WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2022 issue of *CERN Courier*.

Ten years of precision measurements at the LHC have shown the Higgs boson to be remarkably consistent with the minimal version required by the Standard Model. Combined with the no-show of non-Standard Model particles that were expected to accompany the Higgs, theorists are left scratching their heads (p47). As we celebrate the collective effort of high-energy physicists in predicting (p31 and 35) and discovering (p23 and 27) the Higgs boson and determining its properties (p40 and 63), another intriguing journey has opened up.

As "a fragment of vacuum" with the barest of quantum numbers, the Higgs boson is potentially connected to many open questions in fundamental physics – the nature of the electroweak phase transition (p51); hidden sectors relevant to dark matter (p55); the puzzling fermion mass hierarchy (p53); and the ultimate stability of the universe (p59), among others.

With the LHC and its high-luminosity upgrade, physicists have 20 more years of Higgs exploration to look forward to. To fully understand the Higgs boson, however, a successor collider will be needed (p45 and 61), allowing researchers to build upon the events of 4 July 2012 to reach the next level of understanding in fundamental physics.

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EDITOR: MATTHEW CHALMERS, CERN
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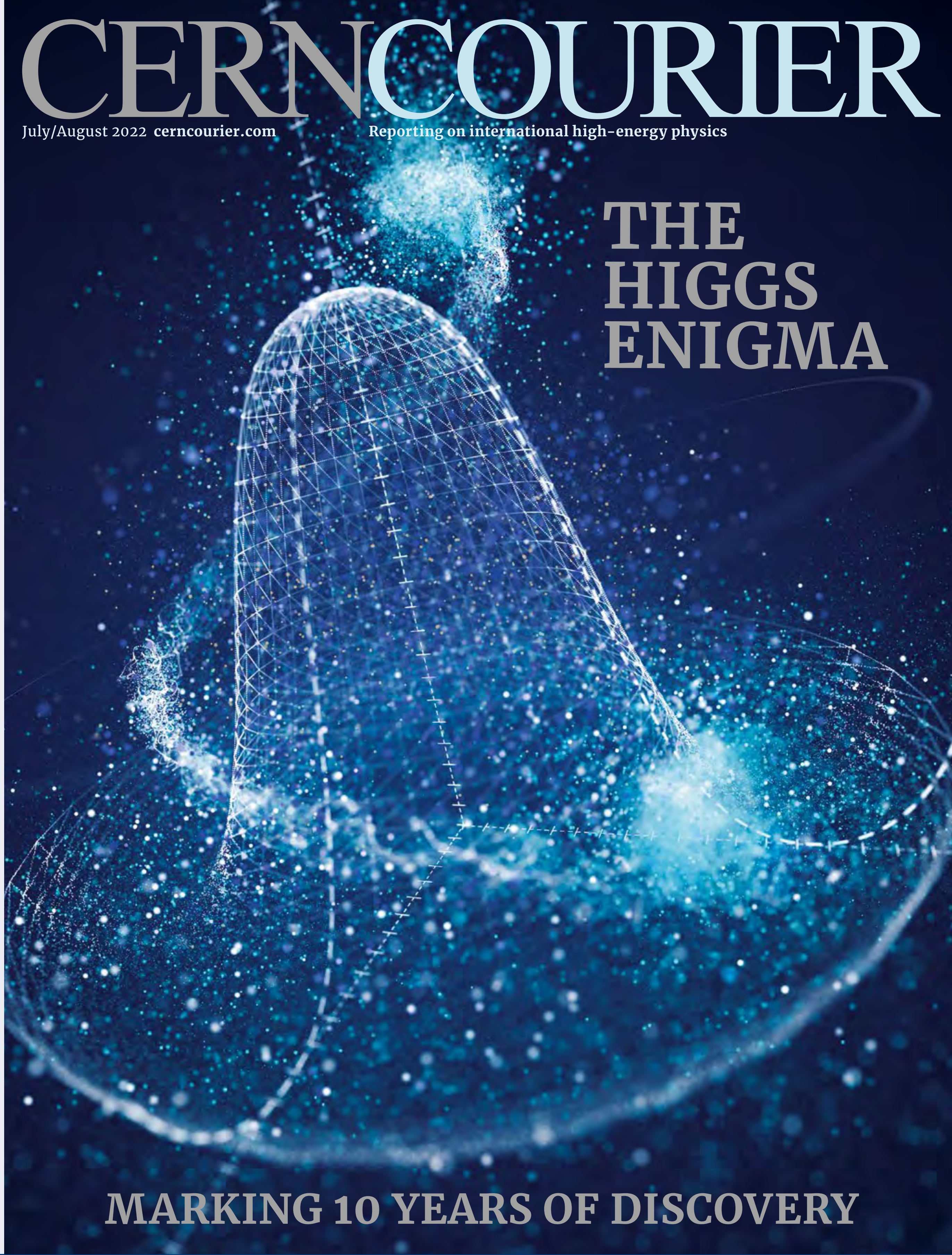

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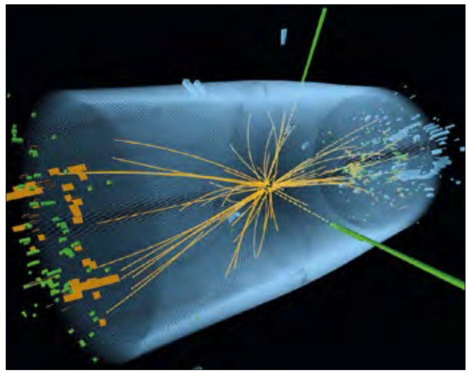
Reporting on international high-energy physics

THE HIGGS ENIGMA

MARKING 10 YEARS OF DISCOVERY

IN THIS ISSUE

Volume 62 Number 4 July/August 2022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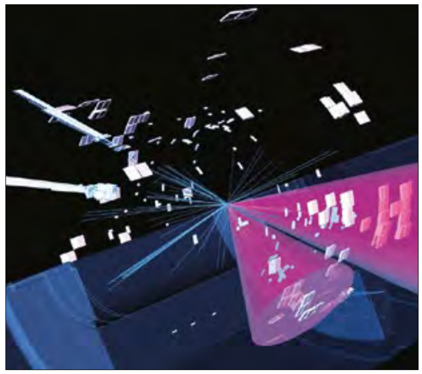
ATLAS


Nobel Foundation/S Jardeback (artist)/L Engblom (reproduction)

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κ factor *Measuring the Higgs couplings at higher precision after the LHC.* **45**

Natural *Scrutinising the electro-weak hierarchy problem.* **47**

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PEOPLE

10 YEARS: HIGGS-BOSON DISCOVERY

A SERIES CELEBRATING THE DISCOVERY OF THE HIGGS BOSON AND EXPLORING ITS IMPLICATIONS


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FROM THE EDITOR

Wonderful, weighty, weird

Matthew Chalmers
Editor

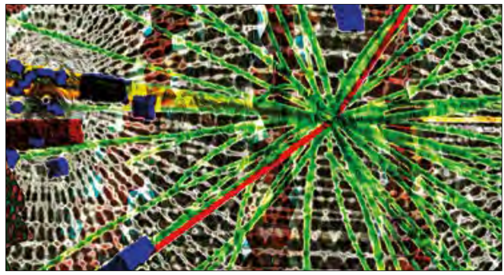
Ten years ago, a series of small bumps in ATLAS and CMS data confirmed a 48 year-old theoretical prediction, and particle physics hasn't been the same since. Behind those sigmas was the hard work, dedication, competence and team spirit of thousands of experimentalists worldwide (p23 and 27). Naturally it was a triumph for theory, too (p31). Peter Higgs, François Englert, Carl Hagen and Gerald Guralnik received a standing ovation in the CERN auditorium on 4 July 2012, although Higgs insisted it was a day to celebrate experiment, not theory. The Nobel prize for Englert and Higgs came a year later (p35). Straying from tradition for elementary-particle discoveries, the citation explicitly acknowledged the experimental effort of ATLAS and CMS, the LHC and CERN.

The implications of the Higgs-boson discovery are still being understood. Ten years of precision measurements (p40) have shown the particle to be consistent with the minimal version required by the Standard Model. Combined with the no-show of non-Standard Model particles that were expected to accompany the Higgs, theorists are left scratching their heads (p47). As we celebrate the collective effort of high-energy physicists in discovering the Higgs boson and determining its properties, another intriguing journey has opened up.

Marvelously mysterious

As "a fragment of vacuum", the Higgs boson's simplicity potentially connects it to many open questions in fundamental physics. The field from which it hails governs the nature of the electroweak phase transition in the early universe, which might be connected with the observed matter–antimatter asymmetry (p51); as the only known elementary scalar, it could serve as a portal to other, hidden sectors relevant to dark matter (p55); its couplings may hold clues to the puzzling hierarchy of fermion masses (p53); and its interactions have implications for the ultimate stability of the universe (p59).

Nobody knows what the Higgs boson has in store


X Cortada/CMS-PHO-PUBLIC-2013-006-1

Higgs light *A stylised $H \to \gamma\gamma$ event in CMS.*

With the LHC and its high-luminosity upgrade, physicists have 15–20 years of Higgs exploration to look forward to. But to fully understand the shape of the Brout–Englert–Higgs potential, the couplings of the Higgs boson to Standard Model particles and its possible connections to new physics, a successor collider will be needed (p45). It is fascinating to picture future generations of particle physicists working as one with astroparticle physicists, cosmologists and others to fill out the details of this potential new vista, with colliders driving progress alongside astrophysical, cosmological and gravitational-wave observatories. Future colliders aren't just about generating knowledge, argues this issue's Viewpoint (p61), but are "moonshots" delivering a competitive edge in technology, innovation, education and training.

Nobody knows what the Higgs boson has in store. Perhaps further studies will confirm the scenario of a Standard-Model Higgs and nothing else. The sheer number and profundity of known unknowns in the universe would suggest otherwise, think many theorists (p63). The good news is that, in the Higgs boson, physicists have clear measurement targets – and in principle the necessary theoretical and experimental machinery – to explore such mysteries, building upon the events of 4 July 2012 to reach the next level of understanding in fundamental physics.

● 2022 also marks 45 years since "Higgs boson" first appeared in the *Courier* (p78). Look out for similar gems from our archive and new content to be showcased on cerncourier.com from 4 July.

Reporting on international high-energy physics

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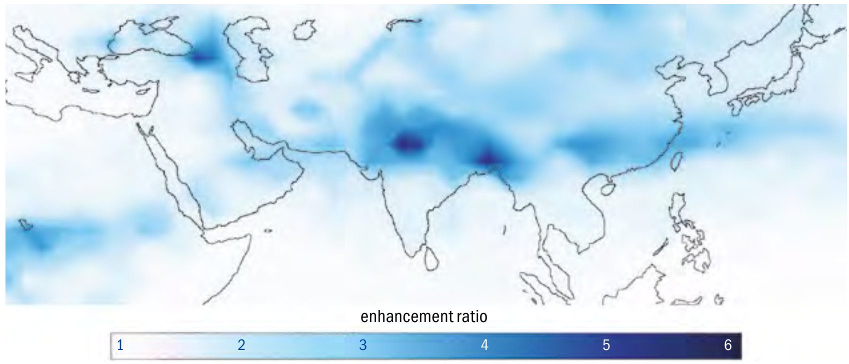
NEWS ANALYSIS

CLOUD

Accelerating aerosol production

The CLOUD collaboration at CERN has uncovered a new mechanism accelerating the formation of aerosol particles in the upper troposphere, with potential implications for air-pollution regulations. The results, published in *Nature* on 18 May, show that an unexpected synergy between nitric acid, sulphuric acid and ammonia leads to the formation of aerosols at significantly faster rates than those from any two of the three components. The mechanism may represent a major source of cloud and ice seed particles in certain regions of the globe, says the team.

Aerosol particles are known to generally cool the climate by reflecting sunlight back into space and by seeding cloud droplets. But the vapours driving their formation are not well understood. The CLOUD (Cosmics Leaving Outdoor Droplets) facility at CERN's East Area replicates the atmosphere in an ultra-clean chamber to study, under precisely-controlled atmospheric conditions, the formation of aerosol particles from trace vapours and how they grow to become the seeds for clouds.



Enhancement *A simulation of aerosol-particle formation during the Asian monsoon in a global aerosol model with efficient vertical transport of ammonia into the upper troposphere. Including a mixture of sulphuric acid, nitric acid and ammonia enhances upper-tropospheric particle number concentrations over the Asian monsoon region by a factor of three to five compared with the same model with only sulphuric acid and ammonia.*

Nature **605** 483

Three is key

Building on earlier findings that ammonia and nitric acid can accelerate the growth rates of newly formed particles, the CLOUD team introduced mixtures of sulphuric acid, nitric acid and ammonia vapours to the chamber and observed the rates at which particles formed. They found that the three vapours together form new particles 10–1000 times faster than a sulphuric acid–ammonia mixture, which previous CLOUD measurements suggested was the dominant source of upper tropospheric particles. Once the three-component particles form, they grow rapidly from the condensation of nitric acid and ammonia alone to sizes where they seed clouds.

Moreover, the team found these particles to be highly efficient at seeding ice crystals, comparable to desert dust particles, which are thought to be the most widespread and effective ice seeds in the atmosphere. When a supercooled cloud droplet freezes, the resulting ice particle will grow at the expense of any unfrozen droplets nearby, making ice a major factor in the microphysical properties of clouds and precipitation. Around three-quarters of global precipitation is estimated to originate from ice particles.

Feeding their measurements into global aerosol models that include vertical transport of ammonia by deep convective clouds, the CLOUD researchers found that although the particles form locally in ammonia-rich regions of the upper troposphere, such as over the Asian monsoon regions, they travel from Asia to North America in just three days via the subtropical jet stream, potentially influencing Earth's climate on an intercontinental scale (see "Enhancement" figure). The importance of the new synergistic mechanism depends on the availability of ammonia in the upper troposphere, which originates mainly from livestock and fertiliser emissions. Atmospheric concentrations of all three compounds are much higher today than in the pre-industrial era.

"Our results will improve the reliability of global climate models in accounting for aerosol formation in the upper troposphere and in predicting how the climate will change in the future," says CLOUD spokesperson Jasper Kirkby. "Once again, CLOUD is finding that anthropogenic ammonia has a major influence on atmospheric aerosol particles, and our studies are informing policies for future air-pollution regulations."

Our results will improve the reliability of global climate models

Working at the intersection between atmospheric science and particle physics, CLOUD has published several important results since it started operations in 2009. These include new mechanisms responsible for driving winter smog episodes in cities and for potentially accelerating the loss of Arctic sea ice, in addition to studies of the impact of cosmic rays on clouds and climate (*CERN Courier* July/August 2020 p48).

"When CLOUD started operation, the prevailing understanding was that sulphuric acid vapour alone could account for almost all observations of new-particle formation in the atmosphere," says Kirkby. "Our first experiments showed that it was around one million times too slow, and CLOUD went on to discover that additional vapours – especially biogenic vapours from trees – form particles together with stabilisers like ammonia, amines or ions from cosmic rays. CLOUD has now established a mechanistic understanding of aerosol particle formation for global climate models – but our work isn't finished yet."

Further reading

CLOUD Collaboration 2022 *Nature* **605** 483.

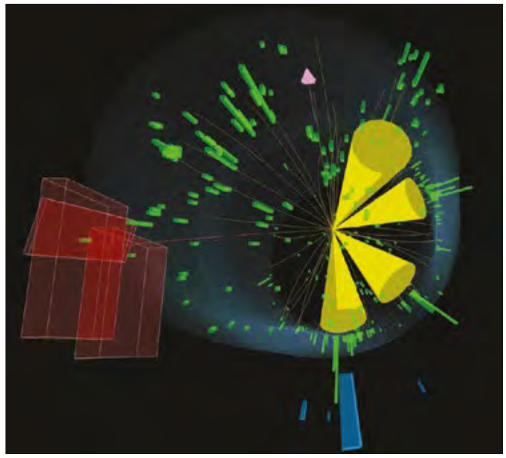
Electroweak

Top quark weighs in with unparalleled precision

The CMS collaboration has substantially improved on its measurement of the top-quark mass. The latest result, 171.77 ± 0.38 GeV, presented at CERN on 5 April, represents a precision of about 0.22% – compared to the 0.36% obtained in 2018 with the same data. The gain comes from new analysis methods and improved procedures to consistently treat uncertainties in the measurement simultaneously.

As the heaviest elementary particle, precise knowledge of the top-quark mass is of paramount importance to test the internal consistency of the Standard Model. Together with accurate knowledge of the masses of the W and Higgs bosons, the top-quark mass is no longer a free parameter but a clear prediction of the Standard Model. Since the top-quark mass dominates higher-order corrections to the Higgs-boson mass, a precise measurement of the top mass also places strong constraints on the stability of the electroweak vacuum (see p59).

Since its discovery at Fermilab in 1995, the mass of the top quark has been measured with increasing precision using the invariant mass of different combinations of its decay products. Measurements by the Tevatron experiments resulted in a combined value of 174.30 ± 0.65 GeV, while the ATLAS and CMS collaborations measured 172.69 ± 0.48 GeV and 172.44 ± 0.48 GeV, respectively, from the combination of their most precise results from LHC Run 1 recorded at a centre-of-mass energy of 8 TeV. The latter measurement achieved a relative precision of about 0.28%. In 2019, the CMS collaboration also experimentally investigated the running of the top quark mass – a prediction of QCD that causes the mass to vary as a function of energy – for the first time at the LHC.



Top marks *The classic signature of a top-quark pair at the LHC is four jets (yellow cones), one muon (red line and boxes) and missing energy from a neutrino (pink arrow).*

CMS

The LHC produces top quarks predominantly in quark–antiquark pairs via gluon fusion, which then decay almost exclusively to a bottom quark and a W boson. Each $t\bar{t}$ event is classified by the subsequent decay of the W bosons. The latest CMS analysis uses semileptonic events – where one W decays into jets and the other into a lepton and a neutrino – selected from 36 fb^{-1} of Run 2 data collected at a centre-of-mass energy of 13 TeV. Five kinematical variables, as opposed to up to three in previous analyses, were used to extract the top-quark mass. While the extra information in the fit improved the precision of the measurement in a novel and unconventional way, it made the analysis significantly more complicated. In addition, the measurement required an extremely precise calibration of the CMS data and an in-depth understanding of the remaining experimental and theoretical uncertainties and their interdependencies.

The final result, 171.77 ± 0.38 GeV, which includes 0.04 GeV statistical uncertainty, is a considerable improvement compared to all previously published top-quark mass measurements and supersedes the previously published measurement in this channel using the same data set.

"The cutting-edge statistical treatment of uncertainties and the use of more information have vastly improved this new measurement from CMS," says Hartmut Stadie of the University of Hamburg, who contributed to the result. "Another big step is expected when the new approach is applied to the more extensive dataset recorded in 2017 and 2018."

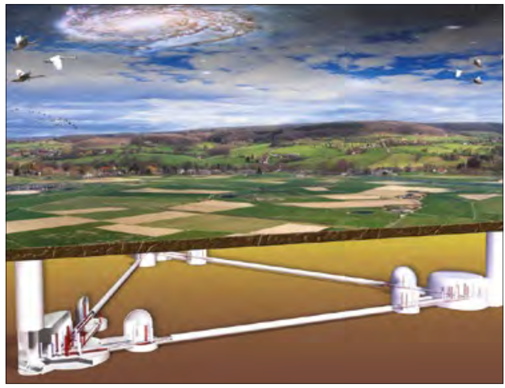
Further reading

CMS Collab. 2022 CMS-PAS-TOP-20-008.

Gravitational waves

Limbering up for the Einstein Telescope

On 14 April the government of the Netherlands announced that it intends to conditionally allocate €42 million to the development of the Einstein Telescope – a proposed next-generation gravitational-wave observatory in Europe. It also pledged a further €870 million for a potential future Dutch contribution to the construction. The decision was taken by the Dutch government based on the advice of the Advisory Committee of the National Growth Fund, stated a press release from Nikhef and the regional development agency for Limburg.



Next generation *How the Einstein Telescope might look in South Limburg in the Netherlands.*

M Kraan/Nikhef

The Einstein Telescope (ET) is a triangular laser interferometer with sides 10 km-long that would be at least 10 times more sensitive than the Advanced LIGO and Virgo observatories, extending its scope for detections and enabling physicists to look back much further in cosmological time. To reach the required sensitivities, the interferometer has to be built at least 200 m underground in a geologically stable area. Its mirrors will have to operate in cryogenic conditions to reduce thermal disturbance, and be larger and heavier than those currently employed to allow for a larger and more powerful laser beam.

Activities have been taking place at two potential sites in Europe: the border region of South Limburg (the Euregio Meuse-Rhine) in the Netherlands; and the Sar-Grav laboratory in the Sos Enattos mine in Sardinia, Italy (*CERN Courier* March/April 2020 p53). For the Sardinia site, a similar proposal has been sub- ▷

mitted to the Italian government and feedback is expected in July.

The Netherlands' intended €42 million investment will go towards preparatory work such as innovation of the necessary technology, location research, building up a high-tech ecosystem and organisation, stated the press release, while the reservation of €870 million is intended to put the Netherlands in a strong position to apply in the future – together with Belgium and Germany – to host and build the ET.

"It is fantastic that the cabinet embraces the ambition to make the Netherlands a world leader in research into gravity waves," said Nikhef director Stan Bentvelsen, who has been involved with the ET for several years. "These growth-fund resources form the basis for further cooperation with our partners in Germany and Belgium, and for research into the geological subsurface in the border region of South Limburg. A major project requires a careful process, and I am confident that we will meet the additional conditions."

Housing the ET in the region could have a major positive impact on science, the economy and society in the Netherlands, said provincial executive member for Limburg Stephan Satijn. "With today's decision, the cabinet places our country at the global forefront of high-tech and science. Limburg is the logical place to help shape this leading position. Not only because of the suitability of our soil, but also because we are accustomed to working together internationally and to connecting science and business."

It is fantastic that the cabinet embraces the ambition to make the Netherlands a world leader in research into gravity waves

At the 12th ET symposium in Budapest on 7–8 June, the ET scientific collaboration was officially born – a crucial step in the project's journey, said ad interim spokesperson Michele Punturo of the INFN: "We were a scientific community, today we are a scientific collaboration, that is, a structured and organised system that works following shared rules to achieve the common goal: the realisation of a large European research infrastructure that will allow us to maintain scientific and technological leadership in this promising field of fundamental physics research."

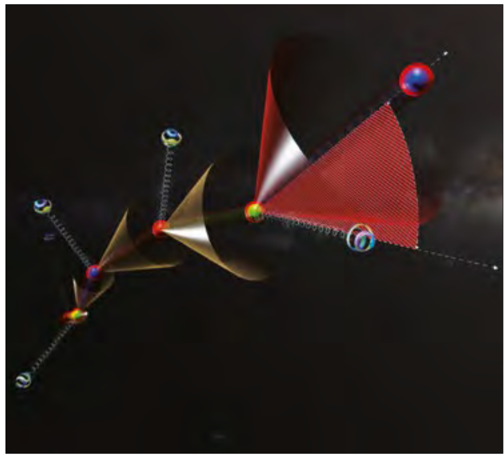
QCD

Dead-cone effect exposed by ALICE

More than 30 years after it was predicted, a phenomenon in quantum chromodynamics (QCD) called the dead-cone effect has been directly observed by the ALICE collaboration. The result, reported in *Nature* on 18 May, not only confirms a fundamental feature of the theory of the strong force, but enables a direct experimental observation of the non-zero mass of the charm quark in the partonic phase.

In QCD, the dead-cone effect predicts a suppression of gluon bremsstrahlung from a quark within a cone centred on the quark's flight direction. This cone has an angular size m$_q$/E, where m$_q$ is the mass of the quark and E is its energy. The effect arises due to the conservation of angular momentum during the gluon emission and is significant for low-energy heavy-flavour quarks.

The dead cone has been indirectly observed at particle colliders. A direct observation from the parton shower's radiation pattern has remained challenging, however, because it relies on the determination of the emission angle of the gluon, as well as the emitting heavy-flavour quark's energy, at each emission vertex in the parton shower (see "Showering" figure). This requires a dynamic reconstruction of the cascading quarks and gluons in the shower from experimentally accessible hadrons, which had not been possible until now. In addition, the dead-cone region can be obscured and filled by other sources such as the decay products of heavy-flavour hadrons, which must be removed during the measurement.



Showering *A charm quark in a parton shower loses energy by emitting gluons. The shower displays a "dead cone" of suppressed radiation around the quark for angles smaller than the ratio of the quark's mass and energy, causing the cone size to increase at each stage of the shower.*

D Dominguez/CERN-GRAPHICS-2022-015-7

To observe the dead-cone effect directly, ALICE used jets tagged with a reconstructed D^0-meson in a 25 nb^{-1} sample of pp collisions at a centre-of-mass-energy of 13 TeV collected between 2016 and 2018. The D^0-mesons were reconstructed with transverse momenta between 2 and 36 GeV/c through their decay into a kaon and pion pair. Jet-finding was then performed on the events with the "anti-k$_T$" algorithm, and jets with the reconstructed D^0-meson amongst their constituents were tagged. The team used recursive jet-clustering techniques to reconstruct the gluon emissions from the radiating charm quark by following the branch containing the D^0-meson at each de-clustering step, which is equivalent to following the emitting charm quark through the shower. A similar procedure was carried out on a flavour-untagged sample of jets, which contain primarily gluon and light-quark emissions and form a baseline where the dead-cone effect is absent.

ALICE's successful technique may offer a way to measure quark masses

Comparisons between the gluon emissions from charm quarks and from light quarks and gluons directly reveal the dead-cone effect through a suppression of gluon emissions from the charm quark at small angles, compared to the emissions from light quarks and gluons. Since QCD predicts a mass-dependence of the dead cones, the result also directly exposes the mass of the charm quark, which is otherwise inaccessible due to confinement. ALICE's successful technique to directly observe a parton shower's dead cone may therefore offer a way to measure quark masses.

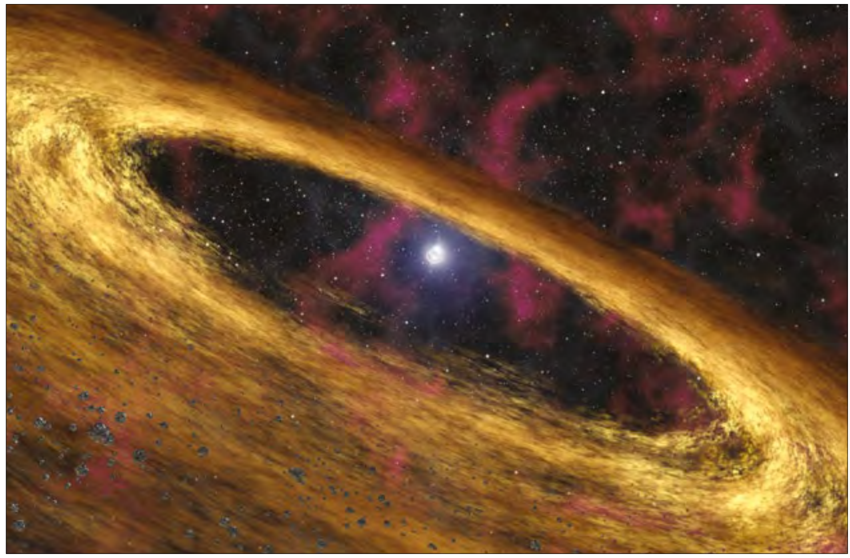
The upgraded ALICE detector in LHC Run 3 will enable an extension of the measurement to jets tagged with a B$^+$ meson. This will allow the reconstruction of gluon emissions from beauty quarks which, due to their larger mass, are expected to have a larger dead cone than charm quarks. Comparisons between the angular distribution of gluon emissions from beauty quarks and those from charm quarks will isolate mass-dependent effects in the shower and remove the contribution from effects pertaining to the differences between quark and gluon fragmentation, bringing deeper insights into the intriguing workings of the strong force.

Further reading

ALICE Collaboration 2022 *Nature* **605** 440.

ASTROWATCH

X-ray polarisation probes extreme physics



NASA/JPL–Caltech/R Hurt (SSC)

Magnetar *Artistic depiction of the accretion disk around the magnetar 4U 0142+61, located in the Cassiopeia constellation 13,000 lights years away.*

X-ray astronomy has been around for more than 50 years and remains responsible for a wealth of discoveries. Astronomical breakthroughs have been the result of detailed measurements of the X-ray arrival time, direction and energy. But the fourth measurable parameter of X-rays, their polarisation, remains largely unexplored. Following the first rough measurements of a handful of objects in the 1970s by Martin Weisskopf and co-workers, there was a hiatus in X-ray polarimetry due to the complexity of the detection mechanism. In recent years, in parallel with the emergence of gamma-ray polarimetry (see *CERN Courier* May/June 2020 p12), interest in the field has returned. Indeed, after some initial measurements using the Chinese–Italian PolarLight Cubesat launched in October 2018, X-ray polarimetry has reached full maturity with the launch of the first large-scale dedicated observatory in December 2021: the Imaging X-ray Polarimetry Explorer (IXPE), a joint project by NASA and the Italian Space Agency, led by Weisskopf.

The IXPE mission uses gas pixel detectors to measure the polarisation for a range of astronomical sources in the 2–8 keV energy range. Incoming X-rays are absorbed in a gas which results in the emission of a photoelectron, the azimuthal emission direction of which is correlated with the polarisation vector of the incoming photon. Tracking the path of the electron therefore allows the polarisation to be inferred. Accurately measuring the emission direction of the low-energy photoelectron, especially in a space-based detector, has been one of the main IXPE challenges and required decades of detector development.

IXPE has already observed a range of sources. Its first public results, posted on arXiv on 18 May, concern a magnetar, a highly magnetic neutron star, called 4U 0142+61, which rotates around its axis in about 8 s and has a magnetic field of 10^{10} T. IXPE's first ever measurement of polarised emission from a magnetar in the X-ray region shows this extreme object to have an energy-integrated polarisation degree of 12%, while in the thermal (2–4 keV) range this is about 12%, and as high as 41% for emission at higher energies (5.5–8 keV). The polarisation angles of the two emission components are orthogonal.

The results appear to agree best with a model where the thermal emission stems from a condensed iron atmosphere: the higher energy emission would be a result of some thermal photons being up-scattered to higher energies when interacting with charged particles following the magnetic field lines. However, since other models link the emission to a gaseous atmosphere heated by a constant bombardment of particles, measurements of additional magnetars are needed.

> **X-ray polarimetry has reached full maturity with the launch of the first large-scale dedicated observatory**

Fundamental physics

Apart from providing novel insights into neutron-star properties, time-resolved studies of the emission during the rotation period hints at more fundamental physics at play. The spectral profile of 4U 0142+61 was found to be rather constant during the rotation, indicating that the emission does not come from hot-spots, such as the poles, but rather from a large area on the surface. As the magnetic field over such a large area would, however, be expected to vary significantly, so would the polarisation angle of the emitted X-rays. As a result, the net polarisation seen on Earth would largely be blurred out, resulting in a much lower polarisation degree than is observed.

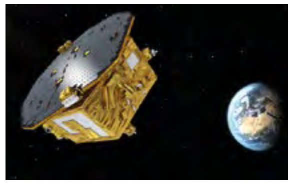
An intriguing explanation for this, note the authors, is vacuum birefringence – an effect predicted to be important in the presence of extreme magnetic fields, but which has never been observed. While for the magnetar the polarisation angle of the emission varies with the emission location, it gets altered as the photons travel through the strong magnetic field in which continuous electron–positron pairs affect their propagation. Only when the magnetic field is weak enough, at around 100 times the radius of the star, does the polarisation angle get frozen. Since this angle is aligned with the magnetic field, which at this point is smoother, the emission will realign the emission travelling towards Earth and allow for a net polarisation.

Although the polarisation degrees measured by IXPE are not high enough to definitively prove vacuum birefringence, the results give a clear hint. Furthermore, the measurements of 4U 0142+61 are only the first of many performed by the IXPE team. Throughout the coming months, detailed measurements of galactic objects such as the Crab Nebula, as well as extra-galactic sources, are predicted to be released. Among these objects there will be other magnetars, the X-ray emission from which will soon bring further understanding of these extreme objects and potentially confirm the existence of vacuum birefringence.

Further reading

R Taverna *et al.* 2022 arXiv:2205.08898.

NEWS DIGEST



ESA/C Carreau

An artist's impression of the LISA pathfinder in space.

Next leap for LISA

The Laser Interferometer Space Antenna (LISA) has moved into its final design phase, announced the European Space Agency (ESA) on 4 May. Having passed an important "mission formulation review", all necessary technology for the space-based gravitational-wave detector will be developed, final designs chosen and international agreements set. First sketched out in the 1980s, LISA was selected for ESA's Cosmic Vision Programme in 2017 and is scheduled for launch in the mid-2030s. Its three spacecraft will form an equilateral triangle in a heliocentric orbit with sides 2.5 million km long, enabling it to detect lower-frequency gravitational waves such as those predicted to have been produced in the very early universe.

Daya Bay on θ_{13}

The Daya Bay collaboration in China has made the most precise measurement yet of the neutrino-mixing angle θ_{13}, a key parameter in understanding neutrino oscillations. The result, announced on 31 May at Neutrino 2022 in Seoul, is the first from the experiment's full dataset and is 2.5 times more precise than its original design goal. Daya Bay made the first conclusive measurement of θ_{13} in 2012 and completed data-taking in December 2020. Its latest result also improves knowledge of the neutrino mass-ordering and will be further improved as the baton passes to the Jiangmen Underground Neutrino Observatory due to complete construction next year.

PandaX limits dark matter

Searching for dark-matter interactions in a 580 kg tank of liquid xenon located beneath Jinping mountain in China, the PandaX-II collaboration has ruled out sub-GeV dark-matter particles in a large and previously unexplored parameter space. Based on its full 100 tonne · day dataset, the team excludes the dark matter–nucleon elastic scattering cross section between 10^{-31} and 10^{-28} cm^2 for dark-matter masses from 0.1 MeV and 0.1 GeV (*Phys. Rev. Lett.* **128** 171801). More sensitive searches will be carried out using the upcoming data from PandaX-4T and other multi-tonne dark-matter experiments, says the team.

PIP-II enters construction

On 20 April the US Department of Energy formally approved the start of full construction of the Proton Improvement Plan II (PIP-II), a significant enhancement of Fermilab's accelerator complex built with international collaboration. The superconducting PIP-II facility will produce 1 MW proton beams to drive high-energy neutrino beams for the LBNF/DUNE experiment located 1300 km away at SURF, South Dakota. The high-power proton beams will also enable muon-based experiments to search for new physics at higher levels of precision. "We are elated to have reached this crucial step for PIP-II," says former PIP-II project director and now Fermilab director Lia Merminga. "Our team around the world has worked tirelessly to prepare for this moment."

Fermilab

The PIP-II vision.

Thin-film strippers for ion beams

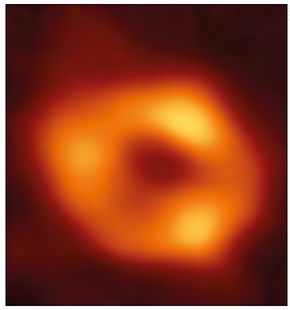
To produce high-quality ion beams for physics experiments, an efficient method to strip sources of electrons is needed. Traditionally, solid sources such as carbon strippers are used, but they suffer radiation damage and must be replaced frequently. Takuji Kanemura and his team at the Facility for Rare Isotope Beams (FRIB) in the US have now demonstrated a new technique based on self-replenishing liquid-metal strippers that prolong the charge stripper's lifetime. By spreading a liquid lithium jet into a film that intersects with the ion beam, they achieved a charge state that is ideal for accelerating FRIB's uranium beams (*Phys. Rev. Lett.* **128** 212301).

Seismic observations with QKD

Jiu-Peng Chen and his team at the University of Science and Technology of China set out to break the distance record for secure twin-field quantum-key distribution (QKD), using a 658 km-long optical fibre. To their surprise, they discovered that it is possible to detect earthquakes or landslides with the setup. Using the precision monitoring system they built to record the position of the fibre and compensate for any changes caused by temperature and ambient vibrations, the team was able to detect the position of the earthquake within a range of 1 km due to the phase variation in the optical fibre (*Phys. Rev. Lett.* **128** 180502).

Echoes from the past

Following the striking image of the black hole at the centre of galaxy M87 three years ago, the Event Horizon Telescope (EHT) collaboration has turned its focus on our own galaxy. The image of Sagittarius A*, the supermassive black hole at the centre of the Milky Way, published on 12 May provides the first direct visual evidence for the existence of our nearest supermassive black hole, says the collaboration. The image, based on data from eight (sub-) millimetre telescopes operating in conjunction in 2017, shows light that is bent by the black hole's gravity, having been emitted by very hot gases on the outskirts of the black hole (*Astrophys. J. Lett.* **930** L12).



EHT

The first sighting of Sagittarius A.*

Coffee that changes minds

A study published in the *Journal of Clinical Investigation* suggests that the most consumed psychoactive substance in the world, caffeine, leads to long-lasting brain changes. The team analysed the hippocampus (the part of the brain responsible for learning and memory) of mice that were fed caffeine-infused water equivalent to two to four cups of coffee per person daily for a period of two weeks. The brains of mice that received caffeine showed a decrease in the protein synthesis involved in processes releasing energy in the mice, whereas the team found an increase in protein synthesis involved neuronal signalling and plasticity compared to the control group. These changes remained for two weeks after the mice received their last dose of caffeine, suggesting that genes could boost information processing, writes the team (*J Clin. Invest.* 2022 doi.org/10.1172/JCI149371).

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Low- and high-voltage power for research labs

The MPOD/MMS universal low/ high-voltage multichannel power supply system is helping to drive research and science at some of the world's most highly respected laboratories.

As part of a joint venture, iseg Spezialelektronik and W-IE-NE-R Power Electronics have developed the universal computer-controlled low- and high-voltage power supply system, MPOD/MMS. The solution can provide hundreds of low-voltage (0 to 120 V) or high-voltage (up to 30 kV) channels.

This multichannel power supply system, based on 19"/6U Euro Cassette standard, is the iseg and W-IE-NE-R vendor-specific multichannel voltage supply standard. With a wide set of modules, this system provides the most advanced features in low- and high-voltage generation.

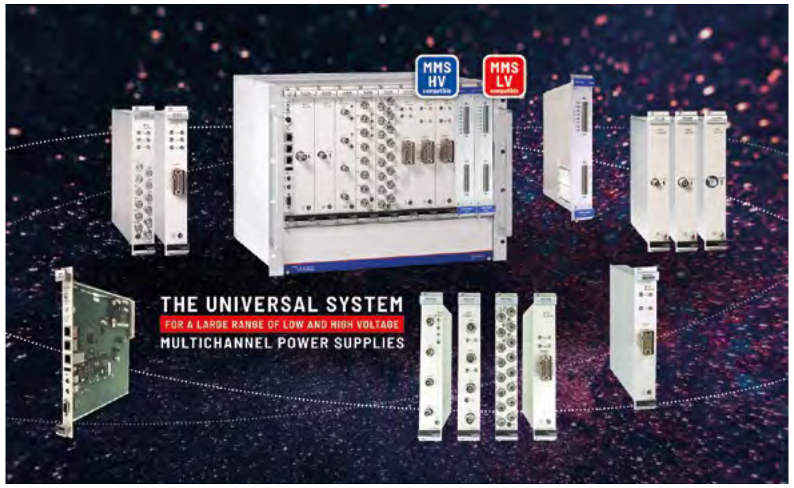
Scalable from small to large applications
Offering a variety of chassis, from a single slot up to 10 slots for 19" rackmount use, the system is scalable from small to large applications. With an enormous channel density, the mainframes can house up to 10 plug-in low- or high-voltage modules. The high-voltage modules are available between one and 48 channels in the maximum voltage range of 100 V up to 30 kV, and the low-voltage modules have up to 16 channels with a maximum of 200 W per channel in different voltage ranges from 0 to 8 V up to 120 V. In order to tailor the system to individual hardware needs, the system can be configured as "low-voltage only", "high-voltage only" or "mixed configuration". In addition, the mainframe is configurable to enable all connectors either on the front or rear side.

Control and monitoring options
All the low- and high-voltage channels are individually controlled and monitored. Systems can be equipped with either the W-IE-NE-R MPOD controller or the CC24 iseg crate controller. The MPOD controller, with Ethernet and USB interfaces, provides a variety of network capabilities. The CC24 iseg crate controller contains an embedded hardware server, which is ideal for the operation of the iCS system (iseg communication server). It enables straightforward and quick access via Ethernet or optional WiFi to the hardware. Numerous features, including CSV data export, channel folders, channel profiles, user management and much more, simplify the iseg hardware process. The iCS system contains two preinstalled software interfaces that are already fit to play at delivery. It is possible to edit Python scripts directly on a browser or locally with access to all the required hardware parameters, enabling the user to easily create their own visualisation. This feature has made thousands of applications possible. The iseg datalogger, which stores measured values directly on a USB flash drive, allows for an easy start.

Vendor for major physics research labs
Many users worldwide trust in the reliability, precision and quality of the established hardware. Being a provider to many major physics research laboratories, including CERN, Fermilab, DESY and many more, these power supplies were designed to feed sensitive analogue electronic circuits with highly stabilised, low-noise DC voltages. The trusted partnership with CERN's Large Hadron Collider (LHC) has also led to the development of new radiation-hard and magnetic-field-tolerant low-voltage power supplies, as well as subsequent special crates in different standards. Since 2006 more than 2000 standard and customised crates and radiation-hard power supplies for the CERN LHC accelerator and experiments have been manufactured, many of which are still in service after more than 20 years of use. For the particle detectors (LHCb, ATLAS, ALICE), iseg has delivered EHS and EDS high-voltage modules.

About iseg
The iseg Spezialelektronik GmbH company specialises in the development and production of high-voltage power supplies for industry and research. By using modern, patented resonant converter technology, iseg delivers efficient and highly precise power supplies in small-form factors and excellent electrical parameters. In addition to the standard product range, iseg produces a substantial amount of customer-specific equipment. In many cases, it will be possible to generate an individual solution based on existing product lines in a timely and cost-efficient manner.

About W-IE-NE-R
From the beginning, W-IE-NE-R has worked closely with nuclear-physics laboratories. As a result, the development and production of NIM crates and electronics started in the 1980s. CAMAC modules and crates came shortly thereafter, followed by FASTBUS, VME, VXI, VME64x, VXS and today's high-speed switched fabric technologies. W-IE-NE-R then began to specialise in custom, high-quality multi-channel power supplies for medium- and high-power applications. W-IE-NE-R crates and power supplies are known to provide the highest possible power output and lowest noise with quality and longevity. All of the products meet the requirements of leading research centres around the world and are often used as a design reference.



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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Probing new physics with the Higgs boson

Due to its connection to the process of electroweak symmetry breaking, the Higgs boson plays a special role in the Standard Model (SM). Its properties, such as its mass and its couplings to fermions and bosons, have been measured with increasing precision. For these reasons, the Higgs boson has become an ideal tool to conduct new-physics searches. Prominent examples are direct searches for new heavy particles decaying into Higgs bosons or searches for exotic decays of the Higgs boson. Such phenomena have been predicted in many extensions of the SM motivated by long-standing open questions, including the hierarchy problem, dark matter and electroweak baryogenesis. Examples of new particles that couple to the Higgs boson are heavy vector bosons (as in models with Higgs compositeness or warped extra dimensions) and additional scalar particles (as in supersymmetric models or axion models).

Searches for resonances

The ATLAS collaboration recently released results of a search for a new heavy particle decaying into a Higgs and a W boson. The search was performed by probing for a localised excess in the invariant mass distribution of the $\ell\nu bb$ final state. As no such excess was found, upper limits at 95% confidence level were set on the production-cross section times branching ratio of the new heavy resonance (figure 1). The results were also interpreted in the context of the heavy vector triplet (HVT) model, which extends the SM gauge group by an additional SU(2) group, to constrain the coupling strengths of heavy vector bosons to SM particles. In two HVT benchmark models, W′ masses below 2.95 and 3.15 TeV are excluded.

Rare or exotic decays are excellent candidates to search for weakly coupled new physics. The Higgs boson is particularly sensitive to such new physics owing to its narrow total width, which is three orders of magnitude smaller than that of the W and Z bosons and the top quark. Several searches for exotic decays of the Higgs boson have been carried out by ATLAS, and they may be broadly classified as those scenarios where the possible new daughter particle decays promptly to SM particles, and those where it would be long-lived or stable.

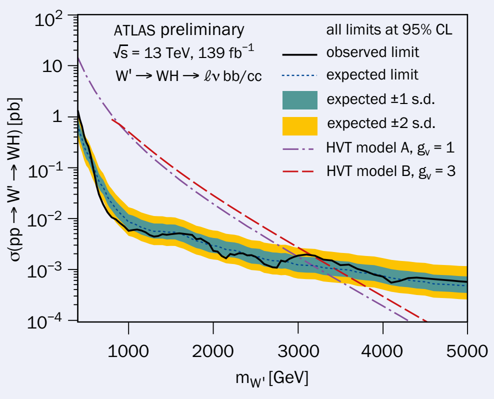

Fig. 1. *Observed (solid) and expected (dashed) upper limits at 95% CL on the production-cross section for* $pp \rightarrow W' \rightarrow WH$. *The green (yellow) band indicates ±1 (±2) standard deviations from the expected limits.*

Source: ATLAS-CONF-2021-026

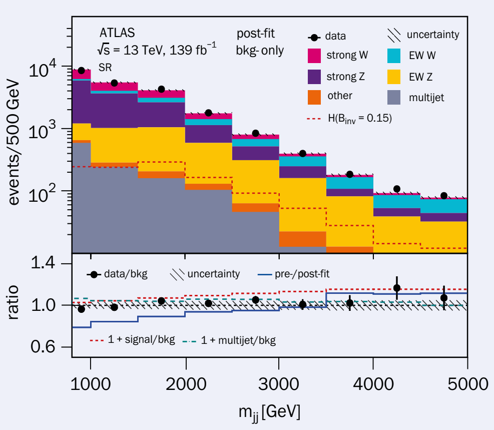

Fig. 2. *Invariant mass distribution of the two jets considered in the search for Higgs-boson decays into invisible particles for the vector-boson fusion production process. The signal (dashed red line) scaled to a branching ratio of 15% for Higgs-boson decays tends to higher masses, corresponding to large angular separation of the jets.*

Source: arXiv:2202.07953

A recent search from ATLAS targeted exotic decays of the Higgs boson into a final state into four electrons or muons, which benefit from a very clean experimental signature. Although a signal was not observed, the search put stringent constraints on decays to new light scalar bosons – particularly in the low mass range of a few GeV – and to new vector bosons, dubbed dark Z bosons or dark photons, in the mass range up to a few tens of GeV. Depending on the new-physics model, this search can exclude branching ratios of the Higgs boson to new particles as low as $O(10^{-5})$.

Invisibles

Another interesting possibility is the case where the Higgs boson decays to particles that are invisible in the detector, such as dark-matter candidates. To select such events, different strategies are pursued depending on the particles produced in association with the Higgs boson. The most powerful channel for such a search is the vector-boson fusion production process, where two energetic jets from quarks are produced with large angular separation alongside the invisibly decaying Higgs boson (figure 2). Another sensitive channel is the associated production of a Higgs boson with a Z boson that decays to a pair of leptons. Improvements in background predictions have made it possible to reach a sensitivity down to 10% on the branching ratio of invisible Higgs-boson decays, while the corresponding observed limit amounts to 15%.

These searches will greatly benefit from the large datasets expected in Run 3 and later High-Luminosity LHC runs, and will enable searches for even more feeble couplings of new particles to the Higgs boson.

Further reading

ATLAS Collab. 2021 ATLAS-CONF-2021-026.
D Pappadopulo *et al.* 2014 *JHEP* **2014** 60.
ATLAS Collab. 2021 arXiv:2110.13673.
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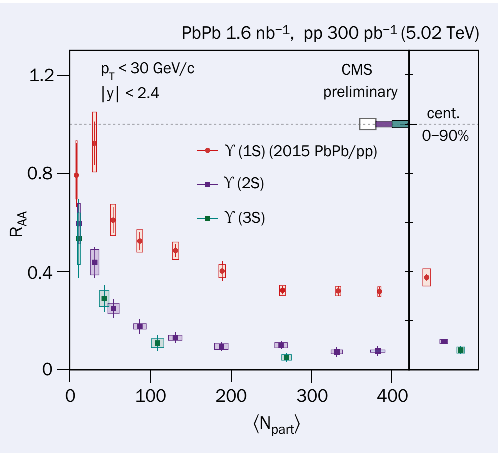
CMS

Upsilon suppression in heavy-ion collisions

The bound states of a heavy quark and its antiquark, called quarkonia, have long been regarded as ideal probes to study the quark–gluon plasma (QGP) formed in high-energy heavy-ion collisions. The golden signature is the suppression of their production yield in lead–lead (PbPb) collisions with respect to extrapolations from proton–proton (pp) collisions, caused by modifications of the binding potential in the QGP. The suppression of the different quarkonium states is expected to depend on their binding energies. Quarkonia can also be produced by recombination processes. The Υ states (bound states of b quarks and antiquarks) are much less affected by recombination effects than charmonium states, given the very small probability that b quarks are produced. A comparison of their suppression patterns is particularly informative because of the different binding energies of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states.

The suppression of quarkonium production is quantified via the nuclear modification factor R_{AA}, defined as the ratio between the yield in nucleus–nucleus (AA) collisions and the yield extrapolated from pp data. Previous measurements of R_{AA} for the Υ mesons by experiments at RHIC and the LHC revealed a significant suppression of the $\Upsilon(1S)$ state and a larger suppression for the $\Upsilon(2S)$ state. However, these experiments could only set upper limits for the $\Upsilon(3S)$ state due to its very low production yield. The CMS experiment recently changed this situation by presenting the first observation of the $\Upsilon(3S)$ meson in heavy-ion collisions. The Υ mesons are detected using their decay to two muons. The analysis used the large PbPb data sample collected in 2018 and extracted the $\Upsilon(3S)$ signals from the large background of muon pairs by using a boosted decision tree algorithm.



Source: CMS-PAS-HIN-21-007

Fig. 1. *The nuclear modification factor R_{AA} of the three Υ states, as a function of $<N_{part}>$ (besides the centrality-integrated values). The error bars (boxes) represent the statistical (systematic) uncertainties. The boxes at unity represent global systematic uncertainties, for both the $\Upsilon(2S)$ and $\Upsilon(3S)$ points (open), and for only the $\Upsilon(2S)$ (purple) or $\Upsilon(3S)$ (green) mesons.*

The new R_{AA} results are shown together with the previously published $\Upsilon(1S)$ values as a function of the average number of nucleons participating in the PbPb collisions, $<N_{part}>$ (figure 1). Collisions with larger $<N_{part}>$ show a bigger overlap between the two nuclei, producing a larger and hotter QGP. As previously observed, the degree of suppression increases from peripheral to central collisions, i.e. as N_{part} increases, indicating a more substantial dissociation effect at higher QGP temperatures. The new $\Upsilon(3S)$ suppression measurement completes the picture of suppression patterns for five different quarkonium states, which was started 35 years ago at the CERN SPS with the J/ψ and ψ(2S) results of NA38. The stage is set for a deeper understanding of deconfinement in the QGP.

Further reading

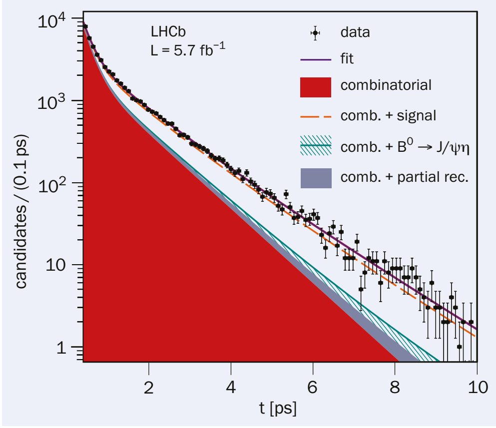
CMS Collab. 2022 CMS-PAS-HIN-21-007.
S Digal *et al.* 2001 *Phys. Rev. D* **64** 094015.

LHCb

Determining the lifetime of the B_s

As the LHCb experiment prepares for data taking with an upgraded detector for LHC Run 3, the rich harvest of results using data collected in Run 1 and Run 2 of the LHC continues.

A fascinating area of study is the quantum-mechanical oscillation of neutral mesons between their particle and antiparticle states, implying a coupled system of two mesons with different lifetimes. The phenomenology of the B_s system is particularly interesting as it provides a sensitive probe to physics beyond the Standard Model. A B_s meson oscillates with a frequency of about 3×10^{12} Hz, or on average about nine times during its lifetime, τ. In addition, a sizeable difference between the decay widths of the heavy (Γ_H) and light (Γ_L) mass eigenstates is expected. Measuring the lifetime of a CP-even B_s-decay mode determines $\tau_L = 1/\Gamma_L$.

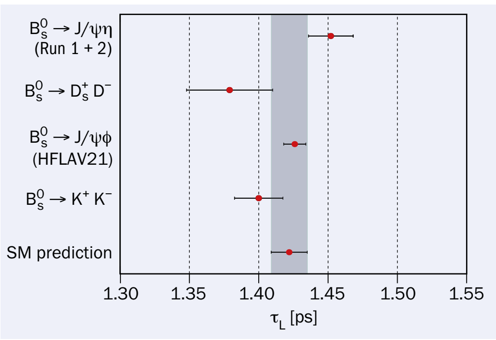


Source: arXiv:2206.03088

Fig. 1. *The exponentially falling decay-time distribution of the decay $B_s \rightarrow J/\psi\eta$.*

LHCb has recently released a new and precise measurement of this parameter, making use of $B_s \rightarrow J/\psi\eta$ decays selected from 5.7 fb^{-1} of Run 2 data. The study improves the previous Run 1 precision by a factor of two. Due to the combinatorial background, the reconstruction of the η meson via its two-photon decay mode is a particular challenge for this analysis. Despite this, and even with the modest energy resolution of the calorimeter leading to a relatively broad mass peak overlapping partially with the signal from the $B^0 \rightarrow J/\psi\eta$ decay, a competitive accuracy has been achieved. By exploiting the latest machine-learning techniques to reduce the background and the well understood LHCb detector, the $B_s \rightarrow J/\psi\eta$ decay is observed (figure 1), and τ_L is extracted from a two-dimensional ▷ fit to the mass and decay time.

The analysis finds $\tau_L = 1.445 \pm 0.016$ (stat) $\pm$ 0.008 (syst) ps, which is the most precise measurement of this quantity. Combined with the LHCb Run 1 study of this and the $B_s \rightarrow D_s^+ D_s^-$ decay mode, $\tau_L = 1.437 \pm 0.014$ ps, which agrees well both with the Standard Model expectation ($\tau_L = 1.422 \pm 0.013$ ps) and the value inferred from measurements of Γ_s and $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi\phi$ decays. Further improvement in the knowledge of τ_L is expected both by considering other CP-even B_s decays to final states containing η or η′ mesons, the $B_s \rightarrow D_s^+ D_s^-$ dataset collected during Run 2 and from the upcoming Run 3.



Source: arXiv:2206.03088

Fig. 2. *Summary of measurements of τ_L by LHCb of the $B_s \rightarrow J/\psi\phi$ decay mode along with the HFLAV average determined using the measurements of Γ_s and $\Delta\Gamma_s$. The Standard Model prediction is shown by the grey band.*

Further reading

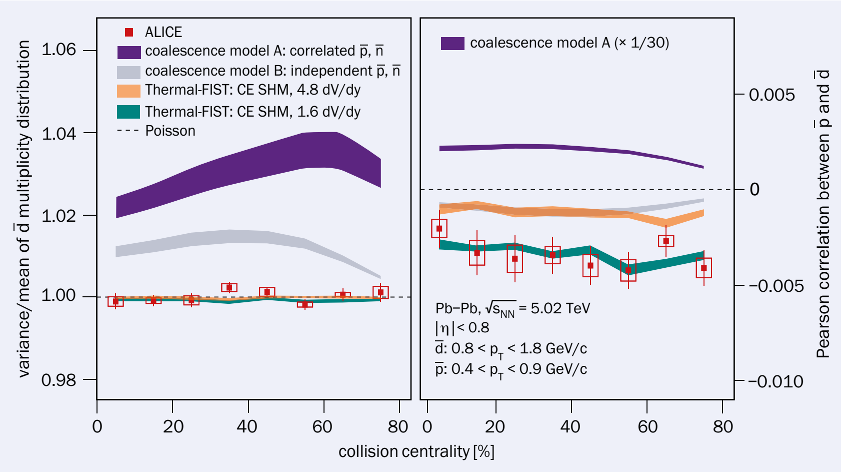
LHCb Collab. 2022 arXiv:2206.03088.
LHCb Collab. 2016 *Phys. Lett. B* **762** 484.
LHCb Collab. 2014 *Phys. Rev. Lett.* **112** 111802.
LHCb Collab. 2014 *Phys. Lett. B* **736** 446.

ALICE

Antinucleosynthesis beyond the average

Despite two decades of extensive studies, the production of antinuclei in heavy-ion collisions is not yet fully understood. Antinuclei production is usually modelled by two conceptually different theoretical models, the statistical hadronisation model (SHM) and coalescence models. In the SHM, deuteron antinuclei are produced from a locally thermally equilibrated source, while antinuclei are formed from the binding of constituent nucleons, which are close in momentum and position phase space in the coalescence model. Both models predict very similar production yields of, for example, deuteron antinuclei, bound states of an antiproton and an antineutron. This calls for new experimental observables that discern different production models.

Measuring higher moments of the multiplicity distribution of antinuclei as well as the correlation with antinucleons produced in the collision have been recently proposed as sensitive variables to antinucleosynthesis processes in heavy-ion collisions. The first measurement of the variance to mean ratio of the multiplicity distribution of antideuterons is compared to the predictions of the SHM and coalescence models (figure 1). The coalescence model fails to describe the observed ratio of the variance and mean of the multiplicity distribution of antideuterons. The measurements are consistent with the statistical baseline, a Poissonian distribution, as well as with the SHM in the presence of baryon number conservation. However, this observable proves insensitive to the size of the correlation volume used in the SHM to conserve the baryon number.



Source: arXiv:2204.10166

Fig. 1. *The ratio of the antideuteron's multiplicity distribution variance and mean as a function of the collision centrality (left), and Pearson correlation coefficient between antideuterons and antiprotons measured as a function of the collision centrality (right). The measurements on both sides are compared to the predictions of the coalescence models with two different initial conditions (violet, grey) and with those of the SHM with two different correlation volumes (yellow, green).*

The Pearson correlation coefficient between the number of produced antideuterons and antiprotons constrains the latter effectively. The small negative correlation reflects that there are less protons observed in events with at least one deuteron than in an average event (figure 1). The coalescence model does not reproduce the measurement, whereas it is possible to fit the measurement to extract the correlation volume out of the SHM. The obtained correlation volume is 1.6 times the volume of the fireball per unit of rapidity, which is smaller compared to those describing proton yields and a similar measurement of net-proton number fluctuations. These findings point to a later formation of the correlation among protons and deuterons compared to that among antiprotons and protons.

Overall, these results present a severe challenge to the current understanding of antinuclei production in heavy-ion collisions at the LHC energies. With the LHC Run 3 data it will be possible to extend these measurements to heavier antinuclei and to higher order correlation coefficients and moments of the antinuclei multiplicity distribution that are even more sensitive to details of the nucleosynthesis process in heavy-ion collisions.

Further reading

ALICE Collab. 2022 arXiv:2204.10166.

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FIELD NOTES

Reports from events, conferences and meetings

56th Rencontres de Moriond on QCD and High Energy Interactions

Tour de QCD and beyond


I Cossin/ARISF

Rencontres *Participants at the 56th Moriond conference were thrilled by the chance to meet in person again, and by the many results presented.*

The 56th Rencontres de Moriond on QCD and High Energy Interactions took place at the Italian resort of La Thuile from 19 to 26 March. More than 100 participants, almost equally split between experimentalists and theorists, were treated to an exciting scientific programme and many in-person interactions, which were especially appreciated after two years of pandemic isolation.

Keeping with the tradition of Moriond, several new experimental results were presented by major experimental collaborations, with participants enjoying ample opportunities to debate cases where measurements and theoretical predictions do not agree. Held 10 years after the Higgs discovery, the conference started with a review of how the Higgs boson came of age – from early exploration to a precision era. An exciting mix of new precision results and interesting observations in Higgs physics were presented, including the first measurement of the Higgs-charm coupling as well as studies of off-shell Higgs production and di-Higgs production by the ATLAS and CMS collaborations.

The first observation of $tq\gamma$ production by ATLAS as well as many measurements in top-quark physics, including a mass measurement based on single top quarks by CMS, were discussed. Many recent studies of Z and W bosons and their interactions were reported, including a new CMS result that resolved an earlier mild LEP tension in the decay rates of W bosons to leptons, and the observation of triple-W production at the LHC by ATLAS. The LHCb collaboration presented its first measurement of the W mass, while CMS discussed the first observation of WW and triple-J/ψ production in double-parton scattering.

Several sessions were devoted to flavour measurements and anomalies, including possible lepton-flavour universality violations in B-meson decays. LHCb presented the most precise value of the CKM matrix angle γ measured in a single experiment, as well as the most precise measurement of the charm mixing parameter y_{CP}. New results on lepton-flavour universality attracted a lot of attention. Among them are LHCb's measurement of the ratio of Br($B^+ \to K^+\mu^+\mu^-$) to Br($B^+ \to K^+e^+e^-$), which is 3.1σ away from the SM, new LHCb limits on rare B^0 decays, and the CMS measurement of the Drell–Yan forward–backward asymmetry difference between di-muons and di-electrons. The status of selected Standard Model (SM) calculations was described with the conclusion that the predictions are robust and therefore possible deficiencies of the SM a very unlikely source of the flavour anomalies. A number of talks demonstrated that there are many ways to accommodate the flavour anomalies into a consistent physics picture, which predicts subtle signals at the LHC that could have easily evaded detection so far.

Continuing the topic of searches for new physics, several speakers emphasised the importance of new creative analysis concepts, including searching for anomalous energy losses, non-pointing tracks, delayed photons, displaced jets, displaced collimated leptons and tagging missing mass with forward detectors. Among the results of many interesting searches presented at Moriond, a 3σ excess in the number of highly ionising particles reported by the ATLAS collaboration caused some excitement and discussion, indicating that further studies (and statistics!) are very much needed.

Several speakers emphasised the importance of new creative analysis concepts

Several talks presented theoretical predictions at high orders of perturbative QCD for basic SM processes at the LHC and future lepton colliders, such as the Drell–Yan and jet-production processes. These tour de force computations, representing cutting-edge applications of quantum field theory to collider physics, force us to think about how such advances in the theory of hard hadron collisions can be used to search for physics beyond the SM. Several talks addressed this issue by considering specific physics examples pointing towards new, exciting opportunities during LHC Run 3.

Emphasising the need for a refined knowledge of the fundamental input parameters used to describe hadron collisions, four new extractions of the strong coupling constant were reported, based on HERA, CDF, LEP and CMS data. The role of precision deep-inelastic scattering (HERA) and W/Z (ATLAS/CMS) data in constraining parton distribution functions was clearly elucidated.

Turning towards the non-perturbative sector of QCD, a measurement of Λ_c production down to zero transverse ▷

momentum allowed the ALICE collaboration to extract the total charm cross-section in pp collisions. Interestingly, the fraction of Λ_c is significantly above the e^+e^- baseline. Jet substructure measurements presented by ALICE and CMS allow a detailed comparison to Monte Carlo event generators. Furthermore, the first direct observation of the dead-cone effect, a suppression of forward gluon radiation in case of a massive emitter, was presented by the ALICE collaboration using charm-tagged jets (see p9).

An element of non-perturbative QCD that keeps theorists on their toes is hadronic spectroscopy. This trend continued at Moriond where the discoveries of several new states were presented, including the same-sign doubly charmed T_{cc}^+ ($c\text{-}c\text{-}\bar{u}\text{-}\bar{d}$) (LHCb) and the Z_{cs}^- ($c\text{-}\bar{c}\text{-}s\text{-}\bar{u}$) (BES III). The exploration of the χ_{c1}, earlier known as X(3872), with the hope of revealing its molecular or tetraquark nature, continues in pp as well as in PbPb collisions.

The best constraint of the charm diffusion coefficient in the quark–gluon plasma (ALICE), jet quenching studies with Z-hadron correlations (CMS) and surprising results on ridge structures in γp and γPb collisions (ATLAS) were presented during a dedicated heavy-ion session. Interestingly, by studying the abundant nuclei produced in heavy-ion collisions, the ALICE collaboration ruled out simple coalescence models for antideuteron production in PbPb collisions (see p15).

Finally, the current status of the muon anomalous magnetic moment was reviewed. The experimental value presented last year by the Fermilab g-2 collaboration shows a $1.5\text{–}4.2\sigma$ discrepancy with the SM prediction, depending on the theoretical baseline. An interesting comparison between continuum and lattice computations of the hadronic vacuum polarisation contributions was presented, and a new lattice result on hadronic light-by-light scattering was described, indicating that this "trouble-making" contribution is being brought under theoretical control.

An element of non-perturbative QCD that keeps theorists on their toes is hadronic spectroscopy

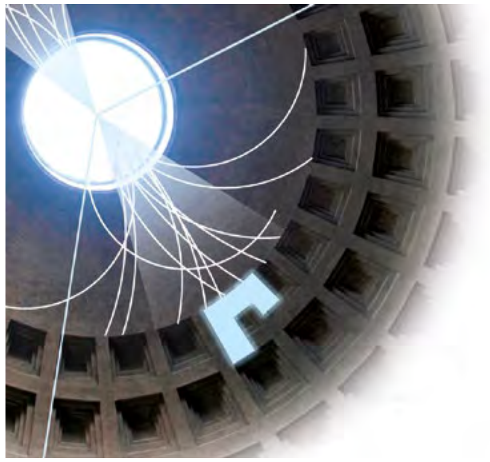
Exciting experimental results and developments in the theory of QCD and high-energy interactions that, perhaps, remained somewhat hidden during the pandemic years, were on full display at Moriond, making the 56th edition of this conference a resounding success.

Jan Fiete Grosse-Oetringhaus *CERN and* **Kirill Melnikov** *KIT Karlsruhe.*

First FCC–Italy Workshop

Future Circular Collider workshop debuts in Italy

The first Italian workshop on the Future Circular Collider (FCC) took place in Rome from 21 to 22 March and was attended by around 120 researchers.



F Ligabue INFN Pisa

Visionary *Participants at the FCC's Rome workshop discussed the proposed project's scientific potential.*

The FCC study is exploring the technical and financial feasibility of a 91 km-circumference collider situated under French and Swiss territory near CERN, thus exploiting existing infrastructures. In a first phase (FCC-ee) the tunnel would host an electron–positron collider at energies from 90 to 365 GeV, which would be replaced by a proton–proton collider (FCC-hh) with a centre-of-mass energy of at least 100 TeV, almost an order of magnitude higher than that of the LHC. The proposed roadmap foresees the R&D for the 16 T superconducting dipole magnets needed to keep the FCC-hh proton beams on track to take place in parallel with FCC-ee construction and operation

"The FCC is a large infrastructure that would allow Europe to maintain its worldwide leadership in high-energy physics research. This project is therefore of strategic importance in the international science scenario of the coming years," remarked INFN president Antonio Zoccoli in his introduction. "INFN has great potential and could make a significant contribution to its implementation. In this perspective, it is important to clearly identify the main activities in which to invest, assemble the necessary human resources and identify possible industrial partners."

The workshop was opened by FCC study leader Michael Benedikt, who gave an overview of the FCC feasibility study, while deputy study leader Frank Zimmermann covered the technological challenges, design features and machine studies for FCC-ee. Opportunities for technological development related to the FCC-ee were then presented, along with machine studies, in which INFN are already involved. Scientific and technological R&D areas where collaborations could be strengthened or initiated were also identified, prompting an interesting discussion with CERN colleagues.

INFN is already well integrated both in the FCC coordination structure and several ongoing studies, having participated in the project since its beginning, and provides important contributions on all aspects of the FCC study. These range from accelerator and detector R&D, such as the development of superconducting magnets, to experimental and theoretical physics studies. This is made evident by the strong Italian involvement in FCC-related European programmes, such as EuroCirCol for FCC-hh and FCC-IS for FCC-ee, and AIDAinnova on innovative detector technologies for future accelerators. INFN is committed to the development of superconducting magnets for FCC-hh, for which substantial additional funding could come from a project in the context of the next-generation funding programme Horizon Europe.

The second day of the workshop focused on the work that experimental and theoretical physicists have been carrying out to deeply understand the scientific potential of the visionary FCC project, the specific requests for the detectors and the associated R&D activities.

This workshop was the first in a series organised by INFN to promote and support the FCC project and pursue the key technological R&D needed to demonstrate its feasibility by the next update of the European strategy for particle physics.

Franco Bedeschi *INFN Pisa,* **Manuela Boscolo** *INFN Frascati and* **Marina Cobal** *University of Udine.*

Second African Conference on Fundamental and Applied Physics

Accelerating knowledge transfer with physics

Science and technology are key instruments for a society's economic growth and development. Yet Africa's science, innovation and education have been chronically under-funded. Transferring knowledge, building research capacity and developing competencies through training and education are major priorities for Africa in the 21st century. Physics combines these priorities by extending the frontiers of knowledge and inspiring young people. It is therefore essential to make basic knowledge of emerging technologies available and accessible to all African citizens to build a steady supply of trained and competent researchers.

K Assamagan

Science for society *Map showing the countries in Africa with home institutes participating in ACP2021 (green).*

In this spirit, the African School of Fundamental Physics and Applications was initiated in 2010 as a three-week biennial event. To increase networking opportunities among participants, the African Conference on Fundamental and Applied Physics (ACP) was included as a one-week extension of the school. The first edition was held in Namibia in 2018 and the second, co-organised jointly by Mohammed V University and Cadi Ayyad University in Morocco, was rebranded ACP2021, originally scheduled to take place in December but postponed due to COVID-19. The virtual event held from 7 to 11 March attracted more than 600 registrants, an order of magnitude higher than its first edition.

The ACP2021 scientific programme covered the three major physics areas of interest in Africa defined by the African Physical Society: particles and related applications; light sources and their applications; and cross-cutting fields covering accelerator physics, computing, instrumentation and detectors. The programme also included topics in quantum computing and quantum information, as well as machine learning and artificial intelligence. Furthermore, ACP2021 focused on topics related to physics education, community engagement, women in physics and early-career physicists. The agenda was stretched to accommodate different time zones and 15 parallel sessions took place.

Welcome speeches by Hassan Hbid (Cadi Ayyad University) and by Mohammed Rhachi (Mohammed V University) were followed by a plenary talk by former CERN Director-General Rolf Heuer, "Science bridging Cultures and Nations" and an overview of the African Strategy for Fundamental and Applied Physics (ASFAP). Launched in 2021, the ASFAP aims to increase African education and research capabilities, build the foundations and frameworks to attract the participation of African physicists, and establish a culture of awareness of grass-roots physics activities contrary to the top-down strategies initiated by governments (*CERN Courier* November/December 2021 p22). Shamila Nair-Bedouelle (UNESCO) conveyed a deep appreciation of and support for the ASFAP initiative, which is aligned with the agenda of the United Nations Sustainable Development Goals. A rich panel discussion followed, raising different views on physics education and research roadmaps in Africa.

A central element of the ACP2021 physics programme is the ASFAP community planning meeting, where physics and community-engagement groups discussed progress in soliciting the community input that is critical for the ASFAP report. The report will outline the direction for the next decade to encourage and strengthen higher education, capacity building and scientific research in Africa.

The motivation and enthusiasm of the ACP2021 participants was notable, and the efforts in support of research and education across Africa were encouraged. The next ACP in 2023 will be hosted by South Africa.

Farida Fassi *Mohammed V University, Morocco.*

SESAME Cultural Heritage Day

SESAME revives the ancient Near East

The Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) is a 2.5 GeV third-generation synchrotron radiation (SR) source developed under the auspices of UNESCO and modelled after CERN. Located in Allan, Jordan, it aims to foster scientific and technological excellence as well as international cooperation amongst its members, which are currently Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, Palestine and Turkey. As a user facility, SESAME hosts visiting scientists from a wide range of disciplines, allowing them to access advanced SR techniques that link the functions and properties of samples and materials to their micro, nano and atomic structure.

SESAME offers a versatile tool for researchers, conservators and cultural-heritage specialists in the region

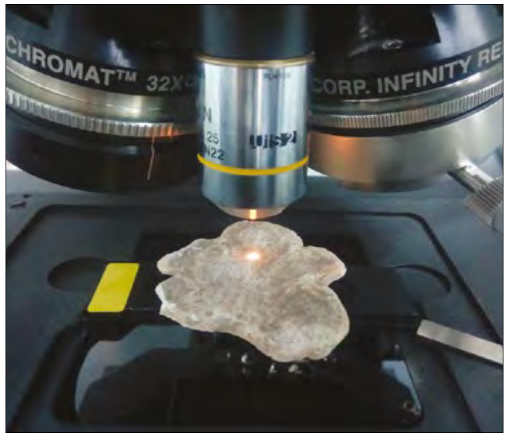
The location of SESAME is known for its richness in archaeological and cultural heritage. Many important museums, collections, research institutions and universities host departments dedicated to the study of materials and tools that are inextricably linked to prehistory and human history, demanding interdisciplinary research agendas and teams. As materials science and condensed-matter physics play an increasing role in understanding and reconstructing the properties of artefacts, SESAME offers a highly versatile tool for the researchers, conservators and cultural-heritage specialists in the region.

The high photon flux, small source size and low divergence available at SR sources allow for advanced spectroscopy and imaging techniques that are well suited for studying ancient and historical materials, and which often present very complex and heterogeneous structures. SR techniques are non-destructive, and ▷

the existence of several beamlines at SR facilities means that samples can easily be transferred and reanalysed using complementary techniques.

At SESAME, an infrared microspectroscopy beamline, an X-ray fluorescence and absorption spectroscopy beamline, and a powder diffraction beamline are available, while a soft X-ray beamline called "HESEB" has been designed and constructed by five Helmholtz research centres and is now being commissioned. Next year, the BEAmline for Tomography at SESAME (BEATS) will also be completed, with the construction and commissioning of a beamline for hard X-ray full-field tomography. BEATS involves the INFN, The Cyprus Institute and the European SR facilities ALBA-CELLS (Spain), DESY (Germany), ESRF (France), Elettra (Italy), PSI (Switzerland) and SOLARIS (Poland).

To explore the potential of these beamlines, the First SESAME Cultural Heritage Day took place online on 16 February with more than 240 registrants in 39 countries. After a welcome by SESAME director Khaled Toukan and president of council Rolf Heuer, Mohamed ElMorsi (Conservation Centre, National Museum of Egyptian Civilization), Marine Cotte (ESRF) and Andrea Lausi (SESAME) presented overviews of ancient Egyptian cultural heritage, heritage studies at the ESRF, and the experimental capabilities of SESAME, respectively. This was followed by several research insights obtained by studies at SESAME and other SR facilities: Maram Na'es (TU Berlin) showed the reconstruction of colour in Petra paintings; Heinz-Eberhard Mahnke and Verena Lepper (Egyptian Museum and Papyrus Collection, FU/HU Berlin and HZB) explained how to analyse ancient Elephantine papyri using X-rays and tomography; Amir Rozatian (University of Isfahan) and Fatma Marii (University of Jordan) determined the material of pottery, glass, metal and textiles from Iran and ancient glass from the Petra church; and Gonca Dardeniz Arıkan (Istanbul University) provided an overview of current research into the metallurgy of Iran and Anatolia, the origins of glassmaking, and the future of cultural heritage studies in Turkey. Palaeontology with computed tomography and bioarchaeological samples were highlighted in talks by Kudakwashe Jakata (ESRF) and Kirsi Lorentz (The Cyprus Institute).


SESAME

Colouring the past *The painting technology of a Petra wall fragment explored using the IR microscope at SESAME.*

During the following discussions, it was clear that institutions devoted to the research, preservation and restoration of materials would benefit from developing research programmes in close cooperation with SESAME. Because of the multiple applications in archaeology, palaeontology, palaeo-environmental science and cultural heritage, it will be necessary to establish a multi-disciplinary working group, which should also share its expertise on practical issues such as handling, packaging, customs paperwork, shipping and insurance.

Andrea Lausi *SESAME.*

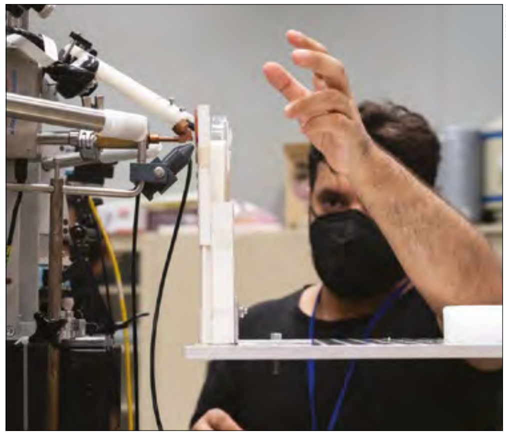
6TH SUMMER SCHOOL ON INTELLIGENT SIGNAL PROCESSING FOR FRONTIER RESEARCH AND INDUSTRY

Fostering cross-disciplinarity

Despite several COVID waves, the organisers of the 6th edition of the International Summer School on Intelligent Signal Processing for Frontier Research and Industry (INFIERI) made this school an in-person event. The INFIERI school was successfully held at UAM from August 23 to September 4 thanks to the unprecedented speed of the vaccine roll out, the responsible behaviour of the school participants and the proper applied logistics.

Against a backdrop of topics ranging from cosmology to the human body and particle physics, the programme covered advanced technologies such as semiconductors, deep sub-micron 3D technologies, data transmission, artificial intelligence and quantum computing.

Topics were presented in lectures and keynote speeches, and the teaching was reinforced via hands-on laboratory sessions, allowing students to practise applications in realistic conditions across a range of areas, such as: theoretical physics, accelerators, quantum communication, Si Photonics and nanotechnology. The latter included medical applications to new mRNA vaccines, which have long been under investigation for cancer treatment, besides their use against COVID-19. For instance, they could analyse combined real PET/MRI images using machine-learning techniques to find biomarkers of illness in a hospital setting, or study the irradiation of a biomaterial using a proton beam. Worldwide experts from academia, industry and laboratories such as CERN either gave lectures or ran lab sessions, most of them attending in person, often for the entire duration of the school.


INFIERI

Lab work *Setting up a beam for irradiating biomaterial.*

During the last day, the students presented posters on their own research projects – the high number and quality of presentations reflecting the cross-disciplinary facets and the excellence of the participants. Many were then selected to be part of the in-preparation proceedings of the *Journal of Instrumentation*.

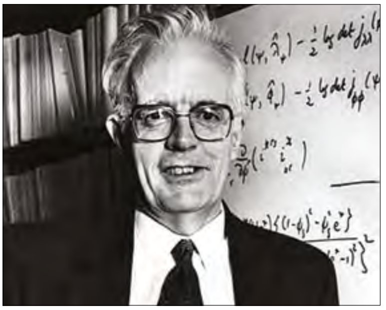
The next INFIERI school will only offer in-person attendance, which is considered essential to the series, but if the pandemic continues it will exploit some of the learning gained from the 6th edition.

Aurore Savoy Navarro *IRFU-CEA Saclay and* **Jose del Peso** *Universidad Autónoma de Madrid.*

PHYSTAT

Seminar remembers eminent David Cox

David Cox, a giant in the world of statistics, passed away earlier this year at the age of 97. As he had been a contributor to PHYSTAT workshops and was a supporter of its activities, a seminar held on 23 March was dedicated to his memory. Brad Efron (Stanford) referred to Cox as the world's most famous statistician – an assessment confirmed by Cox being the first recipient of the International Prize in Statistics, roughly the equivalent of a Nobel Prize. The citation mentioned a lifelong series of contributions to statistics spanning many subjects. In particular, it emphasised his work on what is now called Cox's proportional hazards model, which provides a very useful way to implement regression analysis of survival times (the times to an event of interest such as the death of a person or failure of a machine). His contribution is ranked 16th in *Nature*'s list of most-cited papers in any subject.


General Motors Cancer Research Foundation

Giant of the field *Statistician David Cox was a long-time supporter of the PHYSTAT series.*

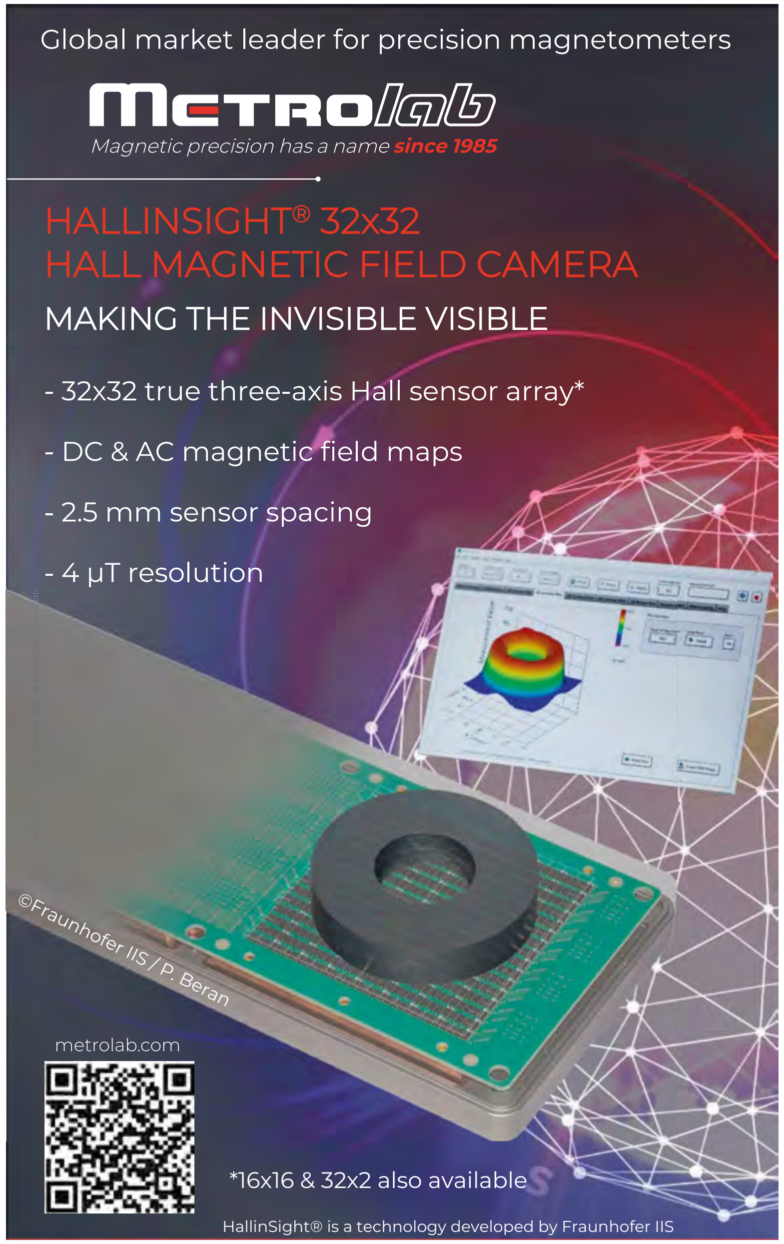
Heather Battey (Imperial College), who collaborated closely with Cox for the past five years, described how he was still very active until his very last days, and highlighted his helpful and charming personality.

Long-time collaborator Nancy Reid (Toronto) concurred, admiring his ability to see through extraneous detail and concentrate on the essence of the problem. She remembers going with him to watch Verdi's *Ernani*, sung in Italian, in Budapest when they were both attending a statistics meeting there. So that Reid wouldn't be completely lost, Cox kindly summarised the lengthy and convoluted plot by telling her "The tenor is in love with the soprano, and the baritone is trying to keep them apart."

It was a special pleasure to have Cox available at our meetings, and he was always prepared to explain statistical issues in informal discussions with particle physicists. Bob Cousins (UCLA) recalled the talks Cox had given at PHYSTAT meetings in 2005, 2007 and 2011. He compared and contrasted frequentist statistics and the "five faces" of Bayesian statistics, repeatedly warning of the dangers of "treacherous" uniform prior probability densities used in attempts to represent ignorance. He alluded to a general key problem in frequentist statistics, that of ensuring that the long run used to calibrate coverage is relevant to the specific data sample being analysed. He also discussed in more technical detail issues of testing multiple hypotheses, including graphical methods. Cox and Reid further offered published thoughts on problems presented to them by LHC physicists. Cousins concluded that we would do well to read Cox's contributions again.

PHYSTAT is pleased and honoured to have had the opportunity of paying its respect to a very eminent statistician and a wonderful person. His memory will long be with us.

Louis Lyons *University of Oxford and Imperial College London.*



THE THRILL OF THE CHASE

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Historic *ATLAS and CMS spokespersons Fabiola Gianotti and Joe Incandela commanding a global audience during their 4 July 2012 presentations.*

Confirming the electroweak Standard Model drove three major projects at CERN spanning three decades, culminating in the discovery of the Higgs boson on 4 July 2012. Matthew Chalmers captures a glimpse of particle physics' great adventure.

At around 10:30 a.m. on 4 July 2012, two remarkable feats of theoretical and experimental physics reached an apex in the CERN auditorium. One was the work of a few individuals using the most rudimentary of materials, the other a global endeavour involving thousands of people and the world's most powerful collider. Forty-eight years after it was predicted, the CMS and ATLAS collaborations presented conclusive evidence for the existence of a new elementary particle, the Higgs boson, the cornerstone of the electroweak Standard Model.

"It took us several years to recover," says CMS experimentalist Chiara Mariotti, who was co-convener of the collaboration's Higgs group at the time. "For me there was a strong sense of 'Higgs blues' afterwards! On the other hand, the excitement was also productive. Immediately after the discovery we managed to invent a new method to measure the Higgs width, with a precision more than 200 times better than what we were thinking – a real breakthrough."

Theoretically, the path to the Higgs boson had been paved by the early 1970s, building on foundations laid by the pioneers of quantum field theory and superconductivity. When Robert Brout and François Englert, and independently Peter Higgs, published their similarly titled papers on broken symmetry and the mass of gauge bosons in 1964, nobody took much notice. One of Higgs's manuscripts was even rejected by an editor based at CERN. The profound consequences of the Brout–Englert–Higgs (BEH) mechanism – that the universe is pervaded by a scalar field responsible for breaking electroweak symmetry and giving elementary particles their mass (see "The Higgs, the universe and everything" panel) – only caught wider attention after further Nobel-calibre feats by Steven Weinberg, who incorporated the BEH mechanism into electroweak theory

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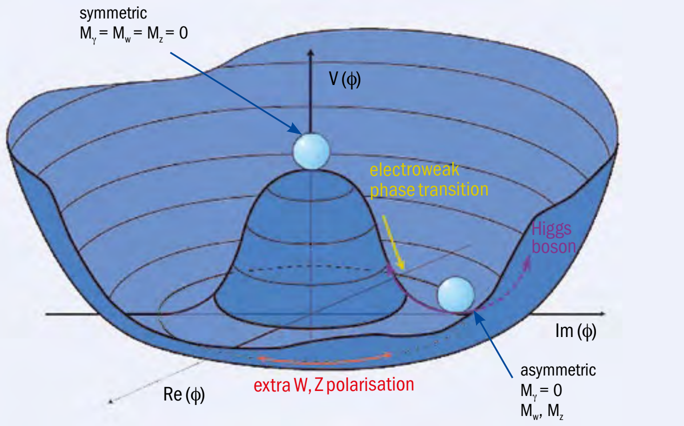
The Higgs, the universe and everything

The Higgs boson is the excitation of a featureless condensate that fills all space – a complex scalar field with a shape resembling a Mexican hat. The universe is pictured as being born in a symmetric state at the top of the hat: the electromagnetic and weak forces were one, and particles moved at the speed of light. A fraction of a nanosecond later, the universe transitioned to a less symmetric but more stable configuration in the rim of the hat, giving the universe a vacuum expectation value of 246 GeV.

During this electroweak symmetry-breaking process, three of the BEH field's components were absorbed to generate polarisation states, and thus masses, for the W and Z bosons; the other component, corresponding to a degree of freedom "up and down" the rim of the hat, is the Higgs boson (see right). The masses of the fermions are generated via Yukawa couplings to the BEH field, implying that mass is not an intrinsic property of elementary particles.

The roots of the BEH mechanism lie in the phenomenon of spontaneous symmetry breaking, which is inherent in superconductivity and superfluidity. In 1960, Yoichiro Nambu and then Jeffrey Goldstone introduced spontaneous symmetry breaking into particle physics, paving the way for taming the weak interaction using gauge theory, like electromagnetism before it. Four years later, Robert Brout and François Englert and, independently, Peter Higgs, showed that a mathematical obstacle called the Goldstone theorem, which implied the existence of unobserved massless particles, is a blessing rather than a curse for gauge theories: the degrees of freedom responsible for the troublesome massless states generate masses for the heavy gauge bosons that mediate the short-range weak interaction (see p31).



Lifting the lid *The famous "Mexican hat" is a simplified picture of the BEH potential. The full SU(2) scalar doublet field ϕ has too many dimensions to draw. In this "U(1)" picture, there is only one degree of freedom (around the rim of the hat) that is absorbed by a gauge boson. In fact, the rim isn't one-dimensional but three-dimensional, and the three components that are absorbed to generate masses for the* W^+, W^- *and Z bosons correspond to field displacements in that space. Results from the LHC so far suggest that the BEH potential turns over at a value of about* 10^{12} *GeV, with implications for the stability of the universe (p59).*

J Ellis/M Neubauer

developed also by Abdus Salam and Sheldon Glashow, and by Gerard 't Hooft and Martinus Veltman, who proved that the unified theory was mathematically consistent and capable of making testable predictions (see p31).

Over to CERN

The first bridge linking the BEH mechanism to the real world was sketched out in CERN's theory corridors in the form of a 50-page-long phenomenological profile of the Higgs boson by John Ellis, Mary Gaillard and Dimitri Nanopoulos published in 1976. The discovery of neutral currents in 1973 by Gargamelle at CERN, and of the charm quark at Brookhaven and SLAC in 1974, had confirmed that the Standard Model was on the right track. Despite their conviction that something like the Higgs boson had to exist, however, Ellis *et al.* ended their paper on a cautionary, somewhat tongue-in-cheek note: "We apologise to experimentalists for having no idea what is the mass of the Higgs boson... and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up".

As it turned out, discovering and measuring the electroweak bosons would drive three major projects at CERN spanning three decades: the SPS proton–antiproton collider, LEP and the LHC. Following Carlo Rubbia and Simon van der Meer's ingenious modification of the SPS to collide protons and antiprotons, greatly increasing the available energy, the UA1 and UA2 collaborations confirmed the existence of the W boson on 25 January 1983. The discovery of the slightly heavier Z boson came a few months later. The discoveries made the case for the Higgs boson stronger, since all three bosons hail from the same scalar field (see panel).

LEP, along with the higher energy Tevatron collider at Fermilab, offered Higgs hunters their first serious chance of a sighting. Dedicated analysis groups formed in the experiments. For a decade they saw nothing. Then, on 14 June 2000, LEP's final year of scheduled running, ALEPH reported a Higgs candidate at around 114–115 GeV, followed soon by a second and third event. LEP was granted a one-month extension. On 16 October, L3 announced a candidate. By 3 November ALEPH had notched up a 2.9σ excess. A request to extend LEP by one year was made, but there was deadlock at CERN. Five days later, Director-General Luciano Maiani announced that LEP had closed for the last time, so as not to delay the LHC. In addition to determining the properties of the W and Z bosons in detail and confirming the existence of electroweak radiative corrections, LEP had planted a flag in energy below which the Higgs would not be found.

J Kvita/CERN

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Closing in *Bill Murray of ATLAS presenting the latest search results at the EPS-HEP conference in Grenoble on 27 July 2011 (left), and CMS spokesperson Guido Tonelli at the 13 December 2011 LHC "jamboree" (right).*

Muscling a discovery

In 1977, CERN Director-General John Adams had the foresight to make the LEP tunnel large enough to accommodate a TeV hadron collider capable of probing the scale of electroweak symmetry breaking. Spurred on by the W and Z discoveries, finding or ruling out the Higgs boson became the central goal of the LHC, greatly influencing the designs of the ATLAS and CMS detectors during the 1990s. Tens of millions of people worldwide watched as the first proton beams were threaded through the machine on 10 September 2008. While the LHC had other goals, the quest for the Higgs boson and the origin of mass resonated with non-experts and brought particle physics to the world.

It was a bumpy start (see p27), but high-energy LHC data began to flood in on 10 March 2010. By the time of the European Physical Society high-energy physics conference in Grenoble in July 2011, ATLAS and CMS were ready to offer a peek of their results. Practically, the search for the Higgs came down to a process of excluding mass ranges in which no signal had been seen. ATLAS and CMS had shrunk the allowed range and found a number of events hinting at a Higgs boson with a mass of about 142 GeV. "We both saw a bump at the same place, and we had champagne after the talks," recalls Kyle Cranmer, co-coordinator of the ATLAS Higgs combination group at the time. "We weren't confident then, but we were optimistic." Fermilab's Tevatron collider was also sensitive to a Higgs in the upper mass range and its CDF and Dø experiments pioneered many of the analysis methods that were used in ATLAS and CMS. Just four years earlier, they had hinted at a possible signal at 160 GeV, only for it to disappear with further data. Was the US machine about to make a last-gasp discovery and scoop the LHC?

The media were hot on the sigma trail. On 13 December 2011, the LHC experiments updated their findings: ATLAS constrained the Higgs to lie in the range 116–130 GeV, and CMS to lie in the range 115–127 GeV. For some, a light Higgs boson was in the bag. Others were hesitant. "There was a three-sigma excess when combining all the channels, but there were also less significant excesses in other mass regions," recalls Mariotti. "I maybe also wanted not to believe it, in order not to be biased when analysing the data in 2012. And maybe because somehow if the Higgs was not there, it would have been really thrilling, much more challenging for us all."

The following year, with the LHC running at a slightly higher energy, the collaborations knew that they would soon be able to say something definitive about the low-mass excess of events. From that moment, CMS decided not to look at the data and instead to redesign its analyses on simulated events "blinded". On the evening of 14 June, all the analysis groups met separately to "open the box". The next day, they shared their results with the collaboration. The two-photon and four-lepton channels had a beautiful peak at the same place. "It was like a very strong punch in the stomach," says Mariotti. "From that moment it was difficult to sleep, and it was hard not to smile!"

Members of both collaborations were under strict internal embargoes concerning the details. ATLAS unblinded its di-photon results late on 31 May, revealing a roughly 2σ excess. By 19 June it had grown to 3.3σ. The four-lepton group saw a similar excess. "My student Sven Kreiss was the first person in ATLAS to combine the channels and see the curve cross the 5σ threshold," says Cranmer. "That was on 24 June, and it started to sink in that we had really found it. But it was still not clear what we would claim or how we would phrase things." Amazingly, he says, he was not aware of the CMS results. "I was also not going out of my way to find out. I was relishing the moment, the excitement, and the last days of uncertainty. I also had more important things to do in preparation for the talk."

With the rumour mill in overdrive, a seminar at CERN was called for 4 July, also the first day of the ICHEP conference in Melbourne. Peter Higgs and François Englert, and Carl Hagan and Gerald Guralnik (who, with Tom Kibble,

The quest for the Higgs boson and the origin of mass resonated with non-experts and brought particle physics to the world

Claudia Marcelloni/CERN

M Hoch *et al*/CERN

Discovery day *Participants of ICHEP 2012 in Melbourne welcoming the new boson late-afternoon local time (left). François Englert and Peter Higgs, who had never physically met until that day, at the CERN press conference following the 4 July seminar (right).*

Every person thought, correctly, that they had played a role in the discovery, which is important, otherwise very large experiments cannot be done

also arrived at the mass-generating mechanism), were to be there. The collaborations were focused only on their presentations. It had to be a masterpiece, says Mariotti. The day before, the CMS and ATLAS Higgs conveners met for coffee. They revealed nothing. "It was really hard not to know. We knew we had it, but somehow if ATLAS did not have it or had it but at a different mass, it all would have been a big disillusion."

Many at CERN decided to spend the night of 3 July in front of the auditorium so as not to miss the historic moment. CMS spokesperson Joe Incandela was first to guide the audience through the checks and balances behind the final plots. Fabiola Gianotti followed for ATLAS. When it was clear that both had seen a 5σ excess of events at around 125 GeV, the room erupted. Was is it really the Higgs? All that was certain was that the particle was a boson, with a mass where the Standard Model expected it. Seizing the moment, and the microphone, Director-General Rolf Heuer announced: "As a layman, I would now say 'I think we have it', do you agree?" It was a spontaneous decision, he says. "For a short period between the unblindings and the seminar, I was one of the few people in the world, just with research director Sergio Bertolucci, in fact, who was aware of both results. We would not have announced a discovery had one experiment not come close to that threshold."

The summer of 2012 produced innumerable fantastic memories, says Marumi Kado, ATLAS Higgs-group co-convener at the time and now a deputy spokesperson. "The working spirit in the group was exceptional. Each unblinding, each combination of the channels was an incredible event. Of course, the 4 July seminar was among the greatest." In CMS, says Mariotti, there was a "party-mood" for months. "Every person thought, correctly, that they had played a role in the discovery, which is important, otherwise very large experiments cannot be done."

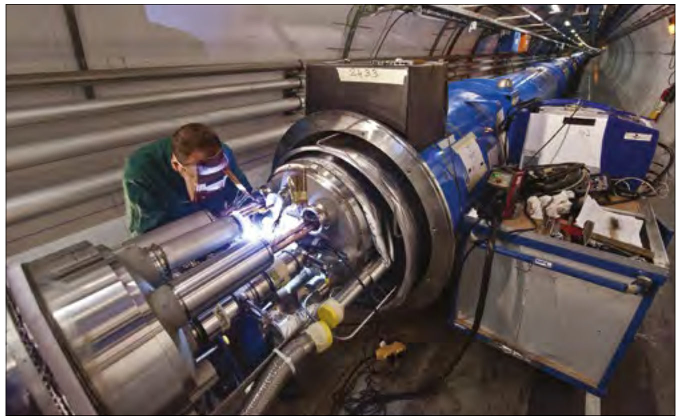
The path from here

Ten years later, ATLAS and CMS measurements have shown the Higgs boson to be consistent with the minimal version required by the Standard Model. Its couplings to the gauge bosons and the heaviest three fermions (top, bottom and tau) have been confirmed, evidence that it couples to a second-generation fermion (the muon) obtained, and first studies of Higgs–charm and Higgs–Higgs couplings reported (see p40). However, data from Run 3, the High-Luminosity LHC and a possible Higgs-factory to follow the LHC, are needed to fully test the Standard-Model BEH mechanism (see p45).

Events on 4 July 2012 brought one scientific adventure to a close, but opened another, fascinating chapter in particle physics with fewer theoretical signposts. What is clear is that precision measurements of the Higgs boson open a new window to explore several pressing mysteries. The field from which the Higgs boson hails governs a critical phase transition that might be linked to the cosmic matter–antimatter asymmetry (see p51); as an elementary scalar, it offers a unique "portal" to dark or hidden sectors which might include dark matter (see p55); as the arbiter of mass, it could hold clues to the puzzling hierarchy of fermion masses (see p53); and its interactions govern the ultimate stability of the universe (see p59). The very existence of a light Higgs boson in the absence of new particles to stabilise its mass is paradoxical (see p47). Like the discovery of the accelerating universe, Nima Arkani-Hamed told the *Courier* in 2019, it is profoundly "new" physics (*CERN Courier* March/April 2019 p45): "Both discoveries are easily accommodated in our equations, but theoretical attempts to compute the vacuum energy and the scale of the Higgs mass pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, the most important path forward for experimentalists is completely clear: measure the hell out of these crazy phenomena!" ●

THE BUMPY RIDE TO THE BUMP

Mike Lamont on the herculean effort that brought the LHC to life and steered it to discovery.



CERN-AC-0904207-04

Downtime *Welding a dipole-magnet interconnect in sector 3–4 in April 2009.*

19 September 2008: the LHC was without beam because of a transformer problem. The hardware commissioning team were finishing off powering tests of the main dipole magnet circuit in sector 3–4 when, at 11:18, an electrical fault resulted in considerable physical damage, the release of helium, and debris in a long section of the machine. In the control room, the alarms came swamping in. The cryogenics team grappled to make sense of what their systems were telling them, and there was frantic effort to interpret the data from the LHC's quench protection system. I called LHC project leader Lyn Evans: "looks like we've got a serious problem here".

Up to this point, 2008 had been non-stop but things were looking good. First circulating beam had been established nine days earlier in a blaze of publicity. Beam commissioning had started in earnest, and the rate of progress was catching some of us by surprise.

It is hard to describe how much of a body blow the sector 3–4 incident was to the community. In the following days, as the extent of the damage became clearer, I remember talking to Glyn Kirby of the magnet team and being aghast when he observed that "it's going to take at least a year to fix". He was, of course, right.

What followed was a truly remarkable effort by everyone involved. A total of 53 cryomagnets (39 dipoles and 14 quadrupoles) covering most of the affected 700 m-long zone were removed and brought to the surface for inspection, cleaning and repair or reuse. Most of the removed magnets were replaced by spares. All magnets whatever their origin had to undergo full functional tests before being installed.

Soot in the vacuum pipes, which had been found to extend beyond the zone of removed magnets, was cleared out using endoscopy and mechanical cleaning. The complete length of the beam pipes was inspected for contamination by flakes of multilayer insulation, which were removed by vacuum cleaning. About 100 plug-in modules installed in the magnet interconnects were replaced.

Following an in-depth analysis of the root causes of the incident, and an understanding of the risks posed by the joints in the magnet interconnects, a new worst-case Maximum Credible Incident was adopted and a wide range of recommendations and mitigation measures were proposed and implemented. These included a major upgrade of the quench protection system, new helium pressure-release ports, and new longitudinal restraints for selected magnets.

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Anticipation *The CERN Control Centre on 20 November 2009 as first proton beams were about to be circulated in the LHC following the September 2008 incident.*

One major consequence of the 19 September incident was the decision to run at a lower-than-design energy until full consolidation of the joints had been performed – hence the adoption of an operational beam energy of 3.5 TeV for Run 1. Away from the immediate recovery, other accelerator teams took the opportunity to consolidate and improve controls, hardware systems, instrumentation, software and operational procedures. As CMS technical coordinator Austin Ball famously noted, come the 2009 restart, CMS, at least, was in an "unprecedented state of readiness".

Take two

Beam was circulated again on 20 November 2009. Progress thereafter was rapid. Collisions with stable-beam conditions were quickly established at 450 + 450 GeV, and a ramp to the maximum beam energy at the time (1.18 TeV, compared to the Tevatron's 0.98 TeV) was successfully performed on 30 November. The first ramps were a lot of fun – there's a lot going on behind the scenes, including compensation of significant field dynamics in the

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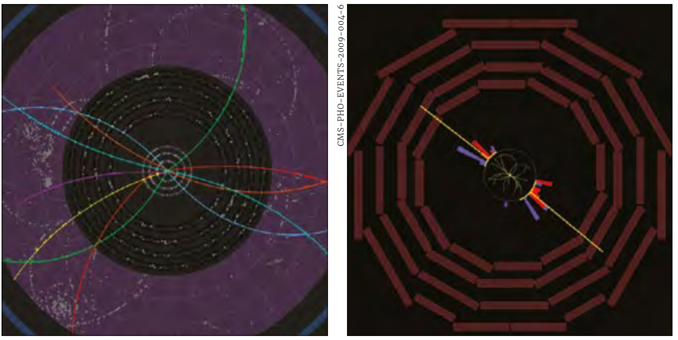
Ramping *Shortly after midnight on 30 November 2009, LHC operators set a new energy record with two beams ramped to 1.18 TeV.*



CERN-EX-0912220-01

CMS-PHO-EVENTS-2009-004-6

And they're off *Some of the first events recorded by ATLAS (left) and CMS (right) on the morning of 6 December 2009, when the LHC achieved collisions at 900 GeV under stable-beam conditions.*

superconducting dipoles. Cue much relief when beam made it up the ramp for the first time. All beam-based systems were at least partially commissioned and LHC operations started a long process to master the control of a hugely complex machine. Following continued deployment of the upgraded quench protection system during the 2009 year-end technical stop, commissioning with beam started again in the new year. Progress was good, with first colliding beams at 3.5 + 3.5 TeV being established under the watchful eye of the media on 30 March 2010. With scheduled collisions delayed by two unsuccessful ramps, it was a gut-knotting experience in the control room. Nonetheless, we finally got there about three hours late. "Stable Beams" was declared, the odd beer was had, and we were off.

Essentially 2010 was then devoted to commissioning and establishing confidence in operational procedures and the machine protection system, before starting to increase the number of bunches in the beam. In June the decision was taken to go for bunches with nominal population (~1.2×10^{11} protons), which involved another extended commissioning period. Up to this point, in deference to machine-protection concerns, only around one fifth of the nominal bunch population had been used. To further increase the number of bunches, the move to a bunch separation of 150 ns was made and the crossing angle bumps spanning the experiments' insertion regions were deployed. After a carefully phased increase in total intensity, the proton run finished with beams of 368 bunches of around 1.2×10^{11} protons per bunch, and a peak luminosity of 2.1×10^{32} cm^{-2}s^{-1}.

Looking back, 2010 was a profoundly important year for a chastened and cautious accelerator sector. The energy stored in the magnets had demonstrated its destructive power, and it was clear from the start that the beam was to be treated with the utmost respect; safe exploitation of the machine was necessarily an underlying principle for all that followed. The LHC became magnetically and optically well understood (judged by the standards at the time – impressively surpassed in later years), and was stunningly magnetically reproducible. The performance of the collimation system was revelatory and accomplished its dual role of cleaning and protection impeccably throughout the full cycle. The injectors were doing a great job throughout in reliably providing high-intensity bunches with unforeseen low transverse emittances.

2010 finished with a switch from protons to operations with lead ions for the first time. Diligent preparation and the experience gained with protons allowed a rapid execution of the ion commissioning programme and Stable Beams for physics was declared on 7 November.

Homing in

The beam energy remained at 3.5 TeV in 2011, with the bunch spacing switched from 75 to 50 ns. A staged ramp in the number of bunches then took place up to a maximum of 1380 bunches, and performance was further increased by reducing the transverse size of the beams delivered by the injectors and by gently increasing the bunch population. The result was a peak luminosity of 2.4×10^{33} cm^{-2}s^{-1} and some healthy delivery rates that topped 90 pb^{-1} in 24 hours. The next step-up in peak luminosity followed a reduction in the β^* parameter in ATLAS and CMS from 1.5 to 1 m (the transverse beam size at the interaction point is directly related to the value of β^*). Along with further gentle increases in bunch population, this produced a peak luminosity of 3.8×10^{33} cm^{-2}s^{-1} – well beyond expectations at the start of the year. Coupled with a concerted effort to improve availability, the machine went on to deliver a total of around 5.6 fb^{-1} for the year to both ATLAS and CMS.

Meanwhile, excitement was building in the experiments. A colloquium at the end of 2011 showed a strengthening significance of an excess at around 125 GeV. The possible discovery of the Higgs boson in 2012 was recognised, and corresponding LHC running scenarios were discussed in depth – first at the Evian workshop (where we heard the plea from CMS spokesperson Guido Tonelli to "gimme 20" [inverse femtobarns]) and crystallised at the 2012 Chamonix workshop, where CERN Director-General Rolf Heuer stated: as a top priority the LHC machine must produce enough integrated luminosity to allow the ATLAS and CMS experiments an independent discovery of the Higgs before the start of long shutdown 1 (LS1). Soon after the workshop, Council president Michel Spiro sent a message to CERN's member states: "After a brilliant year in 2011, 2012 should be historic, with either the discovery of the Standard Model Higgs boson or its exclusion."

An important decision concerned the energy. A detailed risk evaluation concluded that the probability of a splice burn-out at 4 TeV per beam in 2012 was equal to, or less than, the probability that had been estimated in 2011 for 3.5 TeV per beam. The decision to run at 4 TeV helped in a number of ways: higher cross-sections for Higgs-boson production, reduced emittance and the possibility for a further reduction of β^*.

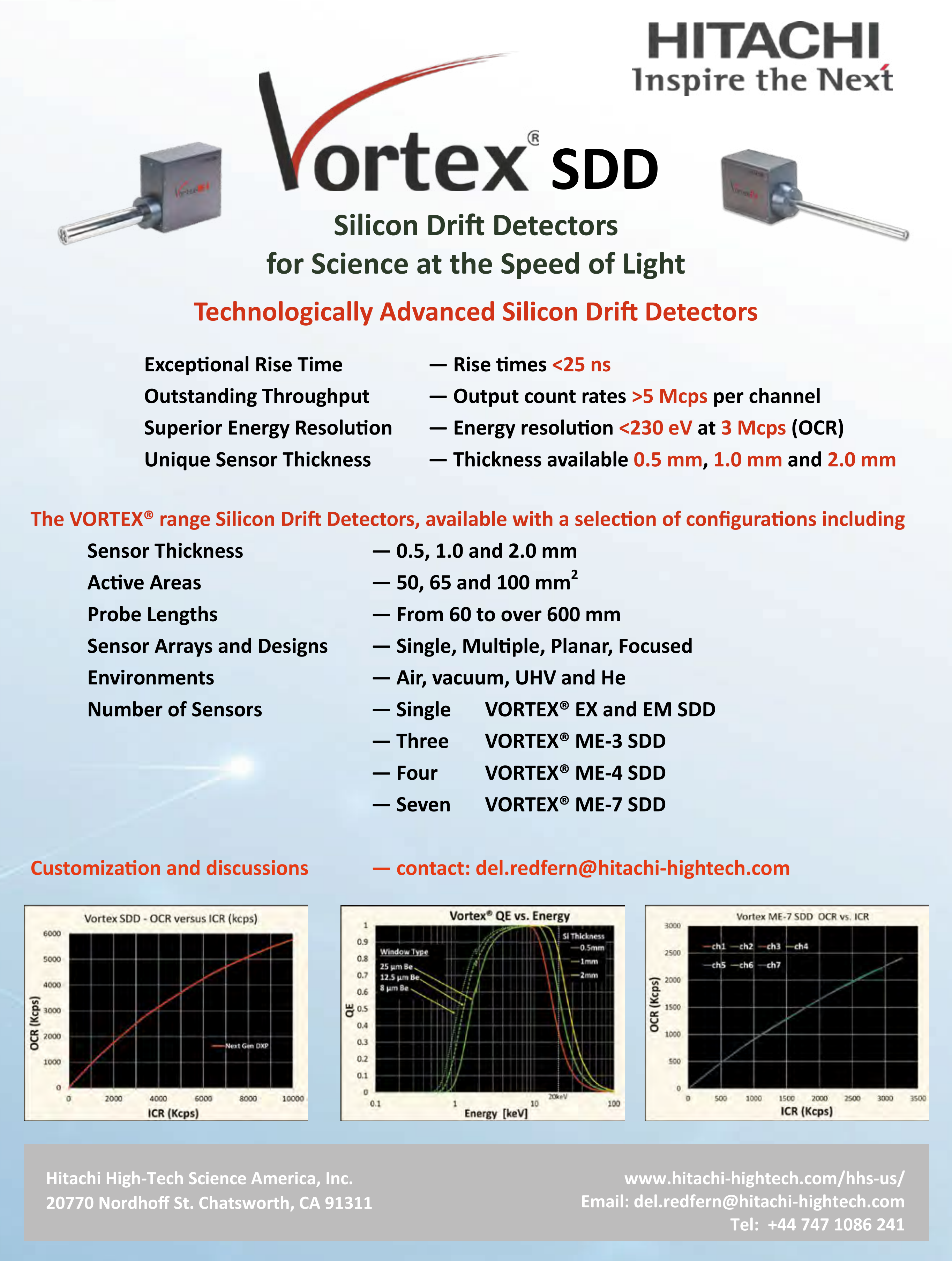
Discovery year

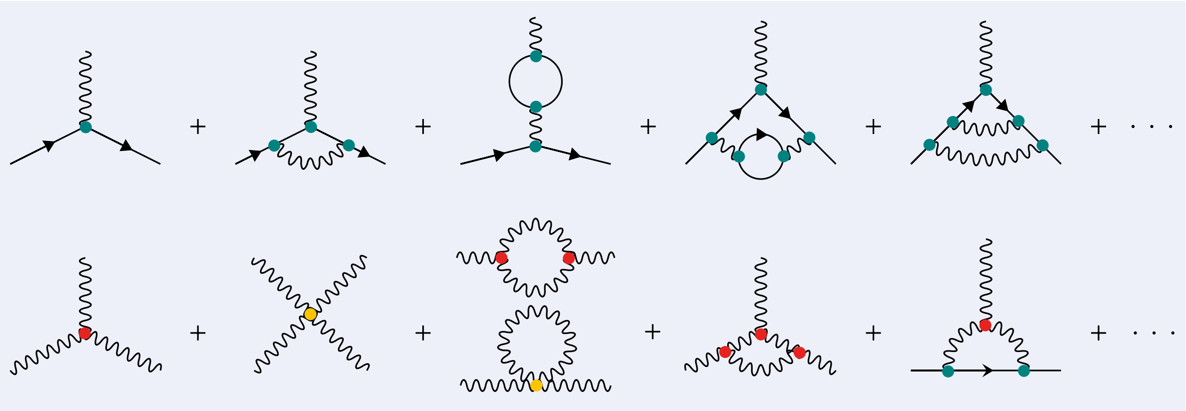
And so 2012 was to be a production year at an increased beam energy of 4 TeV. The choice was made to continue to exploit 50 ns bunch spacing, which offered the advantages of less electron cloud and higher bunch charge compared with 25 ns, and to run with 1380 bunches. Based on the experience of 2011, it was also decided to operate with tight collimator settings, enabling a more aggressive squeeze to $\beta^* = 0.6$ m. The injectors continued to provide exceptional quality beam and routinely delivered 1.7×10^{11} protons per bunch. The peak luminosity quickly rose to its maximum for the year, followed by determined and long running attempts to improve peak performance. Beam instabilities, although never debilitating, were a reoccurring problem and there were phases when they cut into operational efficiency. Nonetheless by the middle of the year another 6 fb^{-1} had been delivered to both ATLAS and CMS. Combined with the 2011 dataset, this paved the way for the announcement of the Higgs-boson discovery.

2012 was a very long operational year and included the extension of the proton–proton run until December to allow the experiments to maximise their 4 TeV data before LS1. Integrated-luminosity rates were healthy at around 1 fb^{-1} per week, and the total for the year came in at about 23 fb^{-1} to both ATLAS and CMS. Run 1 finished with four weeks of proton–lead operations at the start of 2013.

It is impossible to do justice to the commitment and effort that went into establishing, and then maintaining, the complex operational performance of the LHC that underpinned the Higgs-boson discovery: RF, power converters, collimation, injection and beam-dump systems, vacuum, transverse feedback, machine protection, cryogenics, magnets, quench detection and protection, accelerator physics, beam instrumentation, beam-based feedbacks, controls, databases, software, survey, technical infrastructure, handling engineering, access, radiation protection plus material science, mechanical engineering, laboratory facilities ... and the coordination of all that! ●

After a brilliant year in 2011, 2012 should be historic, with either the discovery of the Standard Model Higgs boson or its exclusion




G 't Hooft

Infinity-free *Increasingly complex electroweak processes involving vertices with one (green), three (red) and four (yellow) gauge bosons are kept in check by a procedure called renormalisation, which ensures that the corresponding integrals do not diverge.*

A TRIUMPH FOR THEORY

Gerard 't Hooft reflects on how renormalisation elevated the Brout–Englert–Higgs mechanism to a consistent theory capable of making testable predictions.

Often in physics, experimentalists observe phenomena that theorists had not been able to predict. When the muon was discovered, theoreticians were confused; a particle had been predicted, but not this one. Isidor Rabi came with his famous outcry: "who ordered that?" The J/ψ is another special case. A particle was discovered with properties so different from the particles that were expected, that the first guesses as to what it was were largely mistaken. Soon it became evident that it was a predicted particle after all, but it so happened that its features were more exotic than was foreseen. This was an experimental discovery requiring new twists in the theory, which we now understand very well. The Higgs particle also has a long and interesting history, but from my perspective, it was to become a triumph for theory.

From the 1940s, long before any indications were seen in experiments, there were fundamental problems in all theories of the weak interaction. Then we learned from very detailed and beautiful measurements that the weak force seemed to have a vector-minus axial-vector (V–A) structure. This implied that, just as in Yukawa's theory for the strong nuclear force, the weak force can also be seen as resulting from an exchange of particles. But here, these particles had to be the energy quanta of vector and axial-vector fields, so they must have spin one, with positive and negative parities mixed up. They also must be very heavy. This implied that, certainly in the 1960s, experiments would not be able to detect these intermediate particles directly. But in theory, we should be able to calculate accurately the effects of the weak interaction in terms of just a few parameters, as could be done with the electromagnetic force.

Electromagnetism was known to be renormalisable – that is, by carefully redefining and rearranging the mass and interaction parameters, all observable effects would become calculable and predictable, avoiding meaningless infinities. But now we had a difficulty: the weak exchange particles differed from the electromagnetic ones (the photons) because they had mass. The mass was standing in the way when you tried to do what was well understood in electromagnetism. How exactly a correct formalism should be set up was not known, and the relationship between renormalisability and gauge invariance was not understood at all. Indeed, today we can say that the first hints were already there by 1954, when C N Yang and Robert Mills wrote a beautiful paper in which they generalised the principle of local gauge invariance to include gauge transformations that affect the nature of the particles involved. In its most basic form, their theory described photons with electric charge.

Thesis topic

In 1969 I began my graduate studies under the guidance of Martinus J G Veltman. He explained to me the problem he was working on: if photons were to have mass, then renormalisation would not work the same way. Specifically, the theory would fail to obey unitarity, a quantum mechanical rule that guarantees probabilities are conserved. I was given various options for my thesis topic, but they were not as fundamental as the issues he was investigating. "I want to work with you on the problem you are looking at now," I said. Veltman replied that he had been working on his problem for almost a decade; I would need lots of

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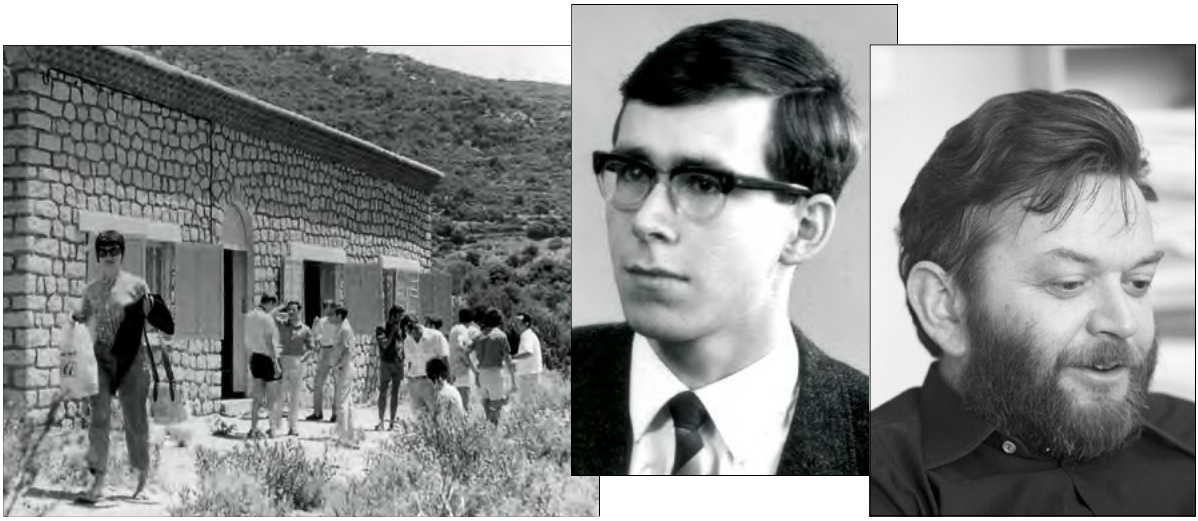


Making history *The Institut d'Etudes Scientifiques de Cargèse, in Corsica, in 1970; the author in around 1971; and (right) the late Martinus Veltman in 1973.*

time to learn about his results. "First, read this," he said, and he gave me the Yang–Mills paper. "Why?" I asked. He said, "I don't know, but it looks important."

That, I could agree with. This was a splendid idea. Why can't you renormalise this? I had convinced myself that it should be possible, in principle. The Yang–Mills theory was a relativistic quantised field theory. But Veltman explained that, in such a theory, you must first learn what the Feynman rules are. These are the prescriptions that you have to follow to get the amplitudes generated by the theory. You can read off whether the amplitudes are unitary, obey dispersion relations, and check that everything works out as expected.

Many people thought that renormalisation – even quantum field theory – was suspect. They had difficulties following Veltman's manipulations with Feynman diagrams, which required integrations that do not converge. To many investigators, he seemed to be sweeping the difficulties with the infinities under the rug. Nature must be more clever than this! Yang–Mills seemed to be a divine theory with little to do with reality, so physicists were trying all sorts of totally different approaches, such as S-matrix theory and Regge trajectories. Veltman decided to ignore all that.

Solid-state inspiration

Earlier in the decade, some investigators had been inspired by results from solid-state physics. Inside solids, vibrating atoms and electrons were described by nonrelativistic quantum field theories, and those were conceptually easier to understand. Philip Anderson had learned to understand the phenomenon of superconductivity as a process of spontaneous symmetry breaking; photons would obtain a mass, and this would lead to a remarkable rearrangement of the electrons as charge carriers that would no longer generate any resistance to electric currents. Several authors realised that this procedure might apply to the weak force. In the summer of 1964, Peter Higgs submitted a manuscript to *Physical Review Letters*, where he noted that the mechanism of making photons massive should also apply to relativistic particle systems. But there was a problem. Jeffrey Goldstone had sound mathematical arguments to expect the emergence of massless scalar particles as soon as a continuous symmetry breaks down spontaneously. Higgs put forward that this theorem should not apply to spontaneously broken *local* symmetries, but critics were unconvinced.

The journal sent Higgs's manuscript out to be peer reviewed. The reviewer did not see what the paper would add to our understanding. "If this idea has anything to do with the real world, would there be any possibility to check it experimentally?" The correct question would have been what the paper would imply for the renormalisation procedure, but this question was in nobody's mind. Anyway, Higgs gave a clear and accurate answer: "Yes, there is a consequence: this theory not only explains where the photon mass comes from, but it also predicts a new particle, a scalar particle (a particle with spin zero), which unlike all other particles, forms an incomplete representation of the local gauge symmetry." In the meantime, other papers appeared about the photon mass-generation process, not only by François Englert and Robert Brout in Brussels, but also by Tom Kibble, Gerald Guralnik and Carl Hagen in London. And Sheldon Glashow, Abdus Salam and Steven Weinberg were formulating their first ideas (all independently) about using local gauge invariance to create models for the weak interaction.

At the time spontaneous symmetry breaking was being incorporated into quantum field theory, the significance of renormalisation and the predicted scalar particles were hardly mentioned. Certainly, researchers were not able to predict the mass of such particles. Personally, although I had heard about these ideas, I also wasn't sure I understood what they were saying. I had my own ways of learning how to understand things, so I started to study everything from the ground up.

If you work with quantum mechanics, and you start from a relativistic classical field theory, to which you add the Copenhagen procedure to turn that into quantum mechanics, then you should get a unitary theory.

I started to study everything from the ground up

The renormalisation procedure amounts to transforming all expressions that threaten to become infinite due to divergence of the integrals, to apply only to unobservable qualities of particles and fields, such as their "bare mass" and "bare charge". If you understand how to get such things under control, then your theory should become a renormalised description of massive particles. But there were complications.

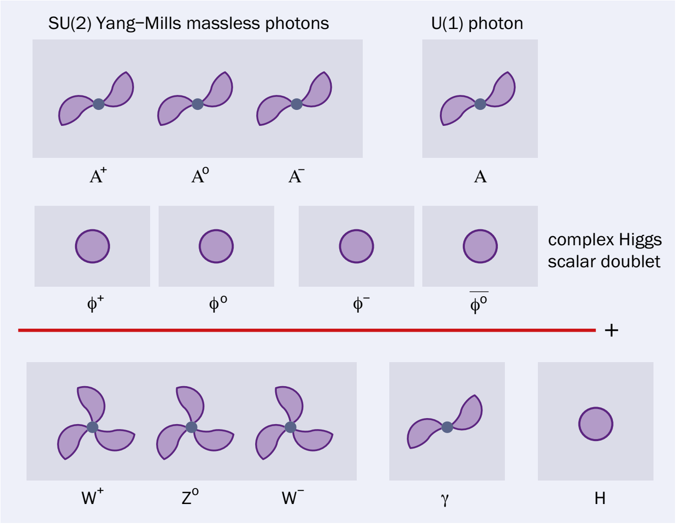
The infinities that require a renormalisation procedure to tame them originate from uncontrolled behaviour at very tiny distances, where the effective energies are large and consequently the effects of mass terms for the particles should become insignificant. This revealed that you first have to renormalise the theory without any masses in them, where also the spontaneous breakdown of the local symmetry becomes insignificant. You had to get the particle book-keeping right. A massless photon has only two observable field components (they can be left- or right-rotating), whereas a massive particle with the same spin can rotate in three different ways. One degree of freedom did not match. This was why an extra field was needed. If you wanted massive photons with electric charges +, 0 or –, you would need a scalar field with four components; one of these would represent the total field strength, and would behave as an extra, neutral, spin-0 particle – the observable particle that Higgs had talked about – but the others would turn the number of spinning degrees of freedom of the three other bosons from two to three each (see "Dynamical" figure).

One question

In 1970 Veltman sent me to a summer school organised by Maurice Lévy in a new science institute at Cargèse on the French island of Corsica. The subject would be the study of the Gell-Mann–Lévy model for pions and nucleons, in particular its renormalisation and the role of spontaneous symmetry breaking. Will renormalisation be possible in this model, and will it affect its symmetry? The model was very different from what I had just started to study: Yang–Mills theory with spontaneous breaking of its symmetry. There were quite a few reputable lecturers besides Lévy himself: Benjamin Lee and Kurt Symanzik had specialised in renormalisation. Shy as I was, I only asked one question to Lee, and the same to Symanzik: does your analysis apply to the Yang–Mills case?

Both gave me the same answer: if you are Veltman's student, ask him. But I had, and Veltman did not believe that these topics were related. I thought that I had a better answer, and I fantasised that I was the only person on the planet who knew how to do it right. It was not obvious at all; I had two German roommates at the hotel where I had been put, who tried to convince me that renormalisation of Feynman graphs where lines cross each other would be unfathomably complicated.

Veltman had not only set up detailed, fully running machinery to handle the renormalisation of all sorts of models, but he had also designed a futuristic computer program to do the enormous amount of algebra required to handle the numerous Feynman diagrams that appear to be relevant for even the most basic computations. I knew he had those programs ready and running. He was now busy with some final checks: if his present attempts to check the unitarity of his renormalised model still failed, we should seriously consider giving this up. Yang–Mills theories for the weak interactions would not work as required.



Dynamical *Massless spin-1 particles (top) have two degrees of freedom (purple shapes), whereas spin-1 particles with mass (middle) have three. Below the solid line the effects of the masses of the particles are included. Note that the electric charges match perfectly.*

But Veltman had not thought of putting a spin-zero, neutral particle in his model, certainly not if it wasn't even in a complete representation of the gauge symmetry. Why should anyone add that? After returning from Cargèse I went to lunch with Veltman, during which I tried to persuade him. Walking back to our institute, he finally said, "Now look, what I need is not an abstract mathematical idea, what I want is a model, with a Lagrangian, from which I can read off the Feynman diagrams to check it with my program…". "But that Lagrangian I can give you," I said. Next, he walked straight into a tree! A few days after I had given him the Lagrangian, he came to me, quite excited. "Something strange," he said, "your theory isn't right because it still isn't unitary, but I see that at several places, if the numbers had been a trifle different, it could have worked out." Had he copied those factors ¼ and ½ that I had in my Lagrangian, I wondered? I knew they looked odd, but they originated from the fact that the Higgs field has isospin ½ while all other fields have isospin one.

No, Veltman had thought that those factors came from a sloppy notation I must have been using. "Try again," I asked. He did, and everything fell into place. Most of all, we had discovered something important. This was the beginning of an intensive but short collaboration. My first publication "Renormalization of massless Yang–Mills fields", published in October 1971, concerned the renormalisation of the Yang–Mills theory without the mass terms. The second publication that year, "Renormalizable Lagrangians for massive Yang–Mills fields," where it was explained how the masses had to be added, had a substantial impact.

There was an important problem left wide open, however: even if you had the correct Feynman diagrams, the process of cancelling out the infinities could still leave finite, non-vanishing terms that ruin the whole idea. These so-called "anomalies" must also cancel out. We found a trick called dimensional renormalisation, which would guarantee that anomalies cancel except in the case where particles spin preferentially in one direction. Fortunately, as charged leptons tend to rotate in opposite directions compared to quarks, it was discovered that the effects of the quarks would cancel those of the leptons.

The fourth component

Within only a few years, a complete picture of the fundamental interactions became visible, where experiment and theory showed a remarkable agreement. It was a fully renormalisable model where all quarks and all leptons were represented as "families" that were only complete if each quark species had a leptonic counterpart. There was an "electroweak force", where electromagnetism and the weak force interfere to generate the force patterns observed in experiments, and the strong force was tamed at almost the same time. Thus the electroweak theory and quantum chromodynamics were joined into what is now known as the Standard Model.

Be patient, we are almost there, we have three of the four components of this particle's field

This theory agreed beautifully with observations, but it did not predict the mass of the neutral, spin-0 Higgs particle. Much later, when the W and the Z bosons were well-established, the Higgs was still not detected. I tried to reassure my colleagues: be patient, we are almost there, we have three of the four components of this particle's field. The fourth will come soon.

As the theoretical calculations and the experimental measurements became more accurate during the 1990s and 2000s, it became possible to derive the most likely mass value from indirect Higgs-particle effects that had been observed, such as those concerning the top-quark mass. On 4 July 2012 a new boson was directly detected close to where the Standard Model said the Higgs would be. After these first experimental successes, it was of utmost importance to check whether this was really the object we had been expecting. This has kept experimentalists busy for the past 10 years, and will continue to do so for the foreseeable future.

The discovery of the Higgs particle is a triumph for high technology and basic science, as well as accurate theoretical analyses. Efforts spanning more than half a century paid off in the summer of 2012, and a new era of understanding the particles, their masses and interactions began. ●

A Mahmoud/Nobel Media

A Mahmoud/Nobel Media

Final summit *François Englert (left) and Peter Higgs (right) in Stockholm on 10 December 2013.*

STEPPING INTO THE SPOTLIGHT

In an excerpt from his new book *Elusive: How Peter Higgs Solved the Mystery of Mass*, Frank Close recounts the story of the 2013 Nobel Prize in Physics.

With the boson confirmed, speculation inevitably grew about the 2012 Nobel Prize in Physics. The prize is traditionally announced on the Tuesday of the first full week in October, at about midday in Stockholm. As it approaches, a highly selective epidemic breaks out: Nobelitis, a state of nervous tension among scientists who crave Nobel recognition. Some of the larger egos will have previously had their craving satisfied, only perhaps to come down with another fear: will I ever be counted as one with Einstein? Others have only a temporary remission, before suffering a renewed outbreak the following year.

Three people at most can share a Nobel, and at least six had ideas like Higgs's in the halcyon days of 1964 when this story began. Adding to the conundrum, the discovery of the boson involved teams of thousands of physicists from all around the world, drawn together in a huge cooperative venture at CERN, using a machine that is itself a triumph of engineering.

The 2012 Nobel Prize in Physics was announced on Tuesday 9 October and went to Serge Haroche and David Wineland for taking the first steps towards a quantum computer. Two days later, I went to Edinburgh to give a colloquium and met Higgs for a coffee beforehand. I asked him how he felt now that the moment had passed, at least for this year. "I'm enjoying the peace and quiet. My phone hasn't rung for two days," he remarked.

That the sensational discovery of 2012 was indeed of Higgs's boson was, by the summer of 2013, beyond dispute. That Higgs was in line for a Nobel prize also seemed highly likely. Higgs himself, however, knew from experience that in the Stockholm stakes, nothing is guaranteed.

Back in 1982, at dawn on 5 October in the Midwest and the eastern US, preparations were in hand for champagne celebrations in three departments at two universities. At Cornell, the physics department hoped they would be honouring Kenneth Wilson, while over in the chemistry department their prospect was Michael Fisher. In Chicago, the physicists' hero was to be Leo Kadanoff. Two years earlier the trio had shared the Wolf Prize, the scientific analogue of the Golden Globes to the Nobel's Oscars, for their work on critical phenomena connected with phase transitions, fuelling speculation that a Nobel would soon follow. At the appointed hour in Stockholm, the chair of

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Build up
ATLAS and CMS physicists gathered in Building 40 on 8 October 2013 for the announcement of the Nobel Prize in Physics.

the awards committee announced that the award was to Wilson alone. The hurt was especially keen in the case of Michael Fisher, whose experience and teaching about phase transitions, illuminating the subtle changes in states of matter such as melting ice and the emergence of magnetism, had inspired Wilson, five years his junior. The omission of Kadanoff and Fisher was a sensation at the time and has remained one of the intrigues of Nobel lore.

Fisher's agony was no secret to Peter Higgs. As undergraduates they had been like brothers and remained close friends for more than 60 years. Indeed, Fisher's influence was not far away in July 1964, for it was while examining how some ideas from statistical mechanics could be applied to particle physics that Higgs had the insight that would become the capstone to the theory of particles and forces half a century later. For this he was to share the 2004 Wolf Prize with Robert Brout (who sadly died in 2011) and François Englert – just as Fisher, Kadanoff and Wilson had shared this prize in 1980. Then as October approached in 2013 Higgs became a hot favourite at least to share the Nobel Prize in Physics, and the bookmakers would only take bets at extreme odds-on.

Time to escape

In 2013, 8 October was the day when the Nobel decision would be announced. Higgs's experiences the year before had helped him to prepare: "I decided not to be at home when the announcement was made with the press at my door; I was going to be somewhere else." His first plan was to disappear into the Scottish Highlands by train, but he decided it was too complicated, and that he could hide equally well in Edinburgh. "All I would have to do is go down to Leith early enough. I knew the announcement would be around noon so I would leave home soon after 11, giving myself a safe margin, and have an early lunch in Leith about noon."

Richard Kenway, the Tait Professor of Mathematical Physics at Edinburgh and one of the university's vice principals, confirmed the tale. "That was what we were all told, and he completely convinced us. Right up to the actual moment when we were sitting waiting for the [Nobel] announcement, we thought he had disappeared off somewhere into the Highlands." Some newspapers got the fake news from the department, and one reporter even went up into the Highlands to look for him.

Robert Brout in spirit completed a trinity of winners

As scientists and journalists across the world were glued to the live broadcast, the Nobel committee was still struggling to reach the famously reclusive physicist. The announcement of his long-awaited crown was delayed by about half an hour until they decided they could wait no longer. Meanwhile, Peter Higgs sat at his favourite table in The Vintage, a seafood bar in Henderson Street, Leith, drinking a pint of real ale and considering the menu. As the committee announced that it had given the prize to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider", phones started going off in the Edinburgh physics department.

Higgs finished his lunch. It seemed a little early to head home, so he decided to look in at an art exhibition. At about three o'clock he was walking along Heriot Row in Edinburgh, heading for his flat nearby, when a car pulled up near the Queen Street Gardens. "A lady in her 60s, the widow of a high-court judge, got out and came across the road in a very excited state to say, 'My daughter phoned from London to tell me about the award', and I said, 'What award?' I was joking of course, but that's when she confirmed that I had won the prize. I continued home and managed to get in my front door with no more damage than one photographer lying in wait." It was only later that afternoon that he finally learned from the radio news that the award was to himself and Englert.

Suited and booted

On arrival in Stockholm in December 2013, after a stressful two-day transit in London, Higgs learned that one of the first appointments was to visit the official tailor. The costume was to be formal morning dress in the mid-19th-century style of Alfred Nobel's time, including elegant shoes adorned with buckles. As Higgs recalled, "Getting into the shirt alone takes considerable skill. It was almost a problem in topology." The demonstration at the tailor's was hopeless. Higgs was tense and couldn't remember the instructions. On the day of the ceremony, fortunately, "I managed somehow." Then there were the shoes. The first pair were too small, but when he tried bigger ones, they wouldn't fit comfortably either. He explained, "The problem is that the 19th-century dress shoes do not fit the shape of one's foot; they were rather pointy." On the day of the ceremony both physics laureates had a crisis with their shoes. "Englert called my room: 'I can't wear these shoes. Can we agree to wear our own?' So we did. We were due to be the first on the stage and it must have been obvious to everyone in the front row that we were not wearing the formal shoes."

On the afternoon of 10 December, nearly 2000 guests filled the Stockholm Concert Hall to see 12 laureates receive their awards from King Gustav of Sweden. They had been guided through the choreography of the occasion earlier, but on the day itself, performing before the throng in the hall, there would be first-night nerves for this once-in-a-lifetime theatre. Winners of the physics prize would be called to receive their awards first, while the others watched and could see what to expect when they were named. The scenery, props and supporting cast were already in place. These included former winners dressed in tail suits and proudly wearing the gold button stud that signifies their membership of this unique club. Among them were Carlo Rubbia, discoverer of the W and Z particles, who instigated the experimental quest for the boson and won the prize in 1984; Gerard 't Hooft, who built on Higgs's work to complete the theoretical description of the weak nuclear force and won in 1999; and 2004 winner Frank Wilczek, who had built on his own prize-winning work to identify the two main pathways by which the Higgs boson had been discovered.

F Close

J MacKenzie

Showtime
(left) Peter Higgs and the author at Palermo airport on 2 July 2012 after attending the Erice summer school. Higgs was en route to CERN but was not aware of the ATLAS and CMS results. (right) Jane MacKenzie and Stephanie Hills guiding Peter Higgs at CERN two days later.

After a 10-minute oration by the chair of the Nobel Foundation and a musical interlude, Lars Brink, chairman of the Nobel Committee for Physics, managed to achieve one of the most daunting challenges in science pedagogy, successfully addressing both the general public in the hall and the assembled academics, including laureates from other areas of science. The significance of what we were celebrating was beyond doubt: "With discovery of the Higgs boson in 2012, the Standard Model of physics was complete. It has been proved that nature follows precisely that law that Brout, Englert and Higgs created. This is a fantastic triumph for science," Brink announced. He also introduced a third name, that of Englert's collaborator, Robert Brout. In so doing, he made an explicit acknowledgement that Brout in spirit completed a trinity of winners.

Brink continued with his summary history of how their work and that of others established the Standard Model of particle physics. Seventeen months earlier the experiments at the LHC had confirmed that the boson is real. What had been suspected for decades was now confirmed forever. The final piece in the Standard Model of particle physics had been found. The edifice was robust. Why this particular edifice is the one that forms our material universe is a question for the future. Brink now made the formal invitation for first Englert and then Higgs to step forward to receive their share of the award.

Higgs, resplendent in his formal suit, and comfortable in his own shoes, rose from his seat and prepared to walk to centre-stage. Forty-eight years since he set out on what would be akin to an ascent of Everest, Higgs had effectively conquered the Hillary step – the final challenge before reaching the peak – on 4 July 2012 when the existence of his boson was confirmed. Now, all that remained while he took nine steps to reach the summit was to remember the choreography: stop at the Nobel Foundation insignia on the carpet; shake the king's hand with your right hand while accepting the Nobel prize and diploma with the other. Then bow three times, first to the king, then to the bust of Alfred Nobel at the rear of the stage, and finally to the audience in the hall.

Higgs successfully completed the choreography and accepted his award. As a fanfare of trumpets sounded, the audience burst into applause. Higgs returned to his seat. The chairman of the chemistry committee took the lectern to introduce the winners of the chemistry prize. To his relief, Higgs was no longer in the spotlight.

All in a name

The saga of Higgs's boson had begun with a classic image – a lone genius unlocking the secrets of nature through the power of human thought. The fundamental nature of Higgs's breakthrough had been immediately clear to him. However, no one, least of all Higgs, could have anticipated that it would take nearly half a century and several false starts to get from his idea to a machine capable of finding the particle. Nor did anyone envision that this single "good idea" would turn a shy and private man into a reluctant celebrity, accosted by strangers in the supermarket. Some even suggested that the reason why the public became so enamoured with Higgs was the solid ordinariness of his name, one syllable long, unpretentious, a symbol of worthy Anglo-Saxon labour.

In 2021, nine years after the discovery, we were reminiscing about the occasion when, to my surprise, Higgs suddenly remarked that it had "ruined my life". To know nature through mathematics, to see your theory confirmed, to win the plaudits of your peers and join the exclusive club of Nobel laureates: how could all this equate with ruin? To be sure I had not misunderstood, I asked again the next time we spoke. He explained: "My relatively peaceful existence was ending. I don't enjoy this sort of publicity. My style is to work in isolation, and occasionally have a bright idea." ●

● This is an edited extract from *Elusive: How Peter Higgs Solved the Mystery of Mass*, by Frank Close, published on 14 June (Basic Books, US) and 7 July (Allen Lane, UK).

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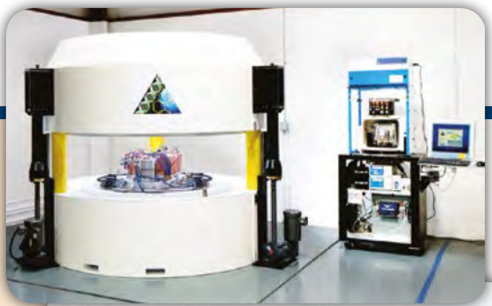
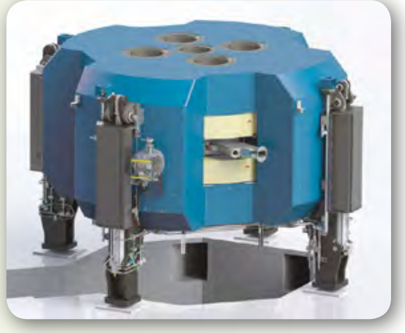
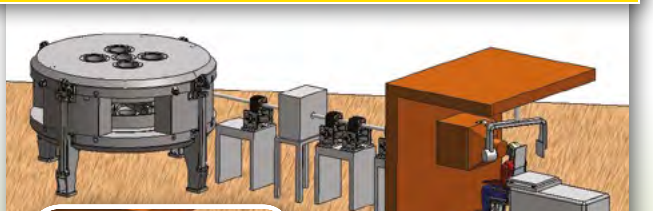
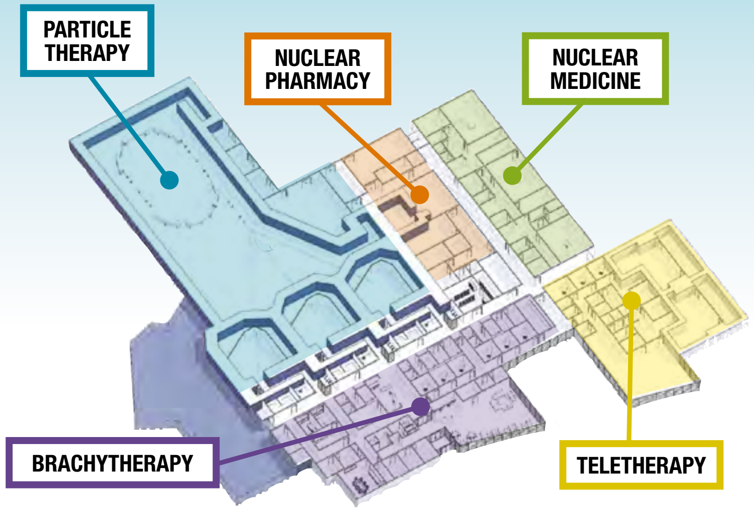







PARTICLE THERAPY
NUCLEAR PHARMACY
NUCLEAR MEDICINE
BRACHYTHERAPY
TELETHERAPY

THE HIGGS BOSON UNDER THE MICROSCOPE

Ten years of experimental scrutiny by ATLAS and CMS strongly suggest the Higgs boson originates from the minimal Higgs sector required by the Standard Model. But as Marco Pieri and Guillaume Unal explain, there is much more to learn about this unique particle.

On 4 July 2012, the ATLAS and CMS collaborations jointly announced their independent discoveries of a new particle directly related to the Brout–Englert–Higgs field that gives mass to all other particles in the Standard Model (SM). The LHC and its two general-purpose experiments were designed and built, among other things, with the aim of detecting or ruling out the SM Higgs boson. Within three years of the LHC startup, the two experiments detected a signal consistent with a Higgs boson with a mass of about 125 GeV, which was perfectly consistent with indications from precision measurements carried out at the electron–positron colliders LEP and SLC, and at the Tevatron proton–antiproton collider.

The discovery was made mainly by detecting decays of the new particle into two photons or two Z bosons (each of which decay into a pair of electrons or muons), for which the invariant mass can be reconstructed with high resolution. The search for the Higgs boson was also performed in other channels, and all results were found to be consistent with the SM expectations. A peculiar feature of the Higgs boson is that it has zero spin. At the time of the discovery, it was already excluded that the particle was a standard vector boson: a spin-1 particle cannot decay into two photons, leaving only spin-0 or spin-2 as the allowed possibilities.

Ten years ago, the vast majority of high-energy physicists were convinced that a Higgs boson had been detected. The only remaining question was whether it was the boson predicted by the SM or part of an extended Higgs sector.

Basic identity

The mass of the Higgs boson is the only parameter of the Higgs sector that is not predicted by the SM. A high-precision measurement of the mass is therefore crucial because, once it is known, all the couplings and production cross sections can be predicted in the SM and then compared with experimental measurements. The mass measurement is carried out using the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels, with a combined ATLAS and CMS measurement based on Run 1 data obtaining a value of 125.09 ± 0.24 GeV. More precise results with a precision at the level of one part per thousand have been obtained by ATLAS and CMS using partial datasets from Run 2.

The width of the Higgs boson, unlike its mass, is well predicted at approximately 4 MeV. Since this is much smaller than the ATLAS and CMS detector resolutions, a precise direct measurement can only be carried out at future electron–positron colliders. At the LHC it is possible to indirectly constrain the width by studying the production of di-boson pairs (ZZ or WW) via the exchange of off-shell Higgs bosons: under some reasonable assumptions, the off-shell cross section at high mass relative to the on-shell cross section increases proportionally to the width. A recent result from CMS constrains the Higgs-boson width to be between 0.0061 and 2.0 times the SM prediction at 95% confidence level. Finding the width to be smaller than the SM would mean that some of the couplings are smaller than predicted, while a larger measured width could reflect additional decay channels beyond the SM, or a larger branching fraction of those predicted by the SM.

The spin and charge-parity (CP) properties of the Higgs boson are other key quantities. The SM predicts that the Higgs boson is a scalar (spin-0 and positive CP) particle, but in extended Higgs models it could be a superposition of positive and negative CP states, for example. The spin and CP properties can be probed using angular distributions of the Higgs-boson decay products, and several decay channels were exploited by ATLAS and CMS: $H \rightarrow \gamma\gamma$, ZZ, WW and $\tau\tau$. All results to date indicate consistency with the SM and exclude most other models at more than 3σ confidence level, including all models with spin different from zero.

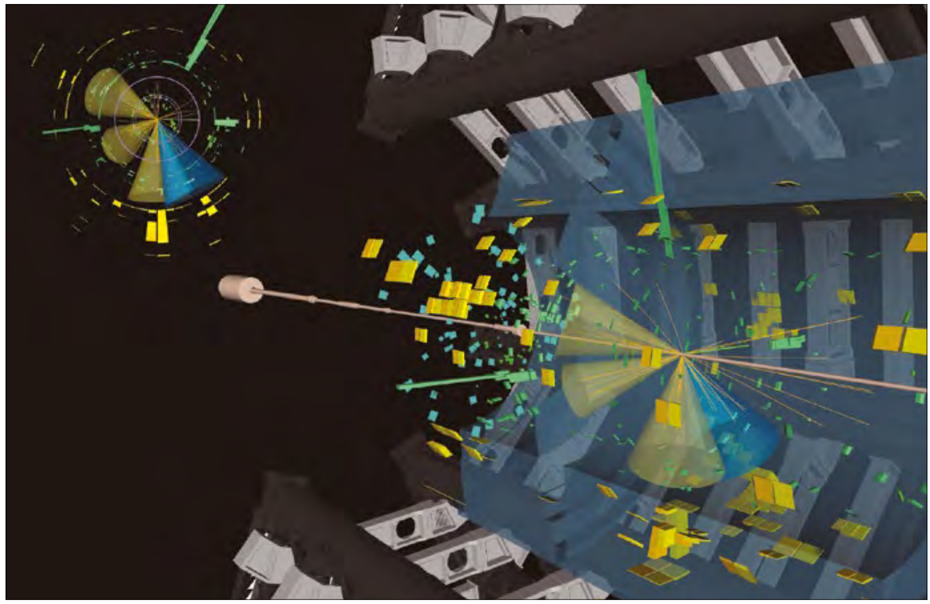
Couplings to others

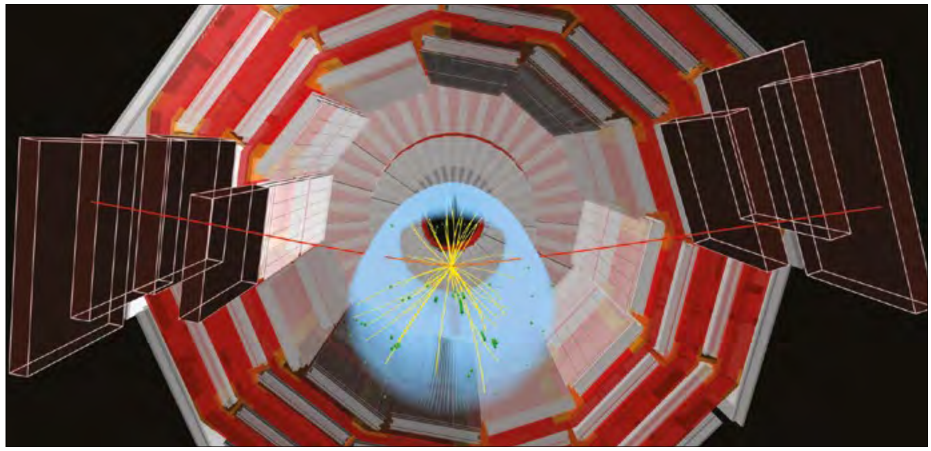
One of the main tools for characterising the Higgs boson is the measurement of its production processes and decays. Thanks to growing datasets, improved analysis techniques, more accurate theoretical tools and better modeling of background processes, ATLAS and CMS have made remarkable progress in this crucial programme over the past decade.

Using Run 1 data recorded between 2010 and 2012, the gluon-fusion and vector-boson fusion production processes were established, as were the decays to pairs of bosons ($\gamma\gamma$, WW^* and ZZ^*) and to a τ-lepton pair from the combination of ATLAS and CMS data. With Run 2 data (2015–2018), both ATLAS and CMS observed the decay to a pair of b quarks. Although the preferred decay mode of the Higgs boson, this channel suffers from larger backgrounds and is mainly accessible in the associated production of the Higgs boson with a vector boson. The rarer production mode of the Higgs boson in association with a t-quark pair was also observed using a combination of different decay modes, providing a direct proof of the Yukawa coupling between the Higgs boson and top quark. The existence of the Yukawa couplings between the Higgs boson and third-generation fermions (t, b, τ) is thus established.

The collaborations also investigated the coupling of the Higgs boson to the second-generation fermions, in particular the muon. With the full Run 2 dataset, CMS reported evidence at the level of 3σ over the background-only hypothesis that the Higgs boson decays into $\mu^+\mu^-$, while ATLAS supported this finding with a 2σ excess. This is the first strong suggestion that the Higgs boson also couples to fermions from generations other than the third, again in

This is the first strong suggestion that the Higgs boson also couples to fermions from generations other than the third


ATLAS


CMS

Higgs encounters *Left: a candidate event recorded by ATLAS in 2017 for the associated production of a Higgs boson with a top quark pair, with the Higgs boson decaying to a photon pair. The event contains one electron candidate (green line) and two photon candidates (green towers) with a diphoton mass of 125.2 GeV. In addition, four jets (cones) are reconstructed, including one (blue) that is b-tagged. Right: a candidate event from CMS in 2018 for a Higgs boson produced via the gluon fusion mode, decaying into a pair of muons (red lines). The event has an invariant mass of 125.46 GeV and per-event mass uncertainty of 1.13 GeV.*

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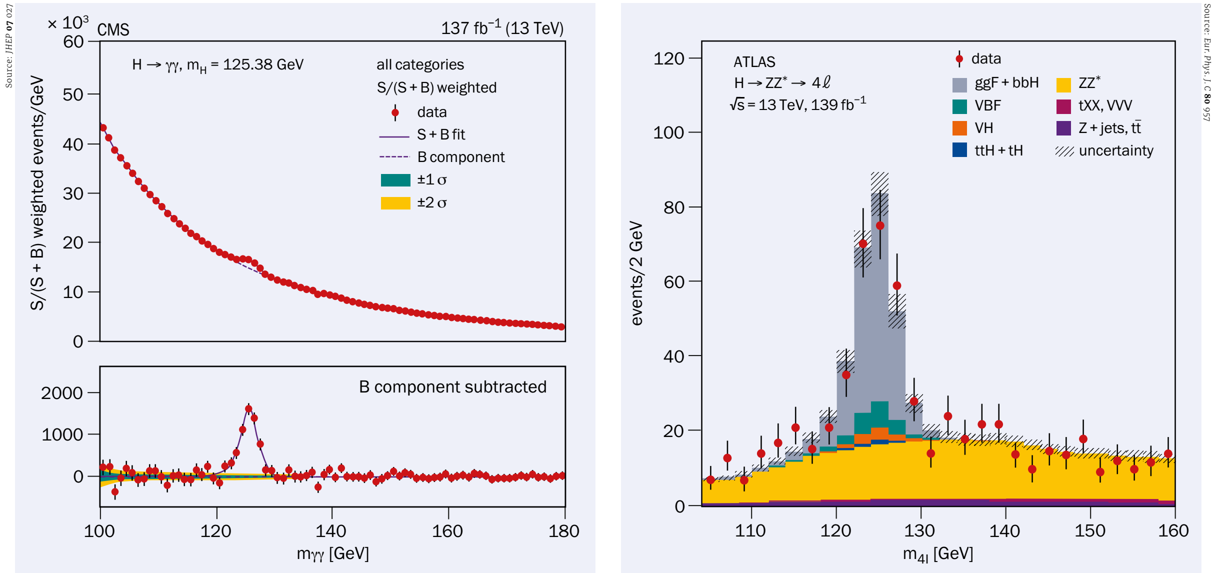


Source: JHEP 07 027

Source: Eur. Phys. J. C 80 957

Mass spectra *Invariant mass distributions reconstructed from $H \to \gamma\gamma$ (CMS, left) and $H \to 4\ell$ (ATLAS, right) decays using the full Run 2 dataset.*

accordance with the SM. Research is also ongoing to constrain the Higgs's coupling to charm quarks via the decay $H \to cc$. This is a much more difficult channel but, thanks to improved detectors and analysis methods, including extensive use of machine learning, ATLAS and CMS recently achieved a sensitivity beyond expectations and excluded a branching fraction of $H \to cc$ relative to the SM prediction larger than O(10). The possibility that the Higgs-boson's coupling to charm is at least as large as the coupling to bottom quarks is excluded by a recent ATLAS analysis at 95% confidence level.

The accuracy of the production cross-section times decay branching-fraction measurements in the bosonic decay channel (diphoton, ZZ and WW) with the full Run 2 dataset is around 10%, allowing measurements in a more restricted kinematical region that can be sensitive to physics beyond the SM. In all probed phase-space regions, the measured cross sections are compatible with the SM expectations (Data used for some of the measurements are shown in the "Mass spectra" figure).

The combination of all measurements in the different production and decay processes can be used to further constrain the measured couplings between the Higgs boson and the other particles. The production cross section for vector-boson-fusion production, for example, is directly proportional to the square of the coupling strengths between the Higgs boson and W or Z bosons. A modification of these couplings will also affect the rate at which the Higgs boson decays to various final states. Assuming no contribution beyond the SM to Higgs decays and that only SM particles contribute to Higgs-boson vertices involving loops, couplings to t, b and τ are currently determined with uncertainties of around 10%, and couplings to W and Z bosons with uncertainties of about 5%.

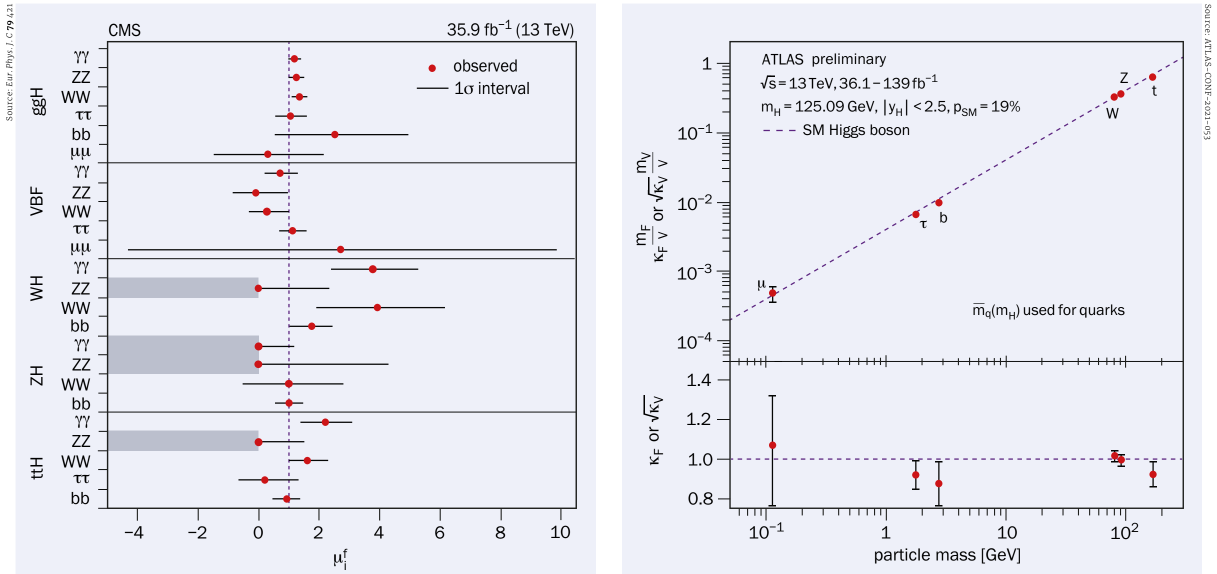
The Higgs sector could also play a role linking the SM to new physics that explains the presence of dark matter

The relation between the mass of a particle and its coupling to the Higgs boson is as expected from the SM, in which the particle masses originate from their coupling to the Brout–Englert–Higgs field (see "Couplings" figure). These measurements thus set bounds on specific new-physics models that predict deviations of the Higgs-boson couplings from the SM. The impact of new physics at a high energy scale is also probed in effective-field-theory frameworks, introducing all possible operators that describe couplings of the Higgs boson to SM particles. No deviations from the predictions are observed.

New physics

The Higgs boson is the only elementary particle with spin-0. However, an extended Higgs sector is a minimal extension of the SM and is predicted by many theories, such as those based on supersymmetry. These extensions predict several neutral or charged spin-0 particles: one is the observed 125 GeV Higgs boson; the others would preferentially couple to heavier SM particles. Searches for heavier scalar (or pseudo-scalar) particles have been carried out in a variety of final states, but no evidence for such particles is found. For example, the search for heavy scalar or pseudo-scalar particles decaying to a pair of τ leptons excludes masses up to 1–1.5 TeV. The extended Higgs sector can also include lighter scalar or pseudo-scalar particles into which the observed Higgs boson could decay. A wide range of final states have been investigated but no evidence found, setting stringent constraints on the corresponding Higgs-boson decay branching fractions.

The Higgs sector could also play a role linking the SM to new physics that explains the presence of dark matter in the form of new neutral, weakly interacting particles. If their mass is less than half that of the Higgs boson, the Higgs boson could decay to a pair of these neutral particles. Since the particles would be invisible in the detector, this process can be detected by observing the presence of missing transverse momentum from the Higgs-boson recoiling against visible particles. The most sensitive processes are those in which the Higgs boson is produced in association to other particles: vector boson fusion, and the associated productions with a vector boson or with a top quark pair. No evidence of such decay has been found, setting upper limits on the invisible decay branching fraction of the Higgs boson at the level of 10%, and providing complementary constraints to those from direct dark-matter detection experiments.



Source: Eur. Phys. J. C 79 421

Source: ATLAS-CONF-2021-053

Couplings *The combined fit for the cross-section times branching fraction of the Higgs boson in all final states, normalised to the SM expectations (left) and the coupling strengths of the Higgs boson to vector bosons and fermions as a function their mass (right).*

Self-interaction

In addition to its couplings to other bosons and to fermions, the structure of the Brout–Englert–Higgs potential predicts a self-coupling of the Higgs boson that is related to electroweak symmetry breaking (see p51). By studying Higgs-boson pair production at the LHC, it is possible to directly probe this self-coupling.

The two main challenges of this measurement are the tiny cross section for Higgs-boson pair production (about 1000 times smaller than the production of a single Higgs boson) and the interference between processes that involve the self-coupling and those that do not. Final states with a favourable combination of the expected signal yield and signal-over-background ratio are exploited. The most sensitive channels are those with one Higgs boson decaying to a b-quark pair and the other decaying either to a pair of photons, τ leptons or b quarks. Upper limits of approximately three times the predicted cross section have been obtained with the Run 2 dataset. These searches can also be used to set constraints on the Higgs boson self-coupling relative to its SM value.

The sensitivities achieved for Higgs-boson pair production searches with the Run 2 dataset are significantly better than expected before the start of Run 2, thanks to several improvements in object reconstruction and analysis techniques. These searches are mostly limited by the size of the dataset and thus will improve further with the Run 3 and much larger High-Luminosity LHC (HL-LHC) datasets.

Going further

Ten years after the discovery of a new elementary boson, considerable progress has been made toward understanding this particle. All measurements so far point to properties that are very consistent with the SM Higgs boson. All main production and decay modes have been observed by ATLAS and CMS, and the couplings to vector bosons and third-generation fermions are probed with 5 to 10% accuracy, confirming the pattern expected from the Brout–Englert–Higgs mechanism for electroweak symmetry breaking and the generation of the masses of elementary particles. Still, there is ample room for improvement in the forthcoming Run 3 and HL-LHC phases, to reduce the uncertainty in the coupling measurements down to a few per cent, to establish couplings to second-generation fermions (muons) and to investigate the Higgs-boson self-coupling. Improved measurements will also significantly expand the sensitivity to a possible extended Higgs sector or new dark sector.

To reach the ultimate accuracy in the measurements of all Higgs-boson properties (including its self-coupling), to remove the assumptions in the determination of the Higgs couplings at the LHC, and to considerably extend the search for new physics in the Higgs sector, new colliders – such as an e^+e^- collider and a future hadron collider – will be required. ●

Ten years after the discovery of a new elementary boson, considerable progress has been made toward understanding this particle

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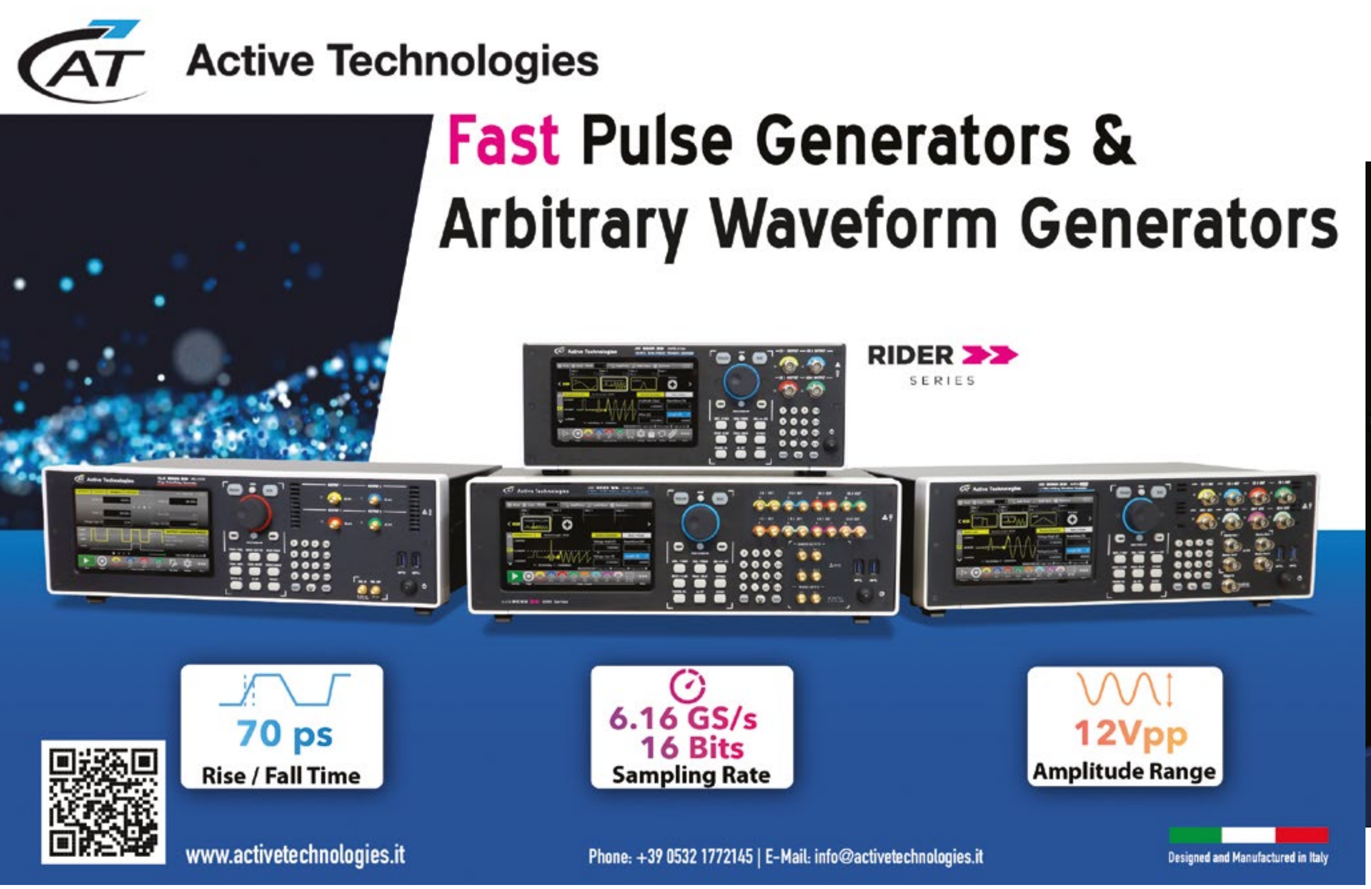

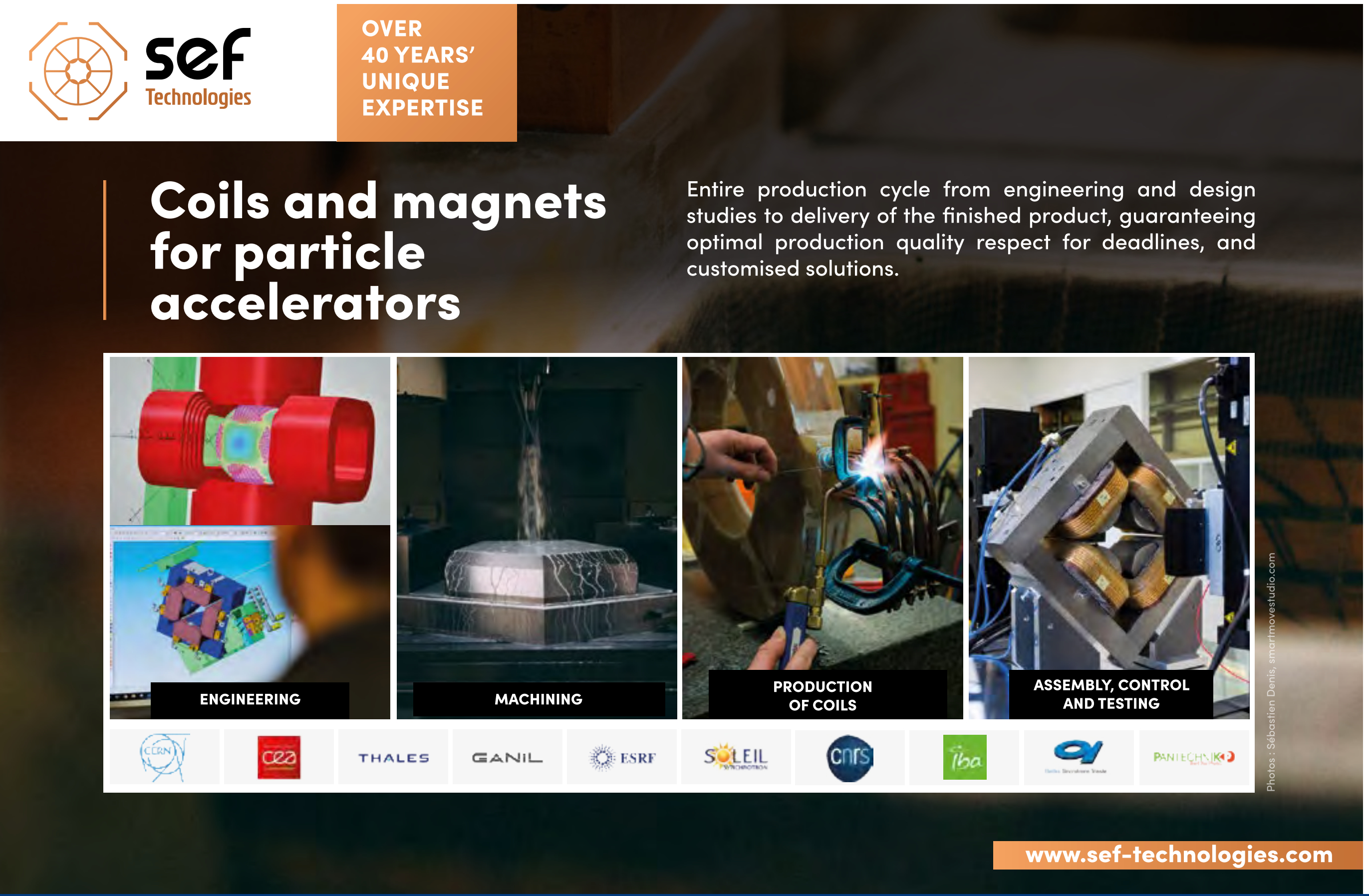

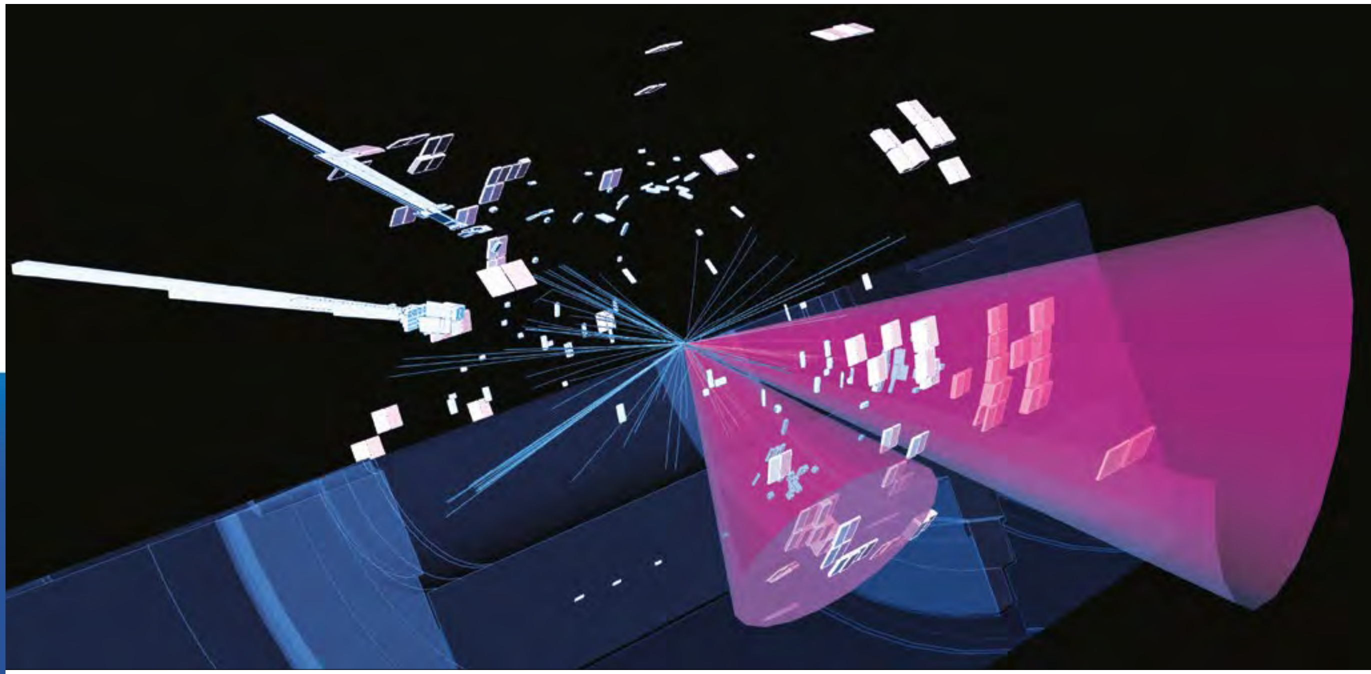
Going further *Di-Higgs events, such as this candidate from ATLAS (original colour scheme modified), probe the Brout–Englert–Higgs potential, but future colliders will be needed to access the cubic and quartic Higgs self-couplings that govern the potential's shape. (Credit: ATLAS)*

THE HIGGS AFTER LHC

Exploring the Higgs boson's couplings to other particles and the shape of its potential could be the key to physics beyond the Standard Model. But only a future collider can fully open such vistas, explains Laura Reina.

Many of the most arbitrary aspects of the Standard Model of particle physics (SM) are intimately connected to the scalar sector of the theory. The SM comprises just one scalar particle, the Higgs boson, and assumes a specific scalar potential (the famous "Mexican hat") to define the dynamics of electroweak (EW) interactions. But the fact that the Higgs boson acquires a non-zero vacuum expectation value that defines the mass scale of EW interactions (around 100–200 GeV) is assumed, not explained, by the SM. Indeed, why the Higgs-boson mass is constrained to be at the EW scale, while quantum corrections should push it to much higher values (the so-called naturalness problem, see p47), is not justified by any symmetry of the SM. At the same time, the SM assumes that fermion masses are generated via arbitrary Yukawa-type interactions with the scalar field but it does not explain the hierarchy of couplings or masses that we observe, nor the specific flavour structure that arises from the presence of just one scalar field.

The scalar sector of the SM may therefore be seen as a messenger of a more fundamental theory that replaces the SM at energies beyond the EW scale and turns apparent arbitrariness into logical consequences. After all, the mechanism of EW symmetry breaking as realised in the SM via the Brout–Englert–Higgs (BEH) field is just the simplest possible way to generate massive EW gauge bosons and fermions while preserving gauge symmetry. The scalar potential could be more complicated, for example involving multiple scalar fields, as is common in many beyond-the-SM (BSM) theories. This would result in a richer pattern of stable and metastable minima and influence the nature of the EW phase transition. A first-order phase transition, together with extra sources of CP violation beyond what is implied by the SM, could explain the origin of the matter–antimatter asymmetry of the universe via EW baryogenesis (see p51). Understanding

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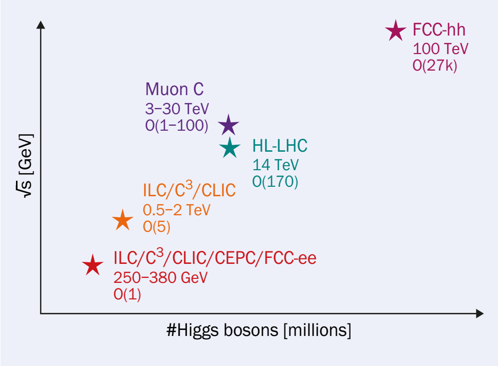
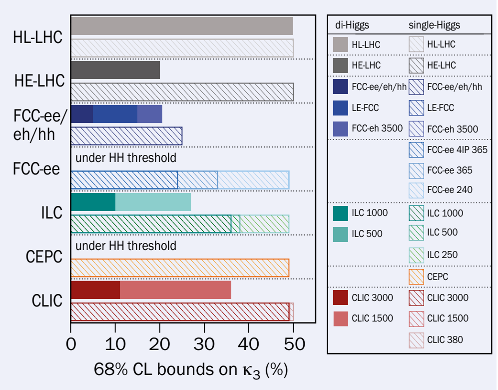


At a glance *Future colliders qualitatively ordered by centre-of-mass energy and number of Higgs bosons produced during their lifespan, with the disclaimer that not all projects and their corresponding physics studies have reached the same level of maturity.*

Source: P Meade and C Vernieri



Source: arXiv:1910.00012

Self-coupling *Uncertainties on the Higgs self-coupling (presented in terms of the "κ factor" of the cubic self-coupling) projected for the HL-LHC and for the various stages of proposed future colliders, with the solid and shaded bars representing di-Higgs and single-Higgs results, respectively.*

the origin of the EW scale is thus key to connecting very different realms of particle physics and cosmology, and the question we face while we look into the future of collider physics.

Game changer

The discovery of the Higgs boson during Run 1 of the LHC has been a game changer in the exploration of new physics beyond the EW scale. The measurement of the Higgs-boson mass has added the last missing input parameter to precision global fits of the SM, which now provide a very powerful tool to constrain BSM scenarios. Thanks to an unprecedented level of precision reached in both theory and experiment, the measurement of Higgs-boson couplings to EW gauge bosons (W, Z) and to the first two generations of quarks and leptons (t, b, τ, μ) from Run 2 data has already constrained their deviations from SM expectations to within 5–20%, with the best accuracy reached for the couplings to the gauge bosons. Based on these results, the High-Luminosity LHC (HL-LHC) is projected to constrain the effects of new physics on Higgs-boson couplings to EW gauge bosons to 1–2%, and to heavy quarks and fermions to 3–5%. If no anomalies are found, this level of accuracy will push the lower bound on the scale of new physics into the TeV ballpark. Vice versa, the detection of possible anomalies may point to the presence of new physics at the TeV scale, possibly just around the corner.

On the other hand, testing the SM scalar potential will still be challenging even during the HL-LHC era. The shape of the BEH potential can be tested by measuring the Higgs-boson self-interactions corresponding to its cubic and quartic terms. In the SM, these interactions are strictly proportional to the Higgs-boson mass via the vacuum expectation value of the BEH field. Deviations from the SM are searched for via Higgs pair production and radiative corrections to single-Higgs measurements. Although the LHC and HL-LHC promise to provide evidence for di-Higgs production, the extraction of the Higgs self-coupling from such measurements will be statistically limited.

Future colliders are vital to push the precision Higgs programme to the next level

Future colliders are vital to push the precision Higgs programme to the next level. While the type and concept of the next collider is yet to be decided, all proposed facilities would deliver a huge number of Higgs bosons over their lifetime, operating at different and well targeted centre-of-mass energies (see "At a glance" figure). They can complement one another and, staggered over a period of the next few decades, provide the missing elements of the EW puzzle.

Among future lepton colliders under study, circular e^+e^- colliders (CEPC, FCC-ee) are expected to operate at lower energies between 90–350 GeV with very high luminosities, while linear e^+e^- colliders (ILC, C^3, CLIC) offer both low- and high-energy phases generally with slightly lower luminosities. Combined with data from the HL-LHC, these "Higgs factories" would enable the SM, including most Higgs couplings, to be stress-tested below the per-cent level and in cases at or below the per-mille level. In particular, FCC-ee operating at the s-channel Higgs resonance (125 GeV) has the capability to provide bounds on couplings as small as the electron Yukawa coupling, while linear e^+e^- colliders operating at 550–600 GeV and above could substantially improve on the top-quark Yukawa coupling with respect to the HL-LHC. A possible muon collider, operated either as a Higgs factory at 125 GeV or as a high-energy discovery machine at 3–10 TeV, is estimated to reach similar precisions on Higgs couplings to other particles as e^+e^- machines.

Finally, high-energy lepton colliders (ILC 1000, CLIC 3000 and a 3–30 TeV muon collider) and very high-energy hadron colliders (FCC-hh at 100 TeV) would reach enough statistics and energy to measure the Higgs self-coupling and investigate the nature of the BEH potential, either via di-Higgs or single-Higgs production (see "Self-coupling" figure). With an aggressive Higgs physics programme they may also reach enough sensitivity to probe the cubic and quartic terms in the BEH potential separately.

Almost half a century after it was predicted, the LHC delivered the Higgs boson in spectacular style on 4 July 2012. Over the next 15–20 years, the machine and its luminosity upgrade will continue to enable ATLAS and CMS to make great strides in understanding the Higgs boson's properties. But to fully exploit the discovery of the Higgs boson and explore its mysterious relation to new physics beyond the EW scale, we will need a successor collider. ●

NATURALNESS AFTER THE HIGGS

Either new particles are keeping the Higgs boson light, or the universe is oddly fine-tuned for our existence. Nathaniel Craig goes down the rabbit hole of the electroweak hierarchy problem.

When Victor Weisskopf sat down in the early 1930s to compute the energy of a solitary electron, he had no way of knowing that he'd ultimately discover what is now known as the electroweak hierarchy problem. Revisiting a familiar puzzle from classical electrodynamics – that the energy stored in an electron's own electric field diverges as the radius of the electron is taken to zero (equivalently, as the energy cutoff of the theory is taken to infinity) – in Dirac's recently proposed theory of relativistic quantum mechanics, he made a remarkable discovery: the contribution from a new particle in Dirac's theory, the positron, cancelled the divergence from the electron itself and left a quantum correction to the self-energy that was only logarithmically sensitive to the cutoff.

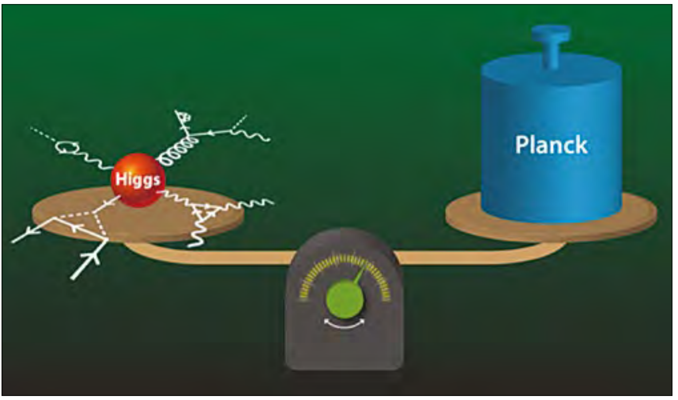
The same cancellation occurred in any theory of charged fermions. But when Weisskopf considered the case for charged scalar particles in 1939, the problem returned. To avoid the need for finely-tuned cancellations between this quantum correction and other contributions to a scalar's self-energy, he posited that the cutoff energy for scalars should be close to their observed self-energy, heralding the appearance of new features that would change the calculation and render the outcome "natural".

Nearly 30 years would pass before Weisskopf's prediction about scalars was put to the test. The charged pion, a pseudoscalar, suffered the very same divergent self-energy that he had computed. As the neutral pion is free from this divergence, Weisskopf's logic suggested that the theory of charged and neutral pions should change at around 800 MeV, the cutoff scale suggested by the observed difference in their self-energies. Lo and behold, the rho meson appeared at 775 MeV. Repeating the self-energy calculation with the rho meson included, the divergence in the charged pion's self-energy disappeared.

This same logic would predict something new. It had been known for some time that the relative self-energy between the neutral kaons K_L and K_S diverged due to contributions from the weak interactions in a theory containing

Nobel Foundation/Susanne Jardeback (artist)/Lovisa Engblom (reproduction)

Mysterious *Artwork from Peter Higgs' Nobel diploma depicting the Brout–Englert–Higgs field, couplings to which lead to a divergent self-energy for the Higgs boson.*



A Stonebraker/APS

Hierarchy problem *The observed mass of the Higgs boson is 125 GeV, yet quantum corrections from interactions with other Standard Model particles should cause it to be 17 orders of magnitude higher at the Planck mass – a conundrum called the electroweak hierarchy problem.*

only the known up, down and strange quarks. Matching the observed difference suggested that the theory should change at around 3 GeV. Repeating the calculation with the addition of the recently proposed charm quark in 1974, Mary K Gaillard and Ben Lee discovered that the self-energy difference became finite, which allowed them to predict that the charm quark should lie below 1.5 GeV. The discovery at 1.2 GeV later that year promoted Weisskopf's reasoning from an encouraging consistency check to a means of predicting new physics.

Higgs, we have a problem

Around the same time, Ken Wilson recognised that the coupling between the Higgs boson and other particles of the Standard Model (SM) leads to yet another divergent self-energy, for which the logic of naturalness implied new physics at around the TeV scale. Thus the electroweak hierarchy problem was born – not as a new puzzle unique to the Higgs, but rather the latest application of Weisskopf's wildly successful logic (albeit one for which the answer is not yet known).

History suggested two possibilities. As a scalar, the Higgs could only benefit from the sort of cancellation observed among fermions if there is a symmetry relating bosons and fermions, namely supersymmetry. Alternatively, it could be a light product of compositeness, just as the pions and kaons are light bound states of the strong interactions. These solutions to the hierarchy problem came to dominate expectations for physics beyond the SM, with a sharp target – the TeV scale – motivating successive generations of collider experiments. Indeed, when the physics case for the LHC was first developed in the mid-1980s, it was thought that new particles associated with supersymmetry or compositeness would be much easier to discover than the Higgs itself. But while the Higgs was discovered, no signs of supersymmetry or compositeness were to be found.

Anthropic reasoning's compatibility with null results at the LHC raises questions about the robustness of natural reasoning

In the meantime, other naturalness problems were brewing. The vacuum energy – Einstein's infamous cosmological constant – suffers a divergence of its own, and even the finite contributions from the SM are many orders of magnitude larger than the observed value. Although natural expectations for the cosmological constant fail, an entirely different set of logic seems to succeed in its place. To observe a small cosmological constant requires observers, and observers can presumably arise only if gravitationally-bound structures are able to form. As Steven Weinberg and others observed in the 1980s, such anthropic reasoning leads to a prediction that is remarkably close to the value ultimately measured in 1998. To have predictive power, this requires a multitude of possible universes across which the cosmological constant varies; only the ones with sufficiently small values of the cosmological constant produce observers to bear witness.

An analogous argument might apply to the electroweak hierarchy problem: the nuclear binding energy is no longer sufficient to stabilise the neutron within typical nuclei if the Higgs vacuum expectation value (VEV) is increased well above its observed value. If the Higgs VEV varies across a landscape of possible universes while its couplings to fermions are kept fixed, only universes with sufficiently small values of the Higgs VEV would lead to complex atoms and, presumably, observers. Although anthropic reasoning for the hierarchy problem requires stronger assumptions than for the cosmological-constant problem, its compatibility with null results at the LHC is enough to raise questions about the robustness of natural reasoning.

Amidst all of this, another proposed scalar particle entered the picture. The observed homogeneity and isotropy of the universe point to a period of exponential expansion of spacetime in the early universe driven by the inflaton. While the inflaton may avoid naturalness problems of its own, the expansion of spacetime and the quantum fluctuations of fields during inflation lead to qualitatively new effects that are driving new approaches to the hierarchy problem at the intersection of particle physics, cosmology and gravitation.

Perhaps the most prominent of these new approaches came, surprisingly enough, from a failed solution to the cosmological constant problem. Around the same time as the first anthropic arguments for the cosmological constant were taking form, Laurence Abbott proposed to "relax" the cosmological constant from a naturally large value by the evolution of a scalar field in the early universe. Abbot envisioned the scalar evolving along a sloping, bumpy potential, much like a marble rolling down a wavy marble run. As it did so, this scalar would decrease the total value of the cosmological constant until it reached the last bump before the cosmological constant turned negative. Although the universe would crunch away into nothingness if the scalar evolved to negative values of the cosmological constant, it could remain poised at the last bump for far longer than the age of the observed universe.

While this fails for the cosmological constant (the resulting metastable universe is largely devoid of matter), analogous logic succeeds for the hierarchy problem. As Peter Graham, David Kaplan and Surjeet Rajendran pointed out in 2015, a scalar evolving down a potential in the early universe can also be used to relax the Higgs mass from naturally large values. Of course, it needs to stop close to the observed mass. But something interesting happens when the Higgs mass-squared passes from positive values to negative values: the Higgs acquires a VEV, which gives mass to quarks, which induces bumps in the potential of a particular type of scalar known as an axion (proposed to explain the unreasonably good conservation of CP symmetry by the strong interactions). So if the relaxing scalar is like an axion – a relaxion, you might say – then it will encounter bumps in its potential when it relaxes the Higgs mass to small values. If the relaxion is rolling during an inflationary period, the expansion of spacetime can provide the "friction" necessary for the relaxion to stop when it hits these bumps and set the observed value of the weak scale. The effective coupling between the relaxion and the Higgs that induces bumps in the relaxion potential is large enough to generate a variety of experimental signals associated with a new, light scalar particle that mixes with the Higgs.

The success of the relaxion hypothesis in solving the hierarchy problem hinges on an array of other questions involving gravity. Whether the relaxion potential can remain sufficiently smooth over the vast trans-Planckian distances in field space required to set the value of the weak scale is an open question, one that is intimately connected to the fate of global symmetries in a theory of quantum gravity (itself the target of active study in what is known as the Swampland programme).

Despite the many differences among the new approaches, they share a common tendency to leave imprints on the Higgs boson

Models abound

In the meantime, the recognition that cosmology might play a role in solving the hierarchy problem has given rise to a plethora of new ideas. For instance, in Raffaele D'Agnolo and Daniele Teresi's recent paradigm of "sliding naturalness", the Higgs is coupled to a new scalar whose potential features two minima. In the true minimum, the cosmological constant is large and negative, and the universe would crunch away into oblivion if it ended up in this vacuum. In the second, local minimum, the cosmological constant is safely positive (and can be made compatible with the small observed value of the cosmological constant by Weinberg's anthropic selection). The Higgs couples to this scalar in such a way that a large value of the Higgs VEV destabilises the "safe" minimum. During the inflationary epoch, only universes with suitably small values of the Higgs VEV can grow and expand, while those with large values of the Higgs VEV crunch away. A second scalar coupled analogously to the Higgs can explain why the VEV is small but non-zero. Depending on how these scalars are coupled to the Higgs, experimental signatures range from the same sort of axion-like signals arising from the relaxion, to extra Higgs bosons at the LHC.

Alternatively, in the paradigm of "Nnaturalness" proposed by Nima Arkani-Hamed and others, the multitude of SMs over which the Higgs mass varies occur in one universe, rather than many. The fact that the universe is predominantly composed of one copy of the SM with a small Higgs mass can be explained if inflation ends and reheats the universe through the decay of a single particle. If this particle is sufficiently light, it will preferentially reheat the copy of the SM with the smallest non-zero value of the Higgs VEV, even if it couples symmetrically to each copy. The sub-dominant energy density deposited in other copies of the SM leaves its mark in the form of dark radiation susceptible to detection by the Simons Observatory or upcoming CMB-S4 facility.

Finally, Gian Giudice, Matthew Mccullough and Tevong You have recently shown that inflation can help to understand the electroweak hierarchy problem by analogy with self-organised criticality. Just as adding individual grains of sand to a sandpile induces avalanches over diverse length scales – a hallmark of critical behaviour, obtained without tuning parameters – so too can inflation drive scalar fields close to critical points in their potential. This may help to understand why the observed Higgs mass lies so close to the boundary between the unbroken and broken phases of electroweak symmetry without fine tuning.

Going the distance

Underlying Weisskopf's natural reasoning is a long-standing assumption about relativistic theories of quantum mechanics: physics at short distances (the ultraviolet, or UV) is decoupled from physics at long distances (the infrared, or IR), making it challenging to apply a theory involving a large energy scale to a much smaller one without fine tuning. This suggests that loopholes may be found in theories that mix the UV and the IR, as is known to occur in quantum gravity.

While the connection between this type of UV/IR mixing and the mass of the Higgs remains tenuous, there are encouraging signs of progress. For instance, Panagiotis Charalambous, Sergei Dubovsky and Mikhail Ivanov recently used it to solve a naturalness problem involving so-called "Love numbers" that characterise the tidal response of black holes. The surprising influence of quantum gravity on the parameter space of effective field theories implied by the Swampland programme also has a flavour of UV/IR mixing to it. And UV/IR mixing may even provide a new way to understand the apparent violation of naturalness by the cosmological constant.

We have come a long way since Weisskopf first set out to understand the self-energy of the electron. The electroweak hierarchy problem is not the first of its kind, but rather the one that remains unresolved. The absence of supersymmetry or compositeness at the TeV scale beckons us to search for new solutions to the hierarchy problem, rather than turning our backs on it. In the decade since the discovery of the Higgs, this search has given rise to a plethora of novel approaches, building new bridges between particle physics, cosmology and gravity along the way. Despite the many differences among these new approaches, they share a common tendency to leave imprints on the Higgs boson. And so, as ever, we must look to experiment to show the way. ●

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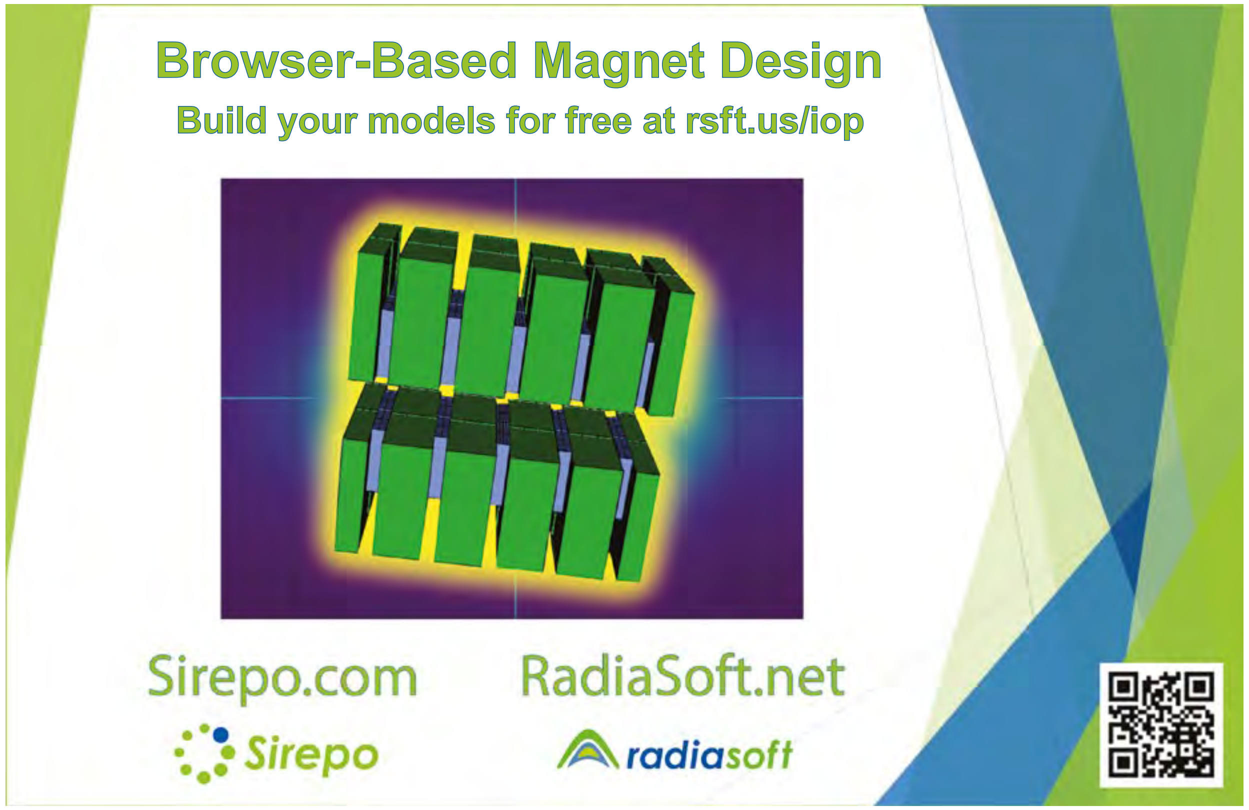
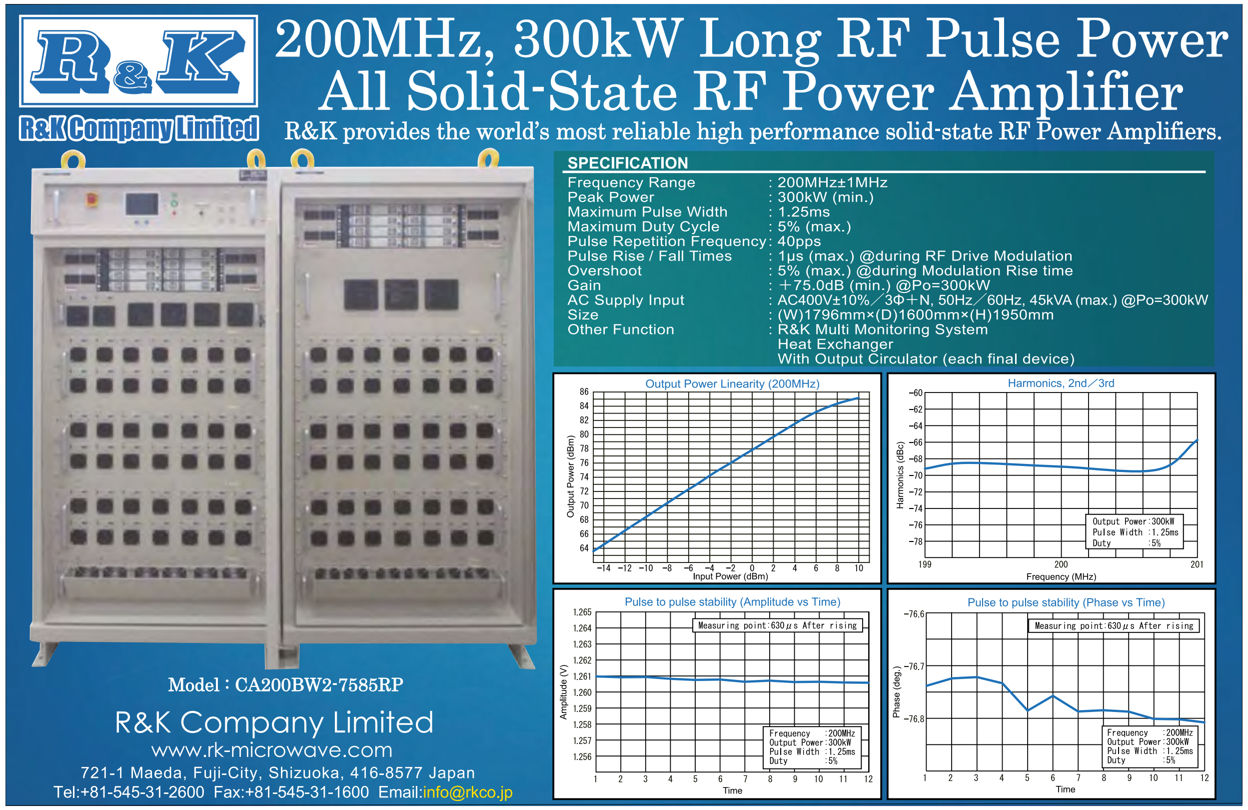
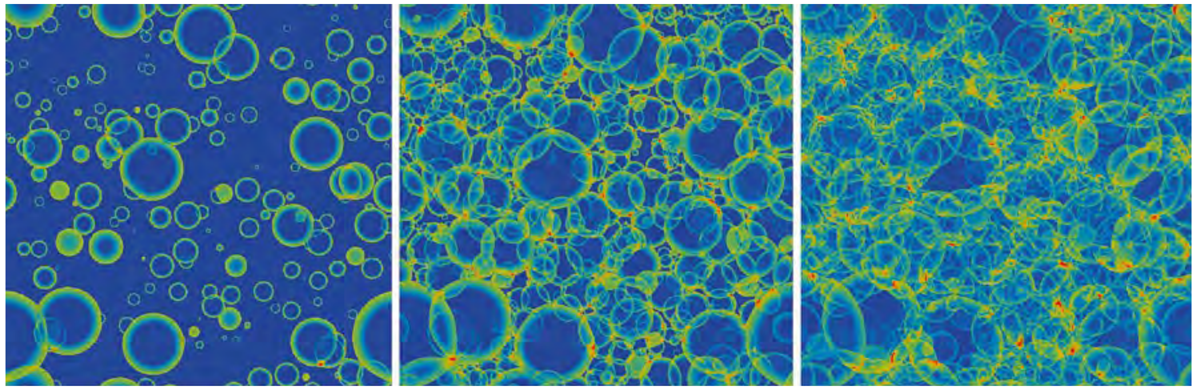




ELECTROWEAK BARYOGENESIS

There are many different ways to explain the cosmic matter–antimatter asymmetry, says Géraldine Servant, but the Higgs boson plays a key role in essentially all of them.



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Bubble nucleation *Simulation of Higgs-bubble nucleation and expansion history during a first-order electroweak phase transition.*

Precision measurements of the Higgs boson open the possibility to explore the moment in cosmological history when electroweak symmetry broke and elementary particles acquired mass. Ten years after the Higgs-boson discovery, it remains a possibility that the electroweak phase transition happened as a rather violent process, with a large departure from thermal equilibrium, via Higgs-bubble nucleations and collisions. This is a fascinating scenario for three reasons: it provides a framework for explaining the matter–antimatter asymmetry of the universe; it predicts the existence of at least one new weak-scale scalar field and thus is testable at colliders; and it would leave a unique signature of gravitational waves detectable by the future space-based interferometer LISA.

One major failure of the Standard Model (SM) is its inability to explain the baryon-to-photon ratio in the universe: $\eta \approx 6 \times 10^{-10}$. Measurements of this ratio from two independent approaches – anisotropies in the cosmic microwave background and the abundances of light primordial elements – are in beautiful agreement. In a symmetric universe, however, the prediction for η is a billion times smaller; big-bang nucleosynthesis could not have occurred and structures could not have formed. This results from strong annihilations between nucleons and antinucleons, which deplete their number densities very efficiently. Only in a universe with a primordial asymmetry between nucleons and antinucleons can these annihilations be prevented. There are many different models to explain such "baryogenesis". Interestingly, however, the Higgs boson plays a key role in essentially all of them.

Accidental symmetry

It is worth recalling how baryon number B gets violated by purely SM physics. B is an "accidental" global symmetry in the SM. There are no B-violating couplings in the SM Lagrangian. But the chiral nature of electroweak interactions, combined with the non-trivial topology of the SU(2) gauge theory, results in non-perturbative, B-violating processes. Technically, these are induced by extended gauge-field configurations called sphalerons, whose energy is proportional to the value of the Brout–Englert–Higgs (BEH) field. The possibility of producing these configurations is totally suppressed at zero temperature, such that B is an extremely good symmetry today. However, at high temperature, and in particular at 100 GeV or so, when the electroweak symmetry is unbroken, the baryon number is violated intensively as there is no energy cost. Since both baryons and antibaryons are created by sphalerons, charge–parity (CP) violation is needed. Indeed, as enunciated by Sakharov in 1967, a theory of baryogenesis requires three main ingredients: B violation, CP violation and a departure from equilibrium, otherwise the baryon number will relax to zero.

The conclusion is that baryogenesis must take place either from a mechanism occurring before the electroweak phase transition (necessitating new sources of B violation beyond

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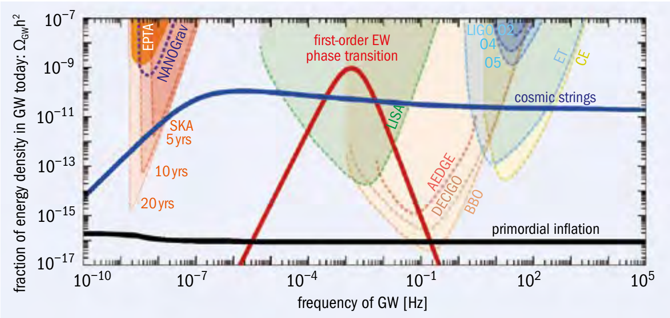


Primordial peak *The stochastic gravitational-wave background inherited from a first-order electroweak phase transition (red) compared to the much broader backgrounds expected from inflation (black) and cosmic strings (blue), as well as sensitivity curves of future experiments.*

the SM) or from a mechanism where B-violation relies exclusively on SM sphalerons and occurring precisely at the electroweak phase transition (provided that it is sufficiently out-of-equilibrium and CP-violating). The most emblematic example in the first category is leptogenesis, where a lepton asymmetry is produced from the decay of heavy right-handed neutrinos and "reprocessed" into a baryon asymmetry by sphalerons. This is a popular mechanism motivated by the mystery of the origin of neutrino masses, but is difficult to test experimentally. The second category, electroweak baryogenesis, involves electroweak-scale physics only and is therefore testable at the LHC.

Electroweak baryogenesis requires a first-order electroweak phase transition to provide a large departure from thermal equilibrium, otherwise the baryon asymmetry is washed out. A prime example of this type of phase transition is boiling water, where bubbles of gas expand into the liquid phase. During a first-order electroweak phase transition, symmetric and broken phases coexist until bubbles percolate and the whole universe is converted into the broken phase (see "Bubble nucleation" image, p51). Inside the bubble, the BEH field has a non-zero vacuum expectation value; outside the bubble, the electroweak symmetry is unbroken. As the wall is passing, chiral fermions in the plasma scatter off the Higgs at the phase interface. If some of these interactions are CP-violating, a chiral asymmetry will develop inside and in front of the bubble wall. The resulting excess of left-handed fermions in front of the bubble wall can be converted into a net baryon number by the sphalerons, which are unsuppressed in the symmetric phase in front of the bubble. Once inside the bubble, this baryon number is preserved as sphalerons are frozen there. In this picture, the baryon asymmetry is determined by solving a diffusion system of coupled differential equations.

During the next decade, precise measurements of the Higgs boson at the LHC will enable a definitive test of the electroweak baryogenesis paradigm

New scalar required

The nature of the electroweak phase transition in the SM is well known: for a 125 GeV Higgs boson, it is a smooth crossover with no departure from thermal equilibrium. This prevents the possibility of electroweak baryogenesis. It is, however, easy to modify this prediction to produce a first-order transition by adding an electroweak-scale singlet scalar field that couples to the Higgs boson, as predicted in many SM extensions. Notably, this is a general feature of composite-Higgs models, where the Higgs boson emerges as a "pseudo Nambu–Goldstone" boson of a new strongly-interacting sector.

An important consequence of such models is that the BEH field is generated only at the TeV scale; there is no field at temperatures above that. In the minimal composite Higgs model, the dynamics of the electroweak phase transition can be entirely controlled by an additional scalar Higgs-like field, the dilaton, which has experimental signatures very similar to the SM Higgs boson. In addition, we expect modifications of the Higgs boson's couplings (to gauge bosons and to itself) induced by its mixing with this new scalar. LHC Run 3 thus has excellent prospects to fully test the possibility of a first-order electroweak phase transition in the minimal composite Higgs model.

The properties of the additional particle required to modify the electroweak phase transition also suggest new sources of CP violation, which is welcome as CP-violating SM processes are not sufficient to explain the baryon asymmetry. In particular, this would generate non-zero electric dipole moments (EDMs). The most recent bounds on the electron EDM from the ACME experiment in the US placed stringent constraints on a large number of electroweak baryogenesis models, in particular two-Higgs-doublet models. This is forcing theorists to consider new paths such as dynamical Yukawa couplings in composite Higgs models, a higher temperature for the electroweak phase transition, or the use of dark particles as the new source of CP violation. Here, there is a tension. To evade the stringent EDM bounds, the new scalar has to be heavy. But if it is too heavy, it reheats the universe too much at the end of the electroweak phase transition and washes out the just-produced baryon asymmetry. During the next decade, precise measurements of the Higgs boson at the LHC will enable a definitive test of the electroweak baryogenesis paradigm.

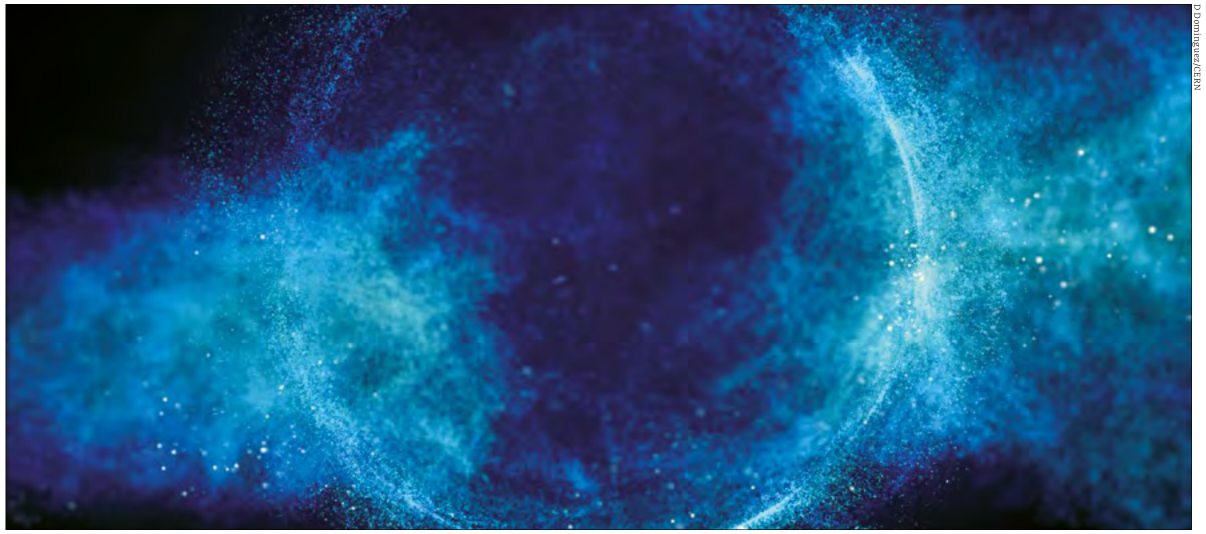
Gravitational waves

There is a further striking consequence of a first-order electroweak phase transition: fluid velocities in the vicinity of colliding bubbles generate gravitational waves (GWs). Today, these would appear as a stochastic background that is homogeneous, isotropic, Gaussian and unpolarised – the superposition of GWs generated by an enormous number of causally-independent sources, arriving at random times and from random directions. It would appear as noise in GW detectors with a frequency (in the mHz region) corresponding to the typical inverse bubble size, redshifted to today (see "Primordial peak" figure). There has been a burst of activity in the past few years to evaluate the chances of detecting such a peaked spectrum at the future space interferometer LISA, opening the fascinating possibility of learning about Higgs physics from GWs.

The results from the LHC so far have pushed theorists to question traditional assumptions about where new physics beyond the SM could lie. Electroweak baryogenesis relies on rather conservative and minimal assumptions, but more radical approaches are now being considered, such as the intriguing possibility of a cosmological interplay between the Higgs boson and a very light and very weakly-coupled axion-like particle. Through complementarity of studies in theory, collider experiments, EDMs, GWs and cosmology, probing the electroweak phase transition will keep us busy for the next two decades. There are exciting times ahead. ●

THE ORIGIN OF PARTICLE MASSES

Gilad Perez links the Higgs boson to the puzzling pattern of the fermion masses.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Massive *An artistic representation of the Higgs boson, which mediates the interaction through which elementary particles gain mass.*

For thousands of years, humans have asked "what are the building blocks of nature?" To those not familiar with the wonders of relativistic quantum mechanics, the question might seem equivalent to asking "what are the smallest particles known?" However, we know that the size of atoms is quantised, and has negligible dependence on the size of nuclei. In fact, atomic size is essentially inversely proportional to the mass of the electron. Therefore, it is the electron mass, in addition to the rules of quantum mechanics, that essentially controls all the inner structure of all the elements. Furthermore, the masses and sizes of nuclei, protons and neutrons cannot simply be obtained by "adding up" smaller degrees of freedom; they are rather dictated by the coupling constant of the strong force, which below a certain energy scale, Λ_{QCD}, becomes so large that the force between two particles becomes approximately independent of their distance, inducing confinement.

The above description suggests that "all" that is required to understand the basic structure of matter is to understand the origin of the electron mass and to study quantum chromodynamics. But this misses the bigger picture revealed by the Standard Model (SM). Protons, neutrons and other light, long-lived baryons are the lightest excitations of the pion field, which is constructed from the ultra-light u and d quarks, and perhaps also s quarks. This reveals the profound importance of the values of the fermion masses: increasing the u and d mass difference by less than 10 MeV (that is, about 1% of the proton mass), for instance, would make hydrogen and its isotopes unstable, thereby preventing the formation of almost all the elements in the early universe. Indeed, there are only certain regions in the vast quark-mass and Λ_{QCD} parameter space that enable the universe as we know it to form.

Having established that the structure of the masses of the elementary particles is an existential issue, what does this have to do with the discovery of the Higgs boson? While the Higgs boson carries a cosmological background value called the vacuum expectation value (VEV), which is associated with the spontaneous breaking of the electroweak symmetry, the VEV is not necessarily the source of the actual value and/or the pattern of fermion masses. The reason is that, in addition to baryonic charge (or number), all the elementary charged particles carry "chiral charge" – they are either left- or right-handed – which is conserved in the absence of the Brout–Englert–Higgs (BEH) field. What is fascinating about the BEH mechanism is that with the appropriate choice of coupling, the product of the field and its coupling-strength to the fermions effectively becomes a source of chiral charge, allowing the fermions to interact with it; the VEV is merely the constant of proportionality that induces the masses of the fermions (and of the weak-force mediators). This is a very minimal setup! In other known symmetry-breaking frameworks – for instance models based on technicolour/QCD-like dynamics or on superconductivity, where the electromagnetic symmetry inside a superconductor is broken by a condensate of electrons denoted Cooper pairs – there is no direct link to the generation of fermion masses.

Standard Model couplings

The BEH mechanism might be minimal, but it still involves many parameters. The origin of fundamental masses requires switching on nine trilinear-couplings, which are broken into three generations of fundamental particles: three involving the u-type left- and right-handed quarks

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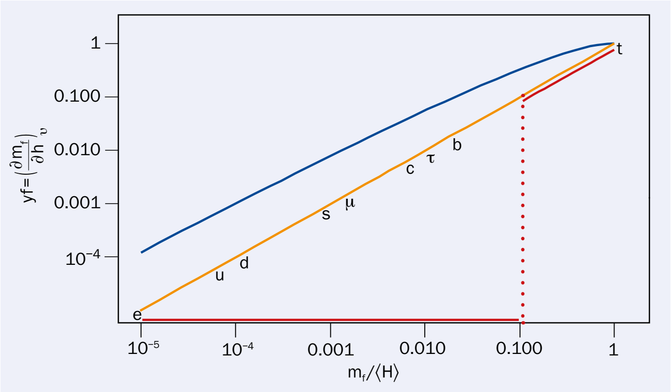


In line *Schematic showing the relationship between the fundamental masses and their Yukawa couplings to the BEH field. The diagonal orange line describes the SM case, the upper blue curve corresponds to a "Yukawa-full" model (arXiv:0804.1753) and the bottom red curve corresponds to a "Yukawa-less" model for the light generations (arXiv:1508.01501).*

G Perez

(u, c, t), three involving the d-type left- and right-handed quarks (d, s, b) and three involving the left- and right-handed charged leptons (e, μ, τ). Each coupling is associated with a linear "Yukawa" coupling of the Higgs boson to fermions, which implies that all the charged fermions acquire a mass proportional to the VEV of the BEH field. In other words, there is a linear relation between the Yukawa coupling and the fermion masses. Strikingly, the observed fermion masses encoded in the Yukawa couplings span some five orders of magnitude, with all but some members of the third generation being extremely small – leading to the fermion mass-hierarchy puzzle.

The coupling between the Higgs boson and the fermions can be pictured as a new force – one that is radically different to the SM gauge forces. Given that this force only works between two particles that are closer than around 10^{-18} m – i.e. 1000 times smaller than the proton radius – it is not relevant to any experimental setup. The Higgs–Yukawa couplings do, however, conceal two interesting aspects related to our existence. The first is that increasing the VEV by a few factors would increase the neutron–proton mass splitting to the point where all nuclei are unstable. The second, pointed out by Giuseppe Degrassi and co-workers in 2013, is that the top-quark Yukawa interaction is close to its maximal size: increasing it by as little as 10% would push the VEV to fantastically large values, rendering our current universe unstable (see p59).

It is now a priority to directly test the mass-generating mechanism of the first two generations

Massive alternatives

The minimal BEH mechanism is not the only way to understand the fermion mass hierarchy. This is illustrated by two radically different options. In the first, proposed in 2008 by Gian Giudice and Oleg Lebedev, the Yukawa couplings are assumed to depend on the BEH field, therefore avoiding hierarchies in the Yukawa couplings. The idea postulates a variation of chiral symmetry (in which the lighter the fermion the more chiral charge it carries) that forbids lighter particles from coupling to the Higgs linearly, but instead generates their masses through appropriate powers of the VEV (see "In line" figure, blue curve). The other extreme possibility, discussed more recently by the present author and colleagues, is where the masses of the light fermions instead come from their interaction with a subdominant additional source of electroweak symmetry breaking, similar to the technicolour framework. This new source replaces the Higgs boson's role as the carrier of the light-generation chiral-charge, causing the light fermion–Higgs couplings to vanish (see figure, red curve). Both cases lead to an alternative understanding of the mass hierarchy puzzle and to the establishment of new physics.

The conclusion is that measuring the fermion–Higgs couplings at higher levels of precision will significantly improve our understanding of the origin of masses in nature. It took a few years after the Higgs-boson discovery, around 2018, for ATLAS and CMS to establish that the standard BEH mechanism is behind the third-generation fermion masses. This is a legacy result from the LHC experiments that is sometimes overlooked by our community (*CERN Courier* September/October 2020 p41). While significant, however, it told us little about the origin of the matter in the universe, which is almost exclusively made out of first-generation fermions with extremely small couplings to the Higgs boson. So far, we only have indirect information, via Higgs-boson couplings to the gauge bosons, about the origin of mass of the first and second generations. But breakthroughs are imminent. In the past two years, ATLAS and CMS have found signs that the Higgs boson contributes to both the second-generation muon and charm masses, which would exclude models leading to both the blue and red curves in the figure. Measuring the smallest electron Yukawa coupling is only possible at a future collider, whereas for the u and d quarks there is no clear experimental pathway.

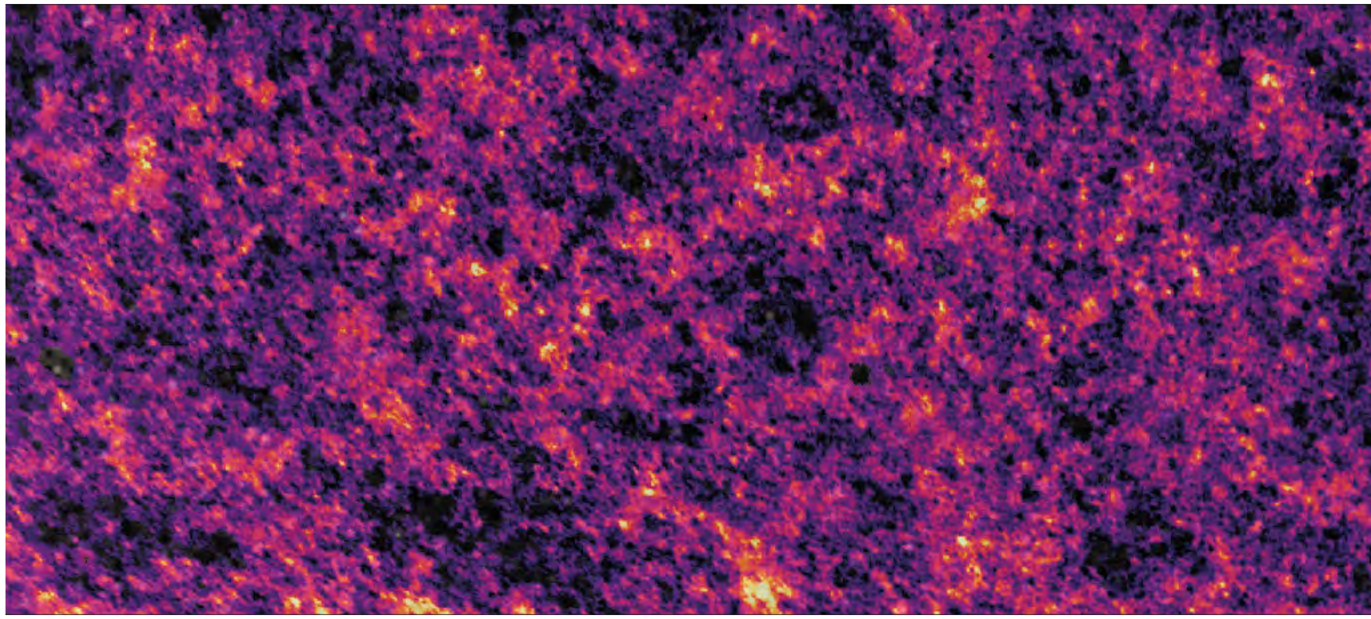
Experimental novelties

A recent, unexpected way to tackle the mystery of fermion masses involves dark matter, specifically a class of models in which the dark-matter particle is ultra-light and its field-value oscillates with time. Such particles would couple to fermions in a way that echoes the Higgs–Yukawa coupling, though with an extremely low interaction strength, and lead to a variation in the masses of the fundamental fermions with time. This feeble effect cannot be searched for at colliders, but it can be probed with quantum sensors such as atomic clocks or future nuclear clocks that reach sensitivity of one part in 10^{19} or more. The strongest sensitivity of these tabletop experiments is the one to the electron mass.

The discovery of the Higgs boson has opened a new window on the origin of masses, and consequently the structure of the basic blocks of nature, with profound links to our existence. ATLAS and CMS have made several breakthroughs, including the observation that the third-generation masses originate from the SM minimal BEH mechanism, and also providing evidence for part of the second-generation fermions. It is now a priority to directly test the mass-generating mechanism of the first two generations, and to determine all the Higgs couplings at higher precision, in search of possible chinks in the SM armour. ●

THROUGH THE HIGGS PORTAL

Frank Wilczek explains why the Higgs sector could act as a portal through which to access a wide class of "phantom" particles that might otherwise elude detection.



Phantom fields *The Higgs boson could connect normal matter to a hidden sector that does not participate in strong or electroweak interactions, as has been proposed to explain dark matter – the most detailed map of which so far (by the Dark Energy Survey) is shown for a patch of sky in the southern hemisphere. (Credit: DES)*

Referring to the field equation of general relativity $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa T_{\mu\nu}$, Einstein is reported to have said that the left-hand side, constructed from space-time curvature, is "a palace of gold"; while the right-hand side, which parameterises the energy and momentum of matter, is by comparison "a hovel of wood". Present-day physics has arrived at much more concrete ideas about the right-hand side than were available to Einstein. It is fair to say that some of it has come to look quite palatial, and fully worthy to stand alongside the left-hand side. These are the terms that involve field kinetic energy and gauge bosons, as described by the Standard Model (SM). Their form follows logically, within the framework of relativistic quantum field theory, directly from the principles of local gauge symmetry and relativity. Mathematically, they also speak the same geometric language as the right-hand side. The gauge bosons are avatars of curvature in "internal spaces", similar to how gravitons are the avatars of space-time curvature. Internal spaces parameterise ways in which fields can vary – and thus, in effect, move – independently of ordinary motion in space-time. In this picture, the strong, weak and electromagnetic interactions arise from the influence of internal space curvature on internal space motion, similar to how gravity arises from the influence of space-time curvature on space-time motion.

The other contributions to $T_{\mu\nu}$, all of which involve the Higgs particle, do not yet reach that standard. We can aspire to do better! They are of three kinds. First, there are the many Yukawa-like terms from which quark and lepton masses and mixings arise. Then there is the Higgs self-coupling and finally a term representing its mass. These contributions to $T_{\mu\nu}$ contain almost two dozen

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dimensionless coupling parameters that present-day theory does not enable us to calculate or even much constrain. It is therefore important to investigate experimentally, through quantitative studies of Higgs-particle properties and interactions, whether this ramshackle structure describes nature accurately.

Higgs potential

The Higgs boson is special among the elementary particles. As the quantum of a condensate that fills all space, it is metaphorically “a fragment of vacuum”. Speaking more precisely, the Higgs particle has no spin, no electric or colour charge and, at the level of strong and electromagnetic interactions, normal charge conjugation and parity. Thus, it can be emitted singly and without angular momentum barriers, and it can decay directly into channels free of colour and electromagnetically charged particles, which might otherwise be difficult to access. For these and other, more technical, reasons, the Higgs particle has the potential to reveal new physical phenomena of several kinds.

A unique aspect of the Higgs mass term is especially promising for revealing possible shortcomings in the SM. In quantum field theory, an important property of an interaction is the “mass dimension” of the operator that implements it – a number that in an important sense indicates its complexity. Scalar and gauge fields have mass dimension 1 as do space–time derivatives, whereas fermion fields have mass dimension 3/2. More complicated operators are built up by multiplying these, and the mass dimension of a product is the sum of the mass dimensions of its factors. Interactions associated with operators whose mass dimension is greater than 4 are problematic because they lead to violent quantum fluctuations and mathematical divergences. Whereas all the other terms in the SM Lagrangian arise from operators of mass dimension 4, the Higgs mass term has mass dimension 2. Thus it is uniquely open to augmentation by couplings to hypothetical new $SU(3)\times SU(2)\times U(1)$ singlet scalar fields, because the mass dimension of the augmented interaction can be 3 or 4 – i.e. still “safe”. The Higgs particle is the only portal connecting normal matter to such phantom fields.

Why is this an interesting observation? There are three main reasons: two broadly theoretical, one pragmatic. First of all, the particles that are generally considered part of the SM carry a variety of charge assignments under the gauge groups $SU(3)\times SU(2)\times U(1)$ that govern the strong and electroweak interactions. For example, the left-handed up quark is charged under all three groups, while the right-handed electron carries only U(1) hypercharge. Thus it is not only logically possible, but reasonably plausible, that there could be particles that are neutral under all three groups. Such phantom particles might easily escape detection, since they do not participate in the strong or electroweak interactions. Indeed, there are several examples of well-motivated candidate particles of that kind. Axions are one. Since they are automatically “dark” in the appropriate sense, phantom particles could contribute to the astronomical dark matter, and might even dominate it, as model-builders have not failed to notice. Also, many models of unification bring in scalar fields belonging to representations of a unifying gauge group that contains $SU(3)\times SU(2)\times U(1)$ singlets, as do models with supersymmetry. Only phantom scalars are directly accessible through the Higgs portal, but phantoms of higher spin, including right-handed neutrinos, could cascade from real or virtual scalars.

The Higgs particle is the only portal connecting normal matter to such phantom fields

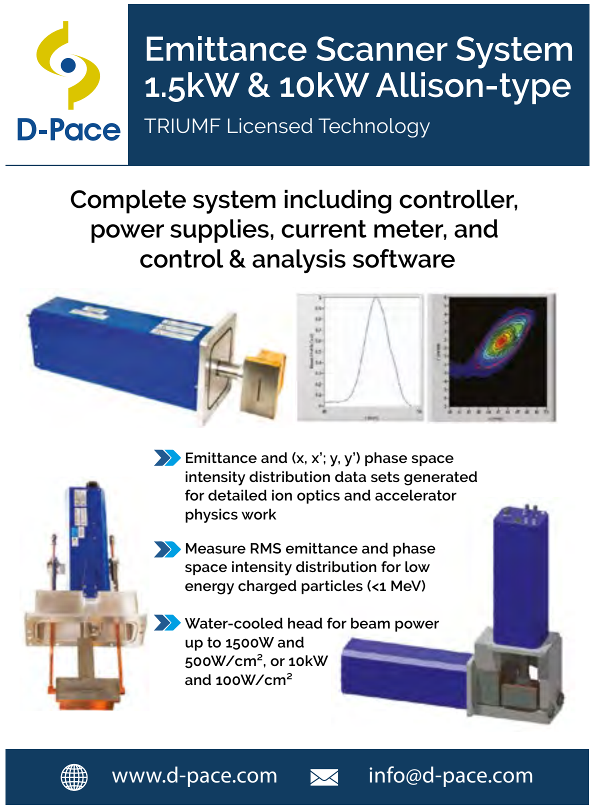
Mysterious values

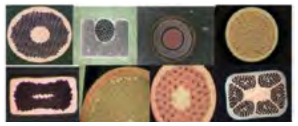
Second, the empirical value of the Higgs mass term is somewhat mysterious and even problematic, given that quantum corrections should push it to a value many orders of magnitude higher. This is the notorious “hierarchy problem” (see p47). Given this situation, it seems appropriate to explore the possibility that part (or all) of the effective mass-term of the SM Higgs particle arises from more fundamental couplings upon condensation of $SU(3)\times SU(2)\times U(1)$ singlet scalar fields, i.e. the emergence of a non-zero space-filling field, as occurs in the Brout–Englert–Higgs mechanism.

Third, the portal idea leads to concrete proposals for directions of experimental exploration. These are of two basic kinds: one involves the observed strength of conventional Higgs couplings, the other the kinematics of Higgs production and decay. Couplings of the Higgs field to singlets that condense will lead to mixing, altering numerical relationships among Higgs-particle couplings and masses of gauge bosons, and of fermions from their minimal SM values. Also, the Higgs-field couplings to gauge bosons and fermions will be divided among two or more mass eigenstates. Since existing data indicates that deviations from the minimal model are small, the coupling of normal matter to the “mostly but not entirely” singlet pieces could be quite small, perhaps leading to very long lifetimes (as well as small production rates) for those particles. Whether or not the phantom particles contribute significantly to cosmological dark matter, they will appear as missing energy or momentum accompanying Higgs particle decay or, through Bremsstrahlung-like processes, when they are produced.

We introduced the term “Higgs portal” to describe this circle of ideas in 2006, triggering a flurry of theoretical discussion. Now that the portal is open for business, and with larger data samples in store at the LHC, we can think more concretely about exploring it experimentally. ●

The portal idea leads to concrete proposals for directions of experimental exploration



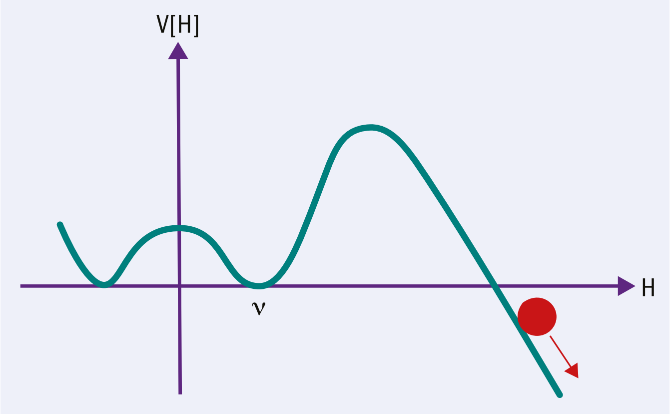


THE HIGGS AND THE FATE OF THE UNIVERSE

The masses of the Higgs boson and the top quark hint that there must be physics beyond the Standard Model that prevents the universe from decaying into a new vacuum state, argues John Ellis.

A vacuum is ordinarily pictured as an empty region containing no particles, atoms or molecules of matter, as in outer space. To a particle physicist, however, it is better defined as the lowest energy state that can be attained when no physical particles are present. Even in empty space there are fields that are invisible to the naked eye but nevertheless influence the behaviour of matter, while quantum mechanics ensures that, even if particles are not physically present, they continually fluctuate spontaneously in and out of existence.

In the Standard Model (SM), in addition to the familiar gravitational and electromagnetic fields, there is the Brout–Englert–Higgs (BEH) field that is responsible for particle masses. It is usually supposed to have a constant value throughout the universe, namely the value that it takes at the bottom of its "Mexican hat" potential (see "New depths" figure). However, as was first pointed out by several groups in 1979, and revisited by many theorists subsequently, the shape of the Mexican hat is subject to quantum effects that change its shape. For example, the BEH field has self-interactions that tend to curl the brim of the hat upwards, but there are additional quantum effects that tend to curl the brim downwards, due to the interactions with the fundamental particles to which the BEH field gives mass. The most important of these is the heaviest matter particle: the top quark.

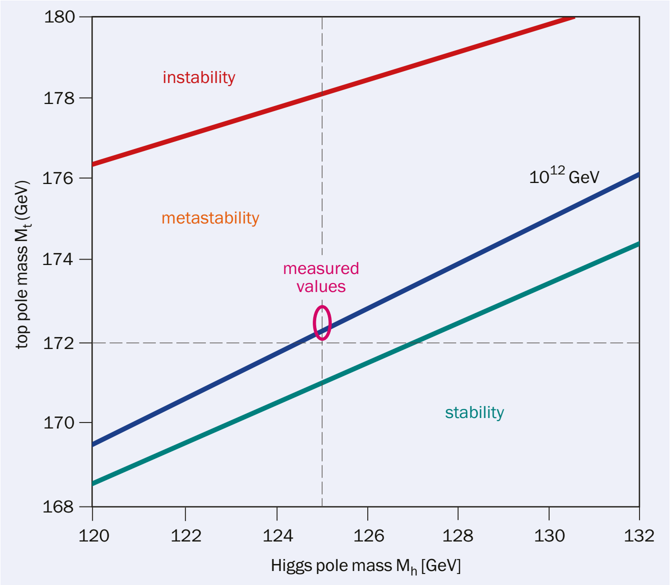


J Ellis

New depths *The transition of the universe to a different vacuum state after electroweak symmetry breaking can be pictured as a ball rolling along a potential. If the SM is correct and there is no new physics beyond it, then the current value of the BEH field (v ~246 GeV) does not have the lowest energy and hence is not the true vacuum of the universe. Rather, the potential "turns over" at around 10^{12} GeV and becomes negative, suggesting that the universe might one day tunnel out of its current state (diagram not to scale).*

Push and pull

The upward push of the Higgs boson's self-interaction and the downward pressure of the top quark are very sensitive to their masses, and also to the strong interactions, which modify the effect of the top quark. Experiments at the LHC have already determined the mass of the Higgs boson with a precision approaching 0.1%, and CMS recently measured the mass of the top quark with an accuracy of almost 0.2%, while the strong coupling strength is known to better than 1%. The latest calculations of the quantum effects of the Higgs boson and the top quark ▷



Particle Data Group/*JHEP* **12** 089

On the cusp *Regions of absolute stability, metastability and instability of the SM vacuum in the m_t–m_H plane. The blue line shows where the brim of the Mexican hat turns down at 10^{12} GeV and the ellipse represents 1σ Particle Data Group values.*

indicate that the brim of the Mexican hat turns down when the BEH field exceeds its value today by 10 orders of magnitude, implying that the current value is not the lowest energy and hence not the true vacuum of the SM. A consequence is that the current BEH value is not stable, because quantum fluctuations would inevitably cause it to decay into a lower-energy state. The universe as we know it would be doomed (see "On the cusp" figure).

Looking up

However, there is no immediate need to panic. First, the universe is metastable with an estimated lifetime before it decays that is many, many orders of magnitude longer than its age so far. Second, one could perhaps cling to the increasingly forlorn hope that the prediction of a lower-energy state of the SM vacuum is somehow mistaken. Perhaps an experimental measurement going into the calculation has an unaccounted uncertainty, or perhaps there is some ingredient that is missing from the theoretical calculation of the shape of the Mexican hat?

If you simply take the calculation at face value and humbly accept the eventual demise of the universe as we know it, however, a further problem arises. Since quantum and thermal fluctuations in the BEH field were probably much larger when the universe was young and much hotter than today, the overwhelming majority of the universe would have been driven into the lower-energy state. Only an infinitesimal fraction would be in the metastable state we find ourselves in today, where the value of the BEH field is relatively small. Of course, one could argue anthropically that this good luck was inevitable, as we could not live in any other "vacuum" state.

To me, this argument reeks of special pleading. Instead, my instinct is to argue that some physics beyond the SM must appear below the turn-down scale and stabilise the vacuum that we live in. This argument is not specific about the type of new physics or the scale at which it appears. One extension of the SM that fits the bill is supersymmetry, but the stability argument offers no guarantee that this or any other extension of the SM is within reach of current experiments.

New physics

It used to be said that the nightmare scenario for the LHC would be to discover the Higgs boson and nothing else. However, the measured masses of the Higgs boson and the top quark may be hinting that there must be physics beyond the SM that stabilises the vacuum. Let us take heart from this argument, and keep looking for new physics, even if there is no guarantee of immediate success. ●

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OPINION VIEWPOINT

Engines of knowledge and innovation

If we don't dare spend money on projects that bring us to the future then we, as Europe, lose a competitive advantage, says Anna Panagopoulou.

CERN-202110-161-4

Anna Panagopoulou *is director of European Research Area and Innovation at the European Commission.*

CERN-201808-226-1

One of a kind *As a large research infrastructure, CERN has a key role in shaping a globally competitive European research and innovation system.*

The search for the Higgs boson is the kind of adventure that draws many young people to science, even if they go on to work in more applied areas. I first set out to become a nuclear physicist, and even applied for a position at CERN, before deciding to specialise in electrical engineering and then moving into science policy. Today, my job at the European Commission (EC) is to co-create policies with member states and stakeholders to shape a globally competitive European research and innovation system.

Large research infrastructures (RIs) such as CERN have a key role to play here. Having visited CERN for the first time last year, I was impressed not just by the basic research but also by the services that CERN provides the collaborations, its relationships with industry, and its work in training and educating young people. It is truly an example of what it means to collaborate on an international level, and it helped me understand better the role of RIs in research and innovation.

Innovation is one of three pillars of the EC's €95.5 billion Horizon Europe programme for the period 2021–2027. The first pillar is basic science, and the second concerns applied research and knowledge diffusion. Much of the programme's focus is "missions" geared to societal challenges such as soil, climate and cancer, driven by the UN's 2030 Sustainable Development Goals. So where does a laboratory like CERN fit in? Pillar one is the natural home of particle physics, where there is well established support via European Research Council grants, Marie Skłodowska-Curie fellowships and RI funding. On the other hand, the success of the Horizon Europe missions relies on the knowledge and new technologies generated by the RIs.

We view the role of RIs as driving knowledge and technology, and ensuring it is transferred in Europe – acting as engines in a local ecosystem involving other laboratories and institutes, hospitals and schools, attracting the best people and generating new labour forces. COVID-19 is a huge social challenge that we also managed to address using basic research, RIs and opening access to data. This is a clear socioeconomic impact of current research and also data collected in the past.

Open science is a backbone of Horizon Europe, and an area where particle physics and CERN in particular are well advanced. I chair the governance board of the European Open Science Cloud, a multi-disciplinary environment where researchers can publish, find and re-use data, tools and services, in which CERN has a long-standing involvement.

Indeed, the EC has established a very strong collaboration with CERN across several areas. Recently we have been meeting to discuss the proposed Future Circular Collider (FCC). The FCC is worthwhile not just to be discussed but supported, and we are already doing so via significant projects. We are now discussing possibilities in Horizon Europe to support more technological aspects, but clearly EU money is not enough. We need commitment from member states, so there needs to be a political decision. And to achieve that we need a very good business plan that turns the long-term FCC vision into clearly defined short-term goals and demonstrates its stability and sustainability.

The FCC brings to mind the Moon landings

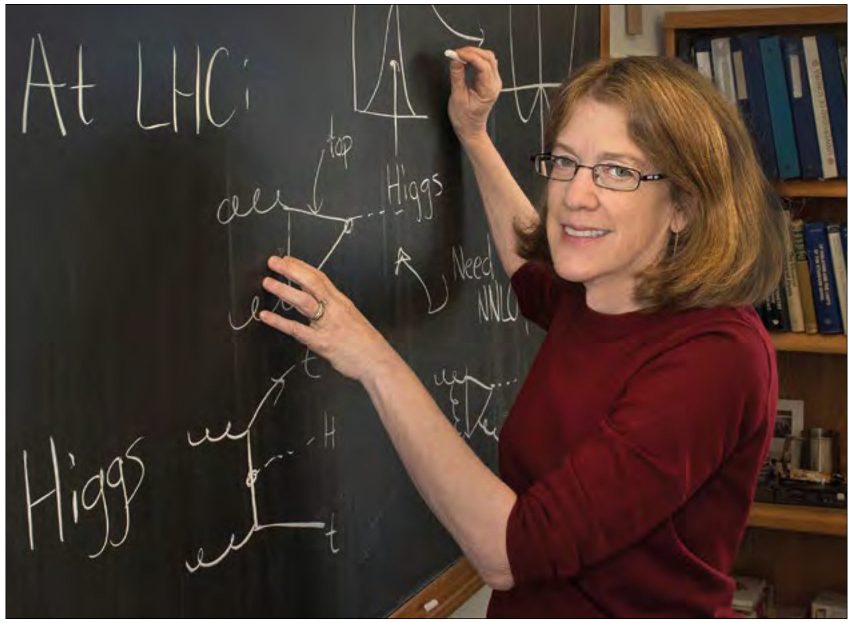
Societal impact

Long-term projects are not new to the EC: we have ITER, for example, while even the neutrality targets for the green-deal and climate missions are for 2050. The key is to demonstrate their relevance. There is sometimes a perception that people doing basic research are closed in their bubble and don't realise what's going on in the "real" world. The space programme has managed to demonstrate over the years that there are sufficient applications providing value beyond its core purpose. Nowadays, with issues of defence, security and connectivity rising up political agendas, researchers can always bring to the table that their work can help society address its needs. For big RIs such as the FCC we need to demonstrate first: what is the added value, even if it's not available today? Why is it important for Europe? And what is the business plan? The FCC is not a typical project. To attract and convince politicians and finance ministers of its merits, it has to be presented in terms of its uniqueness.

The FCC brings to mind the Moon landings. Contrary to popular depictions, this was a long-term project that built on decades of competitive research from different countries. Yes, it was a period during the Cold War, but it was also the basis of fruitful collaboration. If we don't dare to spend money on projects that bring us to the future then we lose, as Europe, a competitive advantage.

Synergy at the Higgs frontier

Working at the forefront of calculations of the Higgs boson's properties, Sally Dawson explains how the codependence of theory and experiment is driving a deeper understanding of the new particle.



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Joined up *Sally Dawson is leader of the high-energy theory group at Brookhaven National Laboratory.*

What impact did the discovery of the Higgs boson have on your work?
It was huge because before then it was possible that maybe there was no Higgs. You could have some kind of dynamical symmetry breaking, or maybe a heavy Higgs, at 400 GeV say, which would be extremely interesting but completely different. So once you knew that the Higgs was at the same mass scale as the W and the Z, our thinking changed because that comes out of only a certain kind of model. And of course once you had it, everyone, including myself, was motivated to calculate everything we could.

I am working on how you tease out new physics from the Higgs boson. It's the idea that even if we don't see new particles at the LHC, precision measurements of the Higgs couplings are going to tell us something about what is happening at very high energy scales. I'm using what's called an effective field theory approach, which is the standard these days for trying to find out what we can learn from combining Higgs measurements with other types of measurements, such as gauge–boson pair production and top-quark physics.

Aside from the early formal work, what was the role of Standard Model calculations in the discovery of the Higgs boson?
You had to know what you were looking for, because there's so many events at the LHC. Otherwise, it would be like looking for a needle in a haystack. The Higgs was discovered, for example, by its decay to two photons and there are millions of two-photon events at the LHC that have nothing to do with the Higgs. Theory told you how to look for this particle, and I think it was really important that a trail was set out to follow. This involves calculating how often you make a Higgs boson and what the background might look like. It wasn't until the late 1980s that people began taking this seriously. It was really the Superconducting Super Collider that started us thinking about how to observe a Higgs at a hadron collider. And then there were the LEP and Tevatron programmes that actively searched for the Higgs boson.

To what order in perturbation theory were those initial calculations performed?
For the initial searches you didn't need the complicated calculations because you weren't looking for precision measurements such as those required at the Z-pole, for example. You really just needed the basic rate and background information. We weren't inspired to do higher order calculations until later in the game. When I was a postdoc at Berkeley in 1986, that's when I really started to calculate things about the Higgs. But there was a long gap between the time when the Brout–Englert–Higgs mechanism was proposed and when people really started doing some hard calculations. There's the famous paper in 1976 by Ellis, Gaillard and Dimopoulos that calculated how the Higgs might be observed, but in essence it said: why bother looking for this thing, we don't know where it is! So people were thinking we could see the Higgs in kaon decays, if it was very light, and in other ways, and were looking at the problem in a global kind of way.

Was this what drove your involvement with *The Higgs Hunter's Guide* in 1990?
We were further along in terms of calculating things precisely by then, and I suppose there was a bit of a

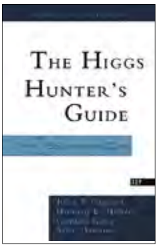
generation gap. It was a wonderful collaboration to produce the guide. We still went through the idea of how you would find the Higgs at different energy scales because we still had no idea where it was. The calculations went into high gear around that time, which was well before the Higgs was discovered. Partly it was the motivation that we were pretty sure we would see it at the LHC. But partly it was developments in theory which meant we could calculate things that we never would have imagined was possible 30 years earlier. The capability of theorists to calculate has grown exponentially.

What have these improvements been?
It's what they call the next-to-next-to-leading order (NNLO) revolution – a new frontier in perturbative QCD where diagrams with two extra emissions of real or extra loops of virtual partons are accounted for. These were new mathematical techniques for evaluating the integrals that come into the quantum field theory, so not just turning the crank computationally but really an intellectual advance in understanding the structure of these calculations. It started with Bern, Dixon and Kosower, who understood the needed amplitudes in a formal way. This enabled all sorts of calculations, and now we have N^3LO calculations for certain Higgs-boson production modes.

What is driving greater precision on Higgs calculations today?
Actually it's really exciting because at the high-luminosity LHC (HL-LHC), experimentalists will be limited in their understanding of the Higgs boson by theory – the theory and experimental uncertainties will be roughly the same. This is truly impressive. You might think that these higher order corrections, which have quite small errors, are enough but they need to be even smaller to match the expected experimental precision. As theorists we have to keep going and do even better, which from my point of view is wonderful. It's the synergy between experiment and theory that is the real story. We're co-dependent. Even now, theory is not so different from ATLAS and CMS in terms of precision. Theory errors are hard things to pin down because you never really know what they are. Unlike an absolute statistical uncertainty, they're always an estimate.

How do the calculations look for measurements beyond the LHC?
It's a very different situation at e^+e^- colliders compared to hadron colliders. The LHC runs with protons containing gluons, so that's why you need the higher order corrections. At a future e^+e^+ collider, you need higher-order corrections but they are much more straightforward because you don't have parton distribution functions to worry about. We know how to do the calculations needed for an e^+e^- Future Circular Collider, for example, but there is not a huge community of people working on them. That's because they are really hard: you can't just sit down and do them as a hobby, they really need a lot of skills.

Basic Books



Essential reading *At 425 pages,* The Higgs Hunters Guide *(Basic Books, 1990) offered a comprehensive guide to the physics of Higgs bosons.*

You are currently leading the Higgs properties working group of the current Snowmass planning exercise. What has been the gist of discussions?
This is really exciting because our job has essentially been to put together the pieces of the puzzle after the European strategy update in 2020. That process did a very careful job of looking at the future Higgs programme, but there have been developments in our understanding since then. For example, the muon collider might be able to measure the Higgs couplings to muons very precisely, and there has been some good work on how to measure the couplings to strange quarks, which is very hard to do.

I would like to see an e^+e^- collider built somewhere, anywhere. In point of fact, when you look at the proposals they're roughly the same in terms of Higgs physics. This was clear from the European strategy report and will be clear from the upcoming Snowmass report. Personally, I don't much care whether there is a precision of 1% or 1.5% on some coupling. I care that you can get down to that order of magnitude, and that e^+e^- machines will significantly improve on the precision of HL-LHC measurements. The electroweak programme of large circular e^+e^- colliders is extremely interesting. At the Z-pole you get some very precise measurements of Standard Model quantities that feed into the whole theory because everything is connected. And at the WW threshold you get very precise measurements in the effective field theory of things that connect the Higgs and WW pairs. As a theorist, it doesn't make sense to think of the Higgs in a vacuum. The Higgs is part of this whole electroweak programme.

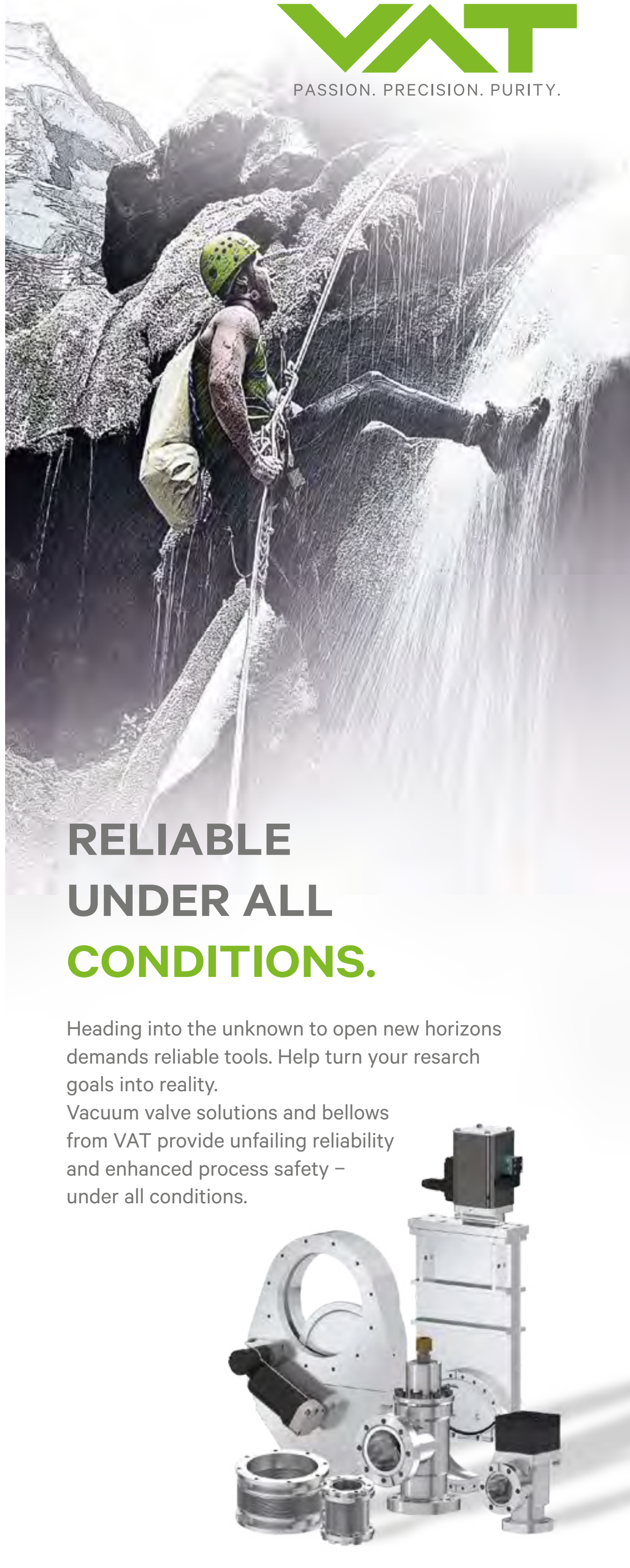
The fact that we haven't seen anything unexpected yet is probably because we haven't probed enough

What are the prospects for finding new physics via the Higgs?
The fact that we haven't seen anything unexpected yet is probably because we haven't probed enough. I'm absolutely convinced we are going to see something, I just don't know what (or where) it is. So I can't believe in the alternative "nightmare" scenario of a Standard-Model Higgs and nothing else because there are just so many things we don't know. You can make pretty strong arguments that we haven't yet reached the precision where we would expect to see something new in precision measurements. It's a case of hard work.

What's next in the meantime?
The next big thing is measuring two Higgs bosons at a time. That's what theorists are super excited about because we haven't yet seen the production of two Higgses and that's a fundamental prediction of our theory. If we don't see it, and it's extremely difficult to do so experimentally, it tells us something about the underlying model. It's a matter of getting the statistics. If we actually saw it, then we would do more calculations. For the trilinear Higgs coupling we now have a complete calculation at next-to-leading order, which is a real tour de force. The calculations are sufficient for a discovery, and because it's so rare it's unlikely we will be doing precision measurements, so it is probably okay for the foreseeable future. For the quartic coupling there are some studies that suggest you might see it at a 100 TeV hadron collider.

With all the Standard Model particles in the bag, does theory take more of a back seat from here?
The hope is that we will see something that doesn't fit our theory, which is of course what we're really looking for. We are not making these measurements at ever higher precisions for the sake of it. We care about measuring something we don't expect, as an indicator of new physics. The Higgs is the only tool we have at the moment. It's the only way we know how to go.

Interview by **Matthew Chalmers** *editor.*



Capturing the intangible

Chasing the Ghost

By Leonard A Cole

World Scientific

Los Alamos Photo Laboratory, courtesy AIP Emilio Segrè Visual Archives

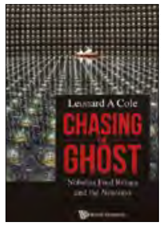
Ghostbuster *Fred Reines, who devoted his life to neutrino physics.*

Every Nobel Prize comes with a story, and Leonard A Cole's *Chasing the Ghost* offers a new perspective on that of Fred Reines, best known for discovering the electron neutrino with Clyde Cowan in 1956. While Cowan passed away in 1974, Reines went on to win the Nobel Prize in Physics for their discovery in 1995. Cole, Reines's cousin, describes the life of Fred Reines – focusing on both his scientific career and extracurricular interests – in a personal way, showing obvious admiration for his elder cousin.

After participating in the Manhattan Project and assisting in developing nuclear weapons in the 1940s, Reines pivoted to study neutrinos, the fundamental particles emitted in nearly every nuclear reaction, which he describes as "the tiniest quantity of reality ever imagined by a human being". While being tiny quantities, neutrinos are abundant, yet mysterious, and Reines's work opened the door to better understand these particles. His research spanned the next five decades, and positions at universities and laboratories across the US, and the techniques that he developed to study neutrinos are used to this day.

Rainbows and Things

Throughout *Chasing the Ghost*, Cole splits his time between describing Reines's career and his extracurricular pursuits. Even among his colleagues, Reines was known to be a prolific singer, performing with groups including the Los Alamos Light Opera Association and the Cleveland Orchestra Chorus. Time spent pondering these activities allowed Reines to connect better with non-science-major students when lecturing at universities. Reines famously taught his course "Rainbows and Things" to much acclaim at the University of California, Irvine, where he encouraged students to think deeply about the connection between classroom physics and the natural world. Cole explains that the course name, and much of its philosophy, stems from the play *Finian's Rainbow*, which Reines performed in 1955.



World Scientific

Throughout his later life, it became apparent that Reines thought his accomplishments deserved more praise than they had received. In fact, it was only after he gave up hope of winning the Nobel Prize that he won it in 1995. Reines had been passed up on many occasions, including in 1988 when the team that discovered the second type of neutrinos was awarded the prize before him. Cole shares a humorous anecdote (in hindsight): at a CERN conference with both Reines and 1988 laureate Leon Lederman in attendance, a speaker suggested an experiment to search for the third type of neutrino, the tau neutrino. However, as the speaker lamented, it seemed as if no one would perform this type of experiment, "because evidently they only give a Nobel Prize for the detection of every other neutrino." While the room may have burst into laughter, Fred Reines didn't budge.

Regardless, Reines's dedication to understand neutrinos persisted until the end of his life. Shortly before passing, when he heard of the ground-breaking news from Super-Kamiokande that neutrinos oscillate, he astutely asked "What's the mass?", understanding the implications of this result.

The work spearheaded by Reines and his contemporaries has made a lasting impact on the field of particle physics, that continues today. As Cole explains, the subfield of neutrino physics has blossomed to include large, international experimental collaborations, which have found even more unexpected results. Those results have spurred investigators to plan ambitious projects, such as the IceCube experiment in Antarctica, the DUNE experiment in the US, and Hyper-Kamiokande in Japan.

Inspiration

Today's neutrino detectors are getting bigger and bigger. However, their forerunners can still serve a purpose: inspiration. Several detectors from Reines's era are now exhibited, such as the Gargamelle detector at CERN. After discovering the electron neutrino, the race was on to build experiments to better understand neutrino properties, and Gargamelle was one such detector. Today, it is on display at the CERN Microcosm, perhaps inspiring a new generation of neutrino physicists.

Overall, Leonard A Cole's *Chasing the Ghost* will inspire readers, especially those new to thinking about neutrino physics. Fred Reines's work, with its focus on a deep understanding of these mysterious, abundant particles, continues to bear fruit to this day. There is no telling what the next neutrino experiments will uncover, but it's a guarantee that sharp thinkers like Reines will be necessary in this field in the generations to come.

Kevin J Kelly *CERN.*

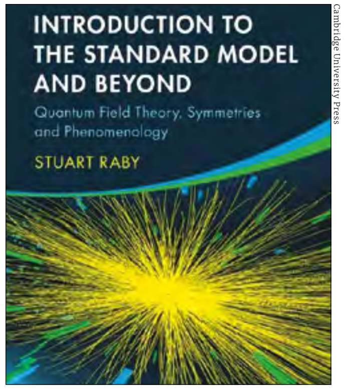
Introduction to the Standard Model and Beyond: Quantum Field Theory, Symmetries and Phenomenology

By Stuart Raby

Cambridge University Press

Stuart Raby has written a modern, comprehensive textbook on quantum field theory, the Standard Model (SM) and its possible extensions. The focus of the book is on symmetries, and it contains a wealth of recent experimental results on Higgs and neutrino physics, which sets it apart from other textbooks addressing the same audience. It is published at a time when the incredible success story of the SM has come to a close with the discovery of the Higgs boson, and when the upcoming neutrino experiments promise to probe beyond-the-SM physics.

Raby is the author of some of the most important papers on supersymmetric grand unified theories and the book reflects that. It is no easy task to cover such a wide range of topics, from the basics of group theory to very advanced concepts such as gauge and gravity-mediated supersymmetry breaking, in one book. Raby devotes 120 pages to the basics of group theory, representations of the Poincaré group and the construction of the S matrix to provide the necessary foundations for the introduction to quantum electrodynamics in part III. Parts IV–VI introduce the reader to discrete symmetries, flavour symmetries and spontaneous symmetry breaking. Next, Raby describes two "Roads to the Standard Model" following the development of quantum chromodynamics and of electroweak theory, before arriving at the SM in part IX. The remaining parts deal with neutrino physics, grand unified theories and the minimal supersymmetric SM.



Cambridge University Press

There are no omissions topic-wise, which makes the book very comprehensive. This comes at a price, however. In several places, complicated topics are discussed with only the most minimal of context, reading like a collection of equations rather than a textbook. Two examples of this are the discussion of causality for fermionic fields or the step from global to local supersymmetry, to which the author devotes only half a page each. In other places, more cross-referencing would improve legibility. For example, the chapter on SU(5) grand unified theory does not mention the automatic cancellation of gauge anomalies, a topic previously introduced in the context of the SM.

The use of materials is very distinctive. I doubt there is another book on the market that presents the reader with such a wealth of plots, figures and sketches, including recent experimental results on all the important topics discussed. The most important plots are reproduced in 12 pages of colour tables in the centre. There are exercises for the first five parts and a single Mathematica notebook is printed for Wigner rotations. Another distinguishing feature are the detailed suggested projects to use during a two-term course based on the book.

A very useful resource for designing a lecture of quantum field theory and beyond-the-SM physics

Although advertised as useful for both theorists and experimentalists, it is undeniably a book written from a theorist's perspective. This becomes most clear in the latter parts, where relevant sections of the plots presenting experimental results remain unexplained. That being said, other very important experimental topics are explained, which you will not find in other textbooks about the SM. Raby explains how the anomalous magnetic moments of the electron and the muon are measured, and goes into quite some detail on neutrino experiments.

The book would benefit from improved editing. For example, the units are sometimes in italics, sometimes not, some equations are double tagged, some plots do not have axes labels, and there is inconsistent use of wavy and curly lines in the Feynman diagrams. Raby does make good use of references though, and points the reader to other textbooks and original literature; although the index needs to be extended significantly to be useful .

I recommend this book for advanced undergraduates, graduate students and lecturers. It provides a very useful resource for designing a lecture of quantum field theory and beyond-the-SM physics, and the amount of material covered is impressive and comprehensive. Beginners might be overwhelmed by Raby's compact style , so I would recommend those who are new to quantum field theory to read a more accessible textbook in parallel.

Martin Bauer *Durham University.*

The A-to-Z of CERN: Universe Unlocked

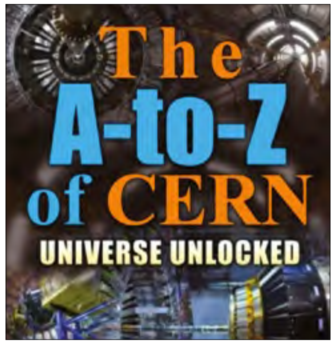
By Archana Sharma, Robin Mathews and Ben Richardson

Shubhi publications

This book by CERN's Archana Sharma and her two students Robin Mathews and Ben Richardson merges the classic A-to-Z formula with CERN concepts, making it suitable for all audiences. Each letter is divided into four categories: physics, accelerator, computing and experiments, allowing the reader to get a good understanding of each area.

All concepts are described in a simple and understandable way, such as antimatter being the same particles of matter with opposite charge. More complex concepts are explained with fun facts to help the reader: the temperature of the quark–gluon plasma is 100,000 times hotter than the centre of the Sun, and the time it takes to record a video call of 1 exabyte is 237,823 years. Each description is accompanied by a photograph, logo or simulation representing the described concept, which makes the book visually attractive for the reader.

An informative, entertaining glossary of CERN and particle physics in general



Shubhi publications

Born at the start of the global pandemic, the A-to-Z of CERN arose from the need to tell science and technology stories at CERN when internships and summer lectures were either limited or cancelled. Overall, it provides an informative and entertaining glossary of CERN and particle physics in general, peppered with some general physics and technology concepts, such as the SI-unit system and even some non-CERN experiments, such as the former ZEUS experiment at DESY.

Bryan Pérez Tapia *editorial assistant.*

PEOPLE CAREERS

You have to be able to explain 'why'

Caltech theorist Sean Carroll describes the pros and cons of a side career as a popular science author and podcaster.

R Porter

Spreading the word *Sean Carroll is a theoretical physicist and science communicator.*

On 4 July 2012, Sean Carroll was at CERN to witness the momentous announcements by ATLAS and CMS – but not in his usual capacity as a physicist. He was there as an accredited member of the media, sharing an overflow room with journalists to get first-hand footage for the final chapter of his book. *The Particle at the End of the Universe* ended up being the first big title on the discovery and went on to win the 2013 Royal Society Science Books Prize. "It got reviewed everywhere, so I am really grateful to the Higgs boson and CERN!"

Carroll's publisher sensed an opportunity for a timely, expert-authored title in 2011, as excitement in ATLAS and CMS grew. He initially said "No" – it wasn't his research area, and he preferred to present a particular point of view, as he did in his first popular work *From Eternity to Here: The Quest for the Ultimate Theory of Time*. "With the Higgs boson, there is no disagreement, he says. "Everyone knows what the boson is, what it does and why is it important." After some negotiation, he received an offer he couldn't refuse. It also delved into the LHC, the experiments and how it all works, with a dash of quantum field theory and particle physics more generally. "We were hoping the book would come out by the time they announced the discovery, but on the other hand at least I got to include the discovery in the book, and was there to see it."

Show me the money

Books are not very lucrative, he says. "Back in the 1980s and 1990s, when the success of Hawking's *A Brief History of Time* awoke the interest of publishers, if you had a good idea for a physics book you could make a million dollars. But it is very hard to earn enough to make a living. "It takes roughly a year, or more depending on how much you have to learn, and depends on luck, the book and the person writing it." His next project is a series of three books aimed at explaining physics to the general reader. The first, *The Biggest Ideas in the Universe: Space, Time and Motion*, due out in September, covers Newtonian mechanics and relativity; the second covers quantum mechanics and quantum field theory, and the third complexity, emergence and large-scale phenomena.

> **We need to take seriously the responsibility to tell people what it is that we have learned about the universe, and why it's exciting to explore further**

Meanwhile, Carroll's podcast *Mindscape*, in which he invites experts from different fields to discuss a range of topics, has produced 200 episodes since it launched in 2018 and attracts around 100,000 listeners weekly. "I thought that it was a very fascinating idea, basically your personal radio show, but I quickly learned that I didn't have that many things to say all by myself," he explains. "Then I realised it would give me an excuse to talk to lot of interesting people and stretch my brain a lot, and that worked out really well."

Reaching out

As someone who fell in love with science at a young age and enjoyed speaking and writing, Carroll has clearly found his ideal career. But stepping outside the confines of research is not without its downsides. "Overall, I think it has been negative actually, as it's hard for some scientists to think that somebody is both writing books and giving talks, and also doing research at the same time. There is a prejudice that if you are a really good researcher then that's all you do, and anything else is a waste of time. But whatever it does to my career, it has been good in many ways, and I think for the field, because I have reached people who wouldn't know about physics otherwise."

Moreover, he says, scientists are obligated to communicate the results of their work. "When it comes to asking the public for lots of money you have to be able to explain why it's needed, and if they understand some of the physics and they have been excited by other discoveries they are much more likely to appreciate that," he says, citing the episode of the Superconducting Super Collider. "When we were trying to build the SSC, physicists were trying their best to explain why we needed it and it didn't work. Big editorials in the *New York Times* clearly revealed that people did not understand the reasons why this was interesting, and furthermore thought that the kind of physics we do does not have any immediate or technological benefit. But they are all also curious like we are. And while we don't all have to become pop-science writers or podcasters (just like I am not going to turn up on Tik Tok or do a demo in the street), as a field we really need to take seriously the responsibility to tell people what it is that we have learned about the universe, and why it's exciting to explore further."

Interview conducted by **Bryan Pérez Tapia** *editorial assistant.*

Appointments and awards

Lia Merminga now leading Fermilab
Accelerator physicist Lia Merminga became the new director of Fermilab on 18 April, succeeding Nigel Lockyer, who announced his departure in September after leading the US lab for the previous eight years. She becomes the seventh director of Fermilab and the first woman to hold this position. Merminga's journey at the laboratory started in 1987 when she joined a graduate programme in accelerator physics, becoming the second student to graduate. She completed her PhD thesis on the Tevatron and went on to serve in several roles and committees, in particular the 2014 Particle Physics Project Prioritization Panel (P5). In 2018 she was appointed director of the Proton Improvement Plan II, part of the 2014 P5 vision, to drive the LBNF/DUNE facility and other experiments. "My goal as Fermilab director is to successfully complete this profound and compelling vision while continuing to deliver groundbreaking science and technology innovation, enable the new P5 strategy, and realise the lab's full potential in workforce development and diversity, lab operations, and in regional, national, and international partnerships."


L Johnson, Fermilab

Taking a lead at DESY
Detector expert Ingrid-Maria Gregor, a DESY physicist and professor at the University of Bonn, has been appointed lead scientist at DESY. A member of the ATLAS collaboration, she previously worked on the HERMES and ZEUS experiments and will take part in the construction of the end caps of the ATLAS silicon-tracker upgrade at DESY in preparation for the High-Luminosity LHC. She is also working on detector R&D for future silicon tracking detectors for particle physics.


I Gregor

Charpak Ritz Prize for Baudis
The 2022 Charpak Ritz Prize has been awarded to Laura Baudis (University of Zurich) for her leadership in international astroparticle physics collaborations, outreach activities and seminal contributions to dark-matter searches. Baudis's work focuses on the search for WIMP dark matter using xenon detectors (*CERN Courier* March 2017 p35). The Charpak Ritz Prize was created in 2016 by the French and Swiss physical societies to commemorate French detector expert Georges Charpak, inventor of the multiwire proportional chamber at CERN, and Swiss theorist Walther Ritz of Rydberg-Ritz-formula fame. It is awarded to physicists who have made significant contributions in France, in odd years, and in Switzerland in even years.


D Auf der Mauer

Guido Altarelli award winners
At the 2022 international workshop on deep-inelastic scattering (DIS2022), held in Santiago de Compostela, Spain from 2–6 May, experimentalist Adi Ashkenazi (below; Tel Aviv University) and theorist Bernhard Mistlberger (below; SLAC) received the 2022 Guido Altarelli Award. Ashkenazi was recognised "for her novel contributions to our understanding of neutrino-nucleus interactions over a wide kinematic range and their impact for precision neutrino oscillations measurements" and Mistlberger "for advancing the frontier of perturbative calculations in QCD to N^{3}LO", respectively. The award was created in 2016 to honour CERN theorist Guido Altarelli.


Shachar/Tel Aviv University


B Mistlberger

ICFA instrumentation
The International Committee for Future Accelerators (ICFA) instrumentation awards were announced during the 15th Pisa meeting on advanced accelerators held in La biodola, Italy, from 22–28 May. The early-career award went to Claudia Nones (CEA) for her leading role in the development of advanced scintillating bolometers for fundamental physic, while Veljko Radeka (below; Brookhaven) received the ICFA instrumentation award for groundbreaking contributions and leadership in the development of advanced low-noise electronics instrumentation in particle physics as well as other fields.


Brookhaven National Laboratory

Dieter Möhl Medal
The 2021 Dieter Möhl Medal, announced during the COOL'21 workshop late last year, has been awarded to four physicists divided in two different categories. Fritz Caspers (CERN) was recognised for his lifetime's work on the development of RF engineering devices for the stochastic cooling systems of the CERN storage rings and worldwide stochastic cooling projects; Alexei Fedotov (Institute of Applied Physics of the RAS) for the successful demonstration of electron cooling of ion beams in a collider with an RF accelerated electron beam; Andreas Wolf (University of Heidelberg) for his pioneering work in the use of low-energy electron coolers in merging electron beams for atomic and molecular physics studies; and Chris Rogers (Rutherford Appleton Laboratory) for the successful demonstration of Muon ionisation cooling on the MICE muon-cooling experiment. The biennial award is sponsored by CERN in memory of the accelerator physicist Dieter Möhl, who worked on its low-energy antiproton programme.

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PEOPLE OBITUARIES

GÉRARD BACHY 1942–2022

A brilliant engineer

Gérard Bachy arrived at CERN in 1967, straight after graduating from ETH Zurich, and spent his entire 35-year career there. He started off as a mechanical engineer with the Big European Bubble Chamber, where he was in charge of the design and manufacture of the expansion system. In 1972 he joined the team of John Adams that was building CERN's new flagship facility, the Super Proton Synchrotron (SPS), taking on responsibility for its coordination and installation. The first protons were injected into the SPS on 3 May 1976. Gérard was then approached by Giorgio Brianti, deputy head of the SPS division, to set up a section in charge of the underground-area infrastructure and installation of the experiments. He formed a motivated team where new ideas thrived and were put into practice – including a bicycle-driven system for moving detector components weighing several dozen tonnes using air cushions.


CERN-040-6-1991

Gérard Bachy played a key role in the LEP project.

In 1981, when the huge Large Electron-Positron (LEP) collider project was taking shape, Gérard and his team were brought in by director-in-charge Emilio Picasso. They were soon merged with the engineering group to become the LEP–IM group, which went on to play a key role in the realisation of LEP. More innovations were in store to solve the many challenges associated with this project: modular access shafts; a monorail to facilitate the installation of various components; highly precise planning, logistics and others. The project moved fast, culminating in the start-up of LEP on 14 July 1989.

The engineering for the accelerators was spread across the various CERN divisions, which hampered efficiency. In 1990, Director-General Carlo Rubbia entrusted Gérard with bringing all the different activities together under one umbrella, and the mechanical technologies division was born. Over the next five years, the focus was on modernising the facilities, infrastructures and working methods, first for the LEP200 project and then for the LHC preparations. Gérard fostered the development of the engineering and equipment data-management service, encouraged the creation of quality assurance plans and promoted a project-management culture.

In 1996, Hans Hoffmann, the technical coordinator for ATLAS, appointed Gérard as project engineer in his technical coordination and integration team. Gérard's experience was to have a big impact on important technical choices, such as the "large wheel" concept for the ATLAS muon spectrometer. He retired in June 2001 to be able to devote more time to his other great passions, sailing and travel.

Gérard Bachy was a brilliant engineer and a charismatic leader. He played an undisputed role at the top level of engineering at CERN and acted as a mentor for many of us.

His friends and former colleagues.

JEAN-CHARLES CHOLLET 1938–2021

Precision and subtlety

Experimental particle physicist Jean-Charles (Charlie) Chollet passed away on 24 August 2021. He had spent his whole scientific career at CERN, working as a member of the Orsay Laboratoire de l'Accélérateur Linéaire. His work was always in the area of precision measurements involving subtle analyses.


L Fayard

Chollet worked on experiments from the PS to the LHC.

Charlie started at the CERN Proton Synchrotron with his thesis, defended in 1969 under the supervision of Jean-Marc Gaillard, on the observation of the interference between K_L and K_S in the $\pi^0\pi^0$ decay mode. He then contributed to the WA2 experiment at the Super Proton Synchrotron (SPS) studying leptonic decays of hyperons, where he took care of one of the most difficult components of the detector, the DISC Cherenkov counter, which led to the impressive achievement of separating ~200 GeV/c Σ^- and Ξ^- hyperons thanks to a combination of subtle optics and of a complex system of photodetection. He then participated in the UA2 experiment at the SPS $p\bar{p}$ collider, where he was in charge of the preshower detector calibration and performance.

Later he engaged himself in the preparation of the ATLAS experiment at the LHC, where he performed several studies, notably on the pileup background properties and their expected impact on the design of the liquid-argon calorimeter electronics. He also participated in test-beam analysis of early "accordion calorimeters", prototypes of this same calorimeter. He ended his career at the NA48 experiment, which was measuring the direct CP violation parameter ε'/ε in neutral kaon decays and where he made an important contribution with the analysis of kaon scattering in the collimator. From small inconsistencies in the data, he managed to find and understand the source of this background, thereby allowing it to be precisely taken into account in the measurement.

He was a great sportsman, especially sailing, skiing and cycling. Those who worked with Jean-Charles Chollet will always remember the pleasure of his company, his dry sense of humour and the depth and refinement of his work, which was always presented with the utmost modesty.

His friends and colleagues.

Tom Cormier 1947–2022

A heavy-ion inspiration

Long-time ALICE collaborator and authority in relativistic heavy-ion physics, Tom Cormier, passed away on 23 March after a brief illness. Tom was born in 1947 in Lexington, a suburb of Boston. After high school he went to MIT where he did both his undergraduate and graduate studies. He was an amazing physicist with a strong drive to explore the frontiers of relativistic nuclear physics, and a profound understanding of the field that enabled him to build the best tools to take us to those frontiers.

After obtaining his PhD from MIT in 1974, Tom took up postdoc positions at Stony Brook and the Max Planck Institute. He then joined the University of Rochester, where he later became director of the Nuclear Structure Research Laboratory. In 1988 he moved to the Cyclotron Institute at Texas A&M University where he stayed for three years. Wayne State University was his next move, where he was chair of the physics and astronomy department. Tom joined the ORNL Physics Division in 2013, and reinvigorated the relativistic nuclear physics group and expanded ORNL's very successful involvement in the ALICE experiment at the LHC, sPHENIX at RHIC and most recently in the Electron–Ion Collider (EIC) under construction at Brookhaven.

J Richards/ORNL

Cormier helped bring US heavy-ion physicists to the LHC.

Tom's work spanned an amazing breadth of physics and technology. Early on he worked on carbon–carbon inelastic scattering and scattering resonances; he then moved to experiments with recoil mass spectrometers at Brookhaven. Tom shifted his focus to relativistic heavy-ion physics with the AGS-E864 experiment at Brookhaven, followed by the STAR experiment at RHIC. He was the project manager for the construction of the STAR electromagnetic calorimeter and worked on the experiment from 1996 to 2005.

Tom was one of the key scientists enabling the US heavy-ion community to join the LHC by proposing the large electromagnetic calorimeter EMCAL for ALICE and by forming the ALICE US collaboration. He was project manager for ALICE US, with a key responsibility for EMCAL and its later extension, the di-jet calorimeter, DCAL. Having successfully completed this project, he took on the leadership of the barrel tracker upgrade for ALICE. He was an architect of the TPC upgrade and was TPC deputy project leader from 2013. His true leadership and professionalism have been central to the success of ALICE in the past two decades. Tom most recently helped form the ECCE detector concept for the EIC.

Both a great leader and project manager, Tom was a real inspiration, not only to his close colleagues but also to the broader community that held him in such high regard. He has been a wonderful mentor to many of us, and his contributions to the global physics programme, and to the ORNL physics division in particular, have been immense. He was an expert navigator of the various funding agencies and always showed immense calm during numerous DOE reviews, his dry sense of humour reflected in one of his memorable quips: "If I would wear a suit today, the DOE would be sure we screwed up badly." He will be sorely missed but his legacy will remain.

His friends and colleagues.

Alberto Sirlin 1930–2022

Electroweak pioneer

Theorist Alberto Sirlin, a pioneer in electroweak radiative corrections, passed away on 23 February aged 91. His work played a key role in confirming predictions of the Standard Model (SM) at the ±0.1% level. He was a professor at New York University for 62 years, mentored 14 PhD students and remained an active researcher until shortly before his death.

Born in Buenos Aires in 1930, Alberto received a physics and mathematics degree from the University of Buenos Aires in 1953. That year he went to Brazil where he took a quantum mechanics course taught by Richard Feynman. In a 2015 essay "Remembering a Great Teacher", Alberto fondly recalled that experience and the enduring friendship that followed. In 1954 he travelled to UCLA and collaborated with Ralph Behrends and Robert Finkelstein on an early study of QED radiative corrections to muon decay in Fermi's general theory of weak interactions. Alberto then moved to graduate school at Cornell University, where he collaborated with Toichiro Kinoshita on the QED corrections to muon and nuclear beta decays in the V–A Fermi theory. Their investigation showed that QED corrections increased the muon lifetime by about 0.4% – an effect still used to define the Fermi constant. For nuclear beta decay, where QED effects were logarithmically dependent on an arbitrary cutoff scale, Alberto would later show how electroweak unification determines this scale. After Cornell he spent two years (1957–1959) as a postdoc at Columbia University, supervised by T D Lee, before joining the faculty of New York University. He also held visiting appointments at BNL, CERN, Hamburg University, Rockefeller University and The Institute for Advanced Study.

NYU

Sirlin excelled in electroweak loop calculations.

When the SM came together in the early 1970s, Alberto's early work on QED corrections to weak-interaction processes uniquely prepared him for a leading role in computing electroweak quantum loop corrections. For example, he showed how additional loop corrections involving W and Z bosons led to a replacement of the logarithmic cutoff found in semi-leptonic beta decays by the Z-boson mass, resulting in a ~2% increase for all semi-leptonic charged-current decay rates. This is essential for unitarity tests of the quark mixing matrix, and confirms the validity of the SM at more than 20σ!

In a 1980 paper that has been cited more than 1400 times, Alberto introduced the on-shell renormalisation scheme based on physical parameters and the quantity Δr, which encodes the radiative effects. This scheme has been used to study deep-inelastic neutrino–nucleus scattering, neutrino–electron scattering, atomic parity violation, polarised electron–electron scattering asymmetries, W&Z precise mass predictions, and more, not only by Alberto and his former students and collaborators, but by the entire particle-physics community in searches for new-physics effects. Together with his former student William Marciano, he won the 2002 J J Sakurai prize of the American Physical Society for their pioneering work on radiative corrections.

In witnessing the rise and then completion of the SM with the discovery of the Higgs boson in 2012, Alberto was able to enjoy the fruits of his labour. We, his students, have been inspired by Alberto's dedication and enthusiasm. We are grateful that we could join his journey through life and physics. He was our great teacher.

Giuseppe Degrassi, **William J Marciano** *and* **Massimo Passera** *on behalf of* **Alberto's students, colleagues and friends**.

BACKGROUND

years HIGGS boson discovery

Notes and observations from the high-energy physics community

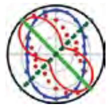
Get on board Higgs@10

The international particle-physics community is celebrating the collective achievement of the 2012 discovery of the Higgs boson. On 9 June the Interactions collaboration launched **Higgs10.org** to gather events and stories – including a limited reprise of the *Quantum Diaries* blog site – culminating in an online anniversary celebration on 4 July. The centre-piece of the Higgs@10 celebrations is a full-day scientific symposium in CERN's main auditorium on 4 July exploring the past, present and future of the Higgs boson. Public screenings of *Particle Fever* are taking place at several locations around CERN, and events ranging from science cafés to lunchtime exhibits for decision-makers are being prepared throughout CERN's member states and at partner laboratories worldwide.

Approximate number of Higgs bosons identified at the LHC so far: around 33,000 from ATLAS and 37,000 from CMS

70,000

Tabletop Higgs?



The existence in superconducting materials of composite analogues of the Higgs boson has been known for some 40 years. In *Nature* on 8 June a US team reported the first detection of what they call an "axial Higgs mode" – a subtle axial-vector excitation mode (illustrated left) in a two-dimensional rare-earth system that was revealed using lasers, not colliders. "It's not every day you find a new particle sitting on your tabletop," said lead researcher Kenneth Burch of Boston College. Particle physicists were quick to concur, noting the difference between phenomena arising from condensed matter's admixtures and from fundamental particle fields. "The material being used is intrinsically composite, so I am not sure how this explores a fundamental question in high-energy physics," wrote CERN's André David on Twitter. John Ellis of King's College London adds: "Key signatures of composite models of the high-energy physics Higgs boson would be additional related particles, but none has been seen so far."

Higgs-trivia tickler

This snakes-and-ladders-themed tea tray is one of the more unusual appearances of the Higgs boson in broader culture. But where, when and why was this object produced? A mystery prize awaits the first correct answer.

Correction

It was, of course, Gargamelle that revealed the existence of the neutral current, not the Big European Bubble Chamber as stated (*CERN Courier* May/June 2022 p65). Both detectors are exhibits in the CERN Microcosm garden.

From the archive: March 1977

Gauge theory predictions and muon decay

One of the 3.4 m scintillator light guides being built by the European Muon Collaboration experiment.

In his talk at the Chicago Meeting of the APS in February, Steve Weinberg reviewed gauge field theories and their experimental implications, including the breakdown of muon conservation. The gauge theories have had dramatic success in explaining the discoveries of recent years, beginning with the observation of the neutral current type of weak interaction at CERN in 1973 and then with the 'new physics' following the J/psi discovery at Brookhaven and Stanford at the end of 1974. The theories make predictions about what will be found when higher energies become available. For example, they set the masses of the carriers of the weak force, the intermediate vector bosons – the charged version, W, is predicted at about 65 GeV and the neutral version, Z, at about 80 GeV. The search for these particles is one of the main motivations for the higher energy facilities, such as proton–antiproton colliding beams, which are now being mooted.

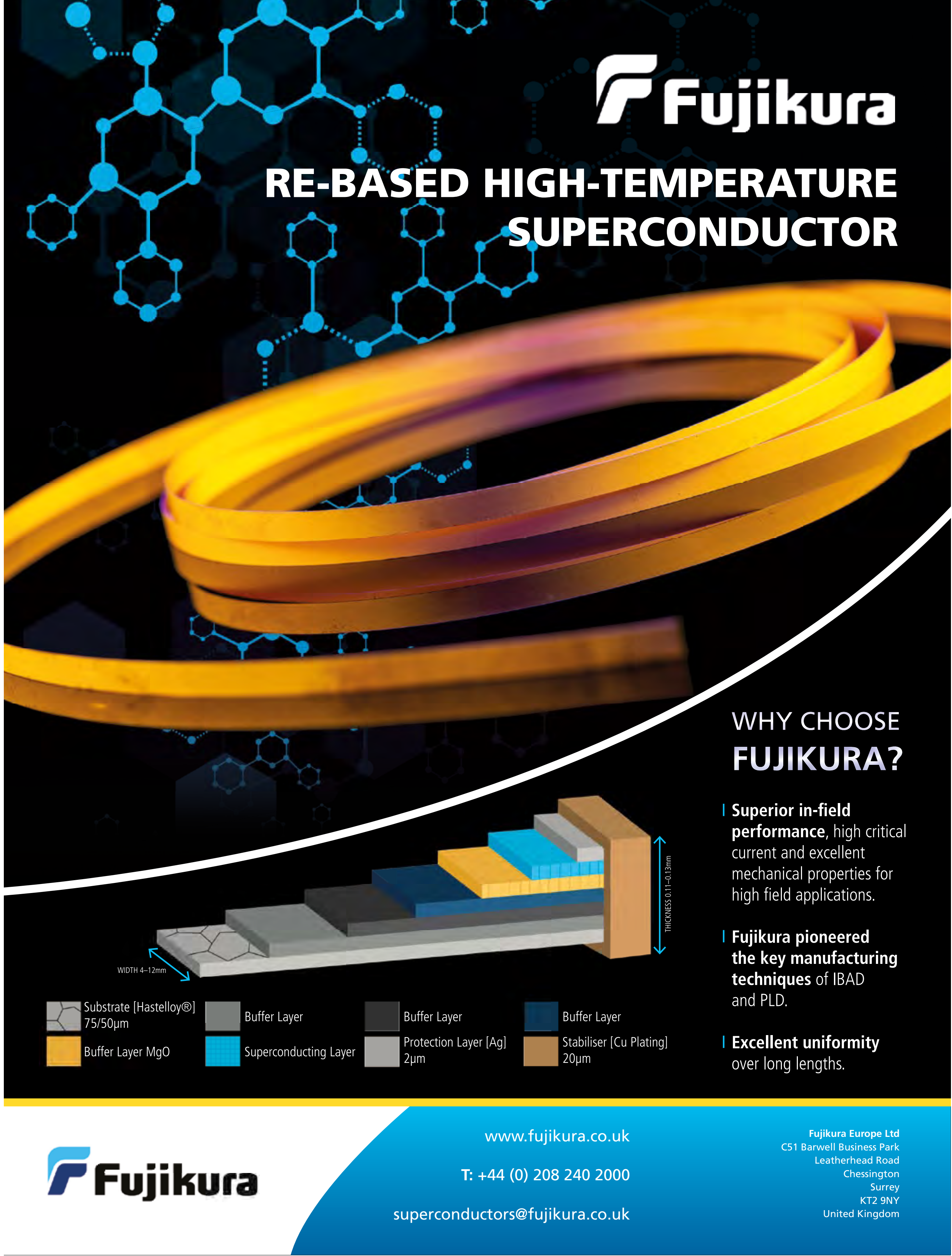
The theories also postulate a set of scalar particles in a similar mass range. Such scalar particles were considered by Peter Higgs in 1964 and are usually referred to as the Higgs bosons. He was following up a 1960 paper of Y Nambu, which carried spontaneous symmetry breaking from statistics into particle physics and on subsequent work by Jeffrey Goldstone (with Salam and Weinberg) that predicted mass-less particles called 'Goldstone bosons', which were not seen. Higgs showed that Goldstone bosons would not be a consequence of the Nambu ideas if gauge theory was used and if integral spin particles were involved. These are the postulated Higgs bosons responsible for spontaneous symmetry breaking.

If Higgs bosons exist, they will affect particle behaviour at all energies. However, their postulated interactions are even weaker than the normal weak interactions. The effects would only be observable on a very small scale and would usually be drowned out by the stronger interactions. Even if the 'forbidden' muon decay does not appear at the energies available in current experiments, Weinberg has enough confidence in the Higgs bosons to believe that it will be seen some day.

- Based on text from p51 of *CERN Courier* March 1977.

Compiler's note

In covering Weinberg's talk on the occasion of the award of the 1977 Dannie Heineman Prize for Mathematical Physics, this article was the first time "Higgs boson" appeared in the Courier*. Weinberg's confidence in the Higgs boson was well founded. While neither the neutron electric dipole moment nor the muon decay into an electron and a photon has been observed, searches instigated at the Swiss Institute for Nuclear Research 40 years ago continue at the Paul Scherrer Institute and elsewhere.*



CAEN
Tools for Discovery

Celebrates the Higgs Discovery 10th anniversary

LHC and CAEN, a new adventure begins

At the dawn of LHC, CAEN started an ambitious R&D program to design and build a new generation of products capable to cope with the demanding conditions of the new hadron collider, after a deep collaboration with researchers a solution was found.

By the startup of the LHC more than 7000 modules were built in many different variants to satisfy all experimental needs.

CAEN has received the "CMS Crystal Award of the year 2009" for the development and production of the power system for the CMS Tracker.

Higgs Boson discovery

After 10 years from the original design and 4 years of continuous operations with excellent performance the experiments to recorded data enough data to announce to the World the discovery of the Higgs boson July 4th, 2012. CAEN materialized its promise to provide *Tools for Discovery* to physicists and researchers Worldwide.

HL-LHC and future works

High Luminosity LHC is the next step of LHC, with almost double luminosity it will run for another 15 years. The increased collisions rate will pose a serious threat to electronics, to be able to operate in the new conditions CAEN accepted the challenge: to provide the next generation of *Tools for Discovery.*

CAEN spa
Viareggio • Italy Headquarters

www.caen.it
*Small details… **Great differences***

Background photo by Arpad Horvath/CERN; photos of the experiments are © CERN; Nobel Prize in meddle hexagon by Maximilien Brice/CERN; Photo on the bottom page DENIS BALIBOUSE/AFP/GettyImages.