked pavilions will feature a 900-seat auditorium, immersive spaces, laboratories for hands-on activities for visitors from age five upwards, and many other interactive learning opportunities.

"I would like to express my deepest gratitude to the many partners in our Member and Associate Member States and beyond who are making the CERN Science Gateway possible, in particular to our generous donors," said CERN Director-General Fabiola Gianotti during her opening speech. "We want the CERN Science Gateway to inspire all those who come to visit with the beauty and the values of science."

First stone *(from left) Architect Renzo Piano, CERN Director-General Fabiola Gianotti, Geneva state councillor Antonio Hodgers and chairman of Stellantis and the FCA Foundation (the main donor) John Elkann with the symbolic foundation stone, adorned with the newly unveiled Science Gateway logo.*

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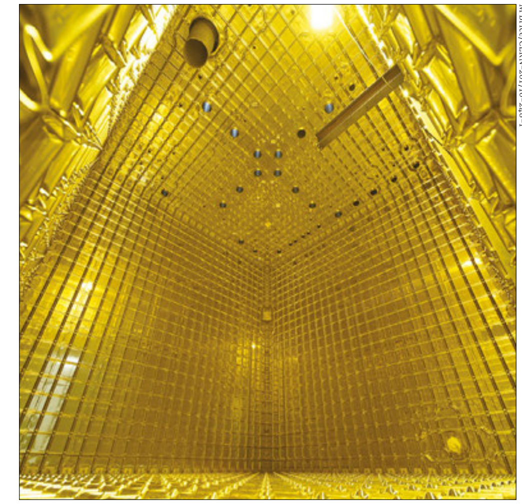
NEWS ANALYSIS

Neutrino detectors

CERN to provide two DUNE cryostats

The Deep Underground Neutrino Experiment (DUNE) in the US is set to replicate that marvel of model-making, the ship-in-a-bottle, on an impressive scale. More than 3000 tonnes of steel and other components for DUNE's four giant detector modules, or cryostats, must be lowered 1.5 km through narrow shafts beneath the Sanford Lab in South Dakota, before being assembled into four $66\times19\times18\,m^3$ containers. And the maritime theme is more than a metaphor: to realise DUNE's massive cryostats, each of which will keep 17.5 kt of liquid argon (LAr) at a temperature of –200°, CERN is working closely with the liquefied natural gas (LNG) shipping industry.

Since it was established in 2013, CERN's Neutrino Platform has enabled significant European participation in long-baseline neutrino experiments in the US and Japan. For DUNE, which will beam neutrinos 1300 km through the Earth's crust from Fermilab to Sanford, CERN has built and operated two large-scale prototypes for DUNE's LAr time-projection chambers (TPCs). All aspects of the detectors have been validated. The "ProtoDUNE" detectors' cryostats will now pave the way for the Neutrino Platform team to design and engineer cryostats that are 20 times bigger. CERN had already committed to build the first of these giant modules. In June, following approval from the CERN Council, the organisation also agreed to provide a second.



Single phase *Inside a prototype liquid-argon time-projection chamber for the DUNE experiment.*

ICARUS, which was shipped to Fermilab in 2017, is a mere twentieth of the size of a single DUNE module

Scaling up

Weighing more than 70,000 tonnes, DUNE will be the largest ever deployment of LAr technology, which serves as both target and tracker for neutrino interactions, and was proposed by Carlo Rubbia in 1977. The first large-scale LAr TPC – ICARUS, which was refurbished at CERN and shipped to Fermilab's short-baseline neutrino facility in 2017 – is a mere twentieth of the size of a single DUNE module.

Scaling LAr technology to industrial levels presents several challenges, explains Marzio Nessi, who leads CERN's Neutrino Platform. Typical cryostats are carved from big chunks of welded steel, which does not lend itself to a modular design. Insulation is another challenge. In smaller setups, a vacuum installation comprising two stiff walls would be used. But at the scale of DUNE, the cryostats will deform by tens of cm when cooled from room temperature, potentially imperilling the integrity of instrumentation, and leading CERN to use an active foam with an ingenious membrane design.

"The nice idea from the LNG industry is that they have found a way to have an internal membrane, which can deform like a spring, as a function of the thermal conditions. It's a really beautiful thing," says Nessi. "We are collaborating with French LNG firm GTT because there is a reciprocal interest for them to optimise the process. They never went to LAr temperatures like these, so we are both learning from each other and have built a fruitful ongoing collaboration."

Having passed all internal reviews at CERN and in the US, the first cryostat is now ready for procurement. Several different industries across CERN's member states and beyond are involved, with delivery and installation at Sanford Lab expected to start in 2024. The cryostat is only one aspect of the ProtoDUNE project: instrumentation, readout, high-voltage supply and many other aspects of detector design have been optimised through more than five years of R&D. Two technologies were trialled at the Neutrino Platform: single- and dual-phase LAr TPCs. The single-phase design has been selected as the design for the first full-size DUNE module. The Neutrino Platform team is now qualifying a hybrid single/dual-phase version based on a vertical drift, which may prove to be simpler, more cost effective and easier-to-install.

Step change

In parallel with efforts towards the US neutrino programme, CERN has developed the BabyMIND magnetic spectrometer, which sandwiches magnetised iron and scintillator to detect relatively low-energy muon neutrinos, and participates in the T2K experiment, which sends neutrinos 295 km from Japan's J-PARC accelerator facility to the Super-Kamiokande detector. CERN will contribute to the upgrade of T2K's near detector, and a proposal has been made for a new water Cherenkov test-beam experiment at CERN, to later be placed about 1 km from the neutrino beam source of the Hyper Kamiokande experiment . Excavation of underground caverns for Hyper Kamiokande and DUNE has already begun (see p13).

DUNE and Hyper-Kamiokande, along with short-baseline experiments and major non-accelerator detectors such as JUNO in China, will enable high-precision neutrino-oscillation measurements to tackle questions such as leptonic CP violation, the neutrino mass hierarchy, and hints of additional "sterile" neutrinos, as well as a slew of questions in multi-messenger astronomy. Entering operation towards the end of the decade, Hyper-Kamiokande and DUNE will mark a step-change in the scale of neutrino experiments, demanding a global approach.

"The Neutrino Platform has become one of the key projects at CERN after the LHC," says Nessi. "The whole thing is a wonderful example – even a prototype – for the global participation and international collaboration that will be essential as the field strives to build ever more ambitious projects like a future collider."

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Future Circular Collider

Surveyors eye up a future collider

CERN surveyors have performed the first geodetic measurements for a possible Future Circular Collider (FCC), a prerequisite for high-precision alignment of the accelerator's components. The millimetre-precision measurements are one of the first activities undertaken by the FCC feasibility study, which was launched last year following the recommendation of the 2020 update of the European strategy for particle physics (p20). During the next three years, the study will explore the technical and financial viability of a 100 km collider at CERN, for which the tunnel is a top priority. Geology, topography and surface infrastructure are the key constraints on the FCC tunnel's position, around which civil engineers will design the optimal route, should the project be approved.

The FCC would cover an area about 10 times larger than the LHC, in which every geographical reference must be pinpointed with unprecedented precision. To provide a reference coordinate system, in May the CERN surveyors, in conjunction with ETH Zürich, the Federal Office of Topography Swisstopo, and the School of Engineering and Management Vaud, performed geodetic levelling measurements along an 8 km profile across the Swiss–French border south of Geneva.

Level headed *CERN's Pierre Valentin performing levelling measurements between Certoux and Saint-Julien in France.*

Such measurements have two main purposes. The first is to determine a high-precision surface model, or "geoid", to map the height above sea level in the FCC region. The second purpose is to improve the present reference system, whose measurements date back to the 1980s when the tunnel housing the LHC was built.

"The results will help to evaluate if an extrapolation of the current LHC geodetic reference systems and infrastructure is precise enough, or if a new design is needed over the whole FCC area," says Hélène Mainaud Durand, group leader of CERN's geodetic metrology group.

The FCC feasibility study, which involves more than 140 universities and research institutions from 34 countries, also comprises technological, environmental, engineering, political and economic considerations. It is due to be completed by the time the next strategy update gets under way in the middle of the decade. Should the outcome be positive, and the project receive the approval of CERN's member states, civil-engineering works could start as early as the 2030s.

World Wide Web

Web code auctioned as crypto asset

Time-stamped files stated by Tim Berners-Lee to contain the original source code for the web and digitally signed by him, have sold for US$5.4 million at auction. The files were sold as a non-fungible token (NFT), a form of a crypto asset that uses blockchain technology to confer uniqueness.

The web was originally conceived at CERN to meet the demand for automated information-sharing between physicists spread across universities and institutes worldwide. Berners-Lee wrote his first project proposal in March 1989, and the first website, which was dedicated to the World Wide Web project itself and hosted on Berners-Lee's NeXT computer, went live in the summer of 1991. Less than two years later, on 30 April 1993, and after several iterations in development, CERN placed version three of the software in the public domain. It deliberately did so on a royalty-free, "no-strings-attached" basis, addressing the memo simply "To whom it may concern."

The seed that led CERN to relinquish ownership of the web was planted 70 years ago, in the CERN Convention, which states that results of its work were to be "published or otherwise made generally available" – a culture of openness that continues to this day.

```
Anchor.m
  /*      Hypertext "Anchor" Object                               Anchor.m
  **      ==========================
  **
  **      An anchor represents a region of a hypertext node which is linked to
  **      another anchor in the same or a different node.
  */
  #define ANCHOR_CURRENT_VERSION 0
  #import &lt;ctype.h&gt;
  #import &lt;objc/Object.h&gt;
  #import &lt;objc/typedstream.h&gt;
  #import &lt;appkit/appkit.h&gt;
  #import "Anchor.h"
  #import "HTUtils.h"
  #import "HTParse.h"
  #import "HyperText.h"
  #import "HyperManager.h"
  @implementation Anchor:Object
  static HyperManager *manager;
  static List * orphans;          // Grand list of all anchors with no parents
  List * HTHistory;               // List of visited anchors
  + initialize
  {
    orphans = [List new];
    HTHistory = [List new];
    [Anchor setVersion:ANCHOR_CURRENT_VERS:
  \
    orphans = [List new];
    HTHistory = [List new];
    [Anchor setVersion:ANCHOR_CURRENT_VERSION];
    return self;
  }
  + setManager:aManager
  {
    manager = aManager;
    return self;
  }
  //                          Creation Methods
  //                          ================
  //
  //      Do not use "new" by itself outside this module. In order to enforce
  //      consistency, we insist that you furnish more information about the
  //      anchor you are creating.
  //
```

Unique *A portion of the web's original source code.*

The auction offer describes the NFT as containing approximately 9555 lines of code, including implementations of the three languages and protocols that remain fundamental to the web today: HTML (Hypertext Markup Language), HTTP (Hypertext Transfer Protocol) and URIs (Uniform Resource Identifiers). The lot also includes an animated visualisation of the code, a letter written by Berners-Lee reflecting on the process of creating it, and a Scalable Vector Graphics representation of the full code created from the original files.

Bidding for the NFT, which auction-house Sotheby's claims is its first-ever sale of a digital-born artefact, opened on 23 June and attracted a total of 51 bids. The sale will benefit initiatives that Berners-Lee and his wife Rosemary Leith support, stated a Sotheby's press release.

Astrowatch

Anisotropies point to cosmic-ray origins

Spanning 13 decades in energy and more than 26 decades in intensity, cosmic rays are one of the hottest topics in astroparticle physics today. Spectral features such as a "knee" at a few PeV and an "ankle" at a few EeV give insights into their varying origins, but studies of their arrival direction can also provide valuable information. Though magnetic fields mean we cannot normally trace cosmic rays directly back to their point of origin, angular anisotropies provide important independent evidence towards probable sources at different energies. In July, at the 37th International Cosmic Ray Conference (ICRC), a range of space- and ground-based experiments greatly increased our knowledge of cosmic-ray anisotropies, with new results spanning 10 decades in energy, from GeV to tens of EeV.

Spectral *Nearby supernova remnants such as Vela could explain sub-TeV spectral features of cosmic rays.*

At sub-TeV energies, spectral features seen by the AMS-02 and CALET detectors on the International Space Station and the Chinese–European DAMPE satellite could potentially be explained by a local galactic source such as a supernova remnant like Vela (see "Spectral" figure). If a nearby source is indeed responsible for a significant fraction of the cosmic rays observed at such energies, it could show up in the arrival direction of these cosmic rays in the form of a dipole feature, despite bending by galactic magnetic fields; however, results from AMS-02 at ICRC showed no evidence of a dipole in the arrival direction of protons or any other light nucleus. This was confirmed by DAMPE, which excluded dipole features with amplitudes above about 0.1% in the 100s of GeV energy range. The search continues, however, with DAMPE, AMS-02 and CALET all set to take further data over the coming years.

Moving to higher energies, clear anisotropic dipole excesses have been observed over the last decade by ground-based experiments such as the ARGO-YBJ observatory in China, the HAWC observatory in Mexico and the IceCube observatory at the South Pole – though with different "phases" at different energies. The anisotropy in the TeV to the 100s of TeV energy range could point towards a nearby source, though models proposing the structure of the interstellar magnetic field as the true origin for the anisotropy also exist. This feature was further confirmed this year by the LHAASO experiment in China, using a year of data that was taken while constructing the detector. The results from LHAASO also confirm a switch in the phase of the anisotropy when moving from 100s of TeV to PeV energies, as reported by IceCube and other experiments in recent years: at PeV energies, close to the knee, the dipole has a maximum rather than a minimum close to the galactic centre. This could indicate an excess of "pevatron" sources near the galactic centre (*CERN Courier* July/August 2021 p11).

Antennae galaxies *Starburst galaxies such as that resulting from the collision of NGC 4038 and NGC 4039 could explain cosmic-ray anisotropies at energies exceeding EeV.*

Extragalactic sources

While results up to PeV energies give an insight into sources within our galaxy, it is theorised that the flux starts to be dominated by extragalactic sources somewhere between the knee and the ankle of the cosmic-ray spectrum. Evidence for this was provided by new results from the Pierre Auger Observatory in Argentina and the Telescope Array in the US. These two observatories, which observe different hemispheres, find strong evidence for excesses in the cosmic-ray flux in certain regions of the sky at energies exceeding EeV. At energies as high as these, cosmic rays point more clearly to their origin, and galactic cosmic rays should have very clear point-like sources that are not observed, providing evidence that they originate outside of our galaxy. A prime candidate for such sources are so-called starburst galaxies, wherein star formation happens unusually rapidly, during a short period of the galaxy's evolution (see "Antennae galaxies" figure). As presented at ICRC 2021, the available data was fitted to models where starburst galaxies are the primary source of EeV cosmic rays. The model fits the anisotropy data with more than 4σ significance relative to the null hypothesis with normal galaxies, indicating starburst galaxies to likely be at least one source of EeV cosmic rays.

While some of the features will likely be fully confirmed within the coming years simply by accumulating statistics, new features are also likely to arise. One example is further constraints on the lack of any observed anisotropy at sub-TeV energies using data from space-based missions, while new data from ground-based experiments will start to bridge the measurement gap between PeV and EeV energies. The latter will be especially important in gaining an understanding of the energy scale at which extragalactic sources start to dominate. To fully exploit the data it will be necessary to compare complex cosmic-ray-propagation simulations with diverse data such as the pevatron sources discovered this year by LHAASO.

CERNCOURIER
VOLUME 61 NUMBER 5 SEPTEMBER/OCTOBER 2021

NEWS DIGEST

M Zacher

Inside the KATRIN spectrometer.

Neutrino mass less than 1 eV
The Karlsruhe Tritium Neutrino (KATRIN) experiment has announced the first model-independent limit on the mass of neutrinos with sensitivity below 1 eV. The best fit to the spectral data yields a squared neutrino mass of $0.26 \pm 0.34\,eV^2$ for the second physics run, thereby excluding neutrino masses above 0.8 eV at 90% confidence when all data is taken into account (arXiv:2105.08533). KATRIN probes the mass of electron anti-neutrinos by measuring the β-decay spectrum of tritium close to its endpoint at 18.6 keV. The collaboration targets an ultimate sensitivity of 0.2 eV at 90% confidence by the end of 2024, close to complementary model-dependent limits based on searches for neutrinoless-double-beta decay and measurements of temperature anisotropies of the cosmic microwave background.

Search for Schwinger monopoles
In a first for an experiment at a particle collider, the Monopole and Exotics Detector at the LHC (MoEDAL) collaboration searched for magnetic monopoles produced by the Schwinger effect (arXiv:2106.11933). Following up an idea from Fritz Sauter in the 1930s, Julian Schwinger showed in 1951 that pairs of particles with opposite electrical charge can be spontaneously created in a strong electric field. MoEDAL is investigating whether the dual effect might reveal long-hypothesised magnetic charges. The collaboration exploited the strongest known magnetic fields probed by scientists: Pb–Pb heavy-ion collisions at the LHC (*CERN Courier* January/February 2020 p17). Scanning MoEDAL detectors with a SQUID magnetometer excluded monopoles with one, two or three Dirac charges up to masses of 75 GeV.

ILC pre-lab proposal published
In June, the International Development Team (IDT) for the International Linear Collider (ILC) proposed to launch a preparatory laboratory (pre-lab) to bring the project to a point of readiness for construction, should the project gain international support (arXiv:2106.00602). The IDT will now facilitate a discussion among candidate founding laboratories to decide whether to proceed with the pre-lab. Over a period of approximately four years, the pre-lab would invite international ideas for experiments, facilitate R&D for superconducting radio-frequency cavities and engineering studies for the whole accelerator complex, and perform geological surveys at the candidate site in the Kitakami Mountains in Japan, says the team.

Hyper-K and DUNE get cracking
Next-generation neutrino experiments Hyper-Kamiokande (Hyper-K) and the Deep Underground Neutrino Experiment (DUNE) have begun excavation for their underground detector caverns. On 28 May,

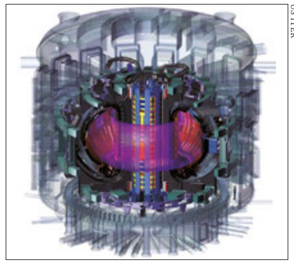
U Tokyo

Groundbreaking ritual.

Hyper-K broke ground in Hida City, Gifu Prefecture, Japan. Meanwhile in the US, 35 pieces of equipment that will carry out the excavation for DUNE are being lowered a mile underground in Lead, South Dakota. Both experiments are due to begin taking data in 2027, and will seek to constrain leptonic CP violation and study astrophysical neutrinos (*CERN Courier* July/August 2020 p32).

Instrumentation training probed
A survey by the European Committee for Future Accelerators (ECFA) reports that 60% of early-career researchers are eager to take on more instrumentation work, however, only 15% felt informed about training opportunities. A quarter feels they have had insufficient training for the instrumentation work that they have undertaken, and a majority believes that there should be a greater emphasis on hands-on instruction. Respondents were almost unanimous in expressing the benefits of peer-to-peer mentoring, and many believe that the quality of training is strongly correlated to both institution and country of residence (arXiv:2107.05739). The results will inform ECFA's detector-R&D roadmap.

Most powerful magnet sets sail
Following testing in the US, the world's most powerful magnet is being shipped to international fusion laboratory ITER in southern France. The central solenoid (CS) stands 18 m tall and 4 m wide, with a maximum field strength of 13 T, and stores 6.4 GJ of field energy – three times as much as the CMS experiment's 14 kton solenoid, which previously held the record. The CS uses 43 km of Nb_3Sn superconductor manufactured in Japan – the same material that will be used for the High-Luminosity LHC's eight new quadrupole triplets (*CERN Courier* January/February 2021 p8). Formally established in 2007, ITER is tasked with demonstrating the feasibility of fusion power by maintaining a plasma in a self-sustaining "ignition" phase. Machine assembly began in July 2020, with the goal of achieving "first plasma" by late 2025.



US ITER

The central solenoid (blue) at the heart of ITER's tokamak design.

Second superconductor supplier
CERN has validated the acceptance testing of Nb_3Sn cables from Russian company TVEL as part of the conductor-development programme for the Future Circular Collider (p20). TVEL is the second manufacturer to comply with CERN's specifications, with development also ongoing in the US, Europe, South Korea, Japan and China.

Galactic geology
A team from Stanford and Stockholm propose using "paleo-detectors" (PDs) to search for dark matter (DM) by observing so-called damage tracks caused by nuclear recoils in small samples of natural minerals (arXiv:2107.02812). Unlike real-time direct-detection experiments, PDs might have been accumulating tracks for up to a billion years, suggesting a unique possibility, claim the authors: by reading out PDs of different ages, one can explore the time-variation of signals on megayear to gigayear timescales. The team discuss two examples of DM substructure that could give rise to time-varying signals: a DM disk through which the Earth passes every ~45 Myr, and a DM "subhalo" that the Earth encountered during the past gigayear.

CERNCOURIER
Volume 61 Number 5 September/October 2021
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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

LHCb

B_s decays remain anomalous

The LHCb experiment recently presented new results on the $b \to s\mu\mu$ decay of a B_s meson to a ϕ meson and a dimuon pair, reinforcing an anomaly last reported in 2015 with improved statistics and theory calculations. Such decays of b hadrons via $b \to s$ quark transitions are strongly suppressed in the Standard Model (SM) and therefore constitute sensitive probes for hypothetical new particles. In recent years, several measurements of rare semileptonic $b \to s\ell\ell$ decays have shown tensions with SM predictions. Anomalies have been spotted in measurements of branching fractions, angular analyses and tests of lepton flavour universality (LFU), leading to cautious excitement that new physics might be at play.

At the SM@LHC conference in April, LHCb presented the most precise determination to date of the branching fraction for the decay using data collected during LHC Run 1 and Run 2 (figure 1). The branching fraction is measured as a function of the dimuon invariant mass (q^2) and found to lie below the SM prediction at the level of 3.6 standard deviations in the low-q^2 region. This deficit of muons is consistent with the pattern seen in LFU tests of $b \to s\ell\ell$ transitions (*CERN Courier* May/June 2021 p17), however calculating the SM prediction for the $B_s \to \phi\mu\mu$ branching fraction is more challenging than for LFU tests as it involves the calculation of non-perturbative hadronic effects.

Calculations based on light-cone sum rules are most precise at low q^2, while lattice-QCD calculations do better at high q^2. A combination is expected to give the best precision over the full q^2 range. If lattice-QCD calculations are not used in the comparison, increased theory errors reduce the tension to 1.8 standard deviations in the low-q^2 region. The previous 2015 measurement by LHCb, which was based exclusively on Run-1 data (grey data points), was reported at the time to be approximately three standard deviations below the best theoretical predictions that were available at the time. Since then, theoretical calculations have generally become more precise with regard to form factors, but more conservatively evaluated with regard to non-local hadronic effects.

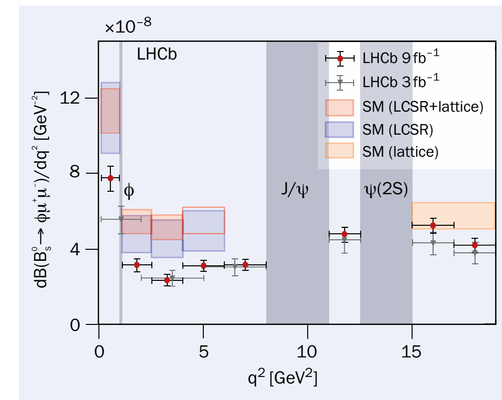

Fig. 1. *Differential branching fractions for the decay $B_s \to \phi\mu\mu$, compared with SM predictions based on light-cone sum rules (LCSR) and lattice-QCD calculations.*

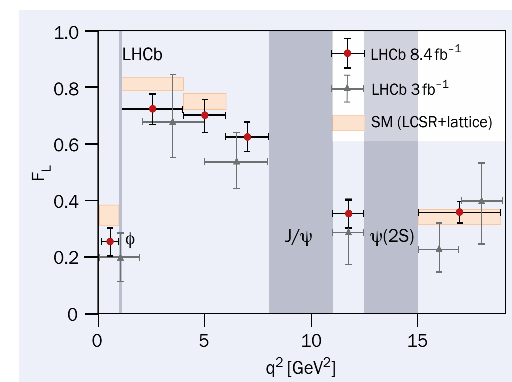

Fig. 2. *The longitudinal polarisation fraction F_L for the decay $B_s \to \phi\mu\mu$, compared with SM predictions based on light-cone sum rules (LCSR) and lattice-QCD calculations.*

The angular distribution of the $B_s \to \phi\mu\mu$ decay products offers complementary information. At the international FPCP conference in June, LHCb presented a measurement of the angular distribution of these decays in different q^2 regions using data collected during LHC Run 1 and Run 2. Figure 2 shows the longitudinal polarisation fraction F_L – one of several variables sensitive to anomalous $b \to s\mu\mu$ couplings. The results are consistent with SM predictions at the level of two standard deviations, but may also hint at the same pattern of unexpected behaviour seen in angular analyses of other $b \to s\mu\mu$ decays (*CERN Courier* May/June 2020 p10) and in branching-fraction measurements.

For both analyses, LHC Run 3 will be crucial to better understanding the anomalous behaviour seen so far in $B_s \to \phi\mu\mu$ decays.

Further reading

LHCb Collab. 2021 arXiv:2105.14007.
LHCb Collab. 2021 arXiv:2107.13428.

ALICE

Charm breaks fragmentation universality

The study of heavy-flavour hadron production in proton–proton (pp) collisions provides an important test for quantum chromodynamics (QCD) calculations. Heavy-flavour hadron production is usually computed with perturbative-QCD (pQCD) calculations as the convolution of the parton distribution functions (PDFs) of the incoming protons, the partonic cross section and the fragmentation functions that describe the transition from charm quarks into charm hadrons. The latter are typically parametrised from measurements performed in e^+e^- or ep collisions, under the assumption that the hadronisation of charm quarks into charm hadrons is a universal process that is independent of the colliding systems.

Universal charm-to-hadron fragmentation may not be valid

The large data samples collected during Run 2 of the LHC at $\sqrt{s} = 5.02$ TeV ▷

CERNCOURIER
Volume 61 Number 5 September/October 2021
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allowed the ALICE collaboration to measure the vast majority of charm quarks produced in the pp collisions by reconstructing the decays of the ground-state charm hadrons, measuring all the charm-meson species and the most abundant charm baryons (Λ_c^+, and $\Xi_c^{0,+}$) down to very low transverse momenta.

Charm fragmentation fractions, $f(c \to H_c)$, represent the probability for a charm quark to hadronise into a given charm hadron. These have now been measured for the first time at the LHC in pp collisions at midrapidity, and, in the case of the Ξ_c^0, for the first time in any collision system (figure 1). The measured $f(c \to H_c)$ are observed to be different from those measured in e^+e^- and ep collisions – evidence that the assumption that charm-to-hadron fragmentation is universal is not valid.

Charm quarks were found to hadronise into baryons almost 40% of the time – four times more often than at colliders with electron beams. Several models have been proposed to explain this "baryon enhancement". The explanations feature various different assumptions, such as including hadronisation via coalescence, considering a set of as-yet-unobserved higher-mass charm-baryon states, and including string formation beyond the leading-colour approximation.

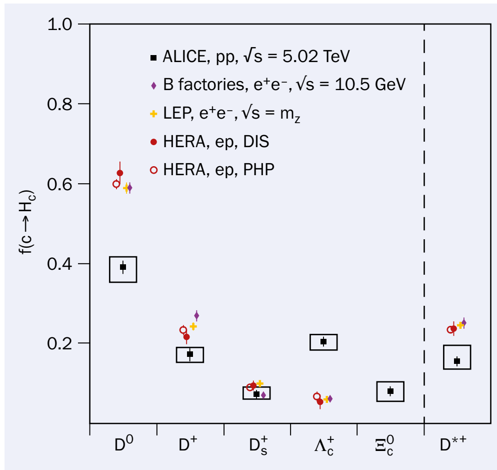

Fig. 1. *Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s} = 5.02$ TeV (black squares), in e^+e^- collisions (purple and yellow markers) and in ep collisions (closed and open red circles). The D^* meson is depicted separately since its contribution is also included in the ground-state charm mesons.*

The $c\bar{c}$ production cross section per unit of rapidity at midrapidity ($d\sigma^{c\bar{c}}/dy|_{|y|<0.5}$) was calculated by summing the cross sections of all measured ground-state charm hadrons (D^0, D^+, D_s^+, Λ_c^+, and Ξ_c^0). The contribution of the Ξ_c^0 was multiplied by a factor of two, in order to account for the contribution of the Ξ_c^+. The resulting $c\bar{c}$ cross section per unit of rapidity at midrapidity is $d\sigma^{c\bar{c}}/dy|_{|y|<0.5} = 1165 \pm 44(\text{stat})^{+134}_{-101}(\text{syst})$ μb. This measurement was obtained for the first time in hadronic collisions at the LHC including the charm-baryon states. The $c\bar{c}$ cross section measured at the LHC lies at the upper edge of the theoretical pQCD calculations.

The measurements described above not only provide constraints to pQCD calculations, but also act as important references for investigating the interaction of charm quarks with the medium created in heavy-ion collisions. These measurements could be extended to include rarer baryons and studied as a function of the event multiplicity in pp and heavy-ion systems in future LHC runs.

Further reading

ALICE Collab. 2021 arXiv:2105.06335.

ATLAS

Strongly unbalanced photon pairs

Most processes resulting from proton–proton collisions at the LHC are affected by the strong force – a difficult-to-model part of the Standard Model involving non-perturbative effects. This can be problematic when measuring rare processes not mediated by strong interactions, such as those involving the Higgs boson, and when searching for new particles or interactions. To ensure such processes are not obscured, precise knowledge of the more dominant strong-interaction effects, including those caused by the initial-state partons, is a prerequisite to LHC physics analyses.

The electromagnetic production of a photon pair is the dominant background to the $H \to \gamma\gamma$ decay channel – a process that is instrumental to the study of the Higgs boson. Despite its electromagnetic nature, diphoton production is affected by surprisingly large strong-interaction effects. Thanks to precise ATLAS measurements of diphoton processes using the full Run-2 dataset, the collaboration is able to probe these effects and scrutinise state-of-the-art theoretical calculations.

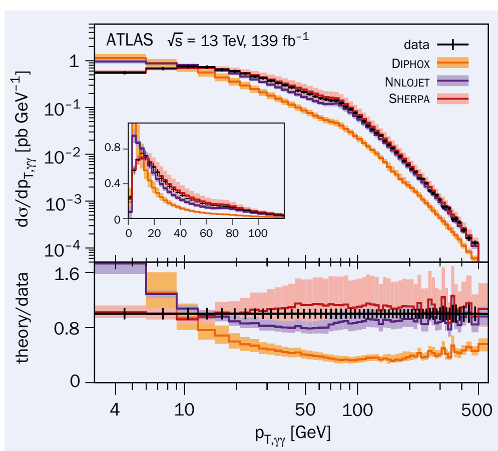

Fig. 1. *Measurements of the differential diphoton cross-section as a function of the transverse momentum of the photon pairs (black points), compared to theoretical predictions including those at next-to-leading order (orange) and next-to-next-to leading order (purple).*

Measurements studying strong interactions typically employ final states that include jets produced from the showering and hadronisation of quarks and gluons. However, the latest ATLAS analysis instead uses photons, which can be very precisely measured by the detector. Although photons do not carry a colour charge, they interact with quarks as the latter carry electric charge. As a result, strong-interaction effects on the quarks can alter the characteristics of the measured photons. The conservation of momentum allows us to quantify this effect: the LHC's proton beams collide head-on, so the net momentum transverse to the beam axis must be zero for the final-state particles. Any signs to the contrary indicate additional activity in the event with equivalent but opposite transverse momentum, usually arising from quarks and gluons radiated from the initial-state partons. Therefore, by measuring the transverse momentum of photon pairs, and related observables, the strong interaction may be indirectly probed.

Comparing the measured values to predictions reveals the surprising role of the strong interaction in electromagnetic diphoton production. In a simple ▷ picture without the strong interaction, the momentum of each photon should perfectly balance in the transverse plane. However, this simplistic expectation does not match the measurements (see figure 1). Measuring the differential cross-section as a function of the transverse momentum of the photon pair, ATLAS finds that most of the measured photon pairs (black points) have low but non-zero transverse momenta, with a peak at approximately 10 GeV, followed by a smoothly falling distribution towards higher values.

A surprising role of the strong interaction in electromagnetic diphoton production is revealed

Extending calculations to encompass next-to-next-to-leading order corrections in the strong-interaction coupling constant (purple line), the impact of the strong interaction becomes manifest. The measured values at high transverse momenta are well described by these predictions, including the bump observed at 70 GeV, which is another manifestation of higher-order strong-interaction effects. Monte Carlo event generators like Sherpa (red line), which combine similar calculations with approximate simulations of arbitrarily many-quark and gluon emissions – especially relevant at low energies – properly describe the entire measured distribution.

The results of this analysis, which also include measurements of other distributions such as angular variables between the two photons, don't just viscerally probe the strong interaction – they also provide a benchmark for this important background process.

Further reading

ATLAS Collab. 2021 arXiv:2107.09330.

CMS

Learning to detect new top-quark interactions

Ever since its discovery in 1995 at the Tevatron, the top quark has been considered to be a highly effective probe of new physics. A key reason is that the last fundamental fermion predicted by the Standard Model (SM) has a remarkably high mass, just a sliver under the Higgs vacuum expectation value divided by the square root of two, implying a Yukawa coupling close to unity. This has far-reaching implications: the top quark impacts the electroweak sector significantly through loop corrections, and may couple preferentially to new massive states. But while the top quark may represent a window into new physics, we cannot know *a priori* whether new massive particles could ever be produced at the LHC, and direct searches have so far been inconclusive. Model-independent measurements carried out within the framework of effective field theory (EFT) are therefore becoming increasingly important as a means to make the most of the wealth of precision measurements at the LHC. This approach makes it possible to systematically correlate sparse deviations observed in different measurements, in order to pinpoint any anomalies in top-quark couplings that might arise from unknown massive particles.

A new CMS analysis searches for anomalies in top-quark interactions with the Z boson using an EFT framework. The cross-section measurements of the rare associated production of either one (tZ) or two ($t\bar{t}Z$) top quarks with a Z boson were statistically limited until recently. These interactions are among the least constrained by the available data in the top-quark sector, despite being modified in numerous beyond-SM models, such as composite Higgs models and minimal supersymmetry. Using the full LHC Run-2 data set, this study targets high-purity final states with multiple electrons and muons. It sets some of the tightest constraints to date on five generic types of EFT interactions that could substantially modify the characteristics of associated top-Z production, while having negligible or no effect on background processes.

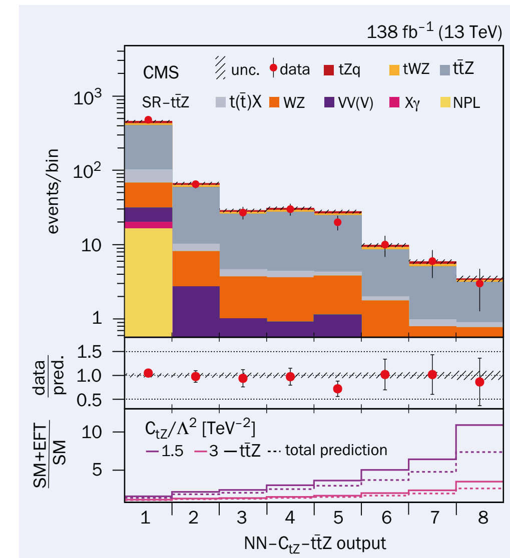

Fig. 1. *The response of a neural network used to target a specific type of EFT interaction in $t\bar{t}Z$ production. The lower panel shows the change of the event yield in each bin with respect to the SM post-fit expectation for two benchmark EFT scenarios, both for the $t\bar{t}Z$ process (solid line) and the total prediction (dotted), illustrating the neural network's ability to isolate anomalous effects.*

In contrast to the more usual reinterpretations of SM measurements that require assumptions on the nature of new physics, this analysis considers EFT effects on observables at the detector level and constrains them directly from the data using a strategy that combines observables specifically selected for their sensitivity to EFT. The key feature of this work is its heavy use of multivariate-analysis techniques based on machine learning, which improve its sensitivity to new interactions. First, to define regions enriched in the processes of interest, a multiclass neural network is trained to discriminate between different SM processes. Subsequently, several binary neural networks learn to separate events generated according to the SM from events that include EFT effects arising from one or more types of anomalous interactions. For the first time in an analysis using LHC data, these classifiers were trained on the full physical amplitudes, including the interference between SM and EFT components.

The binary classifiers are used to construct powerful discriminant variables out of high-dimensional input data. Their distributions are fitted to data to constrain up to five types of EFT couplings simultaneously. The widths of the corresponding confidence intervals are significantly reduced thanks to the combination of the available kinematic information that was specifically chosen to be sensitive to EFT in the top quark sector. All results are consistent with the SM, which indicates either the absence of new effects in the targeted interactions or that the mass scale of new physics is too high to be probed with the current sensitivity. This result is an important step towards the more widespread use of machine learning to target EFT effects, to efficiently explore the enormous volume of LHC data more globally and comprehensively.

Further reading

CMS Collab. 2021 CMS-PAS-TOP-21-001.

CERNCOURIER
VOLUME 61 NUMBER 5 SEPTEMBER/OCTOBER 2021
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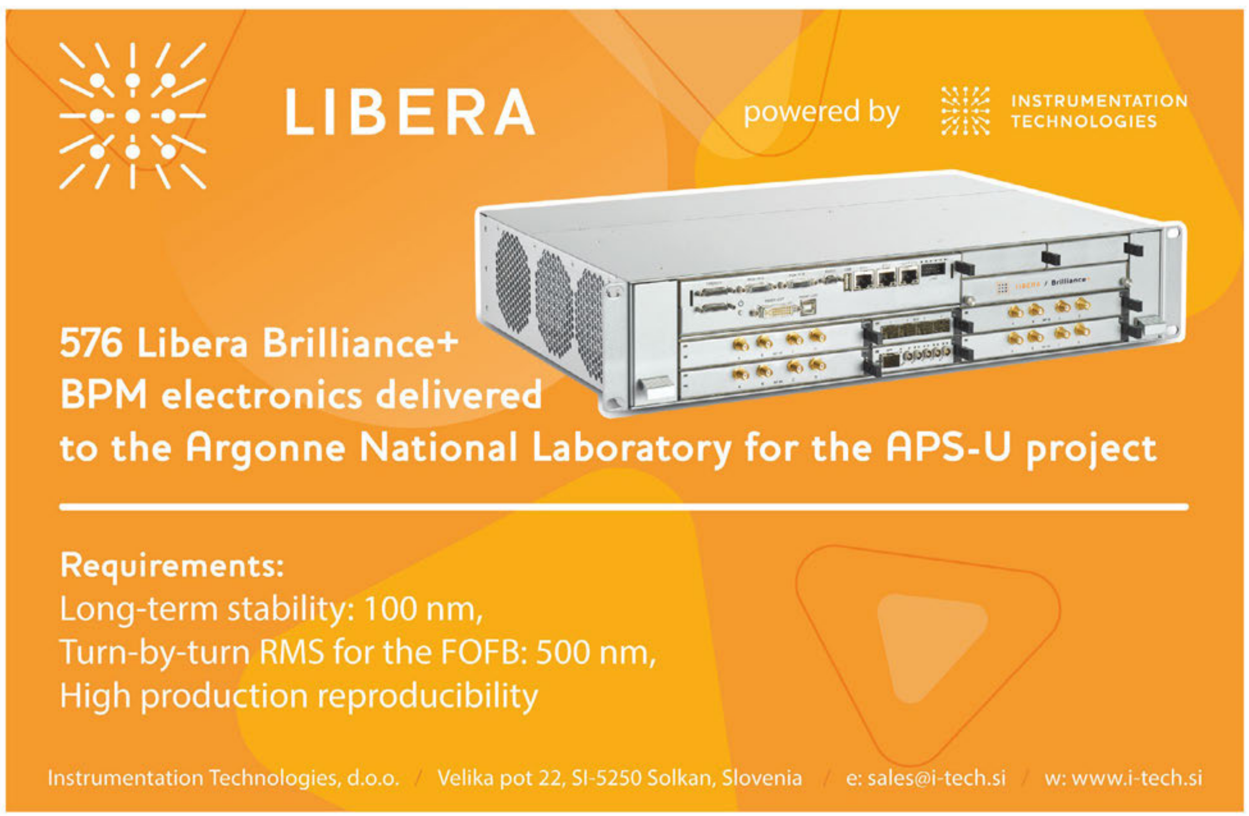


FIELD NOTES

Reports from events, conferences and meetings

Computing in High-Energy Physics

AI and GPUs take centre stage at vCHEP

The 25th International Conference on Computing in High-Energy and Nuclear Physics (CHEP) gathered more than 1000 participants online from 17 to 21 May. Dubbed "vCHEP", the event took place virtually after this year's in-person event in Norfolk, Virginia, had to be cancelled due to the COVID-19 pandemic. Participants tuned in across 20 time zones, from Brisbane to Honolulu, to live talks, recorded sessions, excellent discussions on chat apps (to replace the traditional coffee-break interactions) and special sessions that linked job seekers with recruiters.

Given vCHEP's virtual nature this year, there was a different focus on the content. Plenary speakers are usually invited, but this time the organisers invited papers of up to 10 pages to be submitted, and chose a plenary programme from the most interesting and innovative. Just 30 had to be selected from more than 200 submissions – twice as many as expected – but the outcome was a diverse programme tackling the huge issues of data rate and event complexity in future experiments in nuclear and high-energy physics (HEP).

Artificial intelligence

So what were the hot topics at vCHEP? One outstanding one was artificial intelligence and machine learning. There were more papers submitted on this theme than any other, showing that the field is continuing to innovate in this domain.

Interest in using graph neural networks for the problem of charged-particle tracking was very high, with three plenary talks. Using a graph to represent the hits in a tracker as nodes and possible connections between hits as edges is a very natural way to represent the data that we get from experiments. The network can be effectively trained to pick out the edges representing the true tracks and reject those that are just spurious connections. The time needed to get to a good solution has improved dramatically in just a few years, and the scaling of the solution to dense environments, such as at the High-Luminosity LHC (HL-LHC), is very promising for this relatively new technique.

vCHEP 2021 *More than 1000 participants took part across 20 time zones, from Brisbane to Honolulu.*

On the simulation side, work was presented showcasing new neural-network architectures that use a "bounded information-bottleneck autoencoder" to improve training stability, providing a solution that replicates important features such as how real minimum-ionising particles interact with calorimeters. ATLAS also showed off their new fast-simulation framework, which combines traditional parametric simulation with generative adversarial networks, to provide better agreement with Geant4 than ever before.

Machine learning is very well suited to new computing architectures, such as graphics processing units (GPUs), but many other experimental-physics codes are also being rewritten to take advantage of these new architectures. IceCube are simulating photon transport in the Antarctic ice on GPUs, and presented detailed work on their performance analysis that led to recent significant speed-ups. Meanwhile, LHCb will introduce GPUs to their trigger farm for Run 3, and showed how much this will improve the energy consumption per event of the high-level trigger. This will help to meet the physical constraints of power and cooling close to the detector, and is a first step towards bringing HEP's overall computing energy consumption to the table as an important parameter.

Encouraging work on porting event generation to GPUs was also presented – particularly appropriately, given the spiralling costs of higher order generators for HL-LHC physics. Looking at the long-term future of these new code bases, there were investigations of porting calorimeter simulation and liquid-argon time-projection chamber software to different toolkits for heterogeneous programming, a topic that will become even more important as computing centres diversify their offerings.

ATLAS showed off their new fast-simulation framework

Keeping up with benchmarking and valuing these heterogeneous resources is an important topic for the Worldwide LHC Computing Grid, and a report from the HEPiX Benchmarking group pointed to the future for evaluating modern CPUs and GPUs for a variety of real-world HEP applications. Staying on the facilities topic, R&D was presented on how to optimise delivering reliable and affordable storage for HEP, based on CephFS and the CERN-developed EOS storage system. This will be critical to providing the massive storage needed in the future. The network between facilities will likely become dynamically configurable in the future, and how best to take advantage of machine learning for traffic prediction is being investigated.

Quantum computing

vCHEP was also the first edition of CHEP with a dedicated parallel session on quantum computing. Meshing very well with CERN's Quantum Initiative, this showed how seriously investigations of how to use this technology in the future are being taken. Interesting results on using quantum support-vector machines to train networks for signal/background classification for B-meson decays were highlighted.

On a meta note, presentations also explored how to adapt outreach events to a virtual setup, to keep up public engagement during lockdown, and how best to use online software training to equip the future generation of physicists with the advanced software skills they will need.

Was vCHEP a success? So far, the feedback is overwhelmingly positive. It was a showcase for the excellent work going on in the field, and 11 of the best papers will be published in a special edition of *Computing and Software for Big Science* – another first for CHEP in 2021.

Graeme Stewart *CERN.*

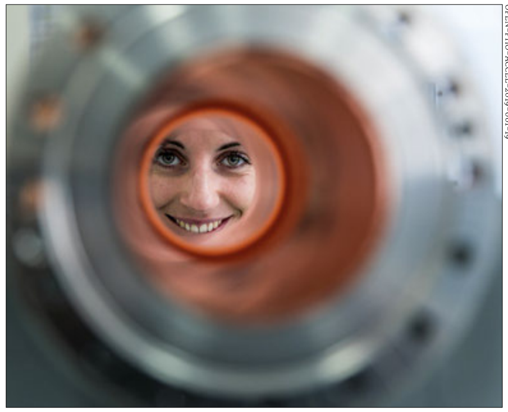
Future Circular Collider Week

FCC feasibility study comes into focus

This year's Future Circular Collider (FCC) Week took place online from 28 June to 2 July, attracting 700 participants from all over the world to debate the next steps needed to produce a feasibility report in 2025/2026, in time for the next update to the European Strategy for Particle Physics in 2026/2027. The current strategy, agreed in 2020, sets an electron–positron Higgs factory as the highest priority facility after the LHC, along with the investigation of the technical and financial feasibility of such a Higgs factory, followed by a high-energy hadron collider placed in the same 100 km tunnel. The FCC feasibility study will focus on the first stage (tunnel and e^+e^- collider) in the next five years.

Although the FCC is a long-term project with a horizon up to the 22nd century, its timescales are rather tight. A post-LHC collider should be operational around the 2040s, ensuring a smooth continuation from the High-Luminosity LHC, so construction would need to begin in the early 2030s. Placement studies to balance geological and territorial constraints with machine requirements and physics performance suggest that the most suitable scenarios are based on a 92 km-circumference tunnel with eight surface sites.

The next steps are subsurface investigations of high-risk areas, surface-site initial-state analysis and verification of in-principle feasibility with local authorities. A "Mining the Future" competition has been launched to solicit ideas for how to best use the nine million cubic metres of molasse that would be excavated from the tunnel.



CERN-PHO-ACCEL-2019-001-19

Superconducting *A key technology for FCC-ee is the development of efficient superconducting radio-frequency cavities, as pictured here with CERN's Sarah Aull.*

Beyond the LHC

A highlight of the week was the exploration of the physics case of a post-LHC collider. Matthew Reece (Harvard University) identified dark matter, the baryon asymmetry and the origin of primordial density perturbations as key experimental motivations, and the electroweak hierarchy problem, the strong CP problem and the mystery of flavour mixing patterns as key theoretical motivations. The present situation in particle physics is reminiscent of the early days of superconductivity, he noted, when we had a phenomenological description of symmetry breaking in superconductivity, but no microscopic picture. Constraining the shape of the Higgs potential could allow a similar breakthrough for electroweak symmetry breaking. Regarding recent anomalous measurements, such as those of the muon's magnetic moment, Reece noted that while these measurements could give us the coefficients of one higher dimension operator in an effective-field-theory description of new physics, only colliders can systematically produce and characterise the nature of any new physics. FCC-ee and FCC-hh both have exciting and complementary roles to play.

A key technology for FCC-ee is the development of efficient superconducting radio-frequency (SRF) cavities to compensate for the 100 MW synchrotron radiation power loss in all modes of operation from the Z pole up to the top threshold at 365 GeV. A staged RF system is foreseen as the baseline scenario, with low-impedance single-cell 400 MHz Nb/Cu cavities for Z running replaced by four-cell Nb/Cu cavities for W and Higgs operation, and later augmented by five-cell 800 MHz bulk Nb cavities at the top threshold.

As well as investigations into the use of HIPIMS coating and the fabrication of copper substrates, an innovative slotted waveguide elliptical (SWELL) cavity design was presented that would operate at 600 or 650 MHz. SWELL cavities optimise the surface area, simplify the coating process and avoid the need for welding in critical areas, which could reduce the performance of the cavity. The design profits from previous work on CLIC, and may offer a simplified installation schedule while also finding applications outside of high-energy physics. A prototype will be tested later this year.

FCC

Several talks also pointed out synergies with the RF systems needed for the proposed electron–ion collider at Brookhaven and the Powerful Energy-Recovery Linac for Experiments (PERLE) project at Orsay, and called for stronger collaboration between the projects.

Machine design

Another key aspect of the study regards the machine design. Since the conceptual design report last year, the pre-injector layout for FCC-ee has been simplified, and key FCC-ee concepts have been demonstrated at Japan's SuperKEKB collider, including a new world-record luminosity of 3.12×10^{34} cm^{-2} s^{-1} in June with a betatron function of $\beta^*_y = 1$ mm. Separate tests squeezed the beam to just $\beta^*_y = 0.8$ mm in both rings.

Other studies reported during FCC Week 2021 demonstrated that hosting four experiments is compatible with a new four-fold symmetric ring. This redundancy is thought to be essential for high-precision measurements, and different detector solutions will be invaluable in uncovering hidden systematic biases. The meeting also followed up on the proposal for energy-recovery linacs (ERLs) at FCC-ee, potentially extending the energy reach to 600 GeV if deemed necessary during the previous physics runs. First studies for the use of the FCC-ee booster as a photon source were also presented, potentially leading to applications in medicine and industry, precision QED studies and fundamental-symmetry tests.

Participants also tackled concepts for power reduction and power recycling, to ensure that FCC is sustainable and environmentally friendly. Ideas relating to FCC-ee include making the magnets superconducting rather than normal conducting, improving the klystron efficiency, using ERLs and other energy-storage devices, designing "twin" dipole and quadrupole magnets with a factor-two power saving, and coating SRF cavities with a high-temperature superconductor.

All in all, FCC Week 2021 saw tremendous progress across different areas of the study. The successful completion of the FCC Feasibility Study (2021–2025) will be a crucial milestone for the future of CERN and the field.

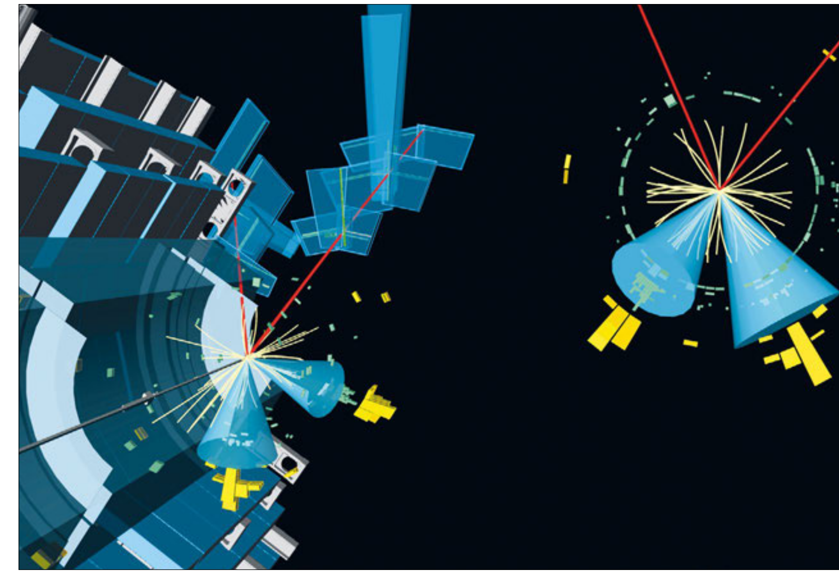
Panos Charitos *CERN.*

LHC Physics

LHCP sees a host of new results

More than 1000 physicists took part in the ninth Large Hadron Collider Physics (LHCP) conference from 7 to 12 June. The in-person conference was to have been held in Paris, however for the second year in a row the organisers efficiently moved the meeting online, without a registration fee, thanks to the support of CERN and IUPAP. While the conference experience cannot be the same over a video link, the increased accessibility for people from all parts of the international community was evident, with LHCP21 participants hailing from institutes across 54 countries

The LHCP format traditionally has plenary sessions in the mornings and late afternoons, with parallel sessions in the middle of the day. This "shape" was kept for the online meeting, with a shorter day to improve the practicality of joining from distant time zones. This resulted in a dense format with seven-fold parallel sessions, allowing all parts of the LHC programme, both experimental and theoretical, to be explored in detail. The overall vitality of the programme is illustrated by the raw statistics: a grand total of 238 talks and 122 posters were presented.



ATLAS-PHOTO-2021-052-1

ZH → μμcc candidate *ATLAS presented a new search for Higgs decays to charm quarks using powerful new charm-tagging techniques.*

From third to second

Nine years on from the discovery of the 125 GeV Higgs boson, measurements have progressed to a new level of precision with the full Run-2 data. Both ATLAS and CMS presented new results on Higgs production, helping constrain the dynamics of the production mechanisms via differential and "simplified template" cross-section measurements. While the couplings of the Higgs to third-generation fermions are now established, last year saw a strong focus on the couplings to the second generation. After first evidence for Higgs decays to muons was reported from CMS and ATLAS results earlier in the year, ATLAS presented a new search with the full Run-2 data for Higgs decays to charm quarks using powerful new charm-tagging techniques. Both CMS and ATLAS showed updated searches for Higgs-pair production, with ATLAS being able to exclude a production rate more than 4.1 times the Standard Model (SM) prediction at 95% confidence. This is a process that should be observable with High-Luminosity LHC statistics, if it is as predicted in the SM. A host of searches were also reported, some using the Higgs as a tool to probe for new physics.

The most puzzling hints from the LHC Run 1 seem to strengthen in Run 2. LHCb presented analyses relating to the "flavour anomalies" found most notably in $b\to s\mu^+\mu^-$ decays, updated to the full data statistics, in multiple channels (p15). While no result yet passes a 5σ difference from SM expectations, the significances continue to creep upwards. Searches by ATLAS and CMS for potential new particles or effects at high masses that could indicate an associated new-physics mechanism continue to draw a blank, however. This remains a dilemma to be studied with more precision and data in Run 3. Other results in the flavour sector from LHCb included a new measurement of the lifetime of the Ω_c, four times longer than previous measurements (*CERN Courier* July/August 2021 p17) and the first observation of a mass difference between the mixed D^0–$\bar{D}^0$ meson mass eigenstates (*CERN Courier* July/August 2021 p8).

A wealth of results was presented from heavy-ion collisions. Measurements with heavy quarks were prominent here as well. ALICE reported various studies of the differences in heavy-flavour hadron production in proton–proton and heavy-ion collisions, for example using D mesons. CMS reported the first observation of B_c meson production in heavy-ion collisions, and also first evidence for top-quark pair production in lead–lead collisions. ATLAS used heavy-flavour decays to muons to compare suppression of b- and c-hadron production in lead–lead and proton–proton collisions. Beyond the ions, ALICE also showed intriguing new results demonstrating that the relative rates of different types of c-hadron production differ in proton–proton collisions compared to earlier experiments using e^+e^- and ep collisions at LEP and HERA (p15).

Last year saw a strong focus on the couplings to the second generation

Looking forward, the experiments reported on their preparations for the coming LHC Run 3, including substantial upgrades. While some work has been slowed by the pandemic, recommissioning of the detectors has begun in preparation for physics data taking in spring 2022, with the brighter beams expected from the upgraded CERN accelerator chain. One constant to rely on, however, is that LHCP will continue to showcase the fantastic panoply of physics at the LHC.

Dave Charlton *University of Birmingham.*

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STRANGE QUARK MATTER

Experiment and theory trade blows at SQM 2021

The 19th international conference on strangeness in quark matter (SQM) was hosted virtually by Brookhaven National Laboratory from 17 to 22 May, attracting more than 300 participants. The series deals with the role of strange and heavy-flavour quarks in high-energy heavy-ion collisions and astro-physical phenomena.

New results on the production of strangeness in heavy-ion collisions were presented for a variety of collision energies and systems. In an experimental highlight, the ALICE collaboration reported that the number of strange baryons depends more on the final-state multiplicity than the initial-state energy. On the theory side, it was shown that several models can explain the suppression of strange particles at low multiplicities. ALICE also presented new measurements of the charm cross section and fragmentation functions in proton–proton (pp) collisions. When compared to e^+e^- collisions, these results suggest that the universality of parton-to-hadron fragmentation may be broken.

Moving on to heavy flavours, the ATLAS collaboration presented results for the suppression of heavy-flavour production compared to pp collisions and the angular anisotropy of heavy mesons in heavy-ion collisions. These measurements are crucial for constraining models of in-medium energy loss. Interestingly, while charm seems to follow the flow of the quark–gluon plasma, beauty does not seem to flow. Better statistics are needed to constrain theoretical models. On the theory side, extremely interesting new calculations using open quantum systems coupled with potential non-relativistic QCD calculations were used to compute both the suppression and anisotropic flow of bottomonium states.

Brookhaven National Laboratory

STAR detector *Experiments at BNL's Relativistic Heavy-Ion Collider are seeking to confirm hints of extrema as a function of beam energy.*

Hints of extrema

Another important goal of the field is to determine experimentally whether a critical point exists in the phase diagram of strongly interacting matter, and, if so, where it is located. The STAR experiment at the Relativistic Heavy Ion Collider (RHIC) presented results on higher order cumulants of net-proton fluctuations over a range of collision energies. Extrema as a function of beam energy are expected to indicate critical behaviour. New data from the Beam Energy Scan II programme at RHIC is expected to provide much-needed statistics to confirm hints of extrema in the data. On the theory side, new lattice QCD calculations of second-order net-baryon cumulants were presented, as well as new expansion schemes to extend the lattice-QCD equation of state to larger net baryon chemical potentials that are not computable directly, because of the fermion-sign problem. Another study included the lattice-QCD equation of state and susceptibilities in a hydrodynamic calculation to allow for a more direct comparison to experimental measurements of net-proton fluctuations. Significant differences between net-proton and net-baryon fluctuations were quantified.

The study of the quark–gluon plasma's vorticity via the measurement of the polarisation of hyperons was also a major topic. Theoretical calculations obtain the opposite sign to the data for the angular differential measurement. Attempts to solve this discrepancy presented at SQM 2021 featured shear-dependent terms and a stronger "memory" of the strange-quark spin.

Various new applications of machine learning and artificial intelligence were also discussed, for example, for determining the order of the phase transition and constraining the neutron-star equation of state.

Overall, there were 41 plenary and 96 parallel talks at SQM 2021, poignantly including presentations in memory of Jean Cleymans, Jean Letessier, Dick Majka and Jack Sandweiss, who all made exceptional impacts on the field.

The next SQM conference will be held from 13 to 18 June 2022 in Busan, South Korea.

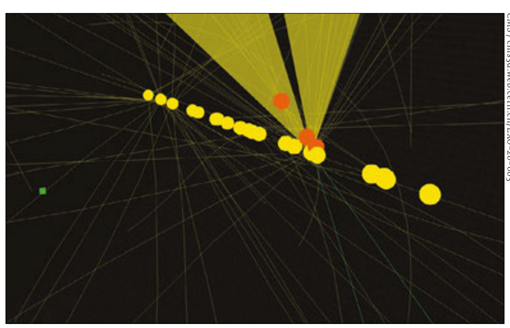
Bjoern Schenke *Brookhaven National Laboratory.*

LLP9

Long-lived particles gather interest

From 25 to 28 May, the long-lived particle (LLP) community marked five years of stretching the limits of searches for new physics with its ninth and best-attended workshop yet, with more than 300 registered participants.

LLP9 played host to six new results, three each from ATLAS and CMS. These included a remarkable new ATLAS paper searching for stopped particles: beyond-the-Standard Model (BSM) LLPs that can be produced in a proton–proton collision and then get stuck in the detector before decaying minutes, days or weeks later. Good hypothetical examples are the so-called gluino R-hadrons that occur in supersymmetric models. Also featured was a new CMS search for displaced di-muon resonances using "data scouting" – a unique method of increasing the number of potential signal events kept at the trigger level by reducing the event information that is retained. Both experiments presented new results searching for the Higgs boson decaying to LLPs (see "LLP candidate" figure).



CMS / cms3d.web.cern.ch/EXO-20-003

LLP candidate *A CMS candidate event for the decay of a Higgs boson into a pair of LLPs, which decay into jets (yellow bands) containing secondary vertices (orange circles), in association with $Z \to e^+e^-$ (green tracks).*

Long-lived particles can also be produced in a collision inside ATLAS, CMS or LHCb and live long enough to drift ▷

entirely outside of the detector volume. To ensure that this discovery avenue is also covered for the future of the LHC's operation, there is a rich set of dedicated LLP detectors either approved or proposed, and LLP9 featured updates from MoEDAL, FASER, MATHUSLA, CODEX-b, MilliQan, FACET and SND@LHC, as well as a presentation about the proposed forward physics facility for the High-Luminosity LHC (HL-LHC).

Reinterpreting machine learning

The liveliest parts of any LLP community workshop are the brainstorming and hands-on working-group sessions. LLP9 included multiple vibrant discussions and working sessions, including on heavy neutral leptons and the ability of physicists who are not members of experimental collaborations to be able to re-interpret LLP searches – a key issue for the LLP community. At LLP9, participants examined the challenges inherent in re-interpreting LLP results that use machine learning techniques, by now a common feature of particle-physics analyses. For example, boosted decision trees (BDTs) and neural networks (NNs) can be quite powerful for either object identification or event-level discrimination in LLP searches, but it's not entirely clear how best to give theorists access to the full original BDT or NN used internally by the experiments.

LLP searches at the LHC often must also grapple with background sources that are negligible for the majority of searches for prompt objects. These backgrounds – such as cosmic muons, beam-induced backgrounds, beam-halo effects and cavern backgrounds – are reasonably well-understood for Run 2 and Run 3, but little study has been performed for the upcoming HL-LHC, and LLP9 featured a brainstorming session about what such non-standard backgrounds might look like in the future.

Also looking to the future, two very forward-thinking working-group sessions were held on LLPs at a potential future muon collider and at the proposed Future Circular Collider (FCC). Hadron collisions at ~100 TeV in FCC-hh would open up completely unprecedented discovery potential, including for LLPs, but it's unclear how to optimise detector designs for both LLPs and the full slate of prompt searches.

Finally, LLP9 hosted an in-depth working-group session dedicated to the simulation of "dark showers", in collaboration with the organisers of the dark-showers study group connected to the Snowmass process, which is currently shaping the future of US particle physics. Dark showers are a generic and poorly understood feature of a potential BSM dark sector with similarities to QCD, which could have its own "dark hadronisation" rules. Simulating dark showers is a longstanding challenge. More than 50 participants joined for a hands-on demonstration of simulation tools and a discussion of the dark-showers Pythia module, highlighting the growing interest in this subject in the LLP community.

Simulating dark showers is a longstanding challenge

LLP9 was raucous and stimulating, and identified multiple new avenues of research. LLPX, the tenth workshop in the series, will be held in November this year.

James Beacham *Duke University and* **Albert De Roeck** *CERN.*

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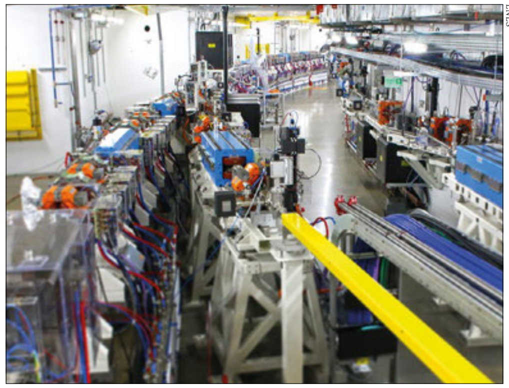
International Particle Accelerator Conference

IPAC thrives online


LNLS

Sirius storage ring *A newly built fourth-generation light source at the Laboratório Nacional de Luz Síncrotron, which virtually hosted IPAC this year.*

The annual International Particle Accelerator Conference (IPAC) promotes collaboration among scientists, engineers, technicians, students and industrial partners across the globe. Originally to be hosted this year by the Laboratório Nacional de Luz Síncrotron (LNLS) in Campinas, Brazil, the conference was moved online when it became clear that the global pandemic would prohibit travel. IPAC21 was nevertheless highly successful, attracting more than 1750 participants online from 24 to 28 May. Despite the technical and logistical challenges, the virtual platform provided many advantages, including low or zero registration fees and a larger, younger and more diverse demographic than typical in-person events, which tend to attract about 1000 delegates.

In order to allow worldwide virtual participation, live plenary presentations were limited to two hours daily. Highlights included Harry Westfahl, Jr (LNLS) on the scientific capabilities of fourth-generation storage-ring light sources; Thomas Glasmacher (FRIB) on the newly commissioned Facility for Rare Isotope Beams at Michigan State University; Norbert Holtkamp (SLAC) on the future of high-power free-electron lasers; Houjun Qian (DESY) on radio-frequency photocathode guns; and Young-Kee Kim (University of Chicago) on future directions in US particle physics. The closing plenary talk was a sobering presentation on climate change and the Brazilian Amazonia region by Paulo Artaxo (University of São Paulo).

The remainder of the talks were pre-recorded with live Q&A sessions, and 400 teleconferencing rooms per day were set up to allow virtual poster sessions. Highlights in topical sessions included "Women in Science: The Inconvenient Truth" by Márcia Barbosa (Universidade Federal do Rio Grande do Sul) and an industrial forum hosted by Raffaella Geometrante (KYMA) on the intersection between government accelerator projects and industry.

IPAC22 is currently planned as an in-person conference in Bangkok, Thailand, from 17 to 22 June next year.

John Byrd *Argonne National Laboratory,* **Liu Lin** *LNLS and* **Regis Neuenschwander** *CNPEM.*

SustHEP 2021

Sustainable high-energy physics


SustHEP 2021

Sustainable participants *Before the pandemic, a typical HEP researcher was expected to cross the world several times a year for conferences, collaboration meetings and detector shifts.*

COVID-19 put the community on a steep learning curve regarding new forms of online communication and collaboration. Before the pandemic, a typical high-energy physics (HEP) researcher was expected to cross the world several times a year for conferences, collaboration meetings and detector shifts, at the cost of thousands of dollars and a sizeable carbon footprint. The online workshop Sustainable HEP – a new initiative this year – attracted more than 300 participants from 45 countries from 28 to 30 June to discuss how the lessons learned in the past two years might help HEP transition to a more sustainable future.

The first day of the workshop focused on how new forms of online interaction could change our professional travel culture. Shaun Hotchkiss (University of Auckland) stressed in a session dedicated to best-practice examples that the purpose of online meetings should not simply be to emulate traditional 20th-century in-person conferences and collaboration meetings. Instead, the community needs to rethink what virtual scientific exchange could look like in the 21st century. This might, for instance, include replacing traditional live presentations by pre-recorded talks that are pre-watched by the audience at their own convenience, leaving more precious conference time for in-depth discussions and interactions among the participants.

Social justice

The second day highlighted social-justice issues, and the potential for greater inclusivity using online formats. Alice Gathoni (British Institute in Eastern Africa) powerfully described the true meaning of online meetings to her: everyone wants to belong. It was only during the first online meetings during the pandemic that she truly felt a real sense of belonging to the global scientific community.

The third day was dedicated to existing sustainability initiatives and new technologies. Mike Seidel (PSI) presented studies on energy-recovery linacs and discussed energy-management concepts for future colliders, including daily "standby modes". Other options include beam dynamics explicitly designed to maximise the ratio of luminosity to power, more efficient radio-frequency cavities, the use of permanent magnets, and high-temperature superconductor cables and cavities. He concluded his talk by asking thought-provoking questions such as whether the HEP community should engage with its international networks to help establish sustainable energy-supply solutions.

The workshop ended by drafting a closing statement that calls upon the HEP community to align its activities with the Paris Climate Agreement and the goal of limiting global warming to 1.5 degrees. This statement can be signed by members of the HEP community until 20 August.

Kai Schmitz *CERN.*

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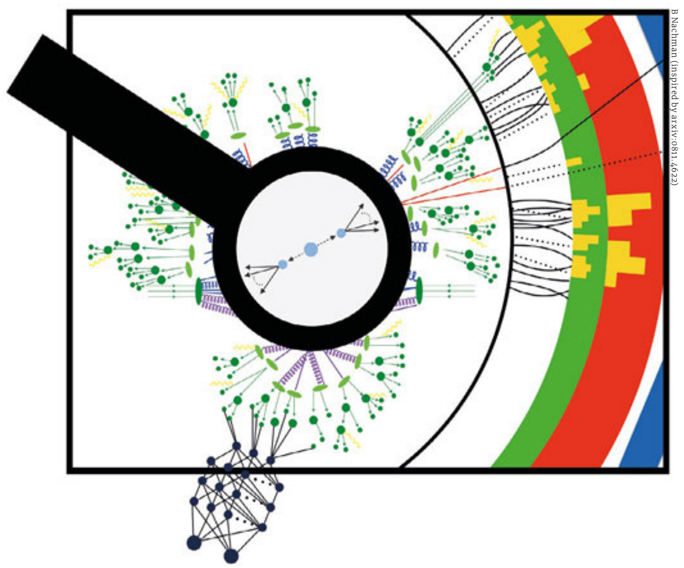
WHAT'S IN THE BOX?



B Nachman (inspired by arxiv:0811.4622)

Magnifying the unexpected *Artist's impression of a neural network probing a black box of complex final states at the LHC.*

The LHC Olympics and Dark Machines data challenges stimulated innovation in the use of machine learning to search for new physics, write Benjamin Nachman and Melissa van Beekveld.

The need for innovation in machine learning (ML) transcends any single experimental collaboration, and requires more in-depth work than can take place at a workshop. Data challenges, wherein simulated "black box" datasets are made public, and contestants design algorithms to analyse them, have become essential tools to spark interdisciplinary collaboration and innovation. Two have recently concluded. In both cases, contestants were challenged to use ML to figure out "what's in the box?"

LHC Olympics

The LHC Olympics (LHCO) data challenge was launched in autumn 2019, and the results were presented at the ML4Jets and Anomaly Detection workshops in spring and summer 2020. A final report summarising the challenge was posted to arXiv earlier this year, written by around 50 authors from a variety of backgrounds in theory, the ATLAS and CMS experiments, and beyond. The name of this community effort was inspired by the first LHC Olympics that took place more than a decade ago, before the start of the LHC. In those olympics, researchers were worried about being able to categorise all of the new particles that would be discovered when the machine turned on. Since then, we have learned a great deal about nature at TeV energy scales, with no evidence yet for new particles or forces of nature. The latest LHC Olympics focused on a different challenge – being able to find new physics in the first place. We now know that new physics must be rare and not exactly like what we expected.

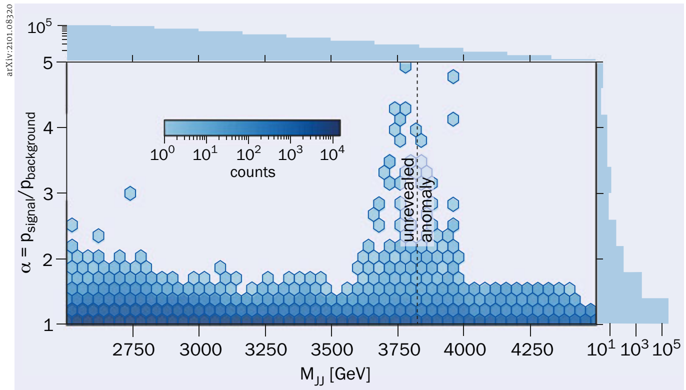
In order to prepare for rare and unexpected new physics, organisers Gregor Kasieczka (University of Hamburg), Benjamin Nachman (Lawrence Berkeley National Laboratory) and David Shih (Rutgers University) provided a set of black-box datasets composed mostly of Standard Model (SM) background events. Contestants were charged with identifying any anomalous events that would be a sign of new physics. These datasets focused on resonant anomaly detection, whereby the anomaly is assumed to be localised – a "bump hunt", in effect. This is a generic feature of new physics produced from massive new particles: the reconstructed parent mass is the resonant feature. By assuming that the signal is localised, one can use regions away from the signal to estimate the background. The LHCO provided one R&D dataset with labels and three black boxes to play with: one with an anomaly decaying into two two-pronged resonances, one without an anomaly, and one with an anomaly featuring two different decay modes (a dijet decay $X \to qq$ and a trijet decay $X \to gY$, $Y \to qq$). There are currently no dedicated searches for these signals in LHC data.

No labels

About 20 algorithms were deployed on the LHCO datasets, including supervised learning, unsupervised learning, weakly supervised learning and semi-supervised learning. Supervised learning is the most widely used method across science and industry, whereby each training example has a label: "background" or "signal". For this challenge, the data do not have labels as we do not know exactly what we are looking for, and so strategies trained with labels from a different dataset often did not work well. By contrast, unsupervised learning generally tries to identify events that are rarely or never produced by the background; weakly supervised methods use some context from data to provide noisy labels; and semi-supervised methods use some simulation information in order to have a partial set of labels. Each method has its strengths and weaknesses,

THE AUTHORS

Benjamin Nachman *Lawrence Berkeley National Laboratory and* **Melissa van Beekveld** *University of Oxford.*



Olympian algorithm *The "anomaly score", α, as a function of the invariant mass of the leading two jets of events in "black box 1" of the LHCO data challenge, in the analysis of Stein, Seljak and Dai, who used an early form of a technique that is now called "Gaussianising iterative slicing". A number of anomalous events are seen near 3750 GeV.*

and multiple approaches are usually needed to achieve a broad coverage of possible signals.

The best performance on the first black box in the LHCO challenge, as measured by finding and correctly characterising the anomalous signals, was by a team of cosmologists at Berkeley (George Stein, Uros Seljak and Biwei Dai) who compared the phase-space density between a sliding signal region and sidebands (see "Olympian algorithm" figure). Overall, the algorithms did well on the R&D dataset, and some also did well on the first black box, with methods that made use of likelihood ratios proving particularly effective. But no method was able to detect the anomalies in the third black box, and many teams reported a false signal for the second black box. This "placebo effect'' illustrates the need for ML approaches to have an accurate estimation of the background and not just a procedure for identifying signals. The challenge for the third black box, however, required algorithms to identify multiple clusters of anomalous events rather than a single cluster. Future innovation is needed in this department.

> **The Dark Machines data challenge focused on developing algorithms broadly sensitive to non-resonant anomalies**

Dark Machines

A second data challenge was launched in June 2020 within the Dark Machines initiative. Dark Machines is a research collective of physicists and data scientists who apply ML techniques to understand the nature of dark matter – as we don't know the nature of dark matter, it is critical to search broadly for its anomalous signatures. The challenge was organised by Sascha Caron (Radboud University), Caterina Doglioni (University of Lund) and Maurizio Pierini (CERN), with notable contributions from Bryan Ostidiek (Harvard University) in the development of a common software infrastructure, and Melissa van Beekveld (University of Oxford) for dataset generation. In total, 39 participants arranged in 13 teams explored various unsupervised techniques, with each team submitting multiple algorithms.

By contrast with LHCO, the Dark Machines data challenge focused on developing algorithms broadly sensitive to non-resonant anomalies. Good examples of non-resonant new physics include many supersymmetric models and models of dark matter – anything where "invisible" particles don't interact with the detector. In such a situation, resonant peaks become excesses in the tails of the missing-transverse-energy distribution. Two datasets were provided: R&D datasets including a concoction of SM processes and many signal samples for contestants to develop their approaches on; and a black-box dataset mixing SM events with events from unspecified signal processes. The challenge has now formally concluded, and its outcome was posted on arXiv in May, but the black-box has not been opened to allow the community to continue to test ideas on it.

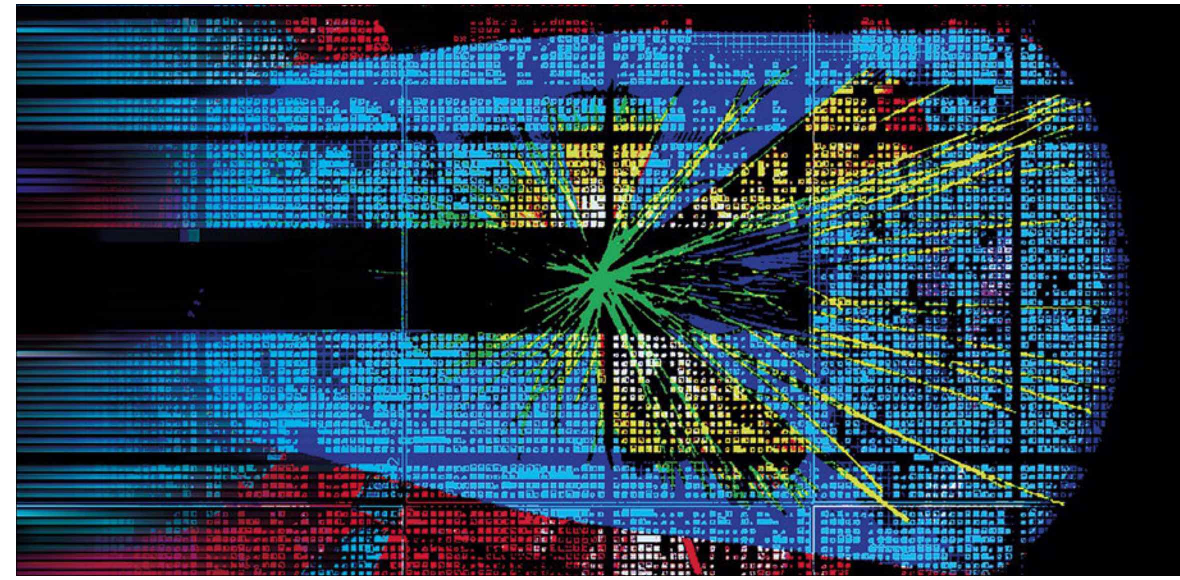
A wide variety of unsupervised methods have been deployed so far. The algorithms use diverse representations of the collider events (for example, lists of particle four-momenta, or physics quantities computed from them), and both implicit and explicit approaches for estimating the probability density of the background (for example, autoencoders and "normalising flows"). While no single method universally achieved the highest sensitivity to new-physics events, methods that mapped the background to a fixed point and looked for events that were not described well by this mapping generally did better than techniques that had a so-called dynamic embedding. A key question exposed by this challenge that will inspire future innovation is how best to tune and combine unsupervised machine-learning algorithms in a way that is model independent with respect to the new physics describing the signal.

The enthusiastic response to the LHCO and Dark Machines data challenges highlights the important future role of unsupervised ML at the LHC and elsewhere in fundamental physics. So far, just one analysis has been published – a dijet-resonance search by the ATLAS collaboration using weakly-supervised ML – but many more are underway, and these techniques are even being considered for use in the level-one triggers of LHC experiments (p31). And as the detection of outliers also has a large number of real-world applications, from fraud detection to industrial maintenance, fruitful cross-talk between fundamental research and industry is possible.

The LHCO and Dark Machines data challenges are a stepping stone to an exciting experimental programme that is just beginning. ●

Further reading

T Aarrestad *et al.* 2021 arXiv:2105.14027.
ATLAS Collaboration 2020 *Phys. Rev. Lett.* **125** 131801.
G Kasieczka *et al.* 2021 arXiv:2101.08320.



S Sioni/CMS-PHO-EVENTS-2021-004-2/M Rayner

Trigger warning *Artist's impression of an FPGA in the level-one trigger scanning for anomalies at a rate of 40 million events per second.*

HUNTING ANOMALIES WITH AN AI TRIGGER

Jennifer Ngadiuba and Maurizio Pierini describe how 'unsupervised' machine learning could keep watch for signs of new physics at the LHC that have not yet been dreamt up by physicists.

In the 1970s, the robust mathematical framework of the Standard Model (SM) replaced data observation as the dominant starting point for scientific inquiry in particle physics. Decades-long physics programmes were put together based on its predictions. Physicists built complex and highly successful experiments at particle colliders, culminating in the discovery of the Higgs boson at the LHC in 2012.

Along this journey, particle physicists adapted their methods to deal with ever growing data volumes and rates. To handle the large amount of data generated in collisions, they had to optimise real-time selection algorithms, or triggers. The field became an early adopter of artificial intelligence (AI) techniques, especially those falling under the umbrella of "supervised" machine learning. Verifying the SM's predictions or exposing its shortcomings became the main goal of particle physics. But with the SM now apparently complete, and supervised studies incrementally excluding favoured models of new physics, "unsupervised" learning has the potential to lead the field into the uncharted waters beyond the SM.

Blind faith

To maximise discovery potential while minimising the risk of false discovery claims, physicists design rigorous data-analysis protocols to minimise the risk of human bias. Data analysis at the LHC is blind: physicists prevent themselves from combing through data in search of surprises. Simulations and "control regions" adjacent to the data of interest are instead used to design a measurement. When the solidity of the procedure is demonstrated, an internal review process gives the analysts the green light to look at the result on the real data and produce the experimental result.

A blind analysis is by necessity a supervised approach. The hypothesis being tested is specified upfront and tested against the null hypothesis – for example, the existence of the Higgs boson in a particular mass range versus its absence. Once spelled out, the hypothesis determines other aspects of the experimental process: how to select the data, how to separate signals from background and how to interpret the result. The analysis is supervised in the sense that humans identify what the possible signals and backgrounds are, and label examples of both for the algorithm.

THE AUTHORS

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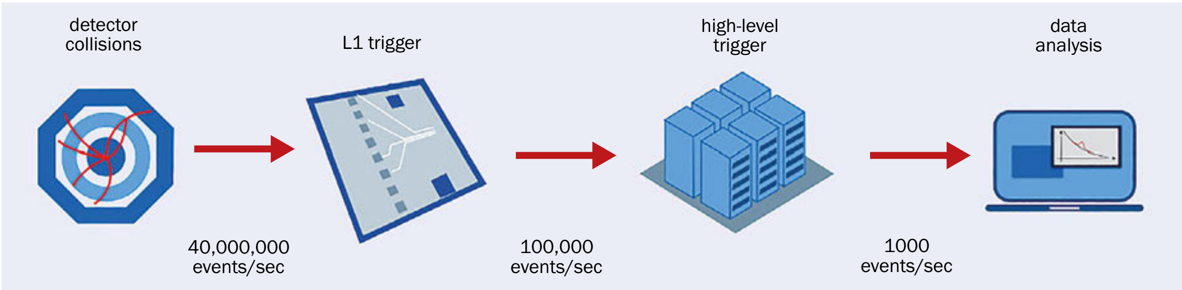


Big data *The data flow from the ATLAS and CMS experiments must be filtered down to just 1000 events per second for the data to be handled by the available downstream computing resources. This is done by a two-stage real-time filtering process. The level-one (L1) trigger is coded on application-specific integrated circuits and field-programmable gate arrays underground near the detectors. The high-level trigger operates on CPUs at ground level. Anomaly detection would be most beneficial at the L1 trigger, where all produced events could be inspected.*

The data flow at the LHC makes the need to specify a signal hypothesis upfront even more compelling. The LHC produces 40 million collision events every second. Each overlaps with 34 others from the same bunch crossing, on average, like many pictures superimposed on top of each other. However, the computing infrastructure of a typical experiment is designed to sustain a data flow of just 1000 events per second. To avoid being overwhelmed by the data pressure, it's necessary to select these 1000 out of every 40 million events in a short time. But how do you decide what's interesting?

This is where the supervised nature of data analysis at the LHC comes into play. A set of selection rules – the trigger algorithms – are designed so that the kind of collisions predicted by the signal hypotheses being studied are present among the 1000 (see "Big data" figure). As long as you know what to look for, this strategy optimises your resources. The discovery in 2012 of the Higgs boson demonstrates this: a mission considered impossible in the 1980s was accomplished with less data and less time than anticipated by the most optimistic guesses when the LHC was being designed. Machine learning played a crucial role in this.

Machine learning

Machine learning (ML) is a branch of computer science that deals with algorithms capable of accomplishing a task without being explicitly programmed to do so. Unlike traditional algorithms, which are sets of pre-determined operations, an ML algorithm is not programmed. It is trained on data, so that it can adjust itself to maximise its chances of success, as defined by a quantitative figure of merit.

To explain further, let's use the example of a dataset of images of cats and dogs. We'll label the cats as "0" and the dogs as "1", and represent the images as a two-dimensional array of coloured pixels, each with a fraction of red, green and blue. Each dog or cat is now a stack of three two-dimensional arrays of numbers between 0 and 1 – essentially just the animal pictured in red, green and blue light. We would like to have a mathematical function converting this stack of arrays into a score ranging from 0 to 1. The larger the score, the higher the probability that the image is a dog. The smaller the score, the higher the probability that the image is a cat. An ML algorithm is a function of this kind, whose parameters are fixed by looking at a given dataset for which the correct labels are known. Through a training process, the algorithm is tuned to minimise the number of wrong answers by comparing its prediction to the labels.

Now replace the dogs with photons from the decay of a Higgs boson, and the cats with detector noise that is mistaken to be photons. Repeat the procedure, and you will obtain a photon-identification algorithm that you can use on LHC data to improve the search for Higgs bosons. This is what happened in the CMS experiment back in 2012. Thanks to the use of a special kind of ML algorithm called boosted decision trees, it was possible to maximise the accuracy of the Higgs-boson search, exploiting the rich information provided by the experiment's electromagnetic calorimeter. The ATLAS collaboration developed a similar procedure to identify Higgs bosons decaying into a pair of tau leptons.

Photon and tau-lepton classifiers are both examples of supervised learning, and the success of the discovery of the Higgs boson was also a success story for applied ML. So far so good. But what about searching for new physics?

Typical examples of new physics such as supersymmetry, extra dimensions and the underlying structure for the Higgs boson have been extensively investigated at the LHC, with no evidence for them found in data. This has told us a great deal about what the particles predicted by these scenarios cannot look like, but what if the signal hypotheses are simply wrong, and we're not looking for the right thing? This situation calls for "unsupervised" learning, where humans are not required to label data. As with supervised learning, this idea doesn't originate in physics. Marketing teams use clustering algorithms based on it to identify customer segments. Banks use it to detect credit-card fraud by looking for anomalous access patterns in customers' accounts. Similar anomaly detection techniques could be used at the LHC to single out rare events, possibly originating from new, previously undreamt of, mechanisms.

Unsupervised learning

Anomaly detection is a possible strategy for keeping watch for new physics without having to specify an exact signal. A kind of unsupervised ML, it involves ranking an unlabelled dataset from the most typical to the most atypical, using a ranking metric learned during training. One of the advantages of this approach is that the algorithm can be trained on data recorded by the experiment rather than simulations. This could, for example, be a control sample that we know to be dominated by SM processes: the algorithm will learn how to reconstruct these events "exactly" – and conversely how to rank unknown processes as atypical. As a proof of principle, this strategy has already been applied to re-discover the top quark using the first open-data release by the CMS collaboration.

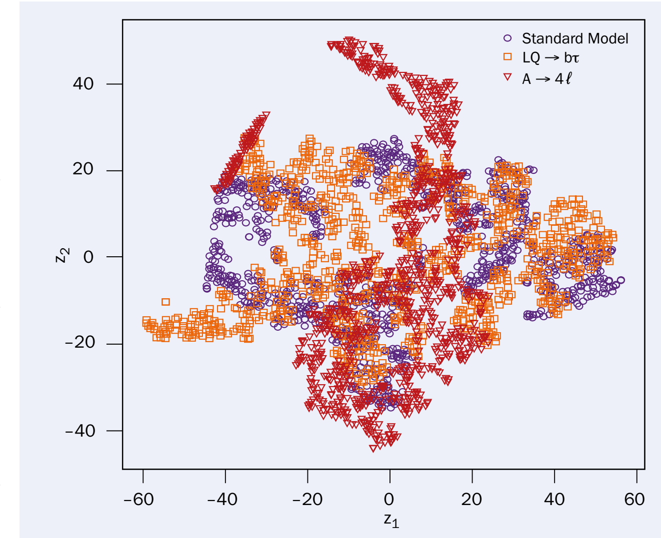
This approach could be used in the online data processing at the LHC and applied to the full 40 million collision events produced every second. Clustering techniques commonly used in observational astronomy could be used to highlight the recurrence of special kinds of events.

In case a new kind of process happens in an LHC collision, but is discarded by the trigger algorithms serving the traditional physics programme, an anomaly-detection algorithm could save the relevant events, storing them in a special stream of anomalous events (see "Anomaly hunting" figure). The ultimate goal of this approach would be the creation of an "anomaly catalogue" of event topologies for further studies, which could inspire novel ideas for new-physics scenarios to test using more traditional techniques. With an anomaly catalogue, we could return to the first stage of the scientific method, and recover a data-driven alternative approach to the theory-driven investigation that we have come to rely on.

This idea comes with severe technological challenges. To apply this technique to all collision events, we would need to integrate the algorithm, typically a special kind of neural network called an autoencoder, into the very first stage of the online data selection, the level-one (L1) trigger. The L1 trigger consists of logic algorithms integrated onto custom electronic boards based on field programmable gate arrays (FPGAs) – a highly parallelisable chip that serves as a programmable emulator of electronic circuits. Any L1 trigger algorithm has to run within the order of one microsecond, and take only a fraction of the available computing resources. To run in the L1 trigger system, an anomaly detection network needs to be converted into an electronic circuit that would fulfill these constraints. This goal can be met using the "hls4ml" (high-level synthesis for ML) library – a tool designed by an international collaboration of LHC physicists that exploits automatic workflows.

Computer-science collaboration

Recently, we collaborated with a team of researchers from Google to integrate the hls4ml library into Google's "QKeras" – a tool for developing accurate ML models on FPGAs with a limited computing footprint. Thanks to this partnership, we developed a workflow that can design a ML model in concert with its final implementation on the experimental hardware. The resulting QKeras+hls4ml bundle is designed to allow LHC physicists to deploy anomaly-detection algorithms in the L1 trigger system. This approach could practically be deployed in L1 trigger systems before the end of LHC Run 3 – a powerful complement to the anomaly-detection techniques that are already being considered for "offline" data analysis on the traditionally triggered samples.



Anomaly hunting *In this illustrative simulation of the unsupervised detection of leptoquark (orange squares) and neutral-scalar-boson (red triangles) decays on a SM background (purple circles), LHC collisions are compressed by an autoencoder and then further compressed to a two-dimensional representation (z_1, z_2), which is suitable for human observation, using the t-SNE algorithm. While most new-physics events overlap with the SM events, the most anomalous populate the outlying regions. These outliers could be used to define a stream of potentially interesting events to be further scrutinised in future data-taking campaigns.*

If this strategy is endorsed by the experimental collaborations, it could create a public dataset of anomalous data that could be investigated during the third LHC long shutdown, from 2025 to 2027. By studying those events, phenomenologists and theoretical physicists could formulate creative hypotheses about new-physics scenarios to test, potentially opening up new search directions for the High-Luminosity LHC.

Blind analyses minimise human bias if you know what to look for, but risk yielding diminishing returns when the theoretical picture is uncertain, as is the case in particle physics after the first 10 years of LHC physics. Unsupervised AI techniques such as anomaly detection could help the field break beyond the limits of human creativity in theory building. In the big-data environment of the LHC, they offer a powerful means to move the field back to data-driven discovery, after 50 years of theory-driven progress. To maximise their impact, they should be applied to every collision produced at the LHC. For that reason, we argue that anomaly-detection algorithms should be deployed in the L1 triggers of the LHC experiments, despite the technological challenges that must be overcome to make that happen. ●

AI techniques could help the field break beyond the limits of human creativity in theory building

Further reading

O Knapp *et al.* 2021 *Eur. Phys. J. Plus* **136** 236.
O Cerri *et al.* 2019 *J. High Energy Phys.* **2019** 36.
J Duarte *et al.* 2018 *J. Instrum.* **13** P07027.

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FORGING THE FUTURE OF AI

The first Sparks! Serendipity Forum at CERN will bring together world experts in artificial intelligence in a spirit of multidisciplinary collaboration. Mark Rayner spoke to some of the participants in the run-up to the September event.

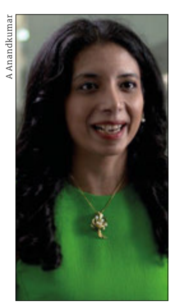
Launching the forum *The CMS collaboration's Jennifer Ngadiuba speaks to fellow Sparks! participant and machine-learning expert Michael Kagan of the ATLAS experiment (right) and Bruno Giussani (left), the global curator of the TED conference series, who will host the public Sparks! event on 18 September.*

Field lines arc through the air. By chance, a cosmic ray knocks an electron off a molecule. It hurtles away, crashing into other molecules and multiplying the effect. The temperature rises, liberating a new supply of electrons. A spark lights up the dark.

This is an excellent metaphor for the Sparks! Serendipity Forum – a new annual event at CERN designed to encourage interdisciplinary collaborations between experts on key scientific issues of the day. The first edition, which will take place from 17 to 18 September, will focus on artificial intelligence (AI). Fifty leading thinkers will explore the future of AI in topical groups, with the outcomes of their exchanges to be written up and published in the journal *Machine Learning: Science and Technology*. The forum reflects the growing use of machine-learning techniques in particle physics and emphasises the importance that CERN and the wider community places on collaborating with diverse technological sectors. Such interactions are essential to the long-term success of the field.

The absence of causal inference in practical machine learning touches on every aspect of AI research, application, ethics and policy

Vivienne Ming is a theoretical neuroscientist and a serial AI entrepreneur



AI is orders of magnitude faster than traditional numerical simulations. On the other side of the coin, simulations are being used to train AI in domains such as robotics where real data is very scarce

Anima Anandkumar is Bren professor at Caltech and director of machine learning research at NVIDIA

The likelihood of sparks flying depends on the weather. To take the temperature, *CERN Courier* spoke to a sample of the Sparks! participants to preview themes for the September event.

Back to the future

In the 1980s, AI research was dominated by code that emulated logical reasoning. In the 1990s and 2000s, attention turned to softening its strong syllogisms into probabilistic reasoning. Huge strides forward in the past decade have rejected logical reasoning, however, instead capitalising on computing power by letting layer upon layer of artificial neurons discern the relationships inherent in vast data sets. Such "deep learning" has been transformative, fuelling innumerable innovations, from self-driving cars to searches for exotica at the LHC (see p31). But many Sparks! participants think that the time has come to reintegrate causal logic into AI.

2020 revealed unexpectedly fragile technological and socio-cultural infrastructures. How we locate our conversations and research about AI in those contexts feels as important as the research itself

Genevieve Bell is director of the School of Cybernetics at the Australian National University and vice president at Intel

Geneva is the home not only of CERN but also of the UN negotiations on lethal autonomous weapons. The major powers must put the evil genie back in the bottle before it's too late

Stuart Russell is professor of computer science at the University of California, Berkeley and coauthor of the seminal text on AI

"A purely predictive system, such as the current machine learning that we have, that lacks a notion of causality, seems to be very severely limited in its ability to simulate the way that people think," says Nobel-prize-winning cognitive psychologist Daniel Kahneman. "Current AI is built to solve one specific task, which usually does not include reasoning about that task," agrees AAAI president-elect Francesca Rossi. "Leveraging what we know about how people reason and behave can help build more robust, adaptable and

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generalisable AI – and also AI that can support humans in making better decisions."

Google's Nyalleng Moorosi identifies another weakness of deep-learning models that are trained with imperfect data: whether AI is deciding who deserves a loan or whether an event resembles physics beyond the Standard Model, its decisions are only as good as its training. "What we call the ground truth is actually a system that is full of errors," she says.

Furthermore, says influential computational neuroscientist Tomaso Poggio, we don't yet understand the statistical behaviour of deep-learning algorithms with mathematical


T Poggio

AI is converging on forms of intelligence that are useful but very likely not human-like

Tomaso Poggio is a cofounder of computational neuroscience and Eugene McDermott professor at MIT

precision. "There is a risk in trying to understand things like particle physics using tools we don't really understand," he explains, also citing attempts to use artificial neural networks to model organic neural networks. "It seems a very ironic situation, and something that is not very scientific."

Stuart Russell, one of the world's most respected voices on AI, echoes Poggio's concerns, and also calls for a greater focus on controlled experimentation in AI research itself. "Instead of trying to compete between Deep Mind and OpenAI on who can do the biggest demo, let's try to answer scientific questions," he says. "Let's work the way scientists work."

Good or bad?

Though most Sparks! participants firmly believe that AI benefits humanity, ethical concerns are uppermost in their minds. From social-media algorithms to autono-


N Moorosi

We always had privacy violation, we had people being blamed falsely for crimes they didn't do, we had mis-diagnostics, we also had false news, but what AI has done is amplify all this, and make it bigger

Nyalleng Moorosi is a research software engineer at Google and a founding member of Deep Learning Indaba

mous weapons, current AI overwhelmingly lacks compassion and moral reasoning, is inflexible and unaware of its fallibility, and cannot explain its decisions. Fairness, inclusivity, accountability, social cohesion, security and international law are all impacted, deepening links between the ethical responsibilities of individuals, multinational corporations and governments. "This is where I appeal to the human-rights framework," says philosopher S Matthew

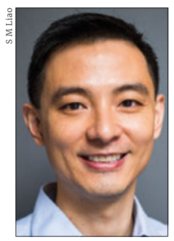

D Kahneman

This idea of partnership, that worries me. It looks to me like a very unstable equilibrium. If the AI is good enough to help the person, then pretty soon it will not need the person

Daniel Kahneman is a renowned cognitive psychologist and a winner of the 2002 Nobel Prize in Economics

Liao. "There's a basic minimum that we need to make sure everyone has access to. If we start from there, a lot of these problems become more tractable."

Far-term ethical considerations will be even more profound if AI develops human-level intelligence. When Sparks! participants were invited to put a confidence interval on when they expect human-level AI to emerge, answers


S M Liao

We need to understand ethical principles, rather than just list them, because then there's a worry that we're just doing ethics washing – they sound good but they don't have any bite

S Matthew Liao is a philosopher and the director of the Center for Bioethics at New York University

ranged from [2050, 2100] at 90% confidence to [2040, ∞] at 99% confidence. Other participants said simply "in 100 years" or noted that this is "delightfully the wrong question" as it's too human-centric. But by any estimation, talking about AI cannot wait.

"With Sparks!, we plan to give a nudge to serendipity in interdisciplinary science by inviting experts from a range of fields to share their knowledge, their visions and their concerns for an area of common interest, first with each other, and then with the public," says Joachim Mnich, CERN's director for research and computing. "For the first edition of Sparks!, we've chosen the theme of AI, which is as important in particle physics as it is in society at large. Sparks! is a unique experiment in interdisciplinarity,


F Rossi

Only a multi-stakeholder and multi-disciplinary approach can build an ecosystem of trust around AI. Education, cultural change, diversity and governance are equally as important as making AI explainable, robust and transparent

Francesca Rossi co-leads the World Economic Forum Council on AI for humanity and is IBM AI ethics global leader and the president-elect of AAAI

which I hope will inspire continued innovative uses of AI in high-energy physics. I invite the whole community to get involved in the public event on 18 September." •

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EMERGENCE

Many physical laws 'emerge' from complexity thanks to a process of data compression. Erik Verlinde sizes up the Standard Model, gravity and intelligence as candidates for future explanation as emergent phenomena.


iStock/georgeclerk

Emergent simplicity *The evolution of a murmuration of starlings cannot be described by following the motion of any individual bird.*

Particle physics is at its heart a reductionistic endeavour that tries to reduce reality to its most basic building blocks. This view of nature is most evident in the search for a theory of everything – an idea that is nowadays more common in popularisations of physics than among physicists themselves. If discovered, all physical phenomena would follow from the application of its fundamental laws.

A complementary perspective to reductionism is that of emergence. Emergence says that new and different kinds of phenomena arise in large and complex systems, and that these phenomena may be impossible, or at least very hard, to derive from the laws that govern their basic constituents. It deals with properties of a macroscopic system that have no meaning at the level of its microscopic building blocks. Good examples are the wetness of water and the superconductivity of an alloy. These concepts don't exist at the level of individual atoms or molecules, and are very difficult to derive from the microscopic laws.

As physicists continue to search for cracks in the Standard Model (SM) and Einstein's general theory of relativity, could these natural laws in fact be emergent from a deeper reality? And emergence is not limited to the world of the very small, but by its very nature skips across orders of magnitude in scale. It is even evident, often mesmerisingly so, at scales much larger than atoms or elementary particles, for example in the murmurations of a flock of birds – a phenomenon that is impossible to describe by following the motion of an individual bird. Another striking example may be intelligence. The mechanism by which artificial intelligence is beginning to emerge from the complexity of underlying computing codes shows similarities with emergent phenomena in physics. One can argue that intelligence, whether it occurs naturally, as in humans, or artificially, should also be viewed as an emergent phenomenon.

Data compression

Renormalisable quantum field theory, the foundation of the SM, works extraordinarily well. The same is true of general relativity. How can our best theories of nature be so successful, while at the same time being merely emergent? Perhaps these theories are so successful precisely because they are emergent.

As a warm up, let's consider the laws of thermodynamics, which emerge from the microscopic motion of many

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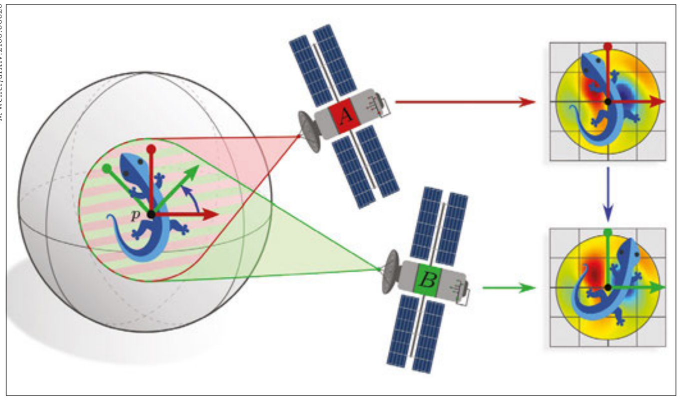


M Weiler/arXiv:2106.06020

Gauge symmetry *To ensure that a neural network recognises a pixelated lizard, its algorithm should be invariant under rotations.*

molecules. These laws are not fundamental but are derived by statistical averaging – a huge data compression in which the individual motions of the microscopic particles are compressed into just a few macroscopic quantities such as temperature. As a result, the laws of thermodynamics are universal and independent of the details of the microscopic theory. This is true of all the most successful emergent theories; they describe universal macroscopic phenomena whose underlying microscopic descriptions may be very different. For instance, two physical systems that undergo a second-order phase transition, while being very different microscopically, often obey exactly the same scaling laws, and are at the critical point described by the same emergent theory. In other words, an emergent theory can often be derived from a large universality class of many underlying microscopic theories.

Entropy is a key concept here. Suppose that you try to store the microscopic data associated with the motion of some particles on a computer. If we need N bits to store all that information, we have 2^N possible microscopic states. The entropy equals the logarithm of this number, and essentially counts the number of bits of information. Entropy is therefore a measure of the total amount of data that has been compressed. In deriving the laws of thermodynamics, you throw away a large amount of microscopic data, but you at least keep count of how much information has been removed in the data-compression procedure.

Successful emergent theories describe universal macroscopic phenomena whose underlying microscopic descriptions may be very different

Emergent quantum field theory

One of the great theoretical-physics paradigm shifts of the 20th century occurred when Kenneth Wilson explained the emergence of quantum field theory through the application of the renormalisation group. As with thermodynamics, renormalisation compresses microscopic data into a few relevant parameters – in this case, the fields and interactions of the emergent quantum field theory. Wilson demonstrated that quantum field theories appear naturally as an effective long-distance and low-energy description of systems whose microscopic definition is given in terms of a quantum system living on a discretised spacetime. As a concrete example, consider quantum spins on a lattice. Here, renormalisation amounts to replacing the lattice by a coarser lattice with fewer points, and redefining the spins to be the average of the original spins. One then rescales the coarser lattice so that the distance between lattice points takes the old value, and repeats this step many times. A key insight was that, for quantum statistical systems that are close to a phase transition, you can take a continuum limit in which the expectation values of the spins turn into the local quantum fields on the continuum spacetime.

This procedure is analogous to the compression algorithms used in machine learning. Each renormalisation step creates a new layer, and the algorithm that is applied between two layers amounts to a form of data compression. The goal is similar: you only keep the information that is required to describe the long-distance and low-energy behaviour of the system in the most efficient way.

So quantum field theory can be seen as an effective emergent description of one of a large universality class of many possible underlying microscopic theories. But what about the SM specifically, and its possible supersymmetric extensions? Gauge fields are central ingredients of the SM and its extensions. Could gauge symmetries and their associated forces emerge from a microscopic description in which there are no gauge fields? Similar questions can also be asked about the gravitational force. Could the curvature of spacetime be explained from an emergent perspective?

String theory seems to indicate that this is indeed possible, at least theoretically. While initially formulated in terms of vibrating strings moving in space and time, it became clear in the 1990s that string theory also contains many more extended objects, known as "branes". By studying the interplay between branes and strings, an even more microscopic theoretical description was found in which the coordinates of space and time themselves start to dissolve: instead of being described by real numbers, our familiar (x, y, z) coordinates are replaced by non-commuting matrices. At low energies, these matrices begin to commute, and give rise to the normal spacetime with which we are familiar. In these theoretical models it was found that both gauge forces and gravitational forces appear at low energies, while not existing at the microscopic level.

While these models show that it is theoretically possible for gauge forces to emerge, there is at present no emergent theory of the SM. Such a theory seems to be well beyond us. Gravity, however, being universal, has been more amenable to emergence.

Emergent gravity

In the early 1970s, a group of physicists became interested in the question: what happens to the entropy of a thermodynamic system that is dropped into a black hole? The surprising conclusion was that black holes have a temperature and an entropy, and behave exactly like thermodynamic systems. In particular, they obey the first law of thermodynamics: when the mass of a black hole increases, its (Bekenstein–Hawking) entropy also increases.

The correspondence between the gravitational laws and the laws of thermodynamics does not only hold near black holes. You can artificially create a gravitational field by accelerating. For an observer who continues to accelerate, even empty space develops a horizon, from behind which light rays will not be able to catch up. These horizons also carry a temperature and entropy, and obey the same thermodynamic laws as black-hole horizons.

It was shown by Stephen Hawking that the thermal radiation emitted from a black hole originates from pair creation near the black-hole horizon. The properties of the pair of particles, such as spin and charge, are undetermined due to quantum uncertainty, but if one particle has spin up (or positive charge), then the other particle must have spin down (or negative charge). This means that the particles are quantum entangled. Quantum entangled pairs can also be found in flat space by considering accelerated observers.

Crucially, even the vacuum can be entangled. By separating spacetime into two parts, you can ask how much entanglement there is between the two sides. The answer to this was found in the last decade, through the work of many theorists, and turns out to be rather surprising. If you consider two regions of space that are separated by a two-dimensional surface, the amount of quantum entanglement between the two sides turns out to be precisely given by the Bekenstein–Hawking entropy formula: it is equal to a quarter of the area of the surface measured in Planck units.

This raises an interesting prospect: if the microscopic quantum data of our universe may be thought of as many entangled qubits, could our current theories of spacetime, particles and forces emerge via data compression? Space, for example, could emerge by forgetting the precise way in which all the individual qubits are entangled, but only preserving the information about the amount of quantum entanglement present in the microscopic quantum state. This compressed information would then be stored in the form of the areas of certain surfaces inside the emergent curved spacetime.

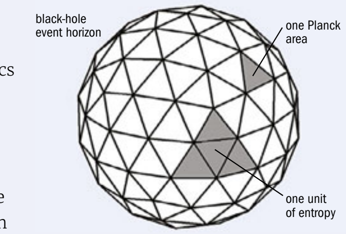
In this description, gravity would follow for free, expressed in the curvature of this emergent spacetime. What is not immediately clear is why the curved spacetime would obey the Einstein equations. As Einstein showed, the amount of curvature in spacetime is determined by the amount of energy (or mass) that is present. It can be shown that his equations are precisely equivalent to an application of the first law of thermodynamics. The presence of mass or energy changes the amount of entanglement, and hence the area of the surfaces in spacetime. This change in area can be computed and precisely leads to the same spacetime curvature that follows from the Einstein equations.

The idea that gravity emerges from quantum entanglement goes back to the 1990s, and was first proposed by Ted Jacobson. Not long afterwards, Juan Maldacena discovered that general relativity can be derived from an underlying microscopic quantum theory without a gravitational force. His description only works for infinite spacetimes with negative curvature called anti-de Sitter (or AdS) space, as opposed to the positive curvature we measure. The microscopic description then takes the form of a scale-invariant quantum field theory – a so-called conformal field theory (CFT) – that lives on the boundary of the AdS-space (see "Holographic renormalisation" panel). It is in this context that the connection between vacuum entanglement and the Bekenstein–Hawking entropy, and the derivation of the Einstein equations from entanglement, are best understood. I have also contributed to these developments in a paper in 2010 that emphasised the role of entropy and information for the emergence of the gravitational force. Over the last decade a lot of progress has been made in our understanding of these connections, in particular the deep connection between gravity and quantum entanglement. Quantum information has taken centre stage in the most recent theoretical developments.

Holographic renormalisation

The AdS/CFT correspondence incorporates a principle called "holography": the gravitational physics inside a region of space emerges from a microscopic description that, just like a hologram, lives on a space with one less dimension and thus can be viewed as living on the boundary of the spacetime region. The extra dimension of space emerges together with the gravitational force through a process called "holographic renormalisation". One successively adds new layers of spacetime. Each layer is obtained from the previous layer through "coarse-graining", in a similar way to both renormalisation in quantum field theory and data-compression algorithms in machine learning.

Unfortunately, our universe is not described by a negatively curved spacetime. It is much closer to a so-called de Sitter spacetime, which has a positive curvature. The main difference between de Sitter space and the negatively curved anti-de Sitter space is that de Sitter space does not have a boundary. Instead, it has a cosmological horizon whose size is determined by the rate of the Hubble expansion. One proposed explanation for this qualitative difference is that, unlike for negatively curved spacetimes, the microscopic quantum state of our universe is not unique, but secretly carries a lot of quantum information. The amount of this quantum information can once again be counted by an entropy: the Bekenstein–Hawking entropy associated with the cosmological horizon.



Black-hole maths *Jacob Bekenstein and Stephen Hawking related entropy to the area of the event horizon. Credit: J Bekenstein*

Emergent intelligence

But what about viewing the even more complex problem of human intelligence as an emergent phenomenon? Since scientific knowledge is condensed and stored in our current theories of nature, the process of theory formation can itself be viewed as a very efficient form of data compression: it only keeps the information needed to make predictions about reproducible events. Our theories provide us with a way to make predictions with the fewest possible number of free parameters.

The same principles apply in machine learning. The way an artificial-intelligence machine is able to predict whether an image represents a dog or a cat is by compressing the microscopic data stored in individual pixels in the most efficient way. This decision cannot be made at the level of individual pixels. Only after the data has been compressed and reduced to its essence does it becomes clear what the picture represents. In this sense, the dog/cat-ness of a pic-

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ture is an emergent property. This is even true for the way humans process the data collected by our senses. It seems easy to tell whether we are seeing or hearing a dog or a cat, but underneath, and hidden from our conscious mind, our brains perform a very complicated task that turns all the neural data that come from our eyes and ears into a signal that is compressed into a single outcome: it is a dog or a cat.

Can intelligence, whether artificial or human, be explained from a reductionist point of view? Or is it an emergent concept that only appears when we consider a complex system built out of many basic constituents? There are arguments in favour of both sides. As human beings, our brains are hard-wired to observe, learn, analyse and solve problems. To achieve these goals the brain takes the large amount of complex data received via our senses and reduces it to a very small set of information that is most relevant for our purposes. This capacity for efficient data compression may indeed be a good definition for intelligence, when it is linked to making decisions towards reaching a certain goal. Intelligence defined in this way is exhibited in humans, but can also be achieved artificially.

Emergence is often summarised with the slogan "the whole is more than the sum of its parts"

Artificially intelligent computers beat us at problem solving, pattern recognition and sometimes even in what appears to be "generating new ideas". A striking example is DeepMind's AlphaZero, whose chess rating far exceeds that of any human player. Just four hours after learning the rules of chess, AlphaZero was able to beat the strongest conventional "brute force" chess program by coming up with smarter ideas and showing a deeper understanding of the game. Top grandmasters use its ideas in their own games at the highest level.

In its basic material design, an artificial-intelligence machine looks like an ordinary computer. On the other hand, it is practically impossible to explain all aspects of human intelligence by starting at the microscopic level of the neurons in our brain, let alone in terms of the elementary particles that make up those neurons. Furthermore, the intellectual capability of humans is closely connected to the sense of consciousness, which most scientists would agree does not allow for a simple reductionist explanation.

Emergence is often summarised with the slogan "the whole is more than the sum of its parts" – or as condensed-matter theorist Phil Anderson put it, "more is different". It counters the reductionist point of view, reminding us that the laws that we think to be fundamental today may in fact emerge from a deeper underlying reality. While this deeper layer may remain inaccessible to experiment, it is an essential tool for theorists of the mind and the laws of physics alike. ●

Further reading
G Musser 2018 *Nature* **557** S3–S6.
M Van Raamsdonk 2020 *Science* **370** 198.
M Weiler *et al.* 2021 arXiv:2106.06020.

BUILDING THE FUTURE OF LHCb

The brand-new "SciFi" tracker and upgraded ring-imaging Cherenkov detectors that are currently being installed are vital for the higher LHC luminosities ahead, write Christoph Frei, Silvia Gambetta and Blake Leverington.

M Brice

Fast track *Planes of LHCb's SciFi tracker being assembled at CERN in late 2019.*

It was once questioned whether it would be possible to successfully operate an asymmetric "forward" detector at a hadron collider. In such a high-occupancy environment, it is much harder to reconstruct decay vertices and tracks than it is at a lepton collider. Following its successes during LHC Run 1 and Run 2, however, LHCb has rewritten the forward-physics rulebook, and is now preparing to take on bigger challenges.

During Long Shutdown 2, which comes to an end early next year, the LHCb detector is being almost entirely rebuilt to allow data to be collected at a rate up to 10 times higher during Run 3 and Run 4 (*CERN Courier* January/February 2019 p34). This will improve the precision of numerous world-best results, such as constraints on the angles of the CKM triangle, while further scrutinising intriguing results in B-meson decays, which hint at departures from the Standard Model.

At the core of the LHCb upgrade project are new detectors capable of sustaining an instantaneous luminosity up to five times that seen at Run 2, and which enable a pioneering software-only trigger that will enable LHCb to process signal data in an upgraded computing farm at the frenetic rate of 40 MHz. The vertex locator (VELO) will be replaced with a pixel version (*CERN Courier* July/August 2021 p36), the upstream silicon-strip tracker will be replaced with a lighter version (the UT) located closer to the beamline, and the electronics for LHCb's muon stations and calorimeters are being upgraded for 40 MHz readout.

Recently, three further detector systems key to dealing with the higher occupancies ahead were lowered into the LHCb cavern for installation: the upgraded ring-imaging

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VOLUME 61 NUMBER 5 SEPTEMBER/OCTOBER 2021
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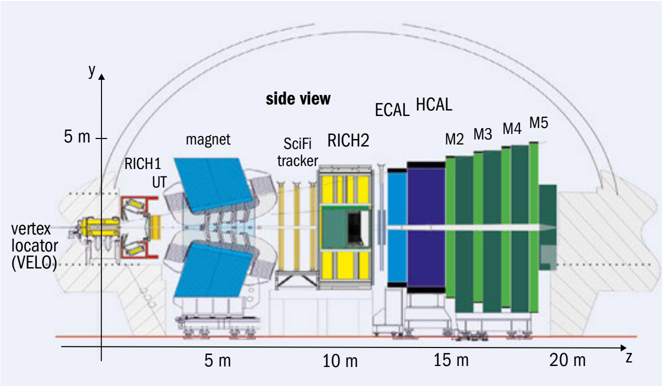
LHCb



Asymmetric anatomy *LHCb's successive detector layers located downstream from the interaction point in the heart of the VELO.*

Cherenkov detectors RICH1 and RICH2 for sharper particle identification, and the brand new "SciFi" (scintillating fibre) tracker.

SciFi tracking

The components of LHCb's SciFi tracker may not seem futuristic at first glance. Its core elements are constructed from what is essentially paper, plastic, some carbon fibre and glue. However, its materials components conceal advanced technologies which, when coupled together, produce a very light and uniform, high-performance detector that is needed to cope with the higher number of particle tracks expected during Run 3.

Located behind the LHCb magnet (see "Asymmetric anatomy" image), the SciFi represents a challenge, not only due to its complexity, but also because the technology – plastic scintillating fibres and silicon photomultiplier arrays – has never been used for such a large area in such a harsh radiation environment. Many of the underlying technologies have been pushed to the extreme during the past decade to allow the SciFi to successfully operate under LHC conditions in an affordable and effective way.

More than 11,000 km of 0.25 mm-diameter polystyrene fibre was delivered to CERN before undergoing meticulous quality checks. Excessive diameter variations were removed to prevent disruptions of the closely packed fibre matrix produced during the winding procedure, and clear improvements from the early batches to the production phase were made by working closely with the industrial manufacturer. From the raw fibres, nearly 1400 multi-layered fibre mats were wound in four of the LHCb collaboration's institutes (see "SciFi spools" image), before being cut and bonded in modules, tested, and shipped to CERN where they were assembled with the cold boxes. The SciFi tracker contains 128 stiff and robust 5 × 0.5 m² modules made of eight mats bonded with two fire-resistant honeycomb and carbon-fibre panels, along with some mechanics and a light-injection system. In total, the design produces nearly 320 m² of detector surface over the 12 layers of the tracking stations.

The scintillating fibres emit photons at blue-green wavelengths when a particle interacts with them. Secondary scintillator dyes added to the polystyrene amplify the light and shift it to longer wavelengths so it can be read out by

P Hopchev/M Pietrzyk

SciFi spools *Scintillating-fibre mat production at EPFL, Lausanne, in 2017.*

custom-made silicon photomultipliers (SiPMs). SiPMs have become a strong alternative to conventional photomultiplier tubes in recent years, due to their smaller channel sizes, easier operation and insensitivity to magnetic fields. This makes them ideal to read out the higher number of channels necessary to identify separate but nearby tracks in LHCb during Run 3.

The width of the SiPM channels, 0.25 mm, is designed to match that of the fibres. Though they need not align perfectly, this provides a better separation power for tracking than the previously used 5 mm gas straw tubes in the outer regions of the detector, while providing a similar performance to the silicon-strip tracker. The tiny channel size results in over 524,288 SiPM channels to collect light from 130 m of fibre-mat edges. A custom ASIC, called the PACIFIC, outputs two bits per channel based on three signal-amplitude thresholds. A field-programmable gate array (FPGA) assigned to each SiPM then groups these signals into clusters, where the location of each cluster is sent to the computing farm. Despite clustering and noise suppression, this still results in an enormous data rate of 20 Tb/s – nearly half of the total data bandwidth of the upgraded LHCb detector.

S Gambetta

RICH2 to go *One of the two photon detector planes of RICH2, fully assembled before installation.*

LHCb's SciFi tracker is the first large-scale use of SiPMs for tracking, and takes advantage of improvements in the technology in the 10 years since the SciFi was proposed. The photon-detection efficiency of SiPMs has nearly doubled thanks to improvements in the design and production of the underlying pixel structures, while the probability of crosstalk between the pixels (which creates multiple fake signals by causing a single pixel to randomly fire without incident light following radiation damage) has been reduced from more than 20% to a few percent by the introduction of microscopic trenches between the pixels. The dark-single-pixel firing rate can also be reduced by cooling the SiPM. Together, these two methods greatly reduce the number of fake-signal clusters such that the tracker can effectively function after several years of operation in the LHCb cavern.

The LHCb collaboration assembled commercial SiPMs on flex cables and bonded them in groups of 16 to a 0.5 m-long 3D-printed titanium cooling bar to form precisely assembled photodetection units for the SciFi modules. By circulating a coolant at a temperature of –50 °C through the cold bar, the dark-noise rate was reduced by a factor of 60. Furthermore, in a first for a CERN experiment, it was

B Leverington

Tracking tall *Completed SciFi C-frames in the assembly hall at Point 8.*

decided to use a new single-phase liquid coolant called Novec-649 from 3M for its non-toxic properties and low greenhouse warming potential (GWP = 1). Historically, C_6F_{14} – which has a GWP = 7400 – was the thermo-transfer fluid of choice. Although several challenges had to be faced in learning how to work with the new fluid, wider use of Novec-649 and similar products could contribute significantly to the reduction of CERN's carbon footprint. Additionally, since the narrow envelope of the tracking stations precludes the use of standard foam insulation of the coolant lines, a significant engineering effort has been required to vacuum insulate the 48 transfer lines from the 24 rows of SiPMs and 256 cold-bars where leaks are possible at every connection.

To date, LHCb collaborators have tirelessly assembled and tested nearly half of the SciFi tracker above ground, where only two defective channels out of the 262,144 tested in the full signal chain were unrecoverable. Four out of 12 "C-frames" containing the fibre modules (see "Tracking tall" image) are now installed and waiting to be connected and commissioned, with a further two installed in mid-July. The remaining six will be completed and installed before the start of operations early next year.

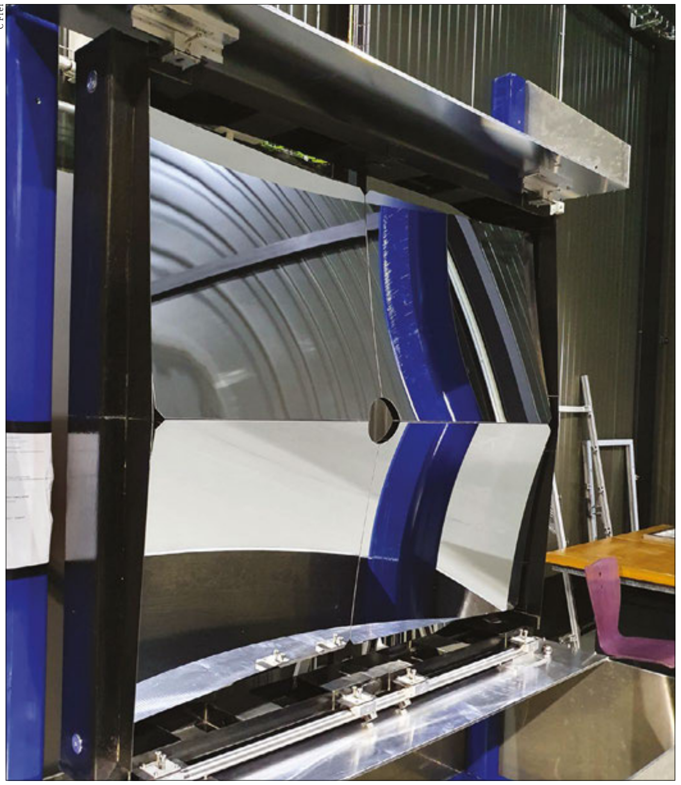
New riches

One of the key factors in the success of LHCb's flavour-physics programme is its ability to identify charged particles, which reduces the background in selected final states and assists in the flavour tagging of b quarks. Two ring-imaging Cherenkov (RICH) detectors, RICH1 and RICH2, located upstream and downstream of the LHCb magnet 1 and 10 m away from the collision point, provide excellent particle identification over a very wide momentum range. They comprise a large volume of fluorocarbon gas (the radiator), in which photons are emitted by charged particles travelling at speeds higher than the speed of light in the gas; spherical and flat mirrors to focus and reflect this Cherenkov light; and two photon-detector planes where the Cherenkov rings are detected and read out by the front-end electronics.

The original RICH detectors are currently being refurbished to cope with the more challenging data-taking conditions of Run 3, requiring a variety of technological

One of the key factors in the success of LHCb's flavour-physics programme is its ability to identify charged particles

CERNCOURIER
Volume 61 Number 5 September/October 2021



C Frei

Cherenkov curves
The spherical mirrors of the new RICH1.

challenges to be overcome. The photon detection system, for example, has been redesigned to adapt to the highly non-uniform occupancy expected in the RICH system, running from an unprecedented peak occupancy of ~35% in the central region of RICH1 down to 5% in the peripheral region of RICH2. Two types of 64-channel multi-anode photomultiplier tubes (MaPMTs) have been selected for the task which, thanks to their exceptional quantum efficiency in the relevant wavelength range, are capable of detecting single photons while providing excellent spatial resolution and very low background noise. These are key requirements to allow pattern-recognition algorithms to reconstruct Cherenkov rings even in the high-occupancy region.

More than 3000 MaPMT units, for a total of 196,608 channels, are needed to fully instrument both upgraded RICH detectors. The already large active area (83%) of the devices has been maximised by arranging the units in a compact and modular "elementary cell" containing a custom-developed, radiation-hard eight-channel ASIC called the Claro chip, which is able to digitise the MaPMT signal at a rate of 40 MHz. The readout is controlled by FPGAs connected to around 170 channels each. The prompt nature of Cherenkov radiation combined with the performance of the new opto-electronics chain will allow the RICH systems to operate within the LHC's 25 ns time window, dictated by the bunch-crossing period, while applying a time-gate of less than 6 ns to provide background rejection.

To keep the new RICHes as compact as possible, the hosting mechanics has been designed to provide both structural support and active cooling. Recent manufacturing techniques have enabled us to drill two 6 mm-diameter ducts over a length of 1.5 m into the spine of the support, through which a coolant (the more environmentally friendly Novec649, as in the SciFi tracker) is circulated. Each element of the opto-electronics chain has been produced and fully validated within a dedicated quality-assurance programme, allowing the position of the photon detectors and their operating conditions to be fine-tuned across the RICH detectors. In February, the first photon-detector plane of RICH2 (see "RICH2 to go" image) became the first active element of the LHCb upgrade to be installed in the cavern. The two planes of RICH2, located at the sides of the beampipe, were commissioned in early summer and will see first Cherenkov light during an LHC beam test in October.

RICH1 presents an even bigger challenge. To reduce the number of photons in the hottest region, its optics have been redesigned to spread the Cherenkov rings over a larger surface. The spatial envelope of RICH1 is also constrained by its magnetic shield, demanding even more compact mechanics for the photon-detector planes. To accommodate the new design of RICH1, a new gas enclosure for the radiator is needed. A volume of 3.8 m^3 of C_4F_{10} is enclosed in an aluminium structure directly fastened to the VELO tank on one side and sealed with a low-mass window on the other, with particular effort placed on building a leak-less system to limit potential environmental impact. Installing these fragile components in a very limited space has been a delicate process, and the last element to complete the gas-enclosure sealing was installed at the beginning of June.

The optical system is the final element of the RICH1 mechanics. The ~2 m^2 spherical mirrors placed inside the gas enclosure are made of carbon fibre composite to limit the material budget (see "Cherenkov curves" image), while the two 1.3 m^2 planes of flat mirrors are made of borosilicate glass for high optical quality. All the mirror segments are individually coated, glued on supports and finally aligned before installation in the detector. The full RICH1 installation is expected to be completed in the autumn, followed by the challenging commissioning phase to tune the operating parameters to be ready for Run 3.

Surpassing expectations

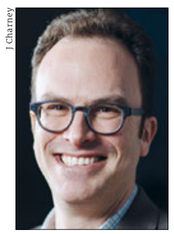
In its first 10 years of operations, the LHCb experiment has already surpassed expectations. It has enabled physicists to make numerous important measurements in the heavy-flavour sector, including the first observation of the rare decay $B_s^0 \to \mu^+\mu^-$, precise measurements of quark-mixing parameters, the discovery of CP violation in the charm sector, and the observation of more than 50 new hadrons including tetraquark and pentaquark states. However, many crucial measurements are currently statistically limited, including those underpinning the so-called flavour anomalies (p15). Together with the tracker, trigger and other upgrades taking place during LS2, the new SciFi and revamped RICH detectors will put LHCb in prime position to explore these and other searches for new physics for the next 10 years and beyond. ●

CERNCOURIER
Volume 61 Number 5 September/October 2021

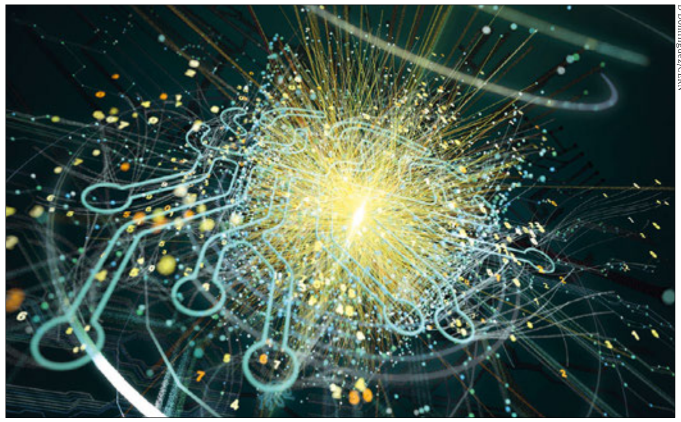
IOP Publishing

Designing an AI physicist

Jesse Thaler argues that particle physicists must go beyond deep learning and design AI capable of deep thinking.


J Charney

Jesse Thaler *is a professor at MIT and director of the US National Science Foundation's Institute for Artificial Intelligence and Fundamental Interactions.*


D Dominguez/CERN

Best of both worlds *We need to merge the insights gained from artificial intelligence and physics intelligence.*

Can we trust physics decisions made by machines? In recent applications of artificial intelligence (AI) to particle physics, we have partially sidestepped this question by using machine learning to augment analyses, rather than replace them. We have gained trust in AI decisions through careful studies of "control regions" and painstaking numerical simulations. As our physics ambitions grow, however, we are using "deeper" networks with more layers and more complicated architectures, which are difficult to validate in the traditional way. And to mitigate 10 to 100-fold increases in computing costs, we are planning to fully integrate AI into data collection, simulation and analysis at the high-luminosity LHC.

To build trust in AI, I believe we need to teach it to think like a physicist.

I am the director of the US National Science Foundation's new Institute for Artificial Intelligence and Fundamental Interactions, which was founded last year. Our goal is to fuse advances in deep learning with time-tested strategies for "deep thinking" in the physical sciences. Many promising opportunities are open to us. Core principles of fundamental physics such as causality and spacetime symmetries can be directly incorporated into the structure of neural networks. Symbolic regression can often translate solutions learned by AI into compact, human-interpretable equations. In experimental physics, it is becoming possible to estimate and mitigate systematic uncertainties using AI, even when there are a large number of nuisance parameters. In theoretical physics, we are finding ways to merge AI with traditional numerical tools to satisfy stringent requirements that calculations be exact and reproducible. High-energy physicists are well positioned to develop trustworthy AI that can be scrutinised, verified and interpreted, since the five-sigma standard of discovery in our field necessitates it.

To build trust in AI, we need to teach it to think like a physicist

It is equally important, however, that we physicists teach ourselves how to think like a machine.

Modern AI tools yield results that are often surprisingly accurate and insightful, but sometimes unstable or biased. This can happen if the problem to be solved is "underspecified", meaning that we have not provided the machine with a complete list of desired behaviours, such as insensitivity to noise, sensible ways to extrapolate and awareness of uncertainties. An even more challenging situation arises when the machine can identify multiple solutions to a problem, but lacks a guiding principle to decide which is most robust. By thinking like a machine, and recognising that modern AI solves problems through numerical optimisation, we can better understand the intrinsic limitations of training neural networks with finite and imperfect datasets, and develop improved optimisation strategies. By thinking like a machine, we can better translate first principles, best practices and domain knowledge from fundamental physics into the computational language of AI.

Beyond these innovations, which echo the logical and algorithmic AI that preceded the deep-learning revolution of the past decade, we are also finding surprising connections between thinking like a machine and thinking like a physicist. Recently, computer scientists and physicists have begun to discover that the apparent complexity of deep learning may mask an emergent simplicity. This idea is familiar from statistical physics, where the interactions of many atoms or molecules can often be summarised in terms of simpler emergent properties of materials. In the case of deep learning, as the width and depth of a neural network grows, its behaviour seems to be describable in terms of a small number of emergent parameters, sometimes just a handful. This suggests that tools from statistical physics and quantum field theory can be used to understand AI dynamics, and yield deeper insights into their power and limitations.

Ultimately, we need to merge the insights gained from artificial intelligence and physics intelligence. If we don't exploit the full power of AI, we will not maximise the discovery potential of the LHC and other experiments. But if we don't build trustable AI, we will lack scientific rigour. Machines may never think like human physicists, and human physicists will certainly never match the computational ability of AI, but together we have enormous potential to learn about the fundamental structure of the universe.

CERNCOURIER
VOLUME 61 NUMBER 5 SEPTEMBER/OCTOBER 2021
IOP Publishing

Stealing theorists' lunch

Artificial-intelligence techniques have been used in experimental particle physics for 30 years, and are becoming increasingly widespread in theoretical physics. Anima Anandkumar and John Ellis explore the possibilities.

How might artificial intelligence make an impact on theoretical physics?

John Ellis (JE): To phrase it simply: where do we go next? We have the Standard Model, which describes all the visible matter in the universe successfully, but we know dark matter must be out there. There are also puzzles, such as what is the origin of the matter in the universe? During my lifetime we've been playing around with a bunch of ideas for tackling those problems, but haven't come up with solutions. We have been able to solve some but not others. Could artificial intelligence (AI) help us find new paths towards attacking these questions? This would be truly stealing theoretical physicists' lunch.

John Ellis *is Clerk Maxwell Professor of Theoretical Physics at King's College London, and* **Anima Anandkumar** *is Bren professor at Caltech and a director of machine-learning research at NVIDIA.*

Anima Anandkumar (AA): I think the first steps are whether you can understand more basic physics and be able to come up with predictions as well. For example, could AI rediscover the Standard Model? One day we can hope to look at what the discrepancies are for the current model, and hopefully come up with better suggestions.

JE: An interesting exercise might be to take some of the puzzles we have at the moment and somehow equip an AI system with a theoretical framework that we physicists are trying to work with, let the AI loose and see whether it comes up with anything. Even over the last few weeks, a couple of experimental puzzles have been reinforced by new results on B-meson decays and the anomalous magnetic moment of the muon. There are many theoretical ideas for solving these puzzles but none of them strike me as being particularly satisfactory in the sense of indicating a clear path towards the next synthesis beyond the Standard Model. Is it imaginable that one could devise an AI system that, if you gave it a set of concepts that we have, and the experimental anomalies that we have, then the AI could point the way?

AA: The devil is in the details. How do we give the right kind of data and knowledge about physics? How do we express those anomalies while at the same time making sure that we don't bias the model? There are anomalies suggesting that the current model is not complete – if you are giving that prior knowledge then you could be biasing the models away from discovering new aspects. So, I think that delicate balance is the main challenge.

JE: I think that theoretical physicists could propose a framework with boundaries that AI could explore. We could tell you what sort of particles are allowed, what sort of interactions those could have and what would still be a well-behaved theory from the point of view of relativity and quantum mechanics. Then, let's just release the AI to see whether it can come up with a combination of particles and interactions that could solve our problems. I think that in this sort of problem space, the creativity would come in the testing of the theory. The AI might find a particle and a set of interactions that would deal with the anomalies that I was talking about, but how do we know what's the right theory? We have to propose some other experiments that might test it – and that's one place where the creativity of theoretical physicists will come into play.

> **Could AI rediscover the Standard Model?**

AA: Absolutely. And many theories are not directly testable. That's where the deeper knowledge and intuition that theoretical physicists have is so critical.

Is human creativity driven by our consciousness, or can contemporary AI be creative?

AA: Humans are creative in so many ways. We can dream, we can hallucinate, we can create – so how do we build those capabilities into AI? Richard Feynman famously said "What I cannot create, I do not understand." It appears that our creativity gives us the ability to understand the complex inner workings of the universe. With the current AI paradigm this is very difficult. Current AI is geared towards scenarios where the training and testing distributions are similar, however, creativity requires extrapolation – being able to imagine entirely new scenarios. So extrapolation is an essential aspect. Can you go from what you have learned and extrapolate new scenarios? For that we need some form of invariance or understanding of the underlying laws. That's where physics is front and centre. Humans have intuitive notions of physics from early childhood. We slowly pick them up from physical interactions with the world. That understanding is at the heart of getting AI to be creative.

JE: It is often said that a child learns more laws of physics than an adult ever will! As a human being, I think that I think. I think that I understand. How can we introduce those things into AI?

AA: We need to get AI to create images, and other kinds of data it experiences, and then reason about the likelihood of the samples. Is this data point unlikely versus another one? Similarly to what we see in the brain, we recently built feedback mechanisms into AI systems. When you are watching me, it's not just a free-flowing system going from the retina into the brain; there's also a feedback system going from the inferior temporal cortex back into the visual cortex. This kind of feedback is fundamental to us being conscious. Building these kinds of mechanisms into AI is the first step to creating conscious AI.

JE: A lot of the things that you just mentioned sound like they're going to be incredibly useful going forward in our systems for analysing data. But how is AI going to devise an experiment that we should do? Or how is AI going to devise a theory that we should test?

AA: Those are the challenging aspects for an AI. A data-driven method using a standard neural network would perform really poorly. It will only think of the data that it can see and not about data that it hasn't seen – what we call "zero-short generalisation". To me, the past decade's impressive progress is due to a trinity of data, neural networks and computing infrastructure, mainly powered by GPUs [graphics processing units], coming together: the next step for AI is a wider generalisation to the ability to extrapolate and predict hitherto unseen scenarios.

Across the many tens of orders of magnitude described by modern physics, new laws and behaviours "emerge" non-trivially in complexity (p39). Could intelligence also be an emergent phenomenon?

JE: As a theoretical physicist, my main field of interest is the fundamental building blocks of matter, and the roles that they play very early in the history of the universe. Emergence is the word that we use when we try to capture

Similarly to what we see in the brain, we recently built feedback mechanisms into AI systems

what happens when you put many of these fundamental constituents together, and they behave in a way that you could often not anticipate if you just looked at the fundamental laws of physics. One of the interesting developments in physics over the past generation is to recognise that there are some universal patterns that emerge. I'm thinking, for example, of phase transitions that look universal, even though the underlying systems are extremely different. So, I wonder, is there something similar in the field of intelligence? For example, the brain structure of the octopus is very different from that of a human, so to what extent does the octopus think in the same way that we do?

AA: There's a lot of interest now in studying the octopus. From what I learned, its intelligence is spread out so that it's not just in its brain but also in its tentacles. Consequently, you have this distributed notion of intelligence that still works very well. It can be extremely camouflaged – imagine being in a wild ocean without a shell to protect yourself. That pressure created the need for intelligence such that it can be extremely aware of its surroundings and able to quickly camouflage itself or manipulate different tools.

JE: If intelligence is the way that a living thing deals with threats and feeds itself, should we apply the same evolutionary pressure to AI systems? We threaten them and only the fittest will survive. We tell them they have to go and find their own electricity or silicon or something like that – I understand that there are some first steps in this direction, computer programs competing with each other at chess, for example, or robots that have to find wall sockets and plug themselves in. Is this something that one could generalise? And then intelligence could emerge in a way that we hadn't imagined?

AA: That's an excellent point. Because what you mentioned broadly is competition – different kinds of pressures that drive towards good, robust objectives. An example is generative adversarial models, which can generate very realistic looking images. Here you have a discriminator that challenges the generator to generate images that look real. These kinds of competitions or games are getting a lot of traction and we have now passed the Turing test when it comes to generating human faces – you can no longer tell very easily whether it is generated by AI or if it is a real person. So, I think those kinds of mechanisms that have competition built into the objective they optimise are fundamental to creating more robust and more intelligent systems.

JE: All this is very impressive – but there are still some elements that I am missing, which seem very important to theoretical physics. Take chess: a very big system but finite nevertheless. In some sense, what I try to do as a theoretical physicist has no boundaries. In some sense, it is infinite. So, is there any hope that AI would eventually be able to deal with problems that have no boundaries?

AA: That's the difficulty. These are infinite-dimensional spaces… so how do we decide how to move around there? What distinguishes an expert like you from an average person is that you build your knowledge and develop intuition – you can quickly make judgments and find which narrow part of the space you want to work on compared to all the possibilities. That's the aspect that is so difficult for AI to figure out. The space is enormous. On the other hand, AI does have a lot more memory, a lot more computational capacity. So can we create a hybrid system, with physicists and machine learning in tandem, to help us harness the capabilities of both AI and humans together? We're currently exploring theorem provers: can we use the theorems that humans have proven, and then add reinforcement learning on top to create very fast theorem solvers? If we can create such fast theorem provers in pure mathematics, I can see them being very useful for understanding the Standard Model and the gaps and discrepancies in it. It is much harder than chess, for example, but there are exciting programming frameworks and data sets available, with efforts to bring together different branches of mathematics. But I don't think humans will be out of the loop, at least for now.

This conversation is abridged from one of a series of podcasts recorded in anticipation of the inaugural Sparks! Serendipity *forum, which will take place at CERN from 17 to 18 September (p36).* **Mark Rayner** *and* **Abha Eli Phoboo** *were asking the questions.*

OPINION LETTERS

Hubble tension questioned

In your recent interview, Licia Verde highlights the "Hubble tension" between the "local measurements of the current expansion rate of the universe, for example, based on supernovae as standard candles, which… give values that cluster around 73 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$" and the value of "around 67 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$" from "measuring what we believe is the same quantity but only within a model, the lambda-cold-dark-matter (ΛCDM) model, which is looking at the baby universe via the cosmic microwave background (CMB)" (*CERN Courier* July/August 2021 p51). "The Hubble tension is certainly one of the most intriguing problems in cosmology," says Verde, who asserts that "it is becoming increasingly unlikely that it is only due to dumb systematics".

In fact, systematic discrepancies that have been noted between supernova datasets are sufficient to undermine the "Hubble tension". Note that the absolute peak magnitude of type-Ia supernovae (assumed to be standard candles) are obtained by calibrating their distances in the "cosmic distance ladder" to local distance anchors via the period-luminosity relation of Cepheid variable stars. The magnitude is then translated into the Hubble parameter via the magnitude–redshift relation of supernovae in the redshift range 0.023–0.15. However, the redshifts of 150 supernovae (all measured in the Sloan Digital Sky Survey) are significantly discrepant between the JLA and Pantheon catalogues. Focusing on these, the latter sample yields 72 $\mathrm{km\,s^{-1}Mpc^{-1}}$, while the former favours 68 $\mathrm{km\,s^{-1}Mpc^{-1}}$ (M Rameez and S Sarkar 2021 *Class. Quantum Grav.* **38** 154005). This is equivalent to the "systematic bias of 0.1–0.15 mag in the intercept of the Cepheid period-luminosity relations of SH0ES galaxies" noted by Efstathiou (G Efstathiou 2020 arXiv:2007.10716). Thus there is no firm basis for the claimed tension. In particular, an independent calibration of supernovae using the "tip of the red giant branch" (TRGB) by Wendy Freedman *et al.* (W Freedman *et al.* 2019 *ApJ* **882** 34) indicates consistency with the CMB value. Nevertheless, more than a hundred theoretical solutions to the Hubble tension have been proposed. As Efstathiou comments (*Mon. Not. R. Astron. Soc* 2021 **505** 3866): "many of the claims in the literature favouring such solutions are caused by a misunderstanding of how distance-ladder measurements actually work".

There are indeed serious problems with the ΛCDM model – not least the complete absence of any theoretical foundation for dark energy – but the "Hubble tension" is not one of them! Indeed "the universe could be much, much more interesting than we assumed," as Verde says, and there is emerging evidence that it is. For example, the rest frames of the CMB and cosmologically distant matter do not coincide, implying a gross violation of the cosmological principle itself (N Secrest *et al.* 2021 *ApJL* **908** L51).

Subir Sarkar *University of Oxford.*

• Author's reply

In this Hubble constant (H_0) matter, the field moves so quickly that plots need to have a full date – not just the year, but also month and day – and publications in many cases become obsolete before they are published. Preprints, seminars and talks are the way to stay up to date with the latest developments. While this opens up a Pandora's box of discussions we could have about the (perhaps too) fast pace of science, let me stick to the point here. As of late July, the consensus among the SH0ES and TRGB groups is that the data agree extremely well in relative distances but not on absolute distances for objects that host Cepheid variables and/or supernovae which are far away enough to be directly useful for constraining H_0. It is crucially important to remember that supernovae alone cannot measure H_0; they need an external calibration. It is this calibration that is uncertain. The moment that the absolute distance of a few key objects that host supernovae/Cepheids is agreed upon at the 1 to 2% level, the local H_0 tension will be resolved. Whether that will yield H_0 near 73 $\mathrm{km\,s^{-1}Mpc^{-1}}$, 68 $\mathrm{km\,s^{-1}Mpc^{-1}}$, or elsewhere, remains to be seen. Data release 4 from the Gaia spacecraft will provide the needed precision.

Licia Verde *University of Barcelona.*

L3 diplomacy

It was a real pleasure to read your article about Paul Lecoq (*CERN Courier* May/June 2021 p59). I was Paul's partner in the development of scintillating crystals, first for L3, then in Crystal Clear, and finally for CMS. With Paul, and to a large extent thanks to him, it was the most enriching period of my career. The inset picture is a good illustration of the importance of links that are forged between first-rank personalities in science and politics – links that were crucial to L3's success.

1982 is certainly the first milestone in L3 history, but it cannot be the date of this picture, which reminds me of exceptional circumstances. The date is 7 February 1986, Chinese New Year, in Shanghai. At that time S.C.C. Ting had already succeeded in involving the Shanghai Institute of Ceramics (SIC) in the L3 experiment, in the production of the BGO crystals for its electromagnetic calorimeter, which started the previous year. However, the initial production rate of the crystals was not sufficient to guarantee that L3's calorimeter would be ready for the planned start of LEP, and a way to double the BGO output had to be found. At this meeting we discussed processing methods, tooling and machinery, and the assembly of a workforce. I was present to address engineering matters. My first visit to SIC had been a two-month stay the previous year, to initiate the crystal machining.

I would like to mention two distinguished members of the Chinese Academy of Sciences (CAS) whose presence was essential to this meeting. Next to and left of S.C.C. Ting is Professor Yan Dongsheng, CAS vice-president and special advisor, and SIC honorary director, who passed away in 2016; and to the far left of the picture is Professor Yin Zhiwen, vice-director of SIC, who passed away in 2006.

Michel Lebeau *retired senior mechanical engineer, IN2P3 and CERN.*

Shanghai City Hall

Not 1982 *Paul Lecoq and Sam Ting (third and fifth from right) stand either side of Jiang Zemin, who went on to become the president of China. Michel Lebeau is at the right of the picture.*

CERNCOURIER

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IOP Publishing

OPINION REVIEWS

An enduring and adaptable design

Resistive Gaseous Detectors: Designs, Performance, and Perspectives

By Marcello Abbrescia, Vladimir Peskov and Paolo Fonte

Wiley

Muon detector *Resistive-plate chambers in the CMS detector (grey disk), pictured during the ongoing second long shutdown of the LHC.*

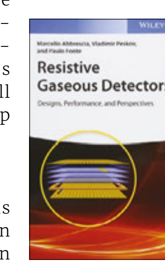
The first truly resistive gaseous detector was invented by Rinaldo Santonico and Roberto Cardarelli in 1981. A kind of parallel-plate detector with electrodes made of resistive materials such as Bakelite and thin-float glass, the design is sometimes also known as a resistive-plate chamber (RPC). Resistive gaseous detectors use electronegative gases and electric fields that typically exceed 10 kV/cm. When a charged particle is incident in the gas gap, the working operational gas is ionised, and primary electrons cause an avalanche as a result of the high electric field. The induced charge is then obtained on the read-out pad as a signal. RPCs have several unique and important practical features, combining good spatial resolution with a time resolution comparable to that of scintillators. They are therefore well suited for fast spacetime particle tracking, as a cost-effective way to instrument large volumes of a detector, for example in muon systems at collider experiments.

Resistive Gaseous Detectors: Designs, Performance, and Perspectives, a new book by Marcello Abbrescia, Vladimir Peskov and Paulo Fonte, covers the basic principles of their operation, historical development, the latest achievements, and their growing applications in various fields from hadron colliders to astrophysics. This book is not only a summary of numerous scientific publications on many different examples of RPCs, but also a detailed description of their design, operation and performance.

The book has nine chapters. The operational principle of gaseous detectors and some of their limitations, most notably the efficiency drop in a high-particle-rate environment, are described. This is followed by a history of parallel-plate detectors, the first classical Bakelite RPC, double-gap RPCs and glass-electrode multi-gap timing RPCs. A modern design of double-gap RPCs and examples for the muon systems like those at ATLAS and CMS at the LHC, the STAR detector at the Relativistic Heavy-Ion Collider at Brookhaven and the multi-gap timing RPC for the time-of-flight system of the HADES experiment at GSI are detailed. Advanced designs with new materials for electrodes for high-rate detectors are then introduced, and ageing and longevity are elaborated upon. A new generation of gaseous detectors with resistive electrodes that can be made with micro-electronic technology is then introduced: these large-area electrodes can easily be manufactured while still achieving high spatial resolutions up to 12 microns.

Homeland security

The final chapter covers applications outside particle physics such as those in medicine exploiting positron-emission tomography. For homeland security, RPCs can be used in muon-scattering tomography with cosmic-ray muons to scan spent nuclear fuel containers without opening them, or to quickly scan incoming cargo trucks without disrupting the traffic of logistics. A key subject not covered in detail, however, is the need to search for environmentally friendly alternatives to gases with high global-warming potential, which are often needed in resistive gaseous detectors at present to achieve stable and sustained operation (*CERN Courier* July/August 2021 p20).



Abbrescia, Peskov and Fonte's book will be useful to researchers specialising in high-energy physics, astronomy, astrophysics, medical physics and radiation measurements, and at all academic levels, from students to seasoned professionals.

Yi Wang *Tsinghua University.*

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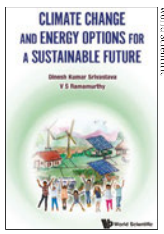
Climate Change and Energy Options for a Sustainable Future

By Dinesh Kumar Srivastava and V S Ramamurthy

World Scientific



Human wellbeing is decided by the rate at which power is consumed

In *Climate Change and Energy Options for a Sustainable Future*, nuclear physicists Dinesh Kumar Srivastava and V S Ramamurthy explore global policies for an eco-friendly future. Facing the world's increasing demand for energy, the authors argue for the replacement of fossil fuels with a new mixture of green energy sources including wind energy, solar photovoltaics, geothermal energy and nuclear energy. Srivastava is a theoretical physicist and Ramamurthy is an experimental physicist with research interests in heavy-ion physics and the quark–gluon plasma. Together, they analyse solutions offered by science and technology with a clarity that will likely surpass the expectations of non-expert readers. Following a pedagogical approach with vivid illustrations, the book offers an in-depth description of how each green-energy option could be integrated into a global-energy strategy.

In the first part of the book, the authors provide a wealth of evidence demonstrating the pressing reality of climate change and the fragility of the environment. Srivastava and Ramamurthy then examine unequal access to energy across the globe. There should be no doubt that human wellbeing is decided by the rate at which power is consumed, they write, and providing enough energy to everyone on the planet to reach a human-development index of 0.8, which is defined by the UN as high human development, calls for about 30 trillion kWh per year – roughly double the present global capacity.

Srivastava and Ramamurthy present the basic principles of alternative renewable sources, and offer many examples, including agrivoltaics in Africa, a floating solar-panel station in California and wind-turbines in the Netherlands and India. Drawing on their own expertise, they discuss nuclear energy and waste-management, accelerator-driven subcritical systems, and the use of high-current electron accelerators for water purification. The book then finally turns to sustainability, showing by means of a wealth of scientific data that increasing the supply of renewable energy, and reducing carbon-intensive energy sources, can lead to sustainable power across the globe, both reducing global-warming emissions and stabilising energy prices for a fairer economy. The authors stress that any solution should not compromise quality of life or development opportunities in developing countries.

This book could not be more timely. It is an invaluable resource for scientists, policymakers and educators.

Panos Charitos *CERN.*

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Volume 61 Number 5 September/October 2021
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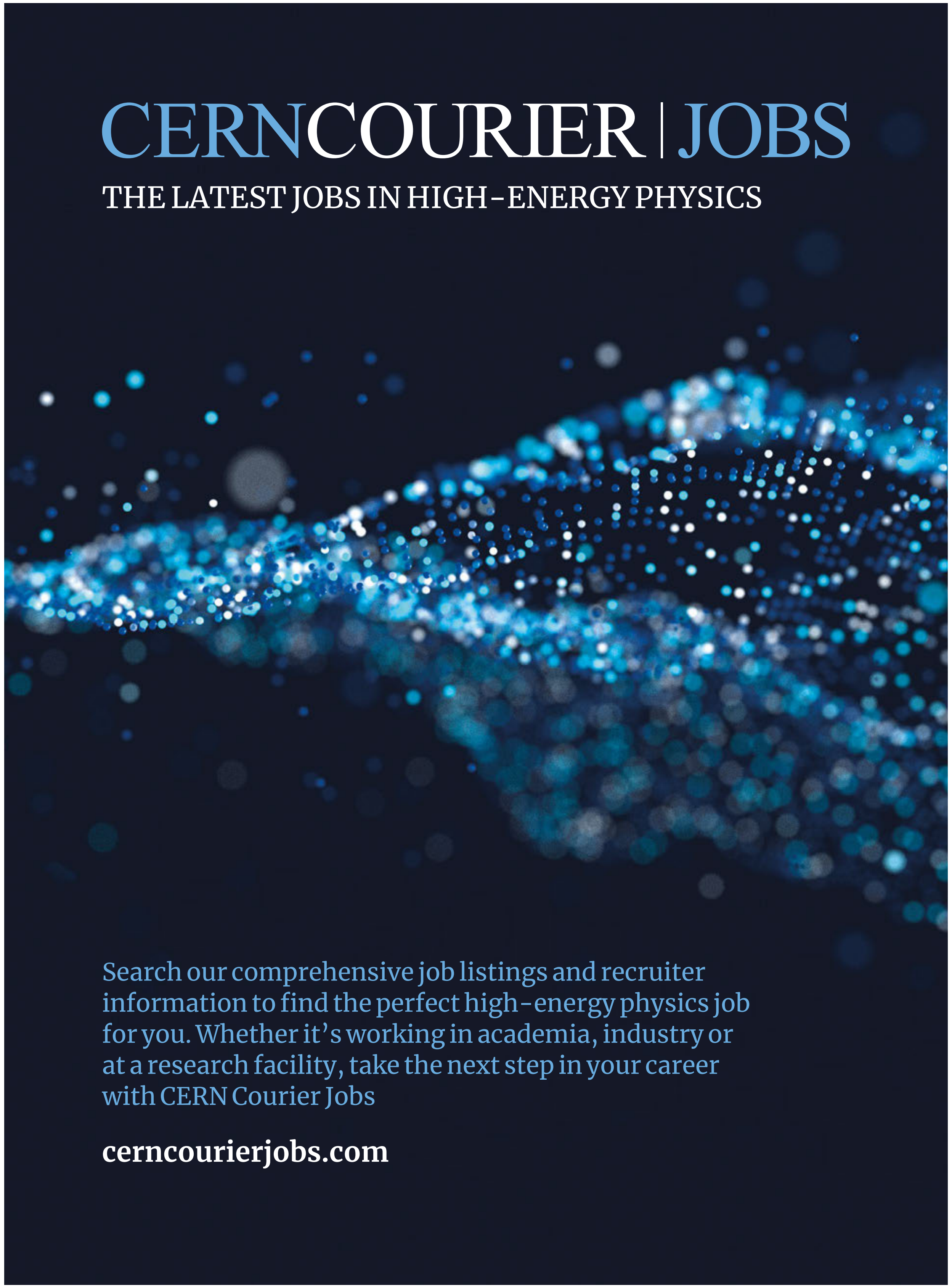


Quantum gravity in the Vatican

Residents of the Vatican Observatory describe life as a full-time physicist in the church.


Vatican Observatory

Missionary of science *Gabriele Gionti presents Pope Francis with a journal containing a recent publication on black holes, gravitational waves and spacetime singularities.*

"Our job is to be part of the scientific community and show that there can be religious people and priests who are scientists," says Gabriele Gionti, a Roman Catholic priest and theoretical physicist specialising in quantum gravity who is resident at the Vatican Observatory.

"Our mission is to do good science," agrees Guy Consolmagno, a noted planetary scientist, Jesuit brother and the observatory's director. "I like to say we are missionaries of science to the believers."

Not only missionaries of faith, then, but also of science. And there are advantages.

"At the Vatican Observatory, we don't have to write proposals, we don't have to worry about tenure and we don't have to have results in three years to get our money renewed," says Consolmagno, who is directly appointed by the Pope. "It changes the nature of the research that is available to us."

"Here I have had time to just study," says Gionti, who explains that he was able to extend his research to string theory as a result of this extra freedom. "If you are a postdoc or under tenure, you don't have this opportunity."

"I remember telling a friend of mine that I don't have to write grant proposals, and he said, 'how do I get in on this?'" jokes Consolmagno, a native of Detroit. "I said that he needed to take a vow of celibacy. He replied, 'it's worth it!'."

Cannonball moment

Clad in T-shirts, Gionti and Consolmagno don't resemble the priests and monks seen in movies. They are connected to monastic tradition, but do not withdraw from the world. As well as being full-time physicists, both are members of the Society of Jesus – a religious order that traces its origin to 1521, when Saint Ignatius of Loyola was struck in the leg by a cannonball at the Battle of Pamplona. Today they help staff at an institution that was founded in 1891, though its origins arguably date back to attempts to fix the date for Easter in 1582.

"It was at the end of the 19th century that the myth began that the church was anti-science, and they would use Galileo as the excuse," says Consolmagno, explaining that the Pope at the time, Pope Leo XIII, wanted to demonstrate that faith and science were fully compatible. "The first thing that the Vatican Observatory did was to take part in the *Carte du Ciel* programme," he says, hinting at a secondary motivation. "Every national observatory was given a region of the sky. Italy was given one region and the Vatican was given another. So, *de facto*, the Vatican became seen as an independent nation state."

The observatory quickly established itself as a respected scientific organisation. Though it is staffed by priests and brothers, there is an absolute rule that science comes first, says Consolmagno, and the stereotypical work of a priest or monk is actually a temptation to be resisted. "Day-to-day life as a scientist can be tedious, and it can be a long time until you see a reward, but pastoral life can be rewarding immediately," he explains.

Consolmagno was a planetary scientist for 20 years before becoming a Jesuit. By contrast, Gionti, who hails from Capua in Italy, joined after his first postdoc at UC Irvine in California. Neither reports encountering professional prejudice as a result of their vocation. "I think that's a generational thing," says Consolmagno. "Scientists working in the 1970s and 1980s were more likely to be anti-religious, but nowadays it's not the case. You are looked on as part of the multicultural nature of the field."

And besides, antagonism between science and religion is largely based on a false dichotomy, says Consolmagno. "The God that many atheists don't believe in is a God that we also don't believe in."

The observatory's director pushes back hard on the idea that faith is incompatible with physics. "It doesn't tell me what science to do. It doesn't tell me what the questions and answers are going to be. It gives me faith that I can understand the universe using reason and logic."

Surprised by CERN

Due to light pollution in Castel Gandolfo, a new outpost of the Vatican Observatory was established in Tucson, Arizona, in 1980. A little later in the day, when the Sun was rising there, I spoke to Paul Gabor – an astrophysicist, Jesuit priest and deputy director for the Tucson observatory. Born in Košice, Slovakia, Gabor was a summer student at CERN in 1992, working on the development of the electromagnetic calorimeter of the ATLAS experiment, a project he later continued in Grenoble, thanks to winning a scholarship at the university. "We were making prototypes and models and software. We tested the actual physical models in a couple of test-beam runs – that was fun," he recalls.

Gabor was surprised at how he found the laboratory. "It was an important part of my journey, because I was quite surprised that I found CERN to be full of extremely nice people. I was expecting everyone to be driven, ambitious, competitive and not necessarily collaborative, but people were very open," he says. "It was a really good human experience for me."

"When I finally caved in and joined the Jesuit order in 1995, I always thought, well, these scientists definitely are a group that I got to know and love, and I would like to, in one way or another, be a minister to them and be involved with them in some way."

"Something that I came to realise, in a beginning, burgeoning kind of way at CERN, is the idea of science being a spiritual journey. It forms your personality and your soul in a way that any sustained effort does."

Scientific athletes

"Experimental science can be a sapiential journey to wisdom," says Gabor. "We are subject to constant frustration, failure and errors. We are confronted with our limitations. This is something that scientists have in common with athletes, for example. These long labours tend to make us grow as human beings. I think this point is quite important. In a way it explains my experience at CERN as a place full of nice, generous people."

Vatican Observatory

The Pope's astronomer *Guy Consolmagno, the director of the Vatican Observatory, poses with a summer student.*

Surprisingly, however, despite being happy with life as a scientific religious and religious scientist, Gabor is not recruiting.

"There is a certain tendency to abandon science to join the priesthood or religious life," he says. "This is not necessarily the best thing to do, so I urge a little bit of restraint. Religious zeal is a great thing, but if you are in the third year of a doctorate, don't just pack up your bags and join a seminary. That is not a very prudent thing to do. That is to nobody's benefit. This is a scenario that is all too common unfortunately."

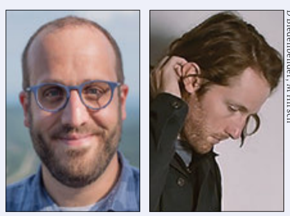
Consolmagno also offers words of caution. "50% of Jesuits leave the order," he notes. "But this is a sign of success. You need to be where you belong."

But Gionti, Consolmagno and Gabor all agree that, if properly discerned, the life of a scientific religious is a rewarding one in a community like the Vatican Observatory. They describe a close-knit group with a common purpose and little superficiality.

"Faith gives us the belief that the universe is good and worth studying," says Consolmagno. "If you believe that the universe is good, then you are justified in spending your life studying things like quarks, even if it is not useful. Believing in God gives you a reason to study science for the sake of science."

Mark Rayner *deputy editor.*

Appointments and awards



D Biedenbender; M Hirsch

New artists at Fermilab

Fermilab have announced their new 2021–2022 guest composer as David Biedenbender (left) and 2021–2022 artist-in-residence as Mark Hirsch (right). Biedenbender becomes the second guest composer at the institute, following on from David Ibbett in 2020, who is currently working on neutrino-inspired music. The role gives a guest composer an opportunity to interpret Fermilab through music and celebrate the relationship between art and science. Biedenbender has written pieces inspired by accelerators before, having in 2017 composed "Cyclotron" – a 10-minute wind ensemble piece inspired by the particle accelerator at the National Superconducting Cyclotron Laboratory at MSU. Now in its seventh year, the artist-in-residence programme will see Hirsch use computer models and coding for his art, and he aims to draw on his data visualisation background to make Fermilab science more accessible and intriguing to the public.

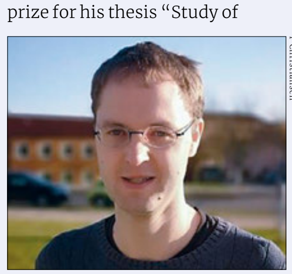
LHCb recognises theses

The 2021 winners of the LHCb thesis prize have been announced as Tom Boettcher (left) (Massachusetts Institute of Technology) and Dmitrii Pereima (right) (Kurchatov Institute, Moscow). The prize is awarded annually to early-career scientists for the best PhD thesis and outstanding contributions to the LHCb collaboration. Boettcher's thesis is on the LHCb GPU high-level trigger and measurements of neutral pion and photon production with the LHCb detector, and he was particularly commended for his contributions to the novel GPU-based first-level trigger of LHCb Upgrade I. Pereima was recognised for his thesis on the search for new decays of beauty particles at the LHCb experiment, and he made significant contributions to the understanding of the X(3872) particle and the calibration of the hadronic calorimeter.

CERN

ALICE PhD winner

Jonatan Adolfsson (Lund University) has been awarded the 2021 ALICE PhD thesis prize for his thesis "Study of Ξ-hadron correlations in pp collisions at $\sqrt{s} = 13$ TeV using the ALICE detector". The annual prize is awarded by the ALICE collaboration to the best PhD thesis based on the excellence of the results obtained, the quality of the thesis manuscript and the importance of the contribution to the collaboration. The award was presented online in June.



P Christiansen

Beamline for Schools

Team "EXTRA" from Liceo Scientifico Statale "A Scacchi" (Italy) and team "Teomiztli" from the Escuela Nacional Preparatoria "Plantel 2" (Mexico) have won the 2021 edition of CERN's Beamline for Schools competition. Every year, the Beamline for Schools competition challenges teams of high-school students across the world to submit proposals for an experiment that utilises a beamline. Team EXTRA proposed to investigate the transition-radiation effect by discriminating signals produced by the particles in a beam from those produced by X-ray photons, while the goal of team Teomiztli was to compare the production of Cherenkov radiation in different materials. The two winning teams, which were chosen from a pool of 289 teams representing 57 countries, will travel to DESY later this year to carry out their proposed experiments with the support of scientists from CERN and DESY.

RECRUITMENT

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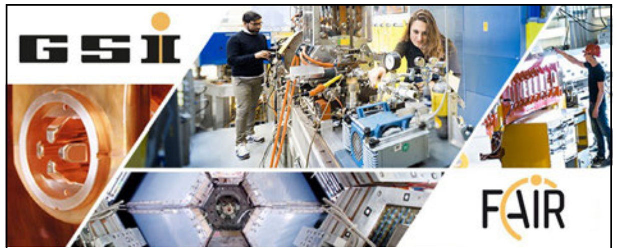

The Research Division of GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany, searches at the earliest possible date for a

Head of the Experiment Electronics Department (EEL) (all genders)

Ref. No.: 21.77-6220

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- goal-oriented and analytical mind-set, strong skills in people management and resource handling

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Please also feel free to contact Dr. Yvonne Leifels (y.leifels(at)gsi.de) in case of questions.

If you find this position interesting, please send your complete application incl. the usual documents, your salary expectation and your earliest start date, stating the **Ref. No.**, by **12. September 2021** at the latest to:

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PEOPLE
OBITUARIES

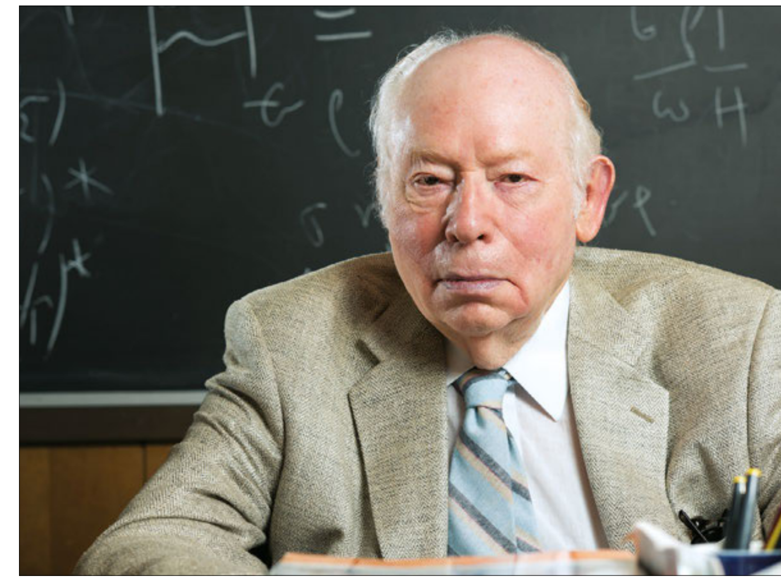
Steven Weinberg 1933–2021

A mind to rank with the greatest

Steven Weinberg, one of the greatest theoretical physicists of all time, passed away on 23 July, aged 88. He revolutionised particle physics, quantum field theory and cosmology with conceptual breakthroughs that still form the foundation of our understanding of physical reality.

Weinberg is well known for the unified theory of weak and electromagnetic forces, which earned him the Nobel Prize in Physics in 1979, jointly awarded with Sheldon Glashow and Abdus Salam, and led to the prediction of the Z and W vector bosons, later discovered at CERN in 1983. His breakthrough was the realisation that some new theoretical ideas, initially believed to play a role in the description of nuclear strong interactions, could instead explain the nature of the weak force. "Then it suddenly occurred to me that this was a perfectly good sort of theory, but I was applying it to the wrong kind of interaction. The right place to apply these ideas was not to the strong interactions, but to the weak and electromagnetic interactions," as he later recalled. With his work, Weinberg had made the next step in the unification of physical laws, after Newton understood that the motion of apples on Earth and planets in the sky are governed by the same gravitational force, and Maxwell understood that electric and magnetic phenomena are the expression of a single force.

In his research, Weinberg always focused on an overarching vision of physics and not on a model description of any single phenomenon. At a lunch among theorists, when a colleague referred to him as a model builder, he jokingly retorted: "I am not a model builder. In my life, I have built only *one* model." Indeed, Weinberg's greatest legacy is his visionary approach to vast areas of physics, in which he starts from complex theoretical concepts, reinterprets them in original ways, and applies them to the description of the physical world. A good example is his construction of effective field theories, which are still today the basic tool to understand the Standard Model of particle interactions. His inimitable way of thinking has been the inspiration and guidance for generations of physicists, and will certainly continue to serve future generations.


M Valentine

Steven Weinberg radically changed the way we look at the universe.

In my life, I have built only *one* model

Steven Weinberg is among the very few individuals who, during the course of the history of civilisation, have radically changed the way we look at the universe.

Gian Giudice *CERN.*

● *Steven Weinberg passed away shortly before the Courier went to press. A featured article exploring his lifetime of extraordinary contributions to fundamental physics will appear in the next issue.*

Felix H Boehm 1924–2021

Always ahead of the game

Felix H Boehm, who was William L Valentine Professor of Physics at Caltech, passed away on 25 May in his Altadena home. He was a pioneer in the study of fundamental laws in nuclear-physics experiments.

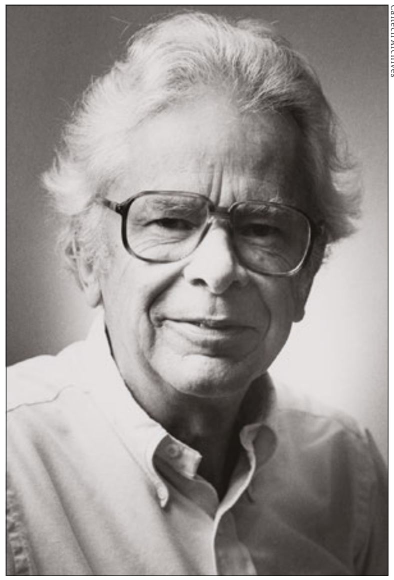
Born in Basel, Switzerland, in 1924, Felix studied physics at ETH Zürich, earning a diploma in 1948 and a PhD in 1951 for a measurement of the (p,n) reaction at the ETH cyclotron. In 1951 he moved to the US and joined the group of Chien-Shiung Wu at Columbia University, which was investigating beta decay. He joined Caltech in 1953 and spent the rest of his academic career there.

Felix worked first with Jesse DuMond, who had developed the bent-crystal spectrometer, an instrument with unrivalled energy resolution in gamma-ray spectrometry. He used it to determine nuclear radii by measuring X-ray isotope shifts in atoms. Later, he installed such devices at LAMPF, SREL and PSI to investigate pionic atoms, which led to a precise determination of the strong-interaction shift in pionic hydrogen. At Caltech, he also became interested in parity violation and time-reversal ▷

invariance. In 1957, in an experiment performed with Aaldert Wapstra, he demonstrated that electrons in beta decay have a predominantly negative helicity.

In the mid 1970s, discussions with Harald Fritzsch and Peter Minkowski convinced Felix that the study of neutrino masses and mixings might provide answers to fundamental questions. From then on, long before it was fashionable, it became his main field of activity. He first looked at neutrino oscillations and initiated an electron–neutrino disappearance experiment with Rudolf Mössbauer.

Theirs was the first dedicated search for neutrino oscillations, beginning with a short-baseline phase at the ILL reactor in Grenoble. The concept of the experiment was presented at the Neutrino '79 conference in Bergen, at which the Gargamelle collaboration also reported limits on $\nu_\mu \leftrightarrow \nu_e$ oscillations. Both talks were relegated to a session on exotic phenomena. The ILL experiment was continued at the Gösgen reactor in Switzerland with a longer baseline. No evidence of oscillations was found and stringent limits in a given parameter space were derived, contradicting positive claims made by others. A larger detector was later built at the Palo Verde nuclear power station in Arizona, where again no evidence for oscillations was found. A logical continuation of the effort initiated by Felix was the KamLAND experiment in Japan, which was exposed to several reactors and eventually, in 2002, observed neutrino oscillations in the disappearance mode at a still-longer baseline.


Caltech Archives

Felix Boehm focused on neutrino masses and mixings long before it was fashionable.

In parallel, Felix decided to probe neutrino masses by searching for neutrinoless double-beta decay. He led a small collaboration that installed a germanium detector in the Gotthard underground laboratory in Switzerland to probe ^{76}Ge, and then searched for the process using a time-projection chamber (TPC) filled with xenon enriched with ^{136}Xe. The TPC, a novel device at the time, improved the event signature and thus reduced the background, allowing stringent constraints to be placed on the effective neutrino mass. The ongoing EXO experiment can be seen as a continuation of this programme, vastly improving the sensitivity in its first phase (EXO-200 at WIPP, New Mexico) and expected to do even better in the second phase, nEXO.

Felix Boehm had a talent to identify important issues on the theoretical side, and to select the appropriate technical methods on the experimental side. He was always ready to innovate. In particular, he realised very early on the importance of selecting radio-pure materials in low-count-rate, low-background experiments. All those who worked with him appreciated his open mind, his determination, his great culture and his kindness.

Jean-Luc Vuilleumier *University of Bern;*
Felix's friends and colleagues.

Anatoly Vasilievich Efremov 1933–2021

An expert in QCD and spin physics

On 1 January, after a long struggle with a serious illness, Anatoly Vasilievich Efremov of the Bogoliubov Laboratory of Theoretical Physics (BLTP) at JINR, Dubna, Russia, passed away. He was an outstanding physicist, and a world expert in quantum field theory and elementary particle physics.

Anatoly Efremov was born in Kerch, Crimea, to the family of a naval officer. Since childhood, he retained his love for the sea and was an excellent yachtsman. After graduating from Moscow Engineering Physics Institute in 1958, where among his teachers were Isaak Pomeranchuk and his master's thesis advisor Yakov Smorodinsky, he started working at BLTP JINR. At the time, Dmitrij Blokhintsev was JINR director. Anatoly always considered him as his teacher, as he did Dmitry Shirkov under whose supervision he defended his PhD thesis "Dispersion theory of low-energy scattering of pions" in 1962.

In 1971, Anatoly defended his DSc dissertation "High-energy asymptotics of Feynman diagrams". The underlying work immediately found application in the factorisation of hard processes in quantum chromodynamics (QCD), which is now the theoretical basis of all hard-hadronic processes. Of particular note are his 1979 articles (written together with his PhD student A V Radyushkin) about the asymptotic behaviour of the pion form factor in QCD, and the evolution equation for hard exclusive processes, which became known as the ERBL (Efremov–Radyushkin–Brodsky–Lepage) equation. Proving the factorisation of hard processes enabled many subtle effects in QCD to be described, in particular parton correlations, which became known as the ETQS (Efremov–Teryaev–Qiu–Sterman) mechanism.


T A Potapova

Anatoly Efremov was one of the key staff at JINR's Bogoliubov Laboratory of Theoretical Physics.

During the past three decades, Efremov, together with his students and colleagues, devoted his attention to several problems: the proton spin; the role of the axial anomaly and spin of gluons in the spin structure of a nucleon; correlations of the spin of partons; and momenta of particles in jets ("handedness"). These effects served as the theoretical basis for polarised particle experiments at RHIC at Brookhaven, the SPS at CERN and the new NICA facility at JINR. Anatoly was a member of the COMPASS collaboration at the SPS, where he helped to measure the effects he had predicted.

In 1976 he suggested the first model for the production of cumulative particles at x > 1 off nuclei. Within QCD, Efremov was the first to develop the concept of nuclear quark–parton structure function, which entails the presence in the nucleus of a hard collective quark sea. This naturally explains both the EMC nuclear effect and cumulative particle production, and unambiguously indicates the existence of multi- quark density fluctuations (fluctons) – a prediction that was later confirmed and led to the so-called nuclear super-scaling phenomenon. Today, similar effects of fluctons or short-range correlations are investigated in a fixed-target experiment at NICA and in several experiments at Jlab in the US.

Throughout his life, Anatoly continued to develop concrete manifestations of his ideas based on fundamental theory, becoming a teacher and advisor of many physicists at JINR, in Russia and abroad. In 1991 he initiated and became the permanent chair of the organising committee of the Dubna International Workshops on Spin Physics at High Energies. He was a long-term and authoritative member of the International Spin Physics Committee coordinating work in this area, and a regular visitor to the CERN theory unit since the 1970s.

Anatoly Vasilievich Efremov was the undisputed scientific leader, who initiated studies of quantum chromodynamics and spin physics in Dubna, one of the key BLTP JINR staff, and at the same time a modest and very friendly person, enjoying the highest authority and respect of colleagues. It is this combination of scientific and human qualities that made Anatoly Efremov's personality unique, and this is how we will remember him.

His colleagues and friends.

Alexei Onuchin 1934–2021

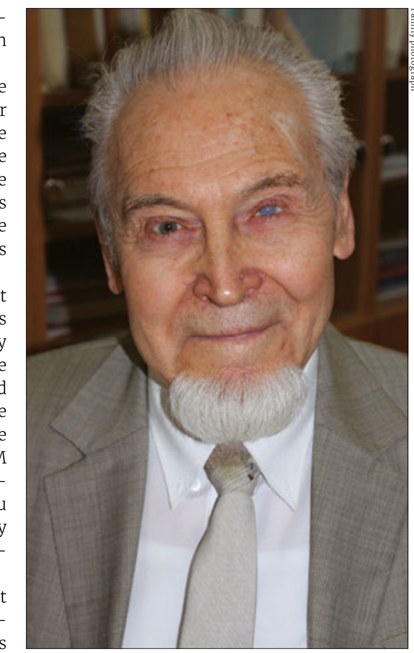
An outstanding experimentalist

Alexei Onuchin, one of the pioneers of experiments at colliding beams, passed away on 9 January in Novosibirsk, Russia.

Onuchin was born in 1934 in a small village in the Gorky (Nizhny Novgorod) region. After graduating from high school with honours, he decided to try his hand at science and in 1953 he entered the physics department of Moscow State University. In 1959 he graduated with honours and was invited by Gersh Budker to work at the newly organised Institute of Nuclear Physics at Novosibirsk (INP).

At INP, Onuchin enjoyed many important roles. He took part in experiments at the world's first electron–electron collider (VEP-1), actively worked on the preparation of a detector for the electron–positron collider VEPP-2, supervised the construction of the MD-1 detector for the VEPP-4 collider, was one of the leaders of the KEDR detector experiment at the VEPP-4M collider and was a great enthusiast of the detector project for the proposed Super Charm-Tau Factory. He was also an organiser and for many years the leader of the Budker INP group working at the BaBar experiment at SLAC.

During his career, Alexei made a great contribution to the development of experimental techniques in particle physics. It was this that determined the high level of experiments carried out at Budker INP and other laboratories. These include the development and production of multiwire proportional chambers for the MD-1, various counters based on Cherenkov radiation and the creation of a calorimeter based on liquid krypton, among many others.


Family photograph

Alexei Onuchin was an expert in Cherenkov counters.

Cherenkov counters held a special place in Alexei's heart from the very beginning of his career as a student in the laboratory of Nobel-laureate Pavel Cherenkov. Starting from pioneering water-threshold counters in the experiment at VEPP-2, he later developed the MD-1 Cherenkov counters filled with ethylene pressurised to 25 bar, and finally suggested the aerogel counters with wavelength shifters (ASHIPH) now operating in the KEDR detector. For this work, in 2008 Alexei Onuchin was awarded the Cherenkov Prize of the Russian Academy of Sciences.

Alexei was a great teacher. Among his former students are professors, group leaders and members of the Russian Academy of Sciences. He was also a caring father and loving husband, who raised a large family with four children, five grandchildren and three great-grandchildren. He will always be remembered by his family, friends and colleagues.

His colleagues and friends.

Tord Riemann 1951–2021

Setting the highest standards

Theorist Tord Riemann, who made key contributions to e^+e^- collider phenomenology, left us on 2 April.

Tord was born in 1951 in East Berlin, educated at the Heinrich-Hertz-Gymnasium specialist mathematics school in Berlin and studied physics at Humboldt University in Berlin from 1970. He graduated in 1977 with a doctorate devoted to studies of the lattice approach to quantum field theory. He obtained a research position in the theory group of the Institute of High Energy Physics of the Academy of Sciences of the GDR in Zeuthen (later DESY Zeuthen), and in 1983–1987 worked at JINR, then in the Soviet Union, in the group of Dmitry Bardin.

Tord's fields of interest were broad, and aimed at predicting observables measured at accelerators

In 1989/1990 Tord visited the L3 experiment at CERN, starting a fruitful collaboration on the application of the ZFITTER project at the Large Electron–Positron (LEP) collider. In 1991–1992 he was a research associate in the CERN theory division, working out the so-called S-matrix approach to the Z resonance. This was a profound contribution to the field, and a breakthrough for the interpretation of LEP data. Tord was one of the first to realise the great potential of a new e^+e^- "Tera-Z" factory at the proposed Future Circular Collider, ▷

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FCC-ee, and led the charge reviving precision calculations for it.

Tord's scientific fields of interest were broad, and aimed at predicting observables measured at accelerators. His research topics included linear-collider physics; Higgs, WW, ZZ, 2f and 4f production in e^+e^- scattering; physics at LEP and FCC-ee; methods in the calculation of multi-loop massive Feynman integrals; NNLO Bhabha scattering in QED; higher-order corrections in the electroweak Standard Model and some extensions; and electroweak corrections for deep inelastic scattering at HERA. Apart from ZFITTER, he co-authored several programmes, including topfit, GENTLE/4fan, HECTOR, SMATASY, TERAD91, DISEPNC, DISEPCC, DIZET, polHeCTOR and AMBRE.

T Riemann

Tord Riemann promoted the application of the ZFITTER project at LEP.

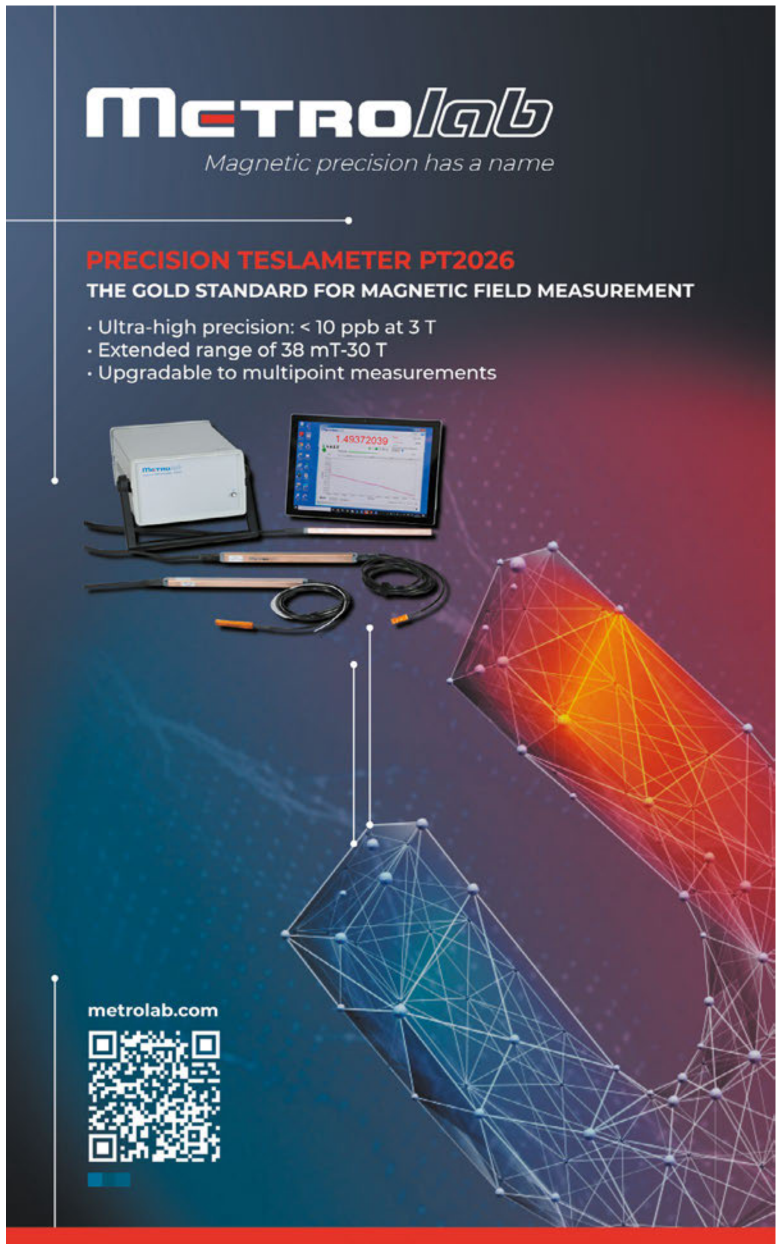
While being an active research scientist throughout his career, Tord will also be warmly remembered as a great mentor to many of us. He was a thesis advisor for two diploma and seven PhD students, and was actively engaged in supporting many postdoctoral researchers. He was co-founder and organiser of the bi-annual workshop series Loops and Legs in Quantum Field Theory and of the biannual DESY school Computer Algebra and Particle Physics.

In 2000, Tord and the ZFITTER collaboration were awarded the First Prize of JINR, and in 2014 the article "The ZFITTER Project" was awarded the JINR prize for the best publication of the year in *Physics of Elementary Particles and Nuclei*. In 2015 Tord was awarded an Alexander von Humboldt Polish Honorary Research Fellowship.

Tord Riemann cared about high standards in scientific research, including ethical issues. He was a true professional of the field. Despite illness, he continued working until his last day.

Tord was an outstanding scientist, a just person of great honesty, a reliable friend, colleague and family man. We feel a great loss, personally and as a scientific community, and remain thankful for his insights, dedication and all the precious moments we have shared.

Arif Akhundov, Andrej Arbuzov, Alain Blondel, Ayres Freitas, Janusz Gluza, Stanisław Jadach, Lida Kalinovskaya *and* **Sabine Riemann** *on behalf of* **his colleagues and friends**.



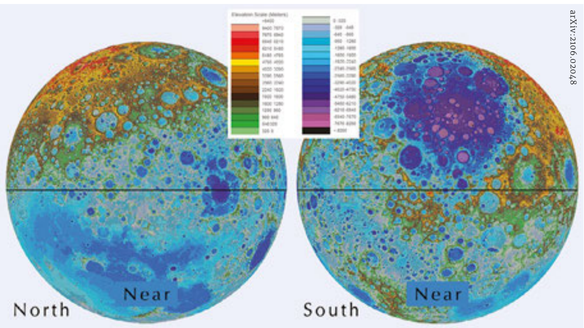
BACKGROUND

Notes and observations from the high-energy physics community

O telescopes, o mores!

In days of yore, an experiment might choose a lovable cartoon elephant for its logo first, and worry about copyright infringement later. In a sign those times are long since past, the SKA Observatory (SKAO) has launched a 49-page "brand book" to police their swanky new style. Meanwhile, on 29 June, SKAO's member states gave the green light for construction in Australia and South Africa of the world's largest radio-telescope arrays.

SKAO



Shoot for the moon *James Beacham (Duke) and Frank Zimmermann (CERN) propose this schematic trajectory (black line) for a 14 PeV circular collider on the moon (CCM) that intersects its poles while minimising elevation changes (arXiv:2106.02048). The pictured elevation varies from about −8 km (purple) to +8 km (red). "A CCM would serve as an important stepping stone towards a Planck-scale collider sited in our Solar System," they write.*

12.3 GJ

Energy stored in the LHC's magnetic circuit, including 8.8 GJ in dipoles and 3.5 GJ in detector magnets. ITER's magnetic system, now under construction (p13), should break this record, exceeding 50 GJ in the 2030s.

From the archive: October 1981

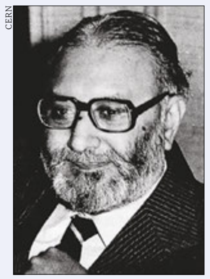
A lot can happen in 40 years

"Using gauge ideas, the basic questions – what are the elementary constituents of matter and the forces among them? – become interrelated through the concept of charges, gravitational, electrical and nuclear, carried by elementary particles, and gauge forces proportional to these charges. A postulated symmetry among the charges leads to a possible unification of the elementary forces.

"But we are still far from the elucidation of the nature of these charges or the problems posed by the mass scales. In the next decade, one may optimistically envisage a superconducting pp collider installed in the LEP tunnel reaching 10 TeV in the centre of mass. But what will happen twenty-five years from now? We desperately need new design ideas on accelerators or they may become as extinct as dinosaurs.

"But I am continually amazed how rapidly our experimental colleagues succeed in demolishing (sometimes demonstrating) seemingly inaccessible and often outrageous theoretical speculations."

● Based on text from pp347–349 of *CERN Courier* October 1981.



Abdus Salam painting a bleak picture for the experimental prospects of particle physics at the UK Royal Society conference on gauge theories earlier this year.

Compiler's note

In 1979, Sheldon Glashow, Abdus Salam and Steven Weinberg shared the Nobel Prize for the unification of electromagnetic and weak forces. In 1983, the W and Z bosons were discovered at LEP, cementing electroweak unification and gaining the 1984 Nobel Prize for Carlo Rubbia and Simon van der Meer. In 2010, the first high-energy pp collisions were achieved in the LHC, the collider Salam dreamed of, and in 2012 it delivered the Higgs boson, postulated to explain electroweak symmetry breaking, earning the 2013 Nobel Prize for François Englert and Peter Higgs. And now, experiments at CERN and Fermilab hint at the possible existence of gauge leptoquarks and a 5th force. There's life in the dinosaurs yet.

Media corner

"Just a few years ago, such an idea was squarely in the realm of science fiction, but now, because there is such a strong interest in humans returning to the Moon, a CCM is a distinct possibility."

India Today's **Sibu Tripathi** reports on speculations (see above) about building a circular collider on the moon (5 July).

"How many posters of Van Gogh's 'The Starry Night' are there out there? They do not devalue the painting at all."

Cassandra Hatton (Sotheby's) justifies the value of non-fungible tokens (p10) (CNN, 1 July).

"Turning to the heavens, special detectors would analyse rays from astrophysical sources, and Moon-based particle accelerators would give new insight into the nature of matter."

Isaac Asimov in *Popular Mechanics* (March 1988).

"There's a quality you shouldn't have – a need for instant gratification."

2017 Nobel laureate **Barry Barish** gives advice to young researchers via the organisation's social-media channels on World Youth Skills Day (15 July).

"We need a commitment and vision with the magnitude of CERN if we are to build climate models that can accurately simulate extremes of climate like the Canadian heatwave."

Tim Palmer (Oxford) speaks to BBC News (16 July, see also *CERN Courier* July/August 2021 p49).

"You should know, there are Nobel laureates and then there are Nobel laureates."

Computer-science-pioneer **John Cocke**, quoted in the *New York Times* obituary for Steven Weinberg (25 July).

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