WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March/April 2021 issue of *CERN Courier*.

Hadron colliders have contributed to a golden era of discovery in high-energy physics, hosting experiments that have enabled physicists to unearth the cornerstones of the Standard Model. This success story began 50 years ago with CERN's Intersecting Storage Rings (featured on the cover of this issue) and culminated in the Large Hadron Collider (p38) – which has spawned thousands of papers in its first 10 years of operations alone (p47). It also bodes well for a potential future circular collider at CERN operating at a centre-of-mass energy of at least 100 TeV, a feasibility study for which is now in full swing.

Even hadron colliders have their limits, however. To explore possible new physics at the highest energy scales, physicists are mounting a series of experiments to search for very weakly interacting "slim" particles that arise from extensions in the Standard Model (p25).

Also celebrating a golden anniversary this year is the Institute for Nuclear Research in Moscow (p33), while, elsewhere in this issue: quantum sensors target gravitational waves (p10); X-rays go behind the scenes of supernova 1987A (p12); a high-performance computing collaboration forms to handle the big-physics data onslaught (p22); Steven Weinberg talks about his latest work (p51); and much more.

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Reporting on international high-energy physics

HADRON COLLIDERS
50 years of discovery

ATLAS spots rare Higgs decay • Weinberg on effective field theory • Hunting for WISPs

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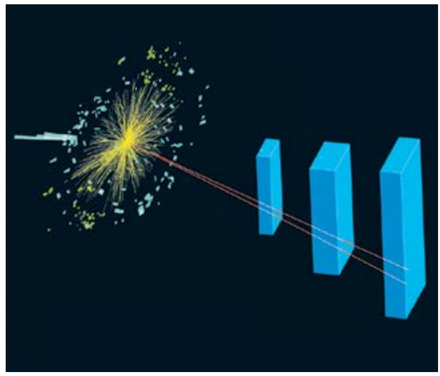

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FROM THE EDITOR

The rewards of bold thinking

Matthew Chalmers
Editor

Back in the early 1960s, as this month's cover feature describes (p38), discussion raged at CERN about the next best step for particle physics. At the time, the high-energy frontier was commanded by the great proton synchrotrons, such as Brookhaven's Cosmotron and, later, CERN's Proton Synchrotron, which drove fixed-target experiments. But a new type of machine capable of exploiting the full energy of proton beams for the production of new particles – the hadron collider – was revving up in the sidelines. In December 1965 the CERN Council approved the construction of the more technologically innovative Intersecting Storage Rings (ISR) over a very high-energy proton synchrotron, although the latter would materialise 10 years later in the Super Proton Synchrotron (SPS). The ISR's first proton–proton collisions, which reached a centre-of-mass energy of 62 GeV, took place on 27 January 1971, opening the era of hadron colliders.

From the ISR came the ingenious conversion of the SPS into a proton–antiproton collider ($\mathrm{Sp\bar{p}S}$), the demonstration of large-scale superconducting magnet technology for the Tevatron at Fermilab, and the LHC, whose elegant magnet design has enabled the highest collision energies (13 TeV) and luminosities to date. Each machine, and its increasingly complex detectors, was a step into the unknown, requiring the invention of new technologies and sharp political and organisational skills to build and operate ever larger facilities. The payoff was the discovery of the Standard Model's cornerstones: the W and Z bosons at the $\mathrm{Sp\bar{p}S}$, the top quark at the Tevatron, and the Higgs boson at the LHC. Not to be omitted from the hadron-beam collider success story are the leaps in understanding of strongly interacting matter brought about by Brookhaven's Relativistic Heavy-Ion Collider and the LHC, and the deep-inelastic scattering experiments at DESY's so-far unique electron–proton collider HERA, which revealed the proton's innards in full colour.

Half a century after the ISR's first collisions, and with at least 15 years of LHC operations still to come, particle physicists once again find themselves debating the next best step for the field. True to form, as recommended by the 2020 update of the European strategy for particle physics, CERN is exploring the most ambitious long-term technological path in undertaking a feasibility study for a future circular hadron collider with a centre-of-mass energy of at least 100 TeV. If built, the success of this mother of all hadron colliders will have each generation of previous machine and its detectors to thank.

Each machine, and its increasingly complex detectors, was a step into the unknown

Know your limits

As productive as hadron colliders are in probing nature at the highest energies, many current mysteries, such as dark matter and the origin of neutrino masses, may well originate from phenomena at energy scales inaccessible to any collider imaginable. Fortunately, models involving such scales can be tested now and in the near future by a series of experiments – some using magnets from the LHC and HERA in fact – searching for very weakly interacting "slim" particles that arise in extensions of the Standard Model (see p25). Effective field theory is another powerful tool to pursue such signals from far beyond the TeV scale, explains Steven Weinberg in this issue's interview (p51).


CERN-PHOTO-201802-030-9

Discovery machine *The LHC.*

Meanwhile at CERN: ATLAS reports the first evidence for a rare "Dalitz" decay of the Higgs boson (p17); pulsed-mode anti-hydrogen paves the way to test antimatter in free fall (p7); and the CLOUD experiment reveals a new mechanism that could accelerate the loss of Arctic sea ice (p9). Elsewhere in this issue: quantum sensors target gravitational waves (p10); X-rays go behind the scenes of supernova 1987A (p12); a high-performance computing collaboration forms to handle the big-physics data onslaught (p22); new twists in the ATOMKI tale (p74); and more.

Reporting on international high-energy physics

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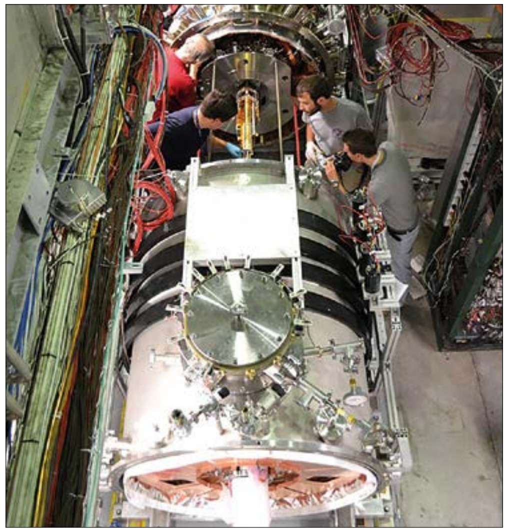
NEWS ANALYSIS

Antimatter

AEgIS on track to test free fall of antimatter

The AEgIS collaboration at CERN's Antiproton Decelerator (AD) has reported a milestone in its bid to measure the gravitational free fall of antimatter – a fundamental test of the weak equivalence principle. Using a series of techniques developed in 2018, the team demonstrated the first pulsed production of antiatoms, which allows the time at which the antiatoms are formed to be known with high accuracy. This is a key step in determining "g" for antimatter.

"This is the first time that pulsed formation of antihydrogen has been established on timescales that open the door to simultaneous manipulation, by lasers or external fields, of the formed atoms, as well as to the possibility of applying the same method to the pulsed formation of other antiprotonic atoms," says AEgIS spokesperson Michael Doser of CERN. "Knowing the moment of antihydrogen formation is a powerful tool."


CERN

Heavy stuff *The AEgIS experiment is built around two powerful superconducting solenoids each housing a Malmberg–Penning trap.*

General relativity's weak equivalence principle holds that all particles with the same initial position and velocity should follow the same trajectories in a gravitational field. It has been verified for matter with an accuracy approaching 10^{-14}. Since theories beyond the Standard Model such as supersymmetry, or the existence of Lorentz-symmetry violating terms, do not necessarily lead to an equivalent force on matter and antimatter, finding even the slightest difference in g could reveal the presence of quantum effects in the gravitational arena. Indirect arguments constrain possible differences to below 10^{-6} g, but no direct measurement for antimatter has yet been performed due to the difficulty in producing and containing large quantities of it.

Antihydrogen's neutrality and long lifetime make it an ideal system in which to test this and other fundamental laws, such as CPT invariance. The first production of low-energy antihydrogen, reported in 2002 by the ATHENA and ATRAP collaborations at the AD, involved a three-body recombination reaction ($e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+$) involving clouds of antiprotons and positrons. Since then, steady progress by the AD's ALPHA collaboration in producing, manipulating and trapping ever larger quantities of antihydrogen has enabled spectroscopic and other properties of antimatter to be determined in exquisite detail (*CERN Courier* March 2018 p30).

Whereas three-body recombination results in an almost continuous antihydrogen source, in which it is not possible to tag the time of the antiatom formation, AEgIS has employed an alternative charge-exchange process between trapped and cooled antiprotons and positronium (a e^+e^- bound system). Bursts of positrons are accelerated and then implanted into a nano-channelled silicon target above an electromagnetic trap containing cold antiprotons, where, with the aid of laser pulses, they produce a cloud of excited positronium a few millimetres across. This can lead to the formation of antihydrogen within sub-μs timescales, the moment of production being defined by the well-known laser firing time and the transit time of positronium toward the antiproton cloud. Since the antihydrogen is not trapped in the apparatus, it drifts in all directions until it annihilates on the surrounding material, producing pions and photons that are detected by a scintillating array read out by photomultipliers. The scheme allows the time at which 90% of the atoms are produced to be determined with an uncertainty of around 100 ns.

Further steps are required before the measurement of g can begin, explains Doser. These include the formation of a pulsed beam, greater quantities of antihydrogen, and the ability to make it colder. "With only three months of beam time this year, and lots of new equipment to commission, most likely 2022 will be the year in which we establish pulsed-beam formation, which is a prerequisite for us to perform a gravity measurement."

ALPHA, AEgIS and GBAR are all targeting a measurement of g at the 1% level in the coming years

Targeted approach

Following a proof-of-principle measurement of g for antihydrogen by the ALPHA collaboration in 2013, ALPHA, AEgIS and a third AD experiment, GBAR, are all targeting a measurement of g at the 1% level in the coming years. In contrast to AEgIS's approach, whereby the vertical deviation of a pulsed horizontal beam of cold antihydrogen atoms will be measured in an approximately 1 m-long flight tube, GBAR will take advantage of advances in ion-cooling techniques to measure ultra-slow antihydrogen atoms as they fall from a height of 20 cm. ALPHA, meanwhile, will release antihydrogen atoms from a vertical magnetic trap and measure the distribution of annihilation positions when they hit the wall – ramping the trap down slowly so that the coldest atoms, which are most sensitive to gravity, come out last. All three experiments have recently been hooked up to the AD's ELENA synchrotron, which enables the production of very low-energy antiprotons (*CERN Courier* December 2016 p16).

Given that most of the mass of antinuclei comes from massless gluons that bind their constituent quarks, physicists think it unlikely that antimatter experiences an opposite gravitational force to matter and therefore "falls up". Nevertheless, precise measurements of the free fall of antiatoms could reveal subtle differences that would open an important crack in our current understanding.

Further reading

C Amsler *et al.* 2021 *Commun. Phys.* **4** 19.

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CLOUD EXPERIMENT

Iodine aerosol production could accelerate Arctic melting

Researchers at CERN’s CLOUD experiment have uncovered a new mechanism that could accelerate the loss of Arctic sea ice. In a paper published in *Science* on 5 February, the team showed that aerosol particles made of iodic acid can form extremely rapidly in the marine boundary layer – the portion of the atmosphere that is in direct contact with the ocean. Aerosol particles are important for the climate because they provide the seeds on which cloud droplets form. Marine new-particle formation is especially important since particle concentrations are low and the ocean is vast. However, how new aerosol particles form and influence clouds and climate remain relatively poorly understood.

“Our measurements are the first to show that the part-per-trillion-by-volume iodine levels found in marine regions will lead to rapid formation and growth of iodic acid particles,” says CLOUD spokesperson Jasper Kirkby of CERN, adding that the particle formation rate is also strongly enhanced by ions from galactic cosmic rays. “Although most atmospheric particles form from sulphuric acid, our study shows that iodic acid – which is produced by the action of sunlight and ozone on molecular iodine emitted by the sea surface, sea ice and exposed seaweed – may be the main driver in pristine marine regions.”

Patrick Kelley, U.S. Coast Guard

Positive feedback *Global iodine emissions at high latitudes have increased threefold during the past seven decades and are likely to continue to increase in the future as sea ice becomes thinner.*

CLOUD is a one-of-a kind experiment that uses an ultraclean cloud chamber to measure the formation and growth of aerosol particles from a mixture of vapours under precisely controlled atmospheric conditions, including the use of a high-energy beam from the Proton Synchrotron to simulate cosmic rays up to the top of the troposphere. Last year, the team found that small inhomogeneities in the concentrations of ammonia and nitric acid can have a major role in driving winter smog episodes in cities (*CERN Courier* July/August 2020 p10). The latest result is similarly important but in a completely different area, says Kirkby.

“In polar regions, aerosols and clouds have a warming effect because they absorb infrared radiation otherwise lost to space and then radiate it back down to the surface, whereas they reflect no more incoming sunlight than the snow-covered surface. As more sea surface is exposed by melting ice, the increased iodic acid aerosol and cloud-seed formation could provide a previously unaccounted positive feedback that accelerates the loss of sea ice. However, the effect has not yet been modelled so we can’t quantify it yet.”

Further reading

X-C He *et al.* 2021 *Science* **371** 589.

JINR

NICA booster achieves first beam

After seven years of construction at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, the Booster synchrotron at the brand-new NICA (Nuclotron-Based Ion Collider Facility) Complex has accelerated its first beam. On 19 December helium ions were injected into the synchrotron and a stable circulation of the beam was obtained at an energy of 3.2 MeV, a milestone towards NICA’s scheduled completion in 2022.

NICA will allow studies of the properties of nuclear matter in the region of maximum baryonic density. By colliding heavy gold ions at energies corresponding to the deconfinement phase transition (4.5 GeV), NICA will access the transition of the quark–gluon plasma into hadrons, complementing studies at higher energy colliders such as the LHC.

JINR

Megascience *A bird’s eye view of the NICA complex in November.*

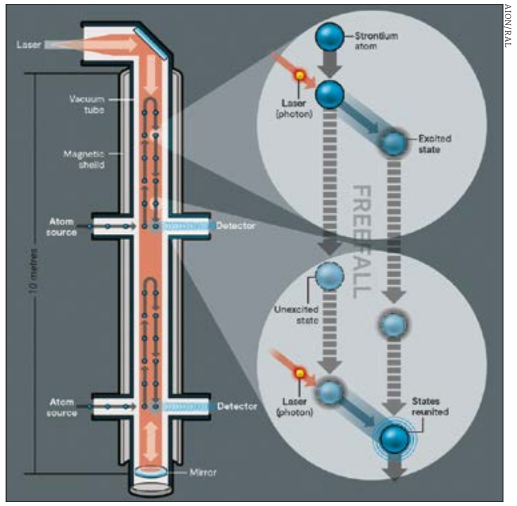
The NICA booster is a 211 m circumference superconducting synchrotron that will accelerate beams to 500 MeV. It uses 2.2 m-long dipole and quadrupole magnets made up of a window-frame iron yoke and a winding made of a hollow niobium-titanium superconducting cable cooled with a two-phase helium flow. Beams will then be transported to a separate ring surrounding the booster, the “nuclotron”, and accelerated to the GeV range. Finally, beams will be injected into two identical 503 m storage rings, which will collide the beams at two detectors: the Multi-Purpose Detector, designed to study dense baryonic matter; and the Spin-Physics Detector, designed to study collisions between polarised beams of protons and deuterons.

The complex is one of six Russian “megascience” facilities that are part of the CREMLIN project, which aims to use large-scale science to improve and strengthen relations and networks between European and Russian research infrastructures. The CREMLIN consortium comprises 19 European and Russian research infrastructures, including CERN and DESY. Other proposed “megascience” facilities included in this project are the Super-Charm-Tau Factory at the Budker Institute of Nuclear Physics, and the Special-purpose Synchrotron-Radiation Source (SSRS-4) at the NRC Kurchatov Institute.

“This is a historic moment for our laboratory and a great milestone in the realisation of our flagship megascience project – we have to thank the CREMLIN grant programme for helping us in these challenges,” says Vladimir Kekelidze, the NICA project leader.

QUANTUM TECHNOLOGIES

Quantum sensing for particle physics



AION/RAL

Physics in the pipeline *AION's initial 10 m stage is hoped to be followed by 100 m and km-scale facilities.*

A particle physics-led experiment called AION (Atomic Interferometric Observatory and Network) is one of several multidisciplinary projects selected for funding by the UK's new Quantum Technologies for Fundamental Physics programme. The successful projects, announced in January following a £31 million call for proposals from UK Research and Innovation (UKRI), will exploit recent advances in quantum technologies to tackle outstanding questions in fundamental physics, astrophysics and cosmology.

UKRI and university funding of about £10 million (UKRI part £7.2 million) will enable the AION team to prepare the construction of a 10 m-tall atomic interferometer at the University of Oxford to explore ultra-light dark matter and provide a pathway towards detecting gravitational waves in the unexplored mid-frequency band ranging from several mHz to a few Hz. The setup will use lasers to drive transitions between the ground and excited states of a cloud of cold strontium atoms in free fall, effectively acting as beam splitters and mirrors for the atomic de Broglie waves (see figure). Ultralight dark matter and exotic light bosons would be expected to have differential effects on the atomic transition frequencies, while a passing gravitational wave would generate a strain in the space through which the atoms fall freely. Either would create a difference between the phases of atomic beams following different paths – the greater their separations, the greater the sensitivity of the experiment.

"AION is a uniquely interdisciplinary mission that will harness cold-atom quantum technologies to address key issues in fundamental physics, astrophysics and cosmology that can be realised in the next few decades," says AION principal investigator Oliver Buchmueller of Imperial College London, who is also a member of the CMS collaboration. "The AION project will also significantly contribute to MAGIS, a 100 m-scale partner experiment being prepared at Fermilab, and we are exploring the possibility of utilising a shaft in the UK or at the LHC for a similar second 100 m detector."

Six other quantum-technology projects involving UK institutes are under way thanks to the UKRI scheme. One, led by experimental particle physicist Ruben Saakyan of University College London, will use ultra-precise B-field mapping and microwave spectrometry to determine the absolute neutrino mass in tritium beta-decay beyond the 0.2 eV sensitivity projected for the KATRIN experiment. Others include the use of new classes of detectors and coherent quantum amplifiers to search for hidden structure in the vacuum state; the development of ultra-low-noise quantum electronics to underpin searches for axions and other light hidden particles; quantum simulators to mimic the extreme conditions of the early universe and black holes; and the development of quantum-enhanced superfluid technologies for cosmology.

The UKRI call is part of a global effort to develop quantum technologies that could bring about a "second quantum revolution". Several major international public and private initiatives are under way. Last autumn, CERN launched its own quantum technologies initiative (*CERN Courier* September/October 2020 p47).

"With the application of emerging quantum technologies, I believe we have an opportunity to change the way we search for answers to some of the biggest mysteries of the universe," said Mark Thomson, executive chair of the UK's Science and Technology Facilities Council. "These include exploring what dark matter is made of, finding the absolute mass of neutrinos and establishing how quantum mechanics fits with gravity."

NEUTRINOS

Farewell Daya Bay, hello JUNO

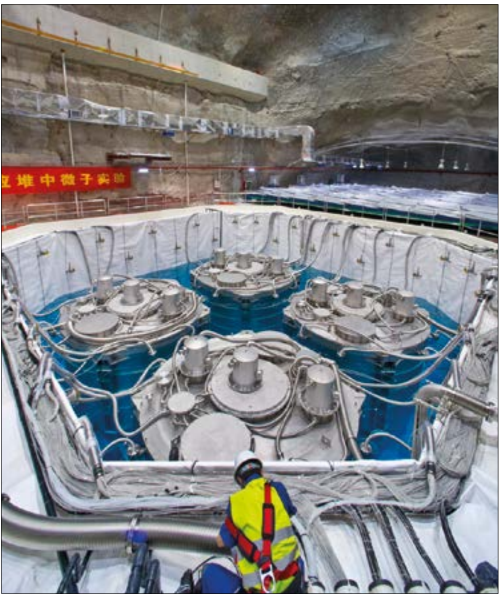
Daya Bay has had a transformative effect on Chinese particle physics

In October 2007, neutrino physicists broke ground 55 km north-east of Hong Kong to build the Daya Bay Reactor Neutrino Experiment. Comprising eight 20-tonne liquid-scintillator detectors sited within 2 km of the Daya Bay nuclear plant, its aim was to look for the disappearance of electron antineutrinos as a function of distance to the reactor. This would constitute evidence for mixing between the electron and the third neutrino mass eigenstate, as described by the parameter θ_{13}. Back then, θ_{13} was the least well known angle in the Pontecorvo–Maki–Nakagawa–Sakata matrix, which quantifies lepton mixing, with only an upper limit available. Today, it is the best known angle by some margin, and the knowledge that it is nonzero has opened the door to measuring leptonic CP violation at long-baseline accelerator-neutrino experiments.

Daya Bay was one of a trio of experiments located in close proximity to nuclear reactors, along with RENO in South Korea and Double Chooz in France, which were responsible for this seminal measurement. Double Chooz published the first hint that θ_{13} was nonzero in 2011, before Daya Bay and RENO established this conclusively the following spring. The experiments also failed to dispel the reactor-antineutrino anomaly, whereby observed neutrino fluxes are a few percent lower than calculations predict. This has triggered a slew of new experiments located mere metres from nuclear-reactor cores, in search of evidence for oscillations involving additional, sterile light neutrinos. As the Daya Bay experiment's detectors are dismantled, after almost a decade of data taking, the three collaborations can reflect on the rare privilege of having pencilled the value of a previously unknown parameter into the Standard- Model Lagrangian.

Founding Daya Bay co-spokesperson Yi-Fang Wang says the experiment has had a transformative effect on Chinese particle physics, emboldening the country to explore major projects such as a circular electron–positron collider. "One important lesson we learnt from Daya Bay is that we should just go ahead and do it if it is a good project, rather than waiting until everything is ready. We convinced our government that we could do a great job, that world-class jobs need to be international, and that particle physics is fundamental and influential, and deserves to be supported."

The experiment has also paved the way for China to build a successor, the Jiangmen Underground Neutrino Observatory (JUNO), for which Wang is now spokesperson. JUNO will tackle the neutrino mass hierarchy – the question of whether the third neutrino mass eigenstate is the most or least massive of the three. An evolution of Daya Bay, the new experiment will also measure a deficit of electron antineutrinos, but at a distance of 53 km, seeking to resolve fast and shallow oscillations that are expected to differ depending on the neutrino mass hierarchy (*CERN Courier* July/August 2020 p32). Excavation of a cavern for the 20 kilotonne liquid-scintillator detector 700 m beneath the Dashi hill in Guangdong was completed at the end of 2020. The construction of a concrete water pool is the next step.



R Kaltschmidt/Berkeley Lab

Transformative *Antineutrino detectors submerged in ultrapure water at one of Daya Bay's experimental sites.*

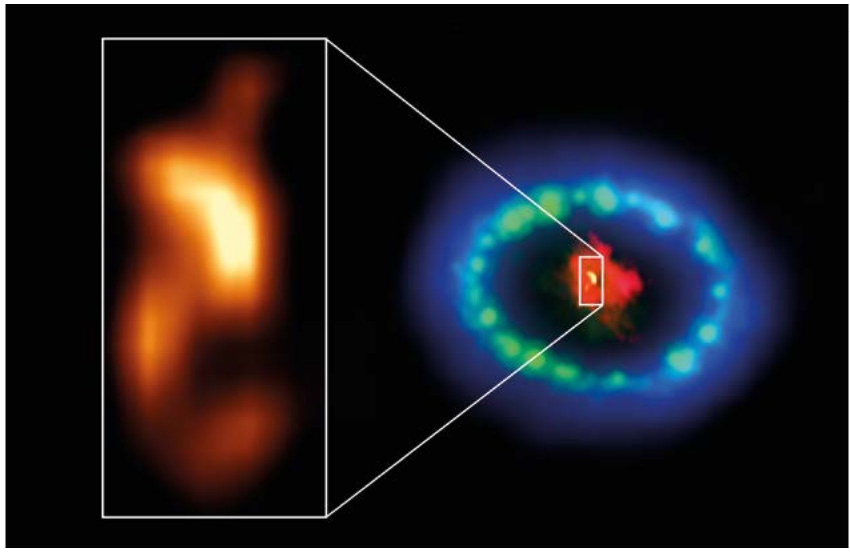
The detector concept that the three experiments used to uncover θ_{13} was designed by the Double Chooz collaboration. Thierry Lasserre, one of the experiment's two founders, recalls that it was difficult, 20 years ago, to convince the community that the measurement was possible at reactors. "It should not be forgotten that significant experimental efforts were also undertaken in Angra dos Reis, Braidwood, Diablo Canyon, Krasnoyarsk and Kashiwazaki," he says. "Reactor neutrino detectors can now be used safely, routinely and remotely, and some of them can even be deployed on the surface, which will be a great advantage for non-proliferation applications." The next steps in reactor-neutrino physics, he explains, will now involve an extraordinary miniaturisation to cryogenic detectors as small as 10 grams, which take advantage of the much larger cross section of coherent neutrino scattering.

Astrowatch

Lifting the veil on supernova 1987A

On 23 February 1987 astronomers around the world saw an extremely bright supernova, now called SN1987A. It was the closest supernova observed for over 300 years and was visible to the naked eye. The event was quickly confirmed to be the result of the collapse of "Sanduleak −69 202", a blue supergiant star in the Large Magellanic Cloud. As the first nearby supernova in the era of modern astronomy, SN1987A remains one of the most monitored objects in the sky. Apart from confirming several important theories, such as radioactive decay being the source of the observed optical emission, the supernova also raised a number of questions that remain unanswered. The most important is: where is the remnant of the progenitor star?

Despite several false detection claims in the past, evidence is mounting that Sanduleak −69 202 collapsed into a neutron star that is becoming more visible as the dust around it starts to settle. A new analysis by researchers in Italy and Japan based on high-energy X-ray data from the Chandra and NuSTAR space telescopes adds the latest support to this idea.



ALMA; NRAO/AUI/NSF; NASA/ESA

Missing link *A hot "blob" (inset) revealed by X-rays in the dusty core of SN1987A could be the location of the missing neutron star formed by the collapse of its progenitor star. The red area shows dust and cold gas observed at radio wavelengths by ALMA; the green and blue hues, recorded by Hubble and Chandra, show the collision between the expanding shock wave and material around the supernova.*

Even before the optical light from SN1987A was detected, several neutrino detectors around the world saw a burst of neutrinos. The brightest one was observed by Japan's Kamiokande II detector, which detected a total of 12 antineutrinos approximately three hours before the first optical light reached Earth. The detection of antineutrinos seemed to confirm theoretical predictions for a star the size of Sanduleak −69 202: namely that it should collapse into a neutron star, and emit large numbers of neutrinos while doing so. The optical light arrives later because it is only produced when the shock waves from the collapse reach the surface of the star. Since the newly formed neutron star would be expected to emit large amounts of energy at various wavelengths, one might assume it would be relatively easy to detect. However, no signs were found in follow-up searches over the past three decades, leading to much speculation about the fate of this star and its surrounding medium.

The first signs of the stellar remnants of SN1987A came from radio observations by the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile in 2019. A group led by Phil Cigan from Cardiff University in the UK used ALMA data at various frequencies to study the core of SN1987A. Close to the centre, they found a bright "blob" structure, the emission from which appeared to be compatible with radio emission from particles accelerated by a neutron star, also called a pulsar wind nebula. Although the researchers could not exclude local heating from ^{44}Ti produced during the supernova as the source, the results provided the first hint that the blob houses a young neutron star.

Wind power

Inspired by the ALMA results, Emanuele Greco from the University of Palermo and coworkers started to study the same region using X-ray data from Chandra and NuSTAR taken during 2012, 2013 and 2014. They found that the detected soft X-ray emission (0.5–8 keV) was compatible with thermal emission produced in the remnant shock waves of the supernova event with the circumstellar medium. However, at higher energies (10–20 keV) the emission was clearly non-thermal in nature. Describing their findings in a preprint posted in January, the group studied the two possible sources for such emission: synchrotron emission from a pulsar wind nebula and synchrotron emission produced in shock waves in the region. Whereas models for both ideas fit the spectral data, the pulsar wind nebula is favoured because the shock emission would not be expected to look like this for such a young remnant.

The results provided the first hint that the blob houses a young neutron star

The reason why this neutron star has escaped previous observations in optical or soft X-ray energies is likely absorption by cold dust emitted during the supernova, which appears to still absorb a large part of the synchrotron emission observed in X-rays, especially at lower energies. But the dust is expected to start to heat up during the coming decades, thereby becoming transparent to lower energy emission. Greco and colleagues predict that, if the emission is indeed induced by a neutron star, it will become visible in the soft X-ray regime by 2030 with Chandra.

Although astronomers have just two observational hints that Sanduleak −69 202 did, as it should according to theory, collapse into a neutron star, it appears that after 34 years of searching we will finally understand what happened in SN1987A.

Further reading

P Cigan *et al.* 2019 *ApJ* **886** 51.

E Greco *et al.* 2021 arXiv:2101.09029 (accepted by *ApJL*).

NEWS DIGEST


CERN-PHOTO-202101-011-5

BASE's Jack Devlin alongside the experiment's superconducting magnet.

Unorthodox ALP antenna
The Baryon Antibaryon Symmetry Experiment (BASE) collaboration at CERN's Antiproton Decelerator has demonstrated an ingenious new way to search for axion-like particles (ALPs, see p25). The team looked for unexpected electrical signals in doughnut-shaped superconducting coils that are usually used to precisely measure the oscillation frequencies of individual trapped antiprotons. Faint signals, which might easily be mistaken for noise, could in fact be caused by ALPs interacting with the strong magnetic field of the Penning trap. The collaboration set a new upper laboratory limit for the coupling between photons and ALPs within a narrow mass range around 2.79 neV, demonstrating the feasibility of using Penning traps to search for cold dark matter (*Phys. Rev. Lett.* **126** 041301).

Dark-age detectors
Valerie Domcke (CERN) and Camilo Garcia-Cely (DESY) have proposed using radio telescopes to detect high-frequency gravitational waves (GWs) from the "dark ages" – the period in the early universe between atoms forming and stars igniting (*Phys. Rev. Lett.* **126** 021104). As a result of embedding classical electrodynamics in general relativistic spacetime, it is expected that GWs can be converted into photons in the presence of magnetic fields, leading to a distortion of the cosmic microwave background. Data from the Square Kilometre Array, which may begin construction in South Africa and Australia as early as this year, could allow the detection of GWs with frequencies in the MHz and GHz regime, far beyond the reach of LIGO, VIRGO or KAGRA, write the pair.

Industrial innovation
DESY virtually kicked-off a new "innovation factory" late last year, allowing detailed planning for the building's infrastructure to begin. The facility will offer laboratories and spaces for start-ups, scientists and established corporations, in the hope of building strong ties between research and industry. Construction is proposed to begin in 2023, with completion aimed for 2025. Science City Bahrenfeld, a new district in Hamburg, Germany, where the facility will be built, is also home to DESY's PETRA III synchrotron X-ray source.

Cosmic rays get weirder
Results from the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station have thrown up another surprise that may shed light on the processes that create and accelerate cosmic rays. Last year, the collaboration reported unexpected differences in the rigidity (momentum divided by charge) dependence of the primary-cosmic-ray spectra of light elements (helium, carbon and oxygen) and heavy elements (neon, magnesium and silicon). A newly published measurement of the spectrum of iron – the rarest and heaviest cosmic ray to be characterised so far – unexpectedly resembles the light elements more than the heavier ones (*Phys. Rev. Lett.* **126** 041104). "Iron is an atomic-number frontier that won't be crossed for years to come," said AMS-02 spokesperson Sam Ting.


NASA

The AMS-02 detector.

Snowmass postponed
The summer study of the 2021 Snowmass exercise has been postponed one year to July 2022, due to the ongoing COVID-19 pandemic. The community exercise, which will plot a course for US particle physics over the coming decade, was originally planned for this summer. First convened in 1982 in the Colorado mountain resort of the same name, Snowmass studies have been produced on numerous occasions throughout the years, most recently in 2013. More than 1500 letters of intent – an unusually large number – have already been submitted across 10 "Snowmass frontiers", from the energy frontier to community engagement.

Novel collider concept
Peking University physicists urge the community to consider the merits of a novel electron-muon collider (arXiv:2010.15144). Collisions between different species of lepton could reduce physics backgrounds for studies of charged-lepton flavour violation and Higgs-boson properties, and the asymmetric nature of the collisions could be used to control troublesome backgrounds caused by muon decays inside the accelerator, argue the authors. The preprint proposes 10 GeV electron and muon beams initially, and upgrades culminating in a TeV-scale muon-muon collider.

32 is not a magic number
A study at CERN's ISOLDE facility has exposed shortcomings in the best nuclear models, which cannot reconcile recent measurements of neutron-rich nuclei. 32 had been thought to be a "magic" number of neutrons that completes a nuclear shell and results in a slimmer nucleus with a greater binding energy than its neighbours. However, researchers using the Collinear Resonance Ionisation Spectroscopy apparatus found that potassium-52, which has 33 neutrons, was not observably fatter than the supposedly magic potassium-51, which boasts 19 protons and 32 neutrons (*Nat. Phys.* doi:10.1038/s41567-020-01136-5).

Rival probes approach Mars
As the *Courier* went to press, probes from the United Arab Emirates (UAE), China and the US were approaching the Red Planet – a testament to the growing desire of many nations to develop space technology and explore the solar system. The UAE's *Hope* – the Arab world's first interplanetary spacecraft – will remain in orbit and make the first map of Mars' surprisingly sparse atmosphere. China's *Tianwen-1* will study the planet for several months before dropping a lander, potentially making China only the second nation in the world to successfully land a robot vehicle on another world, after the US. The US rover *Perseverance* will descend to the planet's surface in search of signs of habitability and evidence of microbial life.


CNSA/PEC

The first image of Mars sent by China's Tianwen-1 *probe.*

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Evidence for Dalitz decays of the Higgs

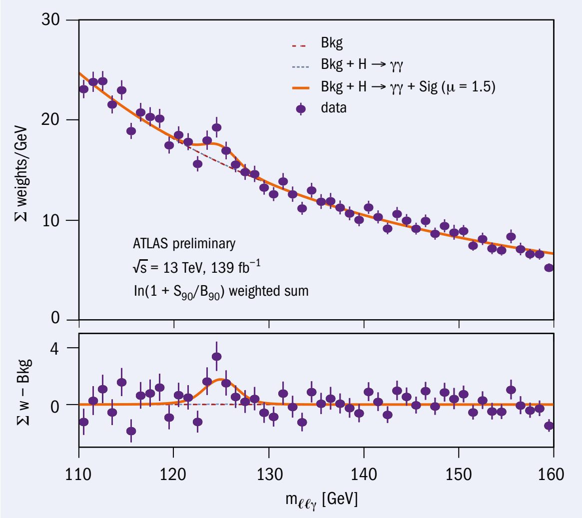
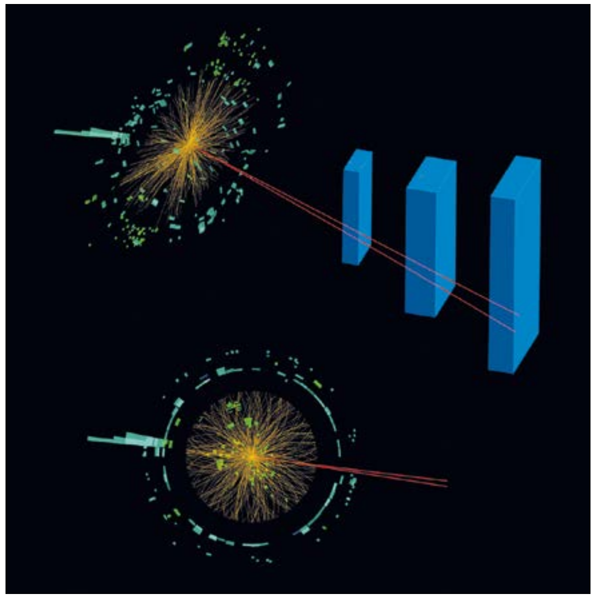


Fig. 1. *Invariant mass of the $\ell\ell\gamma$ system, with every data event contributing a category-dependent weight representing the expected sensitivity of the $H \to \ell\ell\gamma$ signal. The data are shown as purple dots, while the lines show the signal and background functions as obtained by a fit.*



Rare decay *A candidate $H \to \mu^+\mu^-\gamma$ decay in the ATLAS detector.*

Evidence for the decay of the Higgs boson to a photon and a low-mass electron or muon pair, propagated predominantly by a virtual photon (γ^*), $H \to \gamma^*\gamma \to \ell\ell\gamma$, has been obtained at the LHC. In a recent conference note, the ATLAS collaboration reports a 3.2σ excess over background of $H \to \ell\ell\gamma$ decay candidates with dilepton mass $m_{\ell\ell} < 30$ GeV.

The measurement of rare decays of the Higgs boson is a crucial component of the Higgs-boson physics programme at the LHC, since they probe potential new interactions with the Higgs boson introduced by possible extensions of the Standard Model. The $H \to \ell\ell\gamma$ "Dalitz" decay is particularly interesting in this respect as it is a loop process and the three-body final state allows the CP structure of the Higgs boson to be probed. However, the small expected signal-to-background ratio and the typically low dilepton invariant mass make the search for $H \to \ell\ell\gamma$ highly challenging.

> **Measurement of rare decays of the Higgs boson is a crucial component of the Higgs-boson physics programme at the LHC**

The analysis performed by ATLAS searched for $H \to e^+e^-\gamma$ and $H \to \mu^+\mu^-\gamma$ decays. Special treatment was needed in particular for the electron channel: a dedicated electron trigger was developed as well as a specific identification algorithm. The predicted $m_{\ell\ell}$ spectrum rises steeply towards lower values, with a kinematic cutoff at twice the final-state lepton mass. At such low electron–positron invariant masses, and given the large transverse momentum of their system, the electromagnetic showers induced by the electron and the positron in the ATLAS calorimeter can merge, requiring a specially developed reconstruction. Furthermore, a dedicated identification algorithm was developed for these topologies, and its efficiency was measured in data using photon detector-material conversions at low radius into an electron–positron pair from $Z \to \ell\ell\gamma$ events.

The signal extraction is performed by searching in the $\ell\ell\gamma$ invariant mass ($m_{\ell\ell\gamma}$) range between 110 and 160 GeV for a narrow signal peak over smooth background at the mass of the Higgs boson. The sensitivity to the $H \to \ell\ell\gamma$ signal was increased by separating events in mutually exclusive categories based on lepton types and event topologies. ATLAS reports evidence in data for a $H \to \ell\ell\gamma$ signal emerging over the background with a significance of 3.2σ (see figure). The Higgs boson production cross-section times $H \to \ell\ell\gamma$ branching fraction, measured for $m_{\ell\ell} < 30$ GeV, amounts to $8.7^{+2.8}_{-2.7}$ fb. It corresponds to a signal strength – the ratio of the measured cross section times branching fraction to the Standard Model prediction – of 1.5 ± 0.5. Meanwhile, ATLAS has also extended the invariant-mass range of the lepton pair for the related Higgs-boson decay into a photon and a Z boson to lower masses, opening the door to future studies of three-body Higgs-boson decays and investigations of its underlying CP structure.

Further reading

ATLAS Collab. 2021 ATLAS-CONF-2021-002.
ATLAS Collab. 2020 *Phys. Lett. B* **809** 135754.

CMS

Deep learning tailors supersymmetry searches

Supersymmetry is a popular extension of the Standard Model (SM) that has the potential to resolve several open questions in particle physics. As a result of a postulated new symmetry between fermions and bosons, the theory predicts a "superpartner" for each SM particle. The lightest of these new particles could be what makes up dark matter, while additional new superpartners could resolve the question of why the Higgs boson has a relatively low mass. Many searches for supersymmetry have already been performed by the ATLAS and CMS collaborations, but most have focused on strongly interacting superpartners that could be very heavy. It is possible, however, that electroweak production of supersymmetric particles is the dominant or only source of superpartners accessible at the LHC.

The unprecedented data volume of LHC Run 2 provides a unique opportunity to search for rare processes such as electroweak production of supersymmetric particles. A recent result from the CMS collaboration uses the Run-2 dataset to search for the superpartners of the electroweak bosons, called charginos and neutralinos. Events with three or more charged leptons, or two leptons of the same charge, were analysed. Such events are relatively rare in the SM, and, if they exist, charginos and neutralinos are predicted to create an excess of events with these topologies. Supersymmetric events are also expected to have an apparent imbalance in transverse momentum, because the lightest supersymmetric particle should evade detection. Correlations between the multiple leptons in the events, and between the leptons and the momentum imbalance, can be used to define a set of discriminating variables sensitive to chargino and neutralino production. These variables are used to assign the selected events into several search regions that address different possible signals of the production and decay of supersymmetric particles. Making such a multivariate binning optimal in every corner of phase-space, and for any possible manifestation of supersymmetry, is a challenging task.

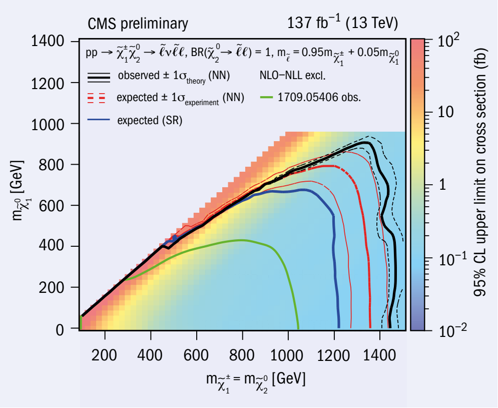


Fig. 1. *Observed and expected exclusion limits for a model of electroweak supersymmetry with slepton-mediated chargino and neutralino decays. Results using neural networks (NN) are compared with the expected limits based on the search-region (SR) approach, and the previous CMS analysis (green).*

Events with three electrons and/or muons provide the bulk of the sensitivity by striking the best balance between signal purity and yields. A novel search approach is used that aims at better capturing the complexity of the events than is possible using predetermined search regions: parametric machine learning. The aim is to achieve the maximum sensitivity for any parameter choice nature might have made, as supersymmetry is not one model, but a class of models. Variations in the masses of the superpartners can substantially modify the observable signatures. Parametric neural networks were trained to find charginos and neutralinos with the unknown mass parameters added as input variables to the training. The network can evaluate the data at fixed values of the mass parameters, effectively performing a dedicated search for a signal with given masses in the data (figure 1).

The parametric neural network, together with a new optimised event binning of the other event categories, makes this analysis the most powerful search for charginos and neutralinos carried out by the CMS collaboration so far. The neural network alone results in a sensitivity boost that ranges from 30% to more than 100%. Substantial improvements occur for models where the decay of the charginos and neutralinos are mediated by the superpartners of leptons. The improvements become even larger when the mass splitting between sleptons and the chargino is relatively small. The data show no evidence for electroweak superpartner production, and chargino masses up to 1450 GeV, compared to 1150 GeV in earlier CMS searches for this scenario, are excluded at 95% confidence.

Further reading

CMS Collab. 2021 CMS-PAS-SUS-19-012.

LHCb

Precision leap for B^0_s fragmentation and decay

How likely is it for a b quark to partner itself with an s quark rather than a light d or u quark? This question is key for understanding the physics of fragmentation and decay following the production of a b quark in proton–proton collisions. In addition, the number of B^0_s mesons to be produced, formed by a pair of b and s quarks, is required for measuring its decay probabilities, most notably to final states that are sensitive to physics beyond the Standard Model, such as the $B^0_s \to \mu^+\mu^-$ decay.

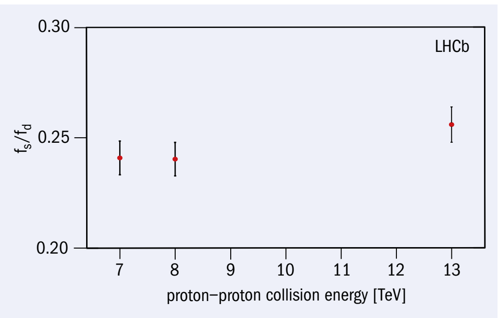


Fig. 1. *The fraction of B^0_s mesons to be produced, relative to the number of B^0 mesons, is shown as a function of the proton–proton collision energy.*

The knowledge of f_s/f_d – the ratio of the fragmentation fraction of a b quark to a B^0_s or a B^0 meson – is thus a key parameter at the LHC. So far it has been measured with limited precision and has been the dominant systematic uncertainty for most B^0_s branching fractions. Now, however, the LHCb collaboration has, in a recent publication, combined the efforts of five different analyses with information on this ▷ parameter. The f_s/f_d ratio was measured in previous publications through semi-leptonic decays, hadronic decays with D mesons and hadronic decays with J/ψ mesons in the final state. Some of these measurements are only sensitive to the product of the fragmentation fraction and the branching fractions. This new work analyses these results simultaneously, obtaining a precise measurement of f_s/f_d as well as branching fraction measurements of two important decays, $B^0_s \to D^-_s \pi^+$ and $B^0_s \to J/\psi\,\phi$. These are golden channels for mixing and CP violation measurements in the B^0_s sector.

The results reduce the uncertainty on f_s/f_d by roughly a factor of two for collisions at 7 TeV, and a factor of 1.5 for collisions at 13 TeV, yielding a precision of about 3%. They also confirm the dependence of f_s/f_d on the transverse momentum of the B^0_s meson, and indicate a slight dependence on the centre-of-mass energy of proton–proton collisions (figure 1). The results are used in this work to update the previous branching-fraction measurements of about 50 different B^0_s decay channels, significantly improving their precision, and boosting several searches for new physics.

The results reduce the uncertainty on f_s/f_d by roughly a factor of two, yielding a precision of about 3%

Further reading

LHCb Collab. 2021 LHCb-PAPER-2020-046.

ALICE

ALICE shines light inside lead nuclei

An ultra-relativistic electromagnetically charged projectile carries a strongly contracted field that can be thought of as a flux of quasi-real photons. This is known as the equivalent-photon approximation, and was proposed by Fermi and later developed by Weizsäcker and Williams. In practice, this means that the proton or lead (Pb) beams of the LHC, moving at ultra-relativistic energies, also carry a quasi-real photon beam, which can be used to look inside protons or nuclei. The ALICE collaboration is in this way using the LHC as a photon–hadron collider, shining light inside lead nuclei to measure the photoproduction of charmonia and provide constraints on nuclear shadowing.

The intensity of the electromagnetic field, and the corresponding photon flux, is proportional to the square of the electric charge. This type of interaction is therefore greatly enhanced in the collisions of lead ions (Z = 82). Ultra-peripheral collisions (UPCs), in which the impact parameter is larger than the sum of the radii of two Pb nuclei, are a particularly useful way to study photonuclear collisions. Here, purely hadronic interactions are suppressed, due to the short range of the strong force, and photonuclear interactions dominate. The photoproduction of vector mesons in these reactions has a clean experimental signature: the decay products of the vector meson are the only signals in an otherwise empty detector.

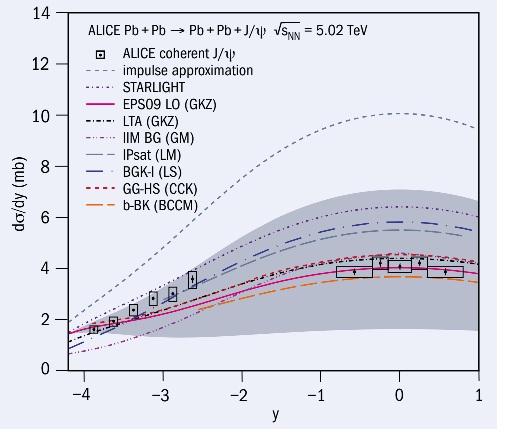


Fig. 1. *Measured differential cross section of the coherent J/ψ photoproduction in Pb–Pb UPC events as a function of rapidity. The error bars (boxes) show the statistical (systematic) uncertainties. Theoretical calculations are also shown. The grey band represents the uncertainties of the EPS09 LO calculation.*

Coherent heavy-vector-meson photoproduction, wherein the photon interacts consistently with all the nucleons in a nucleus, is of particular interest because of its connection with gluon distribution functions (PDFs) in protons and nuclei. At low Bjorken-x values, gluon PDFs are significantly suppressed in the nucleus relative to free proton PDFs – a phenomenon known as nuclear shadowing that was first observed by the European Muon Collaboration at CERN in 1982 by comparing the structure functions of iron and deuterium in the deep inelastic scattering of muons.

Heavy-vector-meson photoproduction measurements provide a powerful tool to study poorly known gluon-shadowing effects at low x. The scale of the four-momentum transfer of the interaction corresponds to the perturbative regime of QCD in the case of heavy charmonium states. The gluon shadowing factor – the ratio of the nuclear PDF to the proton PDF – can be evaluated by measuring the nuclear suppression factor, defined to be the square root of the ratio of the coherent vector-meson photonuclear production cross section on nuclei to the photonuclear cross-section in the impulse approximation that is based on the exclusive photoproduction measurements with a proton target.

The ALICE collaboration recently submitted for publication the measurement of the coherent photoproduction of J/ψ and ψ′ at midrapidity $|y| < 0.8$ in Pb–Pb UPCs at 5.02 TeV. The J/ψ is reconstructed using the dilepton ($\ell^+\ell^-$) and proton–antiproton decay channels, while for the ψ′, the dilepton and the $\ell^+\ell^-\,\pi^+\pi^-$ decay channels are studied. These data complement the ALICE measurement of the coherent J/ψ cross-section at forward rapidity, $-4 < y < -2.5$, providing stringent constraints on nuclear gluon shadowing.

The nuclear gluon shadowing factor of about 0.65 at Bjorken-x between 0.3×10^{-3} and 1.4×10^{-3} is estimated from the comparison of the measured coherent J/ψ cross-section with the impulse approximation at midrapidity, which implies moderate nuclear shadowing. The measured rapidity dependence of the coherent cross-section is not completely reproduced by models in the full rapidity range. The leading twist approximation of the Glauber–Gribov shadowing (LTA-GKZ) and the energy-dependent hot-spot model (GG-HS (CCK)) gives the best overall description of the rapidity dependence but shows tension with data at semi-forward rapidities $2.5 < |y| < 3.5$ (figure 1). The data might be better explained with a model where shadowing has a smaller effect at Bjorken $x \sim 10^{-2}$ or $x \sim 5 \cdot 10^{-5}$, corresponding to this rapidity range.

The ratio of the ψ′ to J/ψ cross-sections at midrapidity is consistent with the ratio of photoproduction cross sections measured by the H1 and LHCb collaborations, with the leading twist approximation predictions for Pb–Pb UPCs as well as with the ALICE measurement at forward rapidities. This leads to the conclusion that shadowing effects are similar for 2S (ψ′) and 1S (J/ψ) states.

In LHC Run 3 and 4, ALICE expects to collect a 10-times-larger data sample than in Run 2, taking data in a continuous mode, and thus with higher efficiency. UPC physics will profit from this by large integrated luminosity as well as lower systematic uncertainty connected to the measurement and will be able to provide the shadowing factor differentially in wide Bjorken-x intervals.

Further reading

ALICE Collab. 2021 arXiv:2101.04577.

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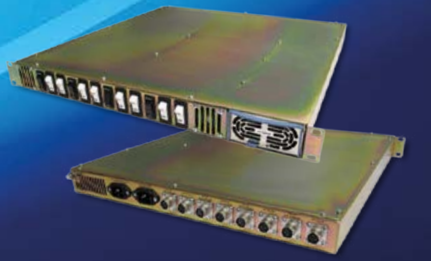
IOP Publishing

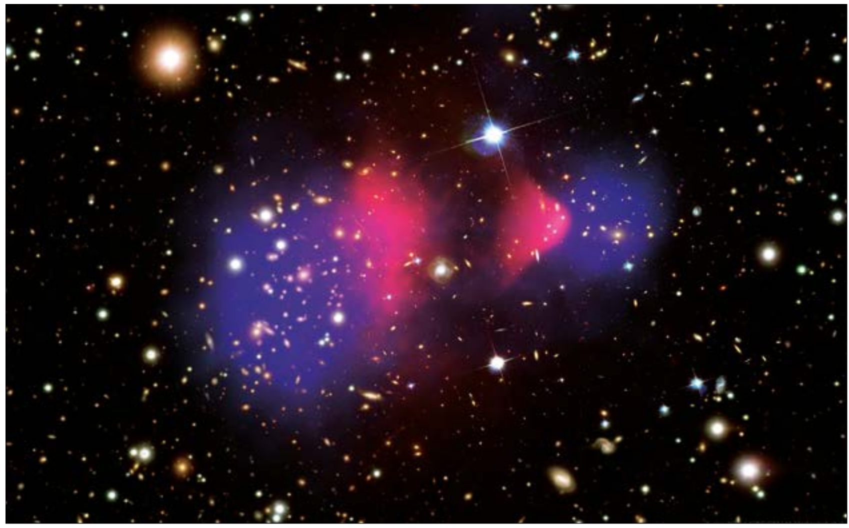


FIELD NOTES

Reports from events, conferences and meetings

TOOLS 2020

Tooling up to hunt dark matter


NASA/CXC/CfA/M Maverik *et al.*/STScl/ESO WFI/Magellan/U. Arizona/D Clowe *et al.*

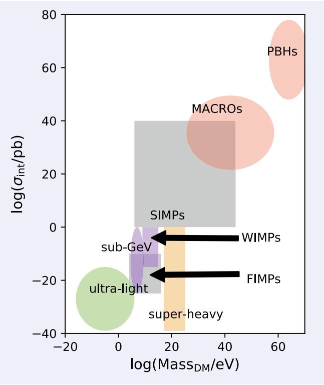
Dark modelling *The famous Bullet Cluster, in which the mass distribution of two colliding clusters (blue) and the distribution of baryonic matter (pink) are overlaid on optical data showing the positions of the galaxies.*

The past century has seen ever stronger links forged between the physics of elementary particles and the universe at large. But the picture is mostly incomplete. For example, numerous observations indicate that 87% of the matter of the universe is dark, suggesting the existence of a new matter constituent. Given a plethora of dark-matter candidates, numerical tools are essential to advance our understanding. Fostering cooperation in the development of such software, the TOOLS 2020 conference attracted around 200 phenomenologists and experimental physicists for a week-long online workshop in November.

The viable mass range for dark matter spans 90 orders of magnitude, while the uncertainty about its interaction cross section with ordinary matter is even larger (see "Theoretical landscape" figure). Dark matter may be new particles belonging to theories beyond-the-Standard Model (BSM), an aggregate of new or SM particles, or very heavy objects such as primordial black holes (PBHs). On the latter subject, Jérémy Auffinger (IP2I Lyon) updated TOOLS 2020 delegates on codes for very light PBHs, noting that "BlackHawk" is the first open-source code for Hawking-radiation calculations.

Flourishing models

Weakly interacting massive particles (WIMPs) have enduring popularity as dark-matter candidates, and are amenable to search strategies ranging from colliders to astrophysical observations. In the absence of any clear detection of WIMPs at the electroweak scale, the number of models has flourished. Above the TeV scale, these include general hidden-sector models, FIMPs (feebly interacting massive particles), SIMPs (strongly interacting massive particles), super-heavy and/or composite candidates and PBHs. Below the GeV scale, besides FIMPs, candidates include the QCD axion, more generic ALPs (axion-like particles) and ultra-light bosonic candidates. ALPs are a class of models that received particular attention at TOOLS 2020, and is now being sought in fixed-target experiments across the globe.



C Arina

Theoretical landscape *Possible interaction cross sections are sketched versus mass for viable dark-matter candidates.*

For each dark-matter model, astroparticle physicists must compute the theoretical predictions and characteristic signatures of the model and confront those predictions with the experimental bounds to select the model parameter space that is consistent with observations. To this end, the past decade has seen the development of a huge variety of software – a trend mapped and encouraged by the TOOLS conference series, initiated by Fawzi Boudjema (LAPTh Annecy) in 1999, which has brought the community together every couple of years since.

Three continuously tested codes currently dominate generic BSM dark-matter model computations. Each allows for the computation of relic density from freeze-out and predictions for direct and indirect detection, often up to next-to-leading corrections. Agreement between them is kept below the percentage level. "micrOMEGAs" is by far the most used code, and is capable of predicting observables for any generic model of WIMPs, including those with multiple dark-matter candidates. "DarkSUSY" is more oriented towards supersymmetric theories, but it can be used for generic models as the code has a very convenient modular structure. Finally, "MadDM" can compute WIMP observables for any BSM model from MeV to hundreds of TeV. As MadDM is a plugin of MadGraph, it inherits unique features such as its automatic computation of new dark-matter ▷

observables, including indirect-detection processes with an arbitrary number of final-state particles and loop-induced processes. This is essential for analysing sharp spectral features in indirect-detection gamma-ray measurements that cannot be mimicked by any known astrophysical background.

Both micrOMEGAs and MadDM permit the user to confront theories with recast experimental likelihoods for several direct and indirect detection experiments. Jan Heisig (UCLouvain) reported that this is a work in progress, with many more experimental data sets to be included shortly. Torsten Bringmann (University of Oslo) noted that a strength of DarkSUSY is the modelling of qualitatively different production mechanisms in the early universe. Alongside the standard freeze-out mechanism, several new scenarios can arise, such as freeze-in (FIMP models, as chemical and kinetic equilibrium cannot be achieved), dark freeze-out, reannihilation and "cannibalism", to name just a few. Freeze-in is now supported by micrOMEGAs.

Models connecting dark matter with collider experiments are becoming ever more optimised to the needs of users

Models connecting dark matter with collider experiments are becoming ever more optimised to the needs of users. For example, micrOMEGAs interfaces with SModelS, which is capable of quickly applying all possible LHC-relevant supersymmetric searches. The software also includes long-lived particles, as commonly found in FIMP models. As MadDM is embedded in MadGraph, noted Benjamin Fuks (LPTHE Paris), tools such as MadAnalysis may be used to recast CMS and ATLAS searches. Celine Degrande (UCLouvain) described another nice tool, FeynRules, which produces model files in both the MadDM and micrOMEGAs formats given the Lagrangian for the BSM model, providing a very useful automatised chain from the model directly to the dark-matter observables, high-energy predictions and comparisons with experimental results. Meanwhile, MadDump expands MadGraph's predictions and detector simulations from the high-energy collider limits to fixed-target experiments such as NA62. To complete a vibrant landscape of development efforts, Tomas Gonzalo (Monash) presented the GAMBIT collaboration's work to provide tools for global fits to generic dark-matter models.

A phenomenologist's dream

Huge efforts are underway to develop a computational platform to study new directions in experimental searches for dark matter, and TOOLS 2020 showed that we are already very close to the phenomenologist's dream for WIMPs. TOOLS 2020 wasn't just about dark matter either – it also covered developments in Higgs and flavour physics, precision tests and general fitting, and other tools. Interested parties are welcome to join in the next TOOLS conference due to take place in Annecy in 2022.

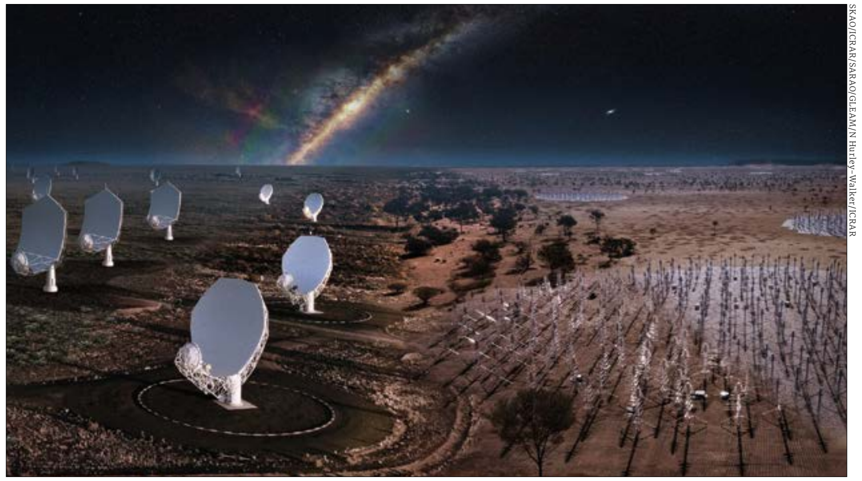
Chiara Arina *Université Catholique de Louvain.*

HPC COLLABORATION KICK-OFF WORKSHOP

HPC computing collaboration kicks off

On 29 September, CERN welcomed more than 120 delegates to an online kick-off workshop for a new collaboration on high-performance computing (HPC). CERN, SKAO (the organisation leading the development of the Square Kilometre Array), GÉANT (the pan-European network and services provider for research and education) and PRACE (the Partnership for Advanced Computing in Europe) will work together to realise the full potential of the coming generation of HPC technology for data-intensive science.

"It is an exascale project for an exascale problem," said Maria Girone, CERN coordinator of the collaboration and CERN openlab CTO, in opening remarks at the workshop. "HPC is at the intersection of several important R&D activities: the expansion of computing resources for important data-intensive science projects like the HL-LHC and the SKA, the adoption of new techniques such as artificial intelligence and machine learning, and the evolution of software to maximise the potential of heterogeneous hardware architectures."



Split screen *The two future SKA telescope arrays, in South Africa (left) and Australia (right), will deliver approximately 8 Tb/s to two supercomputers, before distributing and storing up to 700 PB of data each year.*

SKAO/ICRAR/SARAO/GLEAM/N Hurley-Walker/ICRAR

The full-day workshop, which was organised with the support of CERN openlab, saw participants establish the collaboration's foundations, outline initial challenges and begin to define the technical programme. Four main initial areas of work were discussed at the event: training and centres of expertise, benchmarking, data access, and authorisation and authentication.

One of the largest challenges in using new HPC technology is the need to adapt to heterogeneous hardware. This involves the development and dissemination of new programming skills, which is at the core of the new HPC collaboration's plan. A number of examples showing the potential of heterogeneous systems were discussed. One is the EU-funded DEEP-EST project, which is developing a modular supercomputing prototype for exascale computing. DEEP-EST has already contributed to the re-engineering of high-energy physics algorithms for accelerated architectures, highlighting the significant mutual benefits of collaboration across fields when it comes to HPC. PRACE's excellent record of providing support and training will also be critical to the success of the collaboration.

Establishing a common benchmark suite will help the organisations to measure and compare the performance of different types of computing resources for data-analysis workflows from astronomy and particle physics. The suite will include applications representative of the HEP and astrophysics communities – reflecting today's needs, as well as those of the future – and augment the existing Unified European Applications Benchmark Suite.

It is an exascale project for an exascale problem

Secure access

Access is another challenge when using HPC resources. Data from the HL-LHC and the SKA will be globally distributed and will be moved over high-capacity networks, staged and cached to reduce latency, and eventually processed, analysed and redistributed. Accessing the HPC resources themselves involves adherence to strict cyber-security protocols. A technical area devoted to authorisation and authentication infrastructure is defining demonstrators to enable large scientific communities to securely access protected resources.

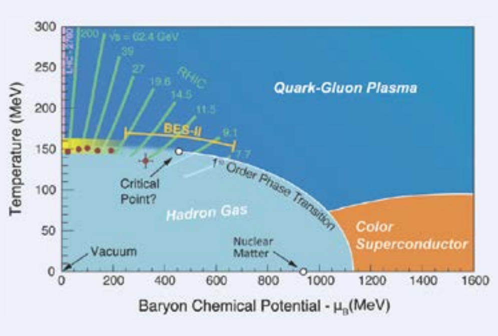
The collaboration will now move forward with its ambitious technical programme. Working groups are forming around specific challenges, with the partner organisations providing access to appropriate testbed resources. Important activities are already taking place in all four areas of work, and a second collaboration workshop will soon be organised.

Andrew Purcell *CERN.*

XXXII INTERNATIONAL WORKSHOP OF THE LOGUNOV INSTITUTE

Quark-matter fireballs hashed out in Protvino

The XXXII international workshop of the Logunov Institute for High-Energy Physics of the NRC Kurchatov Institute in Protvino, near Moscow, brought more than 300 physicists together online from 9 to 13 November to discuss "hot problems in hot and cold quark matter". The focus of the workshop was chiral theories and lattice simulations, which allow estimates beyond perturbation theory for studying the strongly coupled quark–gluon plasma (sQGP) – the hot and/or dense plasma of quarks and gluons that is created in heavy-ion collisions, and which may exist inside neutron stars.



Cooling droplets *The QCD phase diagram as a function of baryon chemical potential and temperature.*

S Mukherjee/BNL

Participants considered the QCD phase diagram (pictured) as a function of temperature, magnetic field (B), baryon and isospin chemical potentials (μ_B and μ_I), and varying quark masses. The crossover line (yellow strip), which marks a transition between hadronic matter and sQGP, has long attracted great interest. Vladimir Skokov (Brookhaven) employed recent progress in the Lee–Yang approach to phase transitions to derive from first principles that $\mu_B > 400$ MeV at the critical end point (a possible termination of the first-order phase-transition boundary). Discussions of the phase diagram also included a decrease in the pseudocritical temperature with B, the possibility of a first-order phase transition at $\mu_B = 0$ as B tends to infinity, the existence and location of a superconducting phase, the disagreement between measured and predicted collective flows of direct photons in heavy-ion collisions, and the diamagnetic and paramagnetic natures of the pion gas and deconfined matter, respectively. Evgeny Zabrodin (Oslo) explained that the rotating fireballs of strongly interacting matter that are produced in heavy-ion collisions are not only superfluids but also supervortical liquids.

Impressive work was also shared at the intersection of heavy-ion collisions and gravitational-wave astrophysics on the subject of the equation of state (EoS) of neutron-star cores. The EoS is the relationship between pressure and density, and can indicate whether hadronic or quark matter is inside. Theoretical bounds on the EoS come from chiral effective theories, perturbative QCD, and the bound on the speed of sound $c_s < 1/3$. The quantities that can be extracted from experimental data are the mass–radius relation and the relationship between the tidal deformabilities of merging neutron stars and the peak frequency of the emitted gravitational waves. Several speakers observed that tidal deformabilities, which are measured in the inspiral phase, and the peak gravitational-wave frequency, which is measured in the post-merger phase, may together reveal the state of a neutron-star interior. Mergers observed since 2017 may already be able to shed light on the existence of a deconfined phase inside these ultra-compact objects.

The Protvino workshop also revealed the enduring importance of studying heavy-quark physics. Since heavy quarks can be considered as approximately statically coloured sources, studies of quarkonia production are a step towards understanding hadron formation and the confinement mechanism. Peter Petreczky (Brookhaven) concluded from a lattice study of Bethe–Salpeter amplitudes that the potential model fails to describe bottomonium in terms of screened potential at high temperatures, with further investigations clearly needed in this field. Carlos Lourenço (CERN) showed that the lowering of quarkonia binding energies in the sQGP leads to nontrivial measured suppression patterns. Eric Braaten (Ohio) showed that the decrease with multiplicity of the ratio of the prompt production rates of X(3872) and $\Psi(2S)$ in proton–proton collisions can be explained by the scattering of co-moving pions off X(3872) if it is a weakly bound charm-meson molecule. With equally impressively scrupulousness, Mariana Araújo (Innsbruck) offered a solution to the longstanding "quarkonium polarisation puzzle" by making use of a model-independent fitting procedure and taking into account correlations between cross sections and polarisations.

The workshop revealed the enduring importance of studying heavy-quark physics

The next "hot problems" workshop will be held in November.

R N Rogalyov *and* **V A Petrov** *NRC Kurchatov Institute IHEP, Protvino, Russia.*

DESY/Heiner Müller-Elsner

Light through a wall *The ALPS II experiment at DESY will target axion-like particles suggested by astrophysical anomalies.*

IN SEARCH OF WISPS

Experiments such as MADMAX, IAXO and ALPS II are expanding the search for axions and other weakly interacting 'slim' particles that could hail from far above the TeV scale, write Axel Lindner, Béla Majorovits and Andreas Ringwald.

The Standard Model (SM) cannot be the complete theory of particle physics. Neutrino masses evade it. No viable dark-matter candidate is contained within it. And under its auspices the electric dipole moment of the neutron, experimentally compatible with zero, requires the cancellation of two non-vanishing SM parameters that are seemingly unrelated – the strong-CP problem. The physics explaining these mysteries may well originate from new phenomena at energy scales inaccessible to any collider in the foreseeable future. Fortunately, models involving such scales can be probed today and in the next decade by a series of experiments dedicated to searching for very weakly interacting slim particles (WISPs).

WISPs are pseudo Nambu–Goldstone bosons (pNGBs) that arise automatically in extensions of the SM from global symmetries which are broken both spontaneously and explicitly. NGBs are best known for being "eaten" by the longitudinal degrees of freedom of the W and Z bosons in electroweak gauge-symmetry breaking, which underpins the Higgs mechanism, but theorists have also postulated a bevy of pNGBs that get their tiny masses by explicit symmetry breaking and are potentially discoverable as physical particles. Typical examples arising in theoretically well-motivated grand-unified theories are axions, flavons and majorons. Axions arise from a broken "Peccei–Quinn" symmetry and could potentially explain the strong-CP problem, while flavons and majorons arise from broken flavour and lepton symmetries.

Being light and very weakly interacting, WISPs would be non-thermally produced in the early universe and thus remain non-relativistic during structure formation. Such particles would inevitably contribute to the dark matter of the universe. WISPs are now the target of a growing number and type of experimental searches that are complementary to new-physics searches at colliders.

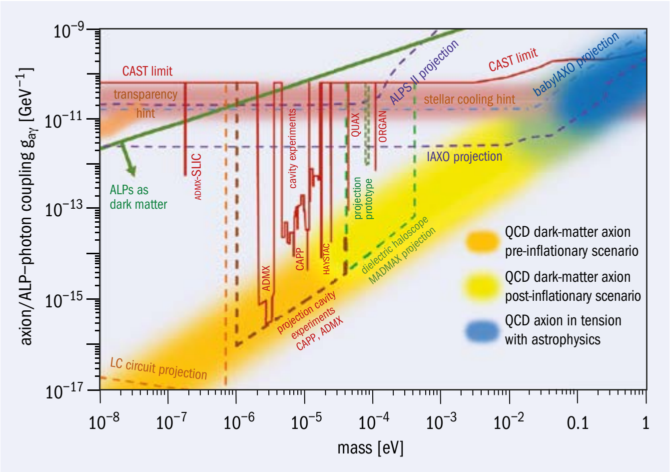
Among theorists and experimentalists alike, the axion is probably the most popular WISP. Recently, massive efforts have been undertaken to improve the calculations

THE AUTHORS

Axel Lindner *and* **Andreas Ringwald**, *DESY, Hamburg, and* **Béla Majorovits** *Max Planck Institute for Physics.*

CERN/MADMAX

Haloscope home *The Morpurgo magnet in CERN's North Area, which will house a prototype MADMAX haloscope.*



APPEC

The field of play *Limits (solid lines), projected sensitivities (dashed lines) and hints and projections (shaded areas) in the axion–photon coupling ($g_{a\gamma}$) versus axion mass (m_a) plane. The axion obtains its mass through mixing with the neutral pion, leading m_a to be inversely proportional to the symmetry-breaking scale f_a and therefore proportional to $g_{a\gamma}$ (orange, yellow and blue bands). Generic ALPs are not expected to exhibit such a relationship.*

of model-dependent relic-axion production in the early universe. This has led to a considerable broadening of the mass range compatible with the explanation of dark matter by axions. The axion could make up all of the dark matter in the universe for a symmetry-breaking scale f_a between roughly 10^8 and 10^{19} GeV (the lower limit being imposed by astrophysical arguments, the upper one by the Planck scale), corresponding to axion masses from 10^{-13} eV to 10 meV. For other light pNGBs, generically dubbed axion-like particles (ALPs), the parameter range is even broader. With many plausible relic-ALP-production mechanisms proposed by theorists, experimentalists need to cover as much of the unexplored parameter range as possible.

Although the strengths of the interactions between axions or ALPs and SM particles are very weak, being inversely proportional to f_a, several strategies for observing them are available. Limits and projected sensitivities span several orders of magnitude in the mass-coupling plane (see "The field of play" figure).

Since axions or ALPs can usually decay to two photons, an external static magnetic field can substitute one of the two photons and induce axion-to-photon conversion. Originally proposed by Pierre Sikivie, this inverse Primakoff effect can classically be described by adding source terms proportional to B and E to Maxwell's equations. Practically, this means that inside a static homogeneous magnetic field the presence of an axion or ALP field induces electric-field oscillations – an effect readily exploited by many experiments searching for WISPs. Other processes exploited in some experimental searches and suspected to lead to axion production are their interactions with electrons, leading to axion bremsstrahlung, and their interactions with nucleons or nuclei, leading to nucleon-axion bremsstrahlung or oscillations of the electric dipole moment of the nuclei or nucleons.

The potential to make fundamental discoveries from small-scale experiments is a significant appeal of experimental WISP physics, however the most solidly theoretically motivated WISP parameter regions and physics questions require setups that go well beyond "table-top" dimensions. They target WISPs that flow through the galactic halo, shine from the Sun, or spring into existence when lasers pass through strong magnetic fields in the laboratory.

Dark-matter halo

Haloscopes target the detection of dark-matter WISPs in the halo of our galaxy, where non-relativistic cold-dark-matter axions or ALPs induce electric field oscillations as they pass through a magnetic field. The frequency of the oscillations corresponds to the axion mass, and the amplitude to B/f_a. When limits or projections are given for these kinds of experiments, it is assumed that the particle under scrutiny homogeneously makes up all of the dark matter in the universe, introducing significant cosmological model dependence.

The furthest developed currently operating haloscopes are based on resonant enhancement of the axion-induced electric-field oscillations in tunable resonant cavities. Using this method, the presently running ADMX project at the University of Washington has the sensitivity to discover dark-matter axions with masses of a few μeV. Nuclear resonance methods could be sensitive to halo dark-matter axions with mass below 1 neV and "fuzzy" dark-matter ALPs down to 10^{-22} eV within the next decade, for example at the CASPEr experiments being developed at the University of Mainz and Boston University. Meanwhile, experiments based on classical LC circuits, such as ABRACADABRA at MIT, are being designed to measure ALP- or axion-induced magnetic field oscillations in the centre of a toroidal magnet. These could be sensitive in a mass range between 10 neV and 1 μeV.

For dark-matter axions with masses up to approximately 50 μeV, promising developments in cavity technologies such as multiple matched cavities and superconducting or diel-

IAXO's design profited greatly from experience with the ATLAS toroid

The clean technology innovations solving challenges in particle physics

Particle physics laboratories across Europe are pushing the frontiers of science and technology every day. To help them excel, they need a cleanroom partner that can resolve contamination issues in new, innovative ways. Over the years, cleanroom specialist Connect 2 Cleanrooms (C2C) has supported research organisations across Europe with cleanroom projects, partnering with CERN, STFC and ESS to find innovative solutions to support the R&D, build, servicing and maintenance of particle accelerators.

Part of CERN's Prevessin site in France is dedicated to producing beam intercepting devices, to be used in different particle accelerators across its world-leading particle physics laboratory. This involves the assembly of highly specialised parts such as collimators to clean the halo of proton beams, beam stoppers and beam dumps to absorb the energy of particles. These beam intercepting devices are built in sections to allow parts to be decommissioned and removed for servicing and maintenance.

With these highly calibrated pieces of machinery there is a risk that exposed parts could be effected by particulate contamination during assembly or servicing. Even a small amount of contamination inside the chamber could affect how the beam is travelling and render them ineffective. Conducting the assembly inside a cleanroom, which has a high air change rate of high efficiency particulate air (HEPA), would greatly reduce the risk of particulate contamination. However, as some of these parts are up to 6 metres in length and 30 tonnes in weight, transportation is only possible by overhead crane. The real challenge then, lies in how these parts would be transferred into a cleanroom.

A telescopic solution
Although on a different scale, C2C have innovated to overcome a similar challenge previously. C2C's R&D team developed an adjustable cleanroom canopy for the plastics industry, that can be incorporated into a modular cleanroom and automated to slide back, giving overhead crane access to injection moulding machinery inside. Scaling up on this principle, C2C collaborated with CERN scientists to design a telescopic cleanroom with three moveable modules. When the larger beam intercepting device sections have been craned into the servicing bay, the cleanroom can be extended to laterally envelope the part. The modules extend on guide rails from a closed position to triple the floor space.When in the closed position the cleanroom can be used for work on smaller parts, which means all the beam intercepting device components can be assembled in the same environment.

The softwall cleanroom is designed to maintain the clean air integrity no matter what the configuration. It achieves particle counts to meet ISO 14644-1 class 8 when in the extended position, and in the closed position it achieves particle counts to meet ISO 14644-1 class 6.

"Connect 2 Cleanrooms was the most competitive company who passed our tender qualification," says Oliver Aberle, project manager at CERN. "The design stage was very fast and the principle of the layout was complete within the first iteration. The end result is unique when you see the extending cleanroom in motion."

STFC & ESS's mobility challenge Science and Technology Facilities Council (STFC) is a world-leading science organisation that supports research in development in many disciplines, including particle physics. C2C has engineered numerous contamination control solutions for STFC, to meet their niche requirements and in 2018 were appointed for a project they were delivering for The European Spallation Source (ESS) in Sweden. These cleanrooms are now facilitating the build and operation of the particle accelerator which will be the world's most powerful neutron source, enabling scientific breakthroughs in research.

The particle accelerator is being built in sections at ESS facilities in Lund, Sweden. Each section is initially built outside of the tunnel as there are fewer restrictions on space and better access to infrastructure. Once completed, the sections are then checked and sealed before being transported down the tunnel.

C2C developed mobile cleanrooms that maintain ISO 14644-1 class 5 conditions and are used to provide end-to-end protection covering the build, transportation within the tunnel and the interconnection of different accelerator sections. The size of the tunnel presented a challenge for the mobile cleanrooms. With an overall height of 4 metres, the services needed to operate the accelerator at points bring the height down to 3.5 metres. For this reason, STFC requested the mobile cleanroom to be in three different sections. Each section can operate independently and be connected together when in position. One section is height adjustable so that it can move freely under the services, then be adjusted to a full height when in position.

C2C worked to STFC's User Requirement Specification and added value to the design in terms of the fine detail, such as how to connect the cleanroom units together and perform the height alteration.

"The biggest stand out I can say about working with Connect 2 Cleanrooms is their flexibility," says Keith Middleman, Senior Vacuum Engineer at STFC. "They bring ideas. For us, it gives them an advantage over other companies who try to offer more off-the-shelf cleanrooms, because STFC need a custom-built solution. "Their mobility and flexibility to find new areas for cleanrooms and having the skill to provide a bespoke solution, is something that isn't readily available elsewhere."

c2 Cleanrooms

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Astrophysical hints

Weakly interacting slim particles (WISPs) could be produced in hot astrophysical plasmas and transport energy out of stars, including the Sun, stellar remnants and other dense sources. Observed lifetimes and energy-loss rates can therefore probe their existence. For the axion, or an axion-like particle (ALP) with sub-MeV mass that couples to nucleons, the most stringent limit, $f_a > \sim 10^8$ GeV, stems from the duration of the neutrino signal from the progenitor neutron star of Supernova 1987A.

Tantalisingly, there are stellar hints from observations of red giants, helium-burning stars, white dwarfs and pulsars that seem to indicate energy losses with slight excesses with respect to those expected from standard energy emission by neutrinos. These hints may be explained by axions with masses below 100 meV or sub-keV-mass ALPs with a coupling to both electrons and photons.


NASA/ESA

47 Tucanae *Globular clusters can be used to compare photon and neutrino emissions from white dwarf stars.*

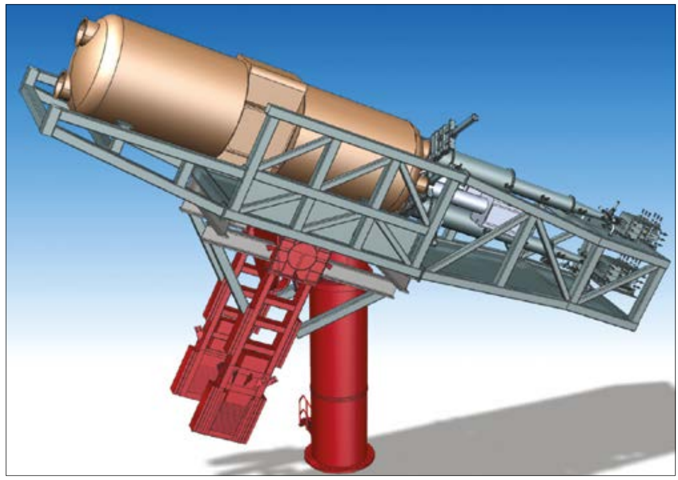
Other observations suggest that TeV photons from distant blazars are less absorbed than expected by standard interactions with extragalactic background light – the so-called transparency hint. This could be explained by the conversion of photons into ALPs in the magnetic field of the source, and back to photons in astrophysical magnetic fields. Interestingly, these would have about the same ALP–photon coupling strength as indicated by the observed stellar anomalies, though with a mass that is incompatible with both ALPs which can explain dark matter and with QCD axions (see "The field of play" figure, p27).

ectric cavities are ongoing at several locations, including at CAPP in South Korea, the University of Western Australia, INFN Legnaro and the RADES detector, which has taken data as part of the CAST experiment at CERN. Above ~40 μeV, however, the cavity concept becomes more and more challenging, as sensitivity scales with the volume of the resonant cavity, which decreases dramatically with increasing mass (as roughly $1/m_a^3$). To reach sensitivity at higher masses, in the region of a few hundred μeV, a novel "dielectric haloscope" is being developed by the MADMAX (Magnetized Disk and Mirror Axion experiment) collaboration for potential installation at DESY. It exploits the fact that static magnetic-field boundaries between media with different dielectric constants lead to tiny power emissions that compensate the discontinuity in the axion-induced electric fields in neighbouring media. If multiple surfaces are stacked in front of each other, this should lead to constructive interference, boosting the emitted power from the expected axion dark matter in the desired mass range to detectable levels. Other novel haloscope concepts, based on meta-materials ("plasma haloscopes", for example) and topological insulators, are also currently being developed. These could have sensitivity to even higher axion masses, up to a few meV.

Staying in tune

In principle, axion-dark-matter detection should be relatively simple, given the very high number density of particles – approximately 3×10^{13} axions/cm^3 for an axion mass of 10 μeV – and the well-established technique of resonant axion-to-photon conversion. But, as the axion mass is unknown, the experiments must be painstakingly tuned to each possible mass value in turn. After about 15 years of steady progress, the ADMX experiment has reached QCD-axion dark-matter sensitivity in the mass regime of a few μeV.

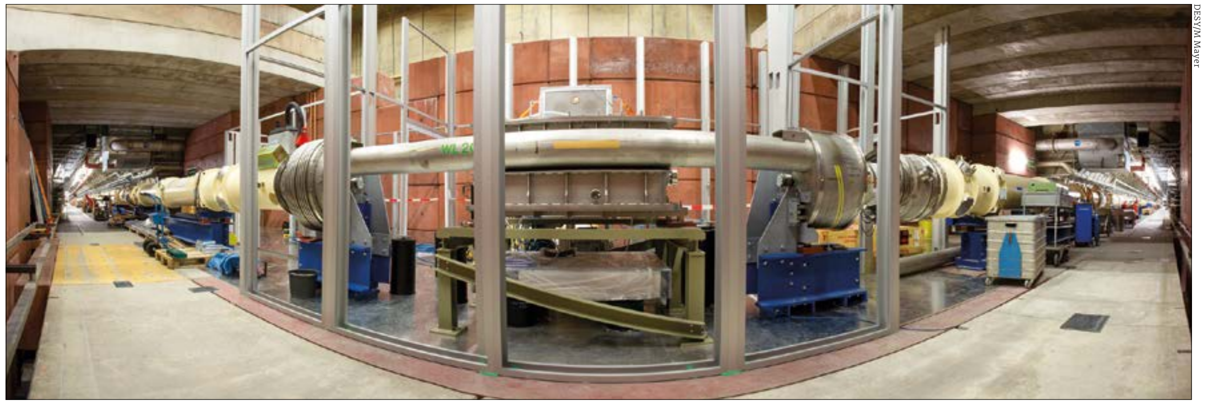
ADMX uses tunable microwave resonators inside a strong solenoidal magnetic field, and modern quantum sensors for readout. Unfortunately, however, this technology is not scalable to the higher axion-mass regions as preferred, for example, by cosmological models where Peccei–Quinn symmetry breaking happened after an inflationary phase of the universe. That's where MADMAX comes in. The collaboration is working on the dielectric-haloscope concept – initiated and led by scientists at the Max Planck Institute for Physics in Munich – to investigate the mass region around 100 μeV.


DESY

Prototype *Conceptual design of the BabyIAXO helioscope, which will seek to observe solar axions.*

MADMAX will use a huge ~9 T superconducting dipole magnet with a bore of about 1.35 m and a stored energy of roughly 480 MJ. Such a magnet has never been built before. The MADMAX collaboration teamed up with CEA-IRFU and Bilfinger-Noell and successfully worked out a conceptual design. First steps towards qualifying the conductor are under way. The plan is for the magnet to be installed at DESY inside the old iron yoke of the former HERA experiment H1. DESY is already preparing the required infrastructure, including the liquid-helium supply necessary to cool the magnet. R&D for the dielectric booster, with up to 80 adjustable 1.25 m^2 disks, is in full swing.

A first prototype, containing a more modest 20 discs of



DESY/M Mayer

Panoramic view *ALPS II is under construction in the HERA tunnel at DESY. WISPs may be produced in the left magnet string before converting back to photons on the right. A large vacuum chamber will house both the "wall" and the optics, which mode-match the two optical resonators.*

30 cm diameter, will be tested in the "Morpurgo" magnet at CERN during future accelerator shutdowns (see "Haloscope home" figure, p27). With a peak field strength of 1.6 T, its dipole field will allow new ALP-dark-matter parameter regions to be probed, though the main purpose of the prototype is to demonstrate the operation of the booster system in cryogenic surroundings inside a magnetic field. The MADMAX collaboration is extremely happy to have found a suitable magnet at CERN for such tests. If sufficient funds can be acquired within the next two to three years for magnet construction, and provided that the prototype efforts at CERN are successful, MADMAX could start data taking at DESY in 2028.

While direct dark-matter search experiments like ADMX and MADMAX offer by far the highest sensitivity for axion searches, this is based on the assumption that the dark matter problem is solved by axions, and if no signal is discovered any claim of an exclusion limit must rely on specific cosmological assumptions. Therefore, other less model-dependent experiments, such as helioscopes or light shining through a wall (LSW) experiments, are extremely beneficial in addition to direct dark-matter searches.

Solar axions

In contrast to dark-matter axions or ALPs, those produced in the Sun or in the laboratory should have considerable momentum. Indeed, solar axions or ALPs should have energies of a few keV, corresponding to the temperature at which they are produced. These could be detected by helioscopes, which seek to use the inverse Primakoff effect to convert solar axions or ALPs into X-rays in a magnet pointed towards the Sun, as at the CERN Axion Solar Telescope (CAST) experiment. Helioscopes could cover the mass range compatible with the simplest axion models, in the vicinity of 10 meV, and could be sensitive to ALPs with masses below 1 eV without any tuning at all.

The CAST helioscope, which reused an LHC prototype dipole magnet, has driven this field in the past decade, and provides the most sensitive exclusion limits to date. Going beyond CAST calls for a much larger magnet. For the next-generation International Axion Observatory (IAXO) helioscope, CERN members of the international collaboration worked out a conceptual design for a 20 m-long toroidal magnet with eight 60 cm-diameter bores. IAXO's design profited greatly from experience with the ATLAS toroid.

In the past three years, the collaboration, led by the University of Zaragoza, has been concentrating its activities on the BabyIAXO prototype in order to finesse the magnet concept, the X-ray telescopes necessary to focus photons from solar axion conversion and the low-background detectors. BabyIAXO will increase the signal-to-noise ratio of CAST by two orders of magnitude; IAXO by a further two orders of magnitude.

In December 2020 the directorates of CERN and DESY signed a collaboration agreement regarding BabyIAXO: CERN will provide the detailed design of the prototype magnet including its cryostat, while DESY will design and prepare the movable platform and infrastructure (see "Prototype" figure). BabyIAXO will be located at DESY in Hamburg. The collaboration hopes to attract the remaining funds for BabyIAXO so construction can begin in 2021 and first science runs could take place in 2025. The timeline for IAXO will depend strongly on experiences during the construction and operation of BabyIAXO, with first light potentially possible in 2028.

Light shining through a wall

In contrast to haloscopes, helioscopes do not rely on the assumption that all dark matter is made up by axions. But light-shining-through-wall (LSW) experiments are even less model dependent with respect to ALP production. Here, intense laser light could be converted to axions or ALPs inside a strong magnetic field by the Primakoff effect. Behind a light-impenetrable wall they would be re-converted to photons and detected at the same wavelength as the laser light. The disadvantage of LSW experiments is that they only reach sensitivity to ALPs with a mass up to a few hundred μeV with comparably high coupling to photons. However, this is sensitive enough to test the parameter range consistent with the transparency hint and parts of the mass range consistent with the stellar hints (see "Astrophysical hints" panel, p29).

The Any Light Particle Search (ALPS II) at DESY follows this approach. By seeking to observe light shining through a wall, any ALPs would be generated in the experiment itself, removing the need to make assumptions about their production. ALPS II is based on 24 modified superconducting dipole magnets that have been straightened by brute-force deformation, following their former existence in the proton accelerator of the HERA complex. With the help of two 124 m-long high-finesse optical resonators, encompassed by the magnets on both sides of the wall, ALPS II is also the first laser-based setup to fully exploit resonance techniques. Two readout systems capable of measuring a 1064 nm photon flux down to a rate of $2\times10^{-5}\,\mathrm{s}^{-1}$ have been developed by the collaboration. Compared to the present best LSW limits provided by OSQAR at CERN, the signal-to-noise ratio will rise by no less than 12 orders of magnitude at ALPS II. Nevertheless, MADMAX would surpass ALPS II in the sensitivity for the axion-photon coupling strength by more than three orders of magnitude. This is the price to pay for a model-independent experiment – however, ALPS II principally targets not dark-matter candidates but ALPs indicated by astrophysical phenomena.

Tunelling ahead

The installation of the 24 dipole magnets in a straight section of the HERA tunnel was completed in 2020. Three clean rooms at both ends and in the centre of the experiment were also installed, and optics commissioning is under way. A first science run is expected for autumn 2021.

In the overlapping mass region up to 0.1 meV, the sensitivities of ALPS II and BabyIAXO are roughly equal. In the event of a discovery, this would provide a unique opportunity to study the new WISP. Excitingly, a similar case might be realised for IAXO: combining the optics and detectors of ALPS II with simplified versions of the dipole magnets being studied for FCC-hh would provide an LSW experiment with "IAXO sensitivity" regarding the axion-photon coupling, albeit in a reduced mass range. This has been outlined as the putative JURA (Joint Undertaking on Research for Axions) experiment in the context of the CERN-led Physics Beyond Colliders study.

The past decade has delivered significant developments in axion and ALP theory and phenomenology. This has been complemented by progress in experimental methods to cover a large fraction of the interesting axion and ALP parameter range. In close collaboration with universities and institutes across the globe, CERN, DESY and the Max Planck society will together pave the road to the exciting results that are expected this decade. ●

ALPS II is the first laser-based setup to fully exploit resonance techniques

Further reading

L Di Luzio *et al.* 2020 *Phys. Rept.* **870** 1.
MADMAX Collaboration 2019 *Eur. Phys. J. C* **79** 3.
IAXO Collaboration 2019 *JCAP* **06** 047.
ALPS II Collaboration 2013 *JINST* **8** T09001.

RUSSIA'S PARTICLE-PHYSICS POWERHOUSE

Fifty years after being established, the Institute for Nuclear Research in Moscow continues to leave its mark on neutrino and high-energy physics.

Founded on 24 December 1970, the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) is a large centre for particle physics in Moscow with wide participation in international projects. The INR RAS conducts work on cosmology, neutrino physics, astrophysics, high-energy physics, accelerator physics and technology, neutron research and nuclear medicine. It is most well-known for its unique research facilities that are spread all across Russia, and its large-scale collaborations in neutrino and high-energy physics. This includes experiments such as the Baksan Neutrino Observatory, and collaborations with a number of CERN experiments including CMS, ALICE, LHCb, NA61 and NA64.

The institute was founded by the Decree of the Presidium of the USSR Academy of Sciences in accordance with the decision of the government. Theoretical physicist Moisey Markov had a crucial role in establishing the institute and influenced the research that would later be undertaken. His ambition is seen in the decision to base INR RAS on three separate nuclear laboratories of the P.N. Lebedev Institute of Physics of the Academy of Sciences of the USSR. Each laboratory had a leading physicist in charge: the Atomic Nucleus Laboratory headed by Nobel laureate Ilya Frank; the Photonuclear Reactions Laboratory under the direction of Lyubov Lazareva; and a neutrino laboratory headed by Georgy Zatsepin and Alexander Chudakov. The man overseeing it all was the first director of INR RAS, Albert Tavkhelidze, a former researcher at the Joint Institute for Nuclear Research (JINR, Dubna). In 1987 Victor Matveev took over as director, followed by Leonid Kravchuk in 2014. Since 2020 the director of INR RAS is Maxim Libanov.

From the very beginning, major efforts were focused on the construction and operation of large-scale research facilities. The hub of INR RAS was built 20 km outside of Moscow, in a town called Troitsk. In 1973 an accelerator division was created, with a long-term goal of creating a meson facility that would house a 600 MeV linear accelerator for protons and H^- ions. The first beam was eventually accelerated to 20 MeV in 1988 and the facility was fully operational by 1993. Now known as the Moscow Meson Facility, it has the most powerful linear proton accelerator in the Euro-Asian region, providing fundamental and applied research in nuclear and neutron physics, condensed matter, development of technologies for the production of a wide range of radioisotopes, operation of a radiation therapy complex and many other applications.


INR

Ice breaker *New clusters of optical modules being installed in the underwater Baikal-GVD Neutrino Telescope in April 2020.*

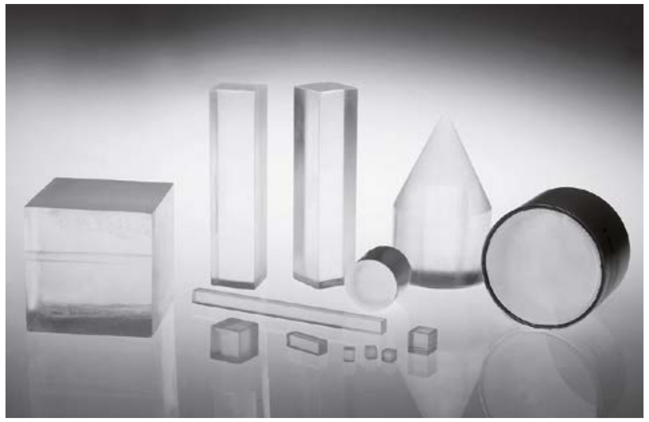
A town called Neutrino

Over 1000 miles south from the Troitsk laboratory, an underground tunnel in the Caucasus mountains is the base of another INR RAS facility, the Baksan Neutrino Observatory (BNO). The facility was established in 1967 and the Baksan Underground Scintillation Telescope (BUST) started taking data in 1978. A town sensibly called "Neytrino" (Russian for neutrino) was constructed in parallel with the facility, and was where scientists and their families could live 1700 m above sea level next to the observatory. In 1987 BUST was one of the four neutrino detectors that first directly observed neutrinos from supernova SN1987A.

The observatory did not finish there, and the next step

THE AUTHORS

Anna Veresnikova *scientific secretary INR RAS and* **Grigory Rubtsov** *deputy director INR RAS.*



was the gallium–germanium neutrino telescope (GGNT), which was home to the Soviet–American Gallium Experiment (SAGE). The experiment made important contributions towards solving the solar neutrino problem and simultaneously gave rise to a new problem known as the gallium anomaly, which is yet to be explained. SAGE is still well and truly alive, and with a recent upgrade of the GGNT completed in 2019, the team will now hunt for sterile neutrinos

By 1990 another neutrino detector was under construction, following the original proposal of Markov and Chudakov. In collaboration with JINR, plans for an underwater neutrino telescope located at the world's largest freshwater lake, Lake Baikal, took shape. Underwater telescopes use glass spheres that house photomultiplier tubes to detect Cherenkov light from the charged particles emerging from neutrino interactions in the lake water. The first detector developed for Lake Baikal was the NT200, which was constructed over five years from 1993–1998 and detected cosmic neutrinos for more than a decade. It has now been replaced with the Gigaton Volume Detector (Baikal-GVD), and plans were concluded in 2015 for the first phase of the telescope to be completed by 2021. Baikal-GVD has an effective volume of 1 km^3 and is designed to register and study ultrahigh-energy neutrino fluxes from astrophysical sources.


INR RAS

A timeline of INR RAS *Clockwise from top left: theoretical physicist Moisey Markov at the foundation of the Meson Factory building, Troitsk, 1971; construction of the first stage of the linear accelerator facility; the top view of the linear accelerator facility; deployment of the underwater optical module of the Baikal neutrino telescope; view of the Baksan Neutrino Observatory laboratories; the tunnel in the Andyrchi mountain for the Baksan Neutrino Observatory experiments; and the neutrino council at the Baksan Neutrino Observatory with the participation of Alexander Chudakov, Vadim Kuzmin, Bruno Pontecorvo, Petr Spivak and Albert Tavkhelidze.*

Left a mark

There is no doubt that INR RAS has left its mark on high-energy physics. While the institute's most recognised work will be in neutrino physics, the Moscow Meson Facility has also contributed to other areas of the field. An experiment was created for direct measurement of the mass of the electron antineutrino via the beta decay of tritium. The "Troitsk nu-mass" experiment started in 1985 and its limit on the electron antineutrino mass was the world's best for years. The improvement of this result became possible only in 2019 with the large-scale KATRIN experiment in Germany that was created in collaboration with INR RAS. In fact, the Troitsk nu-mass experiment was considered as a prototype for KATRIN.

Experimental data have been obtained on nuclear reactions involving protons and neutrons of medium energies along with data on photonuclear reactions, including the study of the spin structure of a proton using an active polarised target. New effects in collisions of relativistic nuclei have been observed and a new scientific direction has been taken, "nuclear photonics". Two effects in astroparticle physics have been named after scientists from INR RAS: the "GZK cut-off", which is a high-energy cut-off in the spectrum of the ultrahigh-energy cosmic rays named after Kenneth Greisen (US), Georgy Zatsepin and Vadim Kuzmin (INR RAS); and the "Mikheyev–Smirnov–Wolfenstein effect" concerning neutrino oscillations in matter, named after Stanislav Mikheyev, Alexei Smirnov (INR RAS) and Lincoln Wolfenstein (US).

Theoretical studies at INR RAS are also widely known, including the development of perturbation theory methods, study of the ground state (vacuum) in gauge theories, methods for studying the dynamics of strong interactions of hadrons outside the framework of perturbation theory, the first ever brane-world models and the development of principles and the search for mechanisms for the formation of the baryon asymmetry of the universe.

Global reach

Scientists from INR RAS take an active part in the work of a number of large international experiments at CERN, JINR, and in Germany, Japan, Italy, USA, China, France, Spain and other countries. The institute also conducts educational activities, having its own graduate school and teaching departments in nearby institutes such as the Moscow Institute for Physics and Technology.

The future of INR RAS is deeply rooted in its new large-scale infrastructures. Baikal-GVD will, along with the IceCube experiment at the South Pole, be able to register neutrinos of astrophysical origin in the hope of establishing their nature. A project has been prepared to modernise the linear proton accelerator in Troitsk using superconducting radio-frequency cavities, while there are also plans to construct a large centre for nuclear medicine based at the linear accelerator centre. There is a proposal to build the Baksan Large-Volume Scintillator Detector at BNO containing 10 ktons of ultra-pure liquid scintillator, which would be able to register neutrinos from the carbon–nitrogen–oxygen (CNO) fusion cycle in the Sun with a precision sufficient to discriminate between various solar models.

The past 50 years have seen consistent growth at INR RAS, and with world-leading future projects on the horizon, the institute shows no signs of slowing down. ●

There are plans to construct a large centre for nuclear medicine based at the linear accelerator centre

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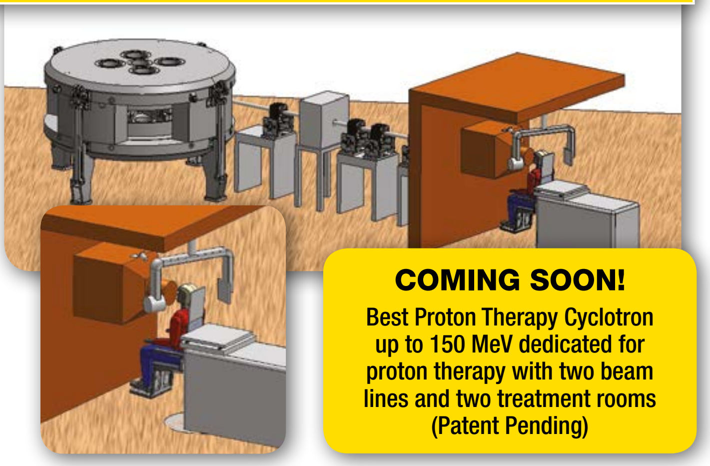

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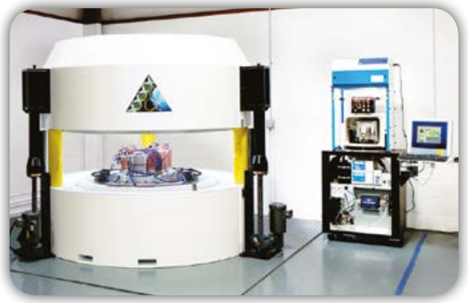

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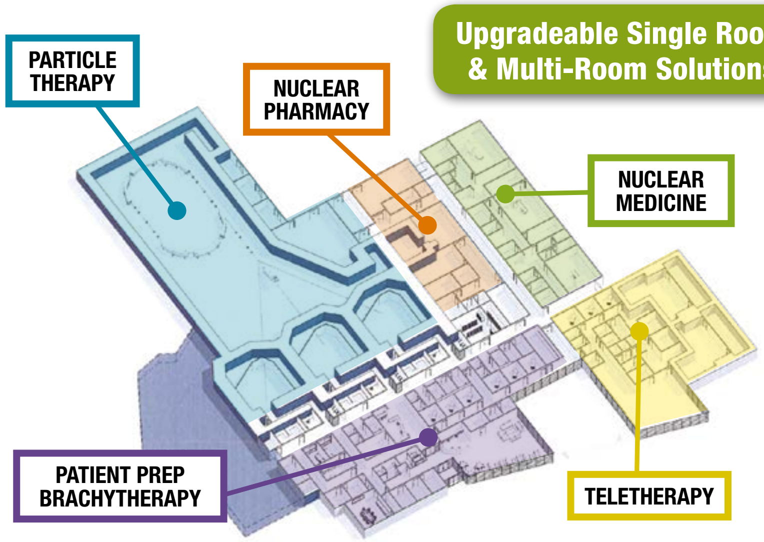

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DISCOVERY MACHINES

50 years ago CERN's Intersecting Storage Rings set in motion a series of hadron colliders charting nature at the highest possible energies, write Lyn Evans and Peter Jenni.

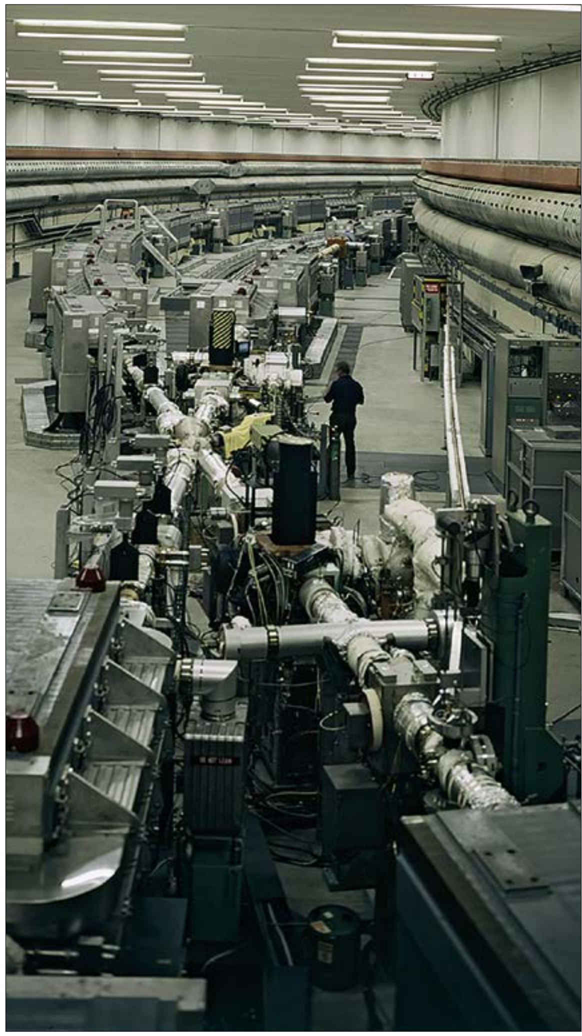
The ability to collide high-energy beams of hadrons under controlled conditions transformed the field of particle physics. Until the late 1960s, the high-energy frontier was dominated by the great proton synchrotrons. The Cosmotron at Brookhaven National Laboratory and the Bevatron at Lawrence Berkeley National Laboratory were soon followed by CERN's Proton Synchrotron and Brookhaven's Alternating Gradient Synchrotron, and later by the Proton Synchrotron at Serpukov near Moscow. In these machines protons were directed to internal or external targets in which secondary particles were produced.

The kinematical inefficiency of this process, whereby the centre-of-mass energy only increases as the square root of the beam energy, was recognised from the outset. In 1943, Norwegian engineer Rolf Widerøe proposed the idea of colliding beams, keeping the centre of mass at rest in order to exploit the full energy for the production of new particles. One of the main problems was to get colliding beam intensities high enough for a useful event rate to be achieved. In the 1950s the prolific group at the University of Wisconsin Midwestern Universities Research Association (MURA), led by Donald Kerst, worked on the problem of "stacking" particles, whereby successive pulses from an injector synchrotron are superposed to increase the beam intensity. They mainly concentrated on protons, where Liouville's theorem (which states that for a continuous fluid under the action of conservative forces the density of phase space cannot be increased) was thought to apply. Only much later, ways to beat Liouville and to increase the beam density were found. At the 1956 International Accelerator Conference at CERN, Kerst made the first proposal to use stacking to produce colliding beams (not yet storage rings) of sufficient intensity.

At that same conference, Gerry O'Neill from Princeton presented a paper proposing that colliding electron beams could be achieved in storage rings by making use of the natural damping of particle amplitudes by synchrotron-radiation emission. A design for the 500 MeV Princeton–Stanford colliding beam experiment was published in 1958 and construction started that same year. At the same time, the Budker Institute for Nuclear Research in Novosibirsk started work on VEP-1, a pair of rings designed to collide electrons at 140 MeV. Then, in March 1960, Bruno Touschek gave a seminar at Laboratori Nazionali di Frascati in Italy where he first proposed a single-ring, 0.6 m-circumference 250 MeV electron–positron collider. "AdA" produced the first stored electron and positron beams less than one year later – a far cry from the time it takes today's machines to go from conception to operation! From these trailblazers evolved the production machines, beginning with ADONE at Frascati and SPEAR at SLAC. However, it was always clear that the gift of synchrotron-radiation damping would become a hindrance to achieving very high energy collisions in a circular electron–positron collider because the power radiated increases as the fourth power of the beam energy and the inverse fourth power of mass, so is negligible for protons compared with electrons.

THE AUTHORS

Lyn Evans *(former LHC project director), Imperial College London, and* **Peter Jenni** *(former ATLAS spokesperson), Albert Ludwig University of Freiburg and CERN.*



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New era *CERN's Intersecting Storage Rings in 1974.*

CERN-AC-7604110

Super collider *CERN's Sp$\bar{p}$S in 1983.*

Fermilab

TeV frontier *The Tevatron at Fermilab in 2011.*

A step into the unknown

Meanwhile, in the early 1960s, discussion raged at CERN about the next best step for particle physics. Opinion was sharply divided between two camps, one pushing a very high-energy proton synchrotron for fixed-target physics and the other using the technique proposed at MURA to build an innovative colliding beam proton machine with about the same centre-of-mass energy as a conventional proton synchrotron of much larger dimensions. In order to resolve the conflict, in February 1964, 50 physicists from among Europe's best met at CERN. From that meeting emerged a new committee, the European Committee for Future Accelerators, under the chairmanship of one of CERN's founding fathers, Edoardo Amaldi. After about two years of deliberation, consensus was formed. The storage ring gained most support, although a high-energy proton synchrotron, the Super Proton Synchrotron (SPS), was built some years later and would go on to play an essential role in the development of hadron storage rings. On 15 December 1965, with the strong support of Amaldi, the CERN Council unanimously approved the construction of the Intersecting Storage Rings (ISR), launching the era of hadron colliders.

First collisions

Construction of the ISR began in 1966 and first collisions were observed on 27 January 1971. The machine, which needed to store beams for many hours without the help of synchrotron-radiation damping to combat inevitable magnetic field errors and instabilities, pushed the boundaries in accelerator science on all fronts. Several respected scientists doubted that it would ever work. In fact, the ISR worked beautifully, exceeding its design luminosity by an order of magnitude and providing an essential step in the development of the next generation of hadron colliders. A key element was the performance of its ultra-high-vacuum system, which was a source of continuous improvement throughout the 13 year-long lifetime of the machine.

On 15 December 1965, the CERN Council unanimously approved the construction of the ISR, launching the era of hadron colliders

For the experimentalists, the ISR's collisions (which reached an energy of 63 GeV) opened an exciting adventure at the energy frontier. But they were also learning what kind of detectors to build to fully exploit the potential of the machine – a task made harder by the lack of clear physics benchmarks known at the time in the ISR energy regime. The concept of general-purpose instruments built by large collaborations, as we know them today, was not in the culture of the time. Instead, many small collaborations built experiments with relatively short lifecycles, which constituted a fruitful learning ground for what was to come at the next generation of hadron colliders.

There was initially a broad belief that physics action would be in the forward directions at a hadron collider. This led to the Split Field Magnet facility as one of the first detectors at the ISR, providing a high magnetic field in the forward directions but a negligible one at large angle with respect to the colliding beams (the nowadays so-important transverse direction). It was with subsequent detectors featuring transverse spectrometer arms over limited

CERN-PHOTO-201802-030

Big beast *The Large Hadron Collider in 2018.*

solid angles that physicists observed a large excess of high transverse momentum particles above low-energy extrapolations. With these first observations of point-like parton scattering, the ISR made a fundamental contribution to strong-interaction physics. Solid angles were too limited initially, and single-particle triggers too biased, to fully appreciate the hadronic jet structure. That feat required third-generation detectors, notably the Axial Field Spectrometer (AFS) at the end of the ISR era, offering full azimuthal central calorimeter coverage. The experiment provided evidence for the back-to-back two-jet structure of hard parton scattering.

For the detector builders, the original AFS concept was interesting as it provided an unobstructed phi-symmetric magnetic field in the centre of the detector, however, at the price of massive Helmholtz coil pole tips obscuring the forward directions. Indeed, the ISR enabled the development of many original experimental ideas. A very important one was the measurement of the total cross section using very forward detectors in close proximity to the beam. These "Roman Pots", named for their inventors, made their appearance in all later hadron colliders, confirming the rising total pp cross section with energy.

It is easy to say after the fact, still with regrets, that with an earlier availability of more complete and selective (with electron-trigger capability) second- and third-generation experiments at the ISR, CERN would not have been left as a spectator during the famous November revolution of 1974 with the J/ψ discoveries at Brookhaven and SLAC. These, and the Υ resonances discovered at Fermilab three years later, were clearly observed in the later-generation ISR experiments.

SPS opens new era

However, events were unfolding at CERN that would pave the way to the completion of the Standard Model. At the ISR in 1972, the phenomenon of Schottky noise (density fluctuations due to the granular nature of the beam in a storage ring) was first observed. It was this very same noise that Simon van der Meer speculated in a paper a few years earlier could be used for what he called "stochastic cooling" of a proton beam, beating Liouville's theorem by the fact that a beam of particles is not a continuous fluid. Although it is unrealistic to detect the motion of individual particles and damp them to the nominal orbit, van der Meer showed that by correcting the mean transverse motion of a sample of particles continuously, and as long as the statistical nature of the Schottky signal was continuously regenerated, it would be theoretically possible to reduce the beam size and increase its density. With the bandwidth of electronics available at the time, van der Meer concluded that the cooling time would be too long to be of practical importance. But the challenge was taken up by Wolfgang Schnell, who built a state-of-the-art feedback system that demonstrated stochastic cooling of a proton beam for the first time. This would open the door to the idea of stacking and cooling of antiprotons, which later led to the SPS being converted into a proton–antiproton collider.

Another important step towards the next generation of hadron colliders occurred in 1973 when the collaboration working on the Gargamelle heavy-liquid bubble chamber published two papers revealing the first evidence for weak neutral currents. These were important observations in support of the unified theory of electromagnetic and weak interactions, for which Sheldon Glashow, Abdus Salam and Steven Weinberg were to receive the Nobel Prize in Physics in 1979. The electroweak theory predicted the existence and approximate masses of two vector bosons, the W and the Z, which were too high to be produced in any existing machine. However, Carlo Rubbia and collaborators proposed that, if the SPS could be converted into a collider with protons and antiprotons circulating in opposite directions, there would be enough energy to create them.

First collisions of protons and antiprotons at 270 GeV were observed on the night of 10 July 1981

To achieve this the SPS would need to be converted into a storage ring like the ISR, but this time the beam would need to be kept "bunched" with the radio-frequency (RF) system working continuously to achieve a high enough luminosity (unlike the ISR where the beams were allowed to de-bunch all around the ring). The challenges here were two-fold. Noise in the RF system causes particles to diffuse rapidly from the bunch. This was solved by a dedicated feedback system. It was also predicted that the beam–beam interaction would limit the performance of a bunched-beam machine with no synchrotron-radiation damping due to the strongly nonlinear interactions between a particle in one beam with the global electromagnetic field in the other beam.

CERN-PHOTO-7708541X

First steps *The R702 experiment at the ISR in 1977.*

A much bigger challenge was to build an accumulator ring in which antiprotons could be stored and cooled by stochastic cooling until a sufficient intensity of antiprotons would be available to transfer into the SPS, accelerate to around 300 GeV and collide with protons. This was done in two stages. First a proof-of-principle was needed to show that the ideas developed at the ISR transferred to a dedicated accumulator ring specially designed for stochastic cooling. This ring was called the Initial Cooling Experiment (ICE), and operated at CERN in 1977–1978. In ICE transverse cooling was applied to reduce the beam size and a new technique for reducing the momentum spread in the beam was developed. The experiment proved to be a big success and the theory of stochastic cooling was refined to a point where a real accumulator ring (the Antiproton Accumulator) could be designed to accumulate and store antiprotons produced at 3.5 GeV by the proton beam from the 26 GeV Proton Synchrotron. First collisions of protons and antiprotons at 270 GeV were observed on the night of 10 July 1981, signalling the start of a new era in colliding beam physics.

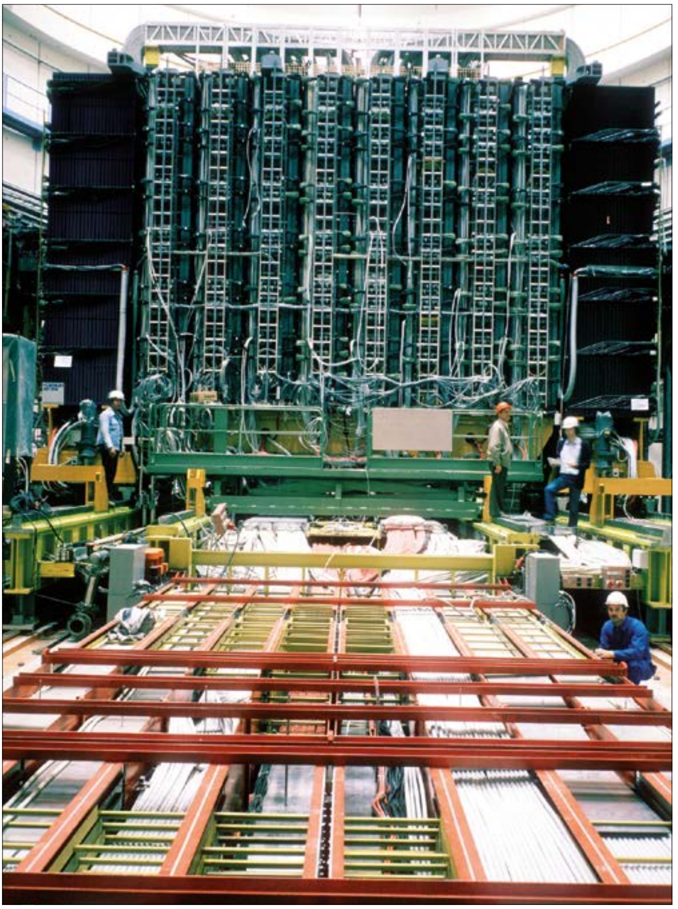
A clear physics goal, namely the discovery of the W and Z intermediate vector bosons, drove the concepts for the two main Sp$\bar{p}$S experiments UA1 and UA2 (in addition to a few smaller, specialised experiments). It was no coincidence that the leaders of both collaborations were pioneers of ISR experiments, and many lessons from the ISR were taken on board. UA1 pioneered the concept of a hermetic detector that covered as much as possible the full solid angle around the interaction region with calorimetry and tracking. This allows measurements of the missing transverse energy/momentum, signalling the escaping neutrino in the leptonic W decays. Both electrons and muons were measured, with tracking in a state-of-the-art drift chamber that provided bubble-chamber-like pictures of the interactions. The magnetic field was provided by a dipole-magnet configuration, an approach not favoured in later generation experiments because of its inherent lack of azimuthal symmetry. UA2 featured a (at the time) highly segmented electromagnetic and hadronic calorimeter in the central part (down to 40 degrees with respect to the beam axis), with 240 cells pointing to the interaction region. But it had no muon detection, and in its initial phase only limited electromagnetic coverage in the forward regions. There was no magnetic field except for the forward cones with toroids to probe the W polarisation.

In 1983 the Sp$\bar{p}$S experiments made history with the direct discoveries of the W and Z. Many other results were obtained, including the first evidence of neutral B-meson particle–antiparticle mixing at UA1 thanks to its tracking and muon detection. The calorimetry of UA2 provided immediate unambiguous evidence for a two-jet structure in events with large transverse energy. Both UA1 and UA2 pushed QCD studies far ahead. The lack of hermeticity in UA2's forward regions motivated a major upgrade (UA2$'$) for the second phase of the collider, complementing the central part with new fully hermetic calorimetry (both electromagnetic and hadronic), and also inserting a new tracking cylinder employing novel technologies (fibre tracking and silicon pad detectors). This enabled the experiment to improve searches for top quarks and supersymmetric particles, as well as making almost background-free first precision measurements of the W mass.

Meanwhile in America

At the time the Sp$\bar{p}$S was driving new studies at CERN, the first large superconducting synchrotron (the Tevatron, with a design energy close to 1 TeV) was under construction at Fermilab. In view of the success of the stochastic cooling experiments, there was a strong lobby at the time to halt the construction of the Tevatron and to divert effort instead to emulate the SPS as a proton–antiproton collider using the Fermilab Main Ring. Wisely this proposal was rejected

At the time the Sp$\bar{p}$S was driving new studies at CERN, the first large superconducting synchrotron was under construction at Fermilab



CERN-HI-8104591

Chasing bosons
The UA1 detector at the $Sp\bar{p}S$.

and construction of the Tevatron continued. It came into operation as a fixed-target synchrotron in 1984. Two years later it was also converted into a proton–antiproton collider and operated at the high-energy frontier until its closure in September 2011.

A huge step was made with the detector concepts for the Tevatron experiments, in terms of addressed physics signatures, sophistication and granularity of the detector components. This opened new and continuously evolving avenues in analysis methods at hadron colliders. Already the initial CDF and D0 detectors for Run I (which lasted until 1996) were designed with cylindrical concepts, characteristic of what we now call general-purpose collider experiments, albeit D0 still without a central magnetic field in contrast to CDF's 1.4 T solenoid. In 1995 the experiments delivered the first Tevatron highlight: the discovery of the top quark. Both detectors underwent major upgrades for Run II (2001–2011) – a theme now seen for the LHC experiments – which had a great impact on the Tevatron's physics results. CDF was equipped with a new tracker, a silicon vertex detector, new forward calorimeters and muon detectors, while D0 added a 1.9 T central solenoid, vertexing and fibre tracking, and new forward muon detectors. Alongside the instrumentation was a breath-taking evolution in real-time event selection (triggering) and data acquisition to keep up with the increasing luminosity of the collider.

The physics harvest of the Tevatron experiments during Run II was impressive, including a wealth of QCD measurements and major inroads in top-quark physics, heavy-flavour physics and searches for phenomena beyond the Standard Model. Still standing strong are its precision measurements of the W and top masses and of the electroweak mixing angle $\sin^2\theta_W$. The story ended in around 2012 with a glimpse of the Higgs boson in associated production with a vector boson. The CDF and D0 experience influenced the LHC era in many ways: for example they were able to extract the very rare single-top production cross-section with sophisticated multivariate algorithms, and they demonstrated the power of combining mature single-experiment measurements in common analyses to achieve ultimate precision and sensitivity.

For the machine builders, the pioneering role of the Tevatron as the first large superconducting machine was also essential for further progress. Two other machines – the Relativistic Heavy Ion Collider at Brookhaven and the electron–proton collider HERA at DESY – derived directly from the experience of building the Tevatron. Lessons learned from that machine and from the $Sp\bar{p}S$ were also integrated into the design of the most powerful hadron collider yet built: the LHC.

The Large Hadron Collider

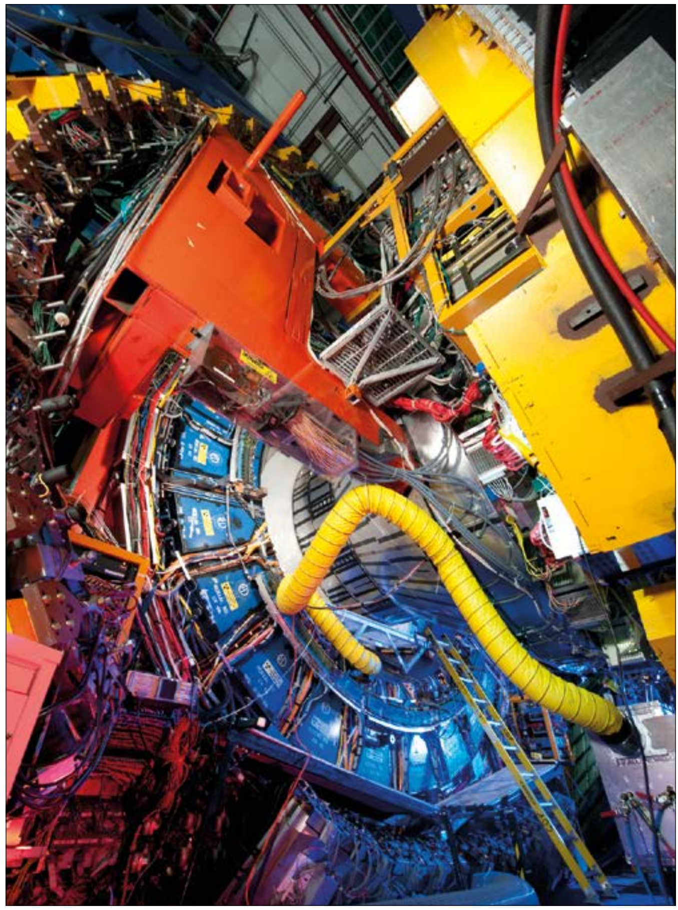
The LHC had a difficult birth. Although the idea of a large proton–proton collider at CERN had been around since at least 1977, the approval of the Superconducting Super Collider (SSC) in the US in 1987 put the whole project into doubt. The SSC, with a centre-of-mass energy of 40 TeV, was almost three times more powerful than what could ever be built using the existing infrastructure at CERN. It was only the resilience and conviction of Carlo Rubbia, who shared the 1984 Nobel Prize in Physics with van der Meer for the project leading to the discovery of the W and Z bosons, that kept the project alive. Rubbia, who became Director-General of CERN in 1989, argued that, in spite of its lower energy, the LHC could be competitive with the SSC by having a luminosity an order of magnitude higher, and at a fraction of the cost. He also argued that the LHC would be more versatile: as well as colliding protons, it would be able to accelerate heavy ions to record energies at little extra cost.

The SSC was eventually cancelled in 1993. This made the case for the LHC even stronger, but the financial climate in Europe at the time was not conducive to the approval of a large project. For example, CERN's largest contributor, Germany, was struggling with the cost of reunification and many other countries were getting to grips with the introduction of the single European currency. In December 1993 a plan was presented to the CERN Council to build the machine over a 10-year period by reducing the other experimental programmes at CERN to the absolute minimum, with the exception of the full exploitation of the flagship Large Electron Positron (LEP) collider. Although the plan was generally well received, it became clear that Germany and the UK were unlikely to agree to the budget increase required. On the positive side, after the demise of the SSC, a US panel on the future of particle physics recommended that "the government should declare its intentions to join other nations in constructing the LHC". Positive signals were also being received from India, Japan and Russia.

In June 1994 the proposal to build the LHC was made once more. However, approval was blocked by Germany and the UK, which demanded substantial additional contributions from the two host states, France and Switzerland. This forced CERN to propose a "missing magnet" machine where only two thirds of the dipole magnets would be installed in a first stage, allowing operation at reduced energy for a number of years. Although costing more in the long run, the plan would save some 300 million Swiss Francs in the first phase. This proposal was put to Council in December 1994 by the new Director-General Christopher Llewellyn Smith and, after a round of intense discussions, the project was finally approved for two-stage construction, to be reviewed in 1997 after non-Member States had made known their contributions. The first country to do so was Japan in 1995, followed by India, Russia and Canada the next year. A final sting in the tail came in June 1996 when Germany unilaterally announced that it intended to reduce its CERN subscription by between 8% and 9%, prompting the UK to demand a similar reduction and forcing CERN to take out loans. At the same time, the two-stage plan was dropped and, after a shaky start, the construction of the full LHC was given the green light.

The fact that the LHC was to be built at CERN, making full use of the existing infrastructure to reduce cost, imposed a number of strong constraints. The first was the 27 km-circumference of the LEP tunnel in which the machine was to be housed. For the LHC to achieve its design energy of 7 TeV per beam, its bending magnets would need to operate at a field of 8.3 T, about 60% higher than ever achieved in previous machines. This could only be done using affordable superconducting material by reducing the temperature of the liquid-helium coolant from its normal boiling point of 4.2 K to 1.9 K – where helium exists in a macroscopic quantum state with the loss of viscosity and a very large thermal conductivity. A second major constraint was the small (3.8 m) tunnel diameter, which made it impossible to house two independent rings like the ISR. Instead, a novel and elegant magnet design, first proposed by Bob Palmer at Brookhaven, with the two rings separated by only 19 cm in a common yoke and cryostat was developed. This also considerably reduced the cost.

At precisely 09:30 on 10 September 2008, almost 15 years after the project's approval, the first beam was injected into the LHC, amid global media attention. In the days that followed good progress was made until disaster struck: during a ramp to full energy, one of the 10,000 superconducting joints between the magnets failed, causing extensive damage which took more than a year to recover from. Following repairs and consolidation, on 29 November 2009 beam was once more circulating and full commissioning and operation could start. Rapid progress in ramping up the luminosity followed, and the LHC physics programme, at an initial energy of 3.5 TeV per beam, began in earnest in March 2010.



Fermilab

Top results
The Tevatron's CDF detector.

LHC experiments

Yet a whole other level of sophistication was realised by the LHC detectors compared to those at previous colliders. The priority benchmark for the designs of the general-purpose detectors ATLAS and CMS was to unambiguously discover (or rule out) the Standard Model Higgs boson for all possible masses up to 1 TeV, which demanded the ability to measure a variety of final states. The challenges for the Higgs search also guaranteed the detectors' potential for all kinds of searches for physics beyond the Standard Model, which was the other driving physics motivation at the energy frontier. These two very ambitious LHC detector designs integrated all the lessons learned from the experiments at the three predecessor machines, as well as further technology advances in other large experiments, most notably at HERA and LEP.

Just a few simple numbers illustrate the giant leap from the Tevatron to the LHC detectors. CDF and D0, in their upgraded versions operating at a luminosity of up to

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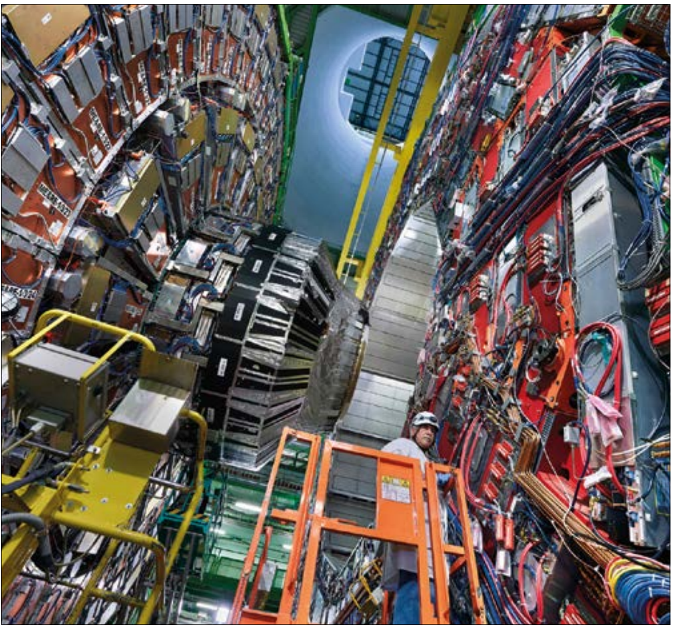


Insert here *The LHC's CMS experiment undergoing upgrades in 2019.*

4×10^{32} cm^{-2}s^{-1}, typically had around a million channels and a triggered event rate of 100 Hz, with event sizes of 500 kB. The collaborations were each about 600 strong. By contrast, ATLAS and CMS operated during LHC Run 2 at a luminosity of 2×10^{34} cm^{-2}s^{-1} with typically 100 million readout channels, and an event rate and size of 500 Hz and 1500 kB. Their publications have close to 3000 authors.

For many major LHC-detector components, complementary technologies were selected. This is most visible for the superconducting magnet systems, with an elegant and unique large 4 T solenoid in CMS serving both the muon and inner tracking measurements, and an air-core toroid system for the muon spectrometer in ATLAS together with a 2 T solenoid around the inner tracking cylinder. These choices drove the layout of the active detector components, for instance the electromagnetic calorimetry. Here again, different technologies were implemented: a novel-configuration liquid-argon sampling calorimeter for ATLAS and lead-tungstate crystals for CMS.

From the outset, the LHC was conceived as a highly versatile collider facility, not only for the exploration of high transverse-momentum physics. With its huge production of b and c quarks, it offered the possibility of a very fruitful programme in flavour physics, exploited with great success by the purposely designed LHCb experiment. Furthermore, in special runs the LHC provides heavy-ion collisions for studies of the quark–gluon plasma – the field of action for the ALICE experiment.

As the general-purpose experiments learned from the history of experiments in their field, the concepts of both LHCb and ALICE also evolved from a previous generation of experiments in their fields, which would be interesting to trace back. One remark is due: the designs of all four main detectors at the LHC have turned out to be so flexible that there are no strict boundaries between these three physics fields for them. All of them have learned to use features of their instruments to contribute at least in part to the full physics spectrum offered by the LHC, of which the highlight so far was the July 2012 announcement of the discovery of the Higgs boson by the ATLAS and CMS collaborations. The following year the collaborations were named in the citation for the 2013 Nobel Prize in Physics awarded to François Englert and Peter Higgs.

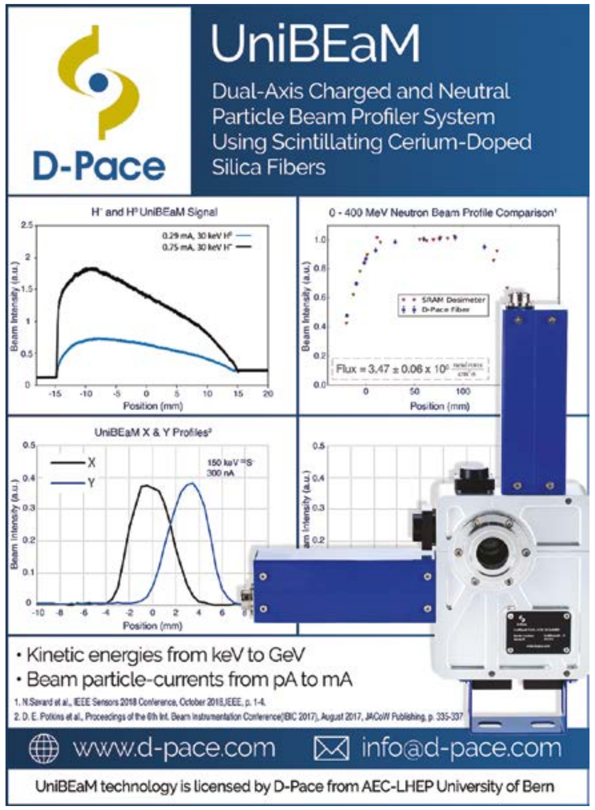
This journey is now poised to continue, as we look ahead towards how a general-purpose detector at a future 100 TeV hadron collider might look like

Since then, the LHC has exceeded its design luminosity by a factor of two and delivered an integrated luminosity of almost 200 fb^{-1} in proton–proton collisions, while its beam energy was increased to 6.5 TeV in 2015. The machine has also delivered heavy ion (lead–lead) and even lead–proton collisions. But the LHC still has a long way to go before its estimated end of operations in the mid-to-late 2030s. To this end, the machine was shut down in November 2018 for a major upgrade of the whole of the CERN injector complex as well as the detectors to prepare for operation at high luminosities, ultimately up to a "levelled" luminosity of 7×10^{34} cm^{-2}s^{-1}. The High Luminosity LHC (HL-LHC) upgrade is pushing the boundaries of superconducting magnet technology to the limit, particularly around the experiments where the present focusing elements will be replaced by new magnets built from high-performance Nb$_3$Sn superconductor. The eventual objective is to accumulate 3000 fb^{-1} of integrated luminosity.

In parallel, the LHC-experiment collaborations are preparing and implementing major upgrades to their detectors using novel state-of-the-art technologies and revolutionary approaches to data collection to exploit the tenfold data volume promised by the HL-LHC. Hadron-collider detector concepts have come a long way in sophistication over the past 50 years. However, behind the scenes are other factors paramount to their success. These include an equally spectacular evolution in data-flow architectures, software and the computing approaches, and analysis methods – all of which have been driven into new territories by the extraordinary needs for dealing with rare events within the huge backgrounds of ordinary collisions at hadron colliders. Worthy of particular mention in the success of all LHC physics results is the Worldwide LHC Computing Grid. This journey is now poised to continue, as we look ahead towards how a general-purpose detector at a future 100 TeV hadron collider might look like.

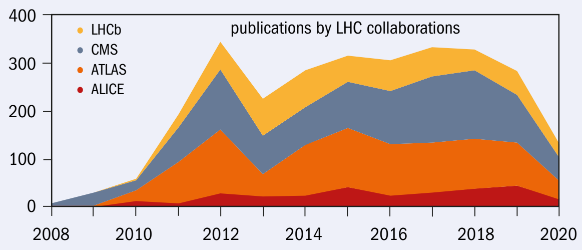
Beyond the LHC

Although the LHC has at least 15 years of operations ahead of it, the question now arises, as it did in 1964: what is the next step for the field? The CERN Council has recently approved the recommendations of the 2020 update of the European strategy for particle physics, which includes, among other things, a thorough study of a very high-energy hadron collider to succeed the LHC. A technical and financial feasibility study for a 100 km circular collider at CERN with a collision energy of at least 100 TeV is now under way. While a decision to proceed with such a facility is to come later this decade, one thing is certain: lessons learned from 50 years of experience with hadron colliders and their detectors will be crucial to the success of our next step into the unknown. ●

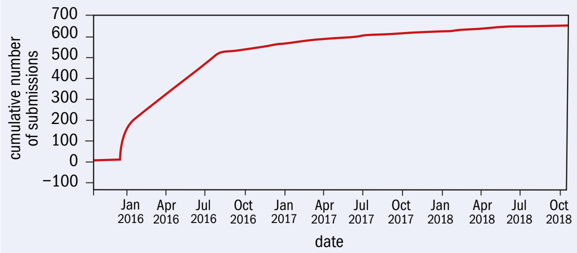


A DECADE IN LHC PUBLICATIONS

The first 10 years of LHC operations have generated a bumper crop of new knowledge.



2852 papers from experiment *From the first publications in 2008 that described the detector designs, through 2012's discovery of the Higgs boson, all the way to CMS's 1000th publication in 2020.*



André David

750 shades of model building *There was a major influx of papers from the theory community when hints of a 750 GeV resonance were found by the LHC experiments – only to turn out to be a statistical fluctuation.*

THE AUTHORS

Alex Kohls, Jens Vigen and **Micha Moskovic** *CERN.*

In June 2020, the CMS collaboration submitted a paper titled "Observation of the production of three massive gauge bosons at $\sqrt{s} = 13$ TeV" to the arXiv preprint server. A scientific highlight in its own right, the paper also marked the collaboration's thousandth publication. ATLAS is not far from reaching the same milestone, currently at 964 publications (data correct as of 7 January). With the rest of the LHC experiments taking the total number of papers to 2852, the first 10 years of LHC operations have generated a bumper crop of new knowledge.

The publication landscape in high-energy physics (HEP) is exceptional due to a long-held preprint culture. At CERN, paper copies were kept in cabinets outside the library from the 1950s onwards, but since the early 1990s a growing number have been stored electronically at arXiv.org. Preprint posting and actual journal publication often happen at the same time, and citations between all types of publications are compiled and counted in the INSPIRE system.

Particle physics has fully embraced the open-science movement, in publishing, software, hardware and, most recently, data. In 2004 former Director-General Robert Aymar encouraged the creation of SCOAP^3 (Sponsoring Consortium for Open Access Publishing in Particle Physics) at CERN. Devoted to converting closed access HEP journals to open access, SCOAP^3 has grown extensively and now has more than 3000 libraries from 44 different countries. All original LHC research results have been published open access. The first collaboration articles by the four main experiments, describing the detector designs, and published in the *Journal of Instrumentation*, remain amongst the most cited articles from LHC collaborations and – despite being more than a decade old – are some of the most recently read articles of the journal.

Since then, along with the 2852 publications by the LHC experiments, some 380 papers have been written by individuals on behalf of the collaboration. A further 10,879 articles (preprints, conference proceedings, etc) from the LHC experiments were not published in a peer-reviewed journal. However, this still represents only part of the scientific relevance of the LHC. There were tens of thousands of additional papers published over the past decade that mention the LHC experiments, use their data or are based on the LHC's findings. The papers published by the four major experiments received on average 112 citations per paper, compared to an average of 41 citations per paper across all experimental papers indexed in INSPIRE and even 30 citations per paper across all HEP publications (4.8 million citations across 163,000 documents since 2008). Unsurprisingly, the number of citations peaks with the CMS and ATLAS papers on the Higgs-boson discovery, with 10,910 and 11,195 citations, respectively, which at the end of 2019 were the two most cited high-energy physics papers released in the past decade.

Large author numbers are another exceptional aspect of LHC-experiment publishing

Large author numbers are another exceptional aspect of LHC-experiment publishing, with papers consistently carrying hundreds or even thousands of names. This culminated in a world record of 5154 authors on a joint paper between CMS and ATLAS in 2015, which reduced the uncertainty on the measurement of the Higgs-boson mass to ±0.25%.

Ten years of LHC publications have established the Standard Model at unprecedented levels of precision. But the hunger for new physics is clear (see "750 shades of model building" figure). On 15 December 2015, ATLAS and CMS presented data that hinted at an excess of events at 750 GeV in proton collisions, fuelling hopes that a new particle might be showing itself. While the significance of the excess was only 2σ and 1.6σ, respectively, theorists were quick to respond with an influx of hundreds of papers. This excitement was, however, damped by the release of the August 2016 data, where there was no further sign of the anomaly, and it became commonly recognised as a statistical fluctuation – part and parcel of the scientific process, if ruining the fun for the theorists.

With the LHC to continue operations to the mid-2030s, and only around 6% of its expected total dataset collected so far, we can look forward to thousands more publications about nature's basic constituents being placed in the public domain. ●

OPINION VIEWPOINT

Connecting physics with society

Audiences never look at particle physics with the same eyes once they've learned about its wider applications, says Barbora Bruant Gulejova

B Gulejova

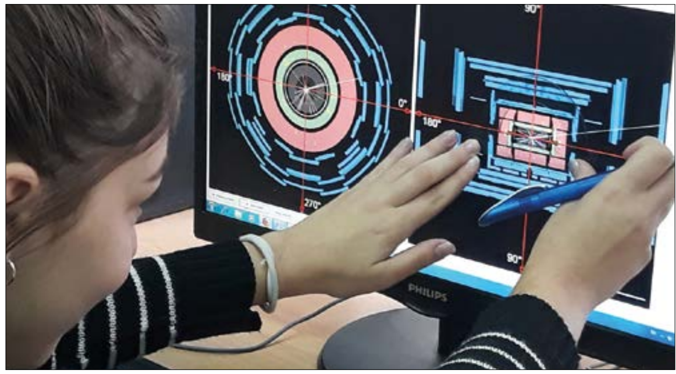
Barbora Bruant Gulejova *is strategic development lead for the International Particle Physics Outreach Group, and former industry and knowledge-transfer liaison officer for Slovakia with CERN.*

Science and basic research are drivers of technologies and innovations, which in turn are key to solving global challenges such as climate change and energy. The United Nations has summarised these challenges in 17 "sustainable development goals", but it is striking how little connection with science they include. Furthermore, as found by a UNESCO study in 2017, the interest of the younger generation in studying science, technology, engineering and mathematics is falling, despite jobs in these areas growing at a rate three times faster than in any other sector. Clearly, there is a gulf between scientists and non-scientists when it comes to the perception of the importance of fundamental research in their lives – to the detriment of us all.

Try asking your neighbours, kids, family members or mayor of your city whether they know about the medical and other applications that come from particle physics, or the stream of highly qualified people trained at CERN who bring their skills to business and industry. While the majority of young people are attracted to physics by its mindboggling findings and intriguing open questions, our subject appeals even more when individuals find out about its usefulness outside academia. This was one of the key outcomes of a recent survey, *Creating Ambassadors for Science in Society*, organised by the International Particle Physics Outreach Group (IPPOG).

Do most "Cernois" even know about the numerous start-ups based on CERN technologies or the hundreds of technology disclosures from CERN, 31 of which came in 2019 alone? Or about the numerous success stories contained within the CERN impact brochure and the many resources of CERN's knowledge-transfer group? Even though "impact" is gaining attention, anecdotally when I presented these facts to my research colleagues they were not fully aware. Yet who else will be our ambassadors, if not us?

Reaching out to non-physicists is more important than ever



M Polykapoulou

Hands on A high-school student analysing ATLAS collisions during World Wide Data Day organised under the umbrella of IPPOG, Serres, Greece.

Some in the community are resistant to communicate physics spin-offs because this is not our primary purpose. Yet, millions of people who have lost their income as a result of COVID-19 are rather more concerned about where their next rent and food payments are coming from, than they are about the couplings of the Higgs boson. Reaching out to non-physicists is more important than ever, especially to those with an indifferent or even negative attitude to science. Differentiating audiences between students, general public and politicians is not relevant when addressing non-scientifically educated people. Strategic information should be proactively communicated to all stakeholders in society in a relatable way, via eye-opening, surprising and emotionally charged stories about the practical applications of curiosity-driven discoveries.

IPPOG has been working to provide such stories since 2017 – and there is no shortage of examples. Take the touchscreen technology first explored at CERN 40 years ago, or humanitarian satellite mapping carried out for almost 20 years by UNOSAT, which is hosted at CERN. Millions of patients are diagnosed daily thanks to tools like PET and MRI, while more recent medical developments include innovative radioisotopes from MEDICIS for precision medicine, the first 3D colour X-ray images, and novel cancer treatments based on superconducting accelerator technology. In the environmental arena, recent CERN spin-offs include a global network of air-quality sensors and fibre-optic sensors for improved water and pesticide management, while CERN open-source software is used for digital preservation in libraries and its computing resources have been heavily deployed in fighting the pandemic.

Building trust

Credibility and trust in science can only be built by scientists themselves, while working hand in hand with professional communicators, but not relying only on them. Extracurricular activities, such as those offered by IPPOG, CERN, other institutions and individual initiatives, are crucial in changing the misperceptions of the public and bringing about fact-based decision-making to the young generation. Scientists should develop a proactive strategic approach and even consider becoming active in policy making, following the shining examples of those who helped realise the SESAME light source in the Middle East and the South East European International Institute for Sustainable Technologies.

Particle physics already inspires some of the brightest minds to enter science. But audiences never look at our subject with the same eyes once they've learned about its applications and science-for-peace initiatives.

OPINION
INTERVIEW

Still seeking solutions

Steven Weinberg reflects on the Breakthrough Prize, effective field theory, and his latest attempt to understand the fermion mass hierarchy.

How did winning a Special Breakthrough Prize last year compare with the Nobel Prize?
It came as quite a surprise because as far as I know, none of the people who have been honoured with the Breakthrough Prize had already received the Nobel Prize. Of course nothing compares with the Nobel Prize in prestige, if only because of the long history of great scientists to whom it has been awarded in the past. But the Breakthrough Prize has its own special value to me because of the calibre of the young – well, I think of them as young – theoretical physicists who are really dominating the field and who make up the selection committee.

The prize committee stated that you would be a recognised leader in the field even if you hadn't made your seminal 1967 contribution to the genesis of the Standard Model. What do you view as Weinberg's greatest hits?
There's no way I can answer that and maintain modesty! That work on the electroweak theory leading to the mass of the W and Z, and the existence and properties of the Higgs, was certainly the biggest splash. But it was rather untypical of me. My style is usually not to propose specific models that will lead to specific experimental predictions, but rather to interpret in a broad way what is going on and make very general remarks, like with the development of the point of view associated with effective field theory. Doing this I hope to try and change the way my fellow physicists look at things, without usually proposing anything specific. I have occasionally made predictions, some which actually worked, like calculating the pion–nucleon and pion–pion scattering lengths in the mid-1960s using the broken symmetry that had been proposed by Nambu. There were other things, like raising the whole issue of the cosmological constant before the discovery of the accelerated expansion of the universe. I worried about that – I gave a series of lectures at Harvard in which I finally concluded that the only way I can understand why there isn't an enormous vacuum energy is because of some kind of anthropic selection. Together with two guys here at Austin, Paul Shapiro and Hugo Martel, we worked out what was the most likely value that would be found in terms of order of magnitude, which was later found to be correct. So I was very pleased that the Breakthrough Prize acknowledged some of those things that didn't lead to specific predictions but changed a general framework.

Deep mind *Steven Weinberg is director of the theory research group, University of Texas at Austin.*

M Valentine

I wish I could claim that I had predicted the neutrino mass

You coined the term effective field theory (EFT) and recently inaugurated the online lecture series *All Things EFT*. What is the importance of EFT today?
My thinking about EFTs has always been in part conditioned by thinking about how we can deal with a quantum theory of gravitation. You can't represent gravity by a simple renormalisable theory like the Standard Model, so what do you do? In fact, you treat general relativity the same way you treat low-energy pions, which are described by a low-energy non-renormalisable theory. (You could say it's a low-energy limit of QCD but its ingredients are totally different – instead of quarks and gluons you have pions). I showed how you can generate a power series for any given scattering amplitude in powers of energy rather than some small coupling constant. The whole idea of EFT is that any possible interaction is there: if it's not forbidden it's compulsory. But the higher, more complicated terms are suppressed by negative powers of some very large mass because the dimensionality of the coupling constants is such that they have negative powers of mass, like the gravitational constant. That's why they're so weak.

If you recognise that the Standard Model is probably a low-energy limit of some more general theory, then you can consider terms that make the theory non-renormalisable and generate corrections to it. In particular, the Standard Model has this beautiful feature that in its simplest renormalisable version there are symmetries that are automatic: at least to all orders of perturbation theory, it can't violate the conservation of baryon or lepton number. But if the Standard Model just generates the first term in a power series in energy and you allow for more complicated non-renormalisable terms in the Lagrangian, then you find it's very natural that there would be baryon and lepton non-conservation. In fact, the leading term of this sort is a term that violates lepton number and gives neutrinos the masses we observe. I wish I could claim that I had predicted the neutrino mass, but there already was evidence from the solar neutrino deficit and also it's not certain that this is the explanation of neutrino masses. We could have Dirac neutrinos in which you have left and right neutrinos and antineutrinos coupling to the Higgs, and in that way get masses without any violation of lepton-number conservation. But I find that thoroughly repulsive because there's no reason in that case why the neutrino masses should be so small, whereas in the EFT case we have Majorana neutrinos whose small masses are much more natural.

On this point, doesn't the small value of the cosmological constant and Higgs mass undermine the EFT view by pointing to extreme fine-tuning?
Yes, they are a warning about things we don't understand. The Higgs mass less so, after all it's only about a hundred times larger than the proton mass and we know why the proton mass is so small compared to the GUT or Planck scale; it is because the proton gets it mass not from the quark masses, which have to do with the Higgs, but from the QCD forces, and we know that those become strong very slowly as you come down from high energy. We don't understand this for the Higgs mass, which, after all, is a term in the Lagrangian, not like the proton mass. But it may be similar – that's the old technicolour idea, that there is another coupling alongside QCD that becomes strong at some energy where it leads to a potential for the Higgs field, which then breaks electroweak symmetry. Now, I don't have such a theory, and if I did I wouldn't know how to test it. But there's at least a hope for that. Whereas regards to the cosmological constant, I can't think of anything along that line that would explain it. I think it was Nima Arkani-Hamed who said to me, "If the anthropic effect works for the cosmological constant, maybe that's the answer with the Higgs mass – maybe it's got to be small for anthropic reasons." That's very disturbing if it's true, as we're going to be left waving our hands. But I don't know.


Effective *Weinberg delivering a special seminar at CERN in December 1979, the year he won the Nobel Prize and published a seminal paper on effective field theory.*

CERN

Early last year you posted a preprint "Models of lepton and quark masses" in which you returned to the problem of the fermion mass hierarchy. How was it received?
Even in the abstract I advertise how this isn't a realistic theory. It's a problem that I first worked on almost 50 years ago. Just looking at the table of elementary particle masses I thought that the electron and the muon were crying out for an explanation. The electron mass looks like a radiative correction to the muon mass, so I spent the summer of 1972 on the back deck of our house in Cambridge, where I said, "This summer I am going to solve the problem of calculating the electron mass as an order-alpha correction to the muon mass." I was able to prove that if in a theory it was natural in the technical sense that the electron would be massless in the tree approximation as a result of an accidental symmetry, then at higher order the mass would be finite. I wrote a paper, but then I just gave it up after no progress, until now when I went back to it, no longer young, and again I found models in which you do have an accidental symmetry. Now the idea is not just the muon and the electron, but the third generation feeding down to give masses to the second, which would then feed down to give masses to the first. Others have proposed what might be a more promising idea, that the only mass that isn't zero in the tree approximation is the top mass, which is so much bigger than the others, and everything else feeds down from that. I just wanted to show the kinds of cancellations in infinites that can occur, and I worked out the calculations. I was hoping that when this paper came out some bright young physicist would come up with more realistic models, and use these calculational techniques – that hasn't happened so far but it's still pretty early.

> **Maybe we have 2500 years ahead of us before we get to the next big step**

What other inroads are there to the mass/flavour hierarchy problem?
The hope would be that experimentalists discover some correction to the Standard Model. The problem is that we don't have a theory that goes beyond the Standard Model, so what we're doing is floundering around looking for corrections in the model. So far, the only one discovered was the neutrino mass and that's a very valuable piece of data which we so far have not figured out how to interpret. It definitely goes beyond the Standard Model – as I mentioned, I think it is a dimension-five operator in the effective field theory of which the Standard Model is the renormalisable part.

The big question is whether we can cut off some sub-problem that we can actually solve with what we already know. That's what I was trying to do in my recent paper and did not succeed in getting anywhere realistically. If that is not possible, it may be that we can't make progress without a much deeper theory where the constituents are much more massive, something like string theory or an asymptotically safe theory. I still think string theory is our best hope for the future, but this future seems to be much further away than we had hoped it would be. Then I keep being reminded of Democritus, who proposed the existence of atoms in around 400 BCE. Even as late as 1900 physicists like Mach doubted the existence of atoms. They didn't become really nailed down until the first years of the 20th century. So maybe we have 2500 years ahead of us before we get to the next big step.

Recently the LHC produced the first evidence that the Higgs boson couples to a second-generation fermion, the muon. Is there reason to think the Higgs might not couple to all three generations?

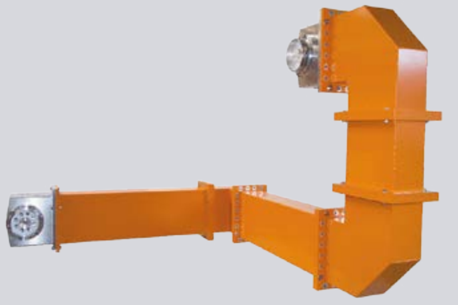
Before the Higgs was discovered it seemed quite possible that the explanation of the hierarchy problem was that there was some new technicolour force that gradually became strong as you came from very high energy to lower energy, and that somewhere in the multi-TeV range it became strong enough to produce a breakdown of the electroweak symmetry. This was pushed by Lenny Susskind and myself, independently. The problem with that theory was then: how did the quarks and leptons get their masses? Because while it gave a very natural and attractive picture of how the W and Z get their masses, it left it really mysterious for the quarks and leptons. It's still possible that something like technicolour is true. Then the Higgs coupling to the quarks and leptons gives them masses just as expected. But in the old days, when we took technicolour seriously as the mechanism for breaking electroweak symmetry, which, since the discovery of the Higgs we don't take seriously anymore, even then there was the question of how, without a scalar field, can you give masses to the quarks and leptons. So, I would say today, it would be amazing if the quarks and leptons were not getting their masses from the expectation value of the Higgs field. It's important now to see a very high precision test of all this, however, because small effects coming from new physics might show up as corrections. But these days any suggestion for future physics facilities gets involved in international politics, which I don't include in my area of expertise.

> **It's still possible that something like technicolour is true**

Any more papers or books in the pipeline?

I have a book that's in press at Cambridge University Press called *Foundations of Modern Physics*. It's intended to be an advanced undergraduate textbook that takes you from the earliest work on atoms, through thermodynamics, transport theory, Brownian motion, to early quantum theory; then relativity and quantum mechanics, and I even have two chapters that probably go beyond what any undergraduate would want, on nuclear physics and quantum field theory. It unfortunately doesn't fit into what would normally be the plan for an undergraduate course, so I don't know if it will be widely adopted as a textbook. It was the result of a lecture course I was asked to give called "thermodynamics and quantum physics" that has been taught at Austin for years. So, I said "alright", and it gave me a chance to learn some thermodynamics and transport theory.

Interview by **Matthew Chalmers**.



OPINION REVIEWS

The hitchhiker's guide to weak decays

Gauge Theory of Weak Decays: The Standard Model and the Expedition to New Physics Summits

By Andrzej J Buras

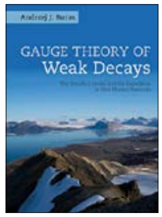
Cambridge University Press

Most travellers know that it is essential to have a good travel guide when setting out into unexplored territory. A book where one can learn what previous travellers discovered about these surroundings, with both global information on the language, history and traditions of the land to be explored, and practical details on how to overcome day-to-day difficulties. Andrzej Buras's recent book, *Gauge Theory of Weak Decays*, is the ideal guide for both new physicists and seasoned travellers, and experimentalists and theoreticians alike, who wish to start a new expedition into the fascinating world of weak meson decays, in pursuit of new physics.

The physics of weak decays is one of the most active and interesting frontiers in particle physics, from both the theoretical and the experimental points of view. Major steps in the construction of the Standard Model (SM) have been made possible only thanks to key observations in weak decays. The most famous example is probably the suppression of flavour-changing neutral currents in kaon decays, which led Glashow, Iliopoulos and Maiani to postulate, in 1970, the existence of the charm quark, well before its direct discovery. But there are many other examples, such as the heaviness of the top quark, inferred from the large matter-to-antimatter oscillation frequency of neutral B mesons, again well before its discovery. In the post-Higgs-discovery era, weak decays are a privileged observatory in which to search for signals of physics beyond the SM. The recent "B-physics anomalies", reported by LHCb and other experiments, could indeed be the first hint of new physics. The strategic role that weak decays play in the search for new physics is further reinforced by the absence on the horizon, at least in the near future, of a collider with a centre-of-mass energy exceeding that of the LHC, while the LHC and other facilities still have a large margin of improvement in precision measurements.


S Berger

Don't forget your towel *Andrzej Buras's new book is an indispensable travel guide to unexplored territory in weak decays, writes our reviewer.*


CUP

As Buras describes with clarity, signals of new physics in the weak decays of K, D, and B mesons, and other rare low-energy processes, could manifest themselves as deviations from the precise predictions of the corresponding decay rates that we are able to derive within the SM. In the absence of a reference beyond-the-SM theory, it is not clear where, and at which level of precision, these deviations could show up. But general quantum field theory arguments suggest that weak decays are particularly sensitive probes of new physics, as they can often be predicted with high accuracy within the SM.

The two necessary ingredients for a journey in the realm of weak decays are therefore precise SM predictions on the one hand, and a broad-spectrum investigation of beyond-the-SM sensitivity on the other. These are precisely the two ingredients of Buras's book. In the first part, he guides the reader though all the steps necessary to arrive to the most up-to-date predictions for rare decays. This part of the book offers different paths to different readers: students are guided, in a very pedagogical way, from tree-level calculations to high-precision multi-loop calculations. Experienced readers can directly find up-to-date phenomenological expressions that summarise the present knowledge on virtually any process of current experimental interest. This part of the book can also be viewed as a well-thought-out summary of the history of precise SM calculations for weak decays, written by one of its most relevant protagonists.

The second part of the book is devoted to physics beyond the SM. Here the style is quite different: less pedagogical and more encyclopaedic. Employing a pragmatic approach, which is well motivated to discuss low-energy processes, extensions of the SM are classified according to properties of hypothetical new heavy particles, from Z′ bosons to leptoquarks, and from charged Higgs bosons to "vector-like" fermions. This allows Buras to analyse the impact of such models on rare processes in a systematic way, with great attention paid to correlations between observables.

To my knowledge, this book is the first comprehensive monograph of this type, covering far more than just the general aspects of SM physics, as may be found in many other texts on quantum field theory. The uniqueness of this book lies in its precious details on a wide variety of interesting rare processes. It is a key reference that was previously missing, and promises to be extremely useful in the coming decades.

Gino Isidori *University of Zurich.*

The Science of Learning Physics: Cognitive Strategies for Improving Instruction

By José P Mestre and Jennifer L Docktor

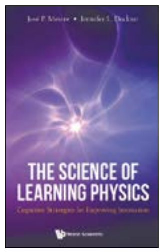
World Scientific

A greying giant of the field speaks to the blackboard for 45 minutes before turning, dismissively seizing paper and scissors, and cutting a straight slit. The sheet is twisted to represent the conical space-time described by the symbols on the board. A lecture theatre of students is transfixed in admiration.

A means for lecturers to reflect on and enrich their teaching strategies

This is not the teaching style advocated by José Mestre and Jennifer Docktor in their new book *The Science of Learning Physics*. And it's no longer typical, say the authors, who suggest that approximately half of physics lecturers use at least one ▷

"evidence-based instructional practice" – jargon, most often, for an interactive teaching method. As colleagues joked when I questioned them on their teaching styles, there is still a performative aspect to lecturing, but these days it is just as likely to reflect the rock-star feeling of having a hundred camera phones pointed at you – albeit so the students can snap a QR code on your slide to take part in an interactive mid-lecture quiz.



World Scientific

Mestre and Docktor, who are both educational psychologists with a background in physics, offer intriguing tips to maximise the impact of such practices. After answering a snap poll, they say, students should discuss with their neighbour before being polled again. The goal is not just to allow the lecturer to tailor their teaching, but also to allow students to "construct" their knowledge. Lecturing, they say, gives piecemeal information, but does not connect it. Neurons fire, but synaptic connections are not trained. And as the list of neurotransmitters that reinforce synaptic connections includes dopamine and serotonin, making students feel good by answering questions correctly may be worth the time investment.

Relative to other sciences, physics lecturers are leading the way in implementing evidence-based instructional practices, but far too few are well trained, say Mestre and Docktor, who want to bring the tools and educational philosophies of the high-school physics teacher to the lecture theatre. Swiss and Soviet developmental psychologists Jean Piaget and Lev Vygotsky are duly namechecked. "Think–pair–share", mini whiteboards and flipping the classroom (not a discourteous gesture but the advance viewing of pre-recorded lectures before a more participatory lecture), are the order of the day. Students are not blank slates, they write, but have strong attachments to deeply ingrained and often erroneous intuitions that they have previously constructed. Misconceptions cannot be supplanted wholesale, but must be unknotted strand by strand. Lecturers should therefore explicitly describe their thought processes and encourage students to reflect on "metacognition", or "thinking about thinking". Here the text is reminiscent of Nobelist Daniel Kahneman's seminal text *Thinking, Fast and Slow*, which divides thinking into two types: "system 1", which is instinctive and emotional, and "system 2", which is logical but effortful. Lecturers must fight against "knee-jerk" reasoning, say Mestre and Docktor, by modelling the time-intensive construction of knowledge, rather than aspiring to misleading virtuoso displays of mathematical prowess. Wherever possible, this should be directly assessed by giving marks not just for correct answers, but also for identifying the "big idea" and showing your working.

Disappointingly, examples are limited to pulleys and ramps, and, somewhat ironically, the book's dusty academic tone may prove ineffective at teaching teachers to teach. But no other book comes close to *The Science of Learning Physics* as a means for lecturers to reflect on and enrich their teaching strategies, and it is highly recommend on that basis. That said, my respect for my old general-relativity lecturer remained undimmed as I finished the last page. Those old-fashioned lectures were hugely inspiring – a "non-cognitive aspect" that Mestre and Docktor admit their book does not consider.

Mark Rayner *associate editor.*

Accelerating talent at CERN

While CERN holds a natural attraction for physicists, hiring the engineers, technicians and others who build, operate and maintain the lab's complex infrastructure is more challenging, explains Anna Cook.

CERN

Engineering prowess *Natalia Magdalena Koziol, an engineer from Poland, is responsible for quality assurance of the LHC's insulation vacuum during Long Shutdown 2.*

CERN enjoys a world-class reputation as a scientific laboratory, with the start-up of the Large Hadron Collider and the discovery of the Higgs boson propelling the organisation into the public spotlight. Less tangible and understood by the public, however, is that to achieve this level of success in cutting-edge research, you need the infrastructure and tools to perform it. CERN is an incredible hub for engineering and technology – hosting a vast complex of accelerators, detectors, experiments and computing infrastructure. Thus, CERN needs to attract candidates from across a wide spectrum of engineering and technical disciplines to fulfil its objectives.

CERN employs around 2600 staff members who design, build, operate, maintain and support an infrastructure used by a much larger worldwide community of physicists. Of these, only 3% are research physicists. The core hiring needs are for engineers, technicians and support staff in a wide variety of domains: mechanical, electrical, engineering, vacuum, cryogenics, civil engineering, radiation protection, radiofrequency, computing, software, hardware, data acquisition, materials science, health and safety... the list goes on. Furthermore, there are also competences needed in human resources, legal matters, communications, knowledge transfer, finance, firefighters, medical professionals and other support functions.

On the radar

CERN's hiring challenge takes on even greater meaning when one considers the drive to attract students, graduates and professionals from across CERN's 32 Member and Associate Member States. In what is already a competitive market, attracting people from a large multitude of disciplines to an organisation whose reputation revolves around particle physics can be a challenge. So how is this challenge tackled? CERN now has a well-established "employer brand", developed in 2010 to promote its opportunities in an increasingly digitalised environment. The brand centres around factors that make working at CERN the rich experience that it is, namely challenge, purpose, imagination, collaboration, integrity and quality of life – underpinned by the slogan "Take part". This serves as an identity to devise attractive campaigns through web content, video, online, social media and job-portal advertisements to promote CERN as an employer of choice to the audiences we seek to reach: from students to professionals, apprenticeships to PhDs, across all diversity dimensions. The intention is to put CERN "on the radar" of people who wouldn't normally identify CERN as a possibility in their chosen career path.

> **I get to challenge myself in areas and with technology you don't see any other place in the world**

As no single channel exists that will allow targeting of, for example, a mechanical technician in all CERN Member States, creative and innovative approaches have to be utilised. The varying landscapes, cultural preferences and languages come into play, and this is compounded by the different job-seeking behaviours of students, graduates and experienced professionals through a constantly evolving ecosystem of channels and solutions. A widespread presence is key. The cornerstones are: an attractive careers website; professional networks such as LinkedIn to promote CERN's employment opportunities and proactively search for candidates; social media to increase visibility of hiring campaigns; and being present on various job portals, for example in the oil, gas and energy arenas. Outreach events, presence at university career fairs and online webinars further serve to present CERN and its diverse opportunities to the targeted audiences.

Storytelling is an essential ingredient in promoting our opportunities, as are the experiences of those already working at CERN. In the words of Håvard, an electromechanical technician from Norway: "I get to challenge myself in areas and with technology you don't see any other place in the world." Gunnar, a firefighter from Germany describes, "I am working as a

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IOP Publishing

firefighter in one of the most international fire brigades at CERN in what is a very complex, challenging and interesting environment." Katarina, a computing engineer from Sweden, says, "The diversity of skills needed at CERN is so much larger than what most people know!" While Julia, a former mechanical engineering technical student from the UK put it simply: "I never knew that CERN recruited students for internships." Natasha, a former software engineering fellow from Pakistan, summed it up with, "Here I am, living my dreams, being a part of an organisation that's helping me grow every single day." Each individual experience is a rich insight for potential candidates to identify with and recognise the possibility of joining CERN in their own right.

CERN doesn't just bring together people from a large scope of fields but unites people from all over the world. Working as summer, technical or doctoral student, as a graduate or professional, builds skills and knowledge that are highly transferable in today's demanding and competitive job market, along with lasting connections. As the cherry on the cake, a job at CERN paves the way to become CERN's future alumni and join the ever-growing High-Energy Network. Take part!

Anna Cook *CERN HR department.*

Appointments and awards

ESA announces new DG

The European Space Agency (ESA) Council has appointed Josef Aschbacher as its next director general for a period of four years. He will succeed Jan Wörner from 30 June. Aschbacher is currently ESA director of Earth observation programmes and head of ESA's centre for Earth observation near Rome. Born in Austria, he studied at the University of Innsbruck, where he obtained Masters and PhD degrees in natural sciences. He has more than three decades of experience working in international organisations, including ESA, the European Commission, the Austrian Space Agency and the Asian Institute of Technology.


ESA

JINR director change

Grigory Trubnikov has been appointed as the new director of the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. Trubnikov, who first joined JINR in 1996 as a researcher, was previously vice-director at JINR and served as Russia's deputy minister of education and science from 2017–2020. He replaces Victor Matveev, who was JINR director since 2012. With a term time of five years, Trubnikov will oversee an important period at JINR, with the scheduled completion of the NICA complex in 2022 (see p9).


S Krasilnikov/TASS

SCIPP's new skipper

Jason Nielsen of the University of California at Santa Cruz has taken over as director of the Santa Cruz Institute for Particle Physics (SCIPP), succeeding Steven Ritz who steps down after 10 years at the helm. Nielsen, who has served as associate director of SCIPP for the past eight years, started out on the ALEPH experiment at LEP and is a long-standing member of the ATLAS collaboration, for which he currently serves on the management advisory committee for the US ATLAS organisation.


G Fisher

France recognises Godbole

Phenomenologist Rohini Godbole of the Centre for High Energy Physics, Indian Institute of Science, Bangalore, has been awarded with the Ordre national du Mérite (National Order of Merit), one of the highest distinctions granted by France. Godbole was recognised for her contributions towards collaborations between France and India and for her role in promoting women's visibility in science. Godbole's decades of work in particle physics has ranged from supersymmetry to electroweak theory, and she is currently a member of the international detector advisory group for the International Linear Collider.


ThinkEdu Conclave

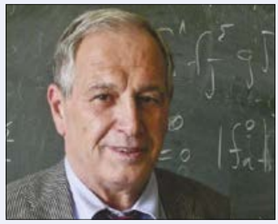
IceCube awarded Rossi Prize

The 2021 Bruno Rossi Prize was awarded to Francis Halzen (below) and the IceCube Collaboration for the discovery of a high-energy neutrino flux of astrophysical origin. Halzen is principal investigator and co-spokesperson of the IceCube project based at the South Pole, which in September 2017 detected a high-energy neutrino from the direction of a blazar, providing the first evidence of a source of high-energy cosmic rays. The Bruno Rossi Prize is awarded for a significant contribution to high-energy astrophysics, with a particular emphasis on recent work.

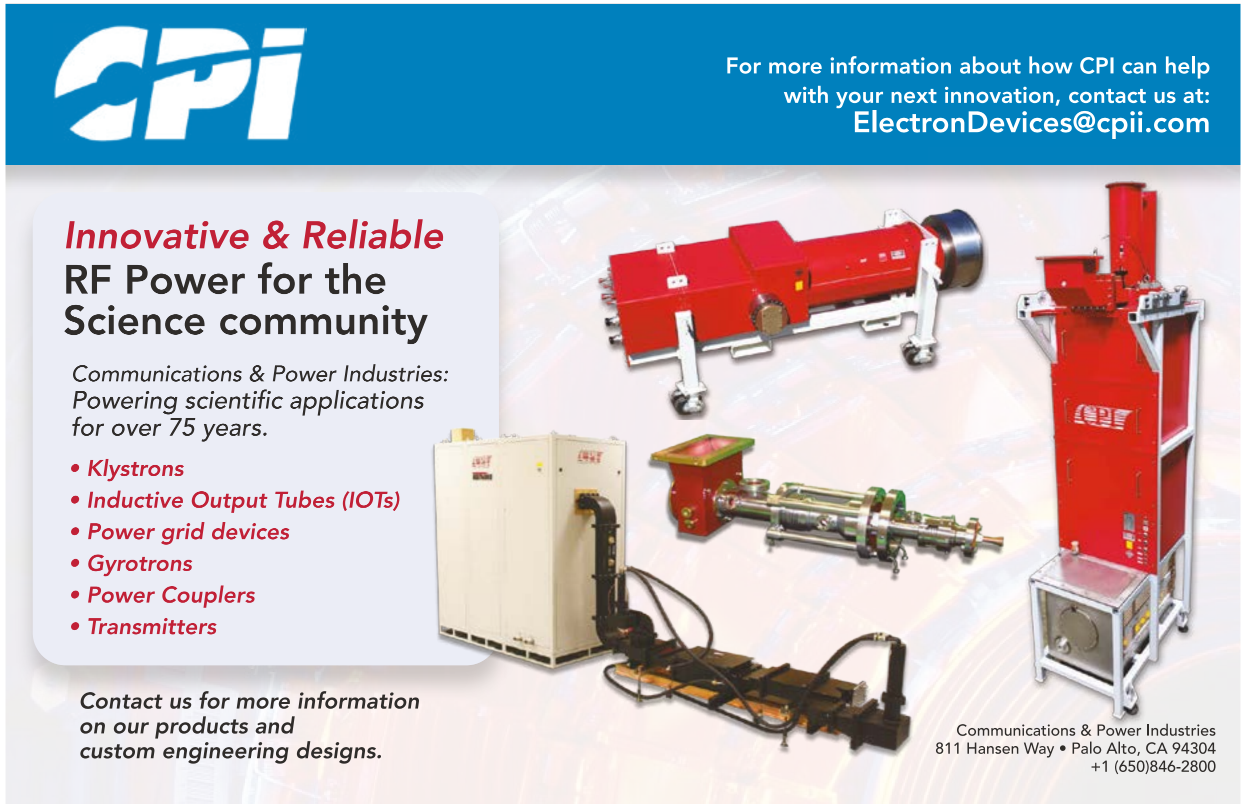

B Richter/UW-Madison

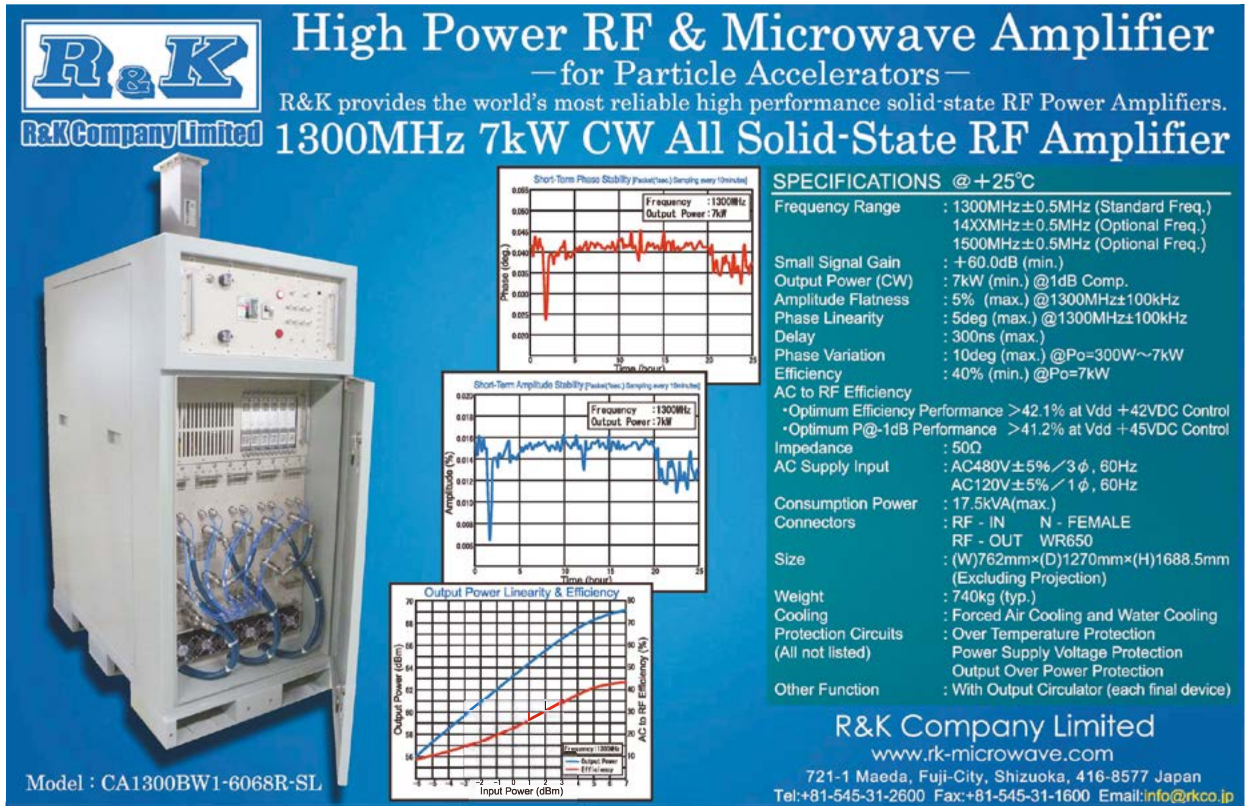
2020 Pomeranchuk Prize

Theorists Sergio Ferrara (CERN) and Mikhail Vasiliev (Lebedev Institute) were awarded the 2020 Pomeranchuk Prize, which has been granted annually since 1998 by the Institute for Theoretical and Experimental Physics in Moscow. Ferrara (top), who co-discovered supergravity in 1976 along with Daniel Freedman and Peter van Nieuwenhuizen, was cited "for his contribution to fundamental aspects of supersymmetry that has been a very important achievement for our understanding of modern supergravity theories", while Vasiliev was recognised for an "outstanding series of papers" on the higher spin theory in Anti-de Sitter and de Sitter spaces.


S Ferrara


M Vasiliev





RECRUITMENT

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CERN HR
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The theory/simulation group RP6 is expanding and recruiting a theoretician in the field of ultra-high intensity laser-plasma interaction. In our team we therefore have this position available.

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For more details please visit

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2. Senior Researcher

An open position in the Department of Plasma Physics and Ultra-High Intensity Interaction.

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The Institute of Physics of the Czech Academy of Sciences is a holder of the HR Excellence in Research Award. It is awarded by the European Commission to institutions which put significant effort into improving their human resources strategy and ensuring professional and ethical working conditions.

eli beamlines

MINISTRY OF EDUCATION, YOUTH AND SPORTS

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For our location in Hamburg we are seeking:

DESY-Fellowships – experimental particle physics

DESY.

DESY, with its 2700 employees at its two locations in Hamburg and Zeuthen, is one of the world‘s leading research centres. Its research focuses on decoding the structure and function of matter, from the smallest particles of the universe to the building blocks of life. In this way, DESY contributes to solving the major questions and urgent challenges facing science, society and industry. With its ultramodern research infrastructure, its interdisciplinary research platforms and its international networks, DESY offers a highly attractive working environment in the fields of science, technology and administration as well as for the education of highly qualified young scientists.

We participate in leading roles in particle physics projects on our campus and in international laboratories such as CERN or KEK. We develop technologies for detectors and accelerators, and work on scientific computing. We operate important infrastructures such as the Tier-2 centre or the electron test beam.

The position

You are invited to take an active role in one or more of the following projects in Hamburg:

- The ATLAS and CMS experiments at CERN or the Belle II experiment at KEK
- Experimental activities on-site (ALPS II and future on-site experiments)
- Preparations for future particle physics experiments, in particular detector and technology development
- Scientific computing
- Accelerator development

Requirements

- Ph.D. in physics (to be eligible, you have to take up the position at the latest 5 years after your doctorate)
- Interest in particle physics
- Expertise relevant in at least one of the areas listed above

DESY-Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year.

Further information and a link to the submission system for your application and the references can be found here: http://www.desy.de/FellowFH

Please note that it is the applicant‘s responsibility that all material, including 3 letters of reference, reach DESY before the deadline.

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DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-time work. During each application procedure DESY will assess whether the post can be filled with part-time employees.

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Human Resources Department | Code: FHFE001/2021
Notkestraße 85 | 22607 Hamburg Germany
Phone: +49 40 8998-3392

Deadline for applications: 2021/03/31 www.desy.de/career

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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A Research Centre of the Helmholtz Association

For our location in Hamburg we are seeking:

The Director of Research for Particle Physics

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The activities of DESY in particle physics comprise a vibrant experimental programme including participation in the ATLAS and CMS experiments at the Large Hadron Collider, the Belle II experiment at SuperKEKB, local experimental activities in dark matter searches, and a strong involvement in developments of detector technologies for future projects in particle physics. DESY hosts a world leading group in theoretical particle physics focused on phenomenology, lattice gauge theory, string theory, and cosmology. DESY also operates one of the largest computing centres for particle physics, astroparticle physics, and photon science. DESY is currently engaged in an international search process for the Director of Research for Particle Physics.

The position

The Director of Research for Particle Physics

- is head of the particle physics division and as member of the board of directors responsible for the development of the lab as whole
- plays a leading role in shaping the future of particle physics at DESY including the cooperation with other research areas
- is responsible for representing the field of particle physics in the Helmholtz Association and for coordinating DESY‘s contribution to international projects in particle physics as well as representing DESY in international networks and/or organisations
- is expected to take over responsibility for infrastructure service groups

Requirements

- Outstanding research record, international stature, and a broad spectrum of interest in particle physics as well as in accelerator-based science
- Long-standing experience in providing leadership of people and larger scientific groups
- Proven scientific leadership and excellent managing skills
- Sound knowledge of the international research landscape

For further information please contact Dr. Rafael Abela (Chairman of the Search Committee) email: rafael.abela@psi.ch

The appointment is for a period of maximum five years. Reappointment is possible. The position is compensated at an international level in accordance with the W3 salary system in Germany which includes the option of performance-related payments.

DESY operates flexible work schemes. DESY‘s goal is to promote more women into leadership positions. Applications from women will therefore be explicitly welcomed. Persons with disabilities will be given preference to other equally qualified applicants.

Please note the data protection instruction under the link www.desy.de/data_privacy_policy/index_eng.html.

We are looking forward to your application via our application system:
www.desy.de/onlineapplication

Deutsches Elektronen-Synchrotron DESY
Particle Physics Search Committee
c/o Human Resources Department | Code: FHDIR/2021
Notkestraße 85 | 22607 Hamburg Germany | Phone: +49 40 8998-3392

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

For our location in Zeuthen we are seeking:

Postdoc for the Photo Injector Test Facility PITZ in Zeuthen

DESY.

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The Photo Injector Test Facility PITZ in Zeuthen (near Berlin) is one of the leading international groups in developments on modern photo injectors and their applications. Current R&D goals of PITZ include improving electron source brightness beyond state of the art and demonstration of accelerator-based THz pump sources for high repetition rate X-ray Free-Electron Lasers (FELs) like FLASH and European XFEL. Such efforts require reliable and comprehensive electron beam characterization, i.e. a detailed reconstruction for both projected and time-resolved phase space measurements. The focus of the offered position will be on further developments of tools for the characterization of high brightness electron beams and/or start-to-end beam dynamics simulations for e.g. commissioning the new THz SASE FEL beamline.

The position

- Develop, test and support software packages for low-emittance electron beam characterization and THz SASE FEL commissioning
- Perform accurate modeling of experimental procedures for electron beam measurements including classification and analysis of systematic errors
- Carry out start-to-end simulations of the beam dynamics in the photo injector for operation conditions as well as for future applications
- Analyze experimental data and compare with start-to-end simulation results
- Participate in shift operation for accelerator R&D at PITZ and/or European XFEL

Requirements

- University degree in accelerator physics with PhD, with very good knowledge in accelerator physics and accelerator technology or equivalent qualification
- Strong background in beam dynamics simulations of space charge dominated beams as well as in numerical and statistical methods
- Good knowledge in experimental characterization of particle beams using image processing; good programming skills and knowledge of high-level scripting languages (Python/Matlab)
- Very good command of English is required and knowledge of German is of advantage
- Excellent teamwork abilities in an international environment

For further information please contact Dr. Mikhail Krasilnikov at +49 33762 7-7213 (mikhail.krasilnikov@desy.de).

The position is limited to 2 years at the beginning.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Persons with disabilities will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women.

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Deadline for applications: 2021/03/10

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FRIB

Research Associate

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is approaching completion and commencement of user operation in early 2022. The FRIB high-power superconducting linear accelerator has already been demonstrated to accelerate ion beams to the design energy of 200 MeV/u to produce rare isotopes. FRIB is poised to be the world's most powerful rare isotope beam facility, with unprecedented opportunities to study the vast unexplored potential of more than 1,000 new rare isotopes never before produced on Earth. FRIB includes a target facility for the in-flight production of rare isotopes. An Advanced Rare Isotope Separator (ARIS) will prepare fast rare isotope beams with high-purity for nuclear physics experiments.

We invite Ph.D. graduates to apply for this Research Associate position and join the FRIB Accelerator Physics Department. The Research Associate will contribute to the commissioning, development, and operation of the FRIB by undertaking projects and activities to improve facility performance as measured by beam quality, intensity, power, purity, and variety.

Position duties can be adjusted according to the candidate's experience, interests, and talents.

For more details and how to apply, please visit:
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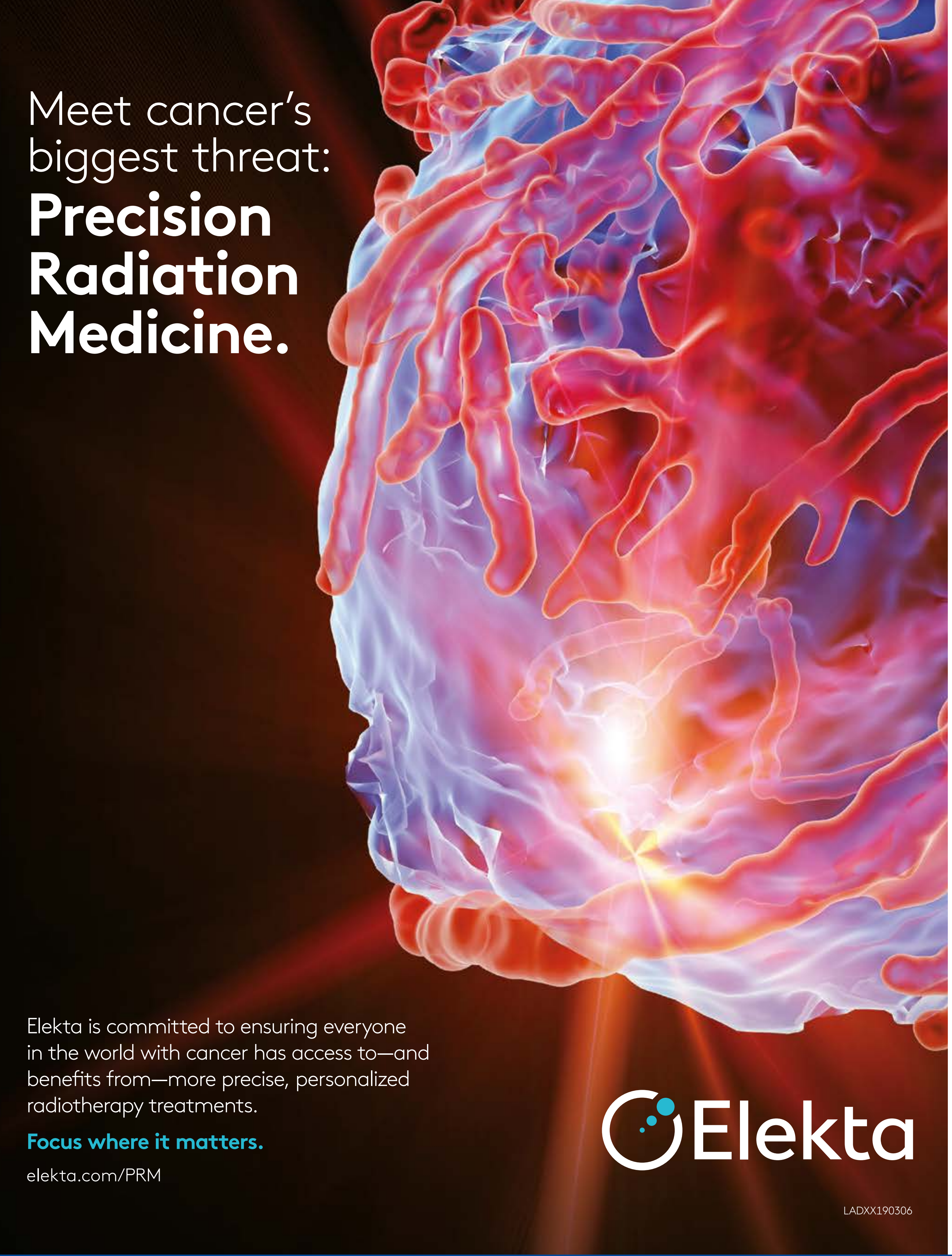
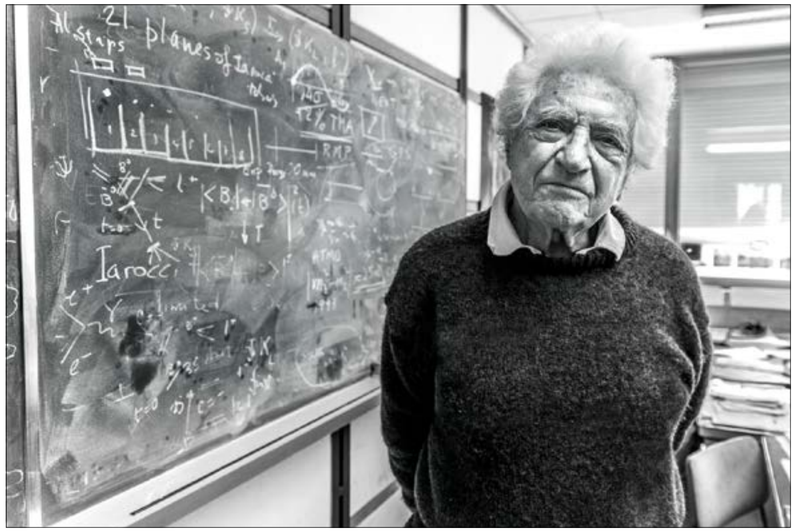


PEOPLE OBITUARIES

Jack Steinberger 1921–2020

A giant of the field

Jack Steinberger, a giant of the field who witnessed and shaped the evolution of particle physics from its beginnings to the confirmation of the Standard Model, passed away on 12 December aged 99. Born in the Bavarian town of Bad Kissingen in 1921, his father was a cantor and religious teacher to the small Jewish community, and his mother gave English and French lessons to supplement the family income. In 1934, after new Nazi laws had excluded Jewish children from higher education, Jack's parents applied for him and his brother to take part in a charitable scheme that saw 300 German refugee children transferred to the US. Jack found his home as a foster child, and was reunited with his parents and younger brother in 1938.


S E Bennett/CERN

Jack photographed at CERN in 2016.

Jack studied chemistry at the University of Chicago until 1942, when he joined the army and was sent to the MIT radiation laboratory to work on radar bomb sights. He was assigned to the antenna group where his attention was brought to physics. After the war he returned to Chicago to embark on a career in theoretical physics. Under the guidance of Enrico Fermi, however, he switched to the experimental side of the field, conducting mountaintop investigations into cosmic rays. He was awarded a PhD in 1948. Fermi, who was probably Jack's most influential physics teacher, described him as "direct, confident, without complication, he concentrated on physics, and that was enough".

In 1949 Steinberger went to the Radiation Lab at the University of California at Berkeley, where he performed an experiment at the electron synchrotron that demonstrated the production of neutral pions and their decay to photon pairs. He stayed only one year in Berkeley, partly because he declined to sign the anti-communist loyalty oath, and moved on to Columbia University.

In the 1960s the construction of a high-energy, high-flux proton accelerator at Brookhaven opened the door to the study of weak interactions using neutrino–beam experiments. This marked the beginning of Jack's interest in neutrino physics. Along with Mel Schwarz and Leon Lederman, he designed and built the experiment that established the difference between neutrinos associated with muons and those associated with electrons, for which they received the 1988 Nobel Prize in Physics.

Jack joined CERN in 1968, working on experiments at the Proton Synchrotron exploring CP violation in neutral kaons. In the 1970s, with the advent of new neutrino beams at the Super Proton Synchrotron, Jack became a founding member of the CERN–Dortmund–Heidelberg–Saclay (CDHS) collaboration. Running from 1976 to 1984, CDHS produced a string of important results using neutrino beams to probe the structure of the nucleon and the Standard Model in general. In particular, the collaboration confirmed the predicted variation of the structure function of the valence quarks with Q^2 (nicknamed "scaling violations"), a milestone in the establishment of QCD.

> **A curious and imaginative physicist with an extraordinary rigour**

When the Large Electron–Positron (LEP) collider was first proposed, a core group from CDHS joined physicists from other institutions to develop a detector for CERN's new flagship collider. This initiative grew into the ALEPH experiment, and Jack, a curious and imaginative physicist with an extraordinary rigour, was the natural choice to become its first spokesperson in 1980, a position he held until 1990. From the outset, he stipulated that standard solutions should be adopted across the whole detector as far as possible. This led to the end-caps reflecting the design of the central detector, for example. Jack was also insistent that all technologies considered for the detector first had to be completely understood. As the LEP era got underway, this level of discipline was reflected in ALEPH's results.

Next to physics, music formed an important part of Jack's life. He organised gatherings of amateur, and occasionally professional, musicians at his house. These were usually marathons of Bach, starting in the late afternoon and continuing until the late evening. In his autobiography, Jack summarised: "I play the flute, unfortunately not very well, and have enjoyed tennis, mountaineering and sailing, passionately."

Jack retired from CERN in 1986 and went on to become a professor at the Scuola Normale Superiore di Pisa. President Ronald Reagan awarded him the National Medal of Science in 1988. In 2001, on the occasion of his 80th birthday, the city of Bad Kissingen named its gymnasium in his honour. Jack continued his association with CERN throughout his 90s. He leaves his mark not just on particle physics but on all of us who had the opportunity to collaborate with him.

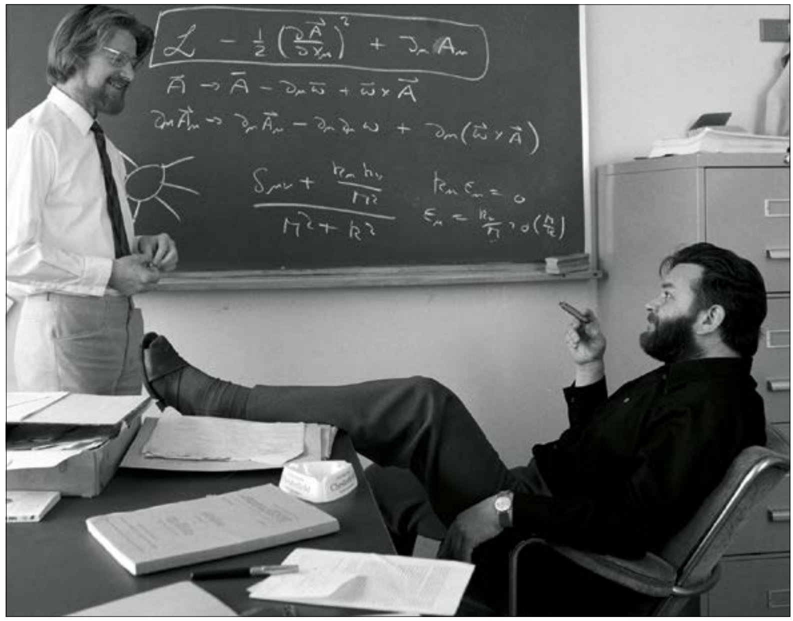
His friends and colleagues.

MARTINUS J G VELTMAN 1931–2021

A lasting impact

Eminent physicist and Nobel laureate Martinus Veltman passed away in his home town of Bilthoven, the Netherlands, on 4 January. Martinus (Tini) Veltman graduated in physics at Utrecht University, opting first for experimental physics but later switching to theory. After his conscript military service in 1959, Léon Van Hove offered him a position as a PhD student. Veltman started in Utrecht, but later followed Van Hove to the CERN theory division.

CERN opened up a new world, and Tini often mentioned how he benefited from contacts with John Bell, Gilberto Bernardini and Sam Berman. The latter got him interested in weak interactions and in particular neutrino physics. During his time there, Tini spent a short period at SLAC where he started to work on his computer algebra program “Schoonschip”. He correctly foresaw that practical calculations of Feynman diagrams would become more and more complicated, particularly for theories with vector bosons. Nowadays extended calculations beyond one loop are unthinkable without computer algebra.


Martinus Veltman (right) with John Bell at CERN in 1973.

CERN

In 1964 Murray Gell-Mann proposed an algebra of conserved current operators for hadronic matter, which included the weak and electromagnetic currents. He argued that commutators of two currents taken at the same instant in time should “close”, meaning that these commutators can be written as linear combinations of the same set of currents. From this relation one could derive so-called sum rules that can be compared to experiments. Facing the technical problems with this approach, Tini came up with an alternative proposal. In a 1966 paper he simply conjectured that the hadronic currents for the electromagnetic and weak interactions had to be covariantly conserved, where he assumed that the weak interactions were mediated by virtual vector bosons, just as electromagnetic processes are mediated by virtual photons. The current conservation laws therefore had to contain extra terms depending on the photon field and the fields associated with the weak intermediate vector bosons. Quite surprisingly, he could then demonstrate that these new conservation equations suffice to prove the same sum rules. A more important aspect of his approach was only gradually realised, namely that the conservation laws for these currents are characteristic of a non-abelian gauge theory as had been written down more than 10 years earlier by Yang and Mills. Hence Veltman started to work on the possible renormalisability of Yang–Mills theory.

Meanwhile, Veltman had left CERN towards the end of 1966 to accept a professorship at Utrecht. At the end of 1969 a prospective PhD student insisted on working on Yang–Mills theories. Veltman, who was already well aware of many of the pitfalls, only gradually agreed, and so Gerard ’t Hooft joined the programme. This turned out to be a very fruitful endeavour and the work was proudly presented in the summer of 1971. Veltman and ’t Hooft continued to collaborate on Yang–Mills theory. Their 1972 papers are among the finest that have been written on the subject. In 1999 they shared the Nobel Prize in Physics “for elucidating the quantum structure of electroweak interactions”.

> **Veltman made a lasting impact on particle physics, and inspired many students**

With the renormalisability of the electroweak theory established, precision comparisons with experiment were within reach, and Veltman started to work on these problems with postdocs and PhD students. One important tool was the so-called rho parameter (a ratio of the masses of the W and Z bosons and the weak mixing angle). Its experimental value was close to one, which showed that only models in which the Higgs field starts as a doublet are allowed. From the small deviations from one, it was possible to estimate the mass of the top quark, which was not yet discovered. Later, when CERN was planning to build the LEP collider, the emphasis changed to the calculation of one-loop corrections for various processes in e^+e^- collisions. As a member of the CERN Scientific Policy Committee (SPC), Veltman strongly argued that LEP should operate at the highest possible energy, well above the W^+W^- threshold, to study the electroweak theory with precision. The Standard Model has since passed all of these tests.

From his early days at CERN it was clear that Tini had a strong interest in confronting theoretical predictions with experimental results, and in the organisation needed to do so. To this end, he was one of a small group of colleagues in the Netherlands to push for a national institute for subatomic physics – Nikhef, which was founded in 1975. In 1981 Tini moved to the University of Michigan in Ann Arbor, returning to the Netherlands after his retirement in 1996.

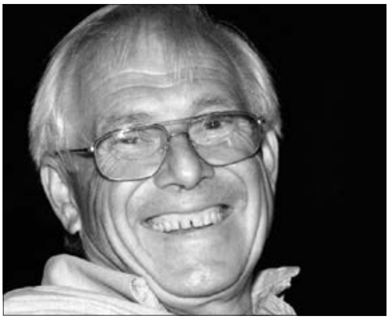
Veltman made a lasting impact on the field of particle physics, and inspired many students. Until recently he followed what was happening in the field, regularly attending the September meetings of the SPC. Our community will miss his sharp reasoning and clear-eyed look at particle physics that are crucial for its development.

Karel Gaemers *Nikhef/University of Amsterdam and* **Bernard De Wit** *Nikhef/Utrecht University.*

GÜNTHER PLASS 1930–2020

Decisive contributions to CERN

Günther Plass, a former CERN director of accelerators who made decisive contributions to the development and successful operation of many of CERN’s large facilities, passed away on 11 December, aged 90. After graduating from the Technical University Berlin-Charlottenburg, and a short detour via an industrial magnet laboratory in Germany, Günther joined CERN in 1956, participating in the construction of the Proton Synchrotron (PS) as a member of the magnet group. Over the years, he made major contributions to the continuous upgrade of the PS complex, the heart of CERN’s accelerator chain to this day. With Berend Kuiper, he led the development of the machine’s novel fast-ejection system, which enabled the first satisfactory neutrino beam benefitting from the magnetic horns invented by Simon van der Meer. Günther was then responsible for the infrastructure for Gargamelle, the bubble chamber where neutral currents were later discovered. As leader of the Synchrotron Ring group, he shaped the massive PS improvement programme launched in 1965.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Günther was instrumental in the development and operation of many of CERN’s large facilities.

Later, in 1978, he oversaw the construction of the new Linac2, which faithfully delivered protons to all CERN’s facilities for 40 years until it gave way to Linac4 in 2018. Günther also left his mark as a member of the SPS design committee as the author, together with Colin Ramm as early as 1961, of a suggestion to construct the SPS near the Meyrin site, well before the final decision was taken in 1970.

Once the antiproton–proton programme was successfully under way, a strong interest in the use of low-energy antiprotons developed. In 1980 Günther was among those proposing the Low-Energy Antiproton Ring (LEAR), which, after modifications, is now a key component of the LHC ion programme as the Low-Energy Ion Ring (LEIR). He displayed the full measure of his talent as leader and conductor of a large orchestra as deputy to Emilio Picasso, the LEP project leader, from 1981 onwards and from 1983 as LEP division leader. His contributions range from optimising the siting of the 27 km-long tunnel within the geological and environmental constraints of the region, planning during construction and integrating frequent last-minute demands by the experimenters, to handling arbitrations with difficult contractors. As director of accelerators from 1990, he lent full support to the upgrade of LEP by means of superconducting cavities, which extended its energy reach from the Z° to the W^+W^- threshold and above, and he strongly encouraged the studies that would ensure the future of CERN, such as those for the LHC and CLIC.

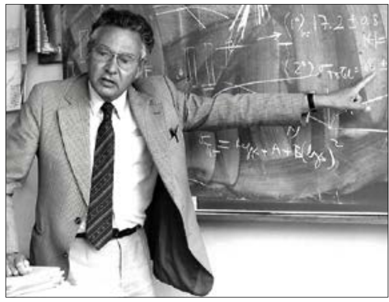
Günther’s success was due to his unassuming character, his patience and ability to listen, his open and calm mind in the face of adversity, and his ability to identify the essential points and the right people for a task or project.

Kurt Hübner *and* **Carlo Wyss** *formerly of CERN (now retired).*

ANDRÉ MARTIN 1929–2020

An ambassador for CERN

André Martin passed away on 11 November 2020, marking a great loss to the theory community worldwide and to the CERN family. André was born in Paris on 20 September 1929 and studied at the École Normale Supérieure (ENS) and the University of Paris. His thesis adviser was Maurice Lévy (ENS theory group), with whom he had a lifelong friendship and many common projects. André arrived at CERN in 1959 as a fellow, became a staff member in 1964 and an honorary member in 1994. He was still working until a few days before he was admitted to hospital, diagnosed with coronavirus and died of pneumonia. He led a cosmopolitan life, travelling all over the world, and had friends and colleagues all over. He had long and productive visits to various US institutions, including Princeton, Stony Brook, Seattle, Caltech, Los Alamos and Rockefeller. André was proud to have contributed to the launching of the Cargese school and supported the Erice and Les Houches centres.


André Martin joined CERN in 1959.

Martin Family

André worked on rigorous mathematical physics and the derived phenomenology applied to the dynamics of strong interactions, both alone and in collaboration. He often came back to problems when he had already obtained striking results but was not fully satisfied. Among the many topics of his scientific contributions, we can highlight the analytic properties of scattering amplitudes, the high-energy behaviour of integrated and differential cross sections, the inverse problem in quantum mechanics, the ambiguities in phase-shift analyses, the range of annihilation and two-dimensional quantum mechanics. After the discovery of charmonium, he became interested in the spectral properties of confining potentials, a subject on which he wrote several important articles and eventually a book. His results and methods applied to quarkonia and baryons were extended to other similar systems, in particular in atomic physics. André also liked lighter topics, such as the stability of four-legged tables on uneven ground, inspired by experiments on the CERN cafeteria terrace, a study widely shared on the Web in the early 2000s.

Among his distinctions, he was admitted to the French Académie des Sciences in 1990, and he was awarded the *Légion d’honneur* in 1992, the Gian-Carlo Wick Medal in 2007 and the Pomeranchuk Prize in 2010. He met his wife, Alice-Anne Schubert (“Schu”), who passed away in 2016, at CERN thanks to his dear friend Julius Wess. They were a wonderful power couple, with an intense cultural and social life. Their hospitality was extraordinary, and it was a pleasure to enjoy their immense culture in literature and art. They are survived by their two sons, Thierry and Philippe, and two grandchildren, Raoul and Jeanne.

André had friends in almost every university or institute, whom he met at CERN or conferences. He was often the go-between who initiated new collaborations. He was deeply committed to CERN’s mission and was one of its best ambassadors and advocates. He will be sorely missed.

Luis Álvarez-Gaumé *Stony Brook University and* **Jean-Marc Richard** *Institut de Physique des 2 Infinis de Lyon.*

CERNCOURIER

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IOP Publishing

Stephanie Zimmermann 1973–2020

Outstanding commitment

Stephanie led the ATLAS New Small Wheel project.

University of Freiburg

ATLAS physicist Stephanie Zimmermann passed away suddenly on 10 November. She joined the experiment when she was studying physics at the University of Freiburg, and worked on the muon system as a Masters student from 1999. After graduating, she continued her work in ATLAS during her doctoral thesis, research fellowship at CERN and subsequent research career at Freiburg. She held many important positions in ATLAS. As a fellow, she coordinated the integration work of the monitored drift-tube chambers and the resistive plate chambers. It was largely thanks to her that this task was completed in time for installation in the ATLAS underground hall. She was involved in the muon-detector control system, and served as muon run coordinator, ATLAS run coordinator and, from 2013, led the New Small Wheel (NSW) project.

Stephanie was an outstanding scientist who received university awards for best Masters thesis and again for best doctoral thesis, the latter also awarded the ATLAS Marc Virchaux Prize. She was highly regarded for her detailed knowledge of every aspect of the project, her outstanding commitment and team spirit, as well as her support and care for her collaborators.

As NSW project manager, she was known and respected for her strong will, assertiveness and matter-of-factness. While she could be uncompromising when defending the project, she was a tender-hearted person who cared deeply about her team members. Her shining example will encourage us to make her dream come true and to finish and install the NSW on schedule.

Philipp Fleischmann *(for the ATLAS Muon System),* **Gregor Herten** *(for the Freiburg ATLAS group) and* **Karl Jakobs** *(for the ATLAS collaboration).*

Stephen Reucroft 1943–2020

An all-round experimentalist

Reucroft actively promoted technology transfer from academia to industry.

BCTV

Experimental particle physicist Stephen Reucroft passed away in October 2020 after a long struggle against cancer.

Steve grew up in Yorkshire, UK, earning a PhD in particle physics in 1969 from the University of Liverpool. His early research career focused on precision measurements using the high-resolution rapid-cycling bubble chambers HYBUC and LEBC at the CERN PS and SPS. These included resonance properties, hyperon magnetic moments, and charm-particle production and decay. He was the CERN-EP group leader for the North Area experiments NA13, 16 and 27. Subsequently, he was spokesperson of E743, which took LEBC to Fermilab to successfully resolve a controversy about the energy dependence of the charm production cross section.

Steve became professor of physics at Northeastern University, Boston, in 1986, working at the highest energy colliders and the Pierre Auger Observatory. He developed novel scintillating fibre detectors that were used successfully in the L3 experiment and proposed for the SSC, and built up and led a large research group on the L3 and DO experiments working on precision electroweak and QCD measurements, among many others. An early collaborator on the CMS experiment, Steve led a consortium of eight NSF-supported university groups that made major contributions to the electromagnetic calorimeter (especially the novel avalanche photodiode sensors), software and computing systems, and physics analyses. He actively promoted technology transfer from academia to industry and co-founded a non-profit company in Boston that was the first to bring silicon photomultipliers to market. He also initiated a cloud service for the protection of elderly and fragile people, and launched a crowd-funding campaign to advance next-generation nuclear energy technologies.

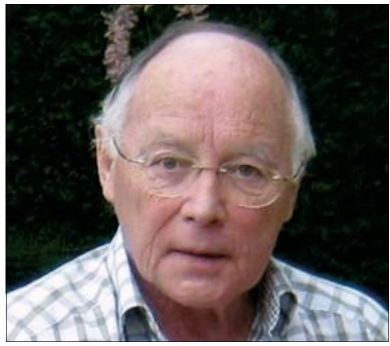
Steve was a strong advocate for young scientists, advising more than 45 PhD students and postgraduates, and was very active in scientific outreach. He co-founded the Research Experience for Undergraduates (REU) programme at CERN, judged the Intel (now Regeneron) International Science and Engineering Fair, and co-wrote a science column for *The Boston Globe* newspaper. He wrote numerous academic papers, popular articles and books, was a regular contributor to *CERN Courier*, and was elected to the National Association of Science Writers.

Steve was invariably cheerful with a unique sense of humour, and his door was always open. He will be much missed.

Lucas Taylor *Fermilab.*

Jean-Claude Berset 1939–2020

An expert engineer



Jean-Claude worked on the PS and ISR, SPS, LEP and finally the LHC.

Family Berset

CERN engineer Jean-Claude Berset passed away on 1 October at the age of 81. Jean-Claude arrived at CERN in 1970 and was assigned as an electronics technician in the former NP division, developing front-end electronics. He participated in the development and construction of systems for various experiments at CERN, from his early days on the PS and ISR, then SPS, LEP and finally the LHC, where he worked on the development of the readout electronics for the ALICE time projection chamber – a system that was in operation until very recently.

Jean-Claude retired from CERN in 2005. His colleagues remember him not only as an expert and competent engineer, highly skilled, analytical, meticulous and always ready to help, but also a colleague and friend whose modesty and fine human qualities we will treasure.

His colleagues and friends *in the ALICE collaboration.*

BACKGROUND

Notes and observations from the high-energy physics community

The great physics bake-off


C Joe

Wilson Hall in gingerbread, by Fermilab accelerator operator Cindy Joe.

Cakes were baked, votes were counted, and UK student Maddie Watkins beat off stiff competition from a baker's dozen of high-energy physicists to be crowned star baker of the inaugural #GreatPhysicsBakeOff for her depiction of Archimedes' eureka moment. "We had gravitational-lensing gateaux, stellar-nucleosynthesis sponge and recreations of the International Space Station, the NASA Space Shuttle and Fermilab's iconic Wilson Hall," says organiser Katharine Leney (Southern Methodist University) of the January competition, which took place on social media. "We're still wondering if you *lose* weight eating antiparticle cupcakes," adds co-organiser Steph Hills (STFC).

247 zs

The shortest unit of time ever measured (1 zs = 10^{-21} s), corresponding to the time it takes light to cross a hydrogen molecule, as clocked by physicists at DESY's PETRA III facility (*Science* 370 339).

ATOMKI boson under fire

Particle physicists in Canada and the US have added a new twist to the tale of the ATOMKI anomaly – a reported 6.8σ excess of e^+e^- pairs created during nuclear transitions of excited ^{8}Be nuclei to their ground state spotted by a team in Hungary in 2015, and for which a new 17 MeV gauge boson ("X17") has been proposed as an explanation (*CERN Courier* January/February 2019 p7). In a preprint posted on 3 February, Aleksandrs Aleksejevs (Memorial University of Newfoundland) and co-workers pour cold water on this interpretation, arguing that the anomaly can be explained by adding the full set of second-order corrections and the interference terms to the Born-level decay amplitudes considered by the ATOMKI team (arXiv:2102.01127).

X17's proponents remain undeterred. "The authors appear to let the size of the higher-order effects be a free parameter and find that by assuming they are much larger than expected, one could produce a bump at 15 MeV, not the 17 MeV observed. So it's an interesting step, but there's still more work to be done," says Jonathan Feng of UC Irvine. Meanwhile, spokesperson for the ATOMKI experiment Attila Krasznahorkay protests that the effect has since also been seen in other nuclear species: "Our results for ^{4}He and ^{12}C would not be affected by any interference phenomenon, while we see the X17 anomaly in both of them, so we continue our experiments, with new results soon to be published."

From the archive: April 1981

Antiprotons à gogo


CERN 27.2.81

The TT6 beamline, soon scheduled to transport 28 GeV antiprotons from the PS to the ISR.

On 11–14 February CERN's 28 GeV Proton Synchrotron, PS, became the world's first antiproton synchrotron. Intense pulses of 3.5 GeV antiprotons from the Antiproton Accumulator are accelerated to 26 GeV in the PS for use in proton–antiproton collisions in the Intersecting Storage Rings or in the Super Proton Synchrotron, SPS, after subsequent acceleration [achieved on 10 July at 540 GeV centre-of-mass energy] in the search for the elusive intermediate bosons of weak interactions. At the other end of the energy scale, preparations are under way in the PS South Hall to construct a Low Energy Antiproton Ring, LEAR, providing intense antiproton beams in the energy range 0.1 to 2 GeV. Investigations of proton–antiproton annihilation should improve our knowledge of quark behaviour. LEAR physics will also cover protonium spectroscopy, exotic proton–antiproton atoms, and could provide a definitive answer on baryonium, states formed from baryons and antibaryons.

● Based on text from pp104–105 and 113–115 of *CERN Courier* April 1981.

Compiler's note

Antimatter – like black holes, wormholes and multiverses – feeds our deep-seated curiosity for the mysterious. The Big Bang is supposed to have created particles in pairs, equal and opposite, that recombine on contact, releasing the energy that produced them. So why is there anything other than energy in the universe? For every billion pairs that annihilated, it seems just one partner survived – a sine que non *for our existence. To date, laboratory efforts to create antimatter have done little to redress the imbalance. By 2015 it was estimated that CERN had created 1 ng of antiprotons, Fermilab an impressive 15 ng, and 2 ng of positrons had been produced at DESY. But the total annihilation energy obtainable using this* ersatz *antimatter is insufficient to boil cup of tea.*

Media corner

"At Brookhaven, I was always sitting on the edge of my chair [during unblinding], and I think I will be here, too."

Experimentalist **Lee Roberts** of Boston University quoted in *Science* (27 January) about the hotly anticipated muon g-2 measurement from Fermilab.

"That statement made me furious, so I started studying physics."

A 1997 quote by the late Nobel laureate **Masatoshi Koshiba**, on how a professor telling him that he cannot study physics made him take it up in the first place, has resurfaced after the 94 year-old neutrino pioneer's passing in November (American Institute of Physics).

"I could not be more excited about the new supercollider!"

Elon Musk on Twitter (2 November) interacting with Fermilab director Nigel Lockyer on the subject of a future circular collider.

"Today, Jane Street's source code is 25M lines long, about half as much as the Large Hadron Collider uses."

The Financial Times (28 January) channels CERN to communicate the complexity of the algorithms used by quantitative trading firm Jane Street.