WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2023 issue of *CERN Courier*.

Meet "the python" – one of eight 60 m-long high-temperature superconducting links to power new magnets for the High-Luminosity LHC. Developed at CERN via a multi-disciplinary approach and in collaboration with industry, the technology has also been used to demonstrate record power-transmission capability for electricity grids, and is being explored for use in electric aircraft.

This year's Recontres de Moriond saw the announcement of the first collider neutrinos (p9), improved measurements of the W mass (p10), new limits on Majorana neutrinos (p9), ever tighter constraints on the properties of dark matter (p15), and much more. While the Standard Model stands strong, ingenious new ways to go beyond it include searches at CERN's NA62 experiment operating in "beam-dump" mode (p11). This issue also marks 60 years since Cabibbo's seminal paper on quark mixing (p43), and 50 years since Kobayashi and Maskawa generalised the description of quark mixing to three generations (p23).

Muons for cultural heritage (p32) and colliders (p47), a new user facility for plasma acceleration (p25), CERN's Science Gateway (p49) and "exotic naturalness" (p21) are further highlights, as high-energy collisions recommence at LHC Run 3 (p8).

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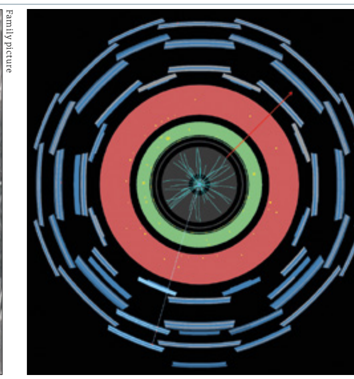

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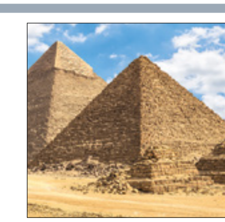

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FROM THE EDITOR

High-T innovation for physics and society

Matthew Chalmers
Editor

Superconductivity is a striking manifestation of quantum mechanics on an everyday scale. A consequence of the spontaneous breaking of electromagnetic gauge invariance, its understanding also laid the foundations for the Brout–Englert–Higgs mechanism. Where particle physics and superconductivity are most deeply entwined – quite literally – is advanced accelerator magnets, which allow higher-energy beams to circulate in colliders. The LHC is the largest superconducting machine ever built. It is also the first to employ high-temperature superconductors, discovered in 1986, on a large scale – used in more than 1000 current leads that transfer millions of amperes generated at room temperature in and out of the LHC magnets' cryogenic environment.

This issue's cover feature by Amalia Ballarino of CERN, who has pioneered the development of advanced superconducting systems, describes unique R&D on high-temperature superconductors for the High-Luminosity LHC (p37). Whereas the LHC's current leads are built from bismuth–strontium–calcium copper oxide ceramic, the HL-LHC will also use magnesium diboride, which in 2001 was discovered to become superconducting at 39 K, some 30 K higher than the niobium titanium used in the LHC magnets. In a further high-temperature innovation, rare-earth barium copper oxide is being incorporated into the HL-LHC superconducting links.

Turning high-temperature superconductors into robust cables for practical devices is no mean feat, and a shining example of how accelerator technology for fundamental exploration is driving innovation that could have a wider impact on society.

The skills and knowledge accrued at CERN for the HL-LHC superconducting links, developed via a multi-disciplinary approach and in collaboration with industry, have already been used to demonstrate record power-transmission capability for electricity grids in the context of the European Union project Best Paths. Last year, CERN entered a project with Airbus UpNext to explore superconducting distribution in aircraft, while a collaboration agreement with Meta is under discussion regarding the potential of superconducting-link technology in large data centres.

Turning high-temperature superconductors into practical devices is no mean feat

Flourishing *A magnesium diboride cable, 19 of which are twisted together inside a compact, flexible cryostat to provide one of eight superconducting links powering the HL-LHC magnets.*

This year's Rencontres de Moriond saw the announcement of the first collider neutrinos (p9), improved measurements of the W mass (p10), new results on Majorana neutrinos (p9), ever tighter limits on the properties of dark matter (p15), and more. While the Standard Model stands strong, ingenious new ways to go beyond it include searches at NA62 in beam-dump mode (p11). This issue also marks 60 years since Cabibbo's seminal paper on quark mixing (p43), and 50 years since Kobayashi and Maskawa generalised mixing to three generations (p23). Muography for cultural heritage (p32), a new user facility for plasma acceleration (p25), CERN's Science Gateway (p49) and "exotic naturalness" (p21) are further highlights.

Concerning the future of the field, muon colliders are back in vogue (p47). Proposals emerging from the Snowmass exercise suggest that a 3 TeV facility built in the US could begin in the mid 2040s, followed by a possible 10 TeV stage a decade or so later – a not too wildly dissimilar timeline to that of the proposed Future Circular Collider based on a more established approach. Whichever collider follows the LHC, next-generation superconductors are sure to play a major role.

Reporting on international high-energy physics

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NEWS ANALYSIS

Cosmology

Euclid to link the largest and smallest scales

Untangling the evolution of the universe, in particular the nature of dark energy and dark matter, is a central challenge of modern physics. An ambitious new mission from the European Space Agency (ESA) called Euclid is preparing to investigate the expansion history of the universe and the growth of cosmic structures over the last 10 billion years, covering the entire period over which dark energy is thought to have played a significant role in the accelerating expansion. The 2 tonne, 4.5 m tall and 3.1 m diameter probe is undergoing final tests in Cannes, France, after which it will be shipped to Cape Canaveral in Florida and inserted into the faring of a SpaceX Falcon 9 rocket, with launch scheduled for July.

Let there be light

Euclid, which was selected by ESA for implementation in 2012 with a budget of about €600 million, has four main objectives. The first is to investigate whether dark energy is real, or whether the apparent acceleration of the universe is caused by a breakdown of general relativity on the largest scales. Second, if dark energy is real, Euclid will investigate whether it is a constant energy spread across space or a new force of nature that evolves with the expansion of the universe. A third objective is to investigate the nature of dark matter, the mass of neutrinos and whether there exist other, so-far undetected fast-moving particle species, and a fourth is to investigate statistics and properties of the early universe that seeded large-scale structures. To meet these goals, the six-year Euclid mission will use a three-mirror system to direct light from up to a billion galaxies across more than a third of the sky towards a visual imager for photometry and a near-infrared spectrophotometer.

So far, the best constraints on the geometry and expansion history of the universe come from cosmic-microwave background (CMB) surveys. Yet these missions are not the best tracers of the curvature, neutrino masses and expansion history, nor for identifying possible exotic subcomponents of dark matter. For this, large surveys on galaxy clustering are required. Euclid will use three methods to achieve this. The first is redshift-space distortions, which combines how fast galaxies move away from us due to the expansion of the universe and how fast galaxies move towards a region of strong gravitational pull in our line-of-sight; measuring these deformations in galactic positions enables the growth rate of structures as well as gravity to be investigated. The second is baryonic acoustic oscillations (BAOs), which arose when the universe was a plasma made from baryons and photons and set a characteristic scale that is related to the sound horizon at recombination. After recombination, photons decoupled from visible matter while baryons were pulled in by gravity and started to form bigger structures, with the BAO scale imprinted in galaxy distributions. BAOs thus serve as a ruler to trace the expansion rate of the universe. The third method, weak gravitational lensing, occurs when light from a background source is bent around a massive foreground object such as a galaxy cluster, from which the distribution of dark matter can be inferred.

ESA/S Corvaja

Counting down *The Euclid payload module at Thales Alenia Space in Cannes, where assembly and testing is taking place ahead of a scheduled launch in July.*

As the breadth and precision of cosmological measurements increase, so do the links with particle physics. CERN and the Euclid Consortium (which consists of more than 2000 scientists from 300 institutes in 13 European countries, the US, Canada and Japan) signed a memorandum of understanding in 2016 after Euclid gained CERN recognised-experiment status in 2015. The collaboration was motivated by technical synergies for the mission's Science Ground Segment (SGS), which will process about 850 Gbit of compressed data per day – the largest of any ESA mission to date. CERN is contributing with the provision of critical software tools and related support activities, explains CERN aerospace and environmental applications coordinator Enrico Chesta: "CernVM-FS, developed by the EP-SFT team to assist high-energy physics collaborations to deploy software on the distributed computing infrastructure used to run data-processing applications, has been integrated into Euclid SGS and will be used for software continuous deployment among the nine Euclid science data centres."

Competitive survey

Euclid's main scientific objectives also align closely with CERN's physics challenges. A 2019 CERN-TH/Euclid workshop identified overlapping areas of interest and options for scientific visitor programmes, with topics of potential interest including N-body CMB simulations, redshift space distortions with relativistic effects, model selection of modified gravity, and dark-energy and neutrino-mass estimation from cosmic voids. Over the coming years, Euclid will provide researchers with data against which they can test different cosmological models. "Galaxy surveys have been happening for decades and have grown in scale, but we didn't hear much about it because the CMB was, until now, more accurate," says theorist Marko Simonović of CERN. "With Euclid there will be a competitive survey that is big enough to be comparable to CMB data. It is exciting to see what Euclid, and other new missions such as DESI, will tell us about cosmology. And maybe we will even discover something new."

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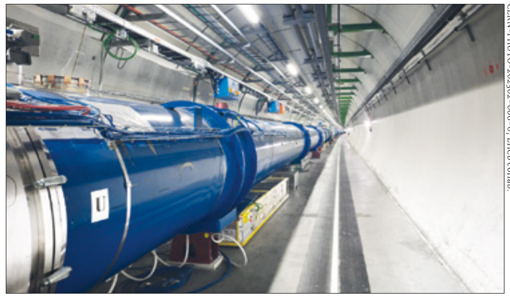
CERN

Back to life: LHC Run 3 recommences

Following its year-end technical stop (YETS) beginning on 28 November 2022, the LHC is springing back to life to continue Run 3 operations at the energy frontier. The restart process began on 13 February with the beam commissioning of Linac4, which was upgraded during the technical stop to allow a 30% increase in the peak current, to be taken advantage of in future runs. On 3 March the Proton Synchrotron Booster began beam commissioning, followed by the Proton Synchrotron (PS).

In the early hours of 17 March, the PS sent protons down the transfer lines to the door of the Super Proton Synchrotron (SPS), and the meticulous process of adjusting the thousands of machine parameters began. Following a rigorous beam-based realignment campaign, and a brief interruption to allow transport and metrology experts to move selected magnets, sometimes by only a fraction of a millimetre, SPS operators re-injected the beam and quantified and validated the orbit correction ready for injection into the LHC. Right on schedule, on 28 March the first beams successfully entered the LHC. Thanks to very fast threading, both beams were circulating the same day, even producing first "splash" events in the detectors. As the *Courier* went to press, the intensity ramp-up was under way. Collisions in the LHC are expected to commence by the end of April, heralding the start of a relatively short but intense physics run that is scheduled to end on 30 October.



Closed for business *The LHC tunnel in February 2023 (top), and half of the LHCb upstream tracker (the final experiment upgrade for Run 3) being lifted over the detector to be put into place.*

Refinements

Among many improvements to the accelerator complex made during the YETS, four modules in the SPS kicker system were upgraded to reduce the amount of heat deposited by the beam, and new instruments were installed in the LHC tunnel. These include the beam gas curtain, which will provide 2D images of the alignment of the beams to make data-taking more precise. Ten years in the making, the device was designed for the high-luminosity upgrade of the LHC (HL-LHC) as part of a collaboration between CERN, Liverpool University, the Cockcroft Institute and GSI.

"It's a challenging year ahead, with the 2023 run length reduced by 20% for energy cost reasons," says Rende Steerenberg, head of the operations group. "But we maintain the integrated-luminosity goal of 75 fb^{-1} by enhancing the beam performance and maximising beam availability."

To cope with the higher luminosities during Run 3, and to prepare for a further luminosity leap at the HL-LHC beginning in 2029, many upgrades to the four main LHC experiments took place during Long Shutdown 2 (LS2) from 2019 to 2022. While the bulk of HL-LHC upgrades for ATLAS and CMS will take place during LS3, beginning in 2026, the ALICE and LHCb detectors underwent significant transformations during LS2. In the final weeks leading to the LHC restart, the LHCb collaboration completed the last element of its Upgrade 1 – the upstream tracker.

This advanced silicon-strip detector, located at the entrance of the LHCb bending magnet, allows fast determination of track momenta. This speeds up the LHCb trigger by a factor of three, which is vital to operate the newly installed 40 MHz fully software-based trigger. The new tracker will also improve the reconstruction efficiency of long-lived particles that decay after the vertex locator (VELO), and will provide better coverage overall, especially in the very forward regions. It is composed of 968 silicon-hybrid modules arranged in four vertical planes to handle the varying occupancy over the detector acceptance. A dedicated front-end ASIC, the "SALT chip", provides pulse shaping with fast baseline restoration and digitisation, while nearby detector electronics implement the transformation to optical signals that are transmitted to the remote data-acquisition system in LHCb's new data centre. Institutes from the US, Italy, Switzerland, Poland and China were involved in designing, building and testing the upstream tracker. Assembly began in 2021 and intensive work took place underground throughout the recent YETS, so the device installation was successfully completed by cavern closure on 27 March.

Under pressure

However, earlier in the year, there was an incident that affected another LHCb subdetector, the VELO. This occurred on 10 January, when there was a loss of control of the LHC primary vacuum system at the interface with the VELO. At the time, the primary and secondary vacuum volumes were filled with neon as the installation of the upstream tracker was taking place. A failure in one of the relays in the overpressure safety system not only prevented the safety system from triggering at the appropriate time, but also led to an issue with the power supply that supports some of the machine instrumentation, causing the pressure balancing system to mistakenly pump on the primary volume. The subsequent pressure build-up went beyond specification limits and led to a plastic deformation of the mechanical interface – an ultrathin aluminium shield called the "RF box" – between the LHC and detector volumes. The RF box is mechanically linked to the VELO and a change in its shape affects the degree to which the VELO can be moved and centred around the colliding beams.

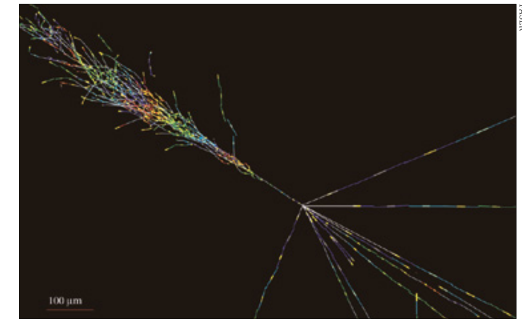
To minimise any risk of impact on the other LHC experiments, the LHCb collaboration will wait until this year's YETS to replace the RF box. In the meantime, the collaboration has been developing ways to mitigate the impact on data-taking, explains LHCb spokesperson Chris Parkes of the University of Manchester: "Initially we were very concerned that the VELO could have been damaged, but fortunately this is not the case. After much careful recovery work, we will be able to operate the system in 2023, and after the RF box is replaced, we will be back to full performance."

Neutrinos

First collider neutrinos detected

Since their discovery 67 years ago, neutrinos from a range of sources – solar, atmospheric, reactor, geological, accelerator and astrophysical – have provided ever more powerful probes of nature. Although neutrinos are also produced abundantly in colliders, until now no neutrinos produced in such a way had been detected, their presence inferred instead via missing energy and momentum.

A new LHC experiment called FASER, which entered operations at the start of Run 3 last year, has changed this picture with the first observation of collider neutrinos. Announcing the result on 19 March at the Rencontres de Moriond, and in a paper submitted to *Physical Review Letters* on 24 March, the FASER collaboration reconstructed 153 candidate muon neutrino and antineutrino interactions in its spectrometer with a significance of 16 standard deviations above the background-only hypothesis. Being consistent with the characteristics expected from neutrino interactions in terms of secondary-particle production and spatial distribution, the results imply the observation of both neutrinos and antineutrinos with an incident neutrino energy significantly above 200 GeV. In addition, an ongoing analysis of data from an emulsion/tungsten subdetector called FASERν revealed a first electron–neutrino interaction candidate (see image above).



New source *A candidate high-energy electron neutrino charged-current interaction recorded by FASERν, with the electron shower (left of the image) balanced by several charged particle tracks (right).*

"FASER has directly observed the interactions of neutrinos produced at a collider for the first time," explains co-spokesperson Jamie Boyd of CERN. "This result shows the detector worked perfectly in 2022 and opens the door for many important future studies with high-energy neutrinos at the LHC."

The extreme luminosity of proton–proton collisions at the LHC produces a large neutrino flux in the forward direction, with energies leading to cross-sections high enough for neutrinos to be detected using a compact apparatus. FASER is one of two new forward experiments situated at either side of LHC Point 1 to detect neutrinos produced in proton–proton collisions in ATLAS. The other, SND@LHC, also reported its first results at Moriond. The team found eight muon–neutrino candidate events against an expected background of 0.2, with an evaluation of systematic uncertainties ongoing.

Covering energies between a few hundred GeV and several TeV, FASER and SND@LHC narrow the gap between fixed-target and astrophysical neutrinos. One of the unexplored physics topics to which they will contribute is the study of high-energy neutrinos from astrophysical sources. Since the production mechanism and energy of neutrinos at the LHC is similar to that of very-high-energy neutrinos from cosmic-ray collisions with the atmosphere, FASER and SND@LHC can be used to precisely estimate this background. Another application is to measure and compare the production rate of all three types of neutrinos, providing an important test of the Standard Model.

Beyond neutrinos, the two experiments open new searches for feebly interacting particles and other new physics. In a separate analysis, FASER presented first results from a search for dark photons decaying to an electron–positron pair. No events were seen in an almost background-free analysis, yielding new constraints on dark photons with couplings of 10^{-5} to 10^{-4} and masses of between 10 and 100 MeV, in a region of parameter space motivated by dark matter.

Further reading

FASER Collab. 2023 arXiv:2303.14185.
FASER Collab. 2023 CERN-FASER-CONF-2023-001.

Majorana neutrinos remain at large

Neutrinoless double-beta decay (0νββ) remains as elusive as ever, following publication of the final results from the Majorana Demonstrator experiment at SURF, South Dakota, in February. Based on six years' monitoring of ultrapure ^{76}Ge crystals, corresponding to an exposure of 64.5 kg × yr, the collaboration has confirmed that the half-life of 0νββ in this isotope is greater than 8.3×10^{25} years. This translates to an upper limit of an effective neutrino mass $m_{ββ}$ of 113–269 meV, and complements a number of other 0νββ experiments that have recently concluded data-taking.

High resolution *Germanium cells in the Majorana Demonstrator cryostat, some of which were exchanged with tantalum to search for dark matter in the decay of metastable tantalum-180.*

Whereas double-beta decay is known to occur in several nuclides, its neutrinoless counterpart is forbidden by the Standard Model. That's because it involves the simultaneous decay of two neutrons into two protons with the emission of two electrons and no neutrinos, which is only possible if neutrinos and antineutrinos are identical "Majorana" particles such that the two neutrinos from the decay cancel each other out. Such a process would violate lepton-number conservation, possibly playing a role in the matter–antimatter asymmetry in the universe, and be a direct sign of new physics. The discovery that neutrinos have mass, which is a necessary condition for them to be Majorana particles, motivated experiments worldwide to search for 0νββ in a variety of candidate nuclei.

Germanium-based detectors have an excellent energy resolution, which is key to be able to resolve the energy of ▷

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the electrons emitted in potential 0νββ decays. The Majorana Demonstrator is also located 1.5 km underground, with low-noise electronics and ultrapure in-house-grown electroformed copper surrounding the detectors to shield it from background events. Despite a lower exposure, the collaboration was able to achieve similar limits to the GERDA experiment at Gran Sasso National Laboratory, which set a lower limit on the ^{76}Ge 0νββ half-life of 1.8×10^{26} yr. Also among the projects of the collaboration is an ongoing search for the influence of dark-matter particles in the decay of metastable ^{180m}Ta – nature's rarest isotope. Although no hints have been found so far, the search has already improved the sensitivity of dark-matter searches in nuclei significantly.

Other experiments, such as KamLAND-ZEN and EXO-200, use ^{136}Xe to search for 0νββ. While the former recently set the most stringent limit of 2.3×10^{26} yr and is ongoing, the latter arrived at a value of 3.5×10^{25} yr with a total ^{136}Xe exposure of 234.1 kg×yr based on its full dataset. Searches at Gran Sasso with CUORE using 1t×yr exposure of ^{130}Te led to a half-life of 2.2×10^{25} yr and at CUORE's successor, CUPID-0, which used ^{82}Se with a total exposure of 8.82 kg×yr, of the order 10^{23} yr.

The search has already improved the sensitivity of dark-matter searches in nuclei significantly

Having demonstrated the required sensitivity for 0νββ detection in ^{76}Ge, the designs of Majorana Demonstrator and GERDA have been incorporated into the next-generation experiment LEGEND-200, which uses high-purity germanium detectors surrounded by liquid argon. The experiment, based at Gran Sasso, started operations last spring and could have initial results later this year, says co-spokesperson Steven Elliott (LANL): "Once all the detectors are installed, we plan to run for five years, while the next stage, LEGEND-1000, is proceeding through the DOE Critical Decision process. We hope to begin construction in summer 2026, with first data available early next decade."

Further reading

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GERDA Collab. 2020 *Phys. Rev. Lett.* **123** 252502.
KamLAND-Zen Collab. 2023 *Phys. Rev. Lett.* **130** 051801.
EXO-200 Collab. 2019 *Phys. Rev. Lett.* **123** 1611802.
CUORE Collab. 2022 *Nature* **604** 53.

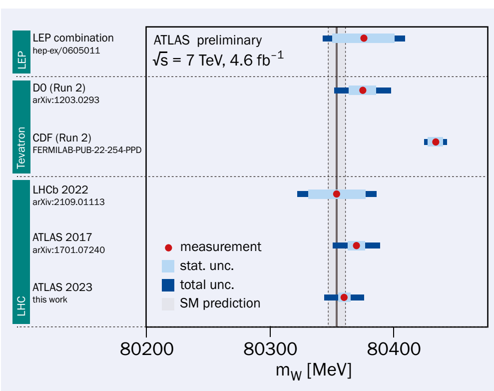
W MASS

ATLAS increases precision on W mass

Since the discovery of the W boson at the Sp$\bar{p}$S 40 years ago, collider experiments at CERN and elsewhere have measured its mass ever more precisely. Such measurements provide a vital test of the Standard Model's consistency, since the W mass is closely related to the strength of the electroweak interaction and to the masses of the Z boson, top quark and Higgs boson; higher experimental precision is needed to keep up with the most recent electroweak calculations.

The latest experiment to weigh in on the W mass is ATLAS. Reanalysing a sample of 14 million W candidates produced in proton–proton collisions at 7 TeV, the collaboration finds $M_W = 80.360 \pm 0.005(\text{stat}) \pm 0.015(\text{syst}) = 80.360 \pm 0.016$ GeV. The value, which was presented on 23 March at the Rencontres de Moriond, is in agreement with all previous measurements except one – the latest measurement from the CDF experiment at the former Tevatron collider at Fermilab.

In 2017 ATLAS released its first measurement of the W-boson mass, which was determined using data recorded in 2011 when the LHC was running at a collision energy of 7 TeV (*CERN Courier* January/February 2017 p10). The precise result (80.370 ± 0.019 GeV) agreed with the Standard Model prediction (80.354 ± 0.007 GeV) and all previous experimental results, including those from the LEP experiments. But last year, the CDF collaboration announced an even more precise measurement, based on an analysis of its full dataset (*CERN Courier* May/June 2022 p9). The result (80.434 ± 0.009 GeV) differed significantly from the Standard Model prediction and from the other experimental results (see figure), calling for more measurements to try to identify the source of the discrepancy.



On point *The latest ATLAS measurement compared to other published results, with the vertical band showing the Standard Model prediction and light- and dark-blue horizontal bands showing the statistical and total uncertainties of the results.*

In its new study, ATLAS reanalysed its 2011 data sample using a more advanced fitting technique as well as improved knowledge of the parton distribution functions that describe how the proton's momentum is shared amongst its constituent quarks and gluons. In addition, the collaboration verified the theoretical description of the W-production process using dedicated LHC proton–proton runs. The new result is 10 MeV lower than the previous ATLAS result and 15% more precise.

"Due to an undetected neutrino in the particle's decay, the W-mass measurement is among the most challenging precision measurements performed at hadron colliders. It requires extremely accurate calibration of the measured particle energies and momenta, and a careful assessment and excellent control of modelling uncertainties," says ATLAS spokesperson Andreas Hoecker. "This updated result from ATLAS provides a stringent test and confirms the consistency of our theoretical understanding of electroweak interactions."

The LHCb collaboration reported a measurement of the W mass in 2021, while the results from CMS are keenly anticipated. In the meantime, physicists from the Tevatron+LHC W-mass combination working group are calculating a combined mass value using the latest measurements from the LHC, Tevatron and LEP. This involves a detailed investigation of higher-order theoretical effects affecting hadron-collider measurements, explains CDF representative Chris Hays from the University of Oxford: "The aim is to give a comprehensive and quantitative overview of W-boson mass measurements and their compatibilities. While no significant issues have been identified that significantly change the measurement results, the studies will shed light on their details and differences."

Further reading

ATLAS Collaboration 2023 ATLAS-CONF-2023-004.

NA62

Searching for dark photons in beam-dump mode

Faced with the no-show of phenomena beyond the Standard Model at the high mass and energy scales explored so far by the LHC, it has recently become a much considered possibility that new physics hides "in plain sight", namely at mass scales that can be very easily accessed but at very small coupling strengths. If this were the case, then high-intensity experiments have an advantage: thanks to the large number of events that can be generated, even the most feeble couplings corresponding to the rarest processes can be accessible.

Such a high-intensity experiment is NA62 at CERN's North Area. Designed to measure the ultra-rare kaon decay $K \rightarrow \pi\nu\bar{\nu}$, it has also released several results probing the existence of weakly coupled processes that could become visible in its apparatus, a prominent example being the decay of a kaon into a pion and an axion. But there is also an unusual way in which NA62 can probe this kind of physics using a configuration that was not foreseen when the experiment was planned, for which the first result was recently reported.

During normal NA62 operations, bunches of 400 GeV protons from the SPS are fired onto a beryllium target to generate secondary mesons from which, using an achromat, only particles with a fixed momentum and charge are selected. These particles (among them kaons) are then propagated along a series of magnets and finally arrive at the detector 100 m downstream. In a series of studies starting in 2015, however, NA62 collaborators with the help of phenomenologists began to explore physics models that could be tested if the target was removed and protons were fired directly into a "dump" that can be arranged by moving the achromat collimators. They concluded that various processes exist in which new MeV-scale particles such as dark photons could be produced and detected from their decays into di-lepton final states. The challenge is to keep the muon-induced background under control, which cannot be easily understood from simulations alone.

Intense *Part of the NA62 detector in the ECN3 experimental hall in Prevessin, where beam travels from right to left. On the right-hand side is the STRAW spectrometer, with the analysing magnet in blue. Four large-angle vetoes serving to clean the samples from non-forward events are visible in white, while the green region houses the RICH detector.*

A breakthrough came in 2018 when beam physicists in the North Area understood how the beamline magnets could be operated in such a way as to vastly reduce the background of both muons and hadrons. Instead of using the two pairs of dipoles as a beam achromat for momentum selection, the currents in the second pair are set to induce additional muon sweeping. The scheme was verified during a 2021 run lasting 10 days, during which 1.4×10^{17} protons were collected on the beam dump. The first analysis of this rapidly collected dataset – a search for dark photons decaying to a di-muon final state – has now been performed.

Hypothesised to mediate a new gauge force, dark photons, A′, could couple to the Standard Model via mixing with ordinary photons. In the modified NA62 set-up, dark photons could be produced either via bremsstrahlung or decays of secondary mesons, the mechanisms differing in their cross-sections and distributions of the momenta and angles of the A′. No sign of $A' \rightarrow \mu^+\mu^-$ was found, excluding a region of parameter space for dark-photon masses between 215 and 550 MeV at 90% confidence. A preliminary result for a search for $A' \rightarrow e^+e^-$ was also presented at the Rencontres de Moriond in March.

"This result is a milestone," explains analysis leader Tommaso Spadaro of LNF Frascati. "It proves the capability of NA62 for studying physics in the beam-dump configuration and paves the way for upcoming analyses checking other final states."

Further reading

NA62 Collab. 2023 arXiv:2303.08666.

ASTROWATCH

X-ray source could reveal new class of supernovae

Type1A supernovae play an important role in the universe, both as the main source of iron and as one of the principal tools for astronomers to measure cosmic-distance scales. They are also important for astroparticle physics, for example allowing the properties of the neutrino to be probed in an extreme environment.

Type1A supernovae make ideal cosmic rulers because they all look very similar, with roughly equal luminosity and emission characteristics. Therefore, when a cosmic explosion that matches the properties of a type1A supernova is detected, its luminosity can be directly used to measure the distance to its host galaxy. Despite this importance, the details surrounding the progenitors of these events are still not fully understood. Furthermore, a group of outliers, now known as type1ax events, has recently been identified that indicate there might be more than one path towards a type1A explosion.

The reason that typical type1A events all have a roughly equal luminosity is because of their progenitors. The general explanation for these events includes a binary system with at least one white dwarf: a very dense old star consisting mostly of oxygen and carbon that is not undergoing fusion. The system is only prevented from collapsing into a neutron star or black hole due to electron-degeneracy pressure. As the white dwarf accumulates matter from a nearby companion, its mass increases to a precise critical limit at which an uncontrolled thermonuclear explosion starts, resulting in the star being unbounded and seen as the supernova.

This peculiar binary system provides strong hints of a new type of progenitor that can explain up to 30% of all supernovae 1a events

As several X-ray sources were identified in the 1990s by the ROSAT mission as being white dwarfs with hydrogen burning on their surface, the source of matter that is accumulated by the white dwarf was long thought to be hydrogen from a companion star. The flaw with this model, however, is that type1A supernovae show no signs of any hydrogen. On the other hand, helium has been seen, particularly in the outlier type1ax supernovae events. These 1ax events, which are predicted to make up 30% of all type1A events, ▷

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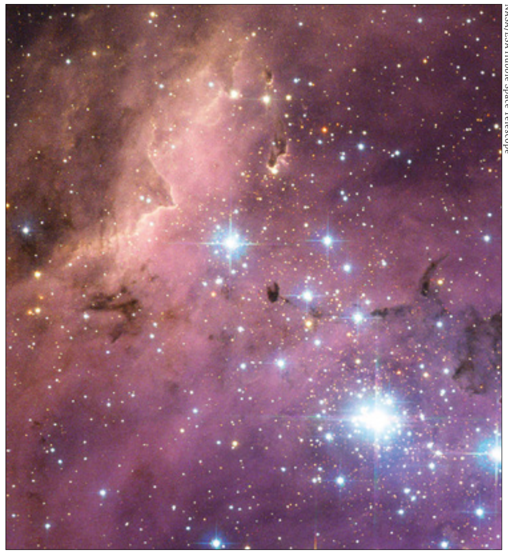
can be explained by a white dwarf accumulating helium from a companion star that has already shed all of its hydrogen. If the helium was able to accumulate on the surface in a stable way, without intermediate explosions due to violent ignition of the helium, it reaches a mass where it violently ignites on the surface. This in turn triggers the ignition of the core and could explain the type1ax events. Evidence of helium accumulating white dwarfs has, however, not been found.

Now, a group led by researchers from the Max Planck Institute for Extraterrestrial Physics (MPE) has used both optical data and X-ray data from the eROSITA and XMM Newton missions to find the first clear evidence of such a progenitor system. The group found an object, known as [HP99] 159, located in the Large Magellanic Cloud, which shows all the characteristics of a white dwarf surrounded by an accretion disk of helium. Using historical X-ray data from as far back as 50 years, the team also showed that the brightness of the source is relatively stable, thereby indicating that it is accumulating the helium at a stable rate, despite the accumulation rate being lower than theoretically predicted for stable burning. This indicates that the system is working its way towards ignition in the future.

The discovery of this new X-ray source therefore proves the existence of white dwarfs that accumulate helium from a companion star at a steady rate, thereby allowing them to reach the conditions to produce a supernova. This peculiar binary system already provides strong hints of a new type of progenitor that can explain up to 30% of all supernovae 1a events. Follow-up measurements will provide further insight into the complex physics at play in the thermonuclear explosions that produce these events, while [HP99] 159's characteristics can be used to find similar sources.


NASA/ESA Hubble Space Telescope

Stellar nursery *A possible precursor to a type1a supernova has been spotted in the Large Magellanic Cloud, a satellite galaxy of the Milky Way almost 200,000 light-years from Earth.*

Further reading

J Greiner et al. 2023 *Nature* **615** 605.

NEWS DIGEST

One of KAGRA's 3 km-long arms.

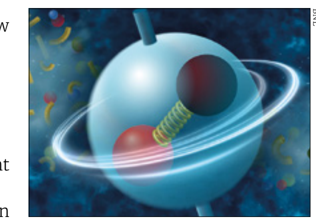
LIGO, Virgo and KAGRA join for O4
After more than two years of upgrades and maintenance work, the fourth observing run (O4) of the LIGO gravitational-wave observatory in the US is to begin in May. LIGO's two detectors will be joined by Virgo in Italy and KAGRA in Japan. Whereas Virgo has observed alongside LIGO in the past and was instrumental in localising the source of the binary neutron-star merger in 2017, KAGRA joined the LIGO–Virgo network in 2020 but an abrupt end to O3 in March of that year due to the pandemic made the alliance brief. O4 will comprise 18 months of active observing time, with the latest upgrades to LIGO and Virgo in particular capable of sensing even fainter gravitational waves and thus more events than before.

LHCb improves on R(D*)
At a CERN seminar on 21 March, the LHCb collaboration presented a new test of lepton universality by measuring the ratio of branching fractions of $B^0 \to D^*$ decays, $R(D^{*-}) = BR(B \to D^{*-}\tau^+\nu_\tau)/BR(B \to D^{*-}\mu^+\nu_\mu)$, extending their 2022 analysis using muonic $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decays based on the Run 1 data sample. The new result uses hadronic $\tau^+ \to \pi^-\pi^+\pi^+(\pi^0)\bar{\nu}_\tau$ decays and updates an earlier analysis of Run 1 data to include data collected in the early years of Run 2. Combining the values, LHCb found $R(D^*) = 0.257 \pm 0.012 \pm 0.014 \pm 0.012$, which is compatible with the Standard Model expectation and is one of the most precise single measurements of $R(D^*)$ to date. Originally thought difficult to measure at the LHC, this precision on $R(D^*)$ is similar to that from the B factories BaBar and Belle, demonstrating LHCb's capabilities as a major player in this field.

New constraints on WIMPs
Designed to hunt dark-matter particles with an order of magnitude higher sensitivity than its predecessor XENON1T, the XENONnT collaboration has reported its first results based on a search for nuclear recoils from weakly interacting massive particles (WIMPs). With a 1.1 t × yr exposure, and a world-leading low background from electron-recoil events and natural radioactivity levels from krypton and radon, a blinded analysis of nuclear recoil events with energies between 3.3 and 60.5 keV showed no significant excess of events. The result sets a new upper limit for the interaction cross section of WIMPs with ordinary matter of 2.6×10^{-47} cm^2 for a WIMP mass of 28 GeV at 90% confidence. XENONnT continues data-taking (arXiv:2303.14729).

Reactor neutrinos in water
The SNO+ collaboration has reported the first evidence for reactor antineutrinos in a Cherenkov detector. The detected antineutrinos most likely stem from a nuclear reactor 240 km away in Ontario. One approach to improving detection is to make use of a higher-energy neutron-capture signal – for example by dissolving chlorine or gadolinium into water – while another is to attain lower thresholds. With a detector energy threshold of around 1.4 MeV, SNO+ has performed the lowest-energy analysis in a large water Cherenkov detector, with two analytical methods used to distinguish reactor antineutrinos from background events in 190 days of data at a significance of 3.5σ (*Phys. Rev. Lett.* **130** 091801).

Strange spin alignment at STAR
A surprising result from the STAR experiment at RHIC suggests that φ mesons produced in Au–Au collisions at a centre-of-mass energy up to 200 GeV/nucleon have a preferred spin-direction. Confirming findings previously seen by the ALICE collaboration, the result may point to a previously unknown influence of the strong force. Whereas conventional mechanisms – such as the magnetic field generated in high-energy collisions – cannot explain the data, a new model that includes local fluctuations in the strong force can, says the team. Analogous to how a moving electric charge generates an electromagnetic field, strange quarks and antiquarks could create an effective φ-meson field, the electric component of which could polarise the quarks and thus enable the spin directions to align with the polarised quark–gluon plasma. To test this hypothesis, STAR plans to study the global spin alignment of J/ψ mesons (*Nature* **614** 244).



A new mechanism could be at work.

Swiss support for CERN's future
Apart from the considerable and unique contribution it makes to science and innovation, CERN's presence on Swiss soil also brings tangible economic benefits, particularly to the Canton of Geneva, stated the Swiss Federal Council on 10 March. Following a decision in December 2021 to initiate a federal sectoral plan for projects at CERN, the council announced further actions to ensure such projects are compatible with the objectives of Swiss research, host-state, environmental and spatial planning policies, and that they are implemented in the best possible administrative conditions. To provide a legal basis for the plan, several changes need to be made to the Federal Act on the Promotion of Research and Innovation, for which the council intends to submit a dispatch to the Swiss parliament by the end of 2023.

Towards a Super τ-Charm Facility
On 28 March, physicists in China published the first volume of a conceptual design report for the Super τ-Charm Facility (STCF) – a proposed e^+e^- collider with an energy between 2 and 7 GeV and peak luminosity of 0.5×10^{35} cm^{-2}s^{-1} that would produce a data sample 100 times larger than the present τ-charm factory, BEPCII. In addition to describing the STCF detector system, the report presents the facility's unique capabilities for exploring CP violation, in-depth studies of the internal structure of hadrons and the nature of non-perturbative strong interactions, as well as searches for exotic hadrons and physics beyond the Standard Model (arXiv:2303.15790).

Seismic predictions
Since the 1960s, earthquakes have been predicted by measuring the leakage of radon gas from deep layers, but traditional measurements in soil or air have large uncertainties. A new European project called artEmis aims to improve the prediction of earthquakes using networks of advanced water-based sensors. Based on detectors, electronics and data-processing systems used for nuclear-physics experiments, the 13-institute project will lay a network of sensors in selected water sources in Europe. Researchers at GSI in Germany are developing sensor units that will combine radon detectors with sensors for temperature, pressure, conductivity and other physical parameters. Operated autonomously using AI methods, the aim is to link changes in local radon concentration to seismic activity and rule out other causes that could lead to false alarms. The first measurements to be carried out are on fault lines in Greece, Italy and Switzerland.

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Searching for electroweak SUSY: a combined effort

The CMS collaboration has been relentlessly searching for physics beyond the Standard Model (SM) since the start of the LHC. One of the most appealing new theories is supersymmetry or SUSY – a novel fermion–boson symmetry that gives rise to new particles, "naturally" leads to a Higgs boson almost as light as the W and Z bosons, and provides candidate particles for dark matter (DM).

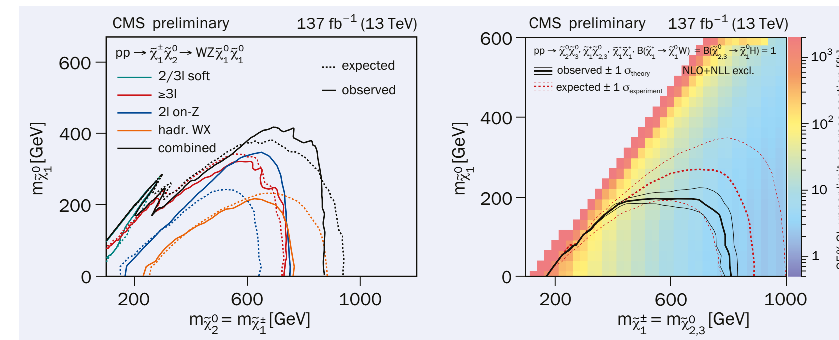


Fig. 1. *Exclusion limits at 95% confidence level for the production of (left) "wino-like" chargino–neutralino pairs decaying via a W and a Z boson, and of (right) "higgsino-like" neutralino–neutralino, chargino–chargino and chargino–neutralino pairs, where the charginos (neutralinos) decay via a W (Higgs) boson, and the lightest chargino and the second- and third-lightest neutralinos are mass-degenerate. On the right, in addition to exclusion limit contours on the mass of the involved SUSY particles, upper limits on the production cross section are also shown.*

By the end of LHC Run 2, in 2018, CMS had accumulated a high-quality data sample of proton–proton (pp) collisions at an energy of 13 TeV, corresponding to an integrated luminosity of 137 fb^{-1}. With such a large data set, it was possible to search for the production of strongly interacting SUSY particles, i.e. the partners of gluons (gluinos) and quarks (squarks), as well as for SUSY partners of the W and Z bosons (electroweakinos: winos and binos), of the Higgs boson (higgsinos), and of the leptons (sleptons). The cross sections for the direct production of SUSY electroweak particles are several orders of magnitude lower than those for gluino and squark pair production. However, if the partners of gluons and quarks are heavier than a few TeV, it could be that the SUSY electroweak sector is the only one accessible at the LHC. In the minimal SUSY extension of the SM, electroweakinos and higgsinos mix to form six mass eigenstates: two charged (charginos) and four neutral (neutralinos). The lightest neutralino is often considered to be the lightest SUSY particle (LSP) and a DM candidate.

CMS has recently reported results, based on the full Run 2 dataset, from searches for the electroweak production of sleptons, charginos and neutralinos. Decays of these particles to the LSP are expected to produce leptons, or Z, W and Higgs bosons. The Z and W bosons subsequently decay to leptons or quarks, while the Higgs boson primarily decays to b quarks. All final states have been explored with complementary channels to enhance the sensitivity to a wide range of electroweak SUSY mass hypotheses. These cover very compressed mass spectra, where the mass difference between the LSP and its parent particles is small (leading to low-momentum particles in the final state) as well as uncompressed scenarios that would instead produce highly boosted Z, W and Higgs bosons. None of the searches showed event counts that significantly deviate from the SM predictions.

The next step was to statistically combine the results of mutually exclusive search channels to set the strongest possible constraints with the Run 2 dataset and interpret the results of searches in different final states under unique SUSY-model hypotheses. For the first time, fully leptonic, semi-leptonic and fully hadronic final states from six different CMS searches were combined to explore models that differ depending on whether the next-to-lightest supersymmetric partner (NLSP) is "wino-like" or "higgsino-like", as shown in the left and right panels of figure 1, respectively. The former are now excluded up to NLSP masses of 875 GeV, extending the constraints obtained from individual searches by up to 100 GeV, while the latter are excluded up to NLSP masses of 810 GeV.

CMS maximised the output of the Run 2 dataset, providing its legacy reference on electroweak SUSY searches

With this effort, CMS maximised the output of the Run 2 dataset, providing its legacy reference on electroweak SUSY searches. While the same data are still being used to search for new physics in yet uncovered corners of the accessible phase-space, CMS is planning to extend its reach in the upcoming years, profiting from the extension of the data set collected during LHC Run 3 at an unprecedented centre-of-mass energy of 13.6 TeV.

Further reading

CMS Collab. 2023 CMS-PAS-SUS-21-008.

LHCb

New insights into CP violation via penguin decays

At the recent Moriond Electroweak conference, the LHCb collaboration presented a new, high-precision measurement of charge–parity (CP) violation using a large sample of $B_s^0 \to \phi\phi$ decays, where the φ mesons are reconstructed in the K^+K^- final state. Proceeding via a loop transition ($\bar{b} \to \bar{s}s\bar{s}$), such "penguin" decays are highly sensitive to possible contributions from unknown particles and therefore provide excellent probes for new sources of CP violation. To date, the only known source of CP violation, which is governed by the Cabibbo–Kobayashi–Maskawa matrix in the quark sector, is ▷

This is the most precise single measurement to date

insufficient to account for the huge excess of matter over antimatter in the universe; extra sources of CP violation are required.

A B_s^0 or $\bar{B}_s^0$ meson can change its flavour and oscillate into its antiparticle at a frequency $\Delta m_s/2\pi$, which has been precisely determined by the LHCb experiment. Thus a B_s^0 meson can decay either directly to the $\varphi\varphi$ state or via changing its flavour to the $\bar{B}_s^0$ state. The phase difference between the two interfering amplitudes changes sign under CP transformations, denoted Φ_s for B_s^0 or $-\Phi_s$ for $\bar{B}_s^0$ decays. A time-dependent CP asymmetry can arise if the phase difference Φ_s is nonzero. The asymmetry between the decay rates of initial B_s^0 and $\bar{B}_s^0$ mesons to the $\varphi\varphi$ state as a function of the decay time follows a sine wave with amplitude $\sin(\Phi_s)$ and frequency $\Delta m_s/2\pi$. In the Standard Model (SM) the phase difference is predicted to be consistent with zero, $\Phi_s^{SM} = 0.00 \pm 0.02$ rad.

The observed asymmetry as a function of the $B_s^0 \to \varphi\varphi$ decay time and the projection of the best fit are shown in figure 1 for the Run 2 data sample. The measured asymmetry is diluted by the finite decay-

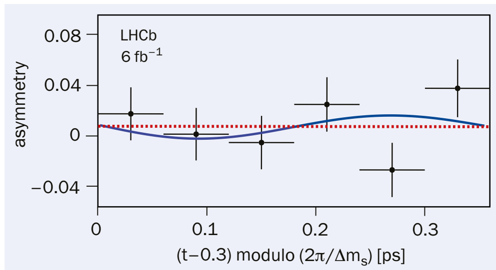


Fig. 1. *Observed rate asymmetry between decays of flavour-tagged B_s^0 or $\bar{B}_s^0$ mesons to a $\varphi\varphi$ pair as a function of decay time, t, folded in a single oscillation period (black points) and overlaid with the projection of the best fit (blue solid line). The red dashed line corresponds to the hypothesis of CP symmetry.*

time resolution and the nonzero flavour mis-identification rate of the initial B_s^0 or $\bar{B}_s^0$ state, and averaged over two types of linear polarisation states of the $\varphi\varphi$ system that have CP asymmetries with opposite signs. Taking these effects into account, LHCb measured the CP-violating phase using the full Run 2 data sample. The result, when combined with the Run 1 measurement, is $\Phi_s = -0.074 \pm 0.069$ rad, which agrees with the SM prediction and improves significantly upon the previous LHCb measurement. In addition to the increased data sample size, the new analysis benefits from improvements in the algorithms for vertex reconstruction and determination of the initial flavour of the B_s^0 or $\bar{B}_s^0$ mesons.

This is the most precise single measurement to date of time-dependent CP asymmetry in any $\bar{b} \to \bar{s}$ transition. With no evidence for CP violation, the result can be used to derive stringent constraints on the parameter space of physics beyond the SM. Looking to the future, the upgraded LHCb experiment and a planned future phase II upgrade (*CERN Courier* March/April 2023 p22) will offer unique opportunities to further explore new-physics effects in $\bar{b} \to \bar{s}$ decays, which could potentially provide insights into the fundamental origin of the puzzling matter–antimatter asymmetry.

Further reading

LHCb Collab. 2023 LHCB-PAPER-2023-001.

ATLAS

Digging deeper into invisible Higgs-boson decays

Studies of the Higgs boson by ATLAS and CMS have observed and measured a large spectrum of production and decay mechanisms. Its relatively long lifetime and low expected width (4.1 MeV, compared with the GeV-range decay widths of the W and Z bosons) make the Higgs boson a sensitive probe for small couplings to new states that may measurably distort its branching fractions. The search for invisible or yet undetected decay channels is thus highly relevant.

Dark-matter (DM) particles created in LHC collisions would have no measurable interaction with the ATLAS detector and thus would be "invisible", but could still be detected via the observation of missing transverse momentum in an event, similarly to neutrinos. The Standard Model (SM) predicts the Higgs boson to decay invisibly via $H \to ZZ^* \to 4\nu$ in only 0.1% of cases. However, this value could be significantly enhanced if the Higgs boson decays into a pair of (light enough) DM particles. Thus, by constraining the branching fraction of Higgs-boson decays to invisible particles it is possible to constrain DM scenarios and probe other physics beyond the SM (BSM).

The ATLAS collaboration has performed comprehensive searches for invisible decays of the Higgs boson considering all its major production modes: vector-boson

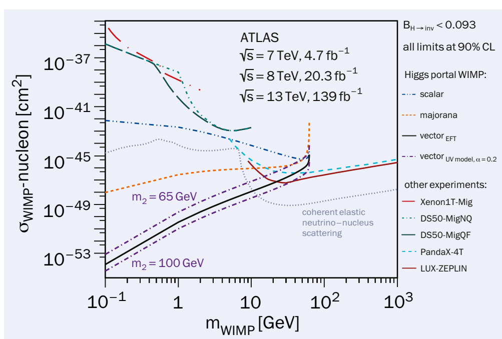


Fig. 1. *Upper limits on the DM–nucleon scattering cross-section as a function of the DM mass for direct detection experiments and the interpretation of the $H \to$ invisible combination result in the context of Higgs-portal models.*

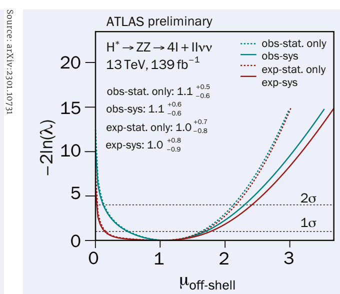


Fig. 2. *The profile likelihood as a function of the off-shell Higgs signal strength $m_{off\text{-}shell}$, for the combination of the $ZZ \to 4l$ and $ZZ \to 2l2\nu$ off-shell analyses. The horizontal dotted lines correspond to the one and two σ confidence intervals on the measurement.*

fusion with and without additional final-state photons, gluon fusion in association with a jet from initial-state radiation, and associated production with a leptonically decaying Z boson or a top quark–antiquark pair. The results of these searches have now been combined, including inputs from Runs 1 and 2 analyses. They yield an upper limit of 10.7% on the branching ratio of the Higgs boson to invisible particles at 95% confidence level, for an unprecedented expected sensitivity of 7.7%. The result is used to extract upper limits on the spin-independent DM-nucleon scattering cross section for DM masses smaller than about 60 GeV in a variety of Higgs-portal models (figure 1). In this range and for the models considered, invisible Higgs-boson decays are more sensitive than the results from DM-nucleon scattering detection experiments.

An alternative way to constrain possible undetected decays of the Higgs boson is to measure its total decay width Γ_H. Combining the observed value of the width with measurements of the branching ▷

fractions to observed decays allows the partial width for decays to new particles to be inferred. Directly measuring Γ_H at the LHC is not possible as it is much smaller than the detector resolution. However, Γ_H can be constrained by taking advantage of an unusual feature of the $H \to ZZ^{(*)}$ decay channel: the rapid increase in available phase space for the $H \to ZZ^{(*)}$ decay as m_H approaches the $2m_Z$ threshold counteracts the mass dependence of Higgs-boson production. Furthermore, this far "off-shell" production above $2m_Z$ has a negligible Γ_H dependence, unlike "on-shell" production near the Higgs-boson mass at 125 GeV. Comparing the Higgs-boson production rates in these two regions therefore allows an indirect measurement of Γ_H. Although some assumptions are required (e.g. that the relation between on-shell and off-shell production is not modified by BSM effects), the measurement is sensitive to the value of Γ_H expected in the SM. Recently, ATLAS measured the off-shell production cross-section using both the four-charged lepton ($4l$) and two-charged lepton plus two neutrino ($2l2\nu$) final states, finding evidence for off-shell Higgs-boson production with a significance of $3.3\,\sigma$ (figure 2). By combining both the previously measured on-shell Higgs-boson production-cross section and the of-shell Higgs-boson production-cross section, Γ_H was found to be $4.5^{+3.3}_{-2.5}$ MeV, which agrees with the SM prediction of 4.1 MeV but leaves plenty of room for possible BSM contributions.

The ATLAS collaboration has performed comprehensive searches for invisible decays of the Higgs boson

This sensitivity will improve thanks to the new data to be collected in Run 3 of the LHC, which should more than triple the size of the Run 2 dataset.

Further reading

ATLAS Collab. 2023 arXiv:2301.10731.
ATLAS Collab. 2022 ATLAS-CONF-2022-068.

ALICE

Beauty quark production versus particle multiplicity

Measurements of the production of hadrons containing heavy quarks (i.e. charm or beauty) in proton–proton (pp) collisions provide an important test of the accuracy of perturbative quantum chromodynamics (pQCD) calculations. The production of heavy quarks occurs in initial hard scatterings of quarks and gluons, whereas the production of light quarks in the underlying event is dominated by soft processes. Thus, measuring heavy-quark hadron production as a function of the charged-particle multiplicity provides insights into the interplay between soft and hard mechanisms of particle production.

Measurements in high-multiplicity pp collisions have shown features that resemble those associated with the formation of quark–gluon plasma in heavy-ion collisions, such as the enhancement of the production of particles with strangeness content and the modification of the baryon-to-meson production ratio as a function of transverse momentum (p_T). These effects can be explained by two different types of models: statistical hadronisation models, which evaluate the population of hadron states according to statistical weights governed by the masses of the hadrons and a universal temperature, or models that include hadronisation via coalescence (or recombination) of quarks and gluons which are close in phase space. Both predict an enhancement of the baryon-to-meson and strange-to-non-strange hadron ratios as a function of charged-particle multiplicity.

In the charm sector, the ALICE collaboration has recently observed a multiplicity dependence of the p_T-differential Λ_c^+/D^0 ratio, smoothly evolving from pp to lead–lead collisions, while no dependence was observed for the D_s^+-meson production yield compared to the one of the D^0 meson.

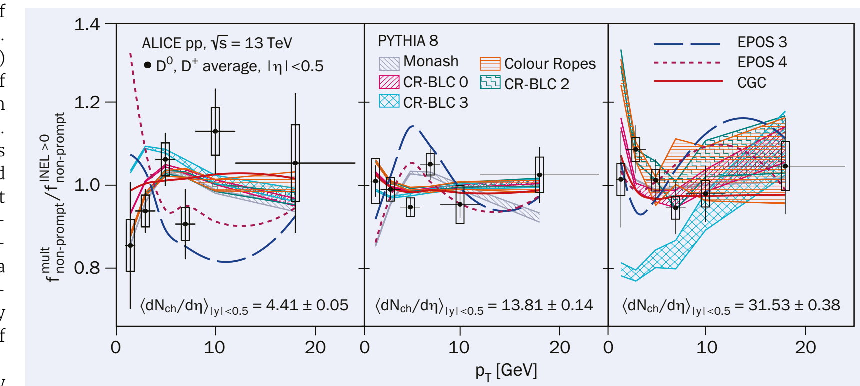


Fig. 1. *The ratio between the fraction of non-prompt D^0 and D^+ mesons measured in three different multiplicity intervals and the multiplicity-integrated fraction in pp collisions at a centre-of-mass energy of 13 TeV. The PYTHIA 8 curves obtained with different tunes describe the data satisfactorily, except for the CR-BLC 3 (cyan), which underestimates the ratio between non-prompt fractions at low p_T for the high-multiplicity class of events.*

Measurements of these phenomena in the beauty sector are needed to shed further light on the hadronisation mechanism.

To investigate beauty-quark production as a function of multiplicity and to put it in relation with that of charm quarks, ALICE measured for the first time the fraction of D^0 and D^+ originating from beauty-hadron decays (denoted as non-prompt) as a function of transverse momentum and charged-particle multiplicity in pp collisions at 13 TeV, using the Run 2 dataset. The measurement exploits different decay-vertex topologies of prompt and non-prompt D mesons with machine-learning classification techniques. The fractions of non-prompt D mesons were observed to somewhat increase with p_T from about 5 to 10%, as expected by pQCD calculations (figure 1). Similar fractions were measured in different charged-particle multiplicity intervals, suggesting either no or only mild multiplicity dependence. This suggests a similar production mechanism of charm and beauty quarks as a function of multiplicity.

The possible influence of the hadronisation mechanism was investigated by comparing the measured D-meson non-prompt fractions with predictions based on Monte Carlo generators such as PYTHIA 8. A good agreement was observed with different PYTHIA tunes, with and without the inclusion of the colour-reconnection mechanism beyond the leading colour approximation (CR-BLC), which was introduced to describe the production of charm baryons in pp collisions. Only the CR-BLC "Mode 3" tune that predicts an increase (decrease) of hadronisation in baryons for beauty (charm) quarks at high multiplicity is disfavoured by the current data.

The measurements of non-prompt D^0 and D^+ mesons represent an important test of production and hadronisation models in the charm and beauty sectors, and pave the way for future measurements of exclusive reconstructed beauty hadrons in pp collisions as a function of charged-particle multiplicity.

Further reading

ALICE Collab. 2023 arXiv:2302.07783.
ALICE Collab. 2021 arXiv:2111.11948.

FIELD NOTES

Reports from events, conferences and meetings

Exotic Approaches to Naturalness

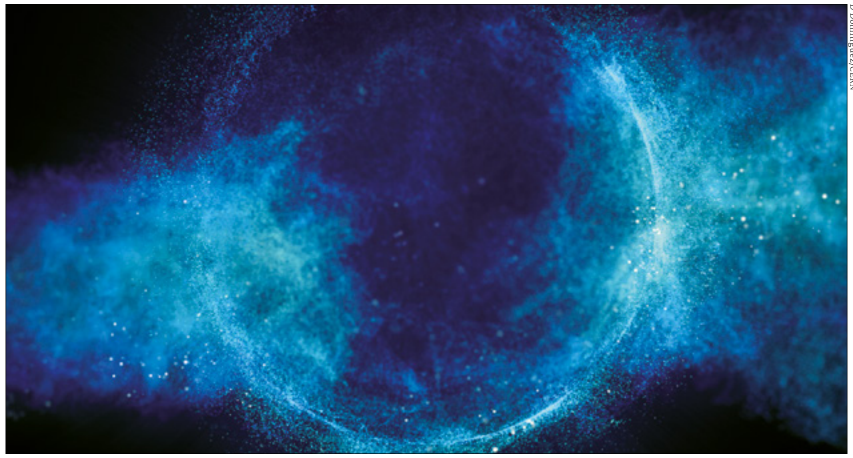
Design principles of theoretical physics

"Now I know what the atom looks like!" Ernest Rutherford's simple statement belies the scientific power of reductionism. He had recently discovered that atoms have substructure, notably that they comprise a dense positively charged nucleus surrounded by a cloud of negatively charged electrons. Zooming forward in time, that nucleus ultimately gave way further when protons and neutrons were revealed at its core. A few stubborn decades later they too gave way with our current understanding being that they are comprised of quarks and gluons. At each step a new layer of nature is unveiled, sometimes more, sometimes less numerous in "building blocks" than the one prior, but in every case delivering explanations, even derivations, for the properties (in practice, parameters) of the previous layer. This strategy, broadly defined as "build microscopes, find answers" has been tremendously successful, arguably for millennia.

Natural patterns

While investigating these successively explanatory layers of nature, broad patterns emerge. One of which is known colloquially as "naturalness". This pattern essentially asserts that in reversing the direction and going from one microscopic theory, "the UV-completion", to its larger-scale shell, "the IR", the values of parameters measured in the latter are, essentially, "typical". Typical, in the sense that they reflect the scales, magnitudes and, perhaps most importantly, the symmetries of the underlying UV completion. As Murray Gell-Mann once said: "everything not forbidden is compulsory".

So, if some symmetry is broken by a large amount by some interaction in the UV theory, the same symmetry, in whatever guise it may have adopted, will also be broken by a large amount in the IR theory. The only exception to this is accidental fine-tuning, where large UV-breakings can in principle conspire and give contributions to IR-breakings that, in practical terms, accidentally cancel to a high degree, giving a much smaller parameter than expected in the IR theory. This is colloquially known as "unnaturalness".



D Dominguez/CERN

Mysterious *Explaining the mass of the Higgs boson, depicted here artistically, is one of the biggest "naturalness" questions in fundamental physics.*

There are good examples of both instances. There is no symmetry in QCD that could keep a proton light; unsurprisingly it has mass of the same order as the dominant mass scale in the theory, the QCD scale, $m_p \sim \Lambda_{QCD}$. But there is a symmetry in QCD that keeps the pion light. The only parameters in UV theory that break this symmetry are the light quark masses. Thus, the pion mass-squared is expected to be around $m_\pi^2 \sim m_q \Lambda_{QCD}$. Turns out, it is.

There are also examples of unnatural parameters. If you measure enough different physical observables, observations that are unlikely on their own become possible in a large ensemble of measurements – a sort of theoretical "look elsewhere effect". For example, consider the fact that the Moon almost perfectly obscures the Sun during a lunar eclipse. There is no symmetry which requires that the angular size of the Moon should almost match that of the Sun to an Earth-based observer. Yet, given many planets and many moons, this will of course happen for some planetary systems.

However, if an observation of a parameter returns an apparently unnatural value, can one be sure that it is accidentally small? In other words, can we be confident we have definitively explored all possible phenomena in nature that can give rise to naturally small parameters?

From 30 January to 3 February, participants of an informal CERN theory institute "Exotic Approaches to Naturalness" sought to answer this question. Drawn from diverse corners of the theorist zoo, more than 130 researchers gathered, both virtually and in person, to discuss questions of naturalness. The invited talks were chosen to expose phenomena in quantum field theory and beyond which challenge the naive naturalness paradigm.

Coincidences and correlations

The first day of the workshop considered how apparent numerical coincidences can lead to unexpectedly small parameters in the IR due to the result of selection rules that do not immediately manifest from a symmetry, known as "natural zeros". A second set of talks considered how, going beyond quantum field theory, the UV and IR can potentially be unexpectedly correlated, especially in theories containing quantum gravity, and how this correlation can lead to cancellations that are not apparent from a purely quantum field theory perspective.

The second day was far-ranging, with the first talk unveiling some lower dimensional theories of the sort one more readily finds in condensed matter systems, in which "topological" effects lead to ▷

constraints on IR parameters. A second discussed how fundamental properties, such as causality, can impose constraints on IR parameters unexpectedly. The last demonstrated how gravitational effective theories, including those describing the gravitational waves emitted in binary black hole inspirals, have their own naturalness puzzles.

Midweek, alongside an inspirational theory colloquium by Nathaniel Craig (UC Santa Barbara), the potential role of cosmology in naturalness was interrogated. An early example made famous by Steven Weinberg concerns the role of the "anthropic principle" in the presently measured value of the cosmological constant. However, since then, particularly in recent years, theorists have found many possible connections and mechanisms linking naturalness questions to our universe and beyond.

The fourth day focussed on the emerging world of generalised and higher-form symmetries, which are new tools in the arsenal of the quantum field theorist. It was discussed how naturalness in IR parameters may potentially arise as a consequence of these recently uncovered symmetries, but whose naturalness would otherwise be obscured from view within a traditional symmetry perspective. The final day studied connections between string theory, the swampland and naturalness, exploring how the space of theories consistent with string theory leads to restricted values of IR parameters, which potentially links to naturalness. An eloquent summary was delivered by Tim Cohen (CERN).

Grand slam

In some sense the goal of the workshop was to push back the boundaries by equipping model builders with new and more powerful perspectives and theoretical tools linked to questions of naturalness, broadly defined. The workshop was a grand slam in this respect. However, the ultimate goal is to now go forth and use these new tools to find new angles of attack on the biggest naturalness questions in fundamental physics, relating to the cosmological constant and the Higgs mass.

The Standard Model, despite being an eminently marketable logo for mugs and t-shirts, is incomplete. It breaks down at very short distances and thus it is the IR of some more complete, more explanatory UV theory. We don't know what this UV theory is, however, it apparently makes unnatural predictions for the Higgs mass and cosmological constant. Perhaps nature isn't unnatural and generalised symmetries are as-yet hidden from our eyes, or perhaps string theory, quantum gravity or cosmology has a hand in things? It's also possible, of course, that nature has fine-tuned these parameters by accident, however, that would seem – à la Weinberg – to point towards a framework in which such parameters are, in principle, measured in many different universes. All of these possibilities, and more, were discussed and explored to varying degrees.

The ultimate goal is to now go forth and find new angles of attack on the biggest naturalness questions in fundamental physics

Perhaps the most radical possibility, the most "exotic approach to naturalness" of all, would be to give up on naturalness altogether. Perhaps, in whatever framework UV completes the Standard Model, parameters such as the Higgs mass are simply incalculable, unpredictable in terms of more fundamental parameters, at any length scale. Shortly before the advent of relativity, quantum mechanics, and all that have followed from them, Lord Kelvin (attribution contested) once declared: "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement". The breadth of original ideas presented at the "Exotic Approaches to Naturalness" workshop, and the new connections constantly being made between formal theory, cosmology and particle phenomenology, suggest it would be similarly unwise now, as it was then, to make such a wager.

Matthew McCullough *CERN.*

CP2023

Exploring the origins of matter–antimatter asymmetry

The first edition of the International Workshop on the Origin of Matter–Antimatter Asymmetry (CP2023), hosted by École de Physique des Houches, took place from 12 to 17 February. Around 50 physicists gathered to discuss the central problem connecting particle physics and cosmology: CP violation. Since one of the very first schools dedicated to time-reversal symmetry in the summer of 1952, chaired by Wolfgang Pauli, research has progressed significantly, especially with the formulation by Sakharov of the conditions necessary to produce the observed matter–antimatter asymmetry in the universe.

The workshop programme covered current and future experimental projects to probe the Sakharov conditions: collider measurements of CP violation (LHCb, Belle II, FCC-ee), searches for electric dipole moments (PSI, FNAL), long-baseline neutrino experiments (NOvA, DUNE, T2K, Hyper-Kamiokande, ESSnuSB) and searches for baryon- and lepton-number violating processes such as neutrinoless double beta decay (GERDA, CUORE, CUPID-Mo, KamLAND-Zen, EXO-200) and neutron–antineutron oscillations (ESS). These were put in context with the different theoretical approaches to baryogenesis and leptogenesis.


CP2023

School's out *The participants of the CP2023 workshop at the legendary venue near Mont Blanc.*

With the workshop's aim to provide a discussion forum for junior and senior scientists from various backgrounds, and following the tradition of the Ecole des Houches, a six-hour mini-school took place in parallel with more specialised talks. A first lecture by Julia Harz (University of Mainz) introduced the hypotheses related to baryogenesis, and another by Adam Falkowski (IJCLab) described how CP violation is treated in effective field theory. Each lecture provided both a common theoretical background, and an opportunity to discuss the fundamental motivation driving experimental searches for new sources of CP violation in particle physics.

In his summary talk, Mikhail Shaposhnikov (EPFL Lausanne) explained that it is impossible to identify which mechanism leads to the existing baryon asymmetry in the universe. He added that we live in exciting times and reviewed the vast number of opportunities in experiment and theory lying ahead.

Mathieu Guigue *Sorbonne Université,* **Guillaume Pignol** *and* **Stéphanie Roccia** *Université Grenoble Alpes.*

CERN Neutrino Platform Pheno Week 2023

Neutrino pheno week back at CERN

Since its inception in 2013, the CERN Neutrino Platform has evolved into a worldwide hub for both experimental and theoretical neutrino physics. Besides its multifaceted activities in hardware development – including most notably the ProtoDUNE detectors for the international long-baseline neutrino programme in the US – the platform also hosts a vibrant group of theorists.

From 13 to 17 March this group once again hosted the CERN Neutrino Platform Pheno Week, after a COVID-related hiatus of more than three years. With about 100 in-person participants and 200 more on Zoom, the meeting has become one of the largest in the field – a testament to the ever-growing popularity of neutrinos among particle physicists, even though neutrinos are the most elusive among all known elementary particles.

Talks at the March event reflected the full breadth of the subject, with the first days devoted to novel theoretical models explaining the peculiar relations observed among neutrino masses and mixing angles, and to understanding the way in which neutrinos interact with nuclei. The latter topic is particularly complex, given the vast range of energies in which neutrinos are studied – from non-relativistic cosmic background neutrinos with sub-meV energies to PeV-scale neutrinos observed in neutrino telescopes. An especially popular topic has also been the possibility of discovering physics beyond the Standard Model in the neutrino sector. In fact, because of their ability to mix with hypothetical "dark sector" fermions – that is, fermions potentially related to the physics of dark matter, or even dark matter itself – neutrinos offer a unique window to new physics.


NASA

Treasure trove *More than 35 years on, supernova 1987A (the double-ring structure at the centre of the image shows its remnant, as observed today) is still a topic of active discussion, including at Neutrino Platform Pheno Week.*

The second part of the workshop was devoted to the neutrino's role in astrophysics and cosmology. "There's actually a two-way relationship between neutrinos and the cosmos," explained invited speaker John Beacom (Ohio State University). "On the one hand, astrophysical and cosmological observations can teach us a lot about neutrino properties. On the other, neutrinos are unique cosmic messengers, and from observations at neutrino telescopes we can learn fascinating things about stars, galaxies and the evolution of the universe." In recent years, for instance, neutrinos have allowed physicists to shed new light on the century-old problem of where ultra-high-energy cosmic rays come from. And the next galactic supernova – an event that happens on average every 30 to 100 years – will be a treasure trove of new information, given that we expect to observe tens of thousands of neutrinos from such an event. At the same time, cosmology sets the strongest upper limits on the absolute scale of neutrino masses, and with the next generation of cosmological surveys we have every expectation to achieve an actual measurement of this quantity. This is interesting because neutrino oscillations, while establishing that neutrinos have non-zero mass, are only sensitive to differences of squared masses, not to the absolute mass scale.

The programme of the Neutrino Platform Pheno Week closed with a tour of the ProtoDUNE experiments, giving the mostly theory-oriented audience an impression of how the magnificent machines testing our theories of the neutrino sector are being developed and assembled.

Vedran Brdar, **Julia Gehrlein** *and* **Joachim Kopp** *CERN.*

KM50

Event celebrates 50 years of Kobayashi–Maskawa theory

Quarks change their flavour through the weak interaction, and the strength of the flavour mixing is parametrised by the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which is an essential part of the Standard Model. This year marks the 60th anniversary of Nicola Cabibbo's paper describing the mixing between down and strange quarks (see p43). It also marks the 50th anniversary of the paper by Makoto Kobayashi and Toshihide Maskawa, published in February 1973, which explained the origin of CP violation by generalising the quark mixing to three generations. To celebrate the magnificent accomplishments of quark-flavour physics during the past 50 years and to discuss the future of this important topic, a symposium was held at KEK in Tsukuba, Japan on 11 February, attracting about 150 participants from around the globe, including Makoto Kobayashi himself.

There are valuable lessons from the KM paper when applied to the search beyond the Standard Model

Opening the event, Masanori Yamauchi, director-general of KEK, summarised the early history of Kobayashi–Maskawa (KM) theory and the ideas to test it as a theory of CP violation. He recalled his time as a member of the Belle collaboration at the KEKB accelerator, including the memorable competition with the BaBar experiment at SLAC during the late 1990s and early 2000s, which finally led to the conclusion that KM theory explains the observed CP violation. Kobayashi and Maskawa shared one half of the 2008 Nobel Prize in Physics "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".

The scientific sessions were initiated by Amarjit Soni (BNL), who summarised various ideas to measure CP violation from cascade decays of B mesons including the celebrated papers by A I Sanda and co-workers in 1980–1981, which gave a strong motivation to build B factories. Stephen Olsen (Chung Ang University), ▷

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who was one of the leaders of the Belle collaboration, looked back at the situation in the early 1980s when B-meson mixing was first observed, and emphasised the role of the accelerator physicists who achieved the 100-fold increase in luminosity that was necessary to measure CP angles. Adrian Bevan (Queen Mary University of London) added a perspective from the BaBar experiment, while the more recent impressive development by the LHCb experiment was summarised by Patrick Koppenburg (Nikhef).


KEK

Mixing *Participants of the KM50 event in Tsukuba.*

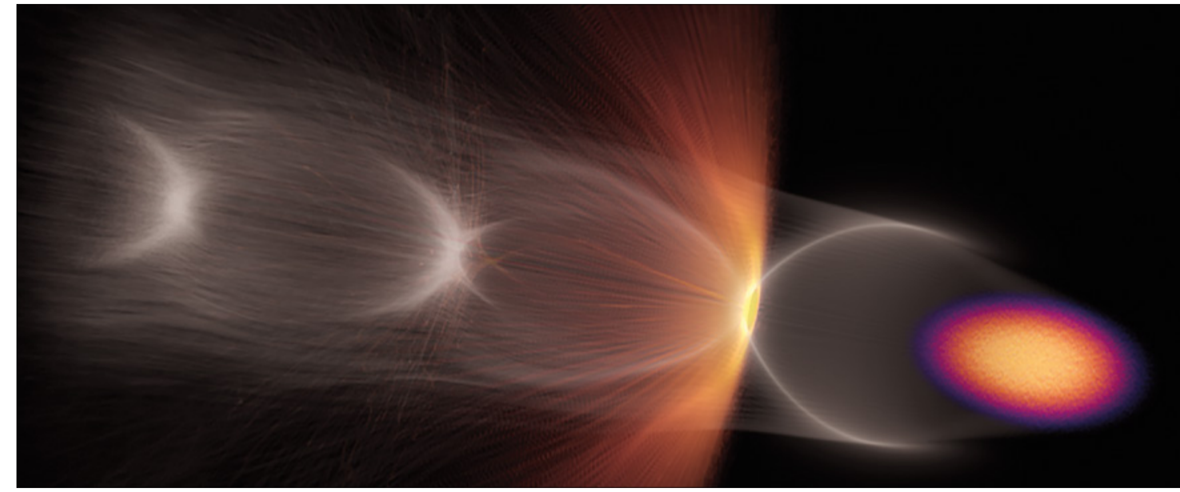
Theoretical developments remain an integral part of quark-flavour physics. Matthias Neubert (University of Mainz) gave an overview of the theoretical tools developed to understand B-meson decays, which include heavy-quark symmetry, heavy-quark effective field theory, heavy-quark expansion and QCD factorisation, and Zoltan Ligeti (LBNL) summarised concurrent developments of theory and experiment to determine the sides of the CKM triangle. Lattice QCD also played a central role in the determination of the CKM matrix elements by providing precision computation of non-perturbative parameters, as discussed by Aida El-Khadra (University of Illinois).

The B sector is not the only place where CP violation is observed. Indeed, it was first observed in kaon mixings, and important pieces of information have been obtained since then. A number of theoretical ideas dedicated to the study of kaon CP violation were discussed by Andrzej Buras (Technical University of Munich), and experimental projects were overviewed by Taku Yamanaka (Osaka University).

There are still unsolved mysteries around quark-flavour physics. The most notable is the origin of the fermion generations, which may only be understood by accumulating more data to find any discrepancy with the Standard Model. SuperKEKB/Belle II, the successor of KEKB/Belle, plans to accumulate 50 times more data in the coming decades, while LHCb will continue to improve the precision of measurement in hadronic collisions. Nanae Taniguchi (KEK) reported the current status of SuperKEKB/Belle II, which has been in physics operation since 2019 and has already broken peak-luminosity records in e^+e^- collisions. Gino Isidori (University of Zurich) gave his view on the possible shape of physics to come. "There are valuable lessons from the KM paper, which are still valuable today, when applied to the search beyond the Standard Model," he concluded.

As a closing remark, Makoto Kobayashi reminisced about the time when he built the theory as well as the time when the KEKB/Belle experiment was running. "I was able to watch the development of the B factory so closely from the very beginning," he said. "I am grateful to the colleagues who gave me such a great opportunity."

Shoji Hashimoto *KEK.*


A Martinez de la Ossa/DESY

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

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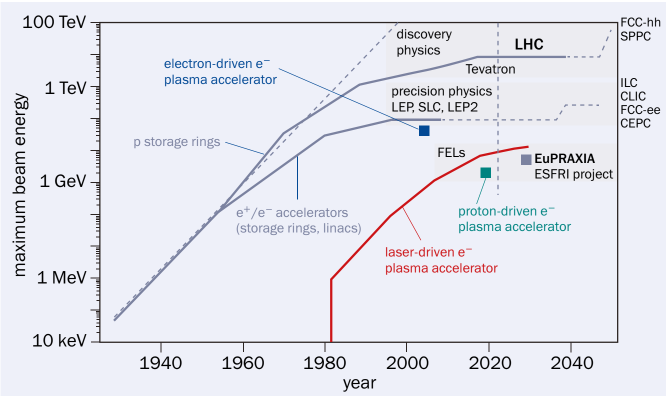
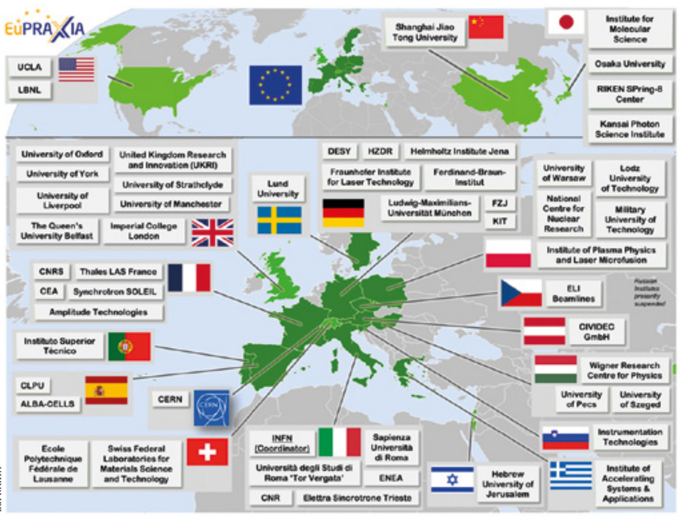
R Assmann/DESY and INFN



Levelling off *Livingston plot showing the maximum beam acceleration achieved versus time in proton storage rings and lepton machines. The progress in plasma accelerators and the position of the EuPRAXIA project are indicated.*



EuPRAXIA

Multinational *The consortia supporting the EuPRAXIA project, indicating members or associated partners of the ESFRI consortium, the EuPRAXIA preparatory-phase project and the EuPRAXIA doctoral network.*

circumference of 27 km at LEP/LHC and close to 100 km for next-generation facilities such as the proposed Future Circular Collider. Machines for photon science, operating in the GeV regime, occupy a footprint of up to several km and the approval of new facilities is becoming limited by physical and financial constraints. As a result, the exponential progress in maximum beam energy that has taken place during the past several decades has started to saturate (see "Levelling off" figure). For photon science, where beam-time on the most powerful facilities is heavily over-subscribed, progress in scientific research and capabilities threatens to become limited by access. It is therefore hoped that the development of innovative and compact accelerator technology will provide a practical path to more research facilities and ultimately to higher beam energies for the same investment.

At present the most successful new technology relies on the concept of plasma acceleration. Proposed in 1979, this technique promises energy gains up to 100 GeV per metre of acceleration and therefore up to 1000 times higher than is possible in RF accelerators. In essence, the metallic walls of an RF cavity, with their intrinsic field limitations, are replaced by a dynamic and robust plasma structure with very high fields. First, the free electrons in a neutral plasma are used to convert the transverse ponderomotive force of a laser, or the transverse space charge force of a charged particle beam, into a longitudinal accelerating field. While the "light" electrons in the plasma column are expelled from the path of the driving force, the "heavy" plasma ions remain in place. The ions therefore establish a restoring force and re-attract the oscillating plasma electrons. A plasma cavity forms behind the drive pulse in which the main electron beam is placed and accelerated with up to 100 GV per metre. Difficulties in the plasma-acceleration scheme arise from the small scales involved (sub-mm transverse diameter), the required micrometre tolerances and stability. Different concepts include laser-driven plasma wakefield acceleration (LWFA), electron-driven plasma wakefield acceleration (PWFA) and proton-beam-driven plasma wakefield acceleration. Gains in electron energy have reached 8 GeV (BELLA, Berkeley), 42 GeV (FFTB, SLAC) and 2 GeV (AWAKE, CERN) in these three schemes, respectively.

At the same time, the beam quality of plasma-acceleration schemes has advanced sufficiently to reach the quality required for free-electron lasers (FELs): linac-based facilities that produce extremely brilliant and short pulses of radiation for the study of ultrafast molecular and other processes. There have been several reports of free-electron lasing in plasma-based accelerators in recent years, one relying on LWFA by a team in China and one on PWFA by the EuPRAXIA team in Frascati, Italy. Another publication by a French and German team has recently demonstrated seeding of the FEL process in a LWFA plasma accelerator.

Scientific and technical progress in plasma accelerators is driven by several dozen groups and a number of major test facilities worldwide, including internationally leading programmes at CERN, STFC, CNRS, DESY, various centres and institutes in the Helmholtz Association, INFN, LBNL, RAL, Shanghai XFEL, SCAPA, SLAC, SPRING-8, Tsinghua University and others. In Europe, the 2020 update of the European strategy for particle physics included plasma accelerators as one of five major themes, and a strategic analysis towards a possible plasma-based collider was published in a 2022 CERN Yellow Report on future accelerator R&D.

Enter EuPRAXIA

In 2014 researchers in Europe agreed that a combined, coordinated R&D effort should be set up to realise a larger plasma-based accelerator facility that serves as a demonstrator. The project should aim to produce high-quality 5 GeV electron beams via innovative laser- and electron-driven plasma wakefield acceleration, achieving a significant reduction in size and possible savings in cost over state-of-the-art RF accelerators. This project was named the European Plasma Research Accelerator with Excellence in Applications (EuPRAXIA) and it was agreed that it should deliver pulses of X rays, photons, electrons and positrons to users from several disciplines.

INFN and Mythos – consorzio stabile s.c.a.r.l.

Frascati future *The proposed building for the EuPRAXIA particle-driven plasma accelerator in Frascati, near Rome.*

EuPRAXIA's beams will mainly serve the fields of structural biology, chemistry, material science, medical imaging, particle-physics detectors and archaeology. It is not a dedicated particle-physics facility but will be an important stepping stone towards any plasma-based collider.

The EuPRAXIA project started in 2015 with a design study, which was funded under the European Union (EU) Horizon 2020 programme and culminated at the end of 2019 with the publication of the worldwide first conceptual design report for a plasma-accelerator facility. The targets set out in 2014 could all be achieved in the EuPRAXIA conceptual design. In particular, it was shown that sufficiently competitive performances could be reached and that an initial reduction in facility size by a factor of two-to-three is indeed achievable for a 5 GeV plasma-based FEL facility. The published design includes realistic constraints on transfer lines, facility infrastructure, laser-lab space, undulator technologies, user areas and radiation shielding. Several innovative solutions were developed, including the use of magnetic chicanes for high quality, multi-stage plasma accelerators. The EuPRAXIA conceptual design report was submitted to peer review and published in 2020.

The EuPRAXIA implementation plan proposes a distributed research infrastructure with two construction and user sites and several centres of excellence. The presently foreseen centres, in the Czech Republic, France, Germany, Hungary, Portugal and the UK, will support R&D, prototyping and the construction of machine components for the two user sites. This distributed concept will ensure international competitiveness and leverage existing investments in Europe in an optimal way. Having received official government support from Italy, Portugal, the Czech Republic, Hungary and UK, the consortium applied in 2020 to the European Strategy Forum on Research Infrastructures (ESFRI). The proposed facility for a free-electron laser was then included in the 2021 ESFRI roadmap, which identifies those research facilities of pan-European importance that correspond to the long-term needs of European research communities. EuPRAXIA is the first ever plasma-accelerator project on the ESFRI roadmap and the first accelerator project since the 2016 placement of the High-Luminosity LHC.

Stepping stones to a user facility

In 2023 the European plasma-accelerator community received a major impulse for the development of a user-ready plasma-accelerator facility with the funding of several multi-million euro initiatives under the umbrella of the EuPRAXIA project. These are the EuPRAXIA preparatory phase, EuPRAXIA doctoral network and EuPRAXIA advanced photon sources, as well as funding for the construction of one of the EuPRAXIA sites in Frascati, near Rome (see "Frascati future" image).

The EU, Switzerland and the UK have awarded €3.69 million to the EuPRAXIA preparatory phase, which comprises 34 participating institutes from Italy, the Czech Republic, France, Germany, Greece, Hungary, Israel, Portugal, Spain, Switzerland, the UK, the US and CERN as an international organisation. The new grant will give the consortium a unique chance to prepare the full implementation of EuPRAXIA over the next four years. The project will fund 548 person-months, including additional funding from the UK and Switzerland, and will be supported by an additional 1010 person-months in-kind. The preparatory-phase project will connect research institutions and industry from the above countries plus China, Japan, Poland and Sweden, which signed the EuPRAXIA ESFRI consortium agreement, and define the full implementation of the €569 million EuPRAXIA facility as a new, distributed research infrastructure for Europe.

Alongside the EuPRAXIA preparatory phase, a new Marie Skłodowska-Curie doctoral network, coordinated by INFN, has also been funded by the EU and the UK. The network, which started in January 2023 and benefits from more than €3.2 million over its four-year duration,

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will offer 12 high-level fellowships between 10 universities, six research centres and seven industry partners that will carry out an interdisciplinary and cross-sector plasma-accelerator research and training programme. The project's focus is on scientific and technical innovations, and on boosting the career prospects of its fellows.

EuPRAXIA at Frascati

Italy is supporting the EuPRAXIA advanced photon sources project (EuAPS) with €22 million. This project has been promoted by INFN, CNR and Tor Vergata University of Rome. EuAPS will fulfil some of the scientific goals defined in the EuPRAXIA conceptual design report by building and commissioning a distributed user facility providing users with advanced photon sources; these consist of a plasma-based betatron source delivering soft X-rays, a mid-power, high-repetition-rate laser and a high-power laser. The funding comes in addition to about €120 million for construction of the beam-driven facility and the FEL facility of EuPRAXIA at Frascati. R&D activities for the beam-driven facility are currently being performed at the INFN SPARC_LAB laboratory.

EuPRAXIA is the first ever plasma-accelerator project on the ESFRI roadmap

EuPRAXIA will be the user facility of the future for the INFN Frascati National Laboratory. The European site for the second, laser-driven leg of EuPRAXIA will be decided in 2024 as part of the preparatory-phase project. Present candidate sites include ELI-Beamlines in the Czech Republic, the future EPAC facility in the UK and CNR in Italy. With its foreseen electron energy range of 1–5 GeV, the facility will enable applications in diverse domains, for instance, as a compact free-electron laser, compact sources for medical imaging and positron generation, tabletop test beams for particle detectors, and deeply penetrating X-ray and gamma-ray sources for materials testing. The first parts of EuPRAXIA are foreseen to enter into operation in 2028 at Frascati and are designed to be a stepping stone for possible future plasma-based facilities, such as linear colliders at the energy frontier. The project is driven by the excellence, ingenuity and hard work of several hundred physicists, engineers, students and support staff who have worked on EuPRAXIA since 2015, connecting, at present, 54 institutes and industries from 18 countries in Europe, Asia and the US. ●

Further reading

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COSMIC RAYS FOR CULTURAL HERITAGE

Taking advantage of detectors used for particle physics, cosmogenic muons are becoming powerful tools for non-destructive imaging of large structures such as pyramids. Physicist and muographer Andrea Giammanco explains.

Structural secrets *Muon tomography is helping researchers to solve some of the enduring mysteries surrounding the pyramids of Giza.*

Khufu's pyramid *Top: a 3D model showing (light blue, based on laser surveys and photogrammetry data): the subterranean chamber (a), queen's chamber (b), grand gallery (c), king's chamber (d), descending corridor (e), ascending corridor (f), al-Ma'mun corridor (g) and north-face chevron area (h). The coloured ellipses depict the Big Void obtained by the ScanPyramids project using muography, showing horizontal (red hatching) and inclined (green hatching) hypotheses. Bottom: two of the detectors used by the ScanPyramids team: "Charpak" (left) and "Degennes" (right).*

In 1965, three years before being awarded a Nobel prize for his decisive contributions to elementary particle physics, Luis Alvarez proposed to use cosmic muons to look inside an Egyptian pyramid. A visit to the Giza pyramid complex a few years earlier had made him ponder why, despite the comparable size of the Great Pyramid of Khufu and the Pyramid of Khafre, the latter was built with a simpler structure – simpler even than the tomb of Khufu's great-grandfather Sneferu, under whose reign there had been architectural experimentation and pyramids had grown in complexity. Only one burial chamber is known in the superstructure of Khafre's pyramid, while two are located in the tombs of each of his two predecessors. Alvarez's doubts were not shared by many archaeologists, and he was certainly aware that the history of architecture is not a continuous process and that family relationships can be complicated; but like many adventurers before him, he was fascinated by the idea that some hidden chambers could still be waiting to be discovered.

The principles of muon radiography or "muography" were already textbook knowledge at that time. Muons are copiously produced in particle cascades originating from naturally occurring interactions between primary cosmic rays and atmospheric nuclei. The energy of most of those cosmogenic muons is large enough that, despite their relatively short intrinsic lifetime, relativistic dilation allows most of them to survive the journey from the upper atmosphere to Earth's surface – where their penetration power makes them a promising tool to probe the depths of very large and dense volumes non-destructively. Thick and dense objects can attenuate the cosmic-muon flux significantly by stopping its low-energy component, thus providing a "shadow" analogous to conventional radiographies. The earliest known attempt to use the muon flux attenuation for practical purposes was the estimation of the overburden of a tunnel in Australia using Geiger counters on a rail, published in 1955 in an engineering journal. The obscure precedent was probably unknown to Alvarez, who didn't cite it.

Led by Alvarez, the Joint Pyramid Project was officially established in 1966. The detector that the team built and installed in the known large chamber at the bottom of Khafre's pyramid was based on spark chambers, which were standard equipment for particle-physics experiments at that time. Less common were the computers provided by IBM for Monte Carlo simulations, which played a crucial role in the data interpretation. It took some time for the project to take off. Just as the experiment was ready to take data, the Six-Day War broke out, delaying progress by several months until diplomatic relationships were restored between Cairo and Washington. All this might sound like a promising subject for a Hollywood blockbuster were it not for its anticlimax: no hidden chamber was found. Alvarez always insisted that there is a difference between not finding what you search for and conclusively excluding its existence, but despite this important distinction, one wonders how much muography's fame would have benefitted from a discovery. Their study, published in *Science* in 1970, set an example that was followed in subsequent decades by many more interdisciplinary applications.

The second pyramid to be muographed was in Mexico more than 30 years later, when researchers from the National Autonomous University of Mexico (UNAM) started to search for hidden chambers in the Pyramid of the Sun at Teotihuacan. Built by the Aztecs about 1800 years ago, it is the third largest pyramid in the world after Khufu's and Khafre's, and its purpose is still a mystery. Although there is no sign that it contains burial chambers, the hypothesis that this monument served as a tomb is not entirely ruled out. After more than a decade of data taking, the UNAM muon detector (composed of six layers of multi-wire chambers occupying a total volume of $1.5\,m^3$) found no hidden chamber. But the researchers did find evidence, reported in 2013, for a very wide low-density volume in the southern side, which is still not understood and led to speculation that this side of the pyramid might be in danger of collapse.

Big void

Muography returned to Egypt with the ScanPyramids project, which has been taking data since 2015. The project made the headlines in 2017 by revealing an unexpected low-density anomaly in Khufu's Great Pyramid, tantalisingly similar in size and shape to the Grand Gallery of the same building. Three teams of physicists from Japan and France participated in the endeavour, cross-checking each other by using different detector technologies: nuclear emulsions, plastic scintillators and micromegas. The latter, being gaseous detectors, had to be located externally to the pyramid to comply with safety regulations. Publishing in *Nature Physics*, all three teams reported a statistically significant excess in muon flux originating from the same 3D position (see "Khufu's pyramid" figure).

This year, based on a larger data sample, the ScanPyramids team concluded that this "Big Void" is a horizontal corridor about 9 m long with a transverse section of around $2\times2\,m^2$. Confidence in the solidity of these conclusions was provided by a cross-check measurement with ground-penetrating radar and ultrasounds, by Egyptian and German experts, which took data since 2020 and was published simultaneously. The consistency of the data from muography and conventional methods motivated visual inspection via an endoscope, confirming the claim. While the purpose of this unexpected feature of the pyramid is not yet known, the work represents the first characterisation of the position and dimensions of a void detected by cosmic-ray muons with a sensitivity of a few centimetres.

New projects exploring the Giza pyramids are now sprouting. A particularly ambitious project by researchers in Egypt, the US and the UK – Exploring the Great Pyramid (EGP) – uses movable large-area detectors to perform precise 3D tomography of the pyramid. Thanks to its larger

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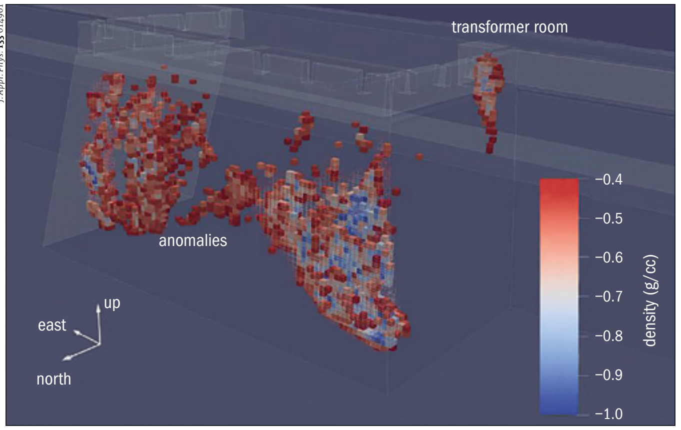
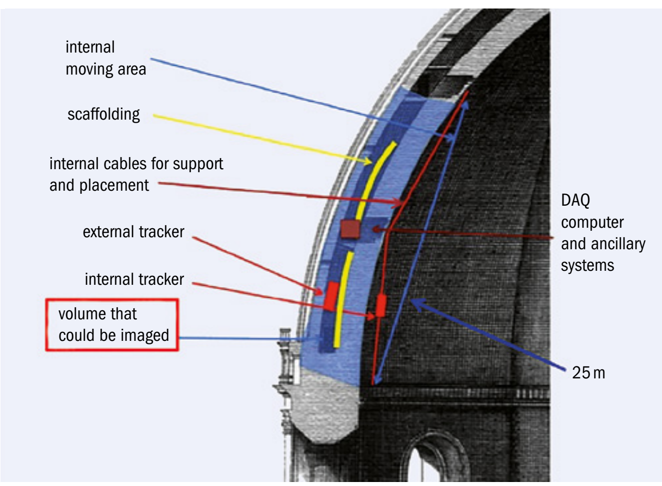


Falling walls *Low-density regions identified via 3D inversion of muography data in the Xi'an city walls. These include a known cavity (the transformer room) and an unexpected pattern near the northern surface of the rampart, hinting at a potential issue for its stability.*



Preserving a masterpiece *Sketch of the proposed experiment to search for iron chains within masonry in the dome of the Santa Maria del Fiore cathedral in Florence.*

surface and some methodological improvements, EGP aims to surpass ScanPyramids' sensitivity after two years of data taking. Although still at the simulation studies stage, the detector technology – plastic scintillator bars with a triangular section and encapsulated wavelength shifter fibres – is already being used by the ongoing MURAVES muography project to scan the interior of the Vesuvius volcano in Italy. The project will also profit from synergy with the upcoming Mu2e experiment at Fermilab, where the very same detectors are used. Finally, proponents of the ScIDEP (Scintillator Imaging Detector for the Egyptian Pyramids) experiment from Egypt, the US and Belgium are giving Khafre's pyramid a second look, using a high-resolution scintillator-based detector to take data from the same location as Alvarez's spark chambers.

Pyramids easily make headlines, but there is no scarcity of monuments around the world where muography can play a role. Recently, a Russian team used emulsion detectors to explore the Svyato-Troitsky Danilov Monastery, the main buildings of which have undergone several renovations across the centuries but with associated documentation lost. The results of their survey, published in 2022, include evidence for two unknown rooms and areas of significantly higher density (possible walls) in the immured parts of certain vaults, and of underground voids speculated to be ancient crypts or air ducts. Muography is also being used to preserve buildings of historical importance. The defensive wall structures of Xi'an, one of the Four Great Ancient Capitals of China, suffered serious damage due to heavy rainfall, but repairs in the 1980s were insufficiently documented, motivating non-destructive techniques to assess their internal status. Taking data from six different locations using a compact and portable muon detector to extract a 3D density map of a rampart, a Chinese team led by Lanzhou University has recently reported density anomalies that potentially pose safety hazards (see "Falling walls" figure).

The many flavours of muography

All the examples described so far are based on the same basic principle as Alvarez's experiment: the attenuation of the muon flux through dense matter. But there are other ways to utilise muons as probes. For example, it is possible to exploit their deflection in matter due to Coulomb scattering from nuclei, offering the possibility of elemental discrimination. Such muon scattering tomography (MST) has been proposed to help preserve the Santa Maria del Fiore cathedral in Florence, built between 1420 and 1436 by Filippo Brunelleschi, the iconic dome of which is cracking under its own weight. Accurate modelling is needed to guide reinforcement efforts, but uncertainties exist on the internal structure of the walls. According to some experts, Brunelleschi might have inserted iron chains inside the masonry of the dome to stabilise it; however, no conclusive evidence has been obtained with traditional remote-sensing methods. Searching for iron within masonry is therefore the goal of the proposed experiment (see "Preserving a masterpiece" figure), for which a proof-of-principle test on a mock-up wall has already been carried out in Los Alamos.

Beyond cultural heritage, muography has also been advocated as a powerful remote-sensing method for a variety of applications in the nuclear sector. It has been used, for example, to assess the damage and impact of radioactivity in the Fukushima power plant, where four nuclear reactors were damaged in 2011. Absorption-based muography was applied to determine the difference in the density, for example the thickness of the walls, within the nuclear reactor while MST was applied to locate the nuclear fuel. Muography, especially MST, has allowed the investigation of other extreme systems, including blast furnaces and nuclear waste barrels.

Volcanology is a further important application of muography, where it is used to discover empty magma chambers and voids. As muons are better absorbed by thick and dense objects, such as rocks on the bottom of a volcano, the absorption provides key information about its inner structure. The density images created via muography can even be fed into machine-learning models to help predict eruptive patterns, and similar methods can be applied to glaciology, as has been done to estimate the topography of mountains hidden by overlaying glaciers. Among these projects is Eiger-μ, designed to explore the mechanisms of glacial erosion.

Powerful partnership

Muography creates bridges across the world between particle physics and cultural-heritage preservation. The ability to perform radiography of a large object from a distance or from pre-existing tunnels is very appealing in situations where invasive excavations are impossible, as is often the case in highly populated urban or severely constrained areas. Geophysical remote-sensing methods are already part of the archaeological toolkit, but in general they are expensive, have a limited resolution and demand strong model assumptions for interpreting the data. Muography is now gaining acceptance in the cultural-heritage preservation world because its data are intrinsically directional and can be easily interpreted in terms of density distributions.

From the pioneering work of Alvarez to the state-of-the-art systems available today, progress in muography has gone hand-in-hand with the development of detectors for particle physics. The ScanPyramids project, for example, uses micropattern gaseous detectors such as those developed within the CERN RD51 collaboration and nuclear emulsion detectors as those of the OPERA neutrino experiment, while the upcoming EGP project will benefit from detector technologies for the Mu2e experiment at Fermilab. R&D for next-generation muography includes the development of scintillator-based muon detectors, resistive plate chambers, trackers based on multi-wire proportional chambers and more. There are proposals to use microstrip silicon detectors from the CMS experiment and Cherenkov telescopes inspired by the CTA astrophysics project, showing how R&D for fundamental physics continues to drive exotic applications in archaeology and cultural-heritage preservation. ●

Muography creates bridges across the world between particle physics and cultural-heritage preservation

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NEW SUPERCONDUCTING TECHNOLOGIES FOR THE HL-LHC AND BEYOND

The development at CERN of magnesium diboride cables and other advanced superconducting systems for the High-Luminosity LHC is also driving applications beyond fundamental research, describes Amalia Ballarino.

The era of high-temperature superconductivity started in 1986 with the discovery, by IBM researchers Georg Bednorz and Alex Muller, of superconductivity in a lanthanum barium copper oxide. This discovery was revolutionary: not only did the new, brittle superconducting compound belong to the family of ceramic oxides, which are generally insulators, but it had the highest critical temperature ever recorded (up to 35 K, compared with about 18 K in conventional superconductors). In the following years, scientists discovered other cuprate superconductors (bismuth–strontium–copper oxide and yttrium–barium–copper oxide) and achieved superconductivity at temperatures above 77 K, the boiling point of liquid nitrogen (see "Heat is rising" figure, p38). The possibility of operating superconducting systems with inexpensive, abundant and inert liquid nitrogen generated tremendous enthusiasm in the superconducting community.

Several applications of high-temperature superconducting materials with a potentially high impact on society were studied. Among them, superconducting transmission lines were identified as an innovative and effective solution for bulk power transmission. The unique advantages of superconducting transmission are high capacity, very compact volume and low losses. This enables the sustainable transfer of up to tens of GW of power at low and medium voltages in narrow channels, together with energy savings. Demonstrators have been built worldwide in conjunction with industry and utility companies, some of which have successfully operated in national electricity grids. However, widespread adoption of the technology has been hindered by the cost of cuprate superconductors.

In particle physics, superconducting magnets allow high-energy beams to circulate in colliders and provide stronger fields for detectors to be able to handle higher collision energies. The LHC is the largest superconducting machine ever built, and the first to also employ high-temperature superconductors at scale. Realising its high-luminosity upgrade and possible future colliders is driving the use of next-generation superconducting materials, with applications stretching far beyond fundamental research.


CERN

Link to the future *Tests at CERN of a full-scale 120 kA MgB_2-based superconducting link "Demo 3", colloquially known as the "python", for the High-Luminosity LHC.*

High-temperature superconductivity (HTS) was discovered at the time when the conceptual study for the LHC was ongoing. While the new materials were still in a development phase, the potential of HTS for use in electrical transmission was immediately recognised. The powering of the LHC magnets (which are based on the conventional superconductor niobium titanium, cooled by superfluid helium) requires the transfer of about 3.4 MA of current, generated at room temperature, in and out of the cryogenic environment. This is done via devices called current leads, of which more than 3000 units are installed at different underground locations around the LHC's circumference. The conventional current-lead design, based on vapour-cooled metallic conductors, imposes a lower limit (about 1.1 W/kA) on the heat in-leak into the liquid helium. The adoption of the HTS BSCCO 2223 (bismuth–strontium–calcium copper oxide ceramic) tape – operated in the LHC current leads in the temperature range 4.5 to 50 K – enabled thermal conduction and ohmic dissipation to be disentangled. Successful multi-disciplinary R&D followed by prototyping at CERN and then industrialisation, with series production of the approximately 1100 LHC HTS current leads starting in 2004, resulted in both capital

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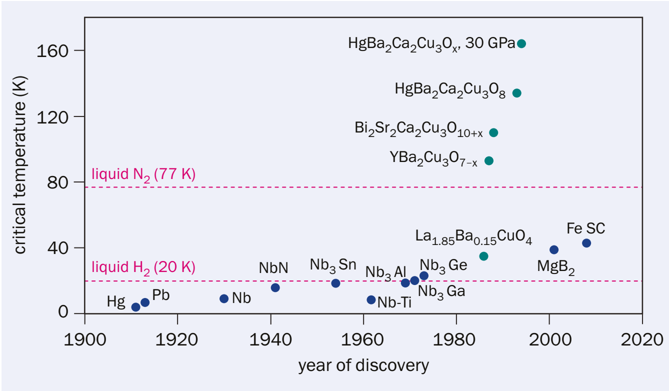
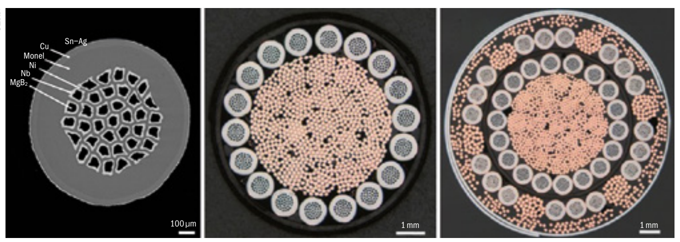


Heat is rising *Critical temperature of superconductors versus year of discovery, with cuprate superconductors shown in green. Fe SC stands for iron-based superconductors.*

CERN



Complex cabling *Left: a 1 mm diameter MgB_2 round wire; centre: a MgB_2 round cable, about 7 mm in diameter, capable of carrying a 3 kA current at a temperature of 25 K in a magnetic field of 0.7 T; right: a coaxial MgB_2 cable, capable of carrying 3 kA at 25 K.*

and operational savings (avoiding one extra cryoplant and an economy of about 5000 l/h of liquid helium). It also encouraged wider adoption of BSCCO 2223 current-lead technology, for instance in the magnet circuits for the ITER tokamak, which benefit via a collaboration agreement with CERN on the development and design of HTS current leads.

MgB_2 links at the HL-LHC

The discovery of superconductivity in magnesium diboride (MgB_2) in 2001 generated new enthusiasm for HTS applications. This material,classified as medium-temperature superconductor, has remarkable features: it has a critical temperature (39 K) some 30 K higher than that of niobium titanium, a high current density (to date in low and medium magnetic fields) and, crucially, it can be industrially produced as round multi-filamentary wire in long (km) lengths. These characteristics, along with a cost that is intrinsically lower than other available HTS materials, make it a promising candidate for electrical applications.

At the LHC the current leads are located in the eight straight sections. For the high-luminosity upgrade of the LHC (HL-LHC), scheduled to be operational in 2029, the decision was taken to locate the power converters in new, radiation-free underground technical galleries above the LHC tunnel. The distance between the power converters and the HL-LHC magnets spans about 100 m and includes a vertical path via an 8 m shaft connecting the technical galleries and the LHC tunnel. The large current to be transferred across such distance, the need for compactness, and the search for energy efficiency and potential savings led to the selection of HTS transmission as the enabling technology.

The electrical connection, at cryogenic temperature, between the HL-LHC current leads and the magnets is performed via superconducting links based on MgB_2 technology. MgB_2 wire is assembled in cables with different layouts to transfer currents ranging from 0.6 kA to 18 kA. The individual cables are then arranged in a compact assembly that constitutes the final cable feeding the magnet circuits of either the HL-LHC inner triplets (a series of quadrupole magnets that provides the final focusing of the proton beams before collision in ATLAS and CMS) or the HL-LHC matching sections (which match the optics in the arcs to those at the entrance of the final-focus quadrupoles), and the final cable is incorporated in a flexible cryostat with an external diameter of up to 220 mm. The eight HL-LHC superconducting links are about 100 m long and transfer currents of about 120 kA for the triplets and 50 kA for the matching sections at temperatures up to 25 K, with cryogenic cooling performed with helium gas.

The R&D programme for the HL-LHC superconducting links started in around 2010 with the evaluation of the MgB_2 conductor and the development, with industry, of a round wire with mechanical properties enabling cabling after reaction. Brittle superconductors, such as Nb_3Sn – used in the HL-LHC quadrupoles and also under study for future high-field magnets – need to be reacted into the superconducting phase via heat treatments, at high temperatures, performed after their assembly in the final configuration. In other words, those conductors are not superconducting until cabling and winding have been performed. When the R&D programme was initiated, industrial MgB_2 conductor existed in the form of multi-filamentary tape, which was successfully used by ASG Superconductors in industrial open MRI systems for transporting currents of a few hundred amperes. The requirement for the HL-LHC to transfer current to multiple circuits for a total of up to 120 kA in a compact configuration, with multiple twisting and transposition steps necessary to provide uniform current distribution in both the wires and cables, called for the development of an optimised multi-filamentary round wire.

Carried out in conjunction with ASG Superconductors, this development led to the introduction of thin niobium barriers around the MgB_2 superconducting filaments to separate MgB_2 from the surrounding nickel and avoid the formation of brittle MgB_2–Ni reaction layers that compromise electro-mechanical performance; the adoption of higher purity boron powder to increase current capability; the optimisation in the fraction of Monel (a nickel-copper alloy used as the main constituent of the wire) in the 1 mm-diameter wire to improve mechanical properties; the minimisation of filament size (about 55 µm) and twist pitch (about 100 mm) for the benefit of electro-mechanical properties; the addition of a copper stabiliser around the Monel matrix; and the coating of tin-silver onto the copper to ensure the surface quality of the wire and a controlled electrical resistance among wires (inter-strand resistance) when assembled into cables. After successive implementation and in-depth experimental validation of all improvements, a robust 1 mm-diameter MgB_2 wire with

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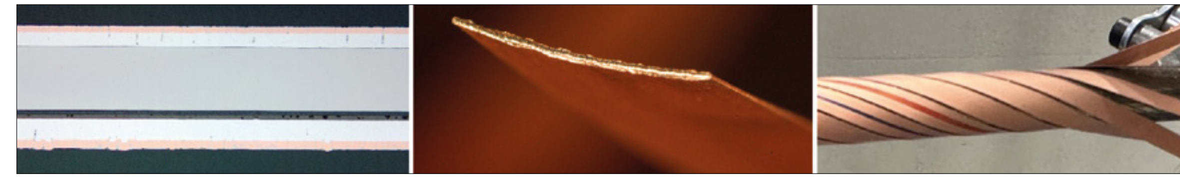

Bridging the gap *Shown on the left is a longitudinal cross-section of 4 mm-wide REBCO tape, pictured from a different perspective in the middle panel, and on the right is a 10 mm-diameter REBCO cable for 3 kA currents at 60 K.*

CERN

kA currents *Delivery and handling of the 120 kA MgB_2 cable assembly. The flexible, double-walled corrugated cryostat comprises 19 MgB_2 superconducting cables in a single assembly, twisted together to form a compact bundle. Each MgB_2 cable is about 140 m long with the bundle diameter around 90 mm.*

required electro-mechanical characteristics was produced.

The next step was to manufacture long unit lengths of MgB_2 wire via larger billets (the assembled composite rods that are then extruded and drawn down in a long wire). The target unit length of several kilometres was reached in 2018 when series procurement of the wire was launched. In parallel, different cable layouts were developed and validated at CERN. This included round MgB_2 cables in a co-axial configuration rated for 3 kA and for 18 kA at 25 K (see "Complex cabling" figure). While the prototypes made at CERN were 20 to 30 m long, the cable layout incorporated, from the outset, characteristics to enable production via industrial cabling machines of the type used for conventional cables. Splice techniques as well as detection and protection aspects were addressed in parallel with wire and cable development. Both technologies are strongly dependent on the characteristics of the superconductor, and are of key importance for the reliability of the final system.

The first qualification at 24 K of a 20 kA MgB_2 cable produced at CERN, comprising two 20 m lengths connected together, took place in 2014. This followed the qualification at CERN of short-model cables and other technological aspects, as well as the construction of a dedicated test station enabling the measurement of long cables operated at higher temperatures, in a forced flow of helium gas. The cables were then industrially produced at TRATOS Cavi via a contract with ICAS, in a close and fruitful collaboration that enabled – while operating heavy industrial equipment – the requirements identified during the R&D phase. The complexity of the final cables required a multi-step process that used different cabling, braiding and electrically insulating lines, and the implementation of a corresponding quality-assurance programme. The first industrial cables, which were 60 m long, were successfully qualified at CERN in 2018. Final prototype cables of the type needed for the HL-LHC (for both the triplets and matching sections) were validated at CERN in 2020, when series production of the final cables was launched. As of today, the full series of about 1450 km of MgB_2 wire – the first large-scale production of this material – and five of the eight final MgB_2 cables needed for the HL-LHC have been produced.

Superconducting wire and cables are the core of a superconducting system, but the system itself requires a global optimisation, which is achieved via an integrated design. Following this approach, the challenge was to investigate and develop, in industry, long and flexible cryostats for the superconducting links with enhanced cryogenic performance. The goal was to achieve a low static heat load (<1.5 W/m) into the cryogenic volume of the superconducting cables while adopting a design – a two-wall cryostat without intermediate thermal screen – that simplifies the cooling of the system, improves the mechanical flexibility of the links and eases handling during transport and installation. This development, which ran in parallel with the wire and cable activities, led to the desired results and, after an extensive test campaign at CERN, the developed technology was adopted. Series production of these cryostats is taking place at Cryoworld in the Netherlands.

The optimised system minimises the cryogenic cost for the cooling such that a superconducting link transfers – from the tunnel to the technical galleries – just enough helium gas to cool the resistive section of the current leads and brings it to the temperature (about 20 K) for which the leads are optimised. In other words, the superconducting link does not add cryogenic cost to the refrigeration of the system. The links, which are rated for currents up to 120 kA, are sufficiently flexible to be transported, as for conventional power cables, on drums about 4 m in diameter and can be manually pulled, without major tooling, during installation (see "kA currents" image). The challenge of dealing

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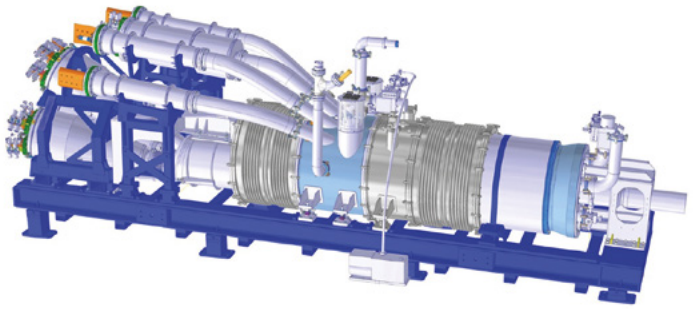


End of the line *Cryostat termination of the superconducting link with the HTS current leads integrated. The total length is about 5.5 m. (Credit: CERN)*

with the thermal contraction of the superconducting links, which shrink by about 0.5 m when cooled down to cryogenic temperature, was also addressed. An innovative solution, which takes advantage of bends and is compatible with the fixed position of the current lead cryostat, was validated with prototype tests.

Novel HTS leads

Whereas MgB_2 cables transfer high DC currents from the 4.5 K liquid helium environment in the LHC tunnel to about 20 K in the HL-LHC new underground galleries, a different superconducting material is required to transfer the current from 20 to 50 K, where the resistive part of the current leads makes the bridge to room temperature. To cope with the system requirements, novel HTS current leads based on REBCO (rare-earth barium copper oxide) HTS superconducting tape – a material still in a development phase at the time of the LHC study – have been conceived, constructed and qualified to perform this task (see "Bridging the gap" image). Compact, round REBCO cables ensure, across a short (few-metre-long) length, the electrical transfer from the MgB_2 to 50 K, after which the resistive part of the current leads finally brings the current to room temperature. In view of the complexity of dealing with the REBCO conductor, the corresponding R&D was done at CERN, where a complex dedicated cabling machine was also constructed.

While REBCO tape is procured from industry, the challenges encountered during the development of the cables were many. Specific issues associated with the tape conductor, for example electrical resistance internal to the tape and the dependence of electrical properties on temperature and cycles applied during soldering, were identified and solved with the tape manufacturers. A conservative approach imposing zero critical current degradation of the tape after cabling was implemented. The lessons learnt from this development are also instrumental for future projects employing REBCO conductors, including the development of high-field REBCO coils for future accelerator magnets.

The full series of about 1450 km of MgB_2 wire and five of the eight MgB_2 final cables needed for the HL-LHC have now been produced

The series components of the HL-LHC cold-powering systems (superconducting links with corresponding terminations) are now in production, with the aim to have all systems available and qualified in 2025 for installation in the LHC underground areas during the following years. Series production and industrialisation were preceded by the completion of R&D and technological validations at CERN. Important milestones have been the test of a sub-scale 18 kA superconducting link connected to a pair of novel REBCO current leads in 2019, and the test of full-cross section, 60 m-long superconducting lines of the type needed for the LHC triplets and for the matching sections, both in 2020.

The complex terminations of the superconducting links involve two types of cryostat that contain, at the 20 K side, the HTS current leads and the splices between REBCO and MgB_2 cables and, at the 4.2 K side, the splices between the niobium titanium and the MgB_2 cables. A specific development in the design was to increase compactness and enable the connection of the cryostat with the current leads to the superconducting link at the surface, prior to installation in the HL-LHC underground areas (see "End of the line" figure). The series production of the two cryostat terminations is taking place via collaboration agreements with the University of Southampton and Uppsala University.

The displacement of the current leads via the adoption of superconducting links brings a number of advantages. These include freeing precious space in the main collider ring, which becomes available for other accelerator equipment, and the ability to locate powering equipment and associated electronics in radiation-free areas. The latter relaxes radiation-hardness requirements for the hardware and eases access for personnel to carry out the various interventions required during accelerator operations.

Cooling with low-density helium gas also makes electrical transfer across long vertical distances feasible. The ability to transfer high currents from underground tunnels to surface buildings – as initially studied for the HL-LHC – is therefore of interest for future machines, such as the proposed Future Circular Collider at CERN. Flexible superconducting links can also be applied to "push–pull" arrangements of detectors at linear colliders such as the proposed CLIC and ILC, where the adoption of flexible powering lines can simplify and reduce the time for the exchange of experiments sharing the same interaction region.

An enabling technology

Going beyond fundamental research in physics, superconductivity is an enabling technology for the transfer of GWs of power across long distances. The main benefits, in addition to incomparably higher power transmission, are small size, low total electrical losses, minimised environmental impact and more sustainable transmission. HTS offers the possibility of replacing resistive high-voltage overhead lines, operated across thousands of kilometres at voltages reaching about 1000 kV, with lower voltage lines, laid underground with reduced footprints.

Long-distance power transmission using hydrogen-cooled MgB_2 superconducting links, potentially associated with renewable energy sources, is identified as one of the leading ways towards a future sustainable energy system. Since hydrogen is liquid at 20 K (the temperature at which MgB_2 is superconducting), large amounts can be stored and used as a coolant for superconducting lines, acting at the same time as the energy vector and cryogen. In this direction, CERN participated – at a very early stage of the HL-LHC superconducting links development – in a project launched by Carlo Rubbia as scientific director of the Institute for Advanced Sustainability Studies (IASS) in Potsdam. Around 10 years ago, CERN and IASS joint research culminated in the record demonstration of the first 20 kA MgB_2 transmission line operated at liquid hydrogen temperature. This activity continued with a European initiative called BestPaths, which demonstrated a monopole MgB_2 cable system operated in helium gas at 20 K. This was qualified in industry for 320 kV operation and at 10 kA at CERN, proving 3.2 GW power transmission capability. This initiative involved European industry and France's transmission system operator. In Italy, the INFN has recently launched a project called IRIS based on similar technology (see *CERN Courier* January/February 2023 p9).

In addition to transferring power across long distances with low losses and minimal environmental impact, the development of high-performance, low-cost, sustainable and environmentally friendly energy storage and production systems is a key challenge for society. The use of hydrogen can diversify energy sources as it significantly reduces greenhouse-gas emissions and environmental pollution during energy conversion. In aviation, alternative-propulsion systems are studied to reduce CO_2 emission and move toward zero-emission flights. Scaling up electric propulsion to larger aircraft is a major challenge. Superconducting technologies are a promising solution as they can increase power density in the propulsion chain while significantly lowering the mass of the electrical distribution system. In this context, a collaboration agreement has recently been launched between CERN and Airbus UpNext. The construction of a demonstrator of superconducting distribution in aircraft called SCALE (Super-Conductor for Aviation with Low Emissions), which uses the HL-LHC superconducting link technology, was recently launched at CERN.

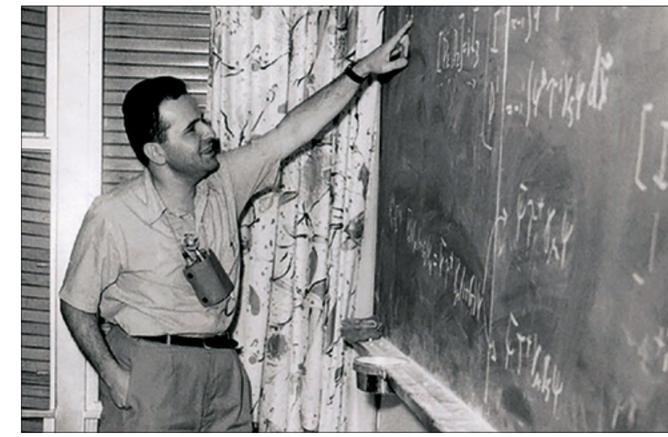
CERN's developed experience in superconducting-link technology is also of interest to large data centres, with a collaboration agreement between CERN and Meta under discussion. The possibility of locating energy equipment remotely from servers, of transferring efficiently large power in a compact volume, and of meeting sustainability goals by reducing carbon footprints are motivating a global re-evaluation of conventional systems in light of the potential of superconducting transmission.

The use of hydrogen can diversify energy sources as it significantly reduces greenhouse-gas emissions and environmental pollution during energy conversion

Such applications demonstrate the virtuous circle between fundamental and applied research. The requirements of fundamental exploration in particle physics research have led to the development of increasingly powerful and sophisticated accelerators. In this endeavour, scientists and engineers engage in developments initially conceived to address specific challenges. This often requires a multi-disciplinary approach and collaboration with industry to transform prototypes into mature technology ready for large-scale application. Accelerator technology is a key driver of innovation that may also have a wider impact on society. The superconducting-link system for the HL-LHC project is a shining example. ●

THE CABIBBO ANGLE, 60 YEARS LATER

Before the discovery of quarks, Nicola Cabibbo arrived at the correct formulation of the mechanism responsible for quark mixing. Luciano Maiani, Guido Martinelli and Giorgio Parisi recount Cabibbo's 1963 feat, which paved the way to the unification of electromagnetic and weak interactions.



Family photograph

Masterful *The young Cabibbo lecturing at about the time he proposed his angle.*

In a 1961 book, Richard Feynman describes the great satisfaction he and Murray Gell-Mann felt in formulating a theory that explained the close equality of the Fermi constants for muon and neutron-beta decay. These two physicists and, independently, Gershtein and Zeldovich, had discovered the universality of weak interactions. It was a generalisation of the universality of electric charge and strongly suggested the existence of a common origin of the two interactions, an insight that was the basis for unified theories developed later.

Fermi's description of neutron beta decay ($n \rightarrow p + e^- + \bar{\nu}_e$) involved the product of two vector currents analogous to the electromagnetic current: a nuclear current transforming the neutron into a proton and a leptonic current creating the electron–antineutrino pair. Subsequent studies of nuclear decays and the discovery of parity violation complicated the description, introducing all possible kinds of relativistically invariant interactions that could be responsible for neutron beta decay.

The decay of the muon ($\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$) was also found to involve the product of two vector currents, one transforming the muon into its own neutrino and the other creating the electron–antineutrino pair. What Feynman and Gell-Mann, and Gershtein and Zeldovich, had found is that the nuclear and lepton vector currents have the same strength, despite the fact that the $n \rightarrow p$ transition is affected by the strong nuclear interaction while $\mu \rightarrow \nu_\mu$ and $e \rightarrow \nu_e$ transitions are not (we are anticipating here what was discovered only later, namely that the electron and muon each have their own neutrino).

At the end of the 1950s, simplicity finally emerged. As proposed by Sudarshan and Marshak, and by Feynman and Gell-Mann, all known beta decays are described by the products of two currents, each a combination of a vector and an axial vector current. Feynman notes: after 23 years, we are back to Fermi!

The book of 1961, however, also records Feynman's dismay after the discovery that the Fermi constants of strange-particle beta decays, for example the lambda-hyperon beta decay: $\Lambda \rightarrow p + e^- + \bar{\nu}_e$ were smaller by a factor of four or five than the theoretical prediction. In 1960 Gell-Mann, together with Maurice Lévy, had tried to solve the problem but, while taking a step in the right direction, they concluded that it was not possible to make quantitative predictions for the observed decays of the hyperons. It was up to Nicola Cabibbo, in a short article published in 1963 in *Physical Review Letters*, to reconcile strange-particle decays with the universality of weak interactions, paving the way to the modern unification of electromagnetic and weak interactions.

Over to Frascati

Nicola had graduated in Rome in 1958, under his tutor Bruno Touschek. Hired by Giorgio Salvini, he was the first theoretical physicist in the Electro-Synchrotron Frascati laboratories. There, Nicola met Raoul Gatto, five years his elder, who was coming back from Berkeley, and they began an extremely fruitful collaboration.

These were exciting times in Frascati: the first e^+e^- collider, AdA (Anello di Accumulazione), was being realised, to

THE AUTHORS

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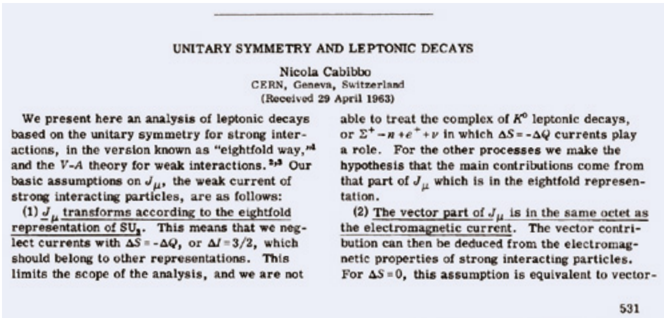

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

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New angle *Cabibbo's 1963 paper in which he concluded that the vector-coupling constant for strange-particle beta decay is modified by a factor sinθ, with θ forever since known as the Cabibbo angle.*

There are very few articles in the scientific literature in which one does not feel the need to change a single word and Cabibbo's is definitely one of them

be followed later by a larger machine, Adone, reaching up to 3GeV in the centre of mass. New particles were studied at the electro-synchrotron, related to the newly discovered SU(3) flavour symmetry (e.g. the η meson). Cabibbo and Gatto authored an important article on e^+e^- physics and, in 1961, they investigated the weak interactions of hadrons in the framework of the SU(3) symmetry. Gatto and Cabibbo and, at the same time, Coleman and Glashow, observed that vector currents associated with the SU(3) symmetry by Noether's theorem include a strangeness-changing current, V(ΔS = 1), that could be associated with strangeness-changing beta-decays in addition to the isospin current, V(ΔS = 0), responsible for strangeness-non-changing beta decays – the same considered by Feynman and Gell-Mann. For strange-particle decays, the identification implied that the variation of strangeness in the hadronic system has to be equal to the variation of the electric charge (in short: ΔS = ΔQ). The rule is satisfied in Λ beta decay (Λ: S = –1, Q = 0; p: S = 0, Q = +1). However, it conflicted with a single event allegedly observed at Berkeley in 1962 and interpreted as $\Sigma^+ \to n + \mu^+ + \nu_\mu$, which had ΔS = –ΔQ ($\Sigma^+$: S = –1, Q = +1; n: S = Q = 0). In addition, the problem remained of how to correctly formulate the concept of muon-hadron universality in the presence of four vector currents describing the transitions $e \to \nu_e$, $\mu \to \nu_\mu$, $n \to p$ and $\Lambda \to p$.

Cabibbo's angle

In his 1963 paper, written while he was working at CERN, Nicola made a few decisive steps. First, he decided to ignore the evidence of a ΔS = –ΔQ component suggested by Berkeley's $\Sigma^+ \to n + \mu^+ + \nu_\mu$ event. Nicola was a good friend of Paolo Franzini, then at Columbia University, and the fact that Paolo, with larger statistics, had not yet seen any such event provided a crucial hint. Next, to describe both ΔS = 0 and ΔS = 1 weak decays, Nicola formulated a notion of universality between each leptonic vector current (electronic or muonic) and one, and only one, hadronic vector current. He assumed the current to be a combination of the two currents determined by the SU(3) symmetry that he had studied with Gatto in Frascati (also identified by Coleman and Glashow): $V_{hadron} = aV(\Delta S = 0) + bV(\Delta S = 1)$, with a and b being numerical constants. By construction, V(ΔS = 0) and V(ΔS = 1) have the same strength of the electron or of the muon currents; for the hadronic current to have the same strength, one requires $a^2 + b^2 = 1$, that is $a = \cos\theta$, $b = \sin\theta$.

Cabibbo obtained the final expression of the hadronic weak current, adding to these hypotheses the V–A formulation of the weak interactions. The angle θ became a new constant of nature, known since then as the Cabibbo angle.

An important point is that the Cabibbo theory is based on the currents associated with SU(3) symmetry. For one, this means that it can be applied to the beta decays of all hadrons, mesons and baryons belonging to the different SU(3) multiplets. This was not the case for the precursory Gell-Mann–Lévy theory, which also assumed one hadron weak current but was formulated in terms of protons and lambdas, and could not be applied to the other hyperons or to the mesons. In addition, in the limit of exact SU(3) symmetry one can prove a non-renormalisation theorem for the ΔS = 1 vector current, which is entirely analogous to the one proved by Feynman and Gell-Mann for the ΔS = 0 isospin current. The Cabibbo combination, then, guarantees the universality of the full hadron weak current to the lepton current for any value of the Cabibbo angle, the suppression of the beta decays of strange particles being naturally explained by a small value of θ. Remarkably, a theorem derived by Ademollo and Gatto, and by Fubini a few years later, states that the non-renormalisation of the vector current's strength is also valid to the first order in SU(3) symmetry breaking.

Photons and quarks

In many instances, Nicola mentioned that a source of inspiration for his assumption for the hadron current was the passage of photons through a polarimeter, a subject he had considered in Frascati in connection with possible experiments of electron scattering through polarised crystals. Linearly polarised photons can be described via two orthogonal states, but what is transmitted is only the linear combination corresponding to the direction determined by the polarimeter. Similarly, there are two orthogonal hadron currents, V (ΔS = 0) and V (ΔS = 1), but only the Cabibbo combination couples to the weak interactions.

An interpretation closer to particle physics came with the discovery of quarks. In quark language, V(ΔS = 0) induces the transition $d \to u$ and V(ΔS = 1) the transition $s \to u$. The Cabibbo combination corresponds then to $d_C = (\cos\theta d + \sin\theta s) \to u$. Stated differently, the u quark is coupled by the weak interaction only to one, specific,superposition of d and s quarks: the Cabibbo combination d_C. This is Cabibbo

mixing, reflecting the fact that in SU(3) there are two quarks with the same charge –1/3.

A first comparison between theory and meson and hyperon beta-decay data was done by Cabibbo in his original paper, in the exact SU(3) limit. Specifically, the value of θ was obtained by comparing K^+ and π^+ semileptonic decays. In baryon semileptonic decays, the matrix elements of vector currents are determined by the SU(3) symmetry, while axial currents depend upon two parameters, the so-called F and D couplings. Many fits have been performed in successive years, which saw a dramatic increase in the decay modes observed, in statistics, and in precision.

Four decades after the 1963 paper, Cabibbo, with Earl Swallow and Roland Winston, performed a complete analysis of hyperon decays in the Cabibbo theory, then embedded in the three-generation Kobayashi and Maskawa theory, taking into account the momentum dependence of vector currents. In their words (and in modern notation): "... we obtain $V_{us} = 0.2250(27)$ (= sin θ). This value is of similar precision, but higher than the one derived from Kl3, and in better agreement with the unitarity requirement, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. We find that the Cabibbo model gives an excellent fit of the existing form factor data on baryon beta decays ($\chi^2 = 2.96$) for three degrees of freedom with F + D = 1.2670 ± 0.0030, F–D = –0.341±0.016, and no indication of flavour SU(3) breaking effects."

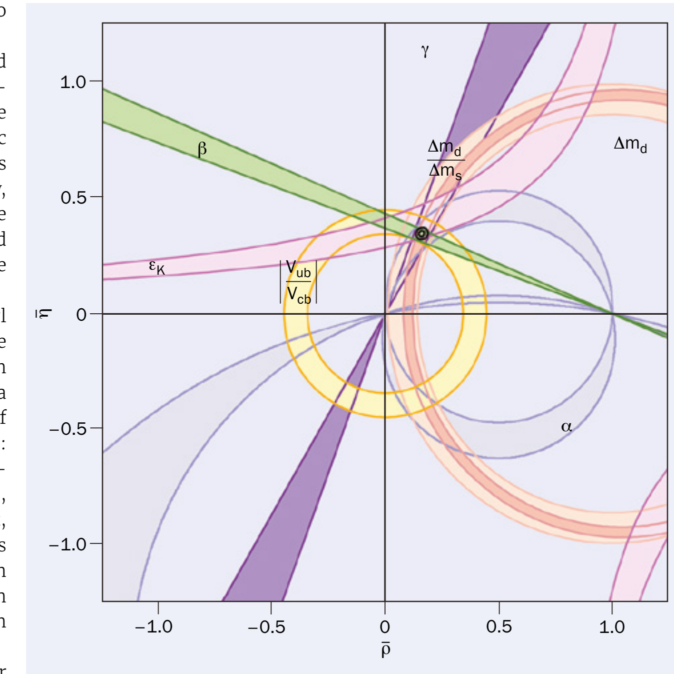
The Cabibbo theory predicts a reduction in the nuclear Fermi constant squared with respect to the muonic one by a factor $\cos^2\theta = 0.97$. The discrepancy had been noticed by Feynman and S Berman, one of Feynman's students, who estimated the possible effect of electromagnetic radiative corrections. The situation is much clearer today, with precise data coming from super-allowed Fermi nuclear transitions and radiative corrections under control.

Closing up

From its very publication, the Cabibbo theory was seen as a crucial development. It indicated the correct way to embody lepton-hadron universality and it enjoyed a heartening phenomenological success, which in turn indicated that we could be on the right track for a fundamental theory of weak interactions.

The idea of quark mixing had profound consequences. It prompted the solution of the spectacular suppression of strangeness-changing neutral processes by the GIM mechanism (Glashow, Iliopoulos and Maiani), where the charm quark couples to the combination of down and strange quarks orthogonal to the Cabibbo combination. Building on Cabibbo mixing and GIM, it has been possible to extend to hadrons the unified $SU(2)_L \otimes U(1)$ theory formulated, for leptons, by Glashow, and by Weinberg and Salam.

CP symmetry violations observed experimentally had no place in the two-generation scheme (four quarks, four leptons) but found an elegant description by Makoto Kobayashi and Toshihide Maskawa in the extension to three generations. Quark mixing introduced by Cabibbo is now described by a three-by-three unitary matrix known in the literature as the Cabibbo–Kobayashi–Maskawa (CKM) matrix. In the past 50 years the CKM scheme has been confirmed with ever increasing accuracy by a plethora of measurements



Source: UTfit/arXiv:2212.03894

Testing quark mixing *The unitarity triangle (defined by the angles α, β and γ), which exists in the complex $\bar\rho - \bar\eta$ plane, represents a requirement that the Cabibbo–Kobayashi–Maskawa (CKM) matrix is unitary, meaning that the number of quarks is conserved in weak interactions and that there are only three generations of quarks. Its area is a measure of the amount of CP violation in the Standard Model. Checking the consistency of different measurements of the unitarity triangle is an important test of the Standard Model. At the apex of the triangle, closed contours at 68% and 95% probability are shown. Full lines correspond to 95% probability regions for each of the physical constraints, given, respectively, by the measurements of $|V_{ub}| / |V_{cb}|$ from semileptonic $b \to c$ and $b \to u$ decays; the $B^0_{d,s} - \bar{B}^0_{d,s}$ mixing amplitudes, Δm_d and Δm_s; the $K^0 - \bar{K}^0$ CP violation parameter ε_K; the angle α from $B \to \pi\pi$, $B \to \rho\pi$ and $B \to \rho\rho$ decays; $\sin^2\beta$ from the measurement of the CP asymmetry in the $J/\psi K^0$ decays; and the angle γ from $B \to D^{(*)}K^{(*)}$ decays.*

and impressive theoretical predictions (see "Testing quark mixing" figure). Major achievements have been obtained in the studies of charm- and beauty-particle decays and mixing. The CKM paradigm remains a great success in predicting weak processes and in our understanding of the sources of CP violation in our universe.

Nicola Cabibbo passed away in 2010. The authoritative book by Abraham Pais, in its chronology, cites the Cabibbo theory among the most important developments in post-war particle physics. In the *History of CERN*, Jean Iliopoulos writes: "There are very few articles in the scientific literature in which one does not feel the need to change a single word and Cabibbo's is definitely one of them. With this work, he established himself as one of the leading theorists in the domain of weak interactions." ●

Further reading

N Cabibbo 1963 *Phys. Rev. Lett.* **10** 531.

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OPINION VIEWPOINT

We can't wait for a future collider

Future colliders are inherently "early-career colliders", and our perspectives must be incorporated into decision making, says Karri DiPetrillo.

K Nimkar

Karri DiPetrillo *is assistant professor at the University of Chicago and a member of the ATLAS collaboration.*

Snowmass local organizing committee

Speaking out *Participants of the Snowmass community workshop in Seattle in July 2022.*

Imagine a world without a high-energy collider. Without our most powerful instrument for directly exploring the smallest scales, we would be incapable of addressing many open questions in particle physics. With the US particle-physics community currently debating which machines should succeed the LHC and how we should fit into the global landscape, this possibility is a serious concern.

The good news is that physicists generally agree on the science case for future colliders. Questions surrounding the Standard Model itself, in particular the microscopic nature of the Higgs boson and the origin of electroweak symmetry breaking, can only be addressed at high-energy colliders. We also know the Standard Model is not the complete picture of the universe. Experimental observations and theoretical concerns strongly suggest the existence of new particles at the multi-TeV scale.

The latest US Snowmass exercise and the European strategy update both advocate for the fast construction of an e^+e^- Higgs factory followed by a multi-TeV collider. The former will enable us to measure the Higgs boson's couplings to other particles with an order of magnitude better precision than the High-Luminosity LHC. The latter is crucial to unambiguously surpass exclusions from the LHC, and would be the only experiment where we could discover or exclude minimal dark-matter scenarios all the way up to their thermal targets. Most importantly, precise measurements of the Brout–Englert–Higgs potential at a 10 TeV scale collider are essential to understand what role the Higgs plays in the origin and evolution of the universe.

We haven't yet agreed on what to build, where and when. We face an unprecedented choice between scaling up existing collider technologies or pursuing new, compact and power-efficient options. We must also choose between centering the energy frontier at a single lab or restoring global balance to the field by hosting colliders at different sites. Our choices in the next few years could determine the next century of particle physics.

The Future Circular Collider programme – beginning with a large circular e^+e^- collider (FCC-ee) with energies ranging from 90 to 365 GeV, followed by a pp collider with energies up to 100 TeV (FCC-hh) – would build on the infrastructure and skills currently present at CERN. A circular e^+e^- machine could support multiple interaction points, produce higher luminosity than a linear machine for energies of interest, and its tunnel could be re-used for a pp collider. While this staged approach has driven success in our field for decades, scaling up to a circumference of 100 km raises serious questions about feasibility, cost and power consumption. As a new assistant professor, I am also deeply concerned about gaps in data-taking and time-scales. Even if there are no delays, I will likely retire during the FCC-ee run and die before the FCC-hh produces collisions.

Assuming the technical challenges can be overcome, a muon collider would be the most attractive way forward

In contrast, there is a growing contingent of physicists who think that a paradigm shift is essential to reach the 10 TeV scale and beyond. The International Muon Collider collaboration has determined that, with targeted R&D to address engineering challenges and make design progress, a few-TeV $\mu^+\mu^-$ collider could be realised on a 20-year technically limited timeline, and would set the stage for an eventual 10 TeV machine. The latter could enable a mass reach equivalent to a 50–200 TeV hadron collider, in addition to precision electroweak measurements, with a lower price tag and significantly smaller footprint. A muon collider also opens the possibility to host different machines at different sites, easing the transition between projects and fostering a healthier, more global workforce. Assuming the technical challenges can be overcome, a muon collider would therefore be the most attractive way forward.

We are not yet ready to decide which path is most optimal, but we are already time-constrained. It is increasingly likely that the next machine will not turn on until after the High Luminosity-LHC. The most senior person today who could reasonably participate is roughly only 10 years into a permanent job. Early-career faculty, who would use this machine, are experienced enough to have well-informed opinions, but are not senior enough to be appointed to decision-making panels. While we value the wisdom of our senior colleagues, future colliders are inherently "early-career colliders", and our perspectives must be incorporated.

The US must urgently invest in future collider R&D. If other areas of physics progress faster than the energy frontier, our colleagues will disengage, move elsewhere and might not come back. If the size of the field and expertise atrophy before the next machine, we risk imperilling future colliders altogether. We agree on the physics case. We want the opportunity to access higher energies in our lifetimes. Let's work together to choose the right path forward.

A game changer for CERN

CERN's new visitor centre, Science Gateway, due to open this autumn, will welcome up to half a million visitors each year. Project leader Patrick Geeraert describes how this iconic building came about, how it will operate and what it aims to achieve.

How did the idea for Science Gateway come about?

I was on detachment at the European Southern Observatory (ESO) in Garching when I was called back to CERN in 2017. The idea for a flagship education and outreach project was already being discussed, and since I had triggered the construction of ESO's Supernova planetarium and visitor centre during my mandate as director of administration, the CERN Director-General (DG) thought I could reiterate this for CERN. There had been various projects for buildings around the Globe, but they never quite took off. I proposed that we dream big to potentially attract another class of donors. The DG made it clear that a large auditorium for CERN events should be part of any plan, and that the entire construction should be financed by donations. I started to work on the concept.

The Italian architect Renzo Piano had visited CERN independently and fell in love with our values. When he left, he said: "If one day I can do something for you, don't hesitate." He proposed to draw the building. At first I hesitated because working with a star architect is not always easy. But it had the potential to help in attracting donors. In June 2018 he showed us his first mockup, the "space station" design you see today. It crossed the Route de Meyrin and encroached on land designated for agricultural use on the north side and the CERN kindergarten on the south side. The design complicated matters, but on the other hand it was really inspiring. My first thought was that my budget will not be sufficient because what is expensive when you do construction are the facades, and here we had five buildings, complicated ones, with some parts suspended. But it was so original, so much in the DNA of CERN, that we thought, okay, let it be five.


M Chalmers

Dreaming big *Science Gateway project leader Patrick Geeraert.*

What will be in the buildings?

There are three "pavilions" and two "tubes". On the north side of the Science Gateway, we have a 900-seat auditorium where we can host large CERN meetings such as collaboration weeks, as well as hiring the venue out. It's modular so we can split it in up to three different rooms and host independent events if needed. This element of the building caused most of the headaches. The second pavilion will house the reception, shop and restaurant. On the upper floor we have the two large lab spaces, where we will have two school groups at a time. Between the restaurant and the auditorium we have a natural amphitheatre where we can also hold events.

Then we enter the two tubes straddling the Route de Meyrin, which are exhibition areas. The first is about CERN – engaging visitors with accelerators, detectors, data acquisition and IT, etc. In the second tube, one half is a journey back to the Big Bang and the other is about open questions such as dark matter, dark energy, extra dimensions and such topics, where we will have art pieces to engage visitors. The third pavilion is an exhibition about the quantum world. The bridge linking the buildings is 220 m long and you can walk from one side to the other unimpeded.

How was the construction managed, and when will the building be open to the public?

The first problem was that the north side of the Science Gateway, previously a temporary car park, was on agricultural land. We had to reclassify that piece of land for it to be authorised to build on, which is extremely complicated in Geneva. The process usually takes at least 10 years if it is successful at all, and we got it done in one. We had a very constructive process with our host authorities, and the Renzo Piano team had made me a case with drawings and models to help communicate our vision. We got the building permit in September 2019 and launched a procurement process for the construction and for the scenographers regarding the exhibitions. In November 2020 we signed the contract with the construction companies and they started to erect the site barracks at the end of 2020. The construction is due to be completed this summer. It was an extremely aggressive schedule, made more difficult by the pandemic and factors relating to Russia's invasion of Ukraine. The inauguration will very likely be in the first week of October, with first visitors in the next day.

Who is the Science Gateway for?

The main objective is to inspire the next generation to engage in STEM (science, technology, engineering, mathematics) studies and careers. To do that, first you need to have a programme for different age ranges. Whereas traditionally we target 16 years and above, Science Gateway

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will start with workshops for visitors as young as five. The exhibitions are suited to all ages above eight. Ideally, we want to engage visitors before they reach high school because that's typically when girls start to think that STEM subjects are not for them. Another important audience is parents, so Science Gateway is also geared towards families and to show adults what it means to be a scientist along with showing diverse role models. The exhibits and installations are developed by a mix of in-house and outside expertise. For the labs, we rely on our education team, which has the experience of S'Cool LAB, but now that we have extended the age range of our audiences, we will also work closely with, for instance, the LEGO foundation, one of our donors, who are very strong in education programmes for children aged 5 to 12. Finally, Science Gateway is an opportunity for us to engage with VIPs and decision makers, to bring support to fundamental research and explain its impact on society.

Touchdown *Science Gateway photographed on 28 March during the installation of solar panels on the pavilion roofs.*

How many visitors do you expect?

A lot! Currently we have more than 300,000 demands for guided tours per year and we can only satisfy about half of them. From those 300,000, more than 70% are based more than 800 km away. The Science Gateway will allow us to welcome up to 500,000 people per year, which is more than 1000 per day on average. We will continue to attract schools and visitors from all CERN member states and beyond, that's for sure, and increase capacity for hands-on lab activities in particular. We also expect many more local visitors. Entry will be free, and we will be open to visitors all year, every day except Mondays. The Science Gateway will only be closed on 24, 25 and 31 December, and 1 January. For groups of 12 or more, people have to book in advance. But individuals and families can just show up on the day and access the auditorium, exhibition tubes, restaurant and the quantum-world pavilion. On the campus, they will also find temporary exhibitions in the Globe, and Ideasquare will also propose activities. Visitors can book a guided tour in the morning for that same day. Guided tours will remain at the same level as today, and we are trying to reduce pressure on existing restaurants on the Meyrin site with the new Science Gateway restaurant.

We will heavily rely on volunteers, from members of the personnel to users and other people linked with CERN

How is the Science Gateway funded?

The construction, landscaping, exhibitions and everything you will see in the building on day one are all funded from donations. The main donor, contributing CHF 45 million, is the Stellantis Foundation. Then we have a private foundation in Geneva that donates CHF 28 million, the LEGO foundation at CHF 5 million, and a number of other donors each at around CHF 2 million or less. So, currently it's about CHF 90 million in total, with some donors sponsoring particular exhibits or spaces. For the operations, the cost is estimated at around CHF 4 million per year. This will be funded from a mix of income from the infrastructure (for example, the shop, restaurant, parking and auditorium) and some limited CERN budget. The operational costs are for staffing in addition to maintenance of the equipment, cleaning and maintaining the forest that surrounds the building.

What is the operational model?

A Science Gateway operations group has been created from the former visits service. With the exception of a small increase in industrial services contracts and two fellows, there are basically no recruitments. We will heavily rely on volunteers, from members of the personnel to users and other people linked with CERN. We already have a pool of guides who provide on average 16,000 hours per year on guided tours and we need to double that amount to ensure the Science Gateway operates as required. We will encourage more people to become guides and start training in July. We want to emphasise that, in addition to the rewards of engaging visitors with CERN's science, this experience will be useful to their professional lives. We are also considering giving certificates and possibly accreditations. Ideally we should have about 650 guides each giving 48 hours per year.

What is the environmental philosophy behind Science Gateway?

We want to pass on the message that we're sustainable. We'll be carbon neutral when we are in the operations phase, and solar panels on the roof of the three pavilions will produce much more energy than we need, with 40% going back into the CERN grid. The use of geothermal probes was explored but had to be abandoned due to local geology. Heating and cooling will be provided by heat exchangers powered by our solar panels. In the restaurant we will avoid single-use plastics, and lights will be dimmed in the evening and switched off at night. There will also be a charge for parking to encourage visitors to come by public transport. We wanted to show the link between science and nature, and that's why we have the forest, with 400 trees and 13,000 shrubs.

How does it feel to see the project coming to completion?

When we started discussions six or so years ago, I thought I had less than a 10% chance of success because the project was so ambitious and had to be completely funded by donations. The fact that it was to be built on agricultural land was another factor. There were more reasons for it to fail than to succeed. But the challenge was worth it. The phase during which we were doing the design of the construction with the architects was really interesting. I think we had 50 different versions, trying to define a design that would fit both the architects' vision and our programme. With the construction, things start to become less fun. But we are almost there now and the Science Gateway will be a game changer for CERN, so I'm pretty proud of it. I had planned to retire at the end of the construction, but now I've decided to stay a bit longer and see the first steps of my big baby.

Interview by **Matthew Chalmers**.

OPINION REVIEWS

A bridge between popular and textbook science

The Biggest Ideas in the Universe: space, time, and motion
By Sean Carroll
Dutton Books

Keeping it real *Sean Carroll's* The Biggest Ideas in the Universe: space, time, and motion *marks the start of a three-book series for physicists and physics enthusiasts.*

Most popular science books are written to reach the largest audience possible, which comes with certain sacrifices. The assumption is that many readers might be deterred by technical topics and language, especially by equations that require higher mathematics. In physics one can therefore usually distinguish textbooks from popular physics books by flicking through the pages and checking for symbols.

The *Biggest Ideas in the Universe: space, time, and motion*, the first in a three-part series by Sean Carroll, goes against this trend. Written for "...people who have no mathematical experience than high-school algebra, but are willing to look at an equation and think about what it means", there is no point in the book at which things are muddied because the maths becomes too advanced.

Concepts and theories

The first part of the book covers nine topics including conservation, space–time, geometry, gravity and black holes. Carroll spends the first few chapters introducing the reader to the thought process of a theoretical physicist: how to develop a sense for symmetries, the conservation of charges and expansions in small parameters. It also gives readers a fast introduction to calculus using geometric arguments to define derivatives and integrals. By the end of the third chapter, the concepts of differential equations, phase space and the principle of least action have been introduced.

The centre part of the book focusses on geometry. A discussion of the meaning of space and time in physics is followed by the introduction of Minkowski spacetime, with considerable effort given to the philosophical meaning of these concepts. The third part is the most technical. It covers differential geometry, a beautiful derivation of Einstein's equation of general relativity and the final chapter uses the Schwarzschild solution to discuss black holes.

It is a welcome development that publishers and authors such as Carroll are confident that books like this will find a sizeable readership (another good, recent example of advanced popular physics texts is Leonard Susskind's "A Theoretical Minimum" series). Many topics in physics can only be fully appreciated if the equations are explained and if chapters go beyond the limitations of typical popular science books. Carroll's writing style and the structure of the book help to make this case: all concepts are carefully introduced and even though the book is very dense and covers a lot of material, everything is interconnected and readers won't feel lost while reading. Regular reference to the historical steps in discovering theories and concepts loosen up the text. Two examples are the correspondence between Leibniz and Clarke about the nature of space and the interesting discussion of Einstein and Hilbert's different approaches to general relativity. The whole series of books, of which two of the three parts will be published soon, is accompanied by recorded lectures that are freely available online and present the topic of every chapter, along with answers to questions on these topics.

It is difficult to find any weaknesses in this book. Figures are often labelled with symbols that readers not used to physics notation can find in the text, so more text in the figures would make them even more accessible. Strangely, the section introducing entropy is not supported by equations and, given the technical detail of all other parts of the book, Carroll could have taken advantage of the mathematical groundwork of the previous chapters here.

I want to emphasise that every topic discussed in *The Biggest Ideas in the Universe* is well established physics. No flashy but speculative theories or unbalanced focus on science-fiction ideas, which are often used to attract readers to theoretical physics, appear. It stands apart from similar titles by offering insights that can only be obtained if the underlying equations are explained and not just mentioned.

Anyone who is interested in fundamental physics is encouraged to read this book, especially young people interested in studying physics because they will get an excellent idea of the type of physical arguments they will encounter at university. Those who think their mathematical background isn't sufficient will likely learn many new things, even though the later chapters are quite technical. And if you are at the other end of the spectrum, such as a working physicist, you will find the philosophical discussions of familiar concepts and the illuminating arguments included to elicit physical intuition most useful.

Martin Bauer *University of Durham.*

CERNCOURIER
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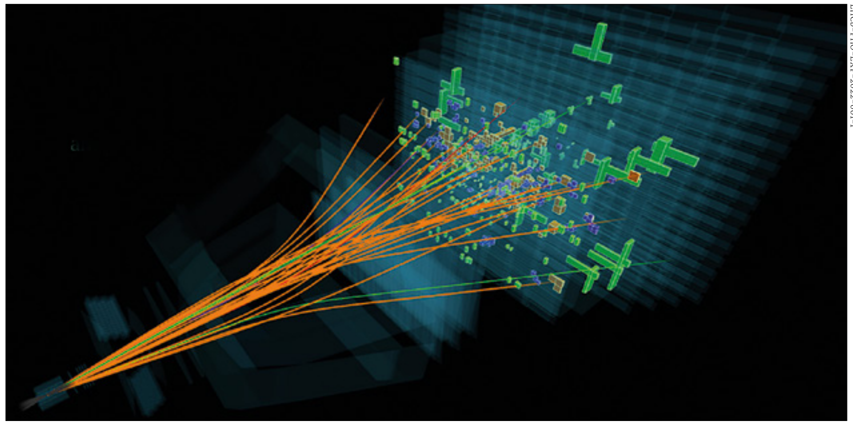
New Physics in b Decays

By Marina Artuso, Gino Isidori and Sheldon Stone

World Scientific



LHCb-PHO-EXP-2022-001-1

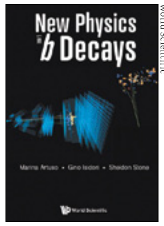
To be, or not to be *Tracks in LHCb, which, along with Belle II, will have a decisive word on the flavour anomalies.*

There are compelling reasons to believe that the Standard Model (SM) of particle physics, while being the most successful theory of the fundamental structure of the universe, does not offer the complete picture of reality. However, until now, no new physics beyond the SM has been firmly established through direct searches at different energy scales. This motivates indirect searches, performed by precision examination of phenomena sensitive to contributions from possible new particles, and comparing their properties with the SM expectations. This is conceptually similar to how, decades ago, our understanding of radioactive beta decay allowed the existence and properties of the W boson to be predicted.

New Physics in b decays, by Marina Artuso, Gino Isidori and the late Sheldon Stone, is dedicated to precision measurements in decays of hadrons containing a b quark. Due to their high mass, these hadrons can decay into dozens of different final states, providing numerous ways to challenge our understanding of particle physics. As is usual for indirect searches, the crucial task is to understand and control all SM contributions to these decays. For b-hadron decays, the challenge is to control the effects of the strong interaction, which is difficult to calculate.

Both sides of the coin

The authors committed to a challenging task: providing a snapshot of a field that has developed considerably during the past decade. They highlight key measurements that generated interest in the community, often due to hints of deviations from the SM expectations. Some of the reported anomalies have diminished since the book was published, after larger datasets were analysed. Others continue to intrigue researchers. This natural scientific progress leads to a better understanding of both the theoretical and experimental sides of the coin. The authors exercise reasonable caution over the significance of the anomalies they present, warning the reader of the look-elsewhere effect, and carefully define the relevant observables. When discussing specific decay modes, they explain their choice compared to other processes. This pedagogical approach makes the book very useful for early-career researchers diving into the topic.



World Scientific

The book starts with a theoretical introduction to heavy-quark physics within the SM, plotting avenues for searches for possible new-physics effects. Key theoretical concepts are introduced, along with the experiments that contributed most significantly to the field. The authors continue with an overview of "traditional" new-physics searches, strongly interleaving them with precision measurements of the free parameters of the SM, such as the couplings between quarks and the W boson. By determining these parameters precisely with several alternative experimental approaches, one hopes to observe discrepancies. An in-depth review of the experimental measurements, also featuring their complications, is confronted with theoretical interpretations. While some of the discrepancies stand out, it is difficult to attribute them to new physics as long as alternative interpretations are not excluded.

The second half of the book dives into recent anomalies in decays with leptons, and the theoretical models attempting to address them. The authors reflect on theoretical and experimental work of the past decade and outline a number of pathways to follow. The book concludes with a short overview of searches for processes that are forbidden or extremely suppressed in the SM, such as lepton-flavour violation. These transitions, if observed, would represent an undeniable signature of new physics, although they only arise in a subset of new-physics scenarios. Such searches therefore allow strong limits to be placed on specific hypotheses. The book concludes with the authors' view of the near future, which is already becoming reality. They expect the ongoing LHCb and Belle II experiments to have a decisive word on the current flavour anomalies, but also to deliver new, unexpected surprises. They rightly conclude that "It is difficult to make predictions, especially about the future."

The remarkable feature of this book is that it is written by physicists who actively contributed to the development of numerous theoretical concepts and key experimental measurements in heavy-quark physics over the past decades. Unfortunately, one of the authors, Sheldon Stone, could not see his last book published. Sheldon was the editor of the book *B decays*, which served as the handbook on heavy-quark physics for decades. One can contemplate the impressive progress in the field by comparing the first edition of *B decays* in 1992 with *New Physics in b decays*. In the 1990s, heavy-quark decays were only starting to be probed. Now, they offer a well-oiled tool that can be used for precision tests of the SM and searches for minuscule effects of possible new physics, using decays that happen as rarely as once per billion b-hadrons.

The key message of this book is that theory and experiment must go hand in hand. Some parameters are difficult to calculate precisely and they need to be measured. The observables that are theoretically clean are often challenging experimentally. Therefore, the searches for new physics in b decays focus on processes that are accessible both from the theoretical and experimental points of view. The reach of such searches is constantly being broadened by painstakingly refining calculations and developing clever experimental techniques, with progress achieved through the routine work of hundreds of researchers in several experiments worldwide.

Vitalii Lisovskyi *EPFL.*

PEOPLE CAREERS

Sharing experience, building connections

Theoretical cosmologist by training, CERN alumna Valeria Pettorino became increasingly interested in data analysis and worked on the Euclid and Planck missions before her project-management skills led her to be appointed a director of research at the French CEA.

A Rassat

It all starts here *Working at CERN 10 years ago was an invaluable experience that led to lifelong connections.*

Like many physicists, Valeria Pettorino's fascination with science started when she was a child. Her uncle, a physicist himself, played a major role by sharing his passion for science fiction, strings and extra dimensions. She studied physics and obtained her PhD from the University of Naples in 2005, followed by a postdoc at the University of Torino and then SISSA in Italy. In 2012 her path took her to the University of Geneva and a Marie Curie Fellowship, where she worked with theorist Martin Kunz from UNIGE/CERN – a mentor and role model ever since.

Visiting CERN was an invaluable experience that led to lifelong connections. "Meeting people who worked on particle-physics missions always piqued my interest, as they had such interesting stories and experiences to share," Valeria explains. "I collaborated and worked alongside people from different areas in cosmology and particle physics, and I got the opportunity to connect with scientists working in different experiments."

After the fellowship, Valeria went to the University of Heidelberg as a research group leader, and during this time she was selected for the "Science to Data Science" programme by the AI software company Pivigo. Working on artificial intelligence and unsupervised learning to analyse healthcare data for a start-up company in London, it presented her with the opportunity to widen her skillset.

Valeria's career trajectory turned towards space science in 2007, when she began working for the Euclid mission of the European Space Agency (ESA) due to launch this year (see p7), with the aim to measure the geometry of the universe for the study of dark matter and energy. Currently co-lead of the Euclid theory science working group, Valeria has held a number of roles in the mission, including deputy manager of the communication group. In 2018 she became the CEA representative for Euclid-France communication and is currently director of research for the CEA astrophysics department/CosmoStat lab. She also worked on data analysis for ESA's Planck mission from 2009 to 2018.

I wanted to deepen my understanding on how science can have an impact on the world and society

Mentoring and networking

In both research collaborations, Valeria worked on numerous projects that she coordinated from start to finish. While leading teams, she studied management with the goal of enabling everyone to reach their full potential. She also completed training in science diplomacy, which helped her gain valuable transferrable skills. "I decided to be proactive in developing my knowledge and started attending webinars, and then training on science diplomacy. I wanted to deepen my understanding on how science can have an impact on the world and society." In 2022 Valeria was selected to participate in the first Science Diplomacy Immersion Programme organised by the Geneva Science and Diplomacy Anticipator (GESDA), which aims to take advantage of the ecosystem of international organisations in Geneva to anticipate, accelerate and translate emerging scientific themes into concrete actions.

Sharing experience and building connections between people have been a theme in Valeria's career. Nowhere is this better illustrated than her role, since 2015, as a mentor for the Supernova Foundation – a worldwide mentoring and networking programme for women in physics. "Networking is very important in any career path and having the opportunity to encounter people from a diverse range of backgrounds allows you to grow your network both personally and professionally. The mentoring programme is open to all career levels. There are no barriers. It is a global network of people from 53 countries and there are approximately 300 women in the programme. I am convinced that it is a growing community that will continue to thrive." Valeria has also acted as mentor for Femmes & Science (a French initiative by Paris-Saclay University) in 2021–2022, and was recently appointed as one of 100 mentors worldwide for #space4women, an initiative of the United Nations Office of Outer Space Affairs to support women pursuing studies in space science.

A member of the CERN Alumni Network, Valeria thoroughly enjoys staying connected with CERN. "Not only is the CERN Alumni Network excellent for CERN as it brings together a wide range of people from many career paths, but it also provides an opportunity for its members to understand and learn how science can be used outside of academia."

Based on an interview published by the CERN Alumni Network.

Appointments and awards

Brookhaven National Laboratory

New DUNE co-spokesperson

Experimental particle physicist Mary Bishai (BNL) has been elected co-spokesperson of the US-based Deep Underground Neutrino Experiment (DUNE), currently under construction. She will lead the 1400-strong collaboration alongside Sergio Bertolucci, a former CERN research director. Bishai previously worked on MINOS and as a project scientist for the Long Baseline Neutrino Experiment, an early incarnation of the experiment. She later chaired DUNE's review office, managing independent reviews of the experiment's technical components. "I've been doing this for 17 years and it was just a drawing on paper when I came to Brookhaven. I want to see that drawing come to life."

Girone leads CERN openlab

In March, Maria Girone took over from Alberto di Meglio as head of CERN openlab – a unique public–private partnership founded in 2001 through which CERN collaborates with leading technology companies and other research organisations. Girone started her career on the ALEPH experiment at LEP and joined the Worldwide LHC Computing Grid as a developer in 2002. In 2009 she was appointed deputy group leader of the CERN IT experiment support group and since 2016 has acted as CERN openlab's chief technical officer, focusing on the delivery of common solutions across the LHC experiments in data management, analysis and monitoring. "I am looking forward to establishing new collaborations and exploring new, emerging technologies through CERN openlab," she said. Di Meglio, who has served as the head of CERN openlab since 2013, is now responsible for running CERN IT's new innovation section.

Theorist takes the helm at AIP

On 2 February theoretical physicist Nicole Bell (University of Melbourne) took up the presidency of the Australian Institute of Physics. With research interests in neutrino physics and dark matter, Bell has led the ARC Centre of Excellence for Dark Matter Particle Physics since 2020. She obtained her doctoral degree at the University of Melbourne in 2001 and worked at Fermilab as a research associate and Caltech as a postdoctoral fellow.

Galileo Galilei Medal

Awarded every two years to honour outstanding contributions in theoretical physics, and organised by INFN and the Galileo Galilei Institute, the 2023 Galileo Galilei Medal goes to Zvi Bern (UCLA), Lance Dixon (SLAC) and David Kosower (CEA/Saclay) "for the development of powerful methods for high-order perturbative calculations in quantum field theory", which helped refine predictions for the efficiency of particle-physics experiments, such as those at the LHC.

New deputy chair at ADUC

On 7 February Barbara Maria Latacz, a CERN research fellow in the BASE collaboration, was appointed deputy chair of the Antiproton Decelerator Users Community (ADUC), supporting

Private

ADUC-chair Stefan Ulmer. During her PhD, Barbara contributed to the setup of the GBAR experiment to study the ballistic properties of antihydrogen in Earth's gravitational field, and in 2020 she joined the BASE collaboration to study the fundamental properties of protons and antiprotons with ultra-high precision. ADUC chairs represent the interests of the AD community and interface the ADUC with CERN management.

Ryan on Irish Council

Theoretical particle physicist Sinéad Ryan (Trinity College Dublin) has been appointed to the Irish Research Council, which exists to enable and sustain a vibrant research community in Ireland. After obtaining her PhD at the University in Edinburgh, Ryan

Private

went to Fermilab as a fellow. A specialist in hadron spectroscopy and QCD under extreme conditions, she is a founding member of two international collaborations (FASTSUM and the Hadron Spectrum Collaboration) and has been part of the International Advisory Committee for the Symposium in Lattice Field Theory since 2000.

Honouring accelerator physicists

The European Physical Society's accelerator group has announced the winners of its 2023 prizes, which are awarded every three years. The Rolf Widerøe Prize for outstanding work in the accelerator field has been given to Katsunobu Oide (KEK, and visiting scientist at CERN/UNIGE) for his many conceptual contributions to linear and circular particle colliders, which include the Oide limit of final focus systems at SLAC, crab crossing in circular colliders, design work for KEKB and KEK-ATF, and advanced lattice design for the FCC study. The Gersh Budker Prize for a recent, significant, original contribution to the accelerator field has been awarded to Mikhail Krasilnikov (top right; DESY/Zeuthen) for his achievements in the development of high-brightness electron beams and a high power, tunable THz SASE free-electron laser, which

Private

demonstrated lasing at the PITZ facility in 2022. The Frank Sacherer Prize for an individual in the early part of his or her career goes to Xingchen Xu (below; Fermilab), for his contributions in demonstrating the effectiveness of the internal oxidation method in Nb_3Sn wires to strongly improve the performance of this superconductor. The prizes will be presented during IPAC'23, which takes place from 7 to 12 May in Venice, Italy.

Private

Wu-Ki Tung Award

Experimentalists Yi Chen (MIT) and Matt LeBlanc (CERN) have been granted the 2022 Wu-Ki Tung Award for Early Career Research on quantum chromodynamics (QCD). Chen was cited "for improving the understanding of quark and gluon interactions within different media through systematic studies and measurements of jet substructure in electron, proton and heavy ion collisions" and LeBlanc "for important contributions to the measurement of QCD dynamics using jets and jet substructure, as well as for long-standing contributions and leadership in jet reconstruction and calibration". The award was established by the CTEQ collaboration in 2014 to honour the legacy of leading QCD theorist Wu-Ki Tung.

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PEOPLE OBITUARIES

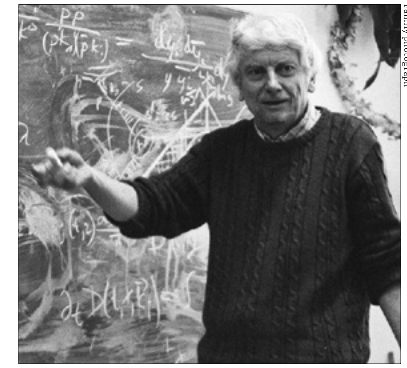
Stanisław Jadach 1947–2023

A leading light in radiative corrections

Stanisław Jadach, an outstanding theoretical physicist, died on 26 February at the age of 75. His foundational contributions to the physics programmes at LEP and the LHC, and for the proposed Future Circular Collider at CERN, have significantly helped to advance the field of elementary particle physics and its future aspirations.

Born in Czerteż, Poland, Jadach graduated in 1970 with a masters in physics from Jagiellonian University. There, he also defended his doctorate, received his habilitation degree and worked until 1992. During this period, whilst partly under martial law in Poland, Jadach took trips to Leiden, Paris, London, Stanford and Knoxville, and formed collaborations on precision theory calculations based on Monte Carlo event-generator methods. In 1992 he moved to the Institute of Nuclear Physics Polish Academy of Sciences (PAS) where, receiving the title of professor in 1994, he worked until his death.

Prior to LEP, all calculations of radiative corrections were based on first- and, later, partially second-order results. This limited the theoretical precision to the 1% level, which was unacceptable for experiment. In 1987 Jadach solved that problem in a single-author report, inspired by the classic work of Yennie, Frautschi and Suura, featuring a new calculational method for any number of photons. It was widely believed that soft-photon approximations were restricted to many photons with very low energies and that it was impossible to relate, consistently, the distributions of one or two energetic photons to those of any number of soft photons. Jadach and his colleagues solved this problem in their papers in 1989 for differential cross sections, and later in 1999 at the level of spin amplitudes. A long series of publications and computer programmes for re-summed perturbative Standard Model calculations ensued.


Family photograph

Stanisław Jadach made major contributions to the physics programmes at LEP and the LHC.

Most of the analysis of LEP data was based exclusively on the novel calculations provided by Jadach and his colleagues. The most important concerned the LEP luminosity measurement via Bhabha scattering, the production of lepton and quark pairs, and the production and decay of W and Z boson pairs. For the W-pair results at LEP2, Jadach and co-workers intelligently combined separate first-order calculations for the production and decay processes to achieve the necessary 0.5% theoretical accuracy, bypassing the need for full first-order calculations for the four-fermion process, which were unfeasible at the time. Contrary to what was deemed possible, Jadach and his colleagues achieved calculations that simultaneously take into account QED radiative corrections and the complete spin-spin correlation effects in the production and decay of two tau leptons. He also had success in the 1970s in novel simulations of strong interaction processes.

After LEP, Jadach turned to LHC physics. Among other novel results, he and his collaborators developed a new constrained Markovian algorithm for parton cascades, with no need to use backward evolution and predefined parton distributions, and proposed a new method, using a "physical" factorisation scheme, for combining a hard process at next-to leading order with a parton cascade, much simpler and more efficient than alternative methods.

Jadach was already updating his LEP-era calculations and software towards the increased precision of FCC-ee, and is the co-editor and co-author of a major paper delineating the need for new theoretical calculations to meet the proposed collider's physics needs. He co-organised and participated in many physics workshops at CERN and in the preparation of comprehensive reports, starting with the famous 1989 LEP Yellow Reports.

Jadach, a member of the Polish Academy of Arts and Sciences (PAAS), received the most prestigious awards in physics in Poland: the Marie Skłodowska-Curie Prize (PAS), the Marian Mięsowicz Prize (PAAS), and the prize of the Minister of Science and Higher Education for lifetime scientific achievements. He was also a co-initiator and permanent member of the international advisory board of the RADCOR conference.

Stanisław (Staszek) was a wonderful man and mentor. Modest, gentle and sensitive, he did not judge or impose. He never refused requests and always had time for others. His professional knowledge was impressive. He knew almost everything about QED, and there were few other topics in which he was not at least knowledgeable. His erudition beyond physics was equally extensive. He is already profoundly and dearly missed.

Wiesław Płaczek *Jagiellonian University,* **Maciej Skrzypek** *and* **Zbigniew Was** *Institute of Nuclear Physics and* **Bennie Ward** *Baylor University.*

Sigurd Hofmann 1944–2022

Discoverer of superheavy elements

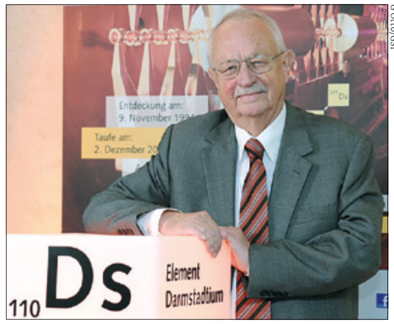
Sigurd Hofmann, an extraordinary scientist, colleague and teacher, passed away on 17 June 2022 at the age of 78. Remarkable in his scientific life was the discovery of proton radioactivity, which was achieved in 1981, as well as the synthesis of six new superheavy chemical elements between 1981 and 1996.

Sigurd was born on 15 February 1944 in Böhmisch-Kamnitz (Bohemia) and studied physics at TH Darmstadt, where he received his diploma in 1969 and his doctorate in 1974 with Egbert Kankeleit. Afterwards, he joined the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, his scientific work there occupying him for almost 50 years. Accuracy and scientific exactness were important to him from the beginning. He investigated fusion reactions and radioactive decays in the group of Peter Armbruster and worked with Gottfried Münzenberg.

Sigurd achieved international fame through the discovery of proton radioactivity from ▷

the ground state of ^{151}Lu in 1981, a previously unknown decay mechanism. When analysing the data, he benefited from his pronounced thoroughness and scientific curiosity. At the same time, he begun work on the synthesis, unambiguous identification and study of the properties of the heaviest chemical elements, which were to shape his further scientific life. The first highlights were the synthesis of the new elements bohrium (Bh), hassium (Hs) and meitnerium (Mt) between 1981 and 1984, with which GSI entered the international stage of this renowned research field. The semiconductor detectors that Sigurd had developed specifically for these experiments were far ahead of their time, and are now used worldwide to search for new chemical elements.

At the end of the 1990s Sigurd took over the management of the Separator for Heavy Ion Reaction Products (SHIP) group and, after making instrumental improvements to detectors and electronics, crowned his scientific success with the discovery of the elements darmstadtium (Ds), roentgenium (Rg) and copernicium (Cn) in the years 1994 to 1996. The concept for "SHIP-2000", a strategy paper developed under his leadership in 1999 for long-term heavy-element research at GSI, is still relevant today. In 2009 he was appointed Helmholtz professor and from then on



G Otto/GSI

Sigurd Hofmann synthesised six new superheavy elements between 1981 and 1996.

was able to devote himself entirely to scientific work again. For many years he also maintained an intensive collaboration and scientific exchange with his Russian colleagues in Dubna, where he co-discovered the element flerovium (Fl) in a joint experiment.

For his outstanding research work and findings, Sigurd received a large number of renowned awards and prizes; too many, in fact, to mention. A diligent writer and speaker, he was invited to talk at countless international conferences, authored a large number of review articles, books and book chapters, and many widely cited publications. He also liked to present scientific results at public events. In doing so, he was able to develop a thrilling picture of modern physics, but also of the big questions of cosmology and element synthesis in stars; he was also able to convey very clearly to the public how atoms can be made "visible".

Many chapters of Sigurd's contemporary scientific life are recorded in his 2002 book *On Beyond Uranium* (CRC Press). His modesty and friendly nature were remarkable. You could always rely on him. His care, accuracy and deliberateness in all work were outstanding, and his persistence was one of the foundations for ground-breaking scientific achievements. He was always in the office or at an experiment, even late in the evening and on weekends, so you could talk to him at any time and were always rewarded with detailed answers and competent advice.

We are pleased that we were able to work with such an excellent scientist and colleague, as well as an outstanding teacher and a great person, for so many years.

Gottfried Münzenberg *and* **Christoph Scheidenberger** *GSI Darmstadt.*

Vittorio Giorgio Vaccaro 1941–2023

Master of beam instabilities

Accelerator physicist Vittorio Giorgio Vaccaro passed away after a short illness on 11 February 2023 in his hometown of Naples, Italy.

Vittorio graduated in 1965 from the University of Naples Federico II. He soon moved to CERN as a fellow, where he remained from 1966 to 1969, contributing to the design and commissioning of the first high-intensity hadron collider, the Intersecting Storage Rings. At CERN, Vittorio introduced the concept of beam-coupling impedance to model the instabilities that were experienced above transition energy, writing a seminal report (*Longitudinal instability of a coasting beam above transition, due to the action of lumped discontinuities*), in which he described for the first time the action of discontinuities in the transverse section of a beam pipe as an impedance. His theory, which after his initial intuition he developed together with Andy Sessler, Alessandro G Ruggiero and many other colleagues, has become a fundamental tool in the design of particle accelerators.

In 1969 he returned to his alma mater in Naples as professor of electromagnetic fields at the faculty of engineering, and continued teaching until he retired. He created an accelerator-physics team in association with INFN within the faculty of physics, and throughout his career remained closely related to CERN, where he visited regularly and where he sent many of his students.

A Passarelli

While at CERN, Vittorio Vaccaro introduced the concept of beam-coupling impedance.

Vittorio collaborated with practically all the studies and accelerator projects in Europe, from the CERN machines to DAFNE, the European Spallation Source and HERA-B at DESY. The group in Naples became, thanks to him, a reference in the world of accelerators for the development of the theory of beam-coupling impedance of accelerator components and the associated bench measurements. Since the mid-1990s, he became increasingly interested in the development of linear accelerators for proton therapy, participating in a large collaboration with the TERA foundation, CERN and INFN. In 2003 he led a new collaboration between the University of Naples and several sections of INFN, which produced the first linac module at 3 GHz capable of accelerating protons from a 30 MeV cyclotron.

In 2019 Vittorio was awarded the IPAC Xie Jialin Award for outstanding work in the accelerator field "For his pioneering studies on instabilities in particle-beam physics, the introduction of the impedance concept in storage rings and, in the course of his academic career, for disseminating knowledge in accelerator physics throughout many generations of young scientists".

It is difficult to find the words to recall Vittorio's immense human qualities, his deep culture and his profound humanity. Several of his students are now scattered around the world, continuing his efforts to propose technical solutions to accelerator-physics problems based on a deep understanding of the phenomena of beam instability. Vittorio was moved by a sincere passion for science, and an irresistible curiosity for everything and everyone around him, which always brought him to approach anyone with an open and friendly spirit.

We will deeply miss a passionate mentor and colleague, his wide knowledge, energy, friendship and humanity.

His friends and colleagues.

Karel Cornelis 1955–2022

A positive thinker and dedicated mentor

Our dear colleague and friend Karel Cornelis passed away unexpectedly on 20 December 2022.

After finishing his studies in physics at the University of Leuven (Belgium), Karel joined CERN in 1983 as engineer-in-charge of the Super Proton Synchrotron (SPS) at the time when the machine was operated as a proton–antiproton collider. During his career Karel greatly contributed to the commissioning and performance development and follow-up of the SPS during its various phases as proton–antiproton collider, LEP injector, high-intensity fixed-target machine and as the LHC injector of proton and ion beams. He had a profound and extensive knowledge of the machine, from complex beam

CERN

Karel Cornelis joined CERN in 1983 as the engineer-in-charge of the SPS.

Karel was an extremely competent and rigorous physicist

dynamics aspects to the engineering details of its various systems, and was the reference whenever new beam requirements or modes of operation were discussed.

Karel was an extremely competent and rigorous physicist, but also a generous and dedicated mentor who trained generations of control-room technicians, shift leaders and machine physicists and engineers, helping them to grow and take on responsibilities while remaining available to lend a hand when needed. His positive attitude and humour have left a lasting imprint, so much so that "Think like a proton: always positive!" has become the motto of the SPS operation team, and is now visible in the SPS island in the CERN Control Centre.

Karel had the rare gift of explaining complex phenomena with simple but accurate models and clear examples, whether it was accelerator physics and technology, or physics and engineering more generally. He gave a fascinating series of machine shut-down lectures covering the history of the SPS, synchrotron radiation and one of his passions, aviation, with a talk on "Air and the airplanes that fly in it".

Karel was a larger-than-life tutor, friend, reference point, expert and father figure to generations of us. He was much missed in the SPS island and beyond following his retirement in September 2019, and will be even more so now.

His former colleagues and friends.

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BACKGROUND

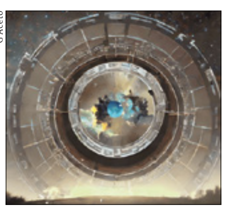
Notes and observations from the high-energy physics community

Fermilab's fashion friends


Sandbox Studio, Chicago

A collaboration between Fermilab and College of DuPage in Chicago has fused physics and fashion to create a new line in personal protective equipment (PPE). Leader of Fermilab's robotics initiative Mayling Wong-Squires teamed up with DuPage fashion students to protect "SPOT", a Boston Dynamics product used to explore how robots could be integrated into regular Fermilab operations, from radioactive dust. Although SPOT is not affected when sent into controlled radiation areas, dust can get stuck in cracks and crevices, potentially contaminating it. Working from a cardboard model, with the constraint to develop a pattern that could be followed by engineers and technicians without a background in fashion design, a modified human PPE garment turned out to be the best fit, matched with fetching rubber dog booties from a local pet store. SPOT hit the catwalk unencumbered by the garment in February during Chicago Engineers Week 2023. Source: *Symmetry Magazine*.

CERN according to AI


G Aceto

Artificial intelligence (AI) is all the rage since the launch of the chatbot ChatGPT by San Francisco firm OpenAI in November – so much so that an open letter by the Future of Life Institute calling on AI labs to pause development of the technology for at least six months has been signed by hundreds of technology leaders and academics. Among OpenAI's tens of millions of users is CERN software designer Giuseppe Aceto, who is exploring the connection between art and science in a multidisciplinary way. Based on OpenAI's StableDiffusion image generator, he developed his own AI model that turns words into images tailored to the physics at CERN (an example of which is pictured), and is working on another that mixes audio recordings and Monte Carlo simulations to produce sound compositions.

Media corner

"In a sense, working on the LHC is like being dropped on to a new planet somewhere in there to understand and catalogue life there."
LHCb physicist ***Tara Shears*** writing in *The New European* (16 March).

"There's a number of counter-arguments and facts that need to be understood if this claim is going to live more than a few months."
Vitor Cardoso of the Niels Bohr Institute on a recent study suggesting that black holes might contain dark energy (*The Guardian*, 15 February).

"As a teenager, I wanted to be the first woman on Mars. That's something I got mocked for."
Astrophysicist and trainee ESA astronaut ***Suzanna Randall***, who is set to become the first German-speaking woman in space (*Der Standard*, 20 March).

"If it's confirmed, it's a very interesting finding as it tells us something deep about how the proton's constituents behave from a spatial point of view."
Theorist ***Juan Rojo*** of the Free University of Amsterdam on a new result determining the gluonic gravitational form factors of the proton (*New Scientist*, 29 March).

From the archive: June 1983

Large-scale computing


Cornell University

Spreading the computer message, Kenneth Wilson.

In a talk given at CERN, 1982 Physics Nobel Laureate Kenneth Wilson criticised the highly traditional computing methods used by many physicists. "Nobody would suggest that someone is ready to do serious experimental work in physics with just a two-week course in soldering, yet the attitude is that a two-week course in FORTRAN gets people ready to do computing! Training in computer science is required, plus a communication network to avoid reinventing the same thing. The 'ultracomputer' design has many processors and memory modules with a network of crisscrossing wires and nodes enabling every processor to access any module. Tree structures are being considered in areas such as artificial intelligence and speech processing. I have no doubt that in the years ahead we are going to see all of these frameworks."

In 1963, a group of European high-energy physicists formed the 'European Committee for Future Accelerators', chaired by Edoardo Amaldi. ECFA is not part of the CERN organization, has no formal links with Member State Governments and no budget. Its only resources are the efforts and enthusiasm of its members, whose studies can lead to recommendations agreed by Plenary ECFA carrying the authority of the whole community. In collaboration with CERN, ECFA recently assessed the physics potential and feasibility of the LEP project. This led to a wide consensus on the main design specifications, paving the way for LEP's approval in 1981– just one year after its first presentation to the CERN Council. Current activities address the future use of computers and networks. Several Working Groups, set up by Egil Lillestøl in Bergen and Peggie Rimmer in CERN, are defining standards for data acquisition and analysis, and for linking European groups in a communication network.

● Based on text on pp173–180 of *CERN Courier* June 1983.

Compiler's note

Wilson's predictions were right – thanks to the high-energy physics community! Launched around 1990, the World Wide Web is now part of everyday life, giving seamless access to information stored in millions of geographical locations. A decade or so later, the Worldwide LHC Computing Grid began providing seamless access to distributed data storage and computing power. Adopted by a wide range of research communities, business and industry, grid technology has evolved to exploit cloud-computing structures.

294 K

Temperature at which evidence for superconductivity in a nitrogen-doped lutetium hydride at 10 kbar has been claimed by a team at the University of Rochester, with independent verification called for (*Nature* 615 244)

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