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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New trends in AI for particle physics

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 analysts 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.

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 Sparkly69 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 (p46).

But with all its inexcusable 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 (2022) 025002) 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 (p99).

Elsewhere in this issue: a tribute to Steven Weinberg (p65); a scUbe upgrade for LHCb (p43); anisotropies point to cosmic-ray origins (p11); the most stable tetraquark yet (p7); reports from the summer conferences (p9); Hubble tension questioned (p53); astrophysics up a SciFi upgrade for LHCb (p43); anisotropies point to cosmic-ray origins (p11); the most stable tetraquark yet (p7); reports from the summer conferences (p9); Hubble tension questioned (p53).
All the exotic hadrons that have been observed so far decay rapidly via the strong interaction. The cold tetraquark (T) just discovered by the LHCb collaboration is no exception. However, it is the longest-lived state yet, and reinforces expectations that the bound cousins, bbud, will be stable with respect to the strong interaction when it peaks emerges in future data.

“We have discovered a ccud tetraquark with a mass just below the D*+D 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 ccqq tetraquarks or ccqqq pentaquarks, where q represents an up, down or strange quark. A year ago LHCb also discovered a hidden–double–charm cc′cc′ tetraquark, X(3872) (CERN Courier September/October 2020 p3), and two open–charm ccdd tetraquarks, X(3850) and X(3930). The new cc ud state, announced at the European Physical Society conference 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 antiquarks of the same flavour.

Prime candidate

Tetraquark states with two heavy quarks and two light antiquarks have been the prime candidates for stable exotic hadronic states since the 1990s. LHCb’s discovery, four years ago, of the Zcc (1060) baryon allowed QCD phenomenologists to firmly predict the existence of a stable bbud tetraquark, however the stability of a potential cc ud state remained unclear. Predictions of the mass of the cc ud state varied substantially, from 250 MeV below to 200 MeV above the D*D mass threshold, says Polyakov. “Unfortunately, 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 lying within the observed resonance’s narrow width of 460 ± 10 keV, prescribed by the uncertainty principle. The T, 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 (Kiev Institute/ITEP). “Until now, the only similar closeness was observed for the enigmatic χc1(3872) state, whose mass coincides with the D*D threshold with a precision of about 120 keV.” As it is wider, however, it is not yet known whether the χc1(3872) is below or above threshold (CERN Courier July/August 2020 p3).”

“The surprising proximity of T and χc1(3872) to the D*D threshold 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*D, or alternatively, bound by the exchange of colour–neutral objects such as light mesons, or a colour–charged cc “diquark” tightly coupled to strange quarks exchanged 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 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 inter–twined in a compact object, or something in between,” says Polyakov. “The first scenario resembles a relatively large c fm deuteron, whereas the second can be compared to a relatively compact ~2fm alpha particle.”

The new T, tetraquark is an enticing target for further study. Its narrow decay into a D*D* final state – the virtual D* decays promptly into D* – includes no particular 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 unmeasurable QCD effects, says the team. And, if detected, its beautiful cousin would be an even bigger boon.

“Observing tightly bound exotic hadrons 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 bbud, 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, jokers and quarks alike inevitably have more peaks than researchers!”

Further reading

LHCb-Collab. 2021 LHCb-PAPER-2021-031.
On 22 June, the SuperKEKB accelerator at the KEK laboratory in Tsukuba, Japan, reached a new world record for peak luminosity, reaching a peak luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$ in the Belle II detector. This is the highest luminosity ever recorded in any particle physics detector, and more than double the previous record set by the KEKB accelerator at the former KEKB detector at the KEK laboratory in Tsukuba in 2012.

In physics since 2019, SuperKEKB is an innovative nano-beam, asymmetric-energy accelerator complex that collides 7 GeV electrons with 4 GeV positrons, sitting mostly on either side of the interaction point. These innovations have enabled the SuperKEKB team to attain record luminosities with carefully tuned sextupole magnets on both sides of the interaction point. These innovations have enabled the SuperKEKB team to attain record luminosities with

### The team is making impressive progress towards a target luminosity of $6.5 \times 10^{35}$ cm$^{-2}$s$^{-1}$

The team to stabilise beam–beam blowup using ground-breaking anomalies in the flavour sector, contain the dark sector, and search for new physics.

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

### SuperKEKB raises the bar

The Deep Underground Neutrino Experiment (DUNE) in the US has achieved the first replicates that model-making, the ship-in-a-bottle, on an impressive scale. More than just B-factories, SuperKEKB and other components for DUNE’s four large detectors, or cryostats, must be lowered 15 km through narrow shafts beneath the Sanford Lab in South Dakota, before being assembled into four 6.6 m x 18 m containers. And the main detector, the metaphor: to realise DUNE’s massive cryostats, of which there will be two, is that they have found a way to have an easier-to-install. 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.

### Scaling up

Weighting more than 70,000 tonnes, DUNE will be the largest ever deployment of a single DUNE module. It will house both target and tracker for neutrino interactions, and was proposed by Carlo Rubbia in 1977. The first large-scale LAr TPC – ICARUS, which was refur- bished for t he first full-size DUNE prototype 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 heads CERN’s Neutrino Platform. Typical cryostats are carved out of high-voltage supply and many other components, in order to protect the detector. Without the Syntec foundation stone, admired with the newly unveiled Science Gateway logo.

Scientists around the world have been working on the global participation partner in our...
CERN's Pierre Valentin performing levelling measurements between Genouix and Saint-Julien in France.

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

A portion of the web's original source code.

The seed that led CERN to relinquish ownership of the web was planted 70 years ago. In the CERN Convention, which is the legal basis of the project, it states that the 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 bundle of three languages and protocols that continue to this day.

Sotheby's press release.

At sub-TeV energies, spectral features seen by the AMS-02 and CALET detectors confirm a switch in the phase of anisotropy with normal galaxies, more clearly to their origin, and galactic cosmic rays should have very clear anisotropies that continue to this day. The auction offer describes the NFT as containing approximately 9555 lines of code, including implementations of the three languages and protocols that continue to this day.

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Inside the KATRIN spectrometer.

Neutrino mass less than 1eV

The Karlsruhe Tritium Neutrino (KATRIN) experiment has announced the first model-independent limit on the mass of neutrinos with sensitivity below 1eV. The best fit to the spectral data yields a squared neutrino mass of 0.26 ± 0.14 eV² for the second physics run, thereby excluding neutrino masses above 0.46 eV at 90% confidence when all data is taken into account (arXiv:2105.08513). 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 ran 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

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 could be spontaneously created in a strong electric field. MoEDAL is searching for magnetic monopoles, whether the dual effect might reveal long-hypothesized 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 p.71). Training MoEDAL detectors with a SQUID magnetometer excluded monopoles with one, two or three Dirac charges up to masses of 716 eV. MoEDAL 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:2108.00602). 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 and 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 neutrinoless double-beta decay

The collaboration exploited the dual effect might reveal long-hypothesized 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 p.71). Training MoEDAL detectors with a SQUID magnetometer excluded monopoles with one, two or three Dirac charges up to masses of 716 eV. MoEDAL pre-lab proposal published

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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, 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 2023, and will seek to constrain lepton CP violation and study astrophysical neutrinos (CERN Courier July/August 2020 p.12).

Instrumentation training probe

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 institutional and country of residence (arXiv:2009.07798). The results will inform ECFA’s detector-R&D roadmap.

Most powerful magnet sets sail

Preliminary 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 56 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 km solenoid, which previously held the record. The CS uses 43 km of Nb, 50 superconductor manufactured in Japan—the same material that will be used for the High-Luminosity LHC’s upgrade. ITER’s construction was approved in 2016 (CERN Courier January/February 2021 p8). Formally established in 2006, ITER is ranked with demonstrating the feasibility of fusion power by maintaining a plasma in a self-sustaining “ignition” phase. Machine assembly began in July 2019, with the goal of achieving “first plasma” by late 2023.

Second superconductor supplier

CERN has validated the acceptance testing of Nb3Sn cables from a Russian company TVEL as part of the conductor-development programme for the Future Circular Collider (FCC). TVEL is the second supplier to comply with CERN’s specifications, with development also ongoing in the US, Europe, South Korea, Japan and China.

Galactic geochemistry

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 1015 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: one related to which the Earth passes every ~45 Myr, and a DM “subhalo” that the Earth encountered during the past gigayear.
Reports from the Large Hadron Collider experiments

**LHCb**

B_s decays remain anomalous

The LHCb experiment recently presented new results on the $B_s \rightarrow \phi \mu \mu$ decay of $B_s$ mesons, which are thought to be produced at the Large Hadron Collider (LHC). These results are measured using data collected during LHC Run 2 (Figure 1). The branching fraction for this decay is measured as a function of the dimuon invariant mass ($q^2$) and found to lie below the standard model (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 previous studies of other $B \rightarrow \phi \mu \mu$ decays, which may hint at the same anomalous behaviour seen so far in $B \rightarrow \phi \mu \mu$. However, lattice-QCD calculations do better at reproducing the branching fractions at the level of two standard deviations, but may also hint at the same pattern of unexpected behaviour seen in other analyses. 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 other analyses. The angular distribution of the $B \rightarrow \phi \mu \mu$ decay products offers complementary information. At the international FOPC 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 polarization fraction $F_L$, one of several variables sensitive to anomalous $B \rightarrow \phi \mu \mu$ 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 other analyses. 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 parameterized from measurements performed in $e^+e^-$ or $e^+e^-$ collisions, under the assumption that the hadronization of charm quarks into charm hadrons is a universal process that is independent of the colliding systems. The large data samples collected during Run 2 of the LHC at $\sqrt{s} = 5.02 \text{ TeV}$...
allowed the ALICE collaboration to measure the yield at trigger level and constrain them directly to new massive states. But while the top quark may represent a window into new physics, it cannot 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.

The LHC's proton beams collide head-on, and the conservation of momentum of each photon should be zero for the photon pair is the dominant background in collisions. However, photons do not carry a colour charge, they interact weakly and are typically not present in collisions. As a result, strong-interaction effects on the quarks can alter the characteristics of the measured photons. The conservation of momentum allows events 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 non-perturbative effects. This can be observed in the initial-state momenta. Therefore, by measuring the transverse momentum of the photons 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 Drell-Yan picture without the strong interaction, the yield of double-photons emissions – especially relevant at higher energies – precisely describe the observed measured distribution. The result of this analysis, which also includes measurements of diphoton production at higher energy, and may couple to the SM from events that include EFT effects arising from one or more anomalous interactions.

Further reading

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 silver 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 impactsthe electroweak sector significantly through loop corrections, and may couple to the SM via new interactions.

Fig. 1. The response of a neural network used to train a specific type of EFT interaction in ttZ production. The lower panel shows the change of the event yield in each bin with respect to the SM hypothesis for two benchmark EFT scenarios. Both fit well and overlap (solid line) and the total prediction (dotted), illustrating the network’s ability to isolate anomalous effects.

A new CMS analysis searches for anomalous production of top quark pairs, with the Z boson using an EFT framework. The cross-section measurements of the rare associate production of either one (1Z) or two (2Z) top quarks with a Z boson are statistically limited by 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 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 natural Drell-Yan channel, and the targeted EFT effects, to efficiently explore the parameter space of EFT models.

Further reading
**XP Power**

High Voltage Power Solutions

**Up to 500kVDC output with power to 200kW**

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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 2000 participants online from 17 to 21 May. Dubbed “vCHEP”, the event took place virtually after the usual 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 rate data 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 connecting. 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.

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 implicates 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 data 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 this will improve the energy consumption per event at 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 HEPS 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.

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 in the field 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 explained how to adapt outreach events to a virtual setup, take up public engagement during lockdowns, 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

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**CERN COURIER SEPTEMBER/OCTOBER 2021**

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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 2023/2024, 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–proton Higgs factory as the highest priority after the LHC, along with the investigations of the technical and financial feasibility of such a Higgs factory, followed by a high–energy hadron collider placed in the same circular 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. As pointed out by the Organisers, ensuring a smooth continuation from the High–Luminosity LHC, so close to the end of its operation around the 2040s, ensuring a smooth collider) in the next five years.

The next steps are to continue the investigations of high–luminosity, surface sites. The most suitable scenarios are based on a 9-km–circuit tunnel with eight surface sites.

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Beyond the LHC

A highlight of the week was the exploration of the physics case of a post–LHC FCC. The recent discovery (Harvard University) identified dark matter, the basic building blocks of the dark matter problem, that are expected to be found outside of high–energy physics. A “Mixing the Future” competition was held in parallel with the week, with prizes for the best strategies on how to best use the nine million cubic metres of molasse that would be excavated from the tunnel.

Several talks also pointed out synergies with the recent results from the proposed electron–ion collider at Brookhaven and the Powerful Energy–beam Experiments (PREE) project at Orsay, and called for stronger collaboration between the projects.

Machine design

Another key aspect of the study is the machine design. Since the conceptual design phase, the machine requirements and physics performance suggest that the deployment of superconducting, he noted, when we physics is reminiscent of the early days of superconductivity, he noted, when we thinking about the first stage (tunnel and e+e− collider) in the next five years. 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 conference is illustrated by the fact that 122 posters were presented.

From third to second

Nine years after the discovery of the 125 GeV Higgs boson, measurements have provided a new level of precision with the full Run–2 data. Both ATLAS and CMS presented new results on Higgs production, helping to constrain the dynamics of the production mechanisms via differential and “simplified template” cross–section measurements. While the couplings of the Higgs to things like Z+H, H→b+bb and H→τ+τ− 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 used the full dataset for these searches, with ATLAS being able to exclude a production rate more than a factor of three from SM expectations, the significance continues to climb upwards. Searches for resonances with masses above the Higgs have been presented by ATLAS and CMS as potential new particles or effects at high masses that could indicate an associated new physics mechanism. The overall vitality of the conference is illustrated by the fact that 122 posters were presented.

A wealth of results was presented from the LHC Run 3, including substantial upgrades. While some work has been slowed by the pandemic, the conference continued, with the organisation of the meetings beginning this year. The overall vitality of the conference is illustrated by the fact that 122 posters were presented.

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

More than 1000 physicists took part in the recent LHChadron Collider (LHC) 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, with the meeting 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 LHC participants hailing from institutes across 54 countries.

The LHC 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 conference is illustrated by the fact that 122 posters were presented.

The most puzzling hints from the LHC Run 3 seem to strengthen in Run 4. LHC presented analyses relating to the “flavour anomalies” found most notably in b→μνμν decays, updated to the full data. Since SM expectations, the significances continue to climb upwards. Searches for resonances with masses above the Higgs have been presented by ATLAS and CMS as potential new particles or effects at high masses that could indicate an associated new physics mechanism. The overall vitality of the conference is illustrated by the fact that 122 posters were presented.

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Strange Quark Matter

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 heavy ions and 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 its pQCD prediction and the angular anisotropy of heavy mesons in heavy-ion collisions. These measurements are crucial for constraining models of medium-modified nuclear physics. Interestingly, while charm seems to follow the flow of the quark–gluon plasma, beauty does not seem to flow. Better statistics will be very important for constraining such models.

LLPs

Long-lived particles gather interest

From 25 to 28 June, the long-lived particle (LLP) community may have been stretching the limits of searches for new physics with its ninth and best-attended workshop yet, with more than 1,000 registered participants.

Six new results, three each from ATLAS and CMS. These included a remarkable new ATLAS paper using LHC data to search for new physics with a significance of 5.7σ. The searches were for new particles with masses of 400 GeV and less.

LLP9 was raucous and stimulating, with dozens of new results and more than 100 contributed talks and hands-on working-group sessions. 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 relevant momentum fraction.

hints of extremal function of beam energy.

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 extremal energy dependence terms and a stronger “memory” of the strange–quark spin.

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International Particle Accelerator Conference

IPAC thrives online

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 Síncrona (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 1700 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 participation, live plenary presentations were limited to two hours daily.

SustHEP 2021

Sustainable high-energy physics

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. After attending 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 Hutchins (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-searched 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 Othoni (British Institute for 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. Alice Field (PIT) 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 30 August.

Kai Schmidt | CERN
WHAT’S IN THE BOX?

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 Rutgers University) 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 $X \rightarrow qq$ and a trijet decay $X \rightarrow gY \rightarrow qq$). 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 rare 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 Dark Machines data challenge focused on developing algorithms broadly sensitive to non-resonant anomalies 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.

**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 Ostindie (Harvard University) in the development of a common software infrastructure, and Melissa van Beekvoord (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 – anywhere 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 explicit and implicit 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 published – a jet-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 (g31). 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**


### **Tony Phillips**

**CERN Courier** September/October 2021
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.

HUNTING ANOMALIES WITH AN AI TRIGGER

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 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 event 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: a two-dimensional array 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. This is a training process, the algorithm is tuned to minimise the number of wrong answers by comparing its prediction to the label.

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. Photo 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 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 ununderstood 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 event data-set 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 consequently 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 a new kind of field hunting, anomaly detection is the method that is used to select these rare events.

Anomaly hunting

In this illustrative simulation of the unsupervised detection of leptoquark (orange squares) and neutral-scalar–boson (red triangles) decays of a SM background (purple circles), LHC collisions are compressed by an outlier monitor and then further compressed to a two-dimensional representation (z1, z2), 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.

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 L1 trigger consists of logic algorithms integrated onto 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.
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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 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 likelihood of sparks flying depends on the weather. To take the temperature, CERN Courier spoke to a sampling of the Sparks! participants to preview themes for the September event.

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.

Vivienne Ming is a theoretical neuroscientist and a serial AI entrepreneur.

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

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

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.

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

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.

Mark Rayner, deputy editor.

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

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

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.

THE AUTHOR
Mack Rayner
deputy editor.

THE AUTHOR
Erik Verlinde
University of Amsterdam.
Successful emergent theories describe universal macroscopic phenomena whose underlying microscopic descriptions can 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 renormalisation. As with all emergent phenomena, renormalisation comprises 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 quantum nature 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. Then one rescales the coarser lattice so that the distance between lattice points takes the old value, and repeats this step many times as the lattice constant is reduced, 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 to those 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 STP specifically, and its possible symmetries? Some of these laws are not fundamental but are derived from the continuum spacetime. As a concrete example, consider quantum spins on a lattice. If we need N bits to store the microscopic data associated with the motion of some particles on a computer. If we need N bits to store the microscopic data associated with a system of particles, and forces emerge via data compression? Space, time, curvature that follows from the Einstein equations. 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, for example, emerge from the complementary description 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. By studying the interplay between branes and strings, an even more microscopic theoretical description was found in which the coordinates of these branes start to converge. Instead of being described by real numbers, our familiar (x, y, z) coordinates are replaced by commuting matrices. At low energies, these matrices behave like a commutative algebra and give rise to the normal spacetime with which we are familiar. In these theoretical models it was found that both gauge theories and gravity are determined by 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 a problem – the amount of mass in the SM. Such a theory seems to be well beyond us. Gravitation, however, being universal, has been more amenable to emergence.

Emergent gravity

In the early 1950s, a group of physicists became interested in describing the gravitational field in the form of a thermal system, a so-called “holodynamic” system. The inverse temperature of this thermal system is determined by the gravitational field. Wilson demonstrated that quantum field theories appear naturally as an effective long-distance and low-energy description of systems whose microscopic quantum nature 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.

Gauge symmetry

To ensure that a neural network recognises a pixelated image, its algorithm should be robust under rotations.

Black-hole maths

Bekenstein and Jacobson showed that the Bekenstein–Hawking entropy is the same as the Bekenstein–Hawking entropy of the event horizon. Credit: J Bekenstein

Holographic renormalisation

The AdS/CFT correspondence is the holographic principle, a so-called “holographic” principle that general relativity can be derived from an underlying microscopic quantum theory without a gravitational force. This principle only works for infinite spacetimes with a negative curvature, called “de Sitter space” or AdS space (see “Holographic renormalisation”). 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 contributed to these developments in a paper in 2010 that emphasised the role of entropy and information for the emergence of the gravitational force.

Emergent intelligence

But what about viewing the even more complex problem of human intelligence as an emergent phenomenon? Since science knows a lot of progress and success 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 the world. The emergence of the Bekenstein–Hawking entropy and with the cosmological horizon.
tecture 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 car, 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 car.

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 also exhibited in humans, but can also be achieved artificially. 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.

Emergence is often summarised with the slogan “the whole is more than the sum of its parts”. 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 p54). 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 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 p16), 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 Cherenkov detectors that are currently being installed are vital for the higher LHC luminosities ahead, write Christoph Frei, Silvia Gambetta and Blake Leverington.
Cherenkov detectors RICH1 and RICH2 provide for sharper particle identification, and the brand new “SciFi” (scintillating fibres) 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 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 polyethylene fibre was delivered to CERN before undergoing meticulous quality checks. Excessive diameter variations were removed prior to being cut and bonded – modules, tested, and shipped to CERN where they were assembled with the cold boxes. The SciFi tracker contains 128 stiff and robust 5 x 0.5 m modules made of eight mats bonded with two fire-resistant honeycomb 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 post-irradiation rays added to the polyethylene amplify the light and shift it to longer wavelengths so it can be read out by 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, where providing a similar performance to the silicon-strip tracker. The tiny channel size results in over 524,288 SiPM channels to collect the start of operations early next year.

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 due 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 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 Tbps – nearly half of the total data bandwidth of the upgraded LHCb detector.


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. Forty 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 the 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 refitted to cope with the more challenging data-taking conditions of Run 3, requiring a variety of technological

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**Asymmetric anatomy**

LHCb’s successive detector layers located downstream from the interaction point in the heart of the VELO.

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**SciFi tracking**

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More than 11,000 km of 0.25 mm – diameter polyethylene 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 x 0.5 m modules made of eight mats bonded with two fire-resistant honeycomb 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 post-irradiation rays added to the polyethylene amplify the light and shift it to longer wavelengths so it can be read out by 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.

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Cherenkov curves
The spherical mirrors of the new RICHs

To keep the new RICHes as compact as possible, the housing 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 Novolac, 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 positioning of the photon detectors and their operating conditions to be fine-tuned across the RICH detectors. In February, the first photon-detector plane of RICH1 (see “RICH to go” image) became the first active element of the LHCb upgrade to be installed in the cavern. The two planes of RICH1, 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.

RICHs present 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 RICH is also constrained by its magnetic shield, demanding even more compact mechanics for the photon-detector planes. To accommodate the new design of RICHs, a new gas enclosure for the radiator is needed. A volume of 3.8 m³ of C₄F₁₀ 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 RICH mechanics. The ~2 m² spherical mirrors placed inside the RICH enclosure 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 RICH 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 $B^0 \to J/\psi K^*$, 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 (Fβ). 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.

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**Designing an AI physicist**

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

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 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.

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 internal 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 trustworthy 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.

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

**OPINION VIEWPOINT**

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

**CERN COURIER**

**SEPTEMBER/OCTOBER 2021**
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 those questions? This would be truly stealing theoretical physicists’ lunch.

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. It is 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 these 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?

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

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
we can introduce those things into AI?

JE: All this is very impressive – but how is AI going to devise an experiment that challenges the generator to extrapolate and predict hitherto unknown scenarios? It is 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, some disconcerting discrepancies between different studies are caused by a misunderstanding of the phenomenon of ‘hierarchical clustering’ between the ‘local measurements of the fundamental constituents of the universe’ and the ‘global measurements of the whole universe as a whole’. There are indeed serious problems with the ACDM model – not least the complete failure of the model to predict the dark energy – but the “bubble 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 don’t violate a gross violation of the cosmological principle itself (N Secrest 2021. 308-135).

Subir Sarkar University of Oxford.

• Author’s reply

In this Hubble constant (H) 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. Periphrases, summaries and rants are the way to stay up to date with the latest developments. While this opens up a Pandora’s box of discussions for all of us, the bubble tension may still be fast pace of science, let me stick to the point here. As of late July, the consensus among the SH0ES and TRIG groups is that the data agree extremely well in relative distances, but there are still some elements that do not seem very satisfactory. For example, the Hubble diagram is not guaranteed to remain a valid method for estimating the Hubble constant, even when the data are sufficiently accurate, especially when the so-called Hubble tension is considered.

Licia Verde University of Barcelona.

LHwp diplomacy

It was a real pleasure to read your article on Paul Lecointre’s LHWP project. I am impressed by the many smart and efficient ideas mentioned in the literature favouring such solutions.
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**Resistive Gaseous Detectors: Designs, Performance, and Perspectives**

By Marcello Abbrescia, Vladimir Peskov and Paolo Fonte

Wiley

The first truly resistive gaseous detector was invented by Rinaldo Santoni, Iaco and Roberto Cardarelli in 1981. A kind of parallel-plate detector with electrodes made of resistive materials such as Bakelite and thin-foil glass, the design is sometimes also known as a resistor-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 ionized, 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 space-time 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 Paolo 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. Different types of gaseous detectors with resistive electrodes that can be made with micro-electronic technology are 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 of particle physics such as those in medicine exploiting positron-emission tomography. For homeland security, RPCs can be used in micro-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 specializing in high-energy physics, astrophysics, medical physics and radiation measurements, and at all academic levels, from students to seasoned professionals.

Vi Wang, Tsinghua University.
Climate Change and Energy Options for a Sustainable Future

By Dinesh Kumar Srivastava and V S Ramamurthy

World Scientific

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 analyze 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
Quantum gravity in the Vatican

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

“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 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 resembles 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 origins 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 – that was fun,” he recalls.

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 1965. A little later in the day, when the Sun was rising there, I spoke to Paul Gabor – a astrophysicist, Jesuit priest and deputy director for the Tucson observatory.

Born in Kolice, 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...”
PEOPLE CAREERS

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 Jesus 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 sapienst 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. Those qualities 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.”

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 somebody’s benefit. This is a scenario that is all too common unfortunately.”

Consolmagno also offers words of caution. "Fifty percent 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, “(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

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

New artists at Fermilab

Fermilab has announced its first 2021-2022 guest composer as David Biedenbender (left) and 2021-2022 artist-in-residence as Mark Hirsh (right). Biedenbender becomes the second guest composer at the institute, following on from David Ibbet 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 9-minute wind ensemble piece inspired by the particle accelerator at the National Superconducting Cyclotron Laboratory at MSU.

In its seventh year, the artist-in-residence programme will see Hirsh 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-HPU 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.

ALICE PhD winner

Jonatan Adolfsson (Lund University) has been awarded the 2021 ALICE PhD thesis prize for his thesis “Study of -hadron correlations in pp collisions at √s = 7 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.

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-rays 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 269 teams representing 25 countries, will travel to DESY later this year to carry out their proposed experiments with the support of scientists from CERN and DESY.
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)**

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- Professional experience in one of these areas: stringent real-time applications / low-latency systems / low-noise systems
- Excellent written and oral English language skills; good German language skills will be essential
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Please provide us with a short summary of your ideas on the future of electronics for experiments in the framework of GSI and FAIR.

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The future is in laser technologies
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.

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 J. Valentine Professor of Physics at Caltech, passed away on 23 July 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 1953 for a measurement of the (p,n) reaction at the ETH cyclotron.

In 1953 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 unrivaled energy resolution in gamma-ray spectroscopy. 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 piconic atoms, which led to a precise determination of the strong-interaction shift in inelastic hydrogen. At Caltech, he also became interested in parity violation and time-reversal.

In my life, I have built only one model

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

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An outstanding experimentalist

Alexei Onuchin was born in 1933, 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 Tsvet 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–neutrino detector, working on the construction of the MD–1 detector for the VEP-2, a superb experiment. For this work, in 2008 Alexei Onuchin was awarded the Chernov 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.

Anatoly Vasilievich Efremov 1933–2021

Theorist Tord Riemann, who made key contributions to the understanding of the ZFITTER project at the Large Electron–Positron (LEP) collider. In 1991-1992 he was a research associate in the hadron-structure division, working on the so-called S-matrix approach to the Z resonance. This work also included the investigation of the electromagnetic form factor of the Z boson in the framework of Quantum Chromodynamics (QCD).

In 1983–1987 Alexei worked at JINR, then in the Soviet Union, in the group of Dmitry Bardin.

Although Vasilievich Efremov was the undisputed leader of the theory group in the Dubna International Workshop 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.

On 3 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 yachtman. After graduating from Moscow Engineering Physics Institute in 1959, where among his teachers were Isaak Pomeranchuk and his master’s thesis adviser Yakov Smorodinsky, he started working at BLTP JINR. At the time, Dmitry Radyushkin, Efremov’s supervisor, was an associate professor of the Institute of Nuclear Physics (INP). Anatoly always considered him as his teacher, and he did Dmitry Shirkov under whose supervision he passed his PhD in theoretical physics on “Dispersion theory of low-energy scattering of pions” in 1962.


In 1961, Anatoly published his doctoral dissertation “High-energy asymptotics of Feynman diagrams”. The underlying work served as the theoretical basis for the newly founded field of quantum chromodynamics (QCD), which is now the theoretical foundation of all hard–hadronic processes. Of particular note were his 1979 articles (written together with his PhD student A V Radyushkin) on the asymptotic form factor in QCD, and the evolution equation for hard exclusive processes, which became known as the EBBR (Efremov–Brodsky–Radyushkin–Lepage) equation. Proving the factorisation of hard processes enabled many subtle effects to be described, in particular parton correlations, which became known as the ETQS (Efremov–Teryaev–Qiu–Sterman) mechanism.

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 nucleus, correlations of the spin of partons, and moments of particles in jets (“handedness”). These effective processes served as the theoretical basis for polarised particle experiments at RHIC at Brookhaven, the SPS at CERN and the new NICA factory at the MD–1 Cherenkov counters filled with ethylene gas pressurised to 25 bar, and finally suggested the construction of water–threshold counters (ASHIPP) for the KEK detector. For this work, in 2008 Alexei Onuchin was awarded the Chernov Prize of the Russian Academy of Sciences.

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Tord Riemann 1951–2021

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Anatoly Efremov was one of the key staff of JINR’s Bogoliubov Laboratory of Theoretical Physics.
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, zf and \( \ell \ell \) 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 topFt, GENTLE/4fan, HECTOR, SMATASY, TERA/dfs, DISFNC, DISFCC, DISEPNC, pHeCTOR and AMBRE.

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 his 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.

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

Arif Akhundov, Andrei Arbuzov, Alain Blondel, Ayres Freitas, Janusz Gluza, Stanislaw Jadach, Lida Kalinovskaya and Sabine Riemann on behalf of his colleagues and friends.
Notes and observations from the high-energy physics community

O telescopes, o more!

In days of yore, an experiment might choose a lovely 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.

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 those 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 so 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 p347–349 of CERN Courier October 1981.

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.

“Just a few years ago, such an idea was squarer 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.”

Indu Today’s Siby Tripathi reports on speculations (see above) about building a circular collider on the moon (CCM) that intersects its poles while minimizing 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.

Energy stored in the LHC’s magnetic circuit, including 8.8 GJ in dipoles and 1.5 GJ in detector magnets. ITER’s magnetic system, now under construction (p13), should break this record, exceeding 50 GJ in the 2030s.

Media corner

“It’s a high-energy physics conference with a high energy.”

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

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CERN Courier
Volume 61 Number 5 September/October 2021

CAERN Courier CAEN Team ADV_OK.indd   1
03/08/21   14:20
WWW.