WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2023 issue of *CERN Courier.*

Links between particle physics and gravitational-wave science are strengthening, both in the theory realm and on the ground. A prime example is CERN's key role in the design of next-generation gravitational-wave observatories, in particular the vacuum tubes for the proposed Einstein Telescope in Europe (p45).

A second in-depth feature by CERN authors explores the potential of this and other gravitational-wave observatories to study high-energy processes in the early universe (p32). Among them are cosmological phase transitions, which are predicted to contribute to a stochastic gravitational-wave background. In late June, networks of radio telescopes around the world spotted tentative evidence for low-frequency waves consistent with such a background (p7).

Take a deep dive into the high-spec world of graphics processing units with the ALICE O^2 computing upgrade (p39), delve into a century of FCC physics (p20), survey the linear-collider marketplace (p23), zoom out on the vast landscape of accelerators in physics and industry (p19), and explore the long-term US vision for particle physics (p50).

This issue also takes a closer look at efforts to understand the wild variation in recent measurements of the W-boson mass (p27), the latest LHC results (p22), careers (p55), reviews (p52) and more.

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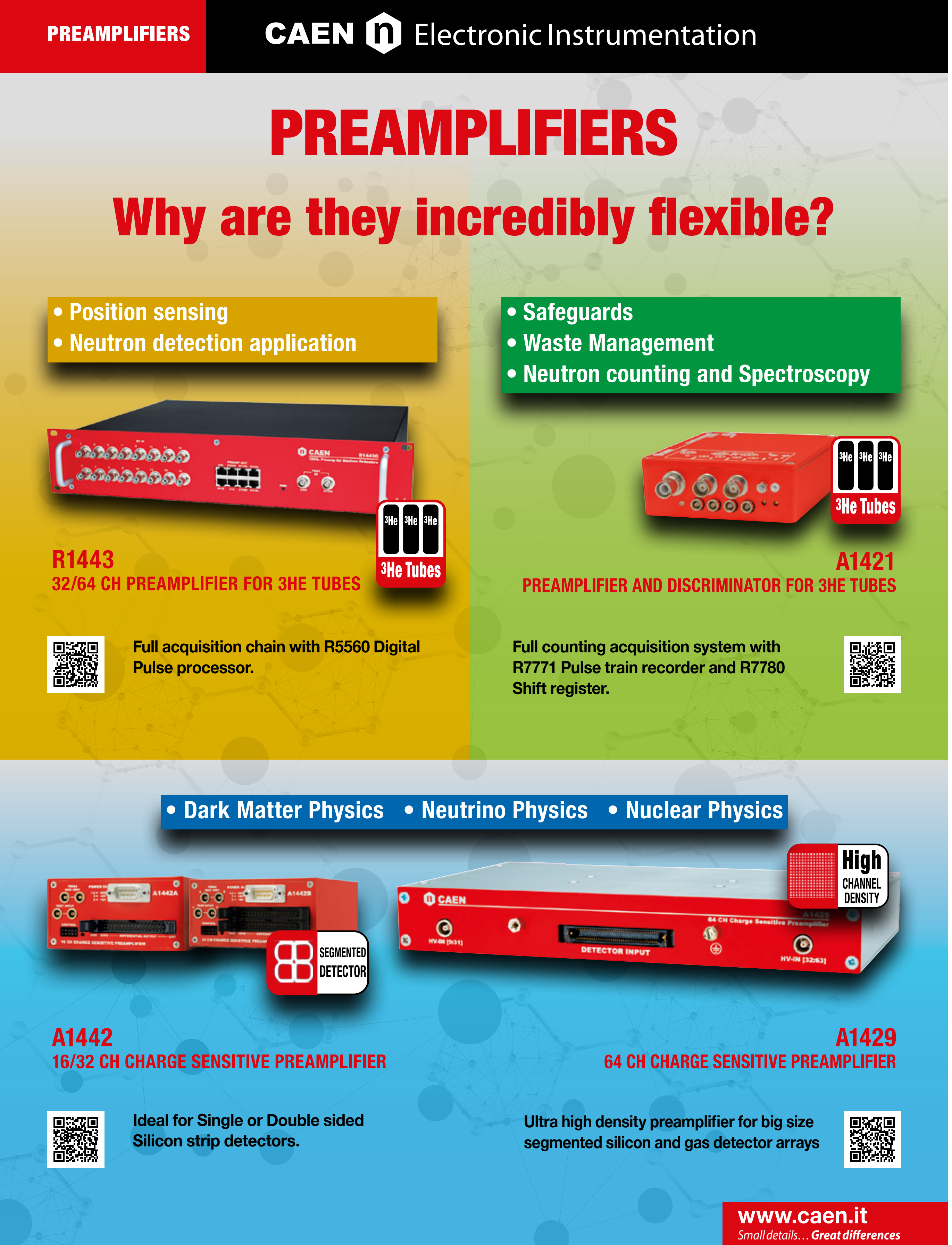

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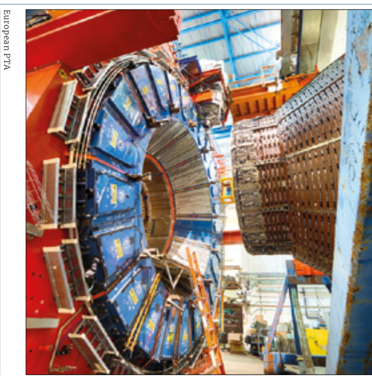

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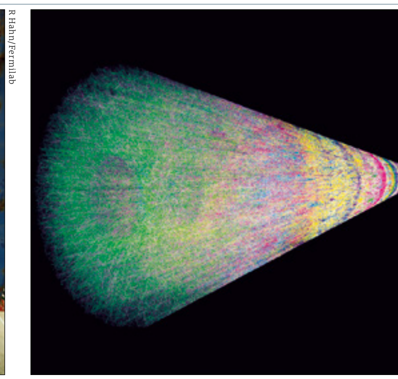

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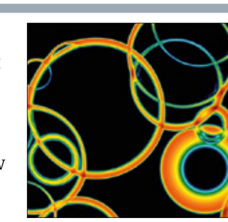

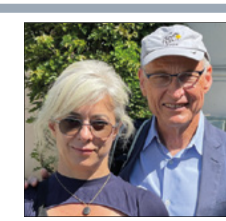

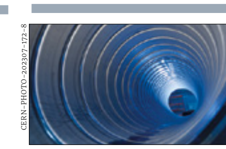

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FROM THE EDITOR

A powerful partnership

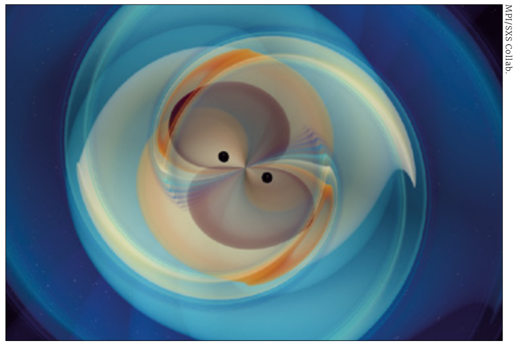
Matthew Chalmers
Editor

The two biggest discoveries in fundamental physics this century so far – that of the Higgs boson by the ATLAS and CMS collaborations in 2012, and of gravitational waves by LIGO and Virgo in 2015 – share much in common. Both confirmed predictions made many decades earlier, crowning the Standard Model of particle physics and Einstein's general relativity. Both required herculean experimental efforts, international collaborations and the invention of new technologies. Most important of all, both provided a tool with which to explore new territory: the scalar sector of nature and the electroweak phase transition in the case of the Higgs boson, and previously unseen processes in the universe at large, possibly at the earliest times, in the case of gravitational waves.

Links between particle physics and gravitational-wave science are strengthening, both in the theory realm and on the ground. This issue describes CERN's key role in the design of next-generation gravitational-wave observatories, in particular the proposed Einstein Telescope in Europe (p45). Such a facility will require the most extensive and ambitious ultra-high vacuum system ever constructed, comprising 130 km of vacuum tubes, with capital equipment costs potentially on a par with civil-engineering works. A collaboration led by CERN, Nikhef and the INFN is exploring scalable vacuum solutions for the Einstein Telescope beam pipes that will enable cost-effective construction without compromising on performance. CERN is also collaborating on the radically different vacuum challenges for the LISA observatory, due to launch around 2035.

A second in-depth feature by CERN authors (p32) explores the potential of these and other gravitational-wave observatories to study high-energy processes in the early universe. Cosmological phase transitions, for example, are predicted by many theories (including models that introduce extended scalar sectors in an attempt to explain dark matter) to produce a background "hum" of gravitational waves. In late June, networks of radio telescopes around the world reported evidence for low-frequency gravitational waves consistent with a stochastic gravitational-wave background (p7). The expected origin of the signal is astrophysical: the superposition of countless massive binary inspirals over the history of the universe. With more data from existing, planned and proposed instruments, however, it will become possible to search for imprints of primordial gravitational waves, which, if found, would offer an unprecedented view of the universe before the recombination epoch.

Links between particle physics and gravitational-wave science are strengthening



MPI/SXS Collab.

Making waves *Simulated gravitational-wave emission from a black-hole binary merger with equal masses.*

Also in the issue

Take a deep dive into the high-spec world of graphics processing units with the ALICE O² computing upgrade – a pioneering effort to keep up with the LHC's ever-increasing luminosity (p39). Delve into a century of FCC physics (p20), survey the linear-collider marketplace (p23), zoom out on the vast landscape of accelerators in physics and industry (p19), and explore the long-term US vision for particle physics (p50).

This issue also takes a closer look at efforts to understand the wild variation in recent measurements of the W-boson mass (p27). And, on the subject of anomalies, news from Fermilab (announced as the *Courier* went to press) that the magnetic moment of the muon has been measured to a precision of 0.2 parts per million sets up a showdown between experiment and theory.

Reporting on international high-energy physics

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NEWS ANALYSIS

GRAVITATIONAL WAVES

Hints of low-frequency gravitational waves found

Since their direct discovery in 2015 by the LIGO and Virgo detectors, gravitational waves (GWs) have opened a new view on extreme cosmic events such as the merging of black holes. These events typically generate gravitational waves with frequencies of a few tens to a few thousand hertz, within reach of ground-based detectors. But the universe is also expected to be pervaded by low-frequency GWs in the nHz range, produced by the superposition of astrophysical sources and possibly by high-energy processes at the very earliest times (see p32).

Announced in late June, news that pulsar timing arrays (PTAs), which infer the presence of GWs via detailed measurements of the radio emission from pulsars, had seen the first evidence for such a stochastic GW background was therefore met with delight by particle physicists and cosmologists alike. "For me it feels that the first gravitational wave observed by LIGO is like seeing a star for the first time, and now it's like seeing the cosmic microwave background for the first time," says CERN theorist Valerie Domcke.

J Young/Green Bank Observatory

Looking up *The Green Bank Telescope in West Virginia, one of several radio telescopes that contributed to the pulsar timing array datasets.*

Clocking signals

Whereas the laser interferometers LIGO and Virgo detect relative length changes in two perpendicular arms, PTAs clock the highly periodic signals from millisecond pulsars (rapidly rotating neutron stars), some of which are in Earth's line of sight. A passing GW perturbs spacetime and induces a small delay in the observed arrival time of the pulses. By observing a large sample of pulsars over a long period and correlating the signals, PTAs effectively turn the galaxy into a low-frequency GW observatory. The challenge is to pick out the characteristic signature of this stochastic background, which is expected to induce "red noise" (meaning there should be greater power at lower fluctuation frequencies) in the differences between the measured arrival times of the pulsars and the timing-model predictions.

The smoking gun of a nHz GW detection is a measurement of the so-called Hellings–Downs (HD) curve based on general relativity. This curve predicts the arrival-time correlations as a function of angular separation for pairs of pulsars, which vary because the quadrupolar nature of GWs introduces directionally dependent changes.

We are opening a new window in the GW universe, where we can observe unique sources and phenomena

Following its first hints of these elusive correlations in 2020 (*CERN Courier* November/December 2020 p12), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has released the results of its 15-year dataset. Based on observations of 68 millisecond-pulsars distributed over half the galaxy (21 more than in the last release) by the Arecibo Observatory, the Green Bank Telescope and the Very Large Array, the team finds 4σ evidence for HD correlations in both frequentist and Bayesian analyses.

A similar signal is seen by the independent European PTA, and the results are also supported by data from the Parkes PTA and others. "Once the partner collaborations of the International Pulsar Timing Array (which includes NANOGrav, the European, Parkes and Indian PTAs) combine these newest datasets, this may put us over the 5σ threshold," says NANOGrav spokesperson Stephen Taylor. "We expect that it will take us about a year to 18 months to finalise."

It will take longer to decipher the precise origin of the low-frequency PTA signals. If the background is anisotropic, astrophysical sources such as supermassive black-hole binaries would be the likely origin and one could therefore learn about their environment, population and how galaxies merge. Phase transitions or other cosmological sources tend to lead to an isotropic background. Since the shape of the GW spectrum encodes information about the source, with more data it should become possible to disentangle the signatures of the two potential sources. PTAs and current, as well as next-generation, GW detectors such as LISA and the Einstein Telescope complement each other as they cover different frequency ranges. For instance, LISA could detect the same supermassive black-hole binaries as PTAs but at different times during and after their merger.

"We are opening a new window in the gravitational-wave universe in the nanohertz regime, where we can observe unique sources and phenomena," says European PTA collaborator Caterina Tiburzi of the Cagliari Observatory in Sardinia.

Further reading

EPTA Collab. 2023 arXiv:2306.16224.
NANOGrav Collab. 2023 *ApJL* **951** L8.
Parkes PTA Collab. 2023 *ApJL* **951** L6.

LHC

Electrical perturbation uproots Run 3 operations

At around 1 a.m. on 17 July, the LHC beams were dumped after only nine minutes in collision due to a radiofrequency interlock caused by an electrical perturbation. Approximately 300 milliseconds after the beams were cleanly dumped, several superconducting magnets lost their superconducting state, or quenched. Among them were the inner-triplet magnets located to the left of Point 8, which focus the beams for the LHCb experiment. While occasional quenches of some LHC magnets are to be expected, the large forces resulting from this particular event led to a breach of the vacuum helium pressure vessel, rapidly degrading the insulation vacuum and prompting a series of interventions with implications for the 2023 Run 3 schedule.

The leak occurred between the LHC's cryogenic circuit, which contains the liquid helium, and the insulation vacuum that separates the cold magnet from the warm outer vessel (the cryostat) – a crucial barrier for preventing heat transfer from the surrounding LHC tunnel to the interior of the cryostat. As a result of the leak, the insulation vacuum filled with helium gas, cooling down the cryostat and causing condensation to form and freeze on the outside.

Root cause *A power glitch caused by a fallen tree led to a magnet quench and ultimately a 1.6 mm-long crack (circled) in one of the LHC's compensation bellows.*

By 24 July the CERN teams had traced the leak to a crack in one of more than 2500 bellows that compensate for thermal expansion and contraction on the cryogenic distribution lines. Measuring just 1.6 mm long, it is thought to have been caused by a sudden increase in vacuum pressure when the magnet quench protection system (QPS) kicked in. Following the electrical perturbation, the QPS had dutifully triggered the quench heaters (which are designed to bring the whole magnet out of the superconducting state in a controlled and homogenous manner) of the magnets concerned, generating a heat wave according to expectations.

It is the first time that such a breach event has occurred; the teamwork between many working groups, including safety, accelerator operations, vacuum, cryogenics, magnets, survey, beam instrumentation, machine protection, electrical quality assurance as well as material and mechanical engineering, made a quick assessment and action plan possible. On 25 July the affected bellow was removed. A new bellow was installed on 28 July, the affected modules were closed, and the insulation vacuum was pumped.

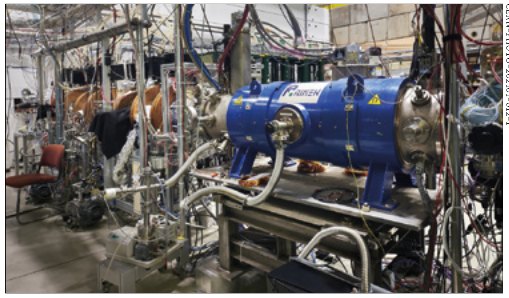
The electrical perturbation turned out to be caused by an uprooted tree falling on power lines in the nearby Swiss municipality of Morges. In early August, as the *Courier* went to press, the repairs were finished and the implications for Run physics were being assessed. The choice is between preparing the machine for a short-term proton–proton phase to account for some of the missed run time or sticking to the planned heavy-ion run at the end of the run year, since in 2022 there was no full heavy-ion run. The favoured scenario is to go with the latter and was presented to the LHC machine committee on 26 July.

Antimatter

GBAR joins the anticlub

The GBAR experiment at CERN has joined the select club of experiments that have succeeded in synthesising antihydrogen atoms. Located at the Antiproton Decelerator (AD), GBAR aims to test Einstein's equivalence principle by measuring the acceleration of an antihydrogen atom in Earth's gravitational field and comparing it with that of normal hydrogen.

Producing and slowing down an antiatom enough to see it in free fall is no mean feat. To achieve this, the AD's 5.3 MeV antiprotons are decelerated and cooled in the ELENA ring and a packet of a few million 100 keV antiprotons is sent to GBAR every two minutes. A pulsed drift tube further decelerates the packet to an adjustable energy of a few keV. In parallel, a linear particle accelerator sends 9 MeV electrons onto a tungsten target, producing positrons, which are accumulated in a series of electromagnetic traps. Just before the antiproton packet arrives, the positrons are sent to a layer of nanoporous silica, from which about one in five positrons emerges as a positronium atom. When the antiproton packet crosses the resulting cloud of positronium atoms, a charge exchange can take place, with the positronium giving up its positron to the antiproton, forming antihydrogen.



Antiatoms in flight *The GBAR experiment in the Antiproton Decelerator hall.*

At the end of 2022, during an operation that lasted several days, the GBAR collaboration detected some 20 antihydrogen atoms produced in this way, validating the "in-flight" production method for the first time. The collaboration will now improve the production of antihydrogen atoms to enable precision measurements, for example, of its spectroscopic properties.

The first antihydrogen atoms were produced at CERN's LEAR facility in 1995, but at an energy too high for any measurement to be made. Following this early success, CERN's Antiproton Accumulator (used for the discovery of the W and Z bosons in 1983) was repurposed as a decelerator, becoming the AD, which is unique worldwide in providing low-energy antiprotons to antimatter experiments. After the demonstration of storing antiprotons by the ATRAP and ATHENA experiments, ALPHA, a successor of ATHENA, was the first experiment to merge trapped antiprotons and positrons and to trap the resulting antihydrogen atoms. Since then, ATRAP and ASACUSA have also achieved these two milestones, and AEgIS has produced pulses of antiatoms. GBAR now joins this elite club, having produced 6 keV antihydrogen atoms in-flight.

GBAR is also not alone in its aim of testing Einstein's equivalence principle with atomic antimatter. ALPHA and AEgIS are also working towards this goal using complementary approaches.

Further reading

P Adrich *et al.* 2023 arXiv:2306.15801.

SESAME

Iraq to join SESAME as associate member

On 25 July, during its 42nd meeting, the Council of SESAME unanimously approved Iraq's request to become an associate member. Iraq will now become a prospective member of SESAME as a stepping stone to full membership.

"My visit to SESAME on 8 June 2023 has convinced me that Iraq will stand to greatly benefit from membership, and that this would be the right moment for it to become a member," stated Naeem Alaboodi, minister of higher education and scientific research and head of the Iraqi Atomic Energy Commission, in his letter to Rolf Heuer, president of the SESAME Council. "However, before doing so it would like to better familiarise itself with the governance, procedures and activity of this centre, and feels that the best way of doing this would be by first taking on associate membership."

SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East), based in Allan, Jordan, was founded on the CERN model and established under the umbrella of UNESCO. It opened its doors to users in 2017, offering third-generation X-ray beamlines for a range of disciplines, with the aim to be the first international Middle-Eastern research institution enabling scientists to collaborate peacefully for the generation of knowledge (*CERN Courier* January/February 2023 p28). SESAME has eight full members (Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestine and Turkey) and 17 observers, including CERN. One of SESAME's main focuses is archaeological heritage. This will be the topic of the first Iraqi user study, which involves two Iraqi institutes collaborating in a project of the Natural History Museum in the UK.

Open door *SESAME hopes to welcome more members in the future.*

Iraq has been following progress at SESAME for some time. As an associate member Iraq will enjoy access to SESAME's facilities for its national priority projects and more opportunities for international collaboration. "Iraq's formal association with SESAME will be very useful for Iraqi scientists to gain the required scientific knowledge in many different areas of science and applications using synchrotron radiation," said Hua Liu, deputy director-general of the International Atomic Energy Agency, which has been actively encouraging its member states located in the region to seek membership of SESAME.

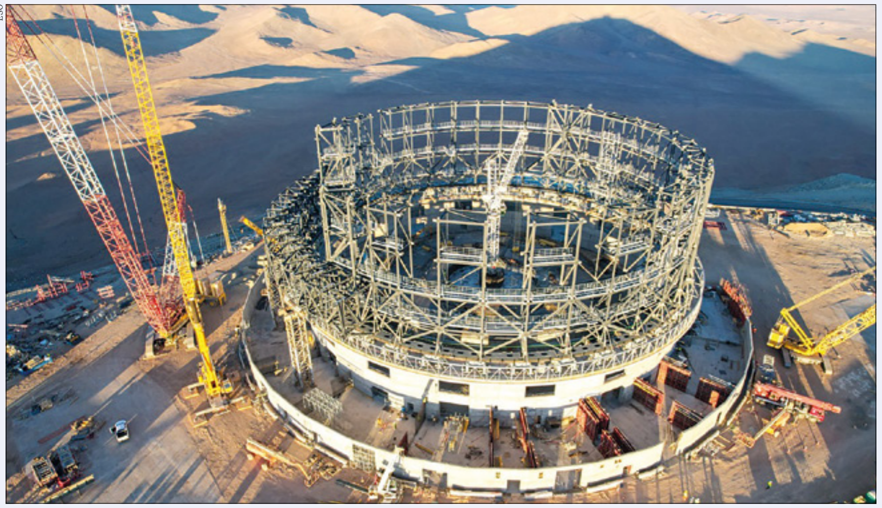
"The Council and all the members of SESAME are delighted by Iraq's decision," added Heuer. "We look forward to further countries of the region joining the SESAME family. With more beamlines available in the future, we hope that user groups from different countries will be working together on projects and we will see more transnational collaboration."

Facilities

ESO's Extremely Large Telescope halfway to completion

The construction of the world's largest optical telescope, the Extremely Large Telescope (ELT), has reached its midpoint, stated the European Southern Observatory (ESO) on 11 July. Originally planned to see first light in the early 2020s, operations will now start in 2028 due to delays inherent to building such a large and complex instrument, as well as the COVID-19 pandemic.

The base and frame of the ELT's dome structure on Cerro Armazones in the Chilean Atacama Desert have now been set. Meanwhile at European sites, the five-system mirrors for the ELT are being manufactured. More than 70% of the supports and blanks for the main mirror – which at 39 m across will be the biggest primary mirror ever built – are complete, and mirrors two and three are cast and now in the process of being polished.



Mountain view *The ELT's dome building takes shape in the Chilean Atacama Desert.*

Along with six laser guiding sources that will act as reference stars, mirrors four and five form part of a sophisticated adaptive-optics system to correct for atmospheric disturbances. The ELT will observe the universe in the near-infrared and visible regions to track down Earth-like exoplanets, investigate faint objects in the solar system and study the first stars and galaxies. It will also explore black holes, the dark universe and test fundamental constants (*CERN Courier* November/December 2019 p25).

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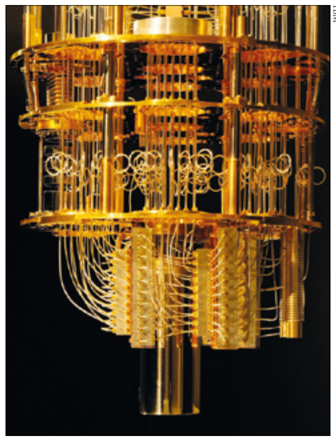
Quantum computing

Report explores quantum computing in particle physics

Researchers from CERN, DESY, IBM Quantum and more than 30 other organisations have published a white paper identifying activities in particle physics that could benefit from quantum-computing technologies. Posted on arXiv on 6 July, the 40 page-long paper is the outcome of a working group set up at the QT4HEP conference held at CERN last November, which identified topics in theoretical and experimental high-energy physics where quantum algorithms may produce significant insights and results that are very hard or even not accessible by classical computers (*CERN Courier* January/February 2023 p17).

Combining quantum and information theory, quantum computing is natively aligned with the underlying physics of the Standard Model. Quantum bits, or qubits, are the computational representation of a state that can be entangled and brought into superposition. Once measured, qubits do not represent discrete numbers 0 and 1 as their classical counterparts, but a probability ranging from 0 to 1. Hence quantum-computing algorithms can be exploited to achieve computational advantages in terms of speed and accuracy, especially for processes that are yet to be understood.

"Quantum computing is very promising, but not every problem in particle physics is suited to this model of computing," says Alberto Di Meglio, head of IT Innovation at CERN and one of the white paper's lead authors alongside Karl Jansen of DESY and Ivano Tavernelli of IBM Quantum. "It's important to ensure that we are ready and that we can accurately identify the areas where these technologies have the potential to be most useful."



IBM

Quantum potential *A quantum computer built by IBM based on superconducting qubits.*

Neutrino oscillations in extreme environments, such as supernovae, are one promising example given. In the context of quantum computing, neutrino oscillations can be considered strongly coupled many-body systems that are driven by the weak interaction. Even a two-flavour model of oscillating neutrinos is almost impossible to simulate exactly for classical computers, making this problem well suited for quantum computing. The report also identifies lattice-gauge theory and quantum field theory in general as candidates that could enjoy a quantum advantage. The considered applications include quantum dynamics, hybrid quantum/classical algorithms for static problems in lattice gauge theory, optimisation and classification problems.

With quantum computing we address problems in those areas that are very hard to tackle with classical methods

In experimental physics, potential applications range from simulations to data analysis and include jet physics, track reconstruction and algorithms used to simulate the detector performance. One key advantage here is the speed up in processing time compared to classical algorithms. Quantum-computing algorithms might also be better at finding correlations in data, while Monte Carlo simulations could benefit from random numbers generated by a quantum computer.

"With quantum computing we address problems in those areas that are very hard – or even impossible – to tackle with classical methods," says Karl Jansen (DESY). "We can now explore physical systems to which we still do not have access."

The working group will meet again at CERN for a special workshop on 16 and 17 November, immediately before the Quantum Techniques in Machine Learning conference from 19 to 24 November.

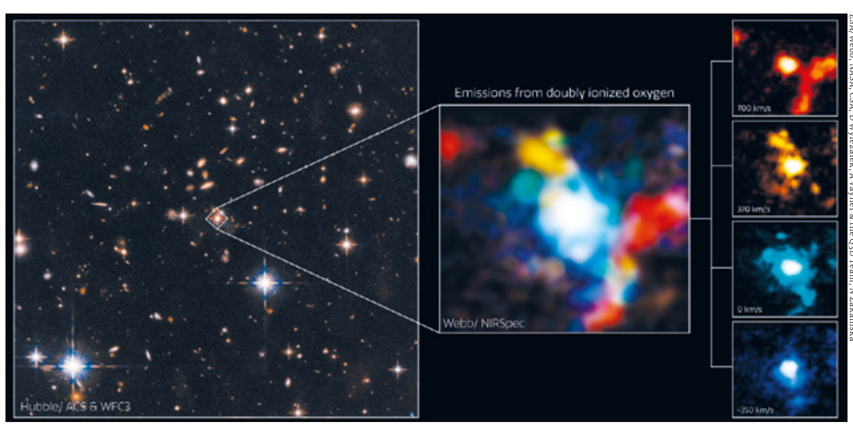
Further reading

A Di Meglio *et al.* 2023 arXiv:2307.03236.

Astrowatch

Time dilation finally observed in quasars

Within astronomy and cosmology, the idea that the universe is continuously expanding is a cornerstone of the standard cosmological model. For example, when measuring the distance of astronomical objects one often uses their redshift, which is induced by their velocity with respect to us due to the expansion. The expansion itself has, however, never been directly measured, i.e. no measurement exists that shows the increasing redshift with time of a single object. Although not far beyond the current capabilities of astrophysics, such a measurement is unlikely to be performed soon. Rather, evidence for it is based on correlations within populations of astrophysical objects. However, not all studies agree with this standard assumption. ▷



ESA/Webb, NASA, CSA, D Wylezalek, A Vayner & the Q3D Team, N Zakamska

Light on time *An "extremely red" quasar in the very early universe, 11.5 billion years ago (corresponding to a redshift of z = 2.94), highlighted in an image from the Hubble (left) and James Webb (inset) space telescopes.*

One population study that supports the standard model concerns type 1A supernovae, specifically the observed correlation between their duration and distance. Such a correlation is predicted to be the result of time dilation induced by the higher velocity of more distant objects. Supporting this picture, gamma-ray bursts occurring at larger distances appear to, on average, last longer than those that occur nearby. However, similar studies of quasars thus far did not show any dependence of the length in their variability with their distance, thereby contradicting special relativity and leading to an array of alternative hypotheses.

Detailed studies

Quasars are active galaxies containing a supermassive blackhole surrounded by a relativistic accretion disk. Due to their brightness they can be observed with redshifts up to z = 8, which, based on special relativity should show variabilities occurring $\sqrt{8}$ times slower than those that occur nearby. As previous studies did not observe such time dilation, alternative theories proposed included those that cast doubt on the extragalactic nature of quasars. A new, detailed study now removes the need for such theories.

In order to observe time dilation one requires a standard clock. Supernovae are ideal for this purpose because these explosions are all nearly identical, allowing their duration to be used to measure time dilation. For quasars the issue is more complicated as the variability of their brightness appears almost random. However, the variability can be modelled using a so-called dampened random walk (DRW), a random process combined with an exponential dampening component. This complex model does not allow the brightness of a quasar to be predicted, but contains a characteristic timescale in the exponent that should correlate to the redshift due to time dilation.

These results do not provide hints of new physics but rather resolve one of the main problems with the standard cosmological model

This idea has now been tested by Geraint Lewis and Brenden Brewer of the universities of Sydney and Auckland, respectively. The pair studied 190 quasars with redshifts up to z = 4, observed over a 20 year period by the Sloan Digital Sky Survey and PanSTARRS-1, and applied a Bayesian analysis to look for a correlation between the DRW parameters and their redshift. The data was found to match best a universe where the DRW parameters scale according to $(1+z)^n$ with $n = 1.28 \pm 0.29$, thereby making it compatible with n = 1, the value expected by standard physics. This contradicts previous measurements, something the authors attribute to the smaller quasar sample used in previous studies. The complex nature of quasars and the large variability in their population requires long observations of a similar population to make the time dilation effect visible.

These new results, which were made possible due to the large amounts of data becoming available from large observatories, do not provide hints of new physics but rather resolve one of the main problems with the standard cosmological model.

Further reading

G Lewis and B Brewer 2023 *Nat. Astron.* (in press).
O Chashchina and Z Silagadze 2015 *Universe* **1** 307.

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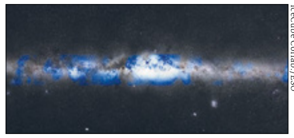
NEWS DIGEST



IceCube Collab./ESO

Galactic neutrino emissions.

Galactic neutrinos spotted

While it has been known for some time that interactions between cosmic rays and galactic gas produce gamma rays and neutrinos, so far only gamma rays have been observed in the Milky Way. After 10 years of data taking and analyses, the IceCube collaboration has now made the first observation of high-energy neutrinos from our galaxy. By comparing diffuse emission models to a background-only hypothesis, the team identified neutrino emission from the galactic plane with a 4.5σ significance. The observed neutrino flux is consistent with the diffuse emission of neutrinos from the Milky Way, but could also arise from a population of unresolved point sources. The result complements IceCube's measurements of the diffuse extragalactic neutrino flux to provide a more complete picture of the neutrino sky (*Science* **380** 6652).

Probing neutrinos via gravity

Stephen King (University of Southampton) and co-workers have proposed a novel way to use gravitational waves (GWs) to determine the origin of small neutrino masses, specifically whether neutrinos are Dirac or Majorana particles. Majorana neutrinos may have small masses due to the spontaneous breaking of lepton-number symmetry at high energies, resulting in cosmic strings that would produce a rather "flat" GW spectrum over a wide frequency range. Dirac neutrinos may have small masses due to a discrete symmetry, spontaneously broken by a new scalar, resulting in domain walls whose annihilation leads to a sharp peak in the GW spectrum. The hypothesis can be tested by pulsar timing arrays as well as with next-generation GW detectors (arXiv:2306.05389).

Rare results at NA62

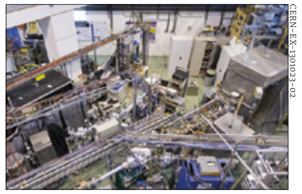
The NA62 collaboration at CERN has reported its first search of the ultra-rare decay $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$, placing an upper limit on its branching ratio of 1.4×10^{-8} at 90% confidence. This decay enables physicists to explore minimal dark sectors not yet excluded by experiment, specifically via the pair-production of dark states. By placing the most stringent upper limit on the branching ratio of a kaon hypothetically decaying into a π^+ and a pair of dark photons or dark scalars that then subsequently decay into e^+e^- pairs, the NA62 data (recorded in 2017 and 2018) exclude these particles with respective masses up to 150 and 300 MeV. Furthermore, the results rule out the QCD axion as an explanation for the 17 MeV anomaly claimed by the ATOMKI experiment (arXiv:2307.04579).

New light on dark photons

The NA64 experiment at CERN searches for particles from a hypothetical dark sector by firing the SPS secondary beams onto a fixed target. In its latest endeavour, the NA64 collaboration hunted for light dark-matter particles that interact with Standard Model particles through a new vector boson, the dark photon. Using electron collision data collected between 2016 and 2022, corresponding to 9.37×10^{11} electrons on target, NA64 has set the most sensitive limits to date on dark-photon couplings to photons for dark-photon masses below 0.35 GeV. The large dataset also excludes scalar and Majorana dark matter with a coupling between the dark-matter particle and the dark photon below 0.1 for a range of dark-matter particle masses (arXiv:2307.02404).

Magic tin returns

In the latest step towards a fully ab initio description of the nucleus, researchers using the ISOLTRAP experiment at CERN's ISOLDE facility have determined the energy necessary to excite the indium-99 nucleus into a long-lived excited state. The result, which follows an earlier ISOLTRAP measurement of indium-99 in the ground state, offers an even closer look at the "doubly magic" tin-100 nucleus, a mere proton above indium-99. The team compared the result with measurements



The ISOLTRAP experiment at CERN.

of isomer excitation energies for other indium neighbours, showing that this energy is essentially the same down to the magic neutron number 50 – in stark contrast with recent results on the magnetic moments of indium nuclei from ISOLDE's CRIS experiment (*Phys. Rev. Lett.* **131** 022502).

DESI's first data

Researchers have released the first batch of data from the Dark Energy Spectroscopic Instrument (DESI), which aims to map more than 40 million galaxies and other cosmic objects to study dark energy. Gathered during the survey-validation phase in 2020 and 2021, the dataset comprises almost two million objects, including distant galaxies and stars in the Milky Way. "The fact that DESI works so well, and that the amount of science-grade data it took during survey validation is comparable to previous completed sky surveys, is a monumental achievement," said DESI co-spokesperson Nathalie Palanque-Delabrouille of Lawrence Berkeley National Laboratory, which manages the experiment. Fermilab contributed several key elements to DESI, including the online databases used for data acquisition and the software that ensures that the instrument's 5000 robotic positioners point to their cosmic targets to within 10 microns.

Dark Matter Lab

The Centre national de la recherche scientifique (CNRS), together with DESY, the GSI Helmholtz Centre for Heavy Ion Research and the Karlsruhe Institute of Technology, has founded the international Dark Matter Lab (DMLab). Initially planned for five years and headquartered at DESY, DMLab aims to increase collaboration between the partners, in particular through research stays. Its topics will range from direct searches for dark-matter particles and the development of detector and accelerator technologies to the theoretical study of dark matter, and include astroparticle physics, gravitational waves and scientific computing. A joint project is the planned MADMAX experiment, for which tests were recently carried out using a prototype at CERN.

EPR paradox goes large

Researchers from the University of Basel have demonstrated for the first time the validity of the Einstein–Podolsky–Rosen paradox between two spatially separated massive systems of atoms. The team split a Bose–Einstein condensate into two spatially entangled atom clouds, each containing about 700 rubidium atoms, separated by 80 to 100 μm. By pulsing microwave and radiofrequency signals, the researchers rotated the spins such that they could repeatedly measure the spin components of the two systems simultaneously. Their findings show that the conflict between quantum mechanics and locality and realism persists even in systems with an increasing complexity and size (*Phys. Rev. X* **13** 021031).

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Using top quarks to probe nature's secrets

Despite its exceptional success, we know that the standard model (SM) is incomplete. To date, the LHC has not yet found clear indications of physics beyond the SM (BSM), which might mean that the BSM energy scale is above what can be directly probed at the LHC. An alternative way to probe BSM physics is through searches of off-shell effects, which can be done using the effective field theory framework (EFT). By treating the SM Lagrangian as the lowest order term in a perturbative expansion, EFT allows us to include higher-dimension operators in the Lagrangian, while respecting the experimentally verified SM symmetries.

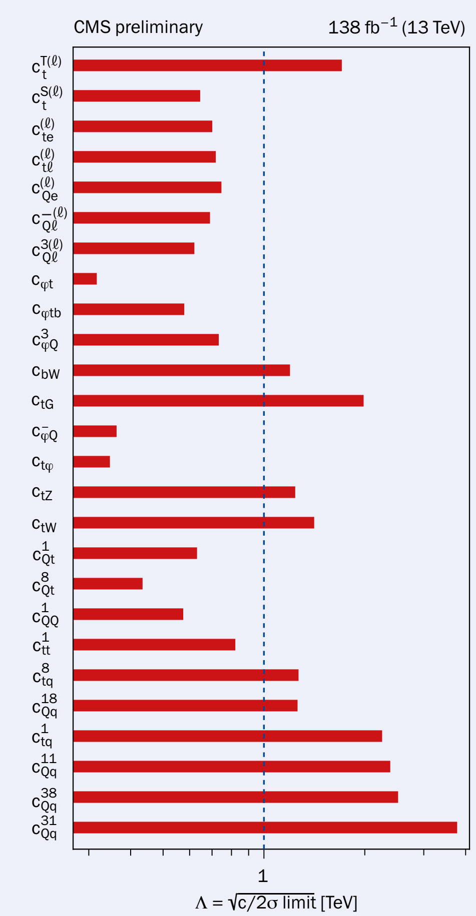
Operators

The CMS collaboration recently performed a search for BSM physics using EFT, analysing data containing top quarks with additional final-state leptons. The top quark is of particular interest because of its large mass, resulting in a Higgs–Yukawa coupling of order unity. Many BSM models connect the top-quark mass to large couplings to new physics. In the context of top quark EFT, there are 59 total operators at dimension six, controlled by the so-called Wilson coefficients, 26 of which produce final-state leptons. These coefficients enter the model as corrections to the SM matrix element, with a first term corresponding to the interference between the SM and BSM contributions, and a second term reflecting pure BSM effects.

The analysis was performed on the Run 2 proton–proton collisions sample, corresponding to an integrated luminosity of 138 fb^{-1}. It obtained limits on those 26 dimension-six coefficients, simulated at detector level with leading order precision (plus an additional parton when possible), exploiting six final-state signals, with different numbers of top quarks and leptons: $t\bar{t}H$, $t\bar{t}\ell\nu$, $t\bar{t}\ell\ell$, $t\ell\ell q$, tHq and $t\bar{t}t\bar{t}$. The analysis splits the data into 43 discrete categories, based primarily on lepton multiplicity, total lepton charge, and total jet or b-quark jet multiplicities. The events are analysed as differential distributions in the kinematics of the final-state leptons and jets.

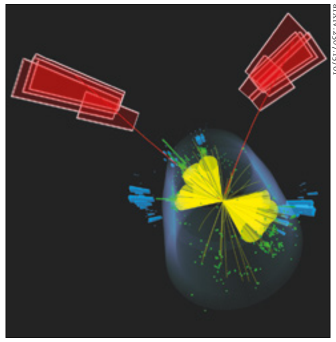
A statistical analysis is performed using a profiled likelihood to extract the 68% and 95% confidence intervals for all 26 Wilson coefficients by varying one of them while profiling the other 25. All the coefficients are compatible with zero (i.e. in agreement with the SM) at the 95% confidence level. For many of them, these results are the most competitive to date, even when compared to analyses that fit only one or two coefficients. Figure 1 shows how the 95% confidence intervals (2σ limit) translate into upper limits on the energy scale of the probed BSM interaction.

The CMS collaboration will continue to refine these measurements by expanding upon the final-state observables and leveraging the Run 3 data sample. With the HL-LHC quickly approaching, the future of BSM physics searches is full of potential.



Source: arXiv:2307.15761

Fig. 1. *The 95% confidence intervals obtained for the energy scale (TeV) when setting each of the 26 coefficients to 1 and profiling the other 25. These intervals can be seen as the current reach of these EFT searches. For example, if nature selected $c_{\varphi t} = 1$, we would derive the upper limit $\Lambda < 0.4$ TeV, meaning that potential signs of new physics coupling to top quarks and Z bosons should be observable at the LHC.*



arXiv:2307.15761

Fig. 2. *A four top-quark candidate event, with muons (red lines) coming from two decaying top quarks and jets (yellow cones) produced by hadronic decays of the other two.*

> **With the HL-LHC quickly approaching, the future of BSM physics searches is full of potential**

Further reading
CMS Collab. 2023 arXiv:2307.15761.

ATLAS

Precision progress on the Higgs boson

Since the discovery of the Higgs boson in 2012, its di-photon and four-lepton decays have played a crucial role in characterising its properties. Despite their small branching ratios, these decay channels are ideal for accurate measurements due to the excellent resolution and efficient identification of photons and leptons provided by the ATLAS detector.

The Higgs-boson mass (m_H) is a free parameter of the Standard Model (SM) that must be determined experimentally. Its value governs the coupling strengths of the Higgs boson with the other SM particles. It also enters as logarithmic corrections to the SM predictions of the W-boson mass and effective weak mixing angle, whose precise measurements allow the electroweak model to be tested. Moreover, the Higgs mass determines the shape and energy evolution of the Brout–Englert–Higgs potential and thus the stability of the electroweak vacuum. A precise measurement of m_H is therefore of paramount importance.

ATLAS has recently published a new result of the Higgs-boson mass in the $H \to \gamma\gamma$ decay channel using proton–proton collision data from LHC Run 2 (2015–2018). The measurement requires a careful control of systematic uncertainties, primarily arising from the photon energy scale. The new analysis has achieved a substantial reduction by more than a factor of three of these uncertainties compared to the previous ATLAS result based on the 2015 and 2016 dataset. That improvement became possible after extensive efforts to refine the photon energy-scale calibration and associated uncertainties.

The calibration benefited from an improved understanding of the energy response across the longitudinal ATLAS electromagnetic calorimeter layers and of nonlinear electronics readout effects.

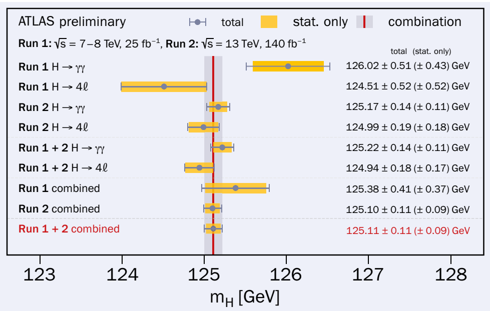


Fig. 1. *The ATLAS Higgs-boson mass measurement combining LHC Run 1 and Run 2 results in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ final states.*

Source: ATLAS-CONF-2023-037

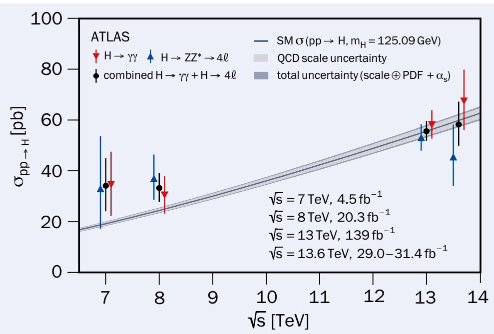


Fig. 2. *ATLAS measurements of the total Higgs-boson production cross section performed in $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and their combination, versus the pp centre-of-mass energy. The grey band shows the state-of-the-art SM prediction and its uncertainties.*

Source: arXiv:2306.11379

A new correction was implemented in the extrapolation of the precisely measured electron-energy scale in $Z \to e^+e^-$ events to photons, to account for differences in the lateral shower development between electrons and photons. These improvements reduced the systematic uncertainty in the mass measurement by about 40%. Moreover, the extrapolation of the electron energy scale from $Z \to e^+e^-$ events to photons originating from the Higgs boson was further refined, and transverse-momentum dependent effects were corrected. Taken together, the improvements allowed ATLAS to measure the Higgs-boson mass in the di-photon channel with a precision of 1.1 per mille.

The new di-photon result was combined with the m_H measurement in the $H \to ZZ^* \to 4\ell$ decay using the full Run 2 dataset, published by ATLAS in 2022, and with the corresponding Run 1 (2011–2012) measurements (see figure 1). The resulting combined Higgs-boson mass $m_H = 125.11 \pm 0.11$ GeV has a precision of 0.9 per mille and is dominated by statistical uncertainties that will further reduce with the Run 3 data.

The high level of readiness and excellent performance of the ATLAS detector also allowed first measurements of the fiducial Higgs-boson production cross-sections in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels using up to 31.4 fb^{-1} of data collected in 2022. Their extrapolation to full phase space and combination gives $\sigma(pp \to H) = 58.2 \pm 8.7$ pb, which agrees with the SM prediction of 59.9 ± 2.6 pb (see figure 2).

With the continuation of Run 3 data taking, the precision of the 13.6 TeV cross-section measurements will improve and the combination with the Run 2 data will allow the exploration of Higgs-boson properties with growing sensitivity.

Further reading

ATLAS Collab. 2023 ATLAS-CONF-2023-036.
ATLAS Collab. 2023 CERN-EP-2023-128.
ATLAS Collab. 2023 *Phys. Lett. B* **843** 137880.
ATLAS Collab. 2023 ATLAS-CONF-2023-037.
ATLAS Collab. 2023 arXiv:2306.11379.

LHCb

CP studies open windows on new physics

Charge-parity (CP) violation parameters in tree-dominated $b \to c\bar{c}s$ quark transitions are a powerful probe of physics beyond the Standard Model (SM). When $B^0_{(s)}$ and $\overline{B}^0_{(s)}$ mesons decay through these transitions to the same final-state particles, an interference between mixing and decay amplitudes occurs, making these processes particularly sensitive to CP violation.

LHCb has become a major actor in precision studies of CP violation

In the SM, $B^0_{(s)}$ – $\overline{B}^0_{(s)}$ mixing is possible because the flavour eigenstates are not the (physical) mass eigenstates: a neutral B meson, once produced, evolves as a quantum superposition of $B^0_{(s)}$ and $\overline{B}^0_{(s)}$ states. Due to this time-dependent mixing amplitude, an interference between mixing and decay amplitudes can lead to an observable time-dependent CP asymmetry in the decay rates. It was through the observation of this phenomenon in the "golden mode" $B^0 \to J/\psi K^0_S$ that, in 2001, the BaBar and Belle collaborations reported the first unequivocal evidence for CP violation in B decays, for which Kobayashi and Maskawa were awarded the 2008 Nobel Prize in Physics.

As the 3×3 Cabibbo–Kobayashi–Maskawa (CKM) matrix that describes quark mixing in the SM is expected to be unitary, it leads to relations among its complex elements. These can be represented as triangles in a complex plane, all of them with the same area (which is a measure of the amount of CP violation in the SM). The most famous of them, the so-called unitary triangle, has sides of roughly the same size and internal angles denoted as α, β and γ. Since individually none of the CKM parameters are predicted by theory, the search for new physics relies on over-constraining them by looking for any hint of internal inconsistency. For that, precision is the key.

Having analysed the full proton–proton collision data set with 13 TeV, and adding it to previous measurements at 7 and 8 TeV, LHCb recently brought the CP-violating parameters in $B^0 \to J/\psi K^0_S$ and in another golden channel, $B^0_s \to J/\psi K^+K^-$, to a new level of precision (*CERN Courier* July/August 2023 p8). These parameters (sin2β and ϕ_s, respectively) are predicted with high accuracy through global CKM fits and, given their clean experimental signatures, are paramount for new-physics searches. The measured time-dependent CP asymmetry of B^0 and $\overline{B}^0$ decay rates is shown in figure 1 with the resulting amplitude proportional to sin2β. Similarly, the update of the $B^0_s \to J/\psi K^+K^-$ analysis with the 13 TeV data resulted in the world's most precise ϕ_s measurement. Both angles agree with SM expectations and with previous measurements.

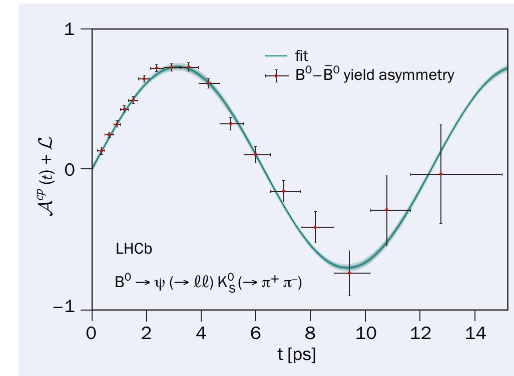


Fig. 1. *Asymmetry in the decay-time dependent decay rate of B^0 and $\overline{B}^0$ decays to ψK^0_S as observed by LHCb. The superimposed curves represent the best-fit result.*

Source: LHCb-PAPER-2023-013

These legacy results for sin2β and ϕ_s from the first LHC runs represent a new milestone in LHCb's hunt for physics beyond the SM. Along with the world-leading determination of γ (with a current precision of less than four degrees), and the discovery of CP violation in charm in 2019, LHCb has fulfilled and exceeded its own goals of more than a decade ago, becoming the major actor in precision studies of CP violation. LHCb is taking data with a brand new detector at larger interaction rates than before, boosting the experimental sensitivity and tightening the grip around the Standard Model.

Further reading

HFLAV 2022 arXiv:2206.07501 and online updates.
LHCb Collab. 2023 LHCB-PAPER-2023-013.
LHCb Collab. 2023 LHCB-PAPER-2023-016.

ALICE

Probing gluonic saturated matter

To advance our understanding of gluonic saturated matter at the LHC, the ALICE collaboration has presented a new study using photon-induced interactions in ultra-peripheral collisions (UPCs). In this type of collision, one beam emits a very high energetic photon that strikes the other beam, giving rise to photon–proton, photon–nucleus and even photon–photon collisions.

While we know that the proton – and most of the visible matter of the universe – is made of quarks bound together by gluons, quantum chromodynamics (QCD) has not yet provided a complete understanding of the rich physics phenomena that occur in high-energy interactions involving hadrons. For example, it is not known how the distribution of gluons evolve at low values of Bjorken-x. The rapid increase in gluon density observed with decreasing x cannot continue forever as it would eventually violate unitarity. At some point "gluon saturation" must set in to curb this growth.

So far, it has been challenging to experimentally establish when saturation sets in. One can expect, however, that it should occur at lower energies for heavy nuclei than for protons. Thus, the ALICE Collaboration has studied the energy dependence of UPC processes for both protons and heavy nuclei. At the same time, other physics phenomena, such as gluon shadowing originating from multi-scattering processes, can exist with similar experimental signatures. The interplay between these phenomena is still an open problem in QCD.

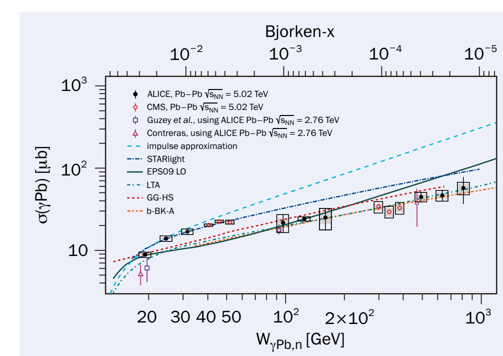


Fig. 1. *Photonuclear cross section for the $\gamma + Pb \to J/\psi + Pb$ process as a function of the photon–nucleus energy, $W_{\gamma Pb,n}$ (lower axis) or Bjorken-x (upper axis) measured using Run 1 and Run 2 data (black circles). Results from the CMS Collaboration are also shown (red circles). See the reference below for more details about the theoretical models (lines).*

Source: arXiv:2305.19060

ALICE has presented new results on J/ψ meson-production UPC, where the photon probes the whole nucleus. The new ALICE results, analysed using LHC Run 1 and Run 2 data, probe a wide range of photon–nucleus collision energies from around 10 GeV to 1000 GeV. These results confirm previous measurements by ALICE, obtained at lower energies, that indicated a strong nuclear suppression when such photon–nucleus data are compared to expectations from photon–proton interactions. The present analysis employs novel methods for extracting the energy dependence, providing new information to test theoretical models. The present data at high energies can be described by both saturation-based and gluon shadowing models. The coherent J/ψ meson production at low energy, in the anti-shadowing region, is not described by these models, nor can available models fully describe the energy dependence of this process over the explored energy range.

ALICE will continue to investigate these phenomena in LHC Runs 3 and 4, where high-precision measurements with larger data samples and upgraded detectors will provide more powerful tools to better understand gluonic saturated matter.

Further reading

ALICE Collab. 2023 arXiv:2305.19060.

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FIELD NOTES

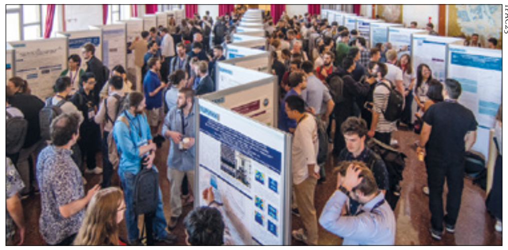
Reports from events, conferences and meetings

IPAC 2023

Record attendance at IPAC23

The 14th International Particle Accelerator Conference (IPAC23) took place from 7 to 12 May in Venice, Italy. The fully in-person event had a record 1660 registered participants (including 273 students) from 37 countries, illustrating the need for real-life interactions after the COVID pandemic. IPAC is not only a scientific meeting but also a global marketplace for accelerators, as demonstrated by the 311 participants from 121 companies present.

Following inspiring opening speeches by Antonio Zoccoli (INFN president) and Alfonso Franciosi (Elettra president) on the important role of particle accelerators in Italy, the scientific programme got underway. It comprised 87 talks and more than 1500 posters covering all particles (including electrons, positrons, protons, ions, muons and neutrons), all types of accelerators (storage rings, linacs, cyclotrons, plasma accelerators, etc), all use-cases (particle physics, photon science, neutron science, medical and industrial applications, material physics, biological and chemical, etc) and institutes across the world. The extensive programme offered such a wide perspective of excellence and ambition that it is only possible to highlight a short subset of what was presented.



Standing out *The poster sessions were a core part of IPAC23, held in Venice in May.*

Upgrade success

Starting proceedings was a report by Malika Meddahi (CERN) on the successful LHC Injectors Upgrade project. This has a predominantly female leadership team and was executed on budget and on schedule. It provides the LHC with beams of increased brightness as required by the ongoing luminosity upgrade, as later reported by CERN's Oliver Brüning. The focus then shifted to advanced X-ray light sources. Emanuel Karantzoulis (Elettra) presented Elettra 2.0 – a new ultra-low emittance light source in construction in Trieste. Axel Brachmann (SLAC) updated participants on the status of LCLS-II, the world's first continuous-wavelength X-ray free-electron laser (XFEL). While beam commissioning is somewhat delayed, the superconducting RF accelerator structures perform beyond the performance specification and the facility is in excellent condition. The week's programme included an impressive overview by Dong Wang (Shanghai Advanced Research Institute) on the future of XFELs, for which user demand has led to an enormous investment aiming in particular at "high average power", which will be used to serve many more experiments, including those for highly non-linear QED. Gianluca Geloni (European XFEL) showed that user operation for the world's presently most powerful XFEL has been successfully enhanced with self-seeding. Massimo Ferrario (INFN) described the promise of a novel, high-tech plasma-based FEL being explored by the European EuPRAXIA project (*CERN Courier* May/June 2023 p25).

Talks argued for new accelerator facilities at the energy frontier to allow further discoveries

Jörg Blaurock (FAIR/GSI) presented the status of the €3.3 billion FAIR project. Major obstacles have been overcome and the completed tunnel and many accelerator components are now being prepared for installation, starting in 2024. The European Spallation Source in Sweden is advancing well and the proton linac is approaching full beam commissioning, as presented by Ryoichi Miyamoto (ESS) and Andrea Pisent (INFN). Yuan He from China (IMP, CAS) presented opportunities in accelerator-driven nuclear power, both in safety and reusing nuclear fuels, and impressed participants with news on a Chinese facility that is progressing well in terms of up-time and reliability. This theme was also addressed by Ulrich Dorda (Belgian Nuclear Research Centre), on the status of the Multi-purpose Hybrid Research Reactor for High-tech Applications (MYRRHA) project. Another impressive moment was Andrey Zelinsky's (NSC in Ukraine) presentation on the Ukraine Neutron Source facility at the National Science Center "Kharkov Institute of Physics & Technology" (NSC KIPT). Construction, system checks and integration tests for this new facility have been completed and beam commissioning is being prepared under extremely difficult circumstances, as a result of Russia's invasion.

Technological highlights included a report by Claire Antoine (CEA) on R&D into thin-film superconducting RF cavities and their potential game-changing role in sustainability. Sustainability was a major discussion topic throughout IPAC23, and several speakers presented the role of accelerators for the development of fusion reactors. The final talk of the conference by Beate Heinemann (DESY) showed that without accelerators, much knowledge in particle physics would still be missing, and she argued for new accelerator facilities at the energy frontier to allow further discoveries.

Prize winners

The prize session saw Xingchen Xu (Fermilab), Mikhail Krasilnikov (DESY/Zeuthen) and Katsunobu Oide (KEK) receive the 2023 EPS-AG accelerator prizes. In addition, the Bruno Touschek prize was awarded to Matthew Signorelli (Cornell University), while two student poster prizes went to Sunar Ezgi (Goethe Universität Frankfurt) and Jonathan Christie (University of Liverpool).

IPAC23 included, for the first time in Europe, an equal-opportunity session, featuring talks from Maria R Masullo (INFN) and Louise Carvalho (CERN) on gender and STEM, pointing to the need to move "from talk to targets". The 300 participants learnt about ways to improve gender balance but also about such important topics as neurodiversity. The very well attended industrial session brought together projects and industry in a mixed presentation and round-table format.

For the organisers, IPAC23 was a remarkable and truly rewarding effort, seeing the many delegates, industry colleagues and students from all over the world come together for a lively and collaborative conference. The many outstanding posters and talks promise a bright future for the field of particle accelerators.

Ralph Assmann *DESY*, **Peter McIntosh** *STFC*, **Alessandro Fabris** *Elettra and* **Giovanni Bisoffi** *INFN*.

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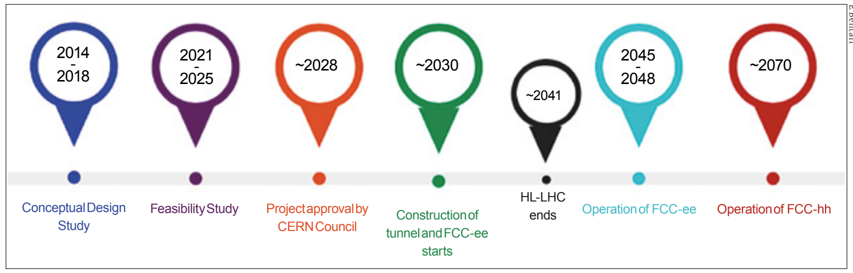
FCC Week 2023

Towards a century of trailblazing physics

The Future Circular Collider (FCC) offers a multi-stage facility – beginning with an e^+e^- Higgs and electroweak factory (FCC-ee), followed by an energy-frontier hadron collider (FCC-hh) in the same 91 km tunnel – that would operate until at least the end of the century. Following the recommendation of the 2020 update of the European strategy for particle physics, CERN together with its international partners have launched a feasibility study that is due to be completed in 2025. FCC Week 2023, which took place in London from 5 to 9 June, and attracted about 500 people, offered an excellent opportunity to strengthen the collaboration, discuss the technological and scientific opportunities, and plan the submission of the mid-term review of the FCC feasibility study to the CERN Council later this year.

The FCC study, along with the support of the European Union FCCIS project, aims to build an ecosystem of science and technology involving fundamental research, computing, engineering and skills for the next generation. It was therefore encouraging that around 40% of FCC Week participants were aged under 40.



Real time *Taking into account past experience with building colliders at CERN, the approval timeline, and assuming that the HL-LHC will run until 2041, FCC could begin operations in 2045–2048. From the perspective of the technical schedule alone, operation of FCC-ee could start in 2040 or earlier.*

Working together

In his welcome speech, Mark Thomson (UK STFC executive chair) stressed the importance of a Higgs factory as the next tool in exploring the universe at a fundamental level. Indeed, one of the no-lose theorems of the FCC programme, pointed out by Gavin Salam (University of Oxford), is that it will shed light on the Higgs' self-interaction, which governs the shape of the Brout–Englert–Higgs potential. In her plenary address, Fabiola Gianotti (CERN Director-General) confirmed that the current schedule for the completion of the FCC feasibility study is on track, and stressed that the FCC is the only facility commensurate with the present size of CERN's community, providing up to four experimental points, concluding "we need to work together to make it happen".

Designing a new accelerator infrastructure poses a number of challenges, from civil engineering and geodesy to the development of accelerator technologies and detector concepts to meet the physics goals. One of the major achievements of the feasibility study so far is the development of a new FCC layout and placement scenario, thanks to close collaboration with CERN's host states and external consultants (*CERN Courier* May/June 2022 p27). As Johannes Gutleber (CERN) reported, the baseline scenario has been communicated with the affected communes in the surrounding area and work has begun to analyse environmental aspects at the surface-site locations. Synergies with the local communities will be strengthened during the next two years, while an authorisation process has been launched to start geophysical investigations next year.

Essential for constructing the FCC tunnel is a robust 3D geological model, for which further input from subsurface investigations into areas of geological uncertainty is needed. On the civil-engineering side, two further challenges include alignment and shape for the new tunnel. Results from these investigations will be collected and fed into the civil-engineering cost and schedule update of the project. Efforts are also focusing on optimising cavern sizes, tunnel widenings and shaft diameters based on more refined requirements from users.

Transfer lines have been optimised such that existing tunnels can be reused as much as possible and to ensure compatibility between the lepton and hadron FCC phases. Taking CERN's full experimental programme into account, the option of using the SPS as pre-booster for FCC-ee will be consolidated and compared with the cost with a high-energy linac option.

At the heart of the FCC study are sustainability and environmental impact. Profiting from an R&D programme on high-efficiency klystrons initially launched for the proposed Compact Linear Collider, the goal is to increase the FCC-ee klystron efficiency from 57% (as demonstrated in the first prototypes) to 80% – resulting in an energy saving of 300 GWh per year without considering the impact that this development could have beyond particle physics. Other accelerator components where work is ongoing to minimise energy consumption include low-loss magnets, SRF cavities and high-efficiency cryogenic compressors.

A new generation of young researchers will need to take the reins to ensure FCC gets delivered and exploit the physics opportunities offered by this visionary research infrastructure

The FCC collaboration is also exploring ways in which to reuse large volumes of excavated materials, including the potential for carbon capture. This effort, which builds on the results of the EU-funded "Mining the Future" competition launched in 2020, aims to re-use the excavated material locally for agriculture and reforestation while minimising global nuisances such as transport. Other discussions during FCC Week focused on the development of a renewable energy supply for FCC-ee.

If approved, a new generation of young researchers will need to take the reins to ensure FCC gets delivered and exploit the physics opportunities offered by this visionary research infrastructure. A dedicated early-career researcher session at FCC Week gave participants the chance to discuss their hopes, fears and experiences so far with the FCC project. A well-attended public event "Giant Experiments, Cosmic Questions" held at the Royal Society and hosted by the BBC's Robin Ince also reflected the enthusiasm of non-physicists for fundamental exploration.

The highly positive atmosphere of FCC Week 2023 projected a strong sense of momentum within the community. The coming months will keep the FCC team extremely busy, with several new institutes expected to join the collaboration and with the scheduled submission of the feasibility-study mid-term review advancing fast ahead of its completion in 2025.

Panos Charitos *CERN.*

LHCP 2023

A treasure trove of LHC results

About 350 physicists attended the 11th edition of the Large Hadron Collider Physics (LHCP) conference in Belgrade, Serbia from 22 to 26 May. The first in-person edition since 2019, the conference triggered productive discussions between experimentalists and theorists across the full LHC physics programme. It also addressed the latest progress of the High-Luminosity LHC upgrades and future-collider developments, in addition to outreach, diversity and education. The conference took place in parallel with the successful restart of LHC Run 3, and saw about 40 new results released for the first time.

The initial physics results from the Run 3 dataset collected in 2022 by ATLAS and CMS were shown, featuring the first measurement of the Higgs-boson production cross-section by ATLAS at 13.6 TeV. Clearly the Run 2 dataset is still a gold mine for the LHC experiments. The programme of precision measurements of Higgs-boson properties is continuing with improved accuracy from the full Run 2 dataset. In particular, ATLAS and CMS reported a new combined result targeting the rare decay $H \rightarrow Z\gamma$, for which they found evidence at the level of 3.4σ and a measured rate slightly higher but comparable to that predicted by the Standard Model (*CERN Courier* July/August 2023 p8).

D Hudson

Lively *Physicists enjoying the poster session at LHCP 2023, from which five winners were selected from a total of 68 posters.*

Innovative signatures

Searches for physics beyond the Standard Model (SM) remains a very active field of research at the LHC, with many innovative signatures explored, including those of long-lived particles. Some of these searches use new anomaly-detection techniques and explore potential lower-production cross sections. A new search of leptoquarks by CMS exploiting the leptonic tau content of the proton was reported, while ATLAS reported a search for stau production in supersymmetry models with much improved sensitivity. Many other searches were also presented, and while a few low-level excesses exist, more data will be required to check if these are statistical fluctuations or not.

The SM is under intense scrutiny but is still very successful at the high-energy frontier. A recent re-analysis of the W-boson mass by ATLAS with the 7 TeV dataset shows good agreement with SM predictions (*CERN Courier* May/June 2023 p10), unlike the CDF result released in 2022 (see p27). Validating the model used for the ATLAS W-mass measurement, new precise measurements of the W and Z bosons' transverse momentum distributions were reported by ATLAS using Run 2 data collected under lower pileup conditions. Vector-boson scattering processes are an important probe of the electroweak symmetry breaking mechanism, and most such processes are now observed at the LHC.

Presentations covered the broad spectrum of physics at the LHC brilliantly

Exploring the top-quark sector, many recent results focused on rare top-production processes. Four-top production was observed recently by ATLAS and CMS. First evidence for the rare tWZ production mode was shown by CMS at LHCP 2023. Some of these rare production modes are seen with rates somewhat higher than predicted, and more data will be required to conclude if the differences are significant. Top production is also used to investigate more exotic scenarios. A new CMS result, measuring the $t\bar{t}$ production cross section as a function of sidereal time, was reported. No indication of Lorentz invariance violation is observed.

On the flavour-physics side, LHCb reported a new precise measurement of CP violation in the "golden" $B \rightarrow J/\psi K_s$ decay, with the most precise extraction of the beta angle of the CKM quark-mixing matrix (see p16). Recent LHCb results on the flavour "anomalies" no longer show an indication for lepton universality violation in $B \rightarrow Ke^+e^-$ compared to $B \rightarrow K\mu^+\mu^-$ decay rates (*CERN Courier* January/February 2023 p7), but some puzzles remain and there is still some tension in the tau-to-muon ratio in the tree-level decays $B \rightarrow B^{(*)}\tau(\mu)\nu$. Lepton-flavour violation is investigated in a new CMS result searching for the forbidden $\tau \rightarrow 3\mu$ decays, where an upper limit close to the Belle result was reported.

Characterisation of the quark–gluon plasma is actively studied using PbPb collision data. New results from ALICE regarding investigations of jet-quenching properties as well as charm fragmentation studies were shown at the conference.

The recent detections of collider-produced neutrinos by the new FASER and SND experiments were also presented, marking the start of a new physics programme at the LHC (*CERN Courier* May/June 2023 p9).

Broad spectrum

Several theory presentations highlighted recent progress in SM predictions for a wide range of processes including the electroweak sector, top-quark and Higgs-boson productions, as well as linking LHC physics to lattice QCD computations – work that is vital to fully exploit the physics potential of the LHC. Open questions in the various sectors were summarised and prospects for new-physics searches in Run 3, including those related to the Higgs-boson sector, were discussed. Links between LHC physics and dark matter were also highlighted, with examples of light dark-matter models and feebly interacting particles. Effective field theories, which are key tools to probe new physics in a generic way, were described with emphasis on the complementarity with searches targeting specific models.

Overall, the presentations covered the broad spectrum of physics at the LHC brilliantly. Future data, including from the High-Luminosity LHC phase, should allow physicists to continue to address many of the field's open questions. Next year's LHCP conference will be held at Northeastern University in Boston.

Eva Halkiadakis *Rutgers University and* **Guillaume Unal** *CERN.*

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6th Forward Physics Facility Meeting

Looking forward at the LHC

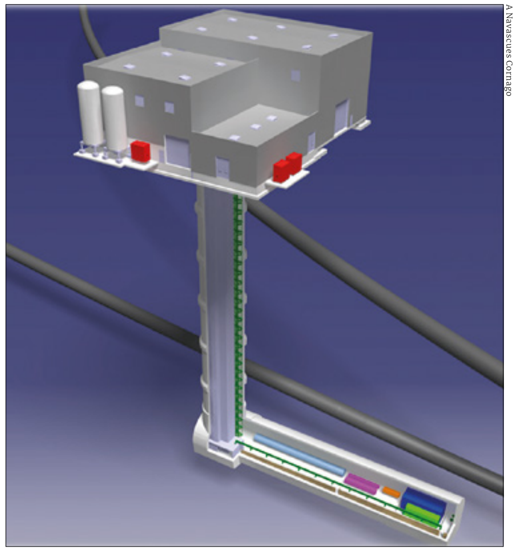
The Forward Physics Facility (FPF) is a proposed new facility to operate concurrently with the High-Luminosity LHC, housing several new experiments on the ATLAS collision axis. The FPF offers a broad, far-reaching physics programme ranging from neutrino, QCD and hadron-structure studies to beyond-the-Standard Model (BSM) searches. The project, which is being studied within the Physics Beyond Colliders initiative, would exploit the pre-existing HL-LHC beams and thus have minimal energy-consumption requirements.

On 8 and 9 June, the 6th workshop on the Forward Physics Facility was held at CERN and online. Attracting about 160 participants, the workshop was organised in sessions focusing on the facility design, the proposed experiments and physics studies, leaving plenty of time for discussion about the next steps.

Groundbreaking

Regarding the facility itself, CERN civil-engineering experts presented its overall design: a 65 m-long, 10 m-high/wide cavern connected to the surface via an 88 m-deep shaft. The facility is located 600 m from the ATLAS collision point, in the SM18 area of CERN. A workshop highlight was the first results from a site investigation study, whereby a 20 cm-diameter core was taken at the proposed location of the FPF shaft to a depth of 100 m. The initial analysis of the core showed that the geological conditions are positive for work in this area. Other encouraging studies towards confirming the FPF feasibility were FLUKA simulations of the expected muon flux in the cavern (the main background for the experiments), the expected radiation level (shown to allow people to enter the cavern during LHC operations with various restrictions), and the possible effect on beam operations of the excavation works. One area where more work is required concerns the possible need to install a sweeper magnet in the LHC tunnel between ATLAS and the FPF to reduce the muon backgrounds.

Currently there are five proposed experiments to be installed in the FPF: FASER2 (to search for decaying long-lived particles); FASERν2 and AdvSND (dedicated neutrino detectors covering complementary rapidity regions); FLArE (a liquid-argon time projection chamber for neutrino physics and light dark-matter searches); and FORMOSA (a scintillator-based detector to search for milli-charged particles). The three neutrino detectors offer complementary designs to exploit the huge number of TeV energy neutrinos of all flavours that would be produced in such a forward-physics configuration. Four of these have smaller pathfinder detectors, FASER(ν), SND@LHC and milliQan that are already operating during LHC Run 3. First results from these pathfinder experiments were presented at the CERN workshop, including the first ever direct observation of collider neutrinos by FASER and SND@LHC, which provide a key proof of principle for the FPF (*CERN Courier* March/April 2023 p9). The latest conceptual design and expected performance of the FPF experiments were presented. Furthermore, first ideas on models to fund these experiments are in place and were discussed at the workshop.



A Navascues Cornago

New territory *3D rendering of the proposed Forward Physics Facility and its experiments.*

In the past year, much progress has been made in quantifying the physics case of the FPF

In the past year, much progress has been made in quantifying the physics case of the FPF. It effectively extends the LHC with a "neutrino–ion collider" with complementary reach to the Electron–Ion Collider under construction in the US. The large number of high-energy neutrino interactions that will be observed at the FPF allows detailed studies of deep inelastic scattering to constrain proton and nuclear parton distribution functions (PDFs). Dedicated projections of the FPF reveal that uncertainties in light-quark PDFs could be reduced by up to a factor of two or even more compared to current models, leading to improved HL-LHC predictions for key measurements such as the W-boson mass.

High-energy electrons and tau neutrinos at the FPF predominantly arise from forward charm production. This is initiated by gluon–gluon scattering involving very low and high momentum fractions, with the former reaching down to Bjorken-x values of 10^{-7} – beyond the range of any other experiment. The same FPF measurements of forward charm production are relevant for testing different models of QCD at small-x, which would be instrumental for Higgs production at the proposed Future Circular Collider (FCC-hh). This improved modeling of forward charm production is also essential for understanding the backgrounds to diffuse astrophysics neutrinos at telescopes such as IceCube and KM3NeT. In addition, measurements of the ratio of electron-to-muon neutrinos at the FPF probe forward kaon-to-pion production ratios that could explain the so-called muon puzzle (a deficit in muons in simulations compared to measurements), affecting cosmic-ray experiments.

The FPF experiments would also be able to probe a host of BSM scenarios in uncharted regions of parameter space, such as dark-matter portals, dark Higgs bosons and heavy neutral leptons. Furthermore, experiments at the FPF will be sensitive to the scattering of light dark-matter particles produced in LHC collisions, and the large centre-of-mass energy enables probes of models, such as quirks (long-lived particles that are charged under a hidden-sector gauge interaction), and some inelastic dark-matter candidates, which are inaccessible at fixed-target experiments. On top of that, the FPF experiments will significantly improve the sensitivity of the LHC to probe millicharged particles.

The June workshop confirmed both the unique physics motivation for the FPF and the excellent progress in technical and feasibility studies towards realising it. Motivated by these exciting prospects, the FPF community is now working on a Letter of Intent to submit to the LHC experiments committee as the next step.

Jamie Boyd *CERN*, **Albert De Roeck** *CERN and* **Juan Rojo** *Nikhef.*

LCWS 2023

Aligning future colliders at SLAC

The 2023 International Workshop on Future Linear Colliders (LCWS2023) took place at SLAC from 15 to 20 May, continuing the series devoted to the study of high-energy linear electron-positron colliders that started in 1992. A linear collider is appealing because it could operate as a Higgs factory during its initial stage, while maintaining a clear path for future energy upgrades. Proposed linear-collider Higgs factories are designed for greater compactness, energy efficiency and sustainability, with lowered construction and operation costs compared to circular machines.

With a wide programme of plenary and parallel sessions, the workshop was a great opportunity for the community to discuss current and future R&D directions, with a focus on sustainability, and was testament to the eagerness of physicists from all over the world to join forces to build the next Higgs factory. More than 200 scientists participated, about 30% of which were early-career researchers and industry partners.

J Orrel

In line *The participants of the International Workshop on Future Linear Colliders gather at SLAC.*

Energy frontiers

As set out by the 2020 update of the European strategy for particle physics and the Energy Frontier report from Snowmass 2021, particle physicists agreed that precision Higgs-boson measurements are the best path toward further progress and to provide insights into potential new-physics interactions. The Higgs boson is central for understanding fundamental particles and interactions beyond the Standard Model. Examples include the nature of dark matter and matter-antimatter asymmetry, which led to the prevalence of matter in our universe.

Ideally, data-taking at a future e^+e^- Higgs factory should follow the HL-LHC directly, requiring construction to start by 2030, in parallel with HL-LHC data-taking. Any significant delay will put at risk the availability of essential and unique expertise, and human resources, and endanger the future of the field.

Among the e^+e^- colliders being evaluated by the community, the International Linear Collider (ILC), based on superconducting RF technology, has the most advanced design. It is currently under consideration for construction in Japan. However, for a long time now, Japan has not initiated a process to host this collider. One alternative approach is to construct a large circular collider – a strategy now being pursued by CERN with the FCC-ee, and by China with the CEPC. Both colliders would require tunnels of about 100 km circumference to limit synchrotron radiation. The FCC-ee machine is foreseen to operate in 2048, seven years after the end of the HL-LHC programme, with a substantial cost in time and resources for the large tunnel. An alternative is to construct a compact linear e^+e^- collider based on high-gradient acceleration. CERN has a longstanding R&D effort along these lines, CLIC, that would operate at a collision energy of 380 GeV.

Given the global uncertainties around each proposal, it is prudent to investigate alternative plans based on technologies that could enable compact designs and possibly provide a roadmap to extend the energy reach of future colliders. As also highlighted in the Snowmass Energy Frontier report, consideration should be given to the timely realisation of a Higgs factory in the US as an international effort. For instance, the Cool Copper Collider (C^3) is a new and even more compact proposal for a Higgs-producing linear collider. It was developed during Snowmass 2021 and made its debut at LCWS with more than 15 talks and five posters. This proposal would use normal-conducting RF cavities to achieve a collision energy of 500 GeV with an 8 km-long collider, making it significantly smaller and likely more cost-effective than other proposed Higgs factories.

There are many advantages of the linear approach. Among them, linear colliders are able to access energies of 500 GeV and beyond, while for circular e^+e^- colliders the expected luminosity drops off above centre-of-mass energies of 350–400 GeV. This would allow precision measurements that are crucial for indirect searches for new physics, including measurements of the top-quark mass and electroweak couplings, the top-Higgs coupling, and the cross section for double-Higgs production.

New technologies proposed for higher-energy stages will require decades of R&D

At LCWS 2023, the community showed progress on R&D for both accelerator and detector technologies and outlined how further advances in ILC technology, as well as alternative technologies such as C^3 and CLIC, promise lower costs and/or extended energy reach for later stages of this programme. Discoveries at a Higgs factory may point to specific goals for higher energy machines, with quark and lepton collisions at least 10 times the energies of the LHC. New technologies proposed for such higher-energy stages – using pp, muon and e^+e^- colliders – will require decades of R&D. Construction and operation of a linear Higgs factory would be a key contribution towards this programme by developing an accelerator workforce and providing challenges to train young scientists.

In this regard, a key outcome of the SLAC workshop was a statement supporting the timely realisation of a Higgs factory based on a linear collider to access energies beyond 500 GeV and enable the measurements vital for new physics to the P5 committee, which is currently evaluating priorities in US high-energy physics for the next two decades.

Emilio Nanni *SLAC*, **Aidan Robson** *University of Glasgow and* **Caterina Vernieri** *SLAC.*

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EuCAPT Annual Symposium

Theoretical astroparticle physicists gather at CERN

The European Consortium for Astroparticle Theory (EuCAPT) was founded in 2019 to bring together the European community of theoretical astroparticle physicists and cosmologists. The goals of EuCAPT include the exchange of ideas and knowledge, coordinating scientific and training activities, helping scientists attract adequate resources for their projects, and promoting a stimulating, fair and open environment in which young scientists can thrive. With these main goals in mind, the annual EuCAPT symposium serves to bring the community together and stimulate discussions on recent developments. After three years with largely online events, EuCAPT gathered for the first time in person for its annual symposium at CERN, the hub of the European initiative.

From 31 May to 2 June, 180 participants came together in the CERN main auditorium (with a further 100 online) to exchange on topics including dark matter, particle astrophysics, cosmology of the early and late universe, and gravitational waves. The programme alternated between invited overview talks from leading scientists and lightning talks by early-career researchers. No fewer than 50 posters reflected the rich diversity of EuCAPT science, with prizes for the best poster and best lightning talks awarded at the end of the conference.

V Domcke

Meeting point *The members of the EuCAPT Symposium converge at CERN.*

A highlight of the symposium was an interactive session with the members of the different EuCAPT task forces, ranging from outreach, training and community building to funding and many more, which allowed participants to learn more about the work done within the consortium and to join these activities. EuCAPT founding director Gianfranco Bertone (University of Amsterdam), who gave a well-attended public evening talk at CERN and who is due to step down in January 2024, said: "Leading EuCAPT has been an incredible experience. In four years we have grown into a vibrant and diverse community of more than 1600 scientists, based at 130 institutions across Europe. With a solid organisational structure in place, and many ongoing scientific activities, we are now ready to take the next steps."

With further EuCAPT activities, such as the first EuCAPT school in Valencia this autumn, ongoing throughout the year, the EuCAPT community will continue to grow such that at the next EuCAPT symposium there will be ample new scientific developments and progress to discuss.

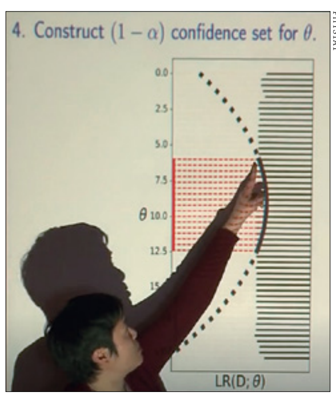
Valerie Domcke, **Julia Gehrlein** *and* **Azadeh Maleknejad** *CERN.*

PHYSTAT 2023

PHYSTAT systematics at BIRS

The PHYSTAT series of seminars and workshops provides a unique meeting ground for physicists and statisticians. The latest in-person meeting, after previously being postponed due to COVID, covered the field of systematic errors (sometimes known as nuisance parameters), which are becoming increasingly important in particle physics as larger datasets reduce statistical errors in many analysis channels. Taking place from 23 to 28 April at the Banff International Research Station (BIRS) in the Canadian Rockies, the workshop attracted 42 delegates working not only on the LHC experiments but also on neutrino physics, cosmic-ray detectors and astrophysics.

The organisers had assigned half of the time to discussions, and that time was used. Information flowed in both directions: physicists learned about the Wasserstein distance and statisticians learned about jet energy scales. The dialogue was constructive and positive – we have moved on from the "Frequentist versus Bayesian" days and now everyone is happy to use both – and the discussions continued during coffee, dinner and hikes up the nearby snow-covered mountains.



PHYSTAT

On point *Ann Lee (Carnegie Mellon University) explaining the construction of confidence regions when the likelihood function is unavailable.*

Our understanding of traditional problems continues to grow. The "signal plus background" problem always has new features to surprise us, unfolding continues to present challenges, and it seems we always have more to learn about simple concepts like errors and significance. There were also ideas that were new to many of us. Optimal transport and the Monge problem provide a range of tools whose use is only beginning to be appreciated, while neural networks and other machine-learning techniques can be used to help find anomalies and understand uncertainties. The similarities and differences between marginalisation and profiling require exploration, and we probably need to go beyond the asymptotic formulae more often than we do in practice.

Another "Banff challenge", the third in a sequence, was set by Tom Junk of Fermilab. The first two had a big impact on the community and statistical practice. This time Tom provided simulated data for which contestants had to find the signal and background sizes, using samples with several systematic uncertainties – these uncertainties were unspecified, but dark hints were dropped. It's an open competition and anyone can try for the glory of winning the challenge.

Collaborations were visibly forming during the latest PHYSTAT event, and results will be appearing in the next few months, not only in papers but in practical procedures and software that will be adopted and used in the front line of experimental research.

This and other PHYSTAT activities continue, with frequent seminars and several workshops (zoom, in-person and hybrid) in the planning stage.

Roger Barlow *University of Huddersfield.*

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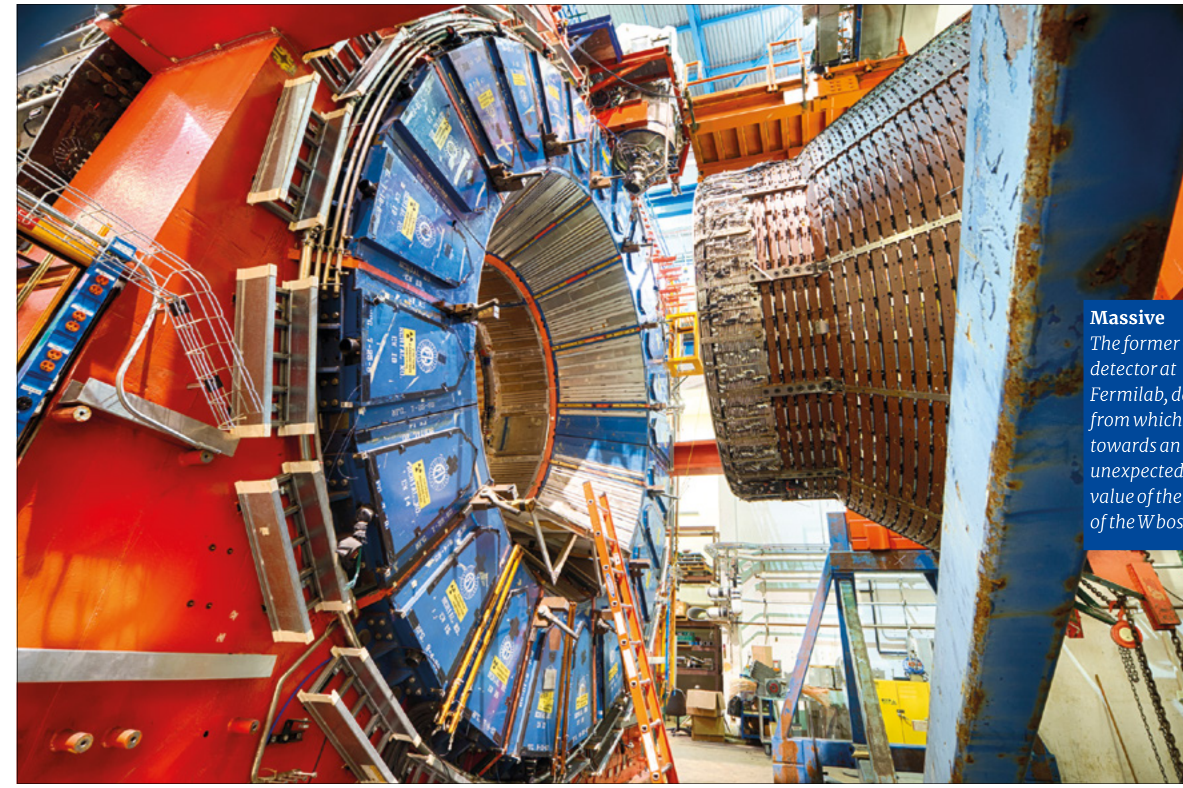

R Hahn/Fermilab

Massive *The former CDF detector at Fermilab, data from which point towards an unexpectedly high value of the mass of the W boson.*

THE W BOSON'S MIDLIFE CRISIS

Forty years after its discovery, the W boson continues to intrigue. Chris Hays describes recent progress in understanding a surprisingly high measurement of its mass using data from the former CDF experiment.

The discovery of the W boson at CERN in 1983 can well be considered the birth of precision electroweak physics. Measurements of the W boson's couplings and mass have become ever more precise, progressively weaving in knowledge of other particle properties through quantum corrections. Just over a decade ago, the combination of several Standard Model (SM) parameters with measurements of the W-boson mass led to a prediction of a relatively low Higgs-boson mass, of order 100 GeV, prior to its discovery. The discovery of the Higgs boson in 2012 with a mass of about 125 GeV was hailed as a triumph of the SM. Last year, however, an unexpectedly high value of the W-boson mass measured by the CDF experiment threw a spanner into the works. One might say the 40-year-old W boson encountered a midlife crisis.

The mass of the W boson, m_W, is important because the SM predicts its value to high precision, in contrast with the masses of the fermions or the Higgs boson. The mass of each fermion is determined by the strength of its interaction with the Brout–Englert–Higgs field, but this strength is currently only known to an accuracy of approximately 10% at best; future measurements from

THE AUTHOR
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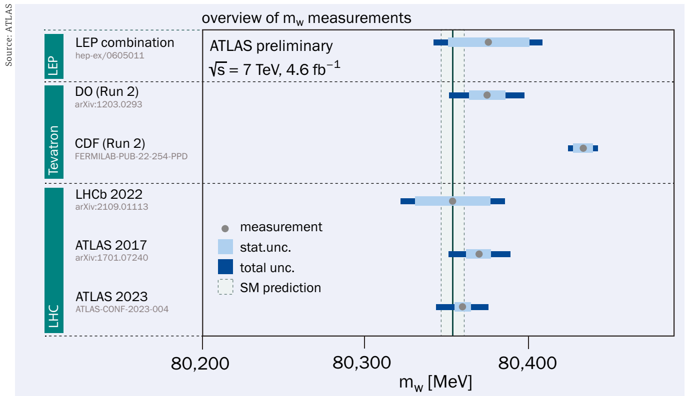


Out of order *The latest CDF measurement of the W mass differs by around seven standard deviations from other Tevatron results, the LEP experiments, ATLAS and LHCb. The total (dark blue) and statistical (light-blue band) uncertainties are shown, along with the SM prediction (vertical band).*

The mass of the W boson is important because the SM predicts its value to high precision, in contrast with the masses of the fermions or the Higgs boson

the High-Luminosity LHC and a future e^+e^- collider are required to achieve percent-level accuracy. Meanwhile, m_W is predicted with an accuracy better than 0.01%. At tree level, this mass depends only on the mass of the Z boson and the weak and electromagnetic couplings. The first measurements of m_W by the UA1 and UA2 experiments at the Sp$\bar{p}$S collider at CERN were in remarkable agreement with this prediction, within the large uncertainties. Further measurements at the Tevatron at Fermilab and the Large Electron Positron collider (LEP) at CERN achieved sufficient precision to probe the presence of higher-order electroweak corrections, such as from a loop containing top and bottom quarks.

Increasing sophistication

Measurements of m_W at the four LEP experiments were performed in collisions producing two W bosons. Hadron colliders, by contrast, can produce a single W-boson resonance, simplifying the measurement when utilising the decay to an electron or muon and an associated neutrino. However, this simplification is countered by the complication of the breakup of the hadrons, along with multiple simultaneous hadron–hadron interactions. Measurements at the Tevatron and LHC have required increasing sophistication to model the production and decay of the W boson, as well as the final-state lepton's interactions in the detectors. The average time between the available datasets and the resulting published measurement have increased from two years for the first CDF measurement in 1991 to more than 10 years for the most recent CDF measurement announced last year (*CERN Courier* May/June 2022 p9). The latter benefitted from a factor of four more W bosons than the previous measurement, but suffered from a higher number of additional simultaneous interactions. The challenge of modelling these interactions while also increasing the measurement precision required many years of detailed study. The end result, $m_W = 80433.5 \pm 9.4$ MeV, differs from the SM prediction of $m_W = 80357 \pm 6$ MeV by approximately seven standard deviations (see "Out of order" figure).

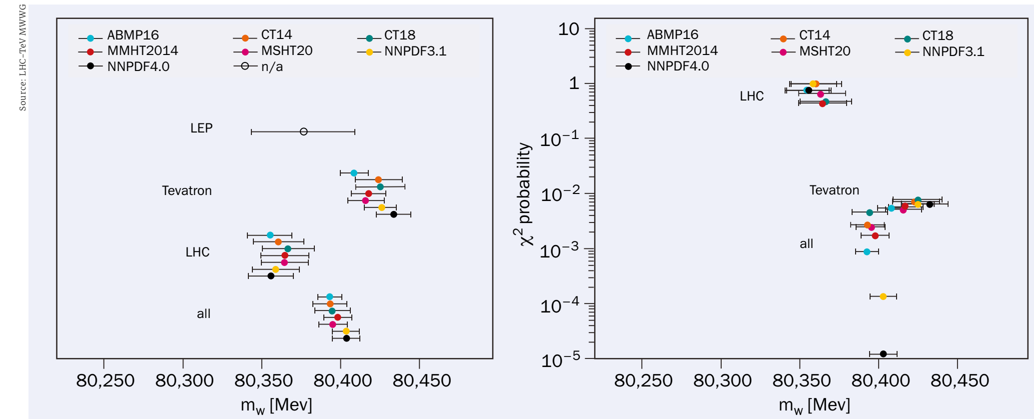
The SM calculation of m_W includes corrections from single loops involving fermions or the Higgs boson, as well as from two-loop processes that also include gluons. The splitting of the W boson into a top- and bottom-quark loop produces the largest correction to the mass: for every 1 GeV increase in top-quark mass the predicted W mass increases by a little over 6 MeV. Measurements of the top-quark mass at the Tevatron and LHC have reached a precision of a few hundred MeV, thus contributing an uncertainty on m_W of only a couple of MeV. The calculated m_W depends only logarithmically on the Higgs-boson mass m_H, and given the accuracy of the LHC m_H measurements, it contributes negligibly to the uncertainty on m_W. The tree-level dependence of m_W on the Z-boson mass and on the electromagnetic coupling strength contribute an additional couple of MeV each to the uncertainty. The robust prediction of the SM allows an incisive test through m_W measurements, and it would appear to fail in the face of the recent CDF measurement.

Since the release of the CDF result last year, physicists have held extensive and detailed discussions, with a recurring focus on the measurement's compatibility with the SM prediction and with the measurements of other experiments. Further discussions and workshops have reviewed the suite of Tevatron and LHC measurements, hypothesising effects that could have led to a bias in one or more of the results. These potential effects are subtle, as fundamentally the W-boson signature is strikingly unique and simple: a single charged electron or muon with no observable particle balancing its momentum. Any source of bias would have to lie in a higher-order theoretical or experimental effect, and the analysts have studied and quantified these in great detail.

Progress

In the spring of this year ATLAS contributed an update to the story. The collaboration re-analysed its data from 2011 to apply a comprehensive statistical fit using a profile likelihood, as well as the latest global knowledge of parton distribution functions (PDFs) – which describe the momentum distribution functions of quarks and gluons inside the proton. The preliminary result ($m_W = 80360 \pm 16$ MeV) reduces the uncertainty and the central value of its previous result published in 2017, further increasing the tension between the ATLAS result and that of CDF.

Meanwhile, the Tevatron+LHC W-mass combination working group has carried out a detailed investigation of higher-order theoretical effects affecting hadron-collider measurements, and provided a combined mass value using the latest published measurement from each experiment



Measuring up *Left: the combined value of the W mass for the LEP, Tevatron, LHC and all experiments. Right: the probability of consistency of the measurements in the combination. The PDF sets used are listed at the top.*

The next milestone will take time due to the exquisite precision that has now been reached

and from LEP. These studies, due to be presented at the European Physical Society High-Energy Physics conference in Hamburg in late August, give a comprehensive and quantitative overview of W-boson mass measurements and their compatibilities. While no significant issues have been identified in the measurement procedures and results, the studies shed significant light on their details and differences.

LHC versus Tevatron

Two important aspects of the Tevatron and LHC measurements are the modelling of the momentum distribution of each parton in the colliding hadrons, and the angular distribution of the W boson's decay products. The higher energy of the LHC increases the importance of the momentum distributions of gluons and of quarks from the second generation, though these can be constrained using the large samples of W and Z bosons. In addition, the combination of results from centrally produced W bosons at ATLAS with more forward W-boson production at LHCb reduces uncertainties from the PDFs. At the Tevatron, proton–antiproton collisions produced a large majority of W bosons via the valence up and down (anti)quarks inside the (anti)proton, and these are also constrained by measurements at the Tevatron. For the W-boson decay, the calculation is common to the LHC and the Tevatron, and precise measurements of the decay distributions by ATLAS are able to distinguish several calculations used in the experiments.

In any combination of measurements, the primary focus is on the uncertainty correlations. In the case of m_W, many uncertainties are constrained *in situ* and are therefore uncorrelated. The most significant source of correlated uncertainty is the PDFs. In order to evaluate these correlations, the combination working group generated large samples of events and produced simplified models of the CDF, DØ and ATLAS detectors. Several sets of PDFs were studied to determine their compatibility with broader W- and Z-boson measurements at hadron colliders. For each of these sets the correlations and combined m_W values were determined, opening a panorama view of the impact of PDFs on the measurement (see "Measuring up" figure).

The first conclusion from this study is that the compatibility of all PDF sets with W- and Z-boson measurements is generally low: the most compatible PDF set, CT18 from the CTEQ collaboration, gives a probability of only 1.5% that the suite of measurements are consistent with the predictions. Using this PDF set for the W-boson mass combination gives an even lower compatibility of 0.5%. When the CDF result is removed, the compatibility of the combined m_W value is good (91%), and when comparing this "N–1" combined value to the CDF value for the CT18 set, the difference is 3.6σ. The results are considered unlikely to be compatible, though the possibility cannot be excluded in the absence of an identified bias. If the CDF measurement is removed, the combination yields a mass of $m_W = 80369.2 \pm 13.3$ MeV for the CT18 set, while including all measurements results in a mass of $m_W = 80394.6 \pm 11.5$ MeV. The former value is consistent with the SM prediction, while the latter value is 2.6σ higher.

Two scenarios

The results of the preliminary combination clearly separate two possible scenarios. In the first, the m_W measurements are unbiased and differ due to large fluctuations and the PDF dependence of the W- and Z-boson data. In the second, a bias in one or more of the measurements produces the low compatibility of the measured values. Future measurements will clarify the likelihood of the first scenario, while further studies could identify effect(s) that point to the second scenario. In either case the next milestone will take time due to the exquisite precision that has now been reached, and to the challenges in maintaining analysis teams for the long timescales required to produce a measurement. The W boson's midlife crisis continues, but with time and effort the golden years will come. We can all look forward to that. ●

Further reading

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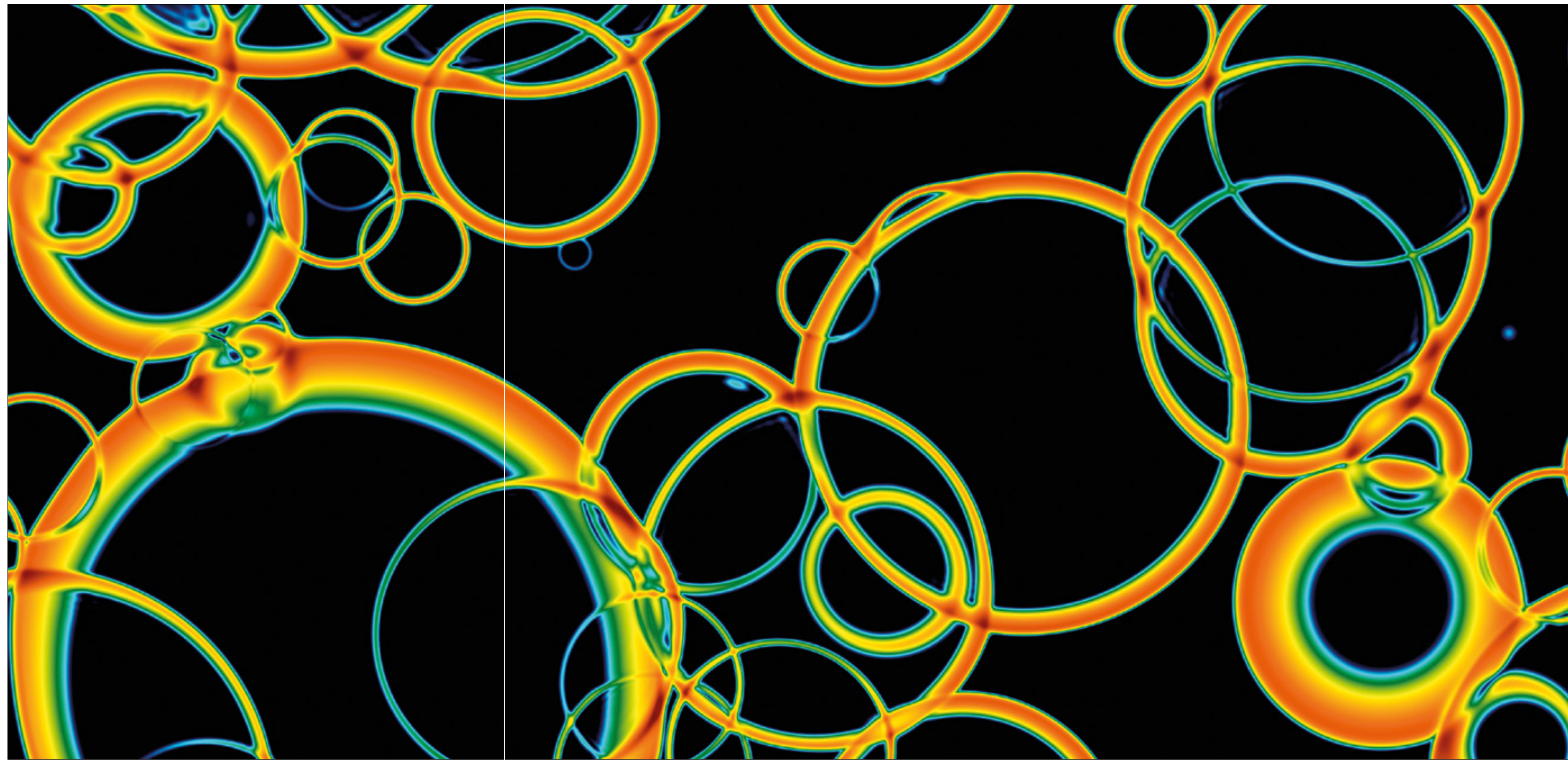
GRAVITATIONAL WAVES: A GOLDEN ERA

Detecting and exploring a stochastic background of gravitational waves predicted to pervade the universe potentially opens a window on the extreme physics of the very early universe. Azadeh Maleknejad and Fabrizio Rompineve explain how a new generation of instruments could bring this cosmic symphony into view.



Ringing out *Simulation of colliding spherical pressure waves from a first-order phase transition immediately after the Big Bang, which would be expected to generate a distinct gravitational-wave signature.*

The existence of dark matter in the universe is one of the most important puzzles in fundamental physics. It is inferred solely by means of its gravitational effects, such as on stellar motions in galaxies or on the expansion history of the universe. Meanwhile, non-gravitational interactions between dark matter and the known particles described by the Standard Model have not been detected, despite strenuous and advanced experimental efforts.

Such a situation suggests that new particles and fields, possibly similar to those of the Standard Model, may have been similarly present across the entire cosmological history of our universe, but with only very tiny interactions with visible matter. This intriguing idea is often referred to as the paradigm of dark sectors and is made even more compelling by the lack of new particles seen at the LHC and laboratory experiments so far.

Dark energy

Cosmological observations, above all those of the cosmic microwave background (CMB), currently represent the main tool to test such a paradigm. The primary example is that of dark radiation, i.e. putative new dark particles that, unlike dark matter, behave as relativistic species at the energy scales probed by the CMB. The most recent data collected by the Planck satellite constrain such dark particles to make at most around 30% of the energy of a single neutrino species at the recombination epoch (when atoms formed and the universe became transparent, around 380,000 years after the Big Bang).

While such observations represent a significant advance, the early universe was characterised by temperatures in the MeV range and above (enabling nucleosynthesis), possibly as large as 10^{16} GeV. Some of these temperatures correspond to energy scales that cannot be probed via the CMB, nor directly with current or prospective particle colliders. Even if new particles had significant interactions with SM particles at such high temperatures, any electromagnetic radiation in the hot universe was continuously scattered off matter (electrons), making it impossible for any light from such early epochs to reach our detectors today. The question then arises: is there another channel to probe the existence of dark sectors in the early universe?

For more than a century, a different signature of gravitational interactions has been known to be possible: waves, analogous to those of the electromagnetic field, carrying fluctuations of gravitational fields. The experimental effort to detect gravitational waves (GWs) had a first amazing success in 2015, when waves generated by the merger of two black holes were first detected by the LIGO and Virgo interferometers in the US and Italy.

Now, the GW community is on the cusp of another incredible milestone: the detection of a GW background, generated by all sources of GWs across the history of our universe. Recently, based on more than a decade of observations, several networks of radio telescopes called pulsar timing arrays (PTAs) – NANOGrav in North America, EPTA in Europe, PPTA in Australia and CPTA in China – produced tentative evidence for such a stochastic GW background based on the influence of GWs on pulsars (see p7 and "Clocking gravity" image). Together with next-generation interferometer-based GW detectors such as LISA and the Einstein Telescope, and new theoretical ideas from particle physics, the observations suggest that we are entering an exciting new era of observational cosmology that connects the smallest and largest scales.

Particle physics and the GW background

Once produced, GWs interact only very weakly with any other component of the universe, even at the high temperatures present at the earliest times. Therefore, whereas photons can tell us about the state of the universe at recombination, the GW background is potentially a direct probe of high-energy processes in the very early universe. Unlike GWs that reach Earth from the locations of binary systems of compact objects, the GW background is expected to be mostly isotropic in the sky, very much like the CMB. Furthermore, rather than being a transient signal, it should persist in the sensitivity bands of GW detectors, similar to a noise component but with peculiarities that are expected to make a detection possible.

As early as 1918, Einstein quantified the power emitted in GWs by a generic source. Compared to electromagnetic radiation, which is sourced by the dipole moment of a charge distribution, the power emitted in GWs is proportional to the third time derivative of the quadrupole moment of the mass-energy distribution of the source. Therefore, the two essential conditions for a source to emit GWs are that it should be sufficiently far from spherical

THE AUTHORS

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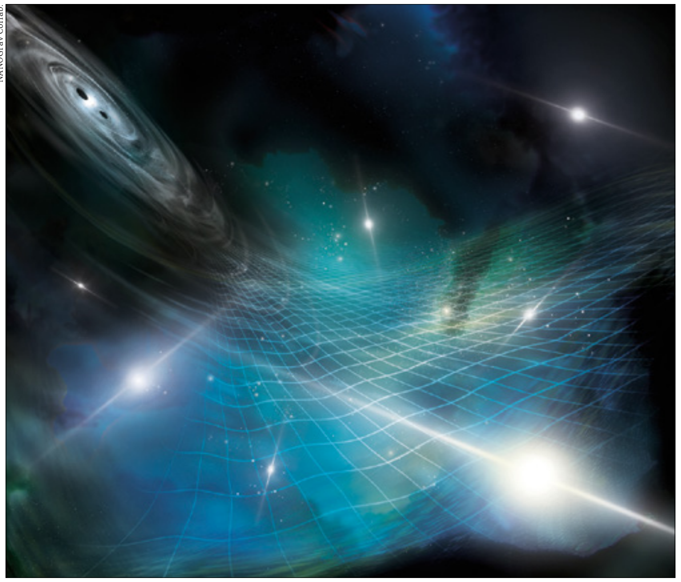
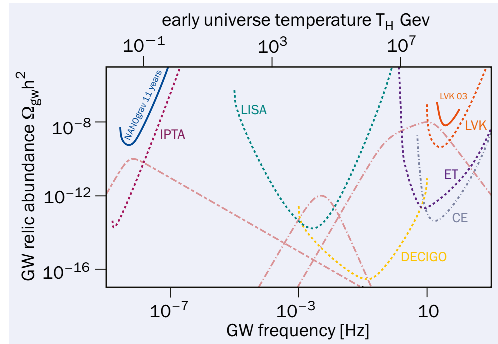


NANOGrav Collab.

Clocking gravity *Artist's interpretation of an array of pulsars (spinning neutron stars that emit radio waves) being affected by a gravitational wave produced by a supermassive black-hole binary in a distant galaxy. Pulsar timing arrays look for deviations in the arrival times of radio pulses, rather than deviations in the arrival times of laser beams as in interferometer-based observatories.*



Source: F Rompineve/arXiv:2101.12130/arXiv:2002.04615

Broadband *Sensitivity of current (solid) and future (dashed) gravitational-wave (GW) observatories to stochastic GW backgrounds (expressed in terms of the energy density fraction in the universe today). On the upper x-axis, the temperature in the early universe is given, which is obtained when the peak frequency of a GW signal is equal to the inverse of the expansion rate when GWs are emitted. Some example possible GW spectra from the early universe are also shown (pink, dashed).*

symmetry and that its distribution should change sufficiently quickly with time.

What possible particle-physics sources would satisfy these conditions? One of the most thoroughly studied phenomena as a source of GWs is the occurrence of a phase transition, typically associated with the breaking of a fundamental symmetry. Specifically, only those phase transitions that proceed via the nucleation, expansion and collision of cosmic bubbles (analogous to the phase transition of liquid water to vapour) can generate a significant amount of GWs (see "Ringing out" image). Inside any such bubble the universe is already in the broken-symmetry phase, whereas beyond the bubble walls the symmetry is still unbroken. Eventually, the state of lowest energy inside the bubbles prevails via their rapid expansion and collisions, which fill up the universe. Even though such bubbles may initially be highly spherical, once they collide the energy distribution is far from being so, while their rapid expansion provides a time variation.

The occurrence of two phase transitions is in fact predicted by the Standard Model (SM): one related to the spontaneous breaking of the electroweak SU(2)×U(1) symmetry, the other associated with colour confinement and thus the formation of hadronic states. However, dedicated analytical and numerical studies in the 1990s and 2000s concluded that the SM phase transitions are not expected to be of first order in the early universe. Rather, they are expected to proceed smoothly, without any violent release of energy to source GWs.

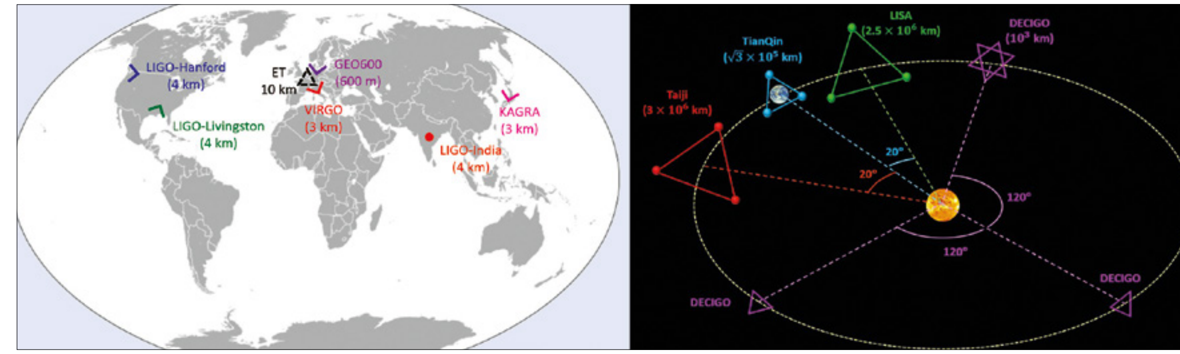
This leads to a striking conclusion: a detection of the GW background would provide evidence for physics beyond the SM – that is, if its origin can be attributed to processes occurring in the early universe. This caveat is crucial, since astrophysical processes in the late universe also contribute to a stochastic GW background.

In order to claim a particle-physics interpretation for any stochastic GW background, it is thus necessary to appropriately account for astrophysical sources and characterise the expected (spectral) shape of the GW signal from early-universe sources of interest. These tasks are being undertaken by a diverse community of cosmologists, particle physicists and astrophysicists at research institutions all around the world, including in the cosmology group in the CERN TH department.

Precise probing

For particle physicists and cosmologists, it is customary to express the strength of a given stochastic GW signal in terms of the fraction of the energy (density) of the universe today carried by those GWs. The CMB already constraints this "relic abundance" to be less than roughly 10% of ordinary radiation, or about one millionth of that of the dominant component of the universe today, dark energy. Remarkably, current GW detectors are already able to probe stochastic GWs that produce only one billionth of the energy density of the universe.

Generally, the stochastic GW signal from a given source extends over a broad frequency range. The spectrum from many early-universe sources typically peaks at a frequency linked to the expansion rate at the time the source was active, redshifted to today. Under standard assumptions, the early universe was dominated by radiation and the peak frequency of the GW signal increases linearly with the temperature. For instance, the GW frequency range in which LIGO/Virgo/KAGRA are most sensitive (10–100 Hz) corresponds to sources that were active when the universe was as hot as 10^8 GeV – six orders of magnitude higher than the LHC. The other currently operating GW observatories,



A Malekmejad

In synch *A network of laser-interferometer GW detectors on Earth (left) and in space (right). The km-scale terrestrial detectors are sensitive to GWs with frequencies of 1–10^3 Hz, while space-based detectors are gigantic 10^3–10^6 km-scale instruments sensitive to GWs in the 10^{-4}–1 Hz range. Yet another space-based GW detector, μAres, has been proposed in the 10^{-6}–10^{-3} Hz range. The location of the Einstein Telescope has not yet been decided and LIGO–India will be operational some 20 years from now.*

PTAs, are sensitive to GWs of much smaller frequencies, around 10^{-9}–10^{-7} Hz, which correspond to temperatures around 10 MeV to 1 GeV (see "Broadband" figure). These are the temperatures at which the QCD phase transition occurred. While, as mentioned above, a signal from the latter is not expected, dark sectors may be active at those temperatures and source a GW signal. In the near (and long-term) future, it is conceivable that new GW observatories will allow us to probe the stochastic GW background across the entire range of frequencies from nHz to 100 Hz.

Together with bubble collisions, another source of peaked GW spectra due to symmetry breaking in the early universe is the annihilation of topological defects, such as domain walls separating different regions of the universe (in this case the corresponding symmetry is a discrete symmetry). Violent (so-called resonant) decays of new particles, such as is predicted by some early-universe scenarios, may also strongly contribute to the GW background (albeit possibly only at very large frequencies, beyond the sensitivity reach of current and forecasted detectors). Yet another discoverable phenomenon is the collapse of large energy (density) fluctuations in the early universe, such as is predicted to occur in scenarios where the dark matter is made of primordial black holes.

On the other hand, particle-physics sources can also be characterised by very broad GW spectra without large peaks. The most important such source is the inflationary mechanism: during this putative phase of exponential expansion of the universe, GWs would be produced from quantum fluctuations of space–time, stretched by inflation and continuously re-entering the Hubble horizon (i.e. the causally connected part of the universe at any given time) throughout the cosmological evolution. The amount of such primordial GWs is expected to be small. Nonetheless, a broad class of inflationary models predicts GWs with frequencies and amplitudes such that they can be discovered by future measurements of the CMB. In fact, it is precisely via these measurements that Planck and BICEP/Keck Array have been able to strongly constrain the simplest models of inflation. The GWs that can be discovered via the CMB would have very small frequencies (around 10^{-17} Hz, corresponding to ~eV temperatures). The full spectrum would nonetheless extend to large frequencies, only with such a small amplitude that detection by GW observatories would be unfeasible (except perhaps for the futuristic Big Bang Observer – a proposed successor to the Laser Interferometer Space Antenna, LISA, currently being prepared by the European Space Agency).

Feeling blue

Certain classes of inflationary models could also lead to "blue-tilted" (i.e. rising with frequency) spectra, which may then be observable at GW observatories. For instance, this can occur in models where the inflaton is a so-called axion field (a generalisation of the predicted Peccei–Quinn axion in QCD). Such scenarios naturally produce gauge fields during inflation, which can themselves act as sources of GWs, with possible peculiar properties such as circular polarisation and non-gaussianities. A final phenomenon that would generate a very broad GW spectrum, unrelated to inflation, is the existence of cosmic strings. These one-dimensional defects can originate, for instance, from the breaking of a global (or gauge) rotation symmetry and persist through cosmological history, analogous to cracks that appear in an ice crystal after a phase transition from water.

Astrophysical contributions to the stochastic GW background are certainly expected from binary black-hole systems. At the frequencies relevant for LIGO/Virgo/KAGRA, such background would be due to black holes with masses of tens of solar masses, whereas in the PTA sensitivity range the background is sourced by binaries of supermassive black holes (with masses up to millions of solar masses), such as those that are believed to exist at the centres of galaxies. The current PTA indications of a stochastic GW background require detailed analyses to understand whether the signal is due to a particle physics or an astrophysics source. A smoking gun for the latter origin would be the observation of significant anisotropies in the signal, as it would come from regions where more binary black holes are clustered.

We are entering a golden era of GW observations across the frequency spectrum

We are entering a golden era of GW observations across the frequency spectrum, and thus in exploring particle

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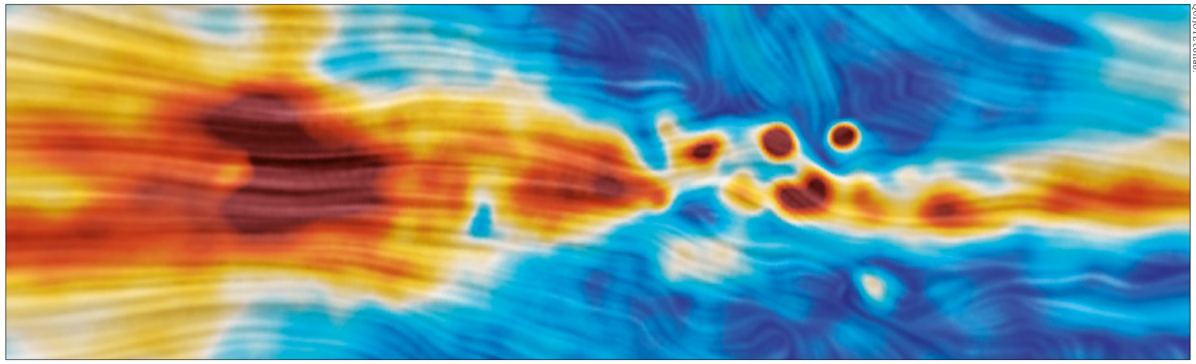

QUIJOTE collab.

Acoustic imprints *Polarised microwave emission from the cosmic microwave background (CMB), where the pattern of lines shows the direction of magnetic field lines. Primordial GWs are predicted to have imprinted characteristic "B mode" patterns into the CMB that are yet to be detected.*

physics beyond the reach of colliders and astrophysical phenomena at unprecedented energies. The first direct detection of GWs by LIGO in September 2015 was one of the greatest scientific achievements of the 21st century. The first generation of laser interferometric detectors (GEO600, LIGO, Virgo and TAMA) did not detect any signal and only constrained the gravitational-wave emission from several sources. The second generation (Advanced LIGO and Advanced Virgo) made the first direct detection and has observed almost 100 GW signals to date. The underground Kamioka Gravitational Wave Detector (KAGRA) in Japan joined the LIGO–VIRGO observations in 2020. As of 2021, the LIGO–Virgo–KAGRA collaboration is working to establish the International Gravitational Wave Network, to facilitate coordination among ground-based GW observatories across the globe. In the near future, LIGO India (IndIGO) will also join the network of terrestrial detectors.

Despite being sensitive to changes in the arm length of the order of 10^{-18} m, the LIGO, Virgo and KAGRA detectors are not sensitive enough for precise astronomical studies of GW sources. This has motivated the new generation of detectors. The Einstein Telescope (ET) is a proposed design concept for a European third-generation GW detector underground, which will be 10 times more sensitive than the current advanced instruments (see p45). On Earth, however, gravitational waves with frequencies lower than 1 Hz are inaccessible due to terrestrial gravity gradient noise and limitations to the size of the device. Space-based detectors, on the other hand, can access frequencies as low as 10^{-4} Hz. Several space-based GW observatories are proposed that will ultimately form a network of laser interferometers in space. They include LISA (planned to launch around 2035), the Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) led by the Japan Aerospace Exploration Agency and two Chinese detectors, TianQin and Taiji (see "In synch" figure).

A new kid on the block, atom interferometry, offers a complementary approach to laser interferometry for the detection of GWs. Two atom interferometers coherently manipulated by the same light field can be used as a differential phase meter tracking the distance traversed by the light field. Several terrestrial cold-atom experiments are under preparation, such as MIGA, ZAIGA and MAGIS, or being proposed, such as ELGAR and AION. These experiments will provide measurements in the mid-frequency range between 10^{-2}–1 Hz. Moreover, a space-based cold-atom GW detector called the Atomic Experiment for Dark Matter and Gravity Exploration (AEDGE) is expected to probe GWs in a much broader frequency range (10^{-7}–10 Hz) compared to LISA.

Astrometry provides yet another powerful way to explore GWs that is not accessible to other probes, i.e. ultra-low frequencies of 10 nHz or less. Here, the passage of a GW over the Earth–star system induces a deflection in the apparent position of a star, which makes it possible to turn astrometric data into a nHz GW observatory. Finally, CMB missions have a key role to play in searching for possible imprints on the polarisation of CMB photons caused by a stochastic background of primordial GWs (see "Acoustic imprints" image). The wavelength of such primordial GWs can be as large as the size of our horizon today, associated with frequencies as low as 10^{-17} Hz. Whereas current CMB missions allow upper bounds on GWs, future missions such as the ground-based CMB-S4 (*CERN Courier* March/April 2022 p34) and space-based LiteBIRD observatories will improve this measurement to either detect primordial GWs or place yet stronger upper bounds on their existence.

Precision detection of the gravitational-wave spectrum is essential to explore particle physics beyond the reach of particle colliders

Outlook

Precision detection of the gravitational-wave spectrum is essential to explore particle physics beyond the reach of particle colliders, as well as for understanding astrophysical phenomena in extreme regimes. Several projects are planned and proposed to detect GWs across more than 20 decades of frequency. Such a wealth of data will provide a great opportunity to explore the universe in new ways during the next decades and open a wide window on possible physics beyond the SM. ●

Further reading

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ALICE collab.

New nodes *The event processing node racks in the ALICE computing farm, part of a completely new computing model for Run 3 and beyond.*

ALICE UPS ITS GAME FOR SUSTAINABLE COMPUTING

The design and deployment of a completely new computing model – the O^2 project – allows the ALICE collaboration to merge online and offline data processing into a single software framework to cope with the demands of Run 3 and beyond. Volker Lindenstruth goes behind the scenes.

The Large Hadron Collider (LHC) roared back to life on 5 July 2022, when proton–proton collisions at a record centre-of-mass energy of 13.6 TeV resumed for Run 3. To enable the ALICE collaboration to benefit from the increased instantaneous luminosity of this and future LHC runs, the ALICE experiment underwent a major upgrade during Long Shutdown 2 (2019–2022) that will substantially improve track reconstruction in terms of spatial precision and tracking efficiency, in particular for low-momentum particles. The upgrade will also enable an increased interaction rate of up to 50 kHz for lead–lead (PbPb) collisions in continuous readout mode, which will allow ALICE to collect a data sample more than 10 times larger than the combined Run 1 and Run 2 samples.

ALICE is a unique experiment at the LHC devoted to the study of extreme nuclear matter. It comprises a central barrel (the largest data producer) and a forward muon "arm". The central barrel relies mainly on four subdetectors for particle tracking: the new inner tracking system (ITS), which is a seven-layer, 12.5 gigapixel monolithic silicon tracker (*CERN Courier* July/August 2021 p29); an upgraded time projection chamber (TPC) with GEM-based readout for continuous operation; a transition radiation detector; and a time-of-flight detector. The muon arm is composed of three tracking devices: a newly installed muon forward tracker (a silicon tracker based on monolithic active pixel sensors), revamped muon chambers and a muon identifier.

THE AUTHOR

Volker Lindenstruth *Goethe University Frankfurt, GSI Helmholtz Centre and Frankfurt Institute for Advanced Studies, on behalf of the ALICE Collaboration.*

Due to the increased data volume in the upgraded ALICE detector, storing all the raw data produced during Run 3 is impossible. One of the major ALICE upgrades in preparation for the latest run was therefore the design and deployment of a completely new computing model: the O^2 project, which merges online (synchronous) and offline (asynchronous) data processing into a single software framework. In addition to an upgrade of the

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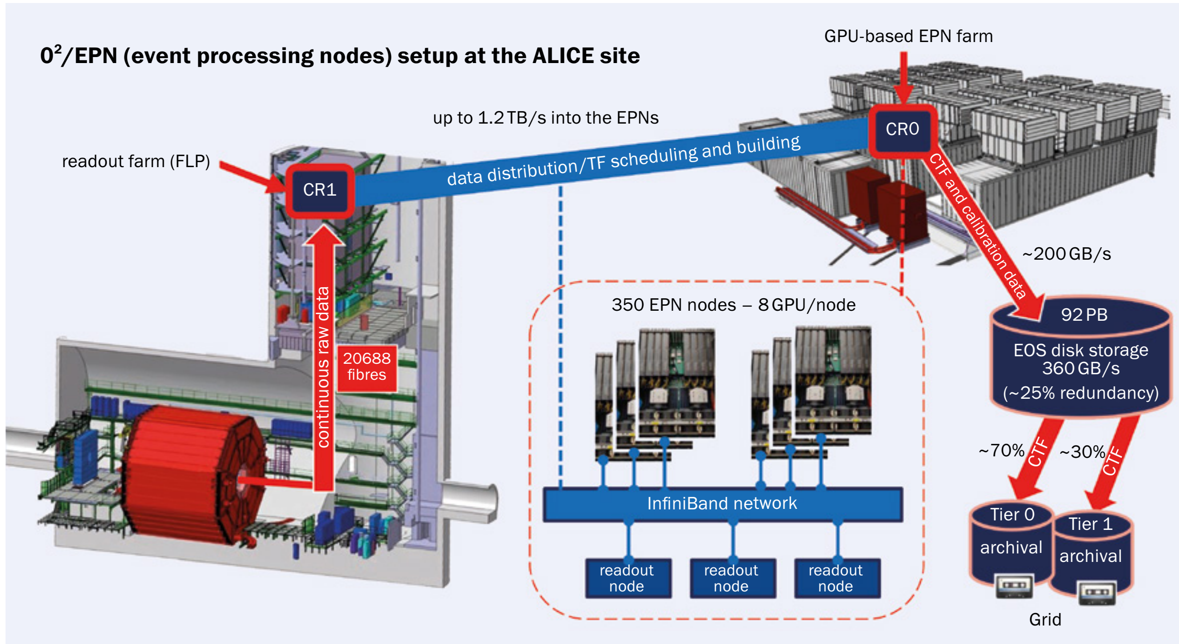


Data flow *Overview of the ALICE detector dataflow. All the detector front-end cards are read out and the readout nodes are connected to the EPN farm hosted in the surface container, where data processing takes place on GPUs and the output is then transferred to the CERN distributed storage system, EOS.*

experiment's computing farms for data readout and processing, this necessitates efficient online compression and the use of graphics processing units (GPUs) to speed up processing.

Pioneering parallelism

As their name implies, GPUs were originally designed to accelerate computer-graphics rendering, especially in 3D gaming. While they continue to be utilised for such workloads, GPUs have become general-purpose vector processors for use in a variety of settings. Their intrinsic ability to perform several tasks simultaneously gives them a much higher compute throughput than traditional CPUs and enables them to be optimised for data processing rather than, say, data caching. GPUs thus reduce the cost and energy consumption of associated computing farms: without them, about eight times as many servers of the same type and other resources would be required to handle the ALICE TPC online processing of PbPb collision data at a 50 kHz interaction rate.

Since 2010, when the high-level trigger online computer farm (HLT) entered operation, the ALICE detector has pioneered the use of GPUs for data compression and processing in high-energy physics. The HLT had direct access to the detector readout hardware and was crucial to compress data obtained from heavy-ion collisions. In addition, the HLT software framework was advanced enough to perform online data reconstruction. The experience gained during its operation in LHC Run 1 and 2 was essential for the design and development of the current O² software and hardware systems.

For data readout and processing during Run 3, the ALICE detector front-end electronics are connected via radiation-tolerant gigabit-transceiver links to custom field programmable gate arrays (see "Data flow" figure). The latter, hosted in the first-level processor (FLP) farm nodes, perform continuous readout and zero-suppression (the removal of data without physics signal). In the case of the ALICE TPC, zero-suppression reduces the data rate from a prohibitive 3.3 TB/s at the front end to 900 GB/s for 50 kHz minimum-bias PbPb operations. This data stream is then pushed by the FLP readout farm to the event processing nodes (EPN) using data-distribution software running on both farms.

Located in three containers on the surface close to the ALICE site, the EPN farm currently comprises 350 servers, each equipped with eight AMD GPUs with 32 GB of RAM each, two 32-core AMD CPUs and 512 GB of memory. The EPN farm is optimised for the fastest possible TPC track reconstruction, which constitutes the bulk of the synchronous processing, and provides most of its computing power in the form of GPU processing. As data flow from the front end into the farms and cannot be buffered, the EPN computing capacity must be sufficient for the highest data rates expected during Run 3.

Due to the continuous readout approach at the ALICE experiment, processing does not occur on a particular "event" triggered by some characteristic pattern in detector signals. Instead, all data is read out and stored during a predefined time slot in a time frame (TF) data structure. The TF length is usually chosen as a multiple of one LHC orbit (corresponding to about 90 microseconds). However, since a whole TF must always fit into the GPU's memory, the collaboration chose to use 32 GB GPU memory to grant enough flexibility in operating with different TF lengths. In addition, an optimisation effort was put in place to reuse GPU memory in consecutive processing steps. During the proton run in 2022 the system was stressed by increasing the proton collision rates beyond those needed in order to maximise the integrated luminosity for physics analyses. In this scenario the TF length was chosen to be 128 LHC orbits. Such high-rate tests aimed to reproduce occupancies similar to the expected rates of PbPb collisions. The experience of ALICE demonstrated that the EPN processing could sustain rates nearly twice the nominal design value (600 GB/s) originally foreseen for PbPb collisions. Using high-rate proton collisions at 2.6 MHz the readout reached 1.24 TB/s, which was fully absorbed and processed on the EPNs. However, due to fluctuations in centrality and luminosity, the number of TPC hits (and thus the required memory size) varies to a small extent, demanding a certain safety margin.

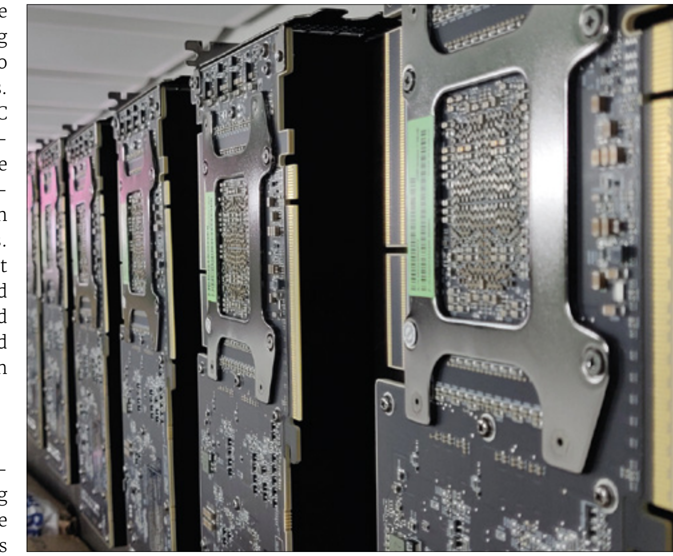
Flexible compression

At the incoming raw-data rates during Run 3, it is impossible to store the data – even temporarily. Hence, the outgoing data is compressed in real time to a manageable size on the EPN farm. During this network transfer, event building is carried out by the data distribution suite, which collects all the partial TFs sent by the detectors and schedules the building of the complete TF. At the end of the transfer, each EPN node receives and then processes a full TF containing data from all ALICE detectors.

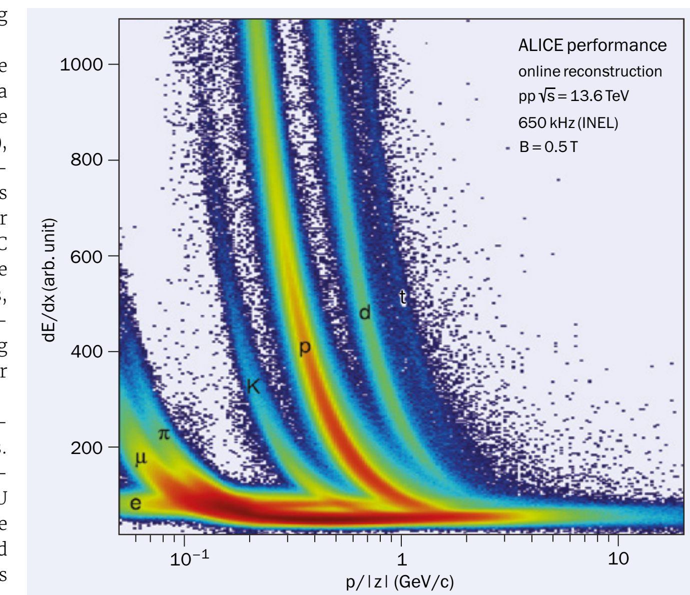
The detector generating by far the largest data volume is the TPC, contributing more than 90% to the total data size. The EPN farm compresses this to a manageable rate of around 100 GB/s (depending on the interaction rate), which is then stored to the disk buffer. The TPC compression is particularly elaborate, employing several steps including a track-model compression to reduce the cluster entropy before the entropy encoding. Evaluating the TPC space-charge distortion during data taking is also the most computing-intensive aspect of online calibrations, requiring global track reconstruction for several detectors. At the increased Run 3 interaction rate, processing on the order of one percent of the events is sufficient for the calibration.

During data taking, the EPN system operates synchronously and the TPC reconstruction fully loads the GPUs. With the EPN farm providing 90% of its compute performance via GPUs, it is also desirable to maximise the GPU utilisation in the asynchronous phase. Since the relative contribution of the TPC processing to the overall workload is much smaller in the asynchronous phase, GPU idle times would be high and processing would be CPU-limited if the TPC part only ran on the GPUs. To use the GPUs maximally, the central-barrel asynchronous reconstruction software is being implemented with native GPU support. Currently, around 60% of the workload can run on a GPU, yielding a speedup factor of about 2.25 compared to CPU-only processing. With the full adaptation of the central-barrel tracking software to the GPU, it is estimated that 80% of the reconstruction workload could be processed on GPUs.

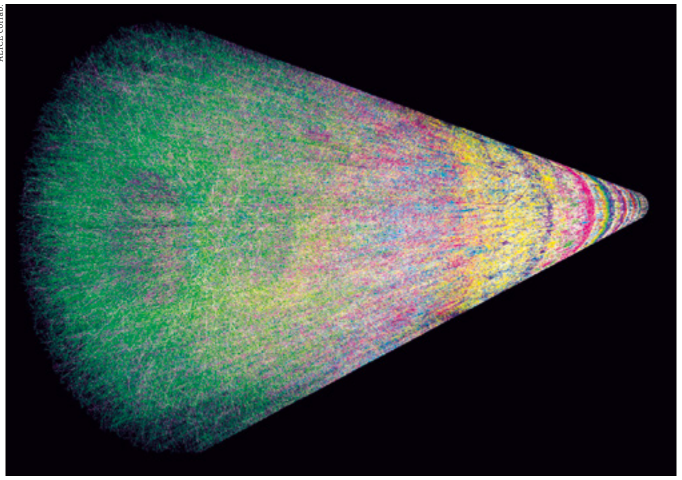
In contrast to synchronous processing, asynchronous processing includes the reconstruction of data from all detectors, and all events instead of only a subset; physics analysis-ready objects produced from asynchronous processing are then made available on the computing Grid. As a result, the processing workload for all detectors, except the TPC, is significantly higher in the asynchronous phase. For the TPC, clustering and data compression are not necessary during asynchronous processing, while the tracking runs on a smaller input data set because some of the detector hits were removed during data compression. Consequently,



Parallel processing *A batch of GPUs manufactured by AMD, which are used extensively in the new ALICE computing model.*



Particle ID *The performance of the ALICE TPC for particle identification by energy loss, dE/dx.*



ALICE collab.

Hard tracking *Visualisation of a 2 ms time frame of PbPb collisions at a 50 kHz interaction rate in the ALICE TPC, showing tracks from different primary collisions in different colours.*

TPC processing is faster in the asynchronous phase than in the synchronous phase. Overall, the TPC contributes significantly to asynchronous processing, but is not dominant. The asynchronous reconstruction will be divided between the EPN farm and the Grid sites. While the final distribution scheme is still to be decided, the plan is to split reconstruction between the online computing farm, the Tier 0 and the Tier 1 sites. During the LHC shutdown periods, the EPN farm nodes will almost entirely be used for asynchronous processing.

Great shape

In 2021, during the first pilot-beam collisions at injection energy, synchronous processing was running and successfully commissioned. In 2022 it was used during nominal LHC operations, where ALICE performed online processing of pp collisions at a 2.6 MHz inelastic interaction rate. At lower interaction rates (both for pp and PbPb collisions), ALICE ran additional processing tasks on free EPN resources, for instance online TPC charged-particle energy-loss determination, which would not be possible at the full 50 kHz PbPb collision rate. The particle-identification performance is demonstrated in the figure "Particle ID", in which no additional selections on the tracks or detector calibrations were applied.

Another performance metric used to assess the quality of the online TPC reconstruction is the charged-particle tracking efficiency. The efficiency for reconstructing tracks from PbPb collisions at a centre-of-mass energy of 5.52 TeV per nucleon pair ranges from 94–100% for $p_T > 0.1$ GeV/c. Here the fake-track rate is rather negligible, however the clone rate increases significantly for low-p_T primary tracks due to incomplete track merging of very low-momentum particles that curl in the ALICE solenoidal field and leave and enter the TPC multiple times.

Having pioneered the use of GPUs in high-energy physics for more than a decade, ALICE now employs GPUs heavily to speed up online and offline processing

The effective use of GPU resources provides extremely efficient processors. Additionally, GPUs deliver improved data quality and compute cost and efficiency – aspects that have not been overlooked by the other LHC experiments. To manage their data rates in real time, LHCb developed the Allen project, a first-level trigger processed entirely on GPUs that reduces the data rate prior to the alignment, calibration and final reconstruction steps by a factor of 30–60. With this approach, 4 TB/s are processed in real time, with 10 GB of the most interesting collisions selected for physics analysis.

At the beginning of Run 3, the CMS collaboration deployed a new HLT farm comprising 400 CPUs and 400 GPUs. With respect to a traditional solution using only CPUs, this configuration reduced the processing time of the high-level trigger by 40%, improved the data-processing throughput by 80% and reduced the power consumption of the farm by 30%. ATLAS uses GPUs extensively for physics analyses, especially for machine-learning applications. Focus has also been placed on data processing, anticipating that in the following years much of that can be offloaded to GPUs. For all four LHC experiments, the future use of GPUs is crucial to reduce the cost, size and power consumption within the higher luminosities of the LHC.

Having pioneered the use of GPUs in high-energy physics for more than a decade, ALICE now employs GPUs heavily to speed up online and offline processing. Today, 99% of synchronous processing is performed on GPUs, dominated by the largest contributor, the TPC.

More code

On the other hand, only about 60% of asynchronous processing (for 650 kHz pp collisions) is currently running on GPUs, i.e. offline data processing on the EPN farm. For asynchronous processing, even if the TPC is still an important contributor to the compute load, there are several other subdetectors that are important. In fact, there is an ongoing effort to port considerably more code to the GPUs. Such an effort will increase the fraction of GPU-accelerated code to beyond 80% for full barrel tracking. Eventually ALICE aims to run 90% of the whole asynchronous processing on GPUs.

In November 2022 the upgraded ALICE detectors and central systems saw PbPb collisions for the first time during a two-day pilot run at a collision rate of about 50 Hz. High-rate PbPb processing was validated by injecting Monte Carlo data into the readout farm and running the whole data processing chain on 230 EPN nodes. Due to the TPC data volumes being somewhat larger than initially expected, this stress test is now being revalidated with continuously optimised TPC firmware using 350 EPN nodes together with the final TPC firmware to provide the required 20% compute margin with respect to foreseen 50 kHz PbPb operations in October 2023. Together with the upgraded detector components, the ALICE experiment has never been in better shape to probe extreme nuclear matter during the current and future LHC runs. ●

Further reading

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JOINED-UP THINKING IN VACUUM SCIENCE

CERN is home to a unique centre-of-excellence in vacuum science, technology and engineering. Paolo Chiggiato and Luigi Scibile explain how that collective expertise is being put to work as part of the international effort to develop the next generation of gravitational-wave telescopes.

Project planning *Two CERN groups are engaged as contributing partners on the beampipe studies for the Einstein Telescope – specifically, the vacuum, surfaces and coatings (TE-VSC) and mechanical and materials engineering (EN-MME) groups. Above: CERN members of the Einstein Telescope beampipe study teams install the first pre-prototype beampipe demonstrator.*

The first detection of gravitational waves in 2015 stands as yet another confirmation of Einstein's general theory of relativity and represents one of the most significant milestones in contemporary physics. Not only that, the direct observation of gravitational ripples in the fabric of space–time has opened up a new window on the universe that enables astronomers to study cataclysmic events such as black-hole collisions, supernovae and the merging of neutron stars. The hope is that the emerging cosmological data sets will, over time, yield unique insights to address fundamental problems in physics and astrophysics – the distribution of matter in the early universe, for example, and the nature of dark matter and dark energy.

By contrast, an altogether more down-to-earth agenda – Beampipes for Gravitational Wave Telescopes 2023 – provided the backdrop for a three-day workshop held at CERN at the end of March 2022. Focused on enabling technologies for current and future gravitational-wave observatories – specifically, their ultrahigh-vacuum (UHV) beampipe requirements – the workshop attracted a cross-disciplinary audience of 85 specialists drawn from the particle-accelerator and gravitational-wave communities alongside industry experts spanning steel production, pipe manufacturing and vacuum technologies (*CERN Courier* July/August 2023 p18).

With more than 125 km of beampipes and liquid-helium transfer lines, CERN is home to one of the world's largest vacuum systems – and certainly the longest and most sophisticated in terms of particle accelerators. Given that the next generation of gravitational-wave observatories require the largest ultrahigh vacuum systems

THE AUTHORS

Paolo Chiggiato *is leader of the vacuum, surfaces and coatings group at CERN.*

Luigi Scibile *is technical coordinator of accelerator technologies at CERN.*

Better by design: the Einstein Telescope beampipes

CERN

Tunnel vision *Left: CERN's microscopy lab in the EN-MME group is deploying a range of techniques – including focused ion-beam microscopy and scanning electron microscopy – for the analysis of candidate steels under consideration for the Einstein Telescope beampipe pilot sector. Right: a "mild-steel" pre-prototype vacuum chamber is shown after manufacturing as part of the beampipe studies at CERN.*

The baseline for the Einstein Telescope's beampipe design studies is the Virgo gravitational-wave observatory. The latter's beampipe – which is made of austenitic stainless steel (AISI 304L) – consists of a 4 mm thick wall reinforced with stiffener rings and equipped with an expansion bellows (to absorb shock and vibration).

While steel remains the material of choice for the Einstein Telescope beampipe, other grades beyond AISI 304L are under consideration. Ferritic steels, for example, can contribute to a significant cost reduction per unit mass compared to austenitic stainless steel, which contains nickel. Ferrite also has a body-centred-cubic crystallographic structure that results in lower residual hydrogen levels versus face-centred-cubic austenite – a feature that eliminates the need for expensive solid-state degassing treatments when pumping down to UHV.

Options currently on the table include the cheapest ferritic steels, known as "mild steels", which are used in gas pipelines after undergoing corrosion treatment, as well as ferritic stainless steels containing more than 12% chromium by weight. While initial results with the latter show real promise, plastic deformation of welded joints remains an open topic; the magnetic properties of these materials must also be considered to prevent anomalous transmission of electromagnetic signals and induced mechanical vibrations.

Along a related coordinate, CERN is developing an alternative solution with respect to the baseline design that involves corrugated walls with a thickness of 1.3 mm, eliminating the need for bellows and reinforcements. Double-wall pipe designs are also in the mix – either with an insulation vacuum or thermal insulators between the two walls.

Beyond the beampipe material, studies are exploring the integration of optical baffles, which intermittently reduce the pipe aperture to block scattered photons. Various aspects such as positioning, material, surface treatment and installation are under review, while the transfer of vibrations from the tunnel structure to the baffle represents another line of enquiry.

With this in mind, the design of the beampipe support system aims to minimise the transmission of vibrations to the baffles and reduce the frequency of the first vibration eigen mode within a range where the Einstein Telescope is expected to be less sensitive. Defining the vibration transfer function from the tunnel's near-environment to the beampipe is another key objective, as are the vibration levels induced by airflow in the tunnel (around the beampipe) and stray electromagnetic fields from beampipe instrumentation.

Another thorny challenge is integration of the beampipes into the Einstein Telescope tunnel. Since the beampipes will be made up of approximately 15 m-long units, welding in the tunnel will be mandatory. CERN's experience in welding cryogenic transfer lines and magnet junctions in the LHC tunnel will be useful in this regard, with automatic welding and cutting machines being one possible option to streamline deployment.

Also under scrutiny is the logistics chain from raw material to final installation. Several options are being evaluated, including manufacturing and treating the beampipes on-site to reduce storage needs and align production with the pace of installation. While this solution would reduce the shipping costs of road and maritime transport, it would require specialised production personnel and dedicated infrastructure at the Einstein Telescope site.

Finally, the manufacturing and treatment processes of the beampipes will have a significant impact on cost and vacuum performance – most notably with respect to dust control, an essential consideration to prevent excessive light scattering due to falling particles and changes in baffle reflectivity. Dust issues are common in particle accelerators and the lessons learned at CERN and other facilities may well be transferable to the Einstein Telescope initiative.

ever built, the experience and expertise of CERN's technology and engineering departments in vacuum science, materials processing, advanced manufacturing and surface treatment offers powerful synergies with the gravitational-wave community.

Measurement science at the limits

The principal way to detect gravitational waves is to use a laser interferometer comprising two perpendicular arms, each several kilometres long and arranged in an L shape. At the intersection of the L, the light beams in the two branches interact, whereupon the resulting interference signal is captured by photodetectors. When a gravitational wave passes through Earth, it induces differential length changes in the interferometer arms – such that the beams traversing the two arms experience dissimilar path lengths, resulting in a phase shift and corresponding alterations in their interference pattern.

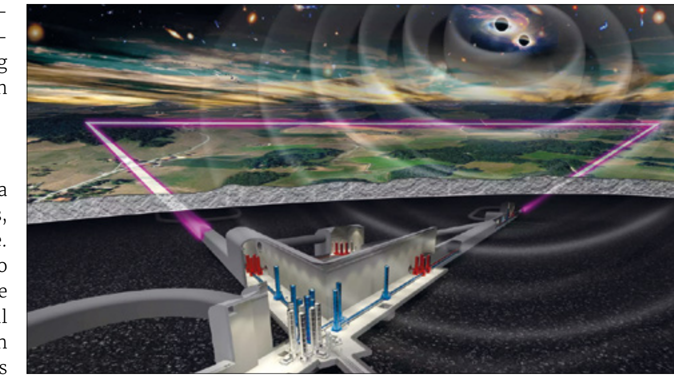
These are no ordinary interferometers, though. The instruments operate at the outer limits of measurement science and are capable of tracking changes in length down to a few tens of zeptometres (10^{-21} m), a length scale roughly 10,000 times smaller than the diameter of a proton. This achievement is the result of extraordinary progress in optical technologies over recent decades – advances in laser stability and mirror design, for example – as well as the ongoing quest to minimise sources of noise arising from seismic vibrations and quantum effects.

With the latter in mind, the interferometer light beams must also propagate through vacuum chambers to avoid potential scattering of photons by gas molecules. The residual gas present within these chambers introduces spatial and temporal fluctuations in the refractive index of the medium through which the laser beam propagates – primarily caused by statistical variations in gas density. As such, the coherence of the beam can be compromised as it traverses regions characterised by a non-uniform refractive index, resulting in phase distortions. To mitigate the detrimental effects of coherence degradation, it is therefore essential to maintain hydrogen levels at pressures lower than 10^{-9} mbar, while even stricter UHV requirements are in place for heavier molecules (depending on their polarisability and thermal speed).

Now and next

Today, there are four gravitational-wave telescopes in operation: LIGO (across two sites in the US), Virgo in Italy, KAGRA in Japan and GEO600 in Germany (while India has recently approved the construction of a new gravitational-wave observatory in the western state of Maharashtra). Coordination is a defining feature of this collective endeavour, with the exchange of data among the respective experiments crucial for eliminating local interference and accurately pinpointing the detection of cosmic events.

Meanwhile, the research community is already planning for the next generation of gravitational-wave telescopes. The primary objective is to expand the portion of the universe that can be comprehensively mapped and, ultimately, to detect the primordial gravitational waves predicted to



Nikhef

Making waves *An artist's impression of the Einstein Telescope, a proposed third-generation gravitational-wave detector in Europe with a total interferometer arm length of 120 km.*

have been generated in the very early universe. In terms of implementation, this will demand experiments with longer interferometer arms accompanied by significant reductions in noise levels (necessitating, for example, the implementation of cryogenic cooling techniques for the mirrors).

Two leading proposals are on the table: the Einstein Telescope in Europe and the Cosmic Explorer in the US. The latter proposes a 40 km long interferometer arm with a 1.2 m diameter beampipe, configured in the traditional L shape and across two different sites (as per LIGO). Conversely, the former proposes six 60° "Ls" in an underground tunnel laid out in an equilateral triangle configuration, with 10 km long sides, 1 m beampipe diameter and a high- and low-frequency detector at each vertex (for comparison, the current LIGO and Virgo installations feature arm lengths of 4 km and 3 km, respectively). As a result, the anticipated length of the vacuum vessel for the Einstein Telescope is projected to be 120 km, while for the Cosmic Explorer it is expected to be 160 km. In short: both programmes will require the most extensive and ambitious UHV systems ever constructed.

Extreme vacuum

At a granular level, the vacuum requirements for the Einstein Telescope and Cosmic Explorer assume that the noise induced by residual gas is significantly lower than the allowable noise budget of the gravitational interferometers themselves. This comparison is typically made in terms of amplitude spectral density. A similar approach is employed in particle accelerators, where an adequately low residual gas density is imperative to minimise any impacts on beam lifetimes (which are predominantly constrained by other unavoidable factors such as beam–beam interactions, magnet imperfections and power converter noise).

The specification for the Einstein Telescope states that the contribution of residual gas density to the overall noise budget must not exceed 10%, which necessitates that hydrogen partial pressure be maintained in the low 10^{-10} mbar range. Achieving such pressures is commonplace in leading-edge particle accelerator facilities and, as it turns out, not far beyond the limits of current gravitational-wave

The Einstein Telescope in Europe and the Cosmic Explorer in the US would require the most extensive and ambitious UHV systems ever constructed

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Materials processing *CERN's main workshop will support the manufacture of the beampipe pilot sector for the Einstein Telescope. The workshop's core activities include welding services (right), sheet-metal work, machining and an independent metrology service.*

observatories. The problem, though, comes when mapping current vacuum technologies to next-generation experiments like the Einstein Telescope.

In such a scenario, the vacuum system would represent one of the biggest capital equipment costs – on a par, in fact, with the civil engineering works (the main cost-sink). As a result, one of the principal tasks facing the project teams is the co-development – in collaboration with industry – of scalable vacuum solutions that will enable the cost-effective construction of these advanced experiments without compromising on UHV performance and reliability.

Value for money

The upward trajectory of capital/operational costs versus length of the experimental beampipe is a challenge that's common to both next-generation particle accelerators and gravitational-wave telescopes – and one that makes cost reduction mandatory when it comes to the core vacuum technologies that underpin these large-scale facilities. In the case of the proposed Future Circular Collider at CERN, for instance, a vacuum vessel exceeding 90 km in length would be necessary.

Of course, while operational and maintenance costs must be prioritised in the initial design phase, the emphasis on cost reduction touches all aspects of project planning and, thereafter, requires meticulous optimisation across all stages of production – encompassing materials selection, manufacturing processes, material treatments, transport, logistics, equipment installation and commissioning. Systems integration is also paramount, especially at the interfaces between the vacuum vessel's technical systems and adjacent infrastructure (for example, surface buildings, underground tunnels and caverns). Key to success in every case is a well-structured project that brings together experts with diverse competencies as part of an ongoing "collective conversation" with their counterparts in the physics community and industrial supply chain.

The European strategy for particle physics explicitly prioritises synergies between particle and astroparticle physics

Within this framework, CERN's expertise in managing large-scale infrastructure projects such as the HL-LHC can help to secure the success of future gravitational-wave initiatives. Notwithstanding CERN's capabilities in vacuum system design and optimisation, other areas of shared interest between the respective communities include civil engineering, underground safety and data management, to name a few.

Furthermore, such considerations align well with the 2020 update of the European strategy for particle physics, which explicitly prioritises the synergies between particle and astroparticle physics. They are also reflected operationally through a collaboration agreement (signed in 2020) between CERN and the lead partners on the Einstein Telescope feasibility study: Nikhef in the Netherlands and INFN in Italy.

In this way, CERN is engaged directly as a contributing partner on the beampipe studies for the Einstein Telescope (see "Better by design: the Einstein Telescope beampipes" panel). The three-year project, which kicked off in September 2022, will deliver the main technical design report for the telescope's beampipes. CERN's contribution is structured in eight work packages, from design and materials choice to logistics and installation, including surface treatments and vacuum systems.

The beampipe pilot sector will also be installed at CERN, in a building previously used for testing cryogenic helium transfer lines for the LHC. Several measurements are planned for 2025, including tests relating to installation, alignment, *in situ* welding, leak detection and achievable vacuum levels. Other lines of enquiry will assess the efficiency of the bakeout process, which involves the injection of electrical current directly into the beampipe walls (heating them in the 100–150 °C range) to minimise subsequent outgassing levels under vacuum.

Given that installation of the beampipe pilot sector is time-limited, while details around the manufacturing and treatment of the vacuum chambers are still to be clarified, the engagement of industry partners in this early design stage is key – an approach, moreover, that seeks to replicate the collaborative working models pursued as standard within the particle-accelerator community. While there's a lot of ground to cover in the next two years, the optimism and can-do mindset of all partners involved in the development of next-generation gravitational-wave telescopes bodes well for the future of this exciting new interdisciplinary field. ●

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OPINION INTERVIEW

EPP-2024: progress and promise

Maria Spiropulu and Michael Turner discuss Elementary Particle Physics: Progress and Promise (EPP-2024), a committee charged with submitting a report on the long-term future of elementary particle physics in the US.

What is the origin and purpose of EPP-2024?

Michael Turner (MT): In June 2022, the US Department of Energy (DOE) and National Science Foundation (NSF) asked the US National Academy of Sciences to convene a committee to provide a long-term (30 years or more) vision for elementary particle physics in the US and to deliver its report in mid 2024. EPP-2024 follows three previous National Academy studies, the last one in 2006 being notable for its composition (more than half of the members were "outsiders") and the fact that it both set a vision and and priorities. EPP-2024 is an 18-member committee, co-chaired by Maria and myself, and comprises mostly particle physicists from across the breadth of the field. It includes two Nobel Prize winners, eight National Academy members and CERN Director-General Fabiola Gianotti. It will recommend a long-term vision, but will not set priorities.

How does EPP-2024 relate to the current "P5" prioritisation process in the US?

MT: The field is in the process of the third P5 (Particle Physics Project Prioritization Panel) exercise, following previous cycles in 2008 and 2014. The DOE and the NSF asked the 30-member P5 committee (chaired by Hitoshi Murayama of UC Berkeley) to provide a prioritised, 10-year budget plan in the context of a 20-year globally-aware strategy by October 2023. By way of contrast, EPP-2024 will assess where the field is today, describe its ambitions and the tools and workforce necessary to achieve those ambitions, all without discussing budgets, specific projects or priorities.

Both P5 and EPP-2024 have benefitted from the community-based activity, Snowmass 2021, sponsored by the American Physical Society, which brought together more than 1000 particle physicists to set their priorities and vision for the future in a report published in January 2023. Together, EPP-2024 and P5 will provide both a long-term vision and a shorter-term detailed plan for particle physics in the US that will maintain a vibrant US programme within the larger context of a field that is very international.

D Overbye

Co-chairs *Maria Spiropulu (Caltech) and Michael Turner (University of Chicago and UCLA) are co-chairs of EPP-2024, which aims to help federal agencies, policymakers and academic leaders understand the future prospects for and societal benefits of particle-physics research.*

What took EPP-2024 to CERN earlier this year?

Maria Spiropulu (MS): CERN, from its inception, has been structured as an international organisation; pan-European surely, but structurally internationally ready. In 2018 I was in the Indian Treaty room of the White House when the then CERN Director-General Rolf Heuer proclaimed CERN as the biggest US laboratory not on US soil. Indeed, in the past decade the ties between US particle physics and CERN have become stronger – in particular via the LHC and HL-LHC and also the neutrino programme – and ever more critical for the future of the field at large, so it was only natural to visit CERN and to discuss with the community in our EPP Town Hall, the early-career contingent and others. It was a very productive visit and we were impressed with what we saw and learned. The early-career scientists were fully engaged and there was a long and lively discussion focused both on the long-term science goals of the field, the planning process in Europe and in the US, the role of the US at CERN and CERN's role in the US, as well as the involvement of early-career researchers in the process. As the field evolves and innovative approaches from other domains are employed to address persistent science questions and challenges, we see our workforce as a major output of the field both feeding back to our research programme and the society writ large.

The questions we are asking now are big questions that require tenacity, resources, innovation and collaboration. Every technology advance and invention we can use to push the frontiers of knowledge we do. Of course, we need to investigate whether we can break these questions into shorter-timescale undertakings, perhaps less demanding in scale and resources, and with even higher levels of innovation, and then put the pieces together. Ultimately it is the will and determination of those who engage in the field that will draft the path forward.

How would you define particle physics today?

MT: There is broad agreement that the mission of particle physics is the quest for a fundamental understanding of matter, energy, space and time. That ambitious mission not only involves identifying the building blocks of matter and energy, and the interactions between them, but also understanding how space, time and the universe originated. As evidenced by the diversity of participants at Snowmass – astronomers and physicists of all kinds – the enterprise encompasses a broad range of activities. Those being prioritised by P5 range from experiments at particle accelerators and underground laboratories to telescopes of all kinds and a host of table-top experiments.

Long ago when I was an undergraduate at Caltech working with experimentalist Barry Barish (now a gravitational-wave astronomer), particle physics comprised experimenters who worked at accelerators and theorists who sought to explain and understand their results. While these two activities remain the core of the field, there is a "cloud" of activities that are also very important to the mission of particle physics. And for good reason: almost all the evidence for physics beyond the Standard Model involves the universe at large: dark matter, dark energy, baryogenesis and inflation. Neutrino masses were discovered in experiments that involved astrophysical sources (e.g. the Sun and cosmic-ray produced atmospheric neutrinos), and many of the big ideas in theoretical particle physics involve connecting quarks and the cosmos. Although some of the researchers involved in such cloud activities are particle physicists who have moved out of the core, the primary research of most isn't directly associated with the mission of particle physics.

We stand on the tall shoulders of the Standard Model of particle physics – and general relativity – with a programme in place that includes the LHC, neutrino experiments, dark-matter and dark-energy experiments, CMB-polarisation measurements, precision tests and searches for rare processes and powerful theoretical ideas – not to mention all the ideas for future facilities. I believe that we are on the cusp of a major transformation in our understanding of the fundamentals of the physical world at least as exciting as the November 1974 revolution that brought us the Standard Model.

CERN-PHOTO-202302-047-8

Down under *CERN director of accelerators and technology Mike Lamont guiding US representatives of the National Academy of Sciences around the LHC during the EPP-2024 visit in February.*

> **I believe that we are on the cusp of a major transformation in our understanding at least as exciting as the November 1974 revolution**

How can particle physics maintain its societal relevance next to more applied domains?

MS: To be sure, the edifice of science is ever more relevant to human civilisation and most of society's functions. Particle physics and associated fields capture human imagination and curiosity in terms of questions that they grapple with – questions that no one else would take up, at least not experimentally. All science domains, technology-needs and products are important to our 21st-century workings. Particle physics is not more or less important, in fact it consumes and optimises and adapts the advances of most other domains toward very ambitious objectives of building an understanding of our universe. I would also argue that because we are the melting pot of so much input and tools from other seemingly unrelated science and technology domains, the field offers a very fertile and attractive ground for training a workforce able to tackle intellectually and technologically ambitious puzzles. It can be seen as overly demanding – and this is where mentorship, guidance and clarity of opportunities play a crucial role.

How does EPP-2024 take into account international aspects of the field?

MS: This is exemplified by a committee membership that includes the CERN Director-General, and also by the multiple testimonies and panels focusing on international collaboration, including the framework, the optimisation of science and societal outcomes, and the training of an outstanding workforce. We have collected information from distinguished panels and experts in Europe, Asia and the US that have traditionally led the field, and we study how smaller economies and nations participate and contribute successfully and to the benefit of their nations and the international discovery science goals at large. We also interrogate the role of our science in diplomacy and in scientific exchanges that may overcome geopolitical tensions. International big projects are not a walk in the park; in our field they have proven to be necessary, so we put in deliberate emphasis to make them work towards achieving ambitious goals that are otherwise intractable.

What has the EPP-2024 committee learned so far – any surprises?

MT: For me, a relative outsider to particle physics, several things have stood out. First, the breadth of the enterprise today: cosmology has become fully integrated into particle physics, and new connections have been made to AMO physics (quantum sensors, trapped atoms and molecules, atomic interferometry), gravitational physics (gravitational waves and precision tests of gravity theory), and nuclear physics (neutrino masses and properties). Not only have dark-matter searches for WIMPs and axions become "big science", but there is exploration of a host of new candidates that has spurred the invention of novel detection schemes.

In the US, particle physics has become a big tent that encompasses tabletop experiments to look for a small electric dipole moment of the electron, large galaxy surveys, cosmic microwave background experiments, long-baseline neutrino experiments, and of course collider experiments to explore the energy frontier. It is difficult to draw a box around a field called elementary particle physics.

On the science side, much has changed since the last National Academy report in 2006, which noted discovering the Higgs boson and exploring the soon-to-be-discovered world of supersymmetry as its big vision. The aspirations of the field are much loftier today, from understanding the emergence of space and time to the deep connections between gravity and quantum mechanics. At the same time, however, the path forward is less clear than it was in 2006.

Interview by **Matthew Chalmers**.

OPINION REVIEWS

A frog among birds

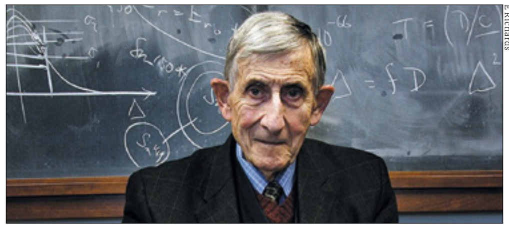
"Well, Doc, You're In": Freeman Dyson's Journey through the Universe

Edited by David Kaiser

MIT Press

"Well, Doc, You're In": Freeman Dyson's Journey through the Universe is a biographical account of an epochal theoretical physicist with a mind that was, by any measure, delightful and diverse. It portrays Dyson, a self-described frog among birds, as a one-off synthesis of blitz-spirit Britishness with American space-age can-do. Of the elite cadre of theoretical physicists who ushered in the era of quantum field theory, which dominates theoretical physics to this day, who else would have devoted so much time and sincere scientific energy to the development of a gargantuan spacecraft, powered by nuclear bombs periodically dropped beneath it, that would take human civilisation beyond our solar system!

Written by colleagues, friends, family members and selected experts, each chapter is more of a self-contained monograph, a link in a chain, than it is a portion of the continuous thread that one would find for a more traditional single-author biography. What is lost as a result of this format, such as an occasional repetition of key life moments, is more than sufficiently compensated by richness of perspective and a certain ease of pick-up put-down that comes from the narrational independence of the various chapters. If it has been a while since the reader last had a moment to pick it up, not much will be lost when one delves back in.



E Richards

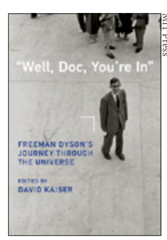
The early years of Dyson-caliber 20th-century theoretical physicists and mathematicians of his cohort are often interwoven with events surrounding the development of nuclear weapons or code-breaking. Dyson's story as told in *"Well, Doc, You're In"* stands apart in this respect, as he spent the war years working in Bomber Command for the Royal Air Force in England. His reflections on aspects of his own experience mirror, in some ways, the sentiments of future colleagues involved in the Manhattan project, noting: "Through science and technology, evil is organised bureaucratically so that no individual is responsible for what happens."

Free flow *Freeman Dyson always took expected and unexpected opportunities as they came.*

The following years spent wrestling with quantum electrodynamics (QED) at Cornell make for lighter reading. The scattered remarks from eminent theorists such as Bethe and Oppenheimer on Dyson and his work, as well as from Dyson on his eminent colleagues, bring a sense of reality to the unfolding developments that would ultimately become a momentous leap forward in the understanding of quantum field theory.

"The preservation and fostering of diversity is the great goal that I would like to see embodied in our ethical principles and in our political actions," said Dyson. Following his deep contributions to QED, Dyson embraced this spirit of diversity and jumped from scientific pond to pond in search of progress, be it the stability of matter or the properties of random matrices. It is interesting to learn, with hindsight, of the questions that gripped Dyson's imagination at a time when particle physics was entering a golden era. As a reader one almost feels the contrarian spirit, or rebellion, in these choices as they are laid out against this backdrop.

Although scientifically Dyson may have been a frog, jumping from pond to pond, professionally he was anything but. Aged 29 he moved to the Institute for Advanced Study at Princeton and he stayed there to the end. In around 1960 Dyson joined the JASON defence advisory group, a group of scientists advising the US government on scientific matters. He remained a member until his passing in 2020. This consistent backdrop makes for a biographical story, which is essentially free from the distractions of the professional manoeuvring that typically punctuates biographies of great scientists. A positive consequence is that the various authors, and the reader, may focus that bit more keenly on the workings of Dyson's mind.



MIT Press

For as long as graduate students learn quantum field theory, they will encounter Dyson. Sci-fi fans will recognise the Dyson Sphere (a structure surrounding a star to allow advanced civilisations to harvest more energy) featured in *Star Trek*, or note the name of the Orion III Spaceplane in *2001: A Space Odyssey*. Dyson's legacy is as vast and diverse as the world his mind explored and *"Well, Doc, You're In"* is a fascinating glimpse within.

Matthew McCullough *CERN.*

Collision – Stories from the Science of CERN

Edited by Rob Appleby and Connie Potter

Comma Press

Comma Press

Collision – Stories from the Science of CERN is a highly readable anthology built on the idea of teaming up great writers with great scientists. There are 13 stories in all, each accompanied by an afterword from a member of the particle-physics community. The authors are a diverse bunch, so there's something for everyone – from exploring the nature of symmetry through the mirror of human interaction, to imagined historical encounters and, inevitably, the apocalyptic: we humans have always ventured into the unknown with trepidation.

Being of the same vintage as the BBC's *Dr Who*, I was pleased to discover that the first story was penned by one of the programme's most successful showrunners, Steven Moffat. Although I found myself doubting the direction of travel after the opening paragraphs, I enjoyed the destination. It was a good start, and it established a standard that the book maintains to the very last word.

In Adam Marek's story, I found myself listening along to protagonist Brody Maitland's selection of music for his appearance on BBC Radio 4's *Desert Island Discs*, something of a national institution in the UK. This story also contains the wonderful line: "We live in a world where it is more impressive to have millions of followers than to lift the stone of the universe and reveal the deep mysteries scurrying beneath it." How true that is in a world of diminishing attention spans.

Broadcaster and journalist Bidisha Mamata provides a welcome commentary on contemporary global politics. An unscrupulous leader manipulates an ambitious individual in a bid to undermine the global order. Sound familiar? In this case the individual concerned is a CERN scientist; the reputation at stake, CERN's, and the tool to achieving that goal, the creation of a locally apocalyptic event. Politically spot on. Scientifically wide of the mark.

Post-apocalyptic scenarios make other appearances, though in these cases it's what happens next that's important. Stephen Baxter's AI protagonist guides us through millennia of human stupidity, while Lillian Weezer imagines what might happen if people unearthed the LHC in some post-apocalyptic world.

Prometheus and Frankenstein make their appearances in Margaret Drabble's wonderfully erudite tale set at CERN in the 2050s. Désirée Reynolds imagines a delicious encounter that never happened between CERN's first Director-General, Felix Bloch, and the American writer and civil-rights activist James Baldwin. Would they have gelled? I'd like to think so. There's a cautionary tale from Courttia Newland about AI, which draws the conclusion that whatever form intelligence may take, life, of a kind, will go on and the laws of the universe will remain the same. Ian Watson's joyous facility with words puts a smile on your face from the first line of his galaxy-skipping parable. You'll have to read it for yourself to find out whether he leaves you smiling at the end.

A recurring theme is the parallel between life and physics: poet Lisa Luxx, for example, entwines forces at work in nature with those between people, while Lucy Caldwell examines notions of uncertainty in life and physics in a story set in her native city Belfast. Peter Kalu applies a similar principle to computer security, with a cautionary yet warming tale about a side-channel attack of sorts.

Enough of the stories, what about the afterwords? Peter Dong's comment leaves you wanting to sit in on his physics classes, while Jens Vigen gives a thoughtful account of the origins of CERN. Kristin Lohwasser does a fine job of bringing Bidisha's science back to the realms of reality. Tessa Charles is bullish about the FCC, currently at the feasibility stage. Michael Davis gives a glimpse of the vast industry that is modern-day computer security.

Anyone that has juggled particle physics and parenting will identify with Luan Goldie's story, which is accompanied by a heartfelt paean to CERN by one who has done just that. "Life is work and work is life," says Carole Weydert, concluding with the words: "CERN. Grey. But sparkling."

Andrea Bersani introduces us to the speculations that distorted spacetime allow, while Andrea Giammanco does a similar job for the dark sector. Daniel Cervenkov discusses CP violation, while Joe Haley ponders the development of ideas over time: Newton subsumed by Einstein, the Standard Model by something yet to be found. Gino Isidor, for his part, takes us on a brief guided tour of a metastable universe. John Ellis's pairing with Stephen Baxter is particularly successful. The writer's central story, which spans millennia and civilisations, resonates well with theoretical physicist's daily work of examining Gauguin's questions: *"D'où venons nous, Que sommes nous, Où allons nous."*

All in all, the book makes for a varied, thought provoking and engaging read. As with the Arts at CERN programme, it demonstrates that creativity is not the preserve of the arts or science, and that great things can happen when the two collide.

If you enjoy the book, then you might also like to explore some of the history of CERN's engagement with the arts, from James Lee Byars visit to the lab in the 1970s to the Signatures of the Invisible project in 1999, or poetry produced for the European Researchers' night in 2014.

James Gillies *CERN.*

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PEOPLE CAREERS

Fault-finding across sectors

Jack Heron, a senior fellow working on R&D for the proposed Future Circular Collider at CERN, reflects on his past experience in the defence sector.

Colliding worlds *Jack Heron is part of the machine protection and electrical integrity group in CERN's technology department. He works on the "availability challenge" for the FCC.*

Jack Heron always liked the idea of being an inventor. After completing a master's in electronics engineering at Durham University, he spent a year in Bangalore, India as part of the "Engineers Without Borders" programme, where he designed solar-powered poverty-alleviation solutions in unelectrified slums. This sparked an interest in renewable energy, and he completed a PhD on smart grid techniques in 2020. With a passion for advanced technology and engineering at the peak of performance, he then joined the "digital twin" R&D programme of international defence company Babcock, dedicated to fault-prediction for defence assets in land, sea and air.

"The military is extremely interested in autonomous vehicles," explains Jack. "But removing the driver from, say, a fleet of tanks, increases the number of breakdowns: many maintenance checks are triggered by the driver noticing, for example, a 'funny noise on start-up', or 'a smell of oil in the cabin'." Jack worked on trying to replicate this intuition by using very early signs in sensor signals. Such a capability permits high confidence in mission success, he adds. "It also ensures that during a mission, if circumstances change, dynamic asset information is available for reconfiguration."

Fast pace

Working in defence was "exciting and fast-paced" and enabled Jack to see his research put to practical use – he got to drive a tank and attend firing tests on a naval frigate. "It's especially interesting because the world of defence is something most people don't have visibility on. Modern warfare is constantly evolving based on technology, but also politics and current affairs, and being on the cusp of that is really fascinating."

It also left him with a wealth of transferable skills: "Defence is a high-performance world where product failure is not an option. This is hardcoded into the organisation from the bottom up."

> **I love the idea of working on the frontiers of science and human understanding**

Back to his roots

Growing up in Geneva, CERN always had a mythical status for Jack as the epitome of science and exploration. In 2022 he applied for a senior fellowship. "Just getting interviewed for this fellowship was a huge moment for me," he says. "I was lucky enough to get interviewed in person, and when I arrived I got a visitor pass with the CERN-logo lanyards attached. Even if I didn't get the job I was going to frame it, just to remember being interviewed at CERN!"

Jack now works on the "availability challenge" for the proposed Future Circular Collider FCC-ee. Availability is the percentage of scheduled physics days the machine is able to deliver beam, (i.e. is not down for repair). To meet physics goals, this must be 80%. The LHC – the world's largest and most complex accelerator, but still a factor three smaller and simpler than the FCC – had an availability of 77% during Run 2. "Modern-day energy-frontier particle colliders aren't built to the availabilities we would need to succeed with the FCC, and that's without considering additional technical challenges," notes Jack. His research aims to break down this problem system by system and find solutions, beginning with the radio frequency (RF).

On the back of an envelope, he says, the statistics are a concern: "The LHC has 16 superconducting RF cavities, which trip about once every five days. If we scale this up to FCC-ee numbers (136 cavities for the Z-pole energy mode and 1352 for the $t\bar{t}$ threshold), this becomes problematic. Orders of magnitude greater reliability is required, and that itself is a defining technical challenge.

Jack's background in defence prepared him well for this task: "Both are systems that cannot afford to fail, and therefore have extremely tight reliability requirements. One hour of down time in the LHC is extremely costly, and the FCC will be no different."

Mirroring what he did at Babcock, one solution could be fault prediction. Others are robot maintenance, and various hardware solutions to make the RF circuit more reliable. "Generally speaking, I love the idea of working on the frontiers of science and human understanding. I find this exploration extremely exciting, and I'm delighted to be a part of it."

Sanje Fenkart *editorial assistant.*

Appointments and awards

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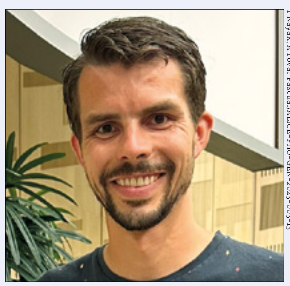
LHCb's new spokesperson
On 1 July the LHCb collaboration welcomed a new management, with Vincenzo Vagnoni (INFN, Bologna) taking over as spokesperson from Chris Parkes (University of Manchester). At his side are Patrick Robbe (IJCLab) and Ulrich Uwer (Heidelberg University) as deputy-spokespersons, succeeding Matteo Palutan (INFN, Frascati). Their three-year tenure will be marked by operations with the new Upgrade I modules, focusing on beauty and charm data samples, and preparations for Upgrade II, coming during LS3, which will amp up the flavour-HL-LHC physics programme.

Fermi accelerator prize
The Italian Physical Society (SIF) awarded this year's Enrico Fermi Prize to three accelerator physicists for their outstanding contributions to the field. Massimo Ferrario (INFN, Frascati) is cited for his work on high-brightness photoinjectors and plasma-acceleration techniques, Lucio Rossi (University of Milan) for his work on superconducting ultra-high-field magnets and his key role in HL-LHC, and Frank Zimmerman (CERN) for his fundamental and pioneering contributions to the understanding and modelling of effects in electron beams. The $30,000 prize will be awarded during the opening session of the 109th National Congress of the SIF in Salerno on 11 September.

Inaugural Eidelman prize
In honour of experimentalist Simon Eidelman (1948–2023), the international advisory committee of the series of conferences on hadron spectroscopy and structure has established an award in his name. The inaugural award of the biennial prize, recognising young researchers working on experimental hadron physics, goes to Ivan Polyakov (CERN) for outstanding contributions to hadron spectroscopy, in particular the discovery and detailed study of the first double charmed tetraquark, T_{cc}^{+}.

Thesis awards from ALICE
The ALICE collaboration has awarded its annual thesis awards, picked from 21 theses submitted, to: Rita Sadek (Subatech/IN2P3) for "MFT (muon forward tracker) commissioning and preparation for Run 3 data analysis with ALICE" and Luuk Vermunt (below; Utrecht) for "Hadronisation of heavy quarks; production



T Nayak, A Tovar Pascual/ALICE-PHO-GEN-2023-003-13

measurements of heavy-flavour hadrons from small to large collision systems". Both defended their theses last year.

Markov Prize for theorists
The 2023 Markov Prize has been awarded to theorists Sergey Troitsky (INR Moscow) and Peter Tinyakov (Free University of Brussels) "for the advancement of astrophysical methods for studying models of elementary particle physics and obtaining constraints on hypothetical particles and new interactions based on it". Troitsky proposed a mechanism where a light pseudoscalar particle mixes with a photon and applied it to the observed TeV gamma radiation from the gamma-ray burst GRB 221009A, while Tinyakov's works include postulating the existence of a massive graviton as a dark-matter candidate.

Success for ATLAS eight
Eight ATLAS PhD students have been announced winners of the collaboration's 2022 thesis awards: Daniel Camarero Munoz (Madrid); Giuseppe Carratta

K Anthony/ ATLAS-PHOTO-2023-004-14

(Bologna); Guglielmo Frattari (Rome); Maria Mironova (above; Oxford); Brian Moser (Nikhef); Giulia Ripellino (Stockholm); Bastian Schlag (Mainz); and Emily Anne Thompson (DESY). Spanning BSM searches and machine-learning approaches, their theses ranged from photon and jet production to type-III see-saw searches, measurements of various decay channels, and searches for supersymmetric particles.

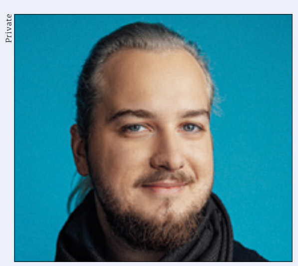
10th winners of BL4S
The winners of the tenth edition of Beamline for Schools (BL4S) were announced by CERN on 28 June. Selected from a total of 379 entries from 63 countries, "Myriad Magnets" will see students from Philip Exeter Academy in the US build and test a permanent magnet geometry that can be configured to produce a dipole or a quadrupole magnetic field, "Particular Perspective" (a joint effort from four schools in Pakistan) will measure in detail the beam composition in the T10 beamline at CERN, and "Wire Wizards'' from Augustinianum School in the Netherlands will design and build a multi-wire proportional chamber to measure the position of an interacting particle at DESY.

CMS recognises theses
The CMS collaboration has recognised three PhD students who recently defended their theses: Angira Rastogi (below; IISER Pune) for "Inclusive nonresonant multilepton probes of new phenomena"; Willem Verbeke (Ghent) for "Searches for undiscovered processes using the multi-lepton final state in proton–proton collisions at CMS"; and David Walter

Private photo

(Hamburg) for "First differential measurements of tZq production and luminosity determination using Z boson rates at the LHC."

LHCb honours students
On 7 June, the LHCb collaboration honoured PhD students who have made exceptional contributions to the collaboration with their theses. Saverio Mariani (University of Florence) was awarded for his work on fixed-target physics with



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the LHCb experiment, using proton–helium collision data to understand antiproton production in cosmic rays, and Peter Svihra (above; University of Manchester) was recognised for detector R&D towards a silicon-pixel detector for the upgraded LHCb detector.

RECRUITMENT

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PEOPLE OBITUARIES

Roger Bailey 1954–2023

Way to go, Rog

It was with deep sadness we learned that Roger Bailey, who played a key role in the operation of CERN's accelerators, passed away on 1 June while mountain biking in Valais, Switzerland. He was 69.

Roger began his career with a doctorate in experimental particle physics from the University of Sheffield in 1979, going on to a postdoctoral position at the Rutherford Appleton Laboratory until 1983. Throughout this time, he worked on experiments at CERN's Super Proton Synchrotron (SPS) and was based at CERN from 1977. In 1983 he joined the SPS operations group, where he was responsible for accelerator operations until 1989. Roger then moved to the Large Electron Positron collider (LEP), coordinating the team's efforts through the commissioning phase and subsequent operation, and became operations group leader in the late 1990s.

After LEP shut down in 2000, Roger became progressively more involved in the Large Hadron Collider (LHC), planning and building the team for commissioning with beam. He then took a leading role in the LHC's early operation, helping to push the LHC's performance to Higgs-discovery levels before becoming director of the CERN Accelerator School, sharing his wealth of experience and inspiring new generations of accelerator physicists.

Roger Bailey front and centre in the CERN Control Centre in late 2009 when the LHC set a new energy record of 1.18 TeV per beam.

Those of us who worked with Rog invariably counted him as a friend: it made perfect sense, given his calm confidence, his kindness and his generosity of spirit. He was straightforward but never outspoken and his well-developed common sense and pragmatism were combined with a subtle and wicked deadpan sense of humour. We had a lot of fun over the years in what were amazing times for CERN. Looking back, things he said, and did, can still make us chuckle, even in the sadness of his untimely passing. Rog had a passionate, playful eye for life's potential and he wasn't shy. There was an adventurous spirit at work, be it in the mountains or the streets of New York, Berlin or Chicago. His specialities were tracking down music and talking amiably to anyone.

During a service to celebrate Roger's life on 16 June, a poem of his called *It's a Wrap* was read by his daughter Ellie, revealing a physicist's philosophical view on life and the universe. Two of his favourite quotes were on the order of service: Mae West's "You only live once, but if you do it right, once is enough" and Einstein's "Our death is not an end if we can live on in our children and the younger generation. For they are us, our bodies are only wilted leaves on the tree of life." Another, by Hunter S Thompson, was mentioned in a homage given by his son, Rob: "Life should not be a journey to the grave with the intention of arriving safely in a pretty and well-preserved body, but rather to skid in broadside in a cloud of smoke, thoroughly used up, totally worn out, and loudly proclaiming "Wow! What a Ride!"

Way to go, Rog, way to go.

His friends and colleagues at CERN.

Milos Lokajicek 1952–2023

A force for Czech particle physics

Milos Lokajicek was at the origin of the participation of Czech physicists in the ATLAS experiment.

Milos Lokajicek, a long-time employee of the division of elementary particle physics of the Institute of Physics of the Czech Academy of Sciences, passed away in June at the age of 70. Milos was involved in almost all the key experiments in which the Czech particle-physics community participated, especially in the collection and processing of experimental data.

Milos began his career in the 1980s on an experiment at the Serpukhov accelerator in the former USSR, investigating proton–antiproton and later deuteron–antideuteron collisions in the Ludmila hydrogen bubble chamber. After obtaining his PhD in 1984, while still at JINR Dubna, he was also involved in the DELPHI experiment at LEP, which played a key role in the Czech Republic's entry into CERN in 1993.

After returning to the Institute of Physics, he was at the origin of the participation of Czech physicists in the ATLAS experiment at the LHC, the construction of which was approved in 1994. Together with other staff of the Institute of Physics and colleagues from Charles University, he initiated the construction of the ATLAS TileCal hadron calorimeter and built a laboratory for the assembly and testing of the calorimeter submodules in the former garage of the Institute of Physics.

Since his participation in the Ludmila and DELPHI experiments, Milos focused on data processing. Already in the mid-1990s, he had built a computer farm for data processing and modelling at the Institute of Physics, which today serves several large experiments.

In 1997, together with colleagues from Charles University and the Czech Technical University, he initiated the group's participation in the DO experiment at the Tevatron, Fermilab. Participation in this experiment was important for the training of young physicists in ATLAS, the construction of which was beginning at that time. After the Tevatron was decommissioned in 2011, Milos obtained funding for the Fermilab–CZ research infrastructure in 2016 with a gradual transition to the neutrino-physics programme. He worked on the NOvA experiment and also used his experience and contacts at CERN for the future DUNE experiment.

The reach of Milos's work extends far beyond his home institute. Within the Czech Republic, it was the coordination of the activities of Czech institutions in Fermilab and the development of data processing. He was also a long-standing member of the Committee for Cooperation of the Czech Republic with CERN. His international reputation is documented by numerous memberships in steering committees of experiments and projects, and a number of conferences he co-organised. Among the most important are ACAT 2014, CHEP2009, DØ Week 2008 and ATLAS Week 2003.

Milos's collegiality and friendship will be missed by all of us.

Jiri Chyla, Alexander Kupco *and* **Petr Zavada** *Institute of Physics of the Czech Academy of Sciences*, **Rupert Leitner** *Charles University.*

Kitty Wakley 1928–2023

Leader of the typing pool

A pillar of CERN is no more. Kitty Wakley, originally from Liverpool, UK started working at CERN in around 1960 and was the beloved leader of the document typing service ("typing pool") until it was dissolved more than 30 years later. Back in the days before physicists and engineers became familiar with word-processing systems and LaTeX, they would present her with their scruffy, hand-written manuscripts for preprints and technical reports. The (occasionally approximate) English would be polished and typed to the highest standards by her team, following the CERN publication rules that her service had established.

Kitty Wakley commanding the CERN document typing service.

Kitty presided over a close-knit team assembled from diverse backgrounds. She was a rather strict boss, in keeping with the usual unwritten standards of the time, but her team members still remember her fondly over 30 years later. Throughout her career at CERN, Kitty was unfailingly kind, cheerful and helpful towards all those who called on her services, from early-career researchers and technicians to Nobel prize-winners. Her mission was to help them disseminate their science in the best possible way, such as by working through the weekend with her team on the presentation of the discovery of the W boson.

Kitty was a much-loved institution of CERN. A lover of Italian opera, following her retirement from CERN she settled in Spain, where she lived for many years before passing away on 13 May, just four days before her 95th birthday. She is remembered fondly by many scientists who have passed through CERN over the decades.

Marie-Suzy Vascotto *and* **John Ellis** *CERN.*

Stanley Wojcicki 1937–2023

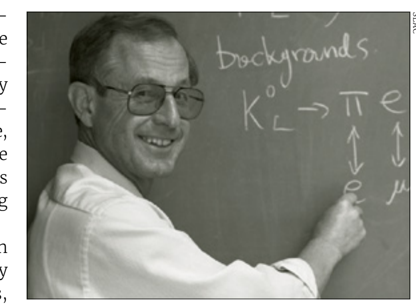
From mesons, to MINOS, to the SSC

Stanley G Wojcicki, a long-time leader in experimental particle physics, died on 31 May at the age of 86. Stan made a number of seminal contributions to the field, beginning with the discovery of many short-lived particles as a graduate student at Berkeley. He quickly rose to prominence, becoming an expert on K-meson physics, where he made a series of investigations and discoveries that played an important role in understanding the structure of the Standard Model.

Stan hardly had a typical childhood. Born in Warsaw, Poland, his youth was dominated by World War II, which caused great hardships, including the separation of his family for several years, followed by a difficult life under the communist regime. Finally, his mother, brother and he managed to escape to Sweden. There, they were refugees for eight months, before they were finally able to move to the US. Stan's father remained in Poland, where he was jailed for five years, and never received a visa to rejoin his family.

From a very young age, Stan was an exceptional student who loved and excelled at mathematics. He continued to stand out in school in his new country and gained admission to Harvard University as an undergraduate, majoring in physics. He went on to Berkeley as a graduate student in physics, which is where he and I met and became lifelong friends, colleagues and sometimes collaborators.

Upon receiving his PhD in 1962, Stan spent a year at CERN and Collège de France, Paris



Stan Wojcicki made many seminal contributions to the field.

(1964–1965). He returned frequently to CERN, including for a period supported through a John Simon Guggenheim Fellowship in 1973–1974. During that year, Stan continued his research on the excited states of hadrons made from combinations of quarks. He continued his close association with CERN, once again as a scientific associate in 1980–1981, and for shorter periods throughout his career.

Stan was appointed assistant professor in the physics department at Stanford in 1966, advanced to full professor in 1974, served as chair from 1982–1985 and stayed on the faculty until his retirement in 2015. He characteristically became interested in the newest and most exciting areas in the field, and was quick to join the design effort for the Superconducting Super Collider (SSC). He served as deputy director of the SSC central design group in Berkeley and was deeply involved in proposing and obtaining approval for the construction of the SSC in Texas. He continued to be active in many aspects of the SSC until it was cancelled by Congress in 1993, and wrote an insightful two-volume history of the project.

After the SSC disappointment, Stan characteristically bounced back to take on a new emerging area of particle physics: neutrino masses and oscillations. He proposed and led the MINOS experiment, a key element of a long-baseline neutrino experiment that sent a beam of neutrinos through a near detector at Fermilab and to a second detector, 735 km away, in a deep mine in Minnesota. MINOS was very important in providing evidence confirming the observations of atmospheric neutrino oscillations from Super-Kamiokande in Japan.

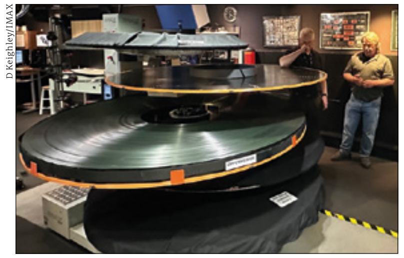
Stan received many honours, including the Pontecorvo Prize in 2011 and the APS Panofsky Prize in 2015 for his neutrino work. He met his wife, Esther, while he was a PhD student at Berkeley. They married in 1961 and had three daughters of whom he was very proud, Susan (CEO of YouTube), Janet (professor of paediatrics at UCSF Medical School) and Anne (founder and CEO of 23andMe). He will be very much missed by his many long-time friends and colleagues.

Barry Barish *Caltech.*

BACKGROUND

Notes and observations from the high-energy physics community

Heavyweight physics



D Keighley/IMAX

The IMAX version of Christopher Nolan's biographical thriller *Oppenheimer* – a portrayal of the Manhattan Project through the eyes of the "father of the atomic bomb" – is heavy in every sense. Weighing 270 kg and 18 km long, the high-resolution 70 mm film runs at close to three hours – longer than Nolan's previous physics-themed epic *Interstellar*. *Oppenheimer* smashed box-office expectations when it opened on 21 July. Still, the moral quandary connecting curiosity-driven research with weapons of mass destruction was not enough to knock fantasy comedy and appeal to feminism *Barbie* – released the same weekend – off the top spot.

After the war, Oppenheimer famously opposed continued nuclear development. He also played a key role in the creation of CERN by advocating for closer collaboration among European scientists.

Tiny Brian's CERN adventures

STFC

Brian Cox has been spotted at CERN. The brainchild of the UK's Science and Technology Facilities Council (STFC), a soft-toy version of the particle physicist turned science celebrity known as "Tiny Brian" has made its social-media debut. The first episode of a new six-part series launched on Twitter, Instagram and Threads in July saw Cox's uncharacteristically silent avatar being carried through basement corridors to the synchrocyclotron, with further adventures in store.

Media corner

"What these pulsar-timing-array observations show is qualitatively consistent with what models predicted but not precisely with the original predictions. That frequency dependence wasn't quite what was expected."

John Ellis talking to *New Scientist* (15 July) about reported evidence for a stochastic GW background (see p7).

"The geological conditions are promising; we'd like to demonstrate that Lusatia [Germany] would be a fitting location for many reasons to host the Einstein Telescope."

Christian Stegman talking about the location of a next-gen GW observatory in Europe (*Der Standard*, 31 July; translated).

"You can have an algorithm that might, inside of it, learn a bunch of physics and then give you an answer, but that's not really satisfying to us as scientists because we want to learn the physics too."

Kevin Pedro on the use of artificial intelligence for Monte Carlo simulations in particle physics (*Symmetry Magazine* 18 July).

"That finding opened a path of exploration that led, by way of numerous breakthroughs, to the discovery of the Higgs boson in 2012 – and it is still revealing new and exciting perspectives today."

Pippa Wells writing in *Nature* (19 July) on the 50th anniversary of the discovery of neutral currents by the Gargamelle experiment.

From the archive: October 1983

Big, bigger, biggest ...

Recent achievements in accelerator physics were celebrated at the 12th International Conference on High Energy Accelerators at Fermilab in August [1983], together with excitement at the birth of a project for a 20 TeV machine in the USA.

Roy Billinge gave the opening talk on achievements at CERN, where the reliable performance of all elements of the Super Proton Synchrotron SPS made proton–antiproton collisions with a centre-of-mass energy above 500 GeV possible, opening the way to the recent W and Z discoveries.

Helen Edwards reported on the success of the Fermilab Energy Doubler. Tevatron peak energy reached 700 GeV during the Conference, with an impressive ring of almost a thousand superconducting magnets operating in a 'plumber's nightmare' of a cryogenic system.

The major recommendation of the High Energy Physics Advisory Panel HEPAP was an immediate start on a high luminosity Superconducting Super Collider SSC as the number one priority in the future USA programme – nicknamed the Desertron because of the vast area necessary for its construction. Even optimistically the SSC is likely to be ten years away and there is some unease about the health of the community after a long period without new machines.

CERN Director General Herwig Schopper reported the start of civil engineering for the LEP electron–positron collider, supported with first priority by the European Committee for Future Accelerators ECFA. ECFA reasserts the importance of maintaining the quality of the SPS fixed-target and LEAR low energy antiproton ring programmes as major sources of physics data throughout the next decade and beyond, even when LEP begins operation.

● Based on text on pp299–302 of *CERN Courier* October 1983.

Compiler's note

In October 1993 the US Congress cancelled the SSC, after 23 km of the planned 87 km tunnel had been bored in Waxachie, Texas. In December 1994 the CERN Council approved the installation of a Large Hadron Collider, LHC, in the existing LEP 27 km tunnel. In 1995 the Tevatron produced the top quark. In 2008 LHC operation began, and in 2012 the Higgs boson appeared. The upgraded high-luminosity LHC is expected to deliver physics data until around 2040. Proposals for post-LHC machines include a Future Circular Collider, FCC, 91 km in circumference, to house a luminosity-frontier highest-energy lepton collider FCC-ee followed by an energy-frontier hadron collider FCC-hh, to explore physics beyond the Standard Model.

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The total number of flights completed by ESA's heavy-lift Ariane 5 spacecraft series, which carried the James Webb Space Telescope among numerous other probes into orbit between 1996 and its final flight on 5 July

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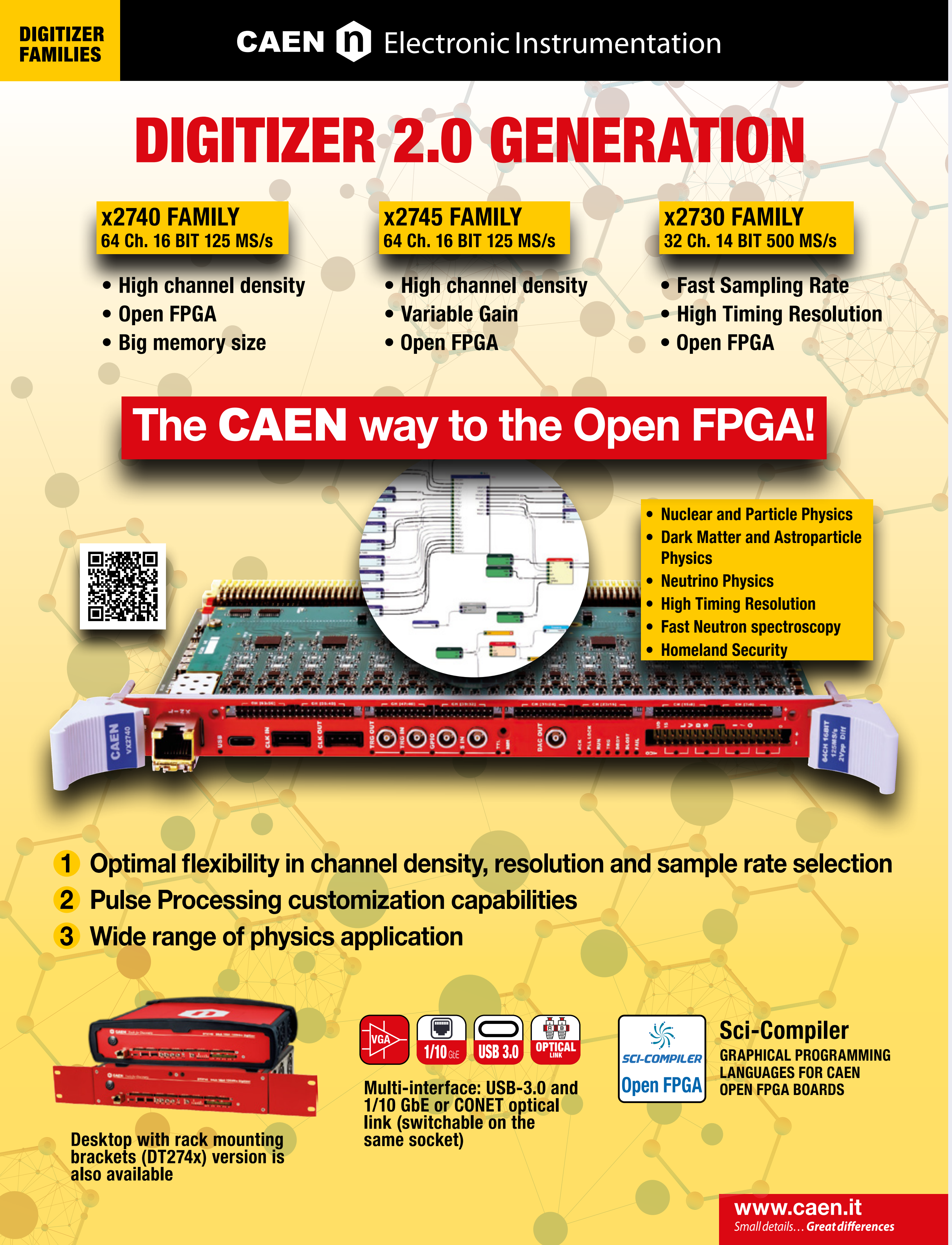
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