WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2024 issue of *CERN Courier.*

This edition marks the 50th anniversary of the November Revolution in particle physics. In 1974, a year after the discovery of neutral currents, experiments at Brookhaven and Stanford discovered an unexpected resonance at 3.1 GeV. Its remarkable stability suggested a new quantum number. Was the state long-lived because it bore the charm quantum number predicted by Glashow, Iliopoulos and Maiani? Shortly after, another narrow resonance appeared at 3.7 GeV. As the *Courier* reported at the time, the new particles were completely unexpected (p41).

It soon became clear that the new resonances did contain charm – hidden charm, to be precise. A rich "charmonium" spectrum followed until, two decades ago, experiments at electron–positron colliders discovered charm–anticharm states with exotic features such as long lifetimes, net electric charges and strangeness. These were the experimental harbingers of a bestiary of tetraquarks and pentaquarks, with a further 23 now discovered at the LHC (p26). They pose a fascinating theoretical puzzle in QCD. Nature employs two very different mechanisms to create them, and for many states it is not yet clear which of the two is at play (p33).

Also in this edition: QCD calculations are key to probing hints of new physics in the charm sector (p37); new results throw a spotlight on anomalous measurements of the mass of the W boson (p7) and of the magnetic moment of the muon (p8); the latest developments in string theory (p21) and machine learning for statistics (p19); and much more.

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EDITOR: MARK RAYNER, CERN
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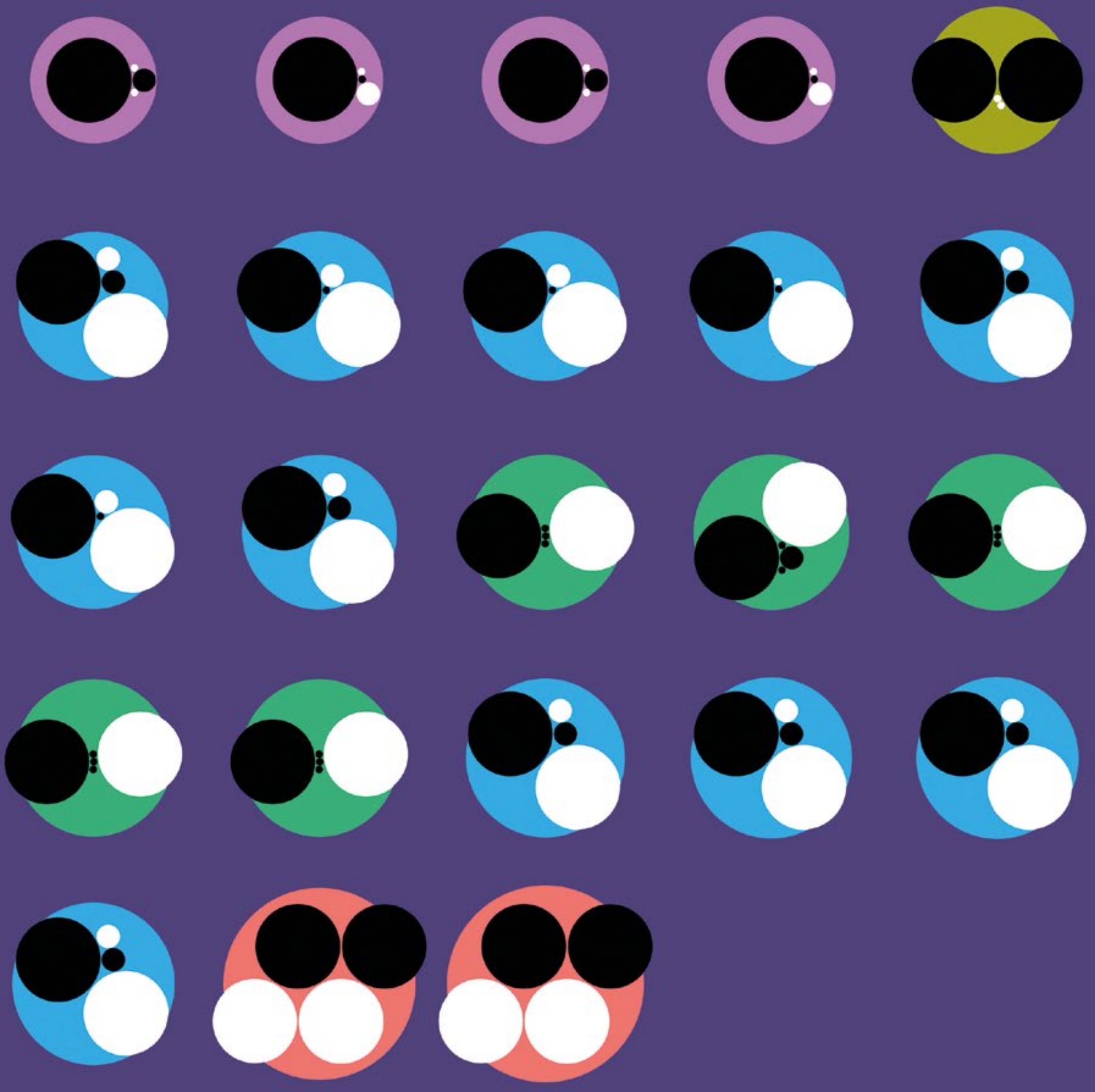
CERNCOURIER

November/December 2024 cerncourier.com Reporting on international high-energy physics

A bestiary of exotic hadrons
QCD at the LHC



The W mass snaps back • Inside tetraquarks and pentaquarks • A renaissance in charm

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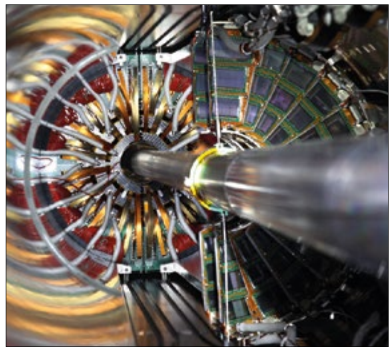

M Hoch/CMS-PHO-TRACKER-2014-001-3

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M Brice, J Ordan/CERN-PHOTO-201812-329-2

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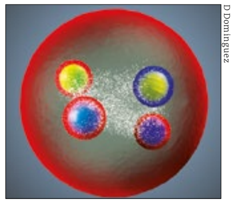

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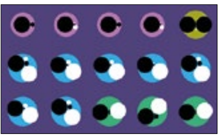

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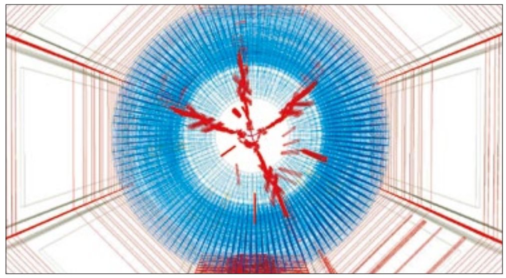
FROM THE EDITOR

50 years on from the November Revolution

Mark Rayner
Editor

Fundamental particles are never naked. Virtual loops and lines envelop them. Given the inability of the Standard Model (SM) to answer key questions about the universe, these loops and lines likely include undiscovered fields and interactions. Measurements of fundamental parameters should eventually reveal their presence. The question is how precise the measurements need to be.

It's possible that the first signs of new physics are already here, though even the strongest hints can disappear under scrutiny. In recent years, measurements of the mass of the W boson and the magnetic moment of the muon have both diverged from SM predictions by more than 5σ. New work reported in this edition throws a spotlight on both anomalies. In the case of the mass of the W boson, a new measurement is consistent with the SM (p7). In the case of the magnetic moment of the muon, the SM prediction shows signs of moving towards the measurement (p8). In both cases, the debate between experimentalists, phenomenologists and theorists is just beginning.



BESIII Collab.

Tetraquark anatomy *A charged $Z_c(3900)$ decays in the BESIII experiment.*

A charmed life

This edition also marks the 50th anniversary of the November Revolution in particle physics. In 1974, a year after the discovery of neutral currents, experiments at Brookhaven and Stanford discovered an unexpected resonance at 3.1 GeV. Its remarkable stability suggested a new quantum number. Was the state long-lived because it bore the charm quantum number predicted by Glashow, Iliopoulos and Maiani, or perhaps one of the colour quantum numbers predicted by the new theory of QCD? Or was the Z boson making a direct appearance in colliders? Shortly after, another narrow resonance appeared at 3.7 GeV. As the *Courier* reported at the time, the new particles were completely unexpected (p41).

It soon became clear that the new resonances did contain charm – *hidden* charm, to be precise. The 3.1 GeV resonance is the ground state of a charm–anticharm system of quarks with aligned spins, and the 3.7 GeV resonance is its first radial excitation. A rich "charmonium" spectrum followed until, two decades ago, experiments at electron–positron colliders discovered charm–anticharm states with exotic features such as long lifetimes, net electric charges and strangeness. These were the experimental harbingers of a bestiary of tetraquarks and pentaquarks, with a further 23 now discovered at the LHC (p26). They pose a fascinating theoretical puzzle in QCD. Nature employs two very different mechanisms to create them, and for many states it is not yet clear which of the two is at play (p33).

Nature employs two very different mechanisms to create exotic hadrons

The computational complexity of QCD also impacts many fundamental questions in physics, not least the two previously mentioned anomalies. QCD calculations are also key to probing hints of new physics in the charm sector, in which two measurements by the LHCb collaboration have sparked fresh excitement. Both concern the D^0 meson – a compact system of a charm quark and an up antiquark.

LHCb have demonstrated that the D^0 decays differently to its antiparticle and that it oscillates into its antiparticle. The magnitude of both effects exceeds naive SM expectations by at least an order of magnitude. The trouble is that these predictions are preliminary and highly uncertain. Improve them, and clues to new physics could be revealed, perhaps shedding light on the matter–antimatter asymmetry in the universe (p37).

Reporting on international high-energy physics

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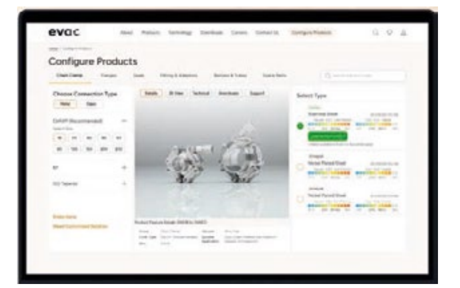


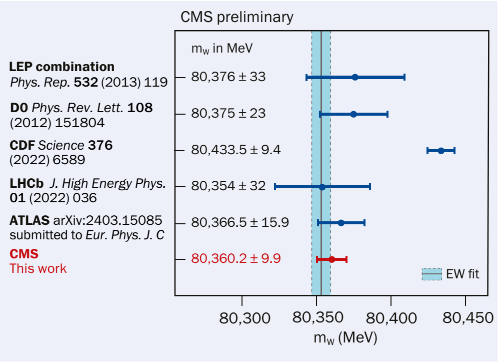
NEWS ANALYSIS

ELECTROWEAK PRECISION

W mass snaps back

Based on the latest data inputs, the Standard Model (SM) constrains the mass of the W boson (m_W) to be 80,353 ± 6 MeV. At tree level, m_W depends only on the mass of the Z boson and the weak and electromagnetic couplings. The boson's tendency to briefly transform into a top quark and a bottom quark causes the largest quantum correction. Any departure from the SM prediction could signal the presence of additional loops containing unknown heavy particles.

The CDF experiment at the Tevatron observed just such a departure in 2022, plunging the boson into a midlife crisis 39 years after it was discovered at CERN's $Sp\bar{p}S$ collider (*CERN Courier* September/October 2023 p27). A new measurement from the CMS experiment at the LHC now contradicts the anomaly reported by CDF. While the CDF result stands seven standard deviations above the SM, CMS's measurement aligns with the SM prediction and previous results at the LHC. The CMS and CDF results claim joint first place in precision, provoking a dilemma for phenomenologists.



CMS Collab. 2024 CMS-PAS-SMP-23-002

Relieving tension *Contradicting an anomaly reported in 2022, a new measurement by the CMS collaboration (red) finds the mass of the W boson to be consistent with the Standard Model.*

New-physics puzzle

"The result by CDF remains puzzling, as it is extremely difficult to explain the discrepancy with the three LHC measurements by the presence of new physics, in particular as there is also a discrepancy with D0 at the same facility," says Jens Erler of Johannes Gutenberg-Universität Mainz. "Together with measurements of the weak mixing angle, the CMS result confirms the validity of the SM up to new physics scales well into the TeV region."

"I would not call this 'case closed'," agrees Sven Heinemeyer of the Universidad Autónoma de Madrid. "There must be a reason why CDF got such an anomalously high value, and understanding what is going on may be very beneficial for future investigations. We know that the SM is not the last word, and there are clear cases that require physics beyond the SM (BSM). The question is at which scale BSM physics appears, or how strongly it is coupled to the SM particles."

To obtain their result, CDF analysed four million W-boson decays originating from 1.96 TeV proton–antiproton collisions at Fermilab's Tevatron collider between 1984 and 2011. In stark disagreement with the SM, the analysis yielded a mass of 80,433.5 ± 9.4 MeV. This result induced the ATLAS collaboration to revisit its 2017 analysis of $W \to \mu\nu$ and $W \to e\nu$ decays in 7 TeV proton–proton collisions using the latest global data on parton distribution functions, which describe the probable momenta of quarks and gluons inside the proton. A newly developed fit was also implemented. The central value remained consistent with the SM, with a reduced uncertainty of 16 MeV increasing its tension with the new CDF result. A less precise measurement by the LHCb collaboration also favoured the SM (*CERN Courier* May/June 2023 p10).

CMS now reports m_W to be 80,360.2 ± 9.9 MeV, concluding a study of $W \to \mu\nu$ decays begun eight years ago.

"One of the main strategic choices of this analysis is to use a large dataset of Run 2 data," says CMS spokesperson Gautier Hamel de Monchenault. "We are using 16.8 fb^{-1} of 13 TeV data at a relatively high pileup of on average 25 interactions per bunch crossing, leading to very large samples of about 7.5 million Z bosons and 90 million W bosons."

With high pileup and high energies come additional challenges. The measurement uses an innovative analysis technique that benchmarks $W \to \mu\nu$ decay systematics using $Z \to \mu\mu$ decays as independent validation wherein one muon is treated as a neutrino. The ultimate precision of the measurement relies on reconstructing the muon's momentum in the detector's silicon tracker to better than one part in 10,000 – a groundbreaking level of accuracy built on minutely modelling energy loss, multiple scattering, magnetic-field inhomogeneities and misalignments. "What is remarkable is that this incredible level of precision on the muon momentum measurement is obtained without using $Z \to \mu\mu$ as a calibration candle, but only using a huge sample of $J/\psi \to \mu\mu$ events," says Hamel de Monchenault. "In this way, the $Z \to \mu\mu$ sample can be used for an independent closure test, which also provides a competitive measurement of the Z mass."

The result confirms the validity of the SM up to new physics scales well into the TeV region

Measurement matters

Measuring m_W using $W \to \mu\nu$ decays is challenging because the neutrino escapes undetected. m_W must be inferred from either the distribution of the transverse mass visible in the events (m_T) or the distribution of the transverse momentum of the muons (p_T). The m_T approach used by CDF is the most precise option at the Tevatron, but typically less precise at the LHC, where hadronic recoil is difficult to distinguish from pileup. The LHC experiments also face a greater challenge when reconstructing m_W from distributions of p_T. In proton–antiproton collisions at the Tevatron, W bosons could be created via the annihilation of pairs of valence quarks. In proton–proton collisions at the LHC, the antiquark in the annihilating pair must come from the less well understood sea; and at LHC energies, the partons have lower fractions of the proton's momentum – a less well constrained domain of parton distribution functions.

"Instead of exploiting the $Z \to \mu\mu$ sample to tune the parameters of W-boson production, CMS is using the W data themselves to constrain the theory parameters of the prediction for the p_T spectrum, and using the independent $Z \to \mu\mu$ sample to validate this procedure," explains Hamel de Monchenault. "This ▷

validation gives us great confidence in our theory modelling."

"The CDF collaboration doesn't have an explanation for the incompatibility of the results," says spokesperson David Toback of Texas A&M University. "Our focus is on the checks of our own analysis and understanding of the ATLAS and CMS methods so we can provide useful critiques that might be helpful in future dialogues. On the one hand, the consistency of the ATLAS and CMS results must be taken seriously. On the other, given the number of iterations and improvements needed over decades for our own analysis – CDF has published five times over 30 years – we still consider both LHC results 'early days' and look forward to more details, improved methodology and additional measurements."

The ATLAS collaboration is extremely impressed with the new measurement by CMS

The LHC experiments each plan improvements using new data. The results will build on a legacy of electroweak precision at the LHC that was not anticipated to be possible at a hadron collider (*CERN Courier* September/October 2024 p29).

"The ATLAS collaboration is extremely impressed with the new measurement by CMS and the extraordinary precision achieved using high-pileup data," says spokesperson Andreas Hoecker. "It is a tour de force, accomplished by means of a highly complex fit, for which we applaud the CMS collaboration." ATLAS's next measurement of m_W will focus on low-pileup data, to improve sensitivity to m_T relative to their previous result.

The LHCb collaboration is working on an update of their measurement using its full Run 2 data set. LHCb's forward acceptance may prove to be powerful in a global fit. "LHCb probes parton density functions in different phase space regions, and that makes the measurements from LHCb anticorrelated with those of ATLAS and CMS, promising a significant impact on the average, even if the overall uncertainty is larger," says spokesperson Vincenzo Vagnoni. The goal is to progress LHC measurements towards a combined precision of 5 MeV. CMS plans several improvements to their own analysis.

"There is still a significant factor to be gained on the momentum scale, with which we could reach the same precision on the Z-boson mass as LEP," says Hamel de Monchenault. "We are confident that we can also use a future, large low-pileup run to exploit the W recoil and m_T to complement the muon p_T spectrum. Electrons can also be used, although in this case the Z sample could not be kept independent in the energy calibration."

Further reading

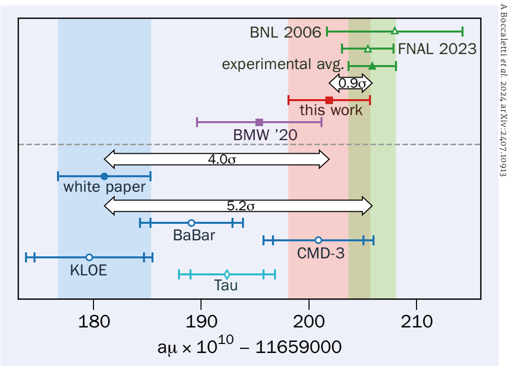
CMS Collab. 2024 CMS-PAS-SMP-23-002.

THEORETICAL PHYSICS

Shifting sands for muon g–2

The Dirac equation predicts the magnetic moment of the muon (g) to be precisely two in units of the Bohr magneton. Virtual lines and loops add roughly 0.1% to this value, giving rise to a so-called anomalous contribution often quantified by $a_\mu = (g-2)/2$. Countless electromagnetic loops dominate the calculation, spontaneous symmetry breaking is evident in the effect of weak interactions, and contributions from the strong force are non-perturbative. Despite this formidable complexity, theoretical calculations of a_μ have been experimentally verified to nine significant figures.

The devil is in the 10th digit. The experimental world average for a_μ currently stands more than 5σ above the Standard Model (SM) prediction published by the Muon g-2 Theory Initiative in a 2020 white paper. But two recent results may ease this tension in advance of a new showdown with experiment next year.



A Boccaletti *et al.* 2024 arXiv:2407.10913

Two-pronged challenge *An improved lattice-QCD calculation modified by data-driven inputs (red) joins new electron–positron data (CMD-3) in casting fresh doubt on the tension between experimental measurements of the anomalous magnetic moment of the muon (green) and the former theoretical consensus on its value (blue bar).*

The first new input is data from the CMD-3 experiment at the Budker Institute of Nuclear Physics, which yields a_μ consistent with experimental data. Comparable electron–positron (e^+e^-) collider data from the KLOE experiment at the National Laboratory of Frascati, the BaBar experiment at SLAC, the BESIII experiment at IHEP Beijing and CMD-3's predecessor CMD-2, were the backbone of the 2020 theory white paper. With KLOE and CMD-3 now incompatible at the level of 5σ, theorists are exploring alternative bases for the theoretical prediction, such as an ab-initio approach based on lattice QCD and a data-driven approach using tau-lepton decays.

The second new result is an updated theory calculation of a_μ by the Budapest-Marseille-Wuppertal (BMW) collaboration. BMW's ab-initio lattice-QCD calculation of 2020 was the first to challenge the data-driven consensus expressed in the 2020 white paper. The recent update now claims a superior precision, driven in part by the pragmatic implementation of a data-driven approach in the low-mass region, where experiments are in good agreement. Though only accounting for 5% of the hadronic contribution to a_μ, this "long distance" region is often the largest source of error in lattice-QCD calculations, and relatively insensitive to the use of finer lattices.

The new BMW result is fully compatible with the experimental world average, and incompatible with the 2020 white paper at the level of 4σ.

"It seems to me that the 0.9σ agreement between the direct experimental measurement of the magnetic moment of the muon and the ab-initio calculation of BMW has most probably postponed the possible discovery of new physics in this process," says BMW spokesperson Zoltán Fodor (Wuppertal). "It is important to mention that other groups have partial results, too, so-called window results, and they all agree with us and in several cases disagree with the result of the data-driven method."

These two analyses were among the many discussed at the seventh plenary workshop of the Muon g-2 Theory Initiative held in Tsukuba, Japan from 9 to 13 September. The theory initiative is planning to release an updated prediction in a white paper due to be published in early 2025. With multiple mature e^+e^- and lattice-QCD analyses underway for several years, attention now turns to tau decays – the subject of a soon-to-be-announced mini-workshop to ensure their full availability for consideration as a possible basis for the 2025 white paper. Input data would likely originate from tau decays recorded by the Belle experiment at KEK and the ALEPH experiment at ▷

CERN, both now decommissioned.

"From a theoretical point of view, the challenge for including the tau data is the isospin rotation that is needed to convert the weak hadronic tau decay to the desired input for hadronic vacuum polarisation," explains theory-initiative chair Aida X El-Khadra (University of Illinois). Hadronic vacuum polarisation (HVP) is the most challenging part of the calculation of a_μ, accounting for the effect of a muon emitting a virtual photon that briefly transforms into a flurry of quarks and gluons just before it absorbs the photon representing the magnetic field (*CERN Courier* May/June 2021 p25).

Lattice QCD offers the possibility of a purely theoretical calculation of HVP. While BMW remains the only group to have published a full lattice-QCD calculation, multiple groups are zeroing in on its most sensitive aspects (*CERN Courier* September/October 2024 p21).

I am hopeful we will be able to establish consolidation between independent lattice calculations at the sub-percent level

"The main challenge in lattice-QCD calculations of HVP is improving the precision to the desired sub-percent level, especially at long distances," continues El-Khadra. "With the new results for the long-distance contribution by the RBC/UKQCD and Mainz collaborations that were already reported this year, and the results that are still expected to be released this fall, I am hopeful that we will be able to establish consolidation between independent lattice calculations at the sub-percent level. In this case we will provide a lattice-only determination of HVP in the second white paper."

Further reading

CMD-3 Collab. 2024 *Phys. Rev. D* **109** 112002.
A Boccaletti *et al.* 2024 arXiv:2407.10913.

ACCELERATORS

CERN to insource beam-pipe production

In the Large Hadron Collider (LHC), counter-rotating beams of protons travel in separate chambers under high vacuum to avoid scattering with gas molecules. At four places around the 27 km ring, the beams enter a single chamber, where they collide. To ensure that particles emerging from the high-energy collisions pass into the ALICE, ATLAS, CMS and LHCb detectors with minimal disturbance, the experiments' vacuum chambers must be as transparent as possible to radiation, placing high demands on materials and production.

The sole material suitable for the beam pipes at the heart of the LHC experiments is beryllium – a substance used in only a few other domains, such as the aerospace industry. Its low atomic number (Z = 4) leads to minimal interaction with high-energy particles, reducing scattering and energy loss. The only solid element with a lower atomic number is lithium (Z = 3), but it cannot be used as it oxidises rapidly and reacts violently with moisture, producing flammable hydrogen gas. Despite being less dense than aluminium, beryllium is six times stronger than steel, and can withstand the mechanical stresses and thermal loads encountered during collider operations. Beryllium also has good thermal conductivity, which helps dissipate the heat generated during beam collisions, preventing the beam pipe from overheating.

But beryllium also has drawbacks. It is expensive to procure as it comes in the form of a powder that must be compressed at very high pressure to obtain metal rods, and as beryllium is toxic, all manufacturing steps require strict safety procedures.

M Brice/CERN-PHOTO-202103-040-36

Pipe dreams *The beam pipe at the heart of the CMS experiment is installed inside the detector's pixel tracker.*

The last supplier worldwide able to machine and weld beryllium beam pipes within the strict tolerances required by the LHC experiments decided to discontinue their production in 2023. Given the need for multiple new beam pipes as part of the forthcoming high-luminosity upgrade to the LHC (HL-LHC), CERN has decided to build a new facility to manufacture vacuum pipes on site, including parts made of beryllium. A 650 m^2 workshop is scheduled to begin operations on CERN's Prévessin site next year.

By insourcing beryllium beam-pipe production, CERN will gain direct control of the manufacturing process, allowing stricter quality assurance and greater flexibility to meet changing experimental requirements. The new facility will include several spaces to perform metallurgical analysis, machining of components, surface treatments, final assembly by electron-beam welding, and quality control steps such as metrology and non-destructive tests. As soon as beryllium beampipes are fabricated, they will follow the usual steps for ultra-high vacuum conditioning that are already available in CERN's facilities. These include helium leak tests, non-evaporable-getter thin-film coatings, the installation of bakeout equipment, and final vacuum assessments.

Once the new workshop is operational, the validation of the different manufacturing processes will continue until mid-2026. Production will then begin for new beam pipes for the ALICE, ATLAS and CMS experiments in time for the HL-LHC, as each experiment will replace their pixel tracker – the sub-detector closest to the beam – and therefore require a new vacuum chamber. With stricter manufacturing requirements, never accomplished until now, and a conical section designed to maximise transparency in the forward regions where particles pass through at smaller angles, ALICE's vacuum chamber will pose a particular challenge. Together totalling 21 m in length, the first three beam pipes to be constructed at CERN will be installed in the detectors during the LHC's Long Shutdown 3 from 2027 to 2028.

By bringing beam-pipe production in-house, CERN will acquire unique expertise that will be useful not only for the HL-LHC experiments but also future projects and other accelerators around the world, and preserve a fundamental technology for experimental beam pipes.

ACCELERATORS

Revised schedule for the High-Luminosity LHC

During its September session, the CERN Council was presented with a revised schedule for Long Shutdown 3 (LS3) of the LHC and its injector complex. For the LHC, LS3 is now scheduled to begin at the start of July 2026, seven and a half months later than planned. The overall length of the shutdown will increase by around four months. Combined, these measures will shift the start of the High-Luminosity LHC (HL-LHC) by approximately one year, to June 2030. The extensive programme of work for the injectors will begin in September 2026, with a gradual restart of operations scheduled to take place in 2028.


CERN

Cool technology *The innovative cold-powering system for the High-Luminosity LHC was successfully installed in the inner-triplet-string test stand above ground in September.*

"The decision to shift the start of the HL-LHC by approximately one year and increase the length of the shutdown reflects a consensus supported by our scientific committees," explains Mike Lamont, CERN director for accelerators and technology. "The delayed start of LS3 is primarily due to significant challenges encountered during the Phase II upgrades of the ATLAS and CMS experiments, which have led to the erosion of contingency time and introduced considerable schedule risks. The challenges faced by the experiment teams included COVID-19 and the impact of the Russian invasion of Ukraine."

LS3 represents a pivotal phase in enhancing CERN's capabilities. During the shutdown, ATLAS and CMS will replace many of their detectors and a large part of their electronics. Schedule contingencies have been insufficient for the new inner tracker for ATLAS, and for the HGCAL and new tracker for CMS. The delayed start of LS3 will allow the collaborations more time to develop and build these highly sophisticated detectors and systems.

On the machine side, a key activity during LS3 is the drilling of 28 vertical cores to link the new HL-LHC technical galleries to the LHC tunnel. Initially expected to take six months, this timeframe was reduced to two months in 2021 to optimise the schedule. However, challenges encountered during the tendering process and in subsequent consultations with specialists necessitated a return to the original six-month timeline for core excavation.

In addition to high-luminosity enhancements, LS3 will involve a major programme of work across the accelerator complex. This includes the North Area consolidation project and the transformation of the ECN3 cavern into a high-intensity fixed-target facility; the dismantling of the CNGS target to make way for the next phase of wakefield-acceleration research at AWAKE; improvements to ISOLDE to boost the facility's nuclear-studies potential; and extensive maintenance and consolidation across all machines and facilities to ensure operational safety, longevity and availability.

"All these activities are essential to ensuring the medium-term future of the laboratory and allowing full exploitation of its remarkable potential in the coming decades," says Lamont.

INTERNATIONAL RELATIONS Dignitaries mark CERN's 70th anniversary

CERN

On 1 October a high-level ceremony at CERN marked 70 years of science, innovation and collaboration. In attendance were 38 national delegations, including eight heads of state or government and 13 ministers, along with many scientific, political and economic leaders who demonstrated strong support for CERN's mission and future ambition. "CERN has become a global hub because it rallied Europe, and this is even more crucial today," said president of the European Commission Ursula von der Leyen. "China is planning a 100 km collider to challenge CERN's global leadership. Therefore, I am proud that we have financed the feasibility study for CERN's Future Circular Collider. As the global science race is on, I want Europe to switch gear." CERN's year-long 70th anniversary programme has seen more than 100 events organised in 63 cities in 28 countries, bringing together thousands of people to discuss the wonders and applications of particle physics. "I am very honoured to welcome representatives from our Member and Associate Member States, our Observers and our partners from all over the world on this very special day," said CERN Director-General Fabiola Gianotti. "CERN is a great success for Europe and its global partners, and our founders would be very proud to see what CERN has accomplished over the seven decades of its life."

SEARCHES FOR NEW PHYSICS

NA62 observes its golden decay

In a game of snakes and ladders, players move methodically up the board, occasionally encountering opportunities to climb a ladder. The NA62 experiment at CERN is one such opportunity. Searching for ultra-rare decays at colliders and fixed- target experiments like NA62 can offer a glimpse at energy scales an order of magnitude higher than is directly accessible when creating particles in a frontier machine.

The trick is to study hadron decays that are highly suppressed by the GIM mechanism (see p37). Should massive particles beyond the Standard Model (SM) exist at the right energy scale, they could disrupt the delicate cancellations expected in the SM by making brief virtual appearances according to the limits imposed by Heisenberg's uncertainty principle. In a recent featured article, Andrzej Buras (Technical University Munich) identified the six most promising rare decays where new physics might be discovered before the end of the decade (*CERN Courier* July/August 2024 p30). Among them is $K^+ \to \pi^+\nu\nu$, the ultra-rare decay sought by NA62. In the SM, fewer than one K^+ in 10 billion decays this way, requiring the team to exercise meticulous attention to detail in excluding backgrounds. The collaboration has now announced that it has observed the process with 5σ significance.

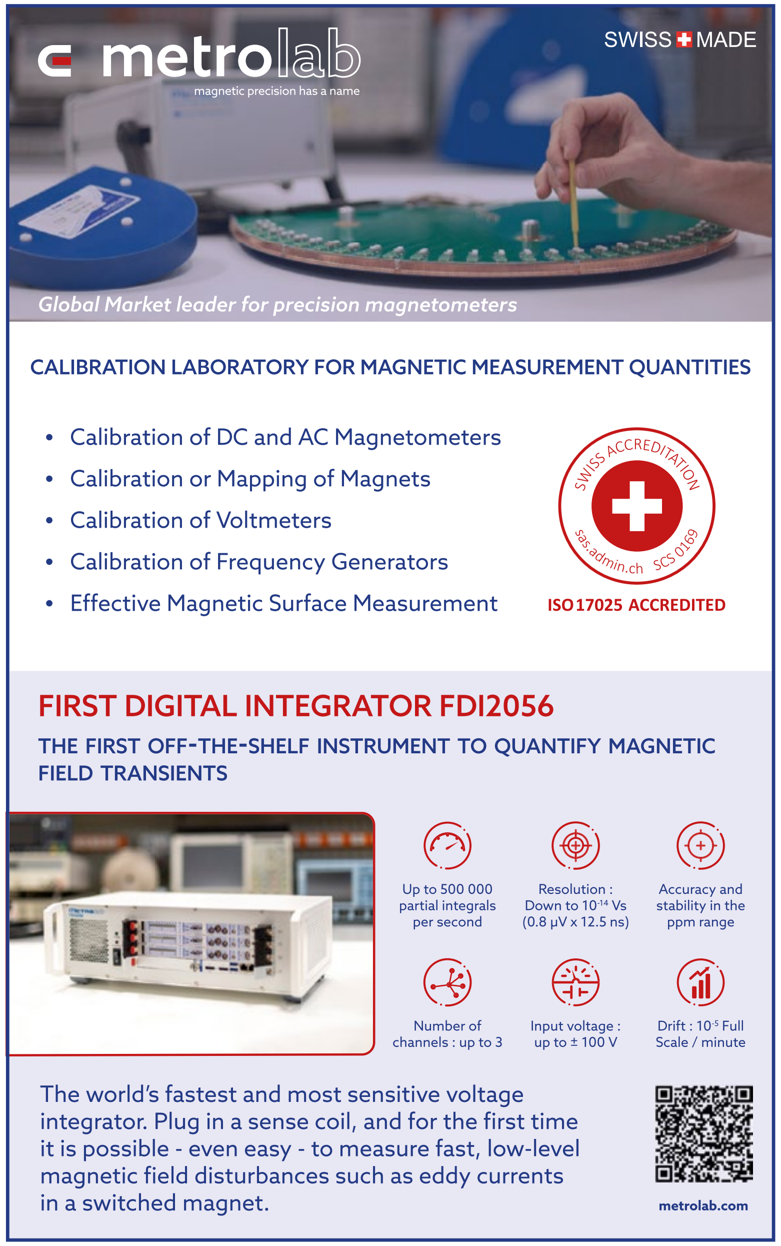
"This observation is the culmination of a project that started more than a decade ago," says spokesperson Giuseppe Ruggiero of INFN and the University of Florence. "Looking for effects in nature that have probabilities of happening of the order of 10^{-11} is both fascinating and challenging. After rigorous and painstaking work, we have finally seen the process NA62 was designed and built to observe."

In the NA62 experiment, kaons are produced by colliding a high-intensity proton beam from CERN's Super Proton Synchrotron into a stationary beryllium target. Almost a billion secondary particles are produced each second. Of these, about 6% are positively charged kaons that are tagged and matched with positively charged pions from the decay $K^+ \to \pi^+\nu\nu$, with the neutrinos escaping undetected. Upgrades to NA62 during Long Shutdown 2 increased the experiment's signal efficiency while maintaining its sample purity, allowing the collaboration to double the expected signal of their previous measurement using new data collected between 2021 and 2022. A total of 51 events pass the stringent selection criteria, over an expected background of 18^{+3}_{-2}, definitely establishing the existence of this decay for the first time.

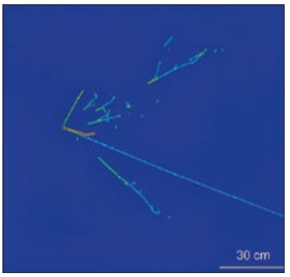

P Traczyk/CERN-PHOTO-202104-059-8

Meticulous *The NA62 experiment in CERN's North Area.*

NA62 measures the branching ratio for $K^+ \to \pi^+\nu\nu$ to be $13.0^{+3.3}_{-2.9} \times 10^{-11}$ – the most precise measurement to date and about 50% higher than the SM prediction, though compatible with it within 1.7σ at the current level of precision. NA62's full data set will be required to test the validity of the SM in this decay. Data taking is ongoing.



NEWS DIGEST



SBND Collab.

A muon neutrino in SBND.

First neutrinos for SBND

Fermilab's Short-Baseline Near Detector (SBND) has reconstructed its first neutrinos, declaring the lab's short-baseline programme fully operational. SBND is half a kilometre upstream of another liquid-argon TPC, the ICARUS detector, allowing sensitive searches for neutrino oscillations involving sterile neutrinos in the gap between them. SBND expects to see 7000 interactions per day – more than any other detector of its kind, the collaboration claims. This will additionally facilitate studies of neutrino interactions with argon nuclei useful to the DUNE experiment, and searches for signatures of physics beyond the Standard Model. The SBND collaboration has been planning, prototyping and constructing the detector for nearly a decade. "Understanding the anomalies seen by previous experiments has been a major goal in the field for the last 25 years," said co-spokesperson David Schmitz (University of Chicago). "Together, SBND and ICARUS will have outstanding ability to test the existence of these new neutrinos."

Flavour universality in B_s^0 decays

The LHCb experiment has tested the principle of lepton flavour universality (LFU) in rare B_s^0 decays for the first time, finding no significant deviation from the Standard Model (SM). The team measured the ratio of branching fractions to the final states ϕe^+e^- and $\phi\mu^+\mu^-$ to be consistent with unity (LHCb-PAPER-2024-032). The electron channel had never been observed before, but the branching fraction for $B_s^0 \to \phi\mu^+\mu^-$ was previously found by LHCb to be systematically below theoretical predictions. Discrepancies with SM predictions have also been found in the angular distributions of this and other decays mediated by $b \to s\mu^+\mu^-$. The new measurement suggests that the $B_s \to \phi e^+e^-$ branching fraction also lies systematically below SM predictions.

Upgrade for most powerful XFEL

The US Department of Energy has given the green light for construction to begin on a high-energy upgrade to SLAC's Linac Coherent Light Source (LCLS) – the world's most powerful X-ray free-electron laser. The upgrade will increase the brightness for high-energy X-rays 3000-fold, enabling studies relating to energy storage, catalysis, biology, materials science and quantum physics. 95% of the cavities have already been produced, and 10 cryomodules delivered (see picture above). "If the LCLS-II upgrade enabled a high-quality movie camera capable of capturing clear and detailed images, the LCLS-II-HE upgrade greatly boosts that camera's resolution and sensitivity," says director Mike Dunne. LCLS switched on in 2009 and LCLS-II was completed last year; LCLS-II-HE is projected to be complete by 2030.

J Ramseyer Orrell/SLAC

A cryomodule arrives at SLAC.

Venice symposium

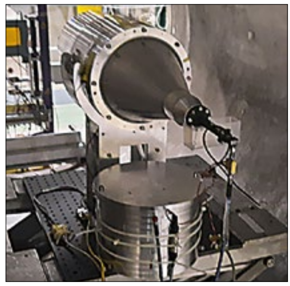
During its September session, the CERN Council finalised the organisation of the European Strategy process by appointing members of the Physics Preparatory Group (PPG) and announcing that the Strategy Open Symposium will take place in Venice from 23 to 27 June next year. The PPG will prepare scientific input to the work of the European Strategy Group (ESG) based on the input submitted by the community between now and 31 March, with researchers then invited to debate the future orientation of European particle physics at the Venice symposium. The ESG is tasked with developing a visionary and concrete plan that greatly advances human knowledge in fundamental physics through the realisation of the next flagship project at CERN. It will submit final recommendations to the CERN Council in early 2026 (*CERN Courier* September/October 2024 p7).

Radiotherapy gap still wide

Cancer treatment with particle beams is a major offshoot of high-energy-physics research, from cutting-edge hadron-therapy techniques to projects designed to increase access to radiotherapy (*CERN Courier* July/August 2024 p46). A new study commissioned by *Lancet Oncology* reinforces the need for accessibility: one machine serves 15.6 million people in low-income countries, compared to just 130,600 people in high-income countries – a factor 120 disparity between rich and poor (M Abdel-Wahab *et al.* 2024 *Lancet Oncology* Commission).

Dielectric haloscope first

The MADMAX collaboration has performed the world's first search for axions using a dielectric haloscope. In the prototype detector, three sapphire disks and a mirror seek to resonantly enhance an axion-induced microwave signal in the dipole magnetic field provided by the 1.6 T Morpurgo magnet at CERN. No signal was detected, though limits are already competitive with those achieved by the CAST helioscope in the mass ranges 76.56 to 76.82 μeV and 79.31 to 79.53 μeV (arXiv:2409.11777). Prototypes will now be scaled up by adding further disks, increasing their diameter, and operating at cryogenic temperatures using quantum-limited detectors, says the collaboration. A dark-matter candidate, axions are hypothesised to explain why the strong interaction conserves CP symmetry.

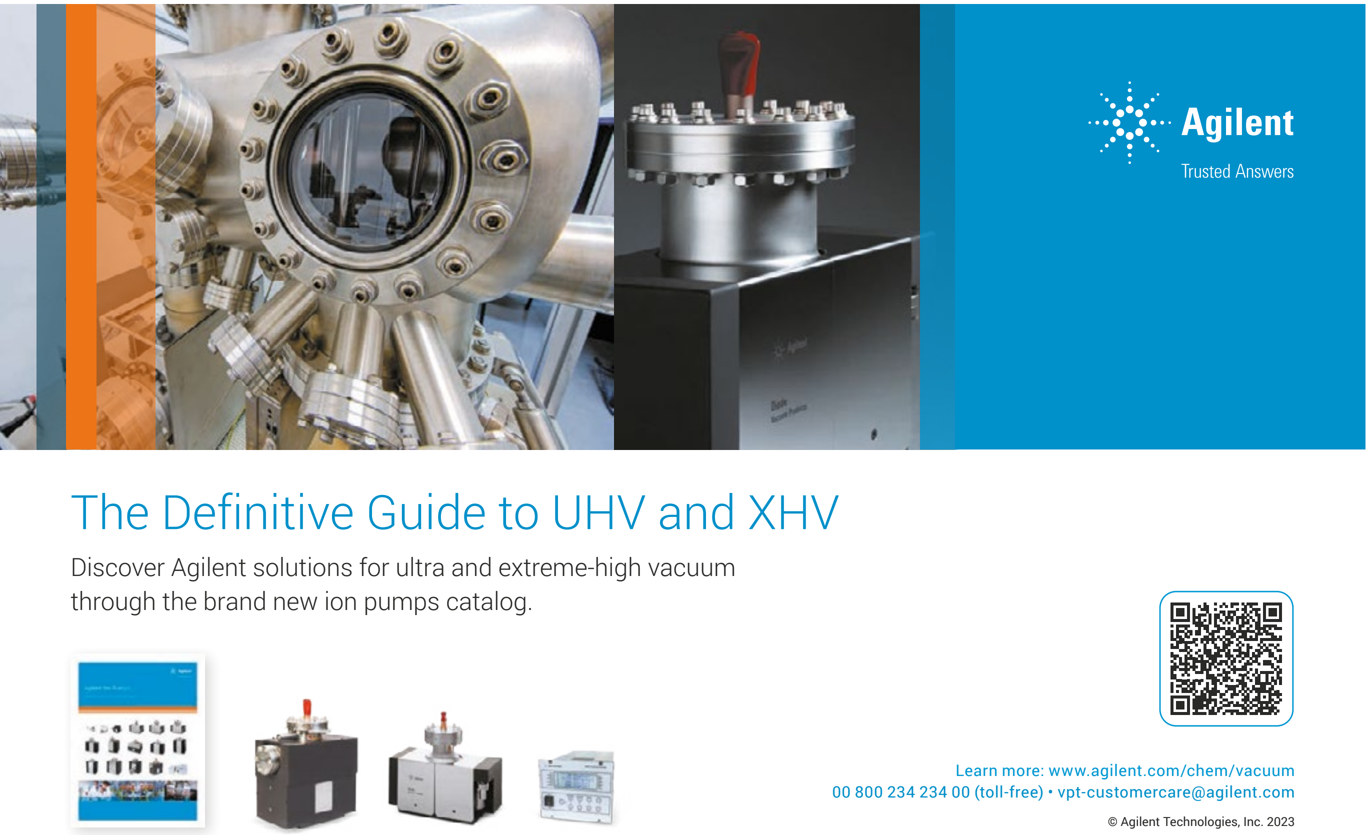


MADMAX Collab.

The MADMAX prototype.

Dielectric haloscopes and gravitational waves

While dielectric haloscopes were originally designed to detect dark matter in the form of axions, a recent study by theorists from CERN and the University of Geneva argues that the devices could double as gravitational-wave detectors. For example, the team claims that MADMAX could be sensitive to high-frequency gravitational waves in the 100 MHz to 10 GHz range – a band complementary to that of detectors like LIGO (arXiv:2409.06462). While the sensitivity of the current prototype would be limited, future evolutions of the technology could potentially probe gravitational-wave emission from violent processes in neutron stars and exotic sources such as primordial black holes.



ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ALICE

Hypertriton and ‘little bang’ nucleosynthesis

According to the cosmological standard model, the first generation of nuclei was produced during the cooling of the hot mixture of quarks and gluons that was created shortly following the Big Bang. Relativistic heavy-ion collisions create a quark–gluon plasma (QGP) on a small scale, producing a “little bang”. In such collisions, the nucleosynthesis mechanism at play is different from the one of the Big Bang due to the rapid cool down of the fireball. Recently, the nucleosynthesis mechanism in heavy-ion collisions has been investigated via the measurement of hypertriton production by the ALICE collaboration.

The hypertriton, which consists of a proton, a neutron and a Λ hyperon, can be considered to be a loosely bound deuteron–Λ molecule (see p33). In this picture, the energy required to separate the Λ from the deuteron (B_Λ) is about 100 keV, significantly lower than the binding energy of ordinary nuclei. This makes hypertriton production a sensitive probe of the properties of the fireball.

In heavy-ion collisions, the formation of nuclei can be explained by two main classes of models. The statistical hadronisation model (SHM) assumes that particles are produced from a system in thermal equilibrium. In this model, the production rate of nuclei depends only on their mass, quantum numbers and the temperature and volume of the system. On the other hand, in coalescence models, nuclei are formed from nucleons that are close together in phase space. In these models, the production rate of nuclei is also sensitive to their nuclear structure and size.

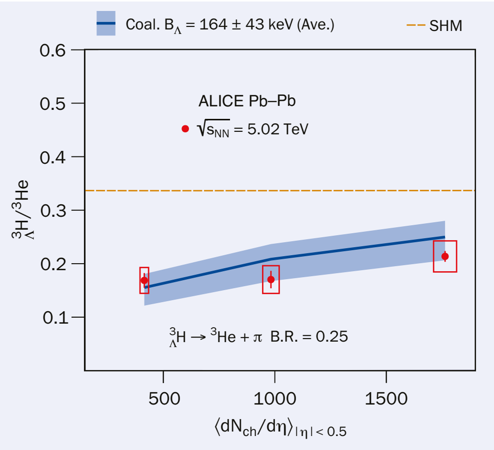


Fig. 1. *Yield ratio of $^{3}_{\Lambda}$H to ^{3}He as a function of the charged-particle multiplicity density of the Pb–Pb collision, together with theoretical predictions.*

ALICE Collab. 2024 arXiv:2405.19839

For an ordinary nucleus like the deuteron, coalescence and SHM predict similar production rates in all colliding systems, but for a loosely bound molecule such as the hypertriton, the predictions of the two models differ significantly. In order to identify the mechanism of nuclear production, the ALICE collaboration used the ratio between the production rates of hypertriton and helium-3 – also known as a yield ratio – as an observable.

ALICE measured hypertriton production as a function of charged-particle multiplicity density using Pb–Pb collisions collected at a centre-of-mass energy of 5.02 TeV per nucleon pair during LHC Run 2. Figure 1 shows the yield ratio of hypertriton to ^{3}He across different multiplicity intervals. The data points (red) exhibit a clear deviation from the SHM (dashed orange line), but are well-described by the coalescence model (blue band), supporting the conclusion that hypertriton formation at the LHC is driven by the coalescence mechanism.

The ongoing LHC Run 3 is expected to improve the precision of these measurements across all collision systems, allowing us to probe the internal structure of hypertriton and even heavier hypernuclei, whose properties remain largely unknown. This will provide insights into the interactions between ordinary nucleons and hyperons, which are essential for understanding the internal composition of neutron stars.

Further reading

ALICE Collab. 2024 arXiv:2405.19839.

LHCb

Using U-spin to squeeze CP violation

The LHCb collaboration has undertaken a new study of B → DD decays using data from LHC Run 2. In the case of $B^0 \to D^+D^-$ decays, the analysis excludes CP-symmetry at a confidence level greater than six standard deviations – a first in the analysis of a single decay mode.

The study of differences between matter and antimatter (CP violation) is a core aspect of the physics programme at LHCb. Measurements of CP violation in decays of neutral B^0 mesons play a crucial role in the search for physics beyond the Standard Model thanks to the ability of the B^0 meson to oscillate into its antiparticle, the $\bar{B}^0$ meson. Given increases in experimental precision, improved control over the magnitude of hadronic effects becomes important, which is a major challenge in most decay modes. In this measurement, a neutral B meson decays to two charm D mesons – an interesting topology that offers a method to control these high-order hadronic contributions from the Standard Model via the concept of U-spin symmetry.

The study of differences between matter and antimatter is a core aspect of the physics programme at LHCb

In the new analysis, $B^0 \to D^+D^-$ and $B^0_s \to D^+_s D^-_s$ are studied simultaneously. U-spin symmetry exchanges the spectator down quarks in the first decay with strange quarks to form the second decay. A joint analysis therefore strongly constrains uncertainties related to hadronic matrix elements by relating CP-violation and branching-fraction measurements in the two decay channels.

In both decays, the same final state is accessible to both matter and antimatter states of the B^0 or B^0_s meson, enabling interference between two decay paths: the direct decay of the meson to the final state; and a decay after the meson has oscillated into its antiparticle counterpart. The time-dependent decay rate of each flavour (matter or antimatter) ▷

of the meson depends on CP-violating effects and is parameterised in terms dependent on the fundamental properties of the B mesons and the fundamental CP-violating weak phases β and β_s, in the case of B^0 and B^0_s decays, respectively. The tree-level and exchange Feynman diagrams participating to this decay process, which in turn depend on specific values of the terms in the Cabibbo–Kobayashi–Maskawa quark-mixing matrix, determine the expected value of the $\beta_{(s)}$ phases. This matrix encodes our best understanding of the CP-violating effects within the Standard Model, and testing its expected properties is a crucial means to fully exploit closure tests of this theoretical framework.

The analysis uses flavour tagging to identify the matter or antimatter flavour of the neutral B meson at its production and thus allows the determination of the decay path – a key task in time-dependent measurements of CP violation. The flavour-tagging algorithms exploit the fact that b and $\bar{b}$ quarks are almost exclusively produced in pairs in pp collisions. When the $\bar{b}$ quark forms a B meson (and similarly for its antimatter equivalent), additional particles are produced in the fragmentation process of the pp collision. From the charges and species of these particles, the flavour of the signal B meson at production can be inferred. This information is combined with the reconstructed position of the decay vertex of the meson, allowing the flavour-tagged decay-time distribution of each analysed flavour to be measured.

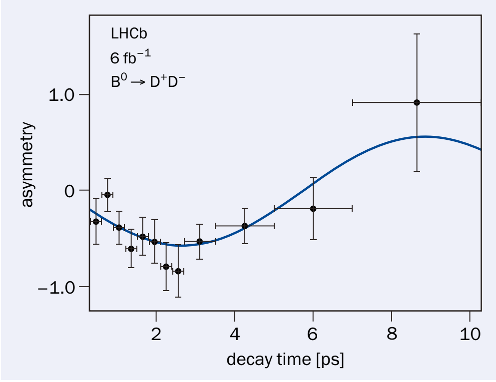


Fig. 1. *The decay-time-dependent CP asymmetry of $B^0 \to D^+D^-$ candidates. The asymmetry in the background-subtracted data is shown as points and the projection of the fitted model is shown as a solid blue line.*

LHCb Collab. 2024 arXiv:2409.03009

Figure 1 shows the asymmetry between the decay-time distributions of the B^0 and the $\bar{B}^0$ mesons for the $B^0 \to D^+D^-$ decay mode. Alongside the $B^0_s \to D^+_s D^-_s$ data, these results represent the most precise single measurements of the CP-violation parameters in their respective channels. Results from the two decay modes are used in combination with other B → DD measurements to precisely determine Standard Model parameters.

Further reading

LHCb Collab. 2024 arXiv:2409.03009.

CMS

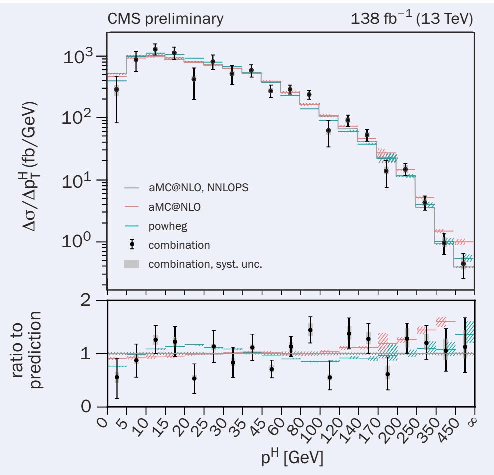
Combining clues from the Higgs boson

Following the discovery of the Higgs boson in 2012, the CMS collaboration has been exploring its properties with ever-increasing precision. Data recorded during LHC Run 2 have been used to measure differential production cross-sections of the Higgs boson in different decay channels – a pair of photons, two Z bosons, two W bosons and two tau leptons – and as functions of different observables. These results have now been combined to provide measurements of spectra at the ultimate achievable precision.

Differential cross-section measurements provide the most model-independent way to study Higgs-boson production at the LHC, for which theoretical predictions exist up to next-to-next-to-next-to-leading order in perturbative QCD. One of the most important observables is the transverse momentum (figure 1). This distribution is particularly sensitive both to modelling issues in Standard Model (SM) predictions and possible contributions from physics-beyond-the-SM (BSM).

In the new CMS result, two frameworks are used to test for hints of BSM: the κ-formalism and effective field theories.

The κ-formalism assumes that new physics effects would only affect the couplings between the Higgs boson and other particles. These new physics effects are then parameterised in terms of coefficients, κ. Using this approach, two-dimensional constraints are set on κ_c (the coupling coefficient of the Higgs boson to the charm quark), κ_b (Higgs to bottom) and κ_t (Higgs to top). None show significant deviations from the SM at present.



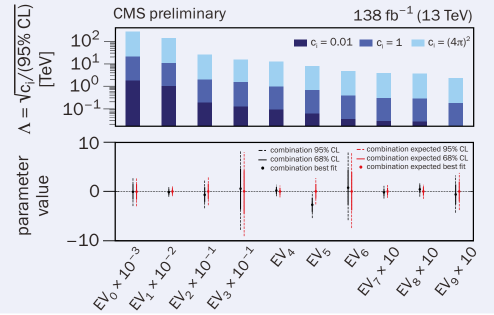


Fig. 1. (top) *Combined measurement of the rate of production of the Higgs boson in bins of its transverse momentum. The measured values (black markers) agree well with SM predictions (grey, green and red histograms).*
Fig. 2. (bottom) *Constraints on linear combinations of EFT coefficients (bottom panel) – the measured values agree well with the SM expectations – and the energy scale of the new physics that they can constrain under certain assumptions (top panel).*

CMS Collab. 2024 CMS-PAS-HIG-23-013

Effective field theories parametrise deviations from the SM by supplementing the Lagrangian with higher-dimensional operators and their associated Wilson coefficients (WCs). The effect of the operators is suppressed by powers of the putative new-physics energy scale, Λ. Measurements of WCs that differ from zero may hint at BSM physics.

The CMS differential cross-section measurements are parametrised, and constraints are derived on the WCs from a simultaneous fit. In the most challenging case, a set of 31 WCs is used as input to a principal-component analysis procedure in which the most sensitive directions in the data are identified. These directions (expressed as linear combinations of the WCs) are then constrained in a simultaneous fit (figure 2). In the upper panel, the limits on the WCs are converted to lower limits on the new physics scale. The results agree with SM predictions, with a moderate 2σ tension present in one of the directions (EV5). Here the major contribution is provided by the c_{Hq3} coefficient, which mostly affects vector-boson fusion, VH production at high Higgs-boson transverse momenta (V = W, Z) and W-boson decays.

The combined results not only provide highly precise measurements of Higgs-boson production, but also place stringent constraints on possible deviations from the SM, deepening our understanding while leaving open the possibility of new physics at higher precision or energy scales.

The results leave open the possibility of new physics at higher precision

Further reading

CMS Collab. 2024 CMS-PAS-HIG-23-013.

ATLAS

Cornering the Higgs couplings to quarks

One of nature's greatest mysteries lies in the masses of the elementary fermions. Each of the three generations of quarks and charged leptons is progressively heavier than the first one, which forms ordinary matter, but the overall pattern and vast mass differences remain empirical and unexplained. In the Standard Model (SM), charged fermions acquire mass through interactions with the Higgs field. Consequently, their interaction strength with the Higgs boson, a ripple of the Higgs field, is proportional to the fermions' mass. Precise measurements of these interaction strengths could offer insights into the mass-generation mechanism and potentially uncover new physics to explain this mystery.

The ATLAS collaboration recently released improved results on the Higgs boson's interaction with second- and third-generation quarks (charm, bottom and top), based on the analysis of data collected during LHC Run 2 (2015–2018). The analyses refine two studies: Higgs-boson decays to charm- and bottom-quark pairs (H → cc and H → bb) in events where the Higgs boson is produced together with a weak boson V (W or Z); and, since the Higgs boson is too light to decay into a top-quark pair, the interaction with top quarks is probed in Higgs production in association with a top-quark pair (ttH) in events with H → bb decays. Sensitivity to H → cc and H → bb in VH production is increased by a factor of three and by 15%, respectively. Sensitivity to ttH, H → bb production is doubled.

Innovative analysis techniques were crucial to these improvements, several involving machine learning techniques, such as state-of-the-art transformers in the extremely challenging ttH(bb) analysis. Both analyses utilised an upgraded algorithm for identifying particle jets from bottom and charm quarks. A bespoke implementation allowed, for the first time, analysis of VH events coherently for both H → cc and H → bb decays. The enhanced classification of the signal from various background processes allowed a tripling of the number of selected ttH, H → bb events, and was the single largest improvement to increase the sensitivity to VH, H → cc. Both analyses improved their methods for estimating background processes including new theoretical predictions and the refined assessment of related uncertainties – a key component to boost the ttH, H → bb sensitivity.

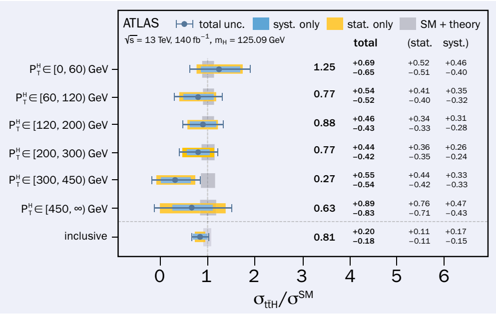


Fig. 1. *Measured ttH cross-sections for the H → bb decay channel, both inclusive and differential in Higgs transverse momentum, and normalised by the prediction.*

ATLAS Collab. 2024 arXiv:2407.10904

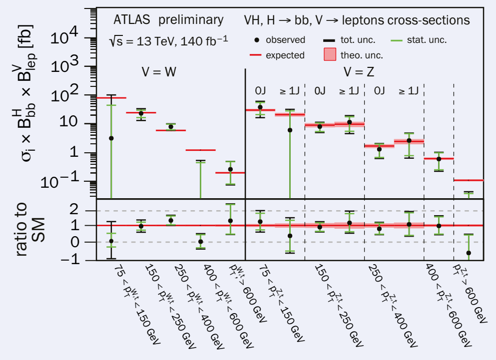


Fig. 2. *Measured VH cross-sections times the branching fractions of H → bb and the vector-boson decays to leptons, as a function of the true vector-boson p_T and, for the Z boson, the number of additional jets.*

ATLAS Collab. 2024 ATLAS-CONF-2024-010

Due to these improvements, ATLAS measured the ttH, H → bb cross-section with a precision of 24%, better than any single measurement before. The signal strength relative to the SM prediction is found to be 0.81 ± 0.21, consistent with the SM expectation of unity. It does not confirm previous results from ATLAS and CMS that left room for a lower-than-expected ttH cross section, dispelling speculations of new physics in this process. The compatibility between new and previous ATLAS results is estimated to be 21%.

In the new analysis VH, H → bb production was measured with a record precision of 18%; WH, H → bb production was observed for the first time with a significance of 5.3σ. Because H → cc decays are suppressed by a factor of 20 relative to H → bb decays, given the difference in quark masses, and are more difficult to identify, no significant sign of this process was found in the data. However, an upper limit on potential enhancements of the VH, H → cc rate of 11.3 times the SM prediction was placed at the 95% confidence level, allowing ATLAS to constrain the Higgs-charm coupling to less than 4.2 times the SM value, the strongest direct constraint to date.

The ttH and VH cross-sections were measured (double-)differentially with increased reach, granularity, and precision (figures 1 and 2). Notably, in the high transverse-momentum regime, where potential new physics effects are not yet excluded, the measurements were extended and the precision nearly doubled. However, neither analysis shows significant deviations from Standard Model predictions.

The significant new dataset from the ongoing Run 3 of the LHC, coupled with further advanced techniques like transformer-based jet identification, promises even more rigorous tests soon, and amplifies the excitement for the High-Luminosity LHC, where further precision will push the boundaries of our understanding of the Higgs boson – and perhaps yield clues to the mystery of the fermion masses.

Further reading

ATLAS Collab. 2024 arXiv:2407.10904.
ATLAS Collab. 2024 ATLAS-CONF-2024-010.

FIELD NOTES

Reports from events, conferences and meetings

ICHEP 2024

A rich harvest of results in Prague

The 42nd international conference on high-energy physics (ICHEP) attracted almost 1400 participants to Prague in July. Expectations were high, with the field on the threshold of a defining moment, and ICHEP did not disappoint. A wealth of new results showed significant progress across all areas of high-energy physics.

With the long shutdown on the horizon, the third run of the LHC is progressing in earnest. Its high-availability operation and mastery of operational risks were highly praised. Run 3 data is of immense importance as it will be the dataset that experiments will work with for the next decade. With the newly collected data at 13.6 TeV, the LHC experiments showed new measurements of Higgs and di-electroweak-boson production, though of course most of the LHC results were based on the Run 2 (2014 to 2018) dataset, which is by now impeccably well calibrated and understood. This also allowed ATLAS and CMS to bring in-depth improvements to reconstruction algorithms.

Beginning of the journey *Monica Dunford (Heidelberg University) explains that the best of the LHC is yet to come.*

J Kvita and R Volfik

Scouting's honour *Maurizio Pierini (CERN) emphasised innovations in data taking at the LHC.*

J Kvita and R Volfik

AI algorithms

A highlight of the conference was the improvements brought by state-of-the-art artificial-intelligence algorithms such as graph neural networks, both at the trigger and reconstruction level. A striking example of this is the ATLAS and CMS flavour-tagging algorithms, which have improved their rejection of light jets by a factor of up to four. This has important consequences. Two outstanding examples are: di-Higgs-boson production, which is fundamental for the measurement of the Higgs boson self-coupling (*CERN Courier* July/August 2024 p7); and the Higgs boson's Yukawa coupling to charm quarks. Di-Higgs-boson production should be independently observable by both general-purpose experiments at the HL-LHC, and an observation of the Higgs boson's coupling to charm quarks is getting closer to being within reach.

The LHC experiments continue to push the limits of precision at hadron colliders. CMS and LHCb presented new measurements of the weak mixing angle. The per-mille precision reached is close to that of LEP and SLD measurements (*CERN Courier* September/October 2024 p29). ATLAS presented the most precise measurement to date (0.8%) of the strong coupling constant extracted from the measurement of the transverse momentum differential cross section of Drell–Yan Z-boson production. LHCb provided a comprehensive analysis of the $B^0 \to K^{0*} \mu^+\mu^-$ angular distributions, which had previously presented discrepancies at the level of 3σ. Taking into account long-distance contributions significantly weakens the tension down to 2.1σ.

Pioneering the highest luminosities ever reached at colliders (setting a record at $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), SuperKEKB has been facing challenging conditions with repeated sudden beam losses. This is currently an obstacle to further progress to higher luminosities. Possible causes have been identified and are currently under investigation. Meanwhile, with the already substantial data set collected so far, the Belle II experiment has produced a host of new results. In addition to improved CKM angle measurements (alongside LHCb), in particular of the γ angle, Belle II (alongside BaBar) presented interesting new insights in the long standing $|V_{cb}|$ and $|V_{ub}|$ inclusive versus exclusive measurements puzzle (*CERN Courier* July/August 2024 p30), with new $|V_{cb}|$ exclusive measurements that significantly reduce the previous 3σ tension.

ATLAS and CMS furthered their systematic journey in the search for new phenomena to leave no stone unturned at the energy frontier, with 20 new results presented at the conference. This landmark outcome of the LHC puts further pressure on the naturalness paradigm.

A highlight of the conference was the overall progress in neutrino physics. Accelerator-based experiments NOvA and T2K presented a first combined measurement of the mass difference, neutrino mixing and CP parameters. Neutrino telescopes IceCube with DeepCore and KM3NeT with ORCA (Oscillation Research with Cosmics in the Abyss) also presented results with impressive precision. Neutrino physics is now at the dawn of a bright new era of precision with the next-generation accelerator-based long baseline experiments DUNE and Hyper Kamiokande, the upgrade of DeepCore, the completion of ORCA and the medium baseline JUNO experiment. These experiments will bring definitive conclusions on the measurement of the CP phase in the neutrino sector and the neutrino mass hierarchy – two of the outstanding goals in the field.

The KATRIN experiment presented a new upper limit on the effective ▷ electron–anti-neutrino mass of 0.45 eV, well en route towards their ultimate sensitivity of 0.2 eV. Neutrinoless double-beta-decay search experiments KamLAND-Zen and LEGEND-200 presented limits on the effective neutrino mass of approximately 100 meV; the sensitivity of the next-generation experiments LEGEND-1T, KamLAND-Zen-1T and nEXO should reach 20 meV and either fully exclude the inverted ordering hypothesis or discover this long-sought process. Progress on the reactor neutrino anomaly was reported, with recent fission data suggesting that the fluxes are overestimated, thus weakening the significance of the anti-neutrino deficits.

Neutrinos were also a highlight for direct-dark-matter experiments as Xenon announced the observation of nuclear recoil events from ^{8}B solar neutrino coherent elastic scattering on nuclei, thus signalling that experiments are now reaching the neutrino fog. The conference also highlighted the considerable progress across the board on the roadmap laid out by Kathryn Zurek at the conference to search for dark matter in an extraordinarily large range of possibilities, spanning 89 orders of magnitude in mass from 10^{-23} eV to 10^{57} GeV. The roadmap includes cosmological and astrophysical observations, broad searches at the energy and intensity frontier, direct searches at low masses to cover relic abundance motivated scenarios, building a suite of axion searches, and pursuing indirect-detection experiments.

Directors general *Fermilab's Lia Merminga and CERN's Fabiola Gianotti at ICHEP 2024.*

J Kvita and R Volfik

Neutrinos also made the headlines in multi-messenger astrophysics experiments with the announcement by the KM3Net ARCA (Astroparticle Research with Cosmics in the Abyss) collaboration of a muon-neutrino event that could be the most energetic ever found. The energy of the muon from the interaction of the neutrino is compatible with having an energy of approximately 100 PeV, thus opening a fascinating window on astrophysical processes at energies well beyond the reach of colliders. The conference showed that we are now well within the era of multi-messenger astrophysics, via beautiful neutrinos, gamma rays and gravitational-wave results.

The conference saw new bridges across fields being built. The birth of collider-neutrino physics with the beautiful results from FASERν and SND fill the missing gap in neutrino–nucleon cross sections between accelerator neutrinos and neutrino astronomy. ALICE and LHCb presented new results on $\overline{\mathrm{He}}^3$ production that complement the AMS results. Astrophysical $\overline{\mathrm{He}}^3$ could signal the annihilation of dark matter. ALICE also presented a broad, comprehensive review of the progress in understanding strongly interacting matter at extreme energy densities.

The highlight in the field of observational cosmology was the recent data from DESI, the Dark Energy Spectroscopic Instrument in operation since 2021, which bring splendid new data on baryon acoustic oscillation measurements. These precious new data agree with previous indirect measurements of the Hubble constant, keeping the tension with direct measurements in excess of 2.5σ. In combination with CMB measurements, the DESI measurements also set an upper limit on the sum of neutrino masses at 0.072 eV, in tension with the inverted ordering of neutrino masses hypothesis. This limit is dependent on the cosmological model.

In everyone's mind at the conference, and indeed across the domain of high-energy physics, it is clear that the field is at a defining moment in its history: we will soon have to decide what new flagship project to build. To this end, the conference organised a thrilling panel discussion featuring the directors of all the major laboratories in the world. "We need to continue to be bold and ambitious and dream big," said Fermilab's Lia Merminga, summarising the spirit of the discussion.

"As we have seen at this conference, the field is extremely vibrant and exciting," said CERN's Fabiola Gianotti at the conclusion of the panel. In these defining times for the future of our field, ICHEP 2024 was an important success. The progress in all areas is remarkable and manifest through the outstanding number of beautiful new results shown at the conference.

Marumi Kado *Max Planck Institute for Physics.*

PHYSTAT STATISTICS MEETS MACHINE LEARNING

Data analysis in the age of AI

Experts in data analysis, statistics and machine learning for physics came together from 9 to 12 September at Imperial College London for PHYSTAT's Statistics meets Machine Learning workshop. The goal of the meeting, which is part of the PHYSTAT series, was to discuss recent developments in machine learning (ML) and their impact on the statistical data-analysis techniques used in particle physics and astronomy.

This new generation of machine-learning models offers great potential for novel uses in physics data analyses

Particle-physics experiments typically produce large amounts of highly complex data. Extracting information about the properties of fundamental physics interactions from these data is a non-trivial task. The general availability of simulation frameworks makes it relatively straightforward to model the forward process of data analysis: to go from an analytically formulated theory of nature to a sample of simulated events that describe the observation of that theory for a given particle collider and detector in minute detail. The inverse process – to infer from a set of observed data what is learned about a theory – is much harder as the predictions at the detector level are only available as "point clouds" of simulated events, rather than as the analytically formulated distributions that are needed by most statistical-inference methods.

Traditionally, statistical techniques have found a variety of ways to deal with this problem, mostly centered on simplifying the data via summary statistics that can be modelled empirically in an analytical form. A wide range of ML algorithms, ranging from neural networks to boosted decision trees trained to classify events as signal- or background-like, ▷


R Bainbridge/Imperial College

Reinvention *Statistics experts in high-energy physics and astronomy discussed machine learning at Imperial College in September.*

have been used in the past 25 years to construct such summary statistics.

The broader field of ML has experienced a very rapid development in recent years, moving from relatively straightforward models capable of describing a handful of observable quantities, to neural models with advanced architectures such as normalising flows, diffusion models and transformers. These boast millions to billions of parameters that are potentially capable of describing hundreds to thousands of observables – and can now extract features from the data with an order-of-magnitude better performance than traditional approaches.

New generation

These advances are driven by newly available computation strategies that not only calculate the learned functions, but also their analytical derivatives with respect to all model parameters, greatly speeding up training times, in particular in combination with modern computing hardware with graphics processing units (GPUs) that facilitate massively parallel calculations. This new generation of ML models offers great potential for novel uses in physics data analyses, but have not yet found their way to the mainstream of published results on a large scale. Nevertheless, significant progress has been made in the particle-physics community in learning the technology needed, and many new developments using this technology were shown at the workshop.

Many of these ML developments showcase the ability of modern ML architectures to learn multidimensional distributions from point-cloud training samples to a very good approximation, even when the number of dimensions is large, for example between 20 and 100.

A prime use-case of such ML models is an emerging statistical analysis strategy known as simulation-based inference (SBI), where learned approximations of the probability density of signal and background over the full high-dimensional observables space are used, dispensing with the notion of summary statistics to simplify the data. Many examples were shown at the workshop, with applications ranging from particle physics to astronomy, pointing to significant improvements in sensitivity. Work is ongoing on procedures to model systematic uncertainties, and no published results in particle physics exist to date. Examples from astronomy showed that SBI can give results of comparable precision to the default Markov chain Monte Carlo approach for Bayesian computations, but with orders of magnitude faster computation times.

An application of machine-learned distributions that was much discussed is data augmentation

Beyond binning

A commonly used alternative approach to the full-fledged theory parameter inference from observed data is known as deconvolution or unfolding. Here the goal is publishing intermediate results in a form where the detector response has been taken out, but stopping short of interpreting this result in a particular theory framework. The classical approach to unfolding requires estimating a response matrix that captures the smearing effect of the detector on a particular observable, and applying the inverse of that to obtain an estimate of a theory-level distribution – however, this approach is challenging and limited in scope, as the inversion is numerically unstable, and requires a low dimensionality binning of the data. Results on several ML-based approaches were presented, which either learn the response matrix from modelling distributions outright (the generative approach) or learn classifiers that reweight simulated samples (the discriminative approach). Both approaches show very promising results that do not have the limitations on the binning and dimensionality of the distribution of the classical response-inversion approach.

A third domain where ML is facilitating great progress is that of anomaly searches, where an anomaly can either be a single observation that doesn't fit the distribution (mostly in astronomy), or a collection of events that together don't fit the distribution (mostly in particle physics). Several analyses highlighted both the power of ML models in such searches and the bounds from statistical theory: it is impossible to optimise sensitivity for single-event anomalies without knowing the outlier distribution, and unsupervised anomaly detectors require a semi-supervised statistical model to interpret ensembles of outliers.

A final application of machine-learned distributions that was much discussed is data augmentation – sampling a new, larger data sample from a learned distribution. If the synthetic data is significantly larger than the training sample, its statistical power will be greater, but will derive this statistical power from the smooth interpolation of the model, potentially generating so-called inductive bias. The validity of the assumed smoothness depends on its realism in a particular setting, for which there is no generic validation strategy. The use of a generative model amounts to a tradeoff between bias and variance.

Interpretable and explainable

Beyond the various novel applications of ML, there were lively discussions on the more fundamental aspects of artificial intelligence (AI), notably on the notion of and need for AI to be interpretable or explainable. Explainable AI aims to elucidate what input information was used, and its relative importance, but this goal has no unambiguous definition. The discussion on the need for explainability centres to a large extent on trust: would you trust a discovery if it is unclear what information the model used and how it was used? Can you convince peers of the validity of your result? The notion of interpretable AI goes beyond that. It is an often-desired quality by scientists, as human knowledge resulting from AI-based science is generally desired to be interpretable, for example in the form of theories based on symmetries, or structures that are simple, or "low-rank". However, interpretability has no formal criteria, which makes it an impractical requirement. Beyond practicality, there is also a fundamental point: why should nature be simple? Why should models that describe it be restricted to being interpretable? The almost philosophical nature of this question made the discussion on interpretability one of the liveliest ones in the workshop, but for now without conclusion.

Human knowledge resulting from AI-based science is generally desired to be interpretable

For the longer-term future there are several interesting developments in the pipeline. In the design and training of new neural models, two techniques were shown to have great promise. The first one is the concept of foundation models, which are very large models that are pre-trained by very large datasets to learn generic features of the data. When these pre-trained generic models are retrained to perform a specific task, they are shown to outperform purpose-trained models for that same task. The second is on encoding domain knowledge in the network. Networks that have known symmetry principles encoded in the model can significantly outperform models that are generically trained on the same data.

The evaluation of systematic effects is still mostly taken care of in the statistical post-processing step. Future ML techniques may more fully integrate systematic uncertainties, for example by reducing the sensitivity to these uncertainties through adversarial training or pivoting methods. Beyond that, future methods may also integrate the currently separate step of propagating systematic uncertainties ("learning the profiling") into the training of the procedure. A truly global end-to-end optimisation of the full analysis chain may ultimately become feasible and computationally tractable for models that provide analytical derivatives.

Wouter Verkerke *University of Amsterdam.*

Strings 2024

An intricate web of interconnected strings

Since its inception in the mid-1980s, the Strings conference has sought to summarise the latest developments in the interconnected fields of quantum gravity and quantum field theory, all under the overarching framework of string theory. As one of the most anticipated gatherings in theoretical physics, the conference serves as a platform for exchanging knowledge, fostering new collaborations and pushing the boundaries of our understanding of the physical laws of nature. The most recent edition, Strings 2024, attracted about 400 in-person participants to CERN in June, with several hundred more scientists following on-line.

One way to view string theory is as a model of fundamental interactions that provides a unification of particle physics with gravity. While generic features of the Standard Model and gravity arise naturally in string theory, it has lacked concrete experimental predictions so far. In recent years, the strategy has shifted from concrete model building to more systematically understanding the universal features that models of particle physics must satisfy when coupled to quantum gravity.


CERN-PHOTO-202406-114-2

Evolving community *In a break from the past, Strings 2024 emphasised younger speakers and community organisation.*

Into the swamp

Remarkably, there are very subtle consistency conditions that are invisible in ordinary particle physics, as they involve indirect arguments such as whether black holes can evaporate in a consistent manner. This has led to the notion of the "Swampland", which encompasses the set of otherwise well-behaved quantum field theories that fail these subtle quantum-gravity consistency conditions. This may lead to concrete implications for particle physics and cosmology.

An important question addressed during the conference was whether these low-energy consistency conditions always point back to string theory as the only consistent "UV completion" (fundamental realisation at distance scales shorter than can be probed at low energies) of quantum gravity, as suggested by numerous investigations. Whether there is any other possible UV completion ▷

involving a version of quantum gravity unrelated to string theory remains an important open question, so it is no surprise that significant research efforts are focused in this direction.

Attempts at explicit model construction were also discussed, together with a joint discussion on cosmology, particle physics and their connections to string theory. Among other topics, recent progress on realising accelerating cosmologies in string theory was reported, as well as a stringy model for dark energy.

A different viewpoint, shared by many researchers, is to employ string theory rather as a framework or tool to study quantum gravity, without any special emphasis on its unification with particle physics. It has long been known that there is a fundamental tension when trying to combine gravity with quantum mechanics, which many regard as one of the most important, open conceptual problems in theoretical physics. This becomes most evident when one zooms in on quantum black holes. It was in this context that the holographic nature of quantum gravity was discovered – the idea that all the information contained within a volume of space can be described by data on its boundary, suggesting that the universe's fundamental degrees of freedom can be thought of as living on a holographic screen. This may not only hold the key for understanding the decay of black holes via Hawking radiation, but can also teach us important lessons about quantum cosmology.

Strings serves as a platform for pushing the boundaries of our understanding of the fundamental aspects of the physical laws of nature

Thousands of papers have been written on this subject within the last decades, and indeed holographic quantum gravity continues to be one of string theory's most active subfields. Recent breakthroughs include the exact or approximate solution of quantum gravity in low-dimensional toy models in anti-de Sitter space, the extension to de-Sitter space, an improved understanding of the nature of microstates of black holes, the precise way they decay, discovering connections between emergent geometry and quantum information theory, and developing powerful tools for investigating these phenomena, such as bootstrap methods.

Other developments that were reviewed include the use of novel kinds of generalised symmetries and string field theory. Strings 2024 also gave a voice to more tangentially related areas such as scattering amplitudes, non-perturbative quantum field theory, particle phenomenology and cosmology. Many of these topics are interconnected to the core areas mentioned in this article and with each other, both technically and/or conceptually. It is this intricate web of highly non-trivial consistent interconnections between subfields that generates meaning beyond the sum of its parts, and forms the unifying umbrella called string theory.

The conference concluded with a novel "future vision" session, which considered 100 crowd-sourced open questions in string theory that might plausibly be answered in the next 10 years. These 100 questions provide a glimpse of where string theory may head in the near future.

David Andriot *Laboratoire d'Annecy-le-Vieux de Physique Théorique,* **Wolfgang Lerche** *CERN,* **Irene Valenzuela** *CERN and* **Sasha Zhiboedov** *CERN.*

INTERNATIONAL COMMITTEE FOR FUTURE ACCELERATORS

ICFA talks strategy and sustainability in Prague

ICFA, the International Committee for Future Accelerators, was formed in 1976 to promote international collaboration in all phases of the construction and exploitation of very-high-energy accelerators. Its 96th meeting took place on 20 and 21 July during the recent ICHEP conference in Prague. Almost all of the 16 members from across the world attended in person, making the assembly lively and constructive.

International committee *ICFA's 96th meeting took place in Prague in July.*

ICFA

The committee heard extensive reports from the leading HEP laboratories and various world regions on their recent activities and plans, including a presentation by Paris Sphicas, the chair of the European Committee for Future Accelerators (ECFA), on the process for the update of the European strategy for particle physics (ESPP). Launched by CERN Council in March 2024, the ESPP update is charged with recommending the next collider project at CERN after HL-LHC operation.

A global task

The ESPP update is also of high interest to non-European institutions and projects. Consequently, in addition to the expected inputs to the strategy from European HEP communities, those from non-European HEP communities are also welcome. Moreover, the recent US P5 report and the Chinese plans for CEPC, with a potential positive decision in 2025/2026, and discussions about the ILC project in Japan, will be important elements of the work to be carried out in the context of the ESPP update. They also emphasise the global nature of high-energy physics.

An integral part of the work of ICFA is carried out within its panels, which have been very active. Presentations were given from the new panel on the Data Lifecycle (chair Kati Lassila-Perini, Helsinki), the Beam Dynamics panel (new chair Yuan He, IMPCAS) and the Advanced and Novel Accelerators panel (new chair Patric Muggli, Max Planck Munich, proxied at the meeting by Brigitte Cros, Paris-Saclay). The Instrumentation and Innovation Development panel (chair Ian Shipsey, Oxford) is setting an example with its numerous schools, the ICFA instrumentation awards and centrally sponsored instrumentation studentships for early-career researchers from underserved world regions. Finally, the chair of the ILC International Development Team panel (Tatsuya Nakada, EPFL) summarised the latest status of the ILC Technological Network, and the proposed ILC collider project in Japan.

ICFA noted interesting structural developments in the global organisation of HEP

A special session was devoted to the sustainability of HEP accelerator infrastructures, considering the need to invest efforts into guidelines that enable better comparison of the environmental reports of labs and infrastructures, in particular for future facilities. It was therefore natural for ICFA to also hear reports not only from the panel on Sustainable Accelerators and Colliders led by Thomas Roser (BNL), but also from the European Lab Directors Working Group on Sustainability. This group, chaired by Caterina Bloise (INFN) and Maxim Titov (CEA), is mandated to develop a set of key indicators and a methodology for the reporting on future HEP projects, to be delivered in time for the ESPP update.

Finally, ICFA noted some very interesting structural developments in the global organisation of HEP. In the Asia-Oceania region, ACFA-HEP was recently formed as a sub-panel under the Asian Committee for Future Accelerators (ACFA), aiming for a better coordination of HEP activities in this particular region of the world. Hopefully, this will encourage other world regions to organise themselves in a similar way in order to strengthen their voice in the global HEP community – for example in Latin America. Here, a meeting was organised in August by the Latin American Association for High Energy, Cosmology and Astroparticle Physics (LAA-HECAP) to bring together scientists, institutions and funding agencies from across Latin America to coordinate actions for jointly funding research projects across the continent.

The next in-person ICFA meeting will be held during the Lepton–Photon conference in Madison, Wisconsin (USA), in August 2025.

Thomas Schörner *DESY.*

FUTURE CIRCULAR COLLIDER

FCC builds momentum in San Francisco

The Future Circular Collider (FCC) is envisaged to be a multi-stage facility for exploring the energy and intensity frontiers of particle physics. An initial electron–positron collider phase (FCC-ee) would focus on ultra-precise measurements at the centre-of-mass energies required to create Z bosons, W-boson pairs, Higgs bosons and top-quark pairs, followed by proton and heavy-ion collisions in a hadron-collider phase (FCC-hh), which would probe the energy frontier directly. As recommended by the 2020 update of the European strategy for particle physics, a feasibility study for the FCC is in full swing. Following the submission to the CERN Council of the study's midterm report earlier this year (*CERN Courier* March/April 2024 pp25–38), and the signing of a joint statement of intent on planning for large research infrastructures by CERN and the US government (*CERN Courier* July/August 2024 p10), FCC Week 2024 convened more than 450 scientists, researchers and industry leaders in San Francisco from 10 to 14 June, with the aim of engaging the wider scientific community, in particular in North America. Since then, more than 20 groups have joined the FCC collaboration.

Drew Bird Photography/FCC-PHOTO-2024-004-116

Public engagement *Participants watching a public panel debate at FCC Week 2024.*

SLAC and LBNL directors John Sarrao and Mike Witherell opened the meeting by emphasising the vital roles of international collaboration between national laboratories in advancing scientific discovery. Sarrao highlighted SLAC's historical contributions to high-energy physics and expressed enthusiasm for the FCC's scientific potential. Witherell reflected on the legacy of particle accelerators in fundamental science and the importance of continued innovation.

CERN Director-General Fabiola Gianotti identified three pillars of her vision for the laboratory: flagship projects like the LHC; a diverse complementary scientific programme; and preparations for future projects. She identified the FCC as the best future match for this vision, asserting that it has unparalleled potential for discovering new physics and can accommodate a large and diverse scientific community. "It is crucial to design a facility that offers a broad scientific programme, many experiments and exciting physics to attract young talents," she said.

FCC-ee would operate at several centre-of-mass energies corresponding to the Z-boson pole, W-boson pair-production, Higgs-boson pole or top-quark pair production. The beam current at each of these points would be determined by the design value of 50 MW synchrotron-radiation power per beam. At lower energies, the machine could accommodate more bunches, achieving 1.3 amperes and a luminosity in excess of $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the Z pole. Measurements of electroweak observables and Higgs-boson couplings would be improved by a factor of between 10 and 50. Remarkably, FCC-ee would also provide 10 times the ambitious design statistics of SuperKEKB/Belle II for bottom and charm quarks, making it the world-leading machine at the intensity frontier. Along with other measurements of electroweak observables, FCC-ee will indirectly probe energies up to 70 TeV for weakly interacting particles. Unlike at proposed linear colliders, four interaction points would increase scientific robustness, reduce systematic uncertainties and allow for specialised experiments, maximising ▷

the collider's physics output.

For FCC-hh, two approaches are being pursued for the necessary high-field superconducting magnets. The first involves advancing niobium–tin technology, which is currently mastered at 11–12 T for the High-Luminosity LHC, with the goal of reaching operational fields of 14 T. The second focuses on high-temperature superconductors (HTS) such as REBCO and iron-based superconductors (IBS). REBCO comes mainly in tape form (*CERN Courier* May/June 2023 p37), whereas IBS comes in both tape and wire form. With niobium–tin, 14 T would allow proton–proton collision energies of 80 TeV in a 90 km ring. HTS-based magnets could potentially reach fields up to 20 T, and centre-of-mass energies proportionally higher, in the vicinity of 120 TeV. If HTS magnets prove technically feasible, they could greatly decrease the cryogenic power. The development of such technologies also holds great promise beyond fundamental research, for example in transportation and electricity transmission.

FCC study leader Michael Benedikt (CERN) outlined the status of the ongoing feasibility study, which is set to be completed by March 2025. No technical showstoppers have yet been found, paving the way for the next phase of detailed technical and environmental impact studies and critical site investigations. Benedikt stressed the importance of international collaboration, especially with the US, in ensuring the project's success.

International collaboration, especially with the US, is important in ensuring the project's success

The next step for the FCC project is to provide information to the CERN Council, via the upcoming update of the European strategy for particle physics, to facilitate a decision on whether to pursue the FCC by the end of 2027 or in early 2028. This includes further developing the civil engineering and technical design of major systems and components to present a more detailed cost estimate, continuing technical R&D activities, and working with CERN's host states on regional implementation development and authorisation processes along with the launch of an environmental impact study. FCC would intersect 31 municipalities in France and 10 in Switzerland. Detailed work is ongoing to identify and reserve plots of land for surface sites, address site-specific design aspects, and explore socio-economic and ecological opportunities such as waste-heat utilisation.

Panos Charitos *CERN.*

SUSTAINABLE HIGH ENERGY PHYSICS

Accelerating climate mitigation

Sustainable HEP 2024, the third online-only workshop on sustainable high-energy physics, convened more than 200 participants from 10 to 12 June. Emissions in HEP are principally linked to building and operating large accelerators, using gaseous detectors and using extensive computing resources. Over three half days, delegates from across the field discussed how best to participate in global efforts at climate-crisis mitigation.

HEP solutions

There is a scientific consensus that the Earth has been warming consistently since the industrial revolution, with the Earth's surface temperature now about 1.2 °C warmer than in the late 1800s. The Paris Agreement of 2015 aims to limit this increase to 1.5 °C, requiring a 50% cut in emissions by 2030. However, the current rise in greenhouse-gas emissions far exceeds this target. The relevance of a 1.5 °C limit is underscored by the fact that the difference between now and the last ice age (12,000 years ago) is only about 5 °C, explained Veronique Boisvert (Royal Holloway) in her riveting talk on the intersection of HEP and climate solutions. If temperatures rise by 4 °C in the next 50 years, as predicted by the Intergovernmental Panel on Climate Change's high-emissions scenario, it could cause disruptions beyond what our civilisation can handle. Intensifying heat waves and extreme weather events are already causing significant casualties and socio-economic disruptions, with 2023 the warmest year on record since 1850.


663highland

Absorption and fixation *Japan's Ichinoseki forest can absorb more CO_2 annually than the construction emissions of the proposed ILC accelerator over a decade.*

Masakazu Yoshioka (KEK) and Ben Shepherd (Daresbury) delved deeply into sustainable accelerator practices. Cement production for facility construction releases significant CO_2, prompting research in material sciences to reduce these emissions. Accelerator systems consume significant energy, and if powered by electricity grids coming from grid fossil fuels, they increase the carbon footprint. Energy-saving measures include reducing power consumption and recovering and reusing thermal energy, as demonstrated by CERN's initiative to use LHC cooling water to heat homes in Ferney-Voltaire. Efforts should also focus on increasing CO_2 absorption and fixation in accelerator regions. Such measures can be effective – Yoshioka estimated that Japan's Ichinoseki forest can absorb more CO_2 annually than the construction emissions of the proposed ILC accelerator over a decade. ▷

Suzanne Evans (ARUP) explained how to perform lifecycle assessments of carbon emissions to evaluate environmental impacts. Sustainability efforts at C3, CEPC, CERN, DESY and ISIS-II were all presented. Thomas Roser (BNL) presented the ICFA strategy for sustainable accelerators, and Jorgen D'Hondt (Vrije Universiteit Brussel) outlined the Horizon Europe project Innovate for Sustainable Accelerating Systems (*CERN Courier* July/August 2024 p20).

Gaseous detectors contribute significantly to emissions through particle detection, cooling and insulation. Ongoing research to develop eco-friendly gas mixtures for Cherenkov detectors, resistive plate chambers and other detectors were discussed at length – alongside an emphasis from delegates on the need for more efficient and leak-free recirculating systems. On the subject of greener computing solutions, Loïc Lannelongue (Cambridge) emphasised the high-energy consumption of servers, storage and cooling. Collaborative efforts from grassroots movements, funding bodies and industry will be essential for progress.

Stopping global warming is an urgent task for humanity

Thijs Bouman (Groningen) delivered an engaging talk on the psychological aspects of sustainable energy transitions, emphasising the importance of understanding societal perceptions and behaviours. Ayan Paul (DESY) advocated for optimising scientific endeavours to reduce environmental impact, urging a balance between scientific advancement and ecological preservation. The workshop concluded with an interactive session on the "Know Your Footprint" tool by the Young High Energy Physicists (yHEP) Association, facilitated by Naman Bhalla (Freiburg), to calculate individual carbon impacts (*CERN Courier* May/June 2024 p66). The workshop also sparked dynamic discussions on reducing flight emissions, addressing travel culture and the high cost of public transport. Key questions included the effectiveness of lobbying and the need for more virtual meetings.

Jyoti Parikh, a recipient of the Nobel Peace Prize awarded to Intergovernmental Panel on Climate Change authors in 2007 and member of India's former Prime Minister's Council on Climate Change, presented the keynote lecture on global energy system and technology choices. While many countries aim to decarbonise their electricity grids, challenges remain. Green sources like solar and wind have low operating costs but unpredictable availability, necessitating better storage and digital technologies. Parikh emphasised that economic development with lower emissions is possible, but posed the critical question: "Can we do it in time?"

Stopping global warming is an urgent task for humanity. We must aim to reduce greenhouse-gas emissions to nearly zero by 2050. While collaboration within local communities and industries is imperative; and individual efforts may seem small, every action is one step toward global efforts for our collective benefit. Sustainable HEP 2024 showcased innovative ideas, practical solutions and collaborative efforts to reduce the environmental impact of HEP. The event highlighted the community's commitment to sustainability while advancing scientific knowledge.

Shreyasi Acharya *INFN Bari,*
Hannah Wakeling *Oxford and*
Juliette Alimena *DESY.*

THESSALONIKI SCHOOL ON FIELD THEORY AND APPLICATIONS IN HEP

The Balkans, in theory

The Southeastern European Network in Mathematical and Theoretical Physics (SEENET-MTP) has organised scientific training and research activities since its foundation in Vrnjačka Banja in 2003. Its PhD programme started in 2014, with substantial support from CERN.

The Thessaloniki School on Field Theory and Applications in HEP was the first school in the third cycle of the programme. Fifty-four students from 16 countries were joined by a number of online participants in a programme of lectures and tutorials.

We are now approaching 110 years since the general theory of relativity was founded and the theoretical prediction of the existence of black holes. There is subsequently at least half a century of developments related to the quantum aspects of black holes. At the Thessaloniki School, Tarek Anous (Queen Mary) delivered a pivotal series of lectures on the thermal properties of black holes, entanglement and the information paradox, which continues to be unresolved.


SEENET

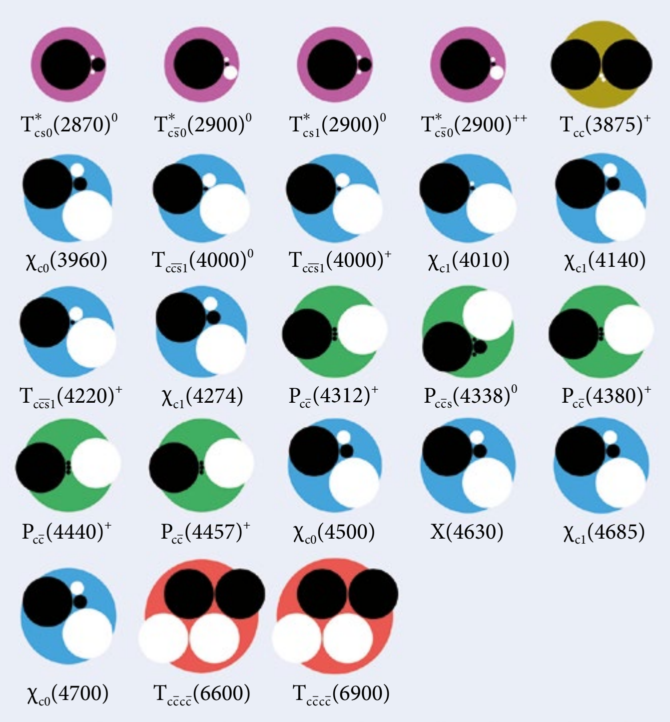
From black holes to renormalisation *The Thessaloniki School attracted 54 students from 16 countries.*

Nikolay Bobev (KU Leuven) summarised the ideas behind holography; Daniel Grumiller (TU Vienna) addressed the application of the holographic principle in flat spacetimes, including Carrollian/celestial holography; Slava Rychkov (Paris-Saclay) gave an introduction to conformal field theory in various dimensions; while Vassilis Spanos (NKU Athens) provided an introduction to modern cosmology. The programme was completed by Kostas Skenderis (Southampton), who addressed renormalisation in conformal field theory, anti-de Sitter and de Sitter spacetimes.

Goran Djordjević *SEENET-MTP Centre and University of Niš.*

A BESTIARY OF EXOTIC HADRONS

Patrick Koppenburg and Marco Pappagallo survey the 23 exotic hadrons discovered at the LHC so far.



Twenty-three exotic states *Five pentaquarks and 18 tetraquarks have been discovered so far at the LHC. Each contains at least one charm quark, and a mixture of up, down and strange quarks. Quark and hadron masses are indicated here by area, and quarks and antiquarks are plotted in black and white, respectively.*

THE AUTHORS
Patrick Koppenburg *Nikhef and* **Marco Pappagallo** *INFN Bari and the University of Bari.*

Seventy-six new particles have been discovered at the Large Hadron Collider (LHC) so far: the Higgs boson, 52 conventional hadrons and a bestiary of 23 exotic hadrons whose structure cannot reliably be explained or their existence predicted.

The exotic states are varied and complex, displaying little discernible pattern at first glance. They represent a fascinating detective story: an experimentally driven quest to understand the exotic offspring of the strong interaction, motivating rival schools of thought among theorists.

This surge in new hadrons has been one of the least expected outcomes of the LHC (see "Unexpected" figure, p28). With a tenfold increase in data at the High-Luminosity LHC (HL-LHC) on the horizon, and further new states also likely to emerge at the Belle II experiment in Japan, the BESIII experiment in China, and perhaps at a super charm–tau factory in the same country, their story is in its infancy, with twists and turns still to come.

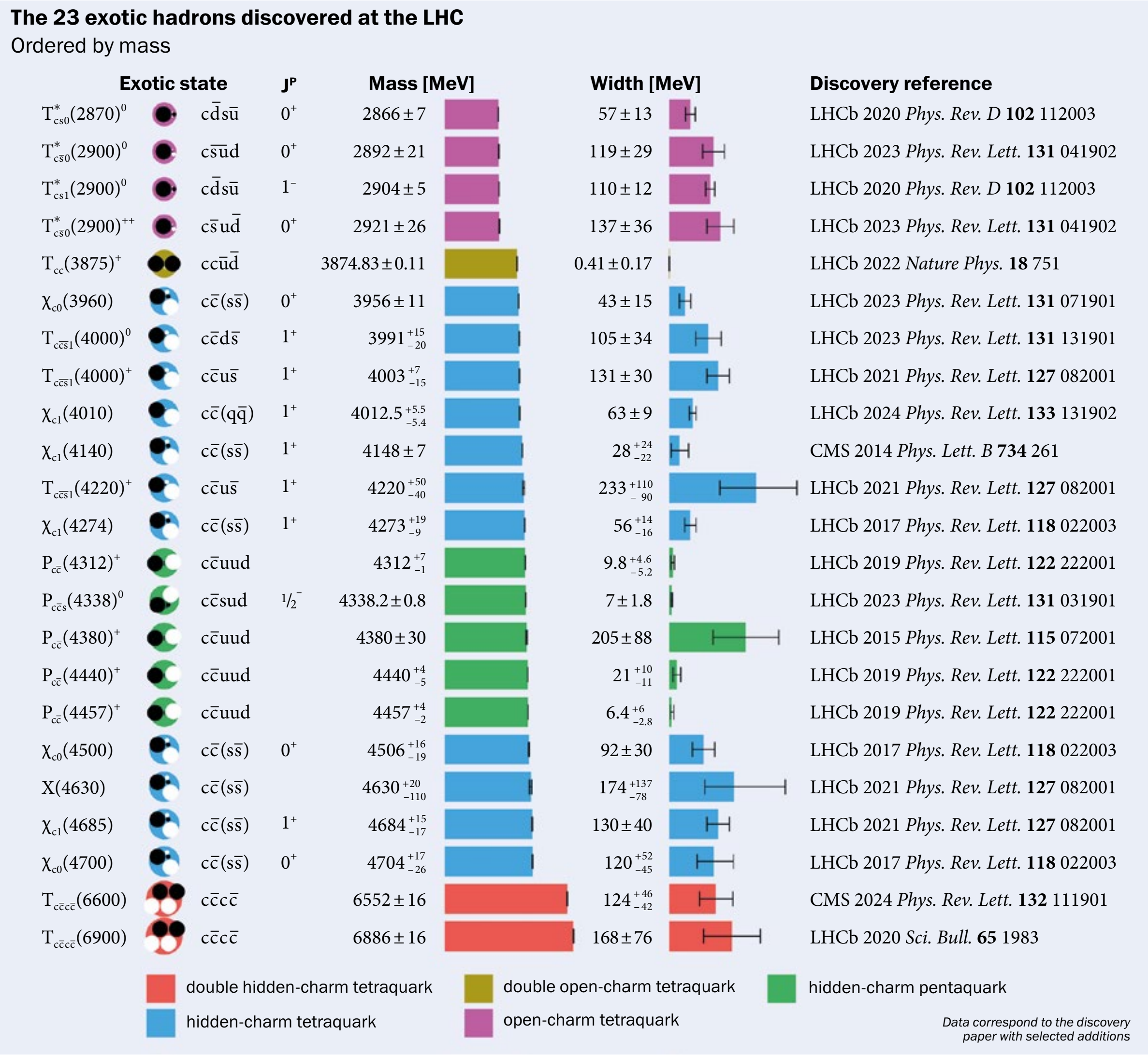
Building blocks

Just as electric charges arrange themselves in neutral atoms, the colour charges that carry the strong interaction arrange themselves into colourless composite states. As fundamental particles with colour charge, quarks (q) and gluons (g) therefore cannot exist independently, but only in colour-neutral composite states called hadrons. Since the discovery of the pion in 1947, a rich phenomenology of mesons ($q\bar{q}$) and baryons (qqq) inspired the quark model and eventually the theory of quantum chromodynamics (QCD), which serves as an impeccable description of the strong interaction to this day.

But why should nature not also contain exotic colour-neutral combinations such as tetraquarks ($q\bar{q}q\bar{q}$), pentaquarks ($qqqq\bar{q}$), hexaquarks ($qqqqqq$ or $q\bar{q}q\bar{q}q\bar{q}$), hybrid hadrons ($q\bar{q}g$ or $q\bar{q}gg$) and glueballs (gg or ggg)?

The existence of exotic hadrons was debated without consensus for decades, with interest growing in the early 2000s, when new states with unexpected features were observed. In 2003, the BaBar experiment at SLAC discovered the $D^{*}_{s0}(2317)^{+}$ meson, with a mass close to the sum of the masses of a D meson and a kaon. A few months later that year, Belle discovered the $\chi_{c1}(3872)$ meson, then called $X(3872)$ (see "What's in a name?" panel), with a mass close to the sum of the masses of a D^{0} meson and a D^{*0} meson. As well as their striking closeness to meson–meson thresholds, the "width" of their signals was much narrower than expected. (Measured in units of energy, such widths are reciprocal to particle lifetimes.)

Soon afterwards, in 2007, a number of other charmonium-like and bottomonium-like states were observed. Belle's observation in 2007 of the electrically charged charmonium-like state $Z(4430)^{+}$ (now called $T_{c\bar{c}1}(4430)^{+}$) was a pathfinder in theorising the existence of QCD exotics. Though these states exhibited the telltale signs of being excitations of a charm–anticharm ($c\bar{c}$) system (p41), their net electric charge indicated a system that could not be composed of only a quark–antiquark pair, as particles and antiparticles have opposite electric charges. Two additional quarks had to be present.



The 23 exotic hadrons discovered at the LHC

Ordered by mass

Exotic state		J^P	Mass [MeV]	Width [MeV]	Discovery reference
$T^{*}_{cs0}(2870)^{0}$	$c\bar{d}s\bar{u}$	0^+	2866 ± 7	57 ± 13	LHCb 2020 *Phys. Rev. D* **102** 112003
$T^{*}_{c\bar{s}0}(2900)^{0}$	$c\bar{s}\bar{u}d$	0^+	2892 ± 21	119 ± 29	LHCb 2023 *Phys. Rev. Lett.* **131** 041902
$T^{*}_{cs1}(2900)^{0}$	$c\bar{d}s\bar{u}$	1^-	2904 ± 5	110 ± 12	LHCb 2020 *Phys. Rev. D* **102** 112003
$T^{*}_{c\bar{s}0}(2900)^{++}$	$c\bar{s}u\bar{d}$	0^+	2921 ± 26	137 ± 36	LHCb 2023 *Phys. Rev. Lett.* **131** 041902
$T_{cc}(3875)^{+}$	$cc\bar{u}\bar{d}$		3874.83 ± 0.11	0.41 ± 0.17	LHCb 2022 *Nature Phys.* **18** 751
$\chi_{c0}(3960)$	$c\bar{c}(s\bar{s})$	0^+	3956 ± 11	43 ± 15	LHCb 2023 *Phys. Rev. Lett.* **131** 071901
$T_{c\bar{c}\bar{s}1}(4000)^{0}$	$c\bar{c}d\bar{s}$	1^+	3991^{+15}_{-20}	105 ± 34	LHCb 2023 *Phys. Rev. Lett.* **131** 131901
$T_{c\bar{c}\bar{s}1}(4000)^{+}$	$c\bar{c}u\bar{s}$	1^+	4003^{+7}_{-15}	131 ± 30	LHCb 2021 *Phys. Rev. Lett.* **127** 082001
$\chi_{c1}(4010)$	$c\bar{c}(q\bar{q})$	1^+	$4012.5^{+5.5}_{-5.4}$	63 ± 9	LHCb 2024 *Phys. Rev. Lett.* **133** 131902
$\chi_{c1}(4140)$	$c\bar{c}(s\bar{s})$	1^+	4148 ± 7	28^{+24}_{-22}	CMS 2014 *Phys. Lett. B* **734** 261
$T_{c\bar{c}\bar{s}1}(4220)^{+}$	$c\bar{c}u\bar{s}$	1^+	4220^{+50}_{-40}	233^{+110}_{-90}	LHCb 2021 *Phys. Rev. Lett.* **127** 082001
$\chi_{c1}(4274)$	$c\bar{c}(s\bar{s})$	1^+	4273^{+19}_{-9}	56^{+14}_{-16}	LHCb 2017 *Phys. Rev. Lett.* **118** 022003
$P_{c\bar{c}}(4312)^{+}$	$c\bar{c}uud$		4312^{+7}_{-1}	$9.8^{+4.6}_{-5.2}$	LHCb 2019 *Phys. Rev. Lett.* **122** 222001
$P_{c\bar{c}s}(4338)^{0}$	$c\bar{c}sud$	$\frac{1}{2}^-$	4338.2 ± 0.8	7 ± 1.8	LHCb 2023 *Phys. Rev. Lett.* **131** 031901
$P_{c\bar{c}}(4380)^{+}$	$c\bar{c}uud$		4380 ± 30	205 ± 88	LHCb 2015 *Phys. Rev. Lett.* **115** 072001
$P_{c\bar{c}}(4440)^{+}$	$c\bar{c}uud$		4440^{+4}_{-5}	21^{+10}_{-11}	LHCb 2019 *Phys. Rev. Lett.* **122** 222001
$P_{c\bar{c}}(4457)^{+}$	$c\bar{c}uud$		4457^{+4}_{-2}	$6.4^{+6}_{-2.8}$	LHCb 2019 *Phys. Rev. Lett.* **122** 222001
$\chi_{c0}(4500)$	$c\bar{c}(s\bar{s})$	0^+	4506^{+16}_{-19}	92 ± 30	LHCb 2017 *Phys. Rev. Lett.* **118** 022003
$X(4630)$	$c\bar{c}(s\bar{s})$		4630^{+20}_{-110}	174^{+137}_{-78}	LHCb 2021 *Phys. Rev. Lett.* **127** 082001
$\chi_{c1}(4685)$	$c\bar{c}(s\bar{s})$	1^+	4684^{+15}_{-17}	130 ± 40	LHCb 2021 *Phys. Rev. Lett.* **127** 082001
$\chi_{c0}(4700)$	$c\bar{c}(s\bar{s})$	0^+	4704^{+17}_{-26}	120^{+52}_{-45}	LHCb 2017 *Phys. Rev. Lett.* **118** 022003
$T_{c\bar{c}c\bar{c}}(6600)$	$c\bar{c}c\bar{c}$		6552 ± 16	124^{+46}_{-42}	CMS 2024 *Phys. Rev. Lett.* **132** 111901
$T_{c\bar{c}c\bar{c}}(6900)$	$c\bar{c}c\bar{c}$		6886 ± 16	168 ± 76	LHCb 2020 *Sci. Bull.* **65** 1983

🟥 double hidden-charm tetraquark
🟨 double open-charm tetraquark
🟩 hidden-charm pentaquark
🟦 hidden-charm tetraquark
🟪 open-charm tetraquark

Data correspond to the discovery paper with selected additions

Exotic states at the LHC

The start-up of the LHC opened up the trail, with 23 new exotic hadrons observed there so far (see "The 23 exotic hadrons discovered at the LHC" table above). The harvest of new states began in autumn 2013 with the CMS experiment at the LHC reporting the observation of the $\chi_{c1}(4140)$ state in the $J/\psi\phi$ mass spectrum in $B^{+}\to J/\psi\phi K^{+}$ decays, confirming a hint from the CDF experiment at Fermilab. Its minimal quark content is likely $c\bar{c}s\bar{s}$. CMS also reported evidence for a state at a higher mass, observed by the LHCb experiment at the LHC in 2016 as the $\chi_{c1}(4274)$, alongside two more states at masses of 4500 and 4700 MeV.

In a 2021 analysis of the same $B^{+}\to J/\psi\phi K^{+}$ decay mode including LHC Run 2 data, LHCb reported two more neutral states, $\chi_{c1}(4685)$ and $X(4630)$, that do not correspond to $c\bar{c}$ states expected from the quark model. The analysis also reported two more resonances seen in the $J/\psi K^{+}$ mass spectrum, $T_{c\bar{c}\bar{s}1}(4000)^{+}$ and $T_{c\bar{c}\bar{s}1}(4220)^{+}$. Carrying charge and strangeness, these charmonia-like states are manifestly exotic, with a minimal quark content $c\bar{c}u\bar{s}$.

For $T_{c\bar{c}\bar{s}1}(4000)^{+}$, LHCb had sufficient data to produce an Argand diagram with the distinct signature of a resonance (see "Round resonances" panel). A possible isospin partner, $T_{c\bar{c}\bar{s}1}(4000)^{0}$ was later found in $B^{0}\to J/\psi\phi K^{0}_{S}$ decays, lending further evidence that it is a resonance and not a kinematical feature. (According to an approximate symmetry of QCD, the strong interaction should treat a $c\bar{c}u\bar{s}$ state almost exactly like a $c\bar{c}d\bar{s}$ state, as up and down quarks have the same colour charges and similar masses.) Other charmonium-like tetraquarks were later seen by LHCb in the decays $\chi_{c0}(3960)\to D^{+}_{s}D^{-}_{s}$ and $\chi_{c1}(4010)\to D^{*+}D^{-}$.

The world's first pentaquarks were discovered by LHCb in 2015. Two pentaquarks appeared in the $J/\psi p$ spectrum by studying $\Lambda^{0}_{b}\to J/\psi pK^{-}$ decays: $P_{c\bar{c}}(4380)^{+}$, a rather broad

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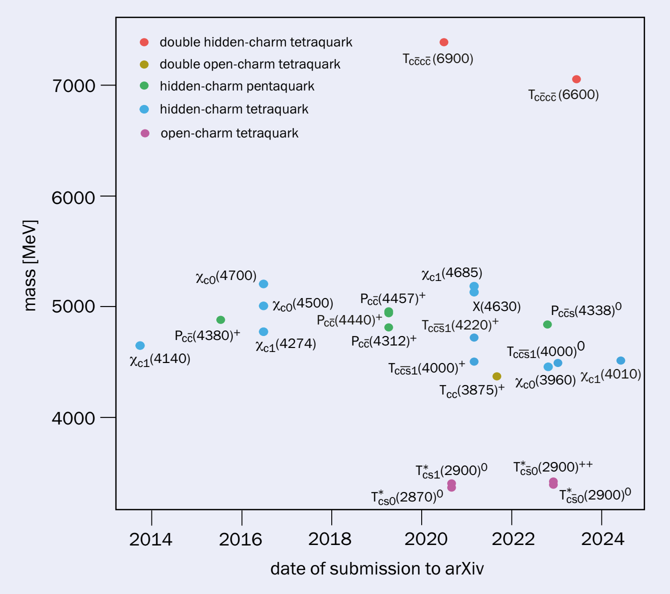
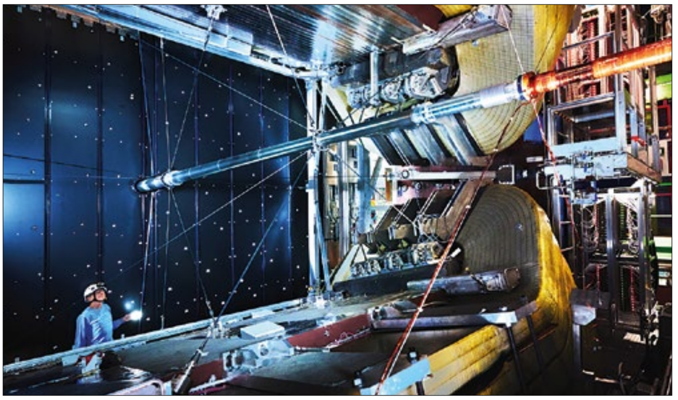


P Koppenberg

Unexpected *Twenty-three exotic hadrons have been discovered so far at the LHC.*



CERN

Discovery machine *A surge in new hadrons has been observed at the LHC, with many found at the LHCb experiment (pictured).*

resonance with a width of 200 MeV; and $P_{c\bar{c}}(4450)^+$, which is narrower at 40 MeV. The observed decay mode implied a minimal quark content $c\bar{c}uud$, excluding any conventional interpretation.

These states were hiding in plain sight: they were spotted independently by several LHCb physicists, including a CERN summer student. In a 2019 analysis using more data, the heavier state was identified as the sum of two overlapping pentaquarks now called $P_{c\bar{c}}(4440)^+$ and $P_{c\bar{c}}(4457)^+$. Another narrow state was also seen at a mass of 4312 MeV. LHCb observed the first strange pentaquark in $B^- \rightarrow J/\psi \Lambda \bar{p}$ decays in 2022, with a quark content $c\bar{c}uds$.

Other manifestly exotic hadrons followed, with two exotic hadrons $T_{c\bar{c}c\bar{c}}(6600)$ and $T_{c\bar{c}c\bar{c}}(6900)$ observed by LHCb, CMS and ATLAS in the $J/\psi J/\psi$ spectrum. They can be interpreted as a tetraquark made of two charm and two anti-charm quarks – a fully charmed tetraquark. When both J/ψ mesons decay to a muon pair, the final state consists of four muons, allowing the LHCb, ATLAS and CMS experiments to study the final spectrum in multiple acceptance regions and transverse momentum ranges. These states do not contain any light quarks, which eases their theoretical study and also implies a state with four bottom quarks that could be long-lived.

What's in a name?

Reflecting their mystery, the first exotic states were named X, Y and Z. Later on, the proliferation of exotic states required an extension of the particle naming scheme. Manifestly exotic tetraquarks and pentaquarks are now denoted T and P, respectively, with a subscript listing the bottom (b), charm (c) and strange (s) quark content. Exotic quarkonium-like states follow the naming scheme of the conventional mesons, where the name is related to the quark content and spin-parity combination. For example, ψ denotes a state with at least a $c\bar{c}$ quark pair and $J^{PC}=1^{--}$, and χ_{c1} denotes a state with at least a $c\bar{c}$ quark pair and $J^{PC}=1^{++}$. Numbers in parentheses refer to approximate measured masses in MeV. Exotic hadrons are classified as mesons or baryons depending on whether they have baryon number zero or not.

Doubly charming

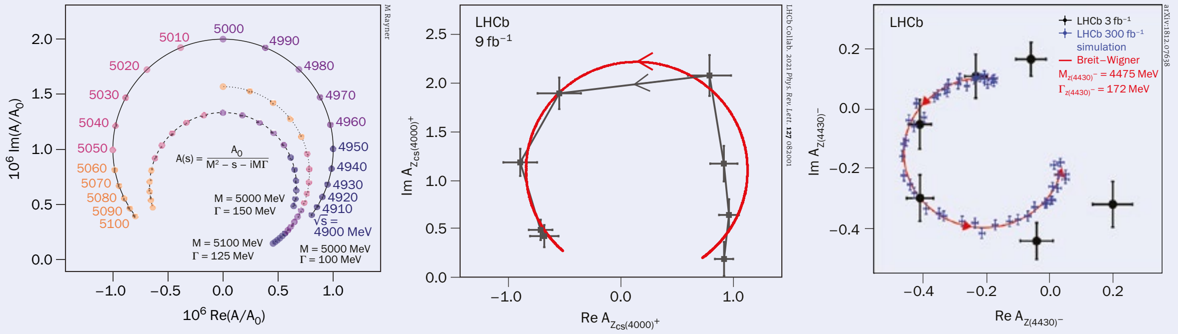
The world's first double-open-charm meson was discovered by LHCb in 2021: the $T_{cc}(3875)^+$. With a charm of two, it cannot be accommodated in the conventional $q\bar{q}$ scheme. There is an intriguing similarity between the exotic $T_{cc}(3875)^+$ $(cc\bar{u}\bar{d})$ and the charmonium-like ($c\bar{c}$-like) $\chi_{c1}(3872)$ meson discovered by Belle in 2003, whose nature is still controversial. Both have similar masses and remarkably narrow widths. The jury is still out on their interpretation (see p33).

The discovery of a $T_{cc}(3875)^+$ $(cc\bar{u}\bar{d})$ meson also implies the existence of a T_{bb} state, with a $bb\bar{u}\bar{d}$ quark content, that should be stable except with regard to weak decays. The observation of the first long-lived exotic state, with a sizable flight distance, is an intriguing goal for future experiments. At the HL-LHC, the search for B_c^+ mesons displaced from the interaction point, could return the first evidence for a T_{bb} tetraquark given that the decays of weakly decaying double-beauty hadrons such as Ξ_{bbq} and T_{bb} are their only known sources.

There are also other exotic states predicted by QCD that are still missing in the particle zoo, such as meson–gluon hybrids and glueballs. Hybrid mesons could be identified by exotic spin-parity (J^P) quantum numbers not allowed in the $q\bar{q}$ scheme. Glueballs could be observed in gluon-enriched heavy-ion collisions. A potential candidate has recently been observed by the BESIII collaboration, which is another major player in exotic spectroscopy.

Exotic hadrons might even have been observed in the light quark sector without having been searched for. The scalar mesons are too numerous to fit in the conventional

Round resonances



M Rayner

LHCb Collab. 2021 *Phys. Rev. Lett.* **127** 082001

arXiv:1812.07638

Particles are most likely to be created in collisions when the centre-of-mass energy matches their mass. The longer the mean lifetime of the new particle, the greater the uncertainty on its decay time and, via Heisenberg's uncertainty principle, the smaller the uncertainty on their energy. Such particles have narrow peaks in their energy spectra. Fast-decaying particles have broad peaks. Searching for such "resonances" can reveal new particles – but bumps can be deceiving. A more revealing analysis fits differential decay rates to measure the complex quantum amplitude A(s) describing the production of the particle. As the energy ($\sqrt{s}$) increases, the amplitude traces a circle counterclockwise in the complex plane, with the magnitude of the amplitude tracing the classic resonant peak observed in energy spectra (see figure above left).

Demonstrating this behaviour, as LHCb did in 2021 for the $T_{c\bar{c}\bar{s}1}(4000)^+$ meson (above, centre) is a significant experimental achievement, which the collaboration also performed in 2018 for the pathfinding $Z(4430)^+$ ($T_{c\bar{c}1}(4430)^+$) meson discovered by Belle in 2007 (black points, above right). The LHCb measurement confirmed its resonant character and resolved any controversy over whether it was a true exotic state. The simulated blue measurement illustrates the improvement such measurements stand to accrue with upgraded detectors and increased statistics at the HL-LHC.

quark model, and some of them, for instance the $f_0(980)$ and $a_0(980)$ mesons, might be tetraquarks. Exotic light pentaquarks may also exist. Twenty years ago, the θ^+ baryon caused quite some excitement, being apparently openly exotic, with a positive strangeness and a minimal quark content $uudd\bar{s}$. No fewer than 10 different experiments presented evidence for it, including several quoting 5σ significance, before it disappeared in blind analyses of larger data samples with better background subtraction (*CERN Courier* April 2004 p29). Its story is now material for historians of science, but its interpretation triggered many theory papers that are still useful today.

The challenge of understanding how quarks are bound inside exotic hadrons is the greatest outstanding question in hadron spectroscopy. Models include a cloud of light quarks and gluons bound to a heavy $q\bar{q}$ core by van-der-Waals-like forces (hadro-quarkonium); colour-singlet hadrons bound by residual nuclear forces (hadronic molecules); and compact tetraquarks $[qq][\overline{qq}]$ and pentaquarks $[qq][qq]\bar{q}$ composed of diquarks $[qq]$ and antidiquarks $[\overline{qq}]$, which masquerade as antiquarks and quarks, respectively.

Some exotic hadrons may also have been misinterpreted as resonant states when they are actually "threshold cusps" – enhancements caused by rescattering. For instance, the $P_{c\bar{c}}(4457)^+$ pentaquark seen in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays could in fact be rescattering between the $\bar{D}^0$ and $\Lambda_c(2595)^+$ decay products in $\Lambda_b^0 \rightarrow \Lambda_c(2595)^+ \bar{D}^0 K^-$ to exchange a charm quark and form a $J/\psi p$ system. This hypothesis can be tested by searching for additional decay modes and isospin partners, or via detailed amplitude analyses – a process already completed for many of the aforementioned states, but not yet all.

Establishing the nature of the exotic hadrons will be challenging, and a comprehensive organisation of exotic hadrons in flavour multiplets is still missing. Establishing whether exotic hadrons obey the same flavour symmetries as conventional hadrons will be an important step forward in understanding their composition.

Effective predictions

The dynamics of quarks and gluons can be described perturbatively in hard processes thanks to the smallness of the strong coupling constant at short distances, but the spectrum of stable hadrons is affected by non-perturbative effects and cannot be computed from the fundamental theory. Though lattice QCD attempts this by discretising space–time in a cubic lattice, the results are time consuming and limited in precision by computational power. Predictions rely on approximate analytical methods such as effective field theories.

Hadron physics is therefore driven by empirical data, and hadron spectroscopy plays a pivotal role in testing the predictions of lattice QCD, which is itself an increasingly important tool in precision electroweak physics and searches for physics beyond the Standard Model.

Like Mendeleev and Gell-Mann, we are at the beginning of a new field, in the taxonomy stage, discovering, studying and classifying exotic hadrons. The deeper challenge is to explain and anticipate them. Though the underlying principles are fully known, we are still far from being able to do the chemistry of quantum chromodynamics. ●

The challenge of understanding how quarks are bound inside exotic hadrons is the greatest outstanding question in hadron spectroscopy

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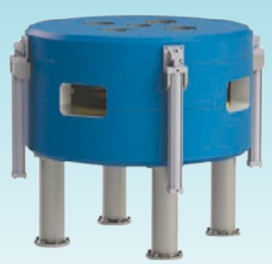

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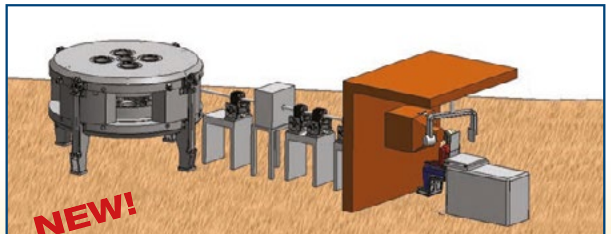

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INSIDE PENTAQUARKS AND TETRAQUARKS

Marek Karliner and Jonathan Rosner ask what makes tetraquarks and pentaquarks tick, revealing them to be at times exotic compact states, at times hadronic molecules and at times both – with much still to be discovered.

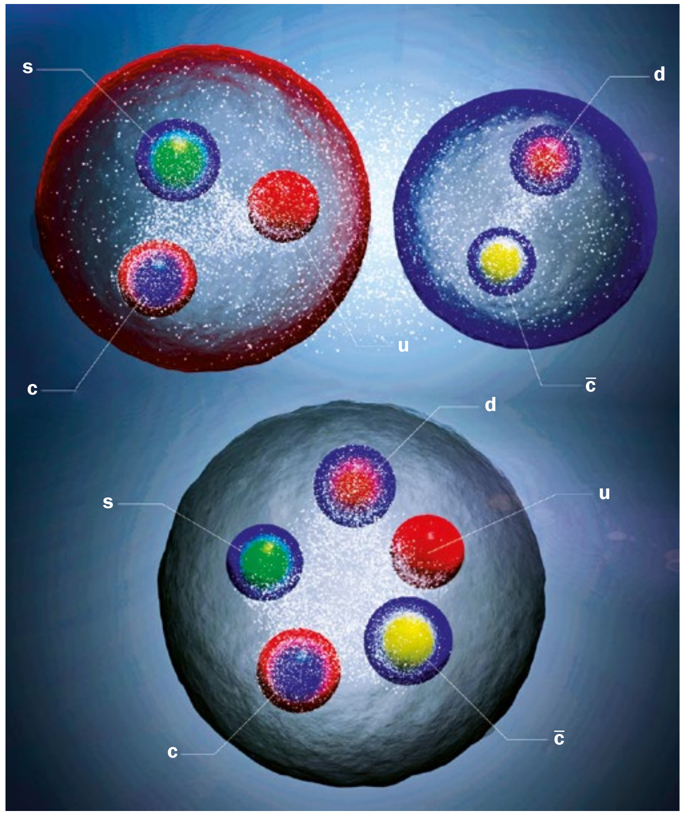
Breakthroughs are like London buses. You wait a long time, and three turn up at once. In 1963 and 1964, Murray Gell-Mann, André Peterman and George Zweig independently developed the concept of quarks (q) and antiquarks ($\bar{q}$) as the fundamental constituents of the observed bestiary of mesons ($q\bar{q}$) and baryons (qqq).

But other states were allowed too. Additional $q\bar{q}$ pairs could be added at will, to create tetraquarks ($q\bar{q}q\bar{q}$), pentaquarks ($qqqq\bar{q}$) and other states besides. In the 1970s, Robert L Jaffe carried out the first explicit calculations of multiquark states, based on the framework of the MIT bag model. Under the auspices of the new theory of quantum chromodynamics (QCD), this computationally simplified model ignored gluon interactions and considered quarks to be free, though confined in a bag with a steep potential at its boundary. These and other early theoretical efforts triggered many experimental searches, but no clear-cut results.

New regimes

Evidence for such states took nearly two decades to emerge. The essential precursors were the discovery of the charm quark (c) at SLAC and BNL in the November Revolution of 1974, some 50 years ago (p41), and the discovery of the bottom quark (b) at Fermilab three years later. The masses and lifetimes of these heavy quarks allowed experiments to probe new regimes in parameter space where otherwise inexplicable bumps in energy spectra could be resolved (see "Heavy breakthroughs" panel).

The first unambiguously exotic hadron, the X(3872) (dubbed $\chi_{c1}(3872)$ in the LHCb collaboration's new taxonomy; see "What's in a name?" panel, p28), was discovered at the Belle experiment at KEK in Japan in 2003. Subsequently confirmed by many other experiments, its nature is still controversial. (More of that later.) Since then, there has been a rapidly growing body of experimental evidence for the existence of exotic multiquark hadrons. New states have been discovered at Belle, at the BaBar experiment at SLAC in the US, at the BESIII experiment at IHEP in China, and at the CMS and LHCb experiments at CERN (p26). In all cases with robust evidence, the exotic new states contain at least one heavy charm or bottom quark. The majority include two.



D Dominguez

Strange pentaquark *Molecular (top) and compact (bottom) interpretations of the $P_{c\bar{c}s}(4338)$ pentaquark discovered by the LHCb collaboration in 2022.*

The key theoretical question is how the quarks are organised inside these multiquark states. Are they hadronic molecules, with two heavy hadrons bound by the exchange of light mesons? Or are they compact objects with all quarks located within a single confinement volume?

The compact and molecular interpretations each provide a natural explanation for part of the data, but neither explains all. Both kinds of structures appear in nature, and certain states may be superpositions of compact and molecular states.

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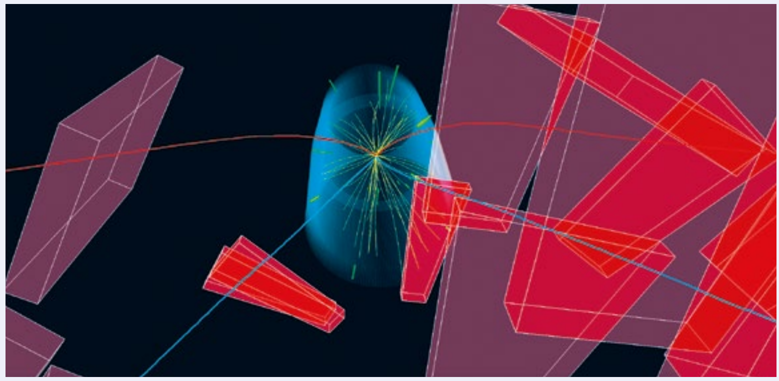
Heavy breakthroughs


CMS Collab

Double hidden charm *A $T_{c\bar{c}c\bar{c}}$(6600) candidate decays to a pair of J/ψ, which in turn decay into two pairs of muons (blue and red trajectories) in the CMS detector at CERN.*

With the benefit of hindsight, it is clear why early experimental efforts did not find irrefutable evidence for multiquark states. For a multiquark state to be clearly identifiable, it is not enough to form a multiquark colour-singlet (a mixture of colourless red–green–blue, red–antired, green–antigreen and blue–antiblue components). Such a state also needs to be narrow and long-lived enough to stand out on top of the experimental background, and has to have distinct decay modes that cannot be explained by the decay of a conventional hadron. Multiquark states containing only light quarks (up, down and strange) typically have many open decay channels, with a large phase space, so they tend to be wide and short-lived. Moreover, they share these decay channels with excited states of conventional hadrons and mix with them, so they are extremely difficult to pin down.

Multiquark states with at least one heavy quark are very different. Once hadrons are "dressed" by gluons, they acquire effective masses of the order of several hundred MeV, with all quarks coupling in the same way to gluons. For light quarks, the bare quark masses are negligible compared to the effective mass, and can be neglected to zeroth order. But for heavy quarks (c or b), the ratio of the bare quark masses to the effective mass of the hadron dramatically affects the dynamics and the experimental situation, creating narrow multiquark states that stand out. These states were not seen in the early searches simply because the relevant production cross sections are very small and particle identification requires very high spatial resolution. These features became accessible only with the advent of the huge luminosity and the superb spatial resolution provided by vertex detectors in bottom and charm factories such as BaBar, Belle, BESIII and LHCb.

The attraction between two heavy quarks scales like $\alpha_s^2 m_q$, where α_s is the strong coupling constant and m_q is the mass of the quarks. This is because the Coulomb-like part of the QCD potential dominates, scaling as $-\alpha_s/r$ as a function of distance r, and yielding an analogue of the Bohr radius $\sim 1/(\alpha_s m_q)$. Thus, the interaction grows approximately linearly with the heavy quark mass. In at least one case (discussed below), the highly anticipated but as yet undiscovered $bb\bar{u}\bar{d}$ tetraquark T_{bb} is expected to result in a state with a mass that is below the two-meson threshold, and therefore stable under strong interactions.

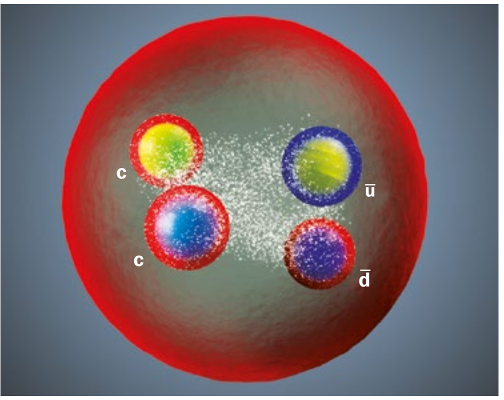
Exclusively heavy states are also possible. In 2020 and in 2024, respectively, LHCb and CMS discovered exotic states $T_{c\bar{c}c\bar{c}}$(6900) and $T_{c\bar{c}c\bar{c}}$(6600), which both decay into two J/ψ particles, implying a quark content $(cc\bar{c}\bar{c})$. J/ψ does not couple to light quarks, so these states are unlikely to be hadronic molecules bound by light meson exchange. Though they are too heavy to be the ground state of a $(cc\bar{c}\bar{c})$ compact tetraquark, they might perhaps be its excitations. Measuring their spin and parity would be very helpful in distinguishing between the various alternatives that have been proposed.

In the molecular case the deuteron is a good mental image. (As a bound state of a proton and a neutron, it is technically a molecular *hexaquark*.) In the compact interpretation, the diquark – an entangled pair of quarks with well-defined spin, colour and flavour quantum numbers – may play a crucial role. Diquarks have curious properties, whereby, for example, a strongly correlated red–green pair of quarks can behave like a blue antiquark, opening up intriguing possibilities for the interpretation of $q\bar{q}q\bar{q}$ and $qqqq\bar{q}$ states.

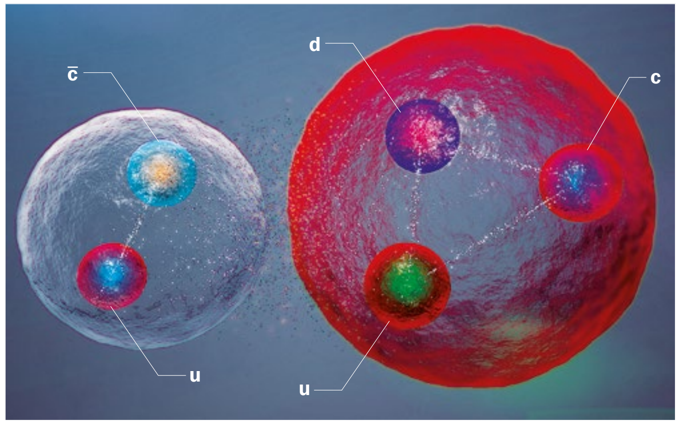
Compact states

A clearcut example of a compact structure is the T_{bb} tetraquark with quark content $bb\bar{u}\bar{d}$. T_{bb} has not yet been observed experimentally, but its existence is supported by robust theoretical evidence from several complementary approaches. As for any ground-state hadron, its mass is given to a good approximation by the sum of its constituent quark masses and their (negative) binding energy. The constituent masses implied here are effective masses that also include the quarks' kinetic energies. The binding energy is negative as it was released when the compact state formed.

In the case of T_{bb}, the binding energy is expected to be so large that its mass is below all two-meson decay channels: it can only decay weakly, and must be stable with respect to the strong interaction. No such exotic hadron has yet been discovered, making T_{bb} a highly prized target for experimentalists. Such a large binding energy cannot be generated by meson exchange and must be due to colour forces between the very heavy b quarks. T_{bb} is an isoscalar with $J^P = 1^+$. Its charmed analogue, $T_{cc} = (cc\bar{u}\bar{d})$, also known as $T_{cc}(3875)^+$, was observed by LHCb in 2021 to be a whisker away from stability, with a very small binding energy and width less than 1 MeV (*CERN Courier* September/October 2021 p7). The big difference between the binding energies of T_{bb} and T_{cc}, which make the former stable and the latter unstable, is due to the substantially greater mass of the b quark than the c quark, as discussed in the panel above. An intermediate case, $T_{bc} = (bc\bar{u}\bar{d})$, is very likely also below threshold for strong decay and therefore stable. It is also easier to produce and detect than T_{bb} and therefore extremely tempting experimentally.


D Dominguez

Compact candidate *The almost-stable T_{cc} tetraquark discovered by LHCb in 2021 could be a charm–charm diquark tightly bound to an up antiquark and down antiquark, but at this stage one cannot rule out a substantial molecular component.*


D Dominguez

Anomalously narrow *Given their surprisingly long lives, the P_c(4312), P_c(4440) and P_c(4457) pentaquarks discovered by the LHCb collaboration in 2019 are most likely hadronic molecules.*

Molecular pentaquarks

At the other extreme, we have states that are most probably pure hadronic molecules. The most conspicuous examples are the P_c(4312), P_c(4440) and P_c(4457) pentaquarks discovered by LHCb in 2019, and labelled according to the convention adopted by the Particle Data Group as $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$ and $P_{c\bar{c}}(4457)^+$. All three have quark content $(c\bar{c}uud)$ and decay into J/ψp, with an energy release of order 300 MeV. Yet, despite having such a large phase space, all three have anomalously narrow widths less than about 10 MeV. Put more simply, the pentaquarks decay remarkably slowly, given how much energy stands to be released.

But why should long life count against the pentaquarks being tightly bound and compact? In a compact $(c\bar{c}uud)$ state there is nothing to prevent the charm quark from binding with the anticharm quark, hadronising as J/ψ and leaving behind a (uud) proton. It would decay immediately with a large width.

On the other hand, hadronic molecules such as $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$ automatically provide a decay-suppression mechanism. Hadronic molecules are typically large, so the c quark inside the Σ_c baryon is typically far from the $\bar{c}$ quark inside the $\bar{D}$ or $\bar{D}^*$ meson. Because of this, the formation of $J/\psi = (c\bar{c})$ has a low probability, resulting in a long lifetime and a narrow width. (Unstable particles decay randomly within fixed half-lives. According to Heisenberg's uncertainty principle, this uncertainty on their lifetime yields a reciprocal uncertainty on their energy, which may be directly observed as the width of the peak in the spectrum of their measured masses when they are created in particle collisions. Long-lived particles exhibit sharply spiked peaks, and short-lived particles exhibit broad peaks. Though the lifetimes of strongly interacting particle are usually not measurable directly, they may be inferred from these "widths", which are measured in units of energy.)

Additional evidence in favour of their molecular nature comes from the mass of P_c(4312) being just below the $\Sigma_c\bar{D}$ production threshold, and the masses of P_c(4440) and P_c(4457) being just below the $\Sigma_c\bar{D}^*$ production threshold. This is perfectly natural. Hadronic molecules are weakly bound, so they typically only form an S-wave bound state, with no orbital angular momentum. So $\Sigma_c\bar{D}$, which combines a spin-1/2 baryon and a spin-0 negative-parity meson, can only form a single state with $J^P = 1/2^-$. By contrast, $\Sigma_c\bar{D}^*$, which combines a spin-1/2 baryon and spin-1 negative-parity meson, can form two closely-spaced states with $J^P = 1/2^-$ and $3/2^-$, with a small splitting coming from a spin–spin interaction.

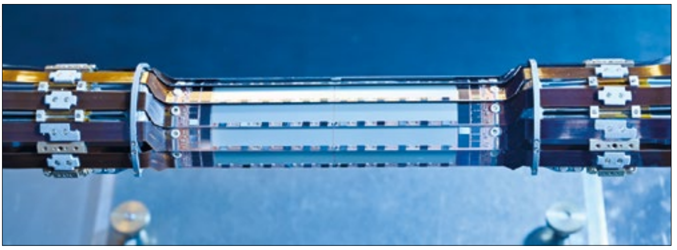
The robust prediction of the J^P quantum numbers makes it very straightforward in principle to kill this physical picture, if one were to measure J^P values different from these. Conversely, measuring the predicted values of J^P would provide a strong confirmation (see "The 23 exotic hadrons discovered at the LHC table", p27).

These predictions have already received substantial indirect support from the strange-pentaquark sector. The spin-parity of the $P_{c\bar{c}s}$(4338), which also has a narrow width below 10 MeV, has been determined by LHCb to be $1/2^-$, exactly as expected for a $\Xi_c\bar{D}$ molecule (see "Strange pentaquark" figure).

The mysterious X(3872)

An example of a possible mixture of a compact state and a hadronic molecule is provided by the already mentioned X(3872) meson. Its mass is so close to the sum of the masses of a $\bar{D}^0$ meson and a $\bar{D}^{*0}$ meson that no difference has yet been established with statistical significance, but it is known to be less than about 1 MeV. It can decay to $J/\psi\pi^+\pi^-$ with a branching ratio $(3.5 \pm 0.9)\%$, releasing almost 500 MeV of energy. Yet its width is only of order 1 MeV. This is an even more striking case of relative stability in the face of naively expected instability than for the pentaquarks. At first sight, then, it is tempting to identify X(3872) as a clearcut $\bar{D}^0 D^{*0}$ hadronic molecule.

An example of a possible mixture of a compact state and a hadronic molecule is provided by the X(3872) meson



B Wankerl/MPP

Particle precision *The upgraded Belle II detector boasts an upgraded pixel vertex detector.*

The situation is not that simple, however. If X(3872) is just a weakly-bound hadronic molecule, it is expected to be very large, of the scale of a few fermi (10^{-15} m). So it should be very difficult to produce it in hard reactions, requiring a large momentum transfer. Yet this is not the case. A possible resolution might come from X(3872) being a mixture of a $\bar{D}^0 D^{*0}$ molecular state and $\chi_{c1}(2P)$, a conventional radial excitation of P-wave charmonium, which is much more compact and is expected to have a similar mass and the same $J^{PC} = 1^{++}$ quantum numbers. Additional evidence in favour of such a mixing comes from comparing the rates of the radiative decays $X(3872) \rightarrow J/\psi\gamma$ and $X(3872) \rightarrow \psi(2S)\gamma$.

The question associated with exotic mesons and baryons can be posed crisply: is an observed state a molecule, a compact multiquark system or something in between? We have given examples of each. Definitive compact-multiquark behaviour can be confirmed if a state's flavour-SU(3) partners are identified. This is because compact states are bound by colour forces, which are only weakly sensitive to flavour-SU(3) rotations. (Such rotations exchange up, down and strange quarks, and to a good approximation the strong force treats these light flavours equally at the energies of charmed and beautiful exotic hadrons.) For example, if X(3872) should in fact prove to be a compact tetraquark, it should have charged isospin partners that have not yet been observed.

On the experimental front, the sensitivity of LHCb, Belle II, BESIII, CMS and ATLAS have continued to reap great benefits to hadron spectroscopy. Together with the proposed super τ-charm factory in China, they are virtually guaranteed to discover additional exotic hadrons, expanding our understanding of QCD in its strongly interacting regime. ●

Further reading

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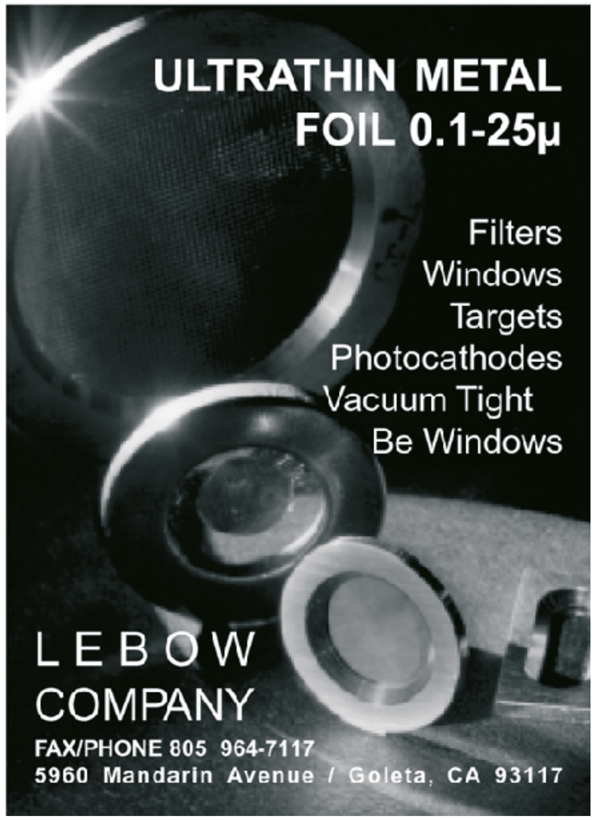

M Brice & J Ordan/CERN-PHOTO-201812-329-18

Threading the needle *The LHCb experiment at CERN sparked a renaissance in charm physics with two intriguing measurements that challenge theorists to improve the precision of their predictions.*

CHARMING CLUES FOR EXISTENCE

Alexander Lenz argues that the charm quark is an experimental and theoretical enigma that has the potential to shed light on the matter–antimatter asymmetry in the universe.

In November 1974, the research groups of Samuel Ting at Brookhaven National Laboratory and Burton Richter at SLAC independently discovered a resonance at 3.1 GeV that was less than 1 MeV wide. Posterity soon named it J/ψ, juxtaposing the names chosen by each group in a unique compromise. Its discovery would complete the second generation of fermions with the charm quark, giving experimental impetus to the new theories of electroweak unification (1967) and quantum chromodynamics (1973). But with the theories fresh and experimenters experiencing an *annus mirabilis* following the indirect discovery of the Z boson in neutral currents the year before, the nature of the J/ψ was not immediately clear.

"Why the excitement over the new discoveries?" asked the *Courier* in December 1974 (see p41). "A brief answer is that the particles have been found in a mass region where they were completely unexpected, with stability properties which, at this stage of the game, are completely inexplicable."

The J/ψ is now known to be made up of a charm quark and a charm antiquark. Unable to decay via the strong interaction, its width is just 92.6 keV, corresponding to an unexpectedly long lifetime of 7.1×10^{-21} s. Charm quarks do not form ordinary matter like protons and neutrons, but J/ψ resonances and D mesons, which contain a charm quark and a less-massive up, down or strange antiquark.

Fifty years on from the November Revolution, charm physics is experiencing a renaissance. The LHCb, BESIII and Belle II experiments are producing a huge number of interesting and precise measurements in the charm system, with two crucial groundbreaking results on D^0 mesons by LHCb holding particular significance: the observation that they violate CP symmetry when they decay; and the obser-

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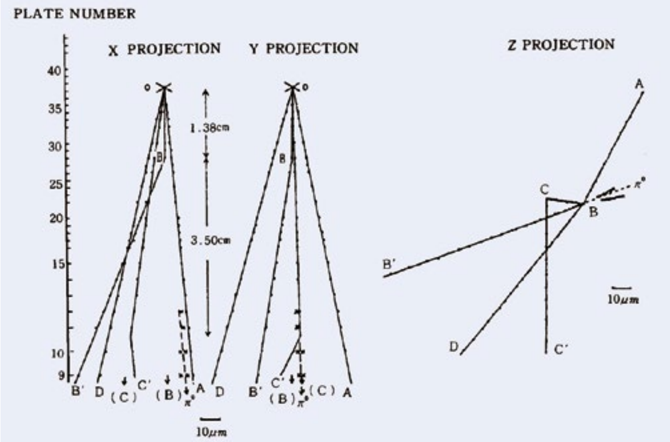
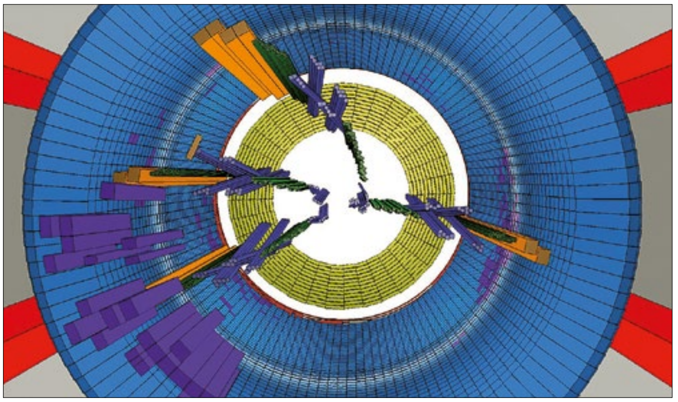


Cosmic charm *A 1971 cosmic-ray interaction in an emulsion chamber aboard a Japanese cargo aeroplane. The event has since been interpreted as the pair production and decay of two open-charm hadrons. The first decays at point B into track B' and a neutral pion that decays into gamma rays which initiate electron showers at plates 10 and 12. The second decays into track C' and undetected neutral hadrons.*

BESIII Collab.



Strange decay *Visualisation of a J/ψ event in the BESIII detector at the Beijing Electron–Positron Collider.*

vation that they oscillate into their antiparticles. The rate of CP violation is particularly interesting – about 10 times larger than the most sophisticated Standard Model (SM) predictions, preliminary and uncertain though they are. Are these predictions naive, or is this the first glimpse of why there is more matter than antimatter in the universe?

Suppressed

Despite the initial confusion, the charm quark had already been indirectly discovered in 1970 by Sheldon Glashow, John Iliopoulos and Luciano Maiani (GIM), who introduced it to explain why $K^0 \to \mu^+\mu^-$ decays are suppressed. Their paper gained widespread recognition during the November Revolution, and the GIM mechanism they discovered impacts cutting-edge calculations in charm physics to this day.

Previously, only the three light quarks (up, down and strange) were known. Alongside electrons and electron neutrinos, up and down quarks make up the first generation of fermions. The detection of muons in cosmic rays in 1936 was the first evidence for a second generation, triggering Isidor Rabi's famous exclamation "Who ordered that?" Strange particles were found in 1947, providing evidence for a second generation of quarks, though it took until 1964 for Murray Gell-Mann and George Zweig to discover this ordering principle of the subatomic world.

In a model of three quarks, the decay of a K^0 meson (a down–antistrange system) into two muons can only proceed by briefly transforming the meson into a W^+W^- pair – an infamous flavour-changing neutral current – linked in a loop by a virtual up quark and virtual muon neutrino. While the amplitude for this process is problematically large given observed rates, the GIM mechanism cancels it almost exactly by introducing destructive quantum interference with a process that replaces the up quark with a new charm quark. The remaining finite value of the amplitude stems from the difference in the masses of the virtual quarks compared to the W boson, m_u^2/M_W^2 and m_c^2/M_W^2. Since both mass ratios are close to zero, $K^0 \to \mu^+\mu^-$ is highly suppressed.

The interference is destructive because the Cabibbo matrix describing the coupling strength of the charged weak interaction is a rotation of the two generations of quarks. All four couplings in the matrix – up–down ($\cos\theta_C$), charm–strange ($\cos\theta_C$), charm–down ($\sin\theta_C$) and up–strange ($-\sin\theta_C$) – arise in the decay of a K^0 meson, with the minus sign causing the cancellation.

The direct experimental detection of the first particle containing charm is typically attributed to Ting and Richter in 1974, however, there was already some direct evidence for charmed mesons in Japan in 1971, though unfortunately in only one cosmic-ray event, and with no estimation of background (see "Cosmic charm" figure). Unnoticed by Western scientists, the measurements indicated a charm-quark mass of the order of 1.5 GeV, which is close to current estimates. In 1973, the quark-mixing formalism was extended by Makoto Kobayashi and Toshihide Maskawa to three generations of quarks, incorporating CP violation in the SM by allowing the couplings to be complex numbers with an imaginary part. The amount of CP violation contained in the resulting Cabibbo–Kobayashi–Maskawa (CKM) matrix does not appear to be sufficient to explain the observed matter–antimatter asymmetry in the universe.

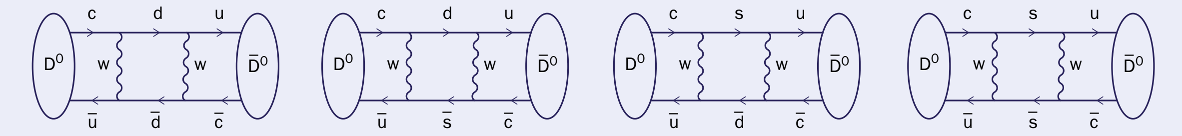
The third generation of quarks began to be experimentally established in 1977 with the discovery of ϒ resonances (bottom–antibottom systems). In 1986, GIM cancellations in the matter–antimatter oscillations of neutral B mesons (B^0–$\bar{B}^0$ mixing) indicated a large value of the top-quark mass, with m_t^2/M_W^2 not negligible, in contrast to m_u^2/M_W^2 and m_c^2/M_W^2. The top quark was directly discovered at the Tevatron in 1995. With the discovery of the Higgs boson in 2012 at the LHC, the full particle spectrum of the SM has now been experimentally confirmed.

Charm renaissance

More recently, two crucial effects in the charm system have been experimentally confirmed. Both measurements present intriguing discrepancies by comparison with naive theoretical expectations.

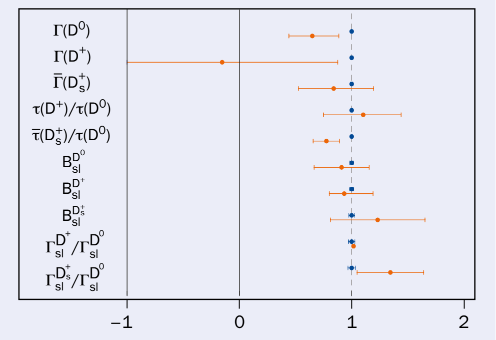
First, in 2019, the LHCb collaboration at CERN observed the first definitive evidence for CP violation in charm.

A Lenz



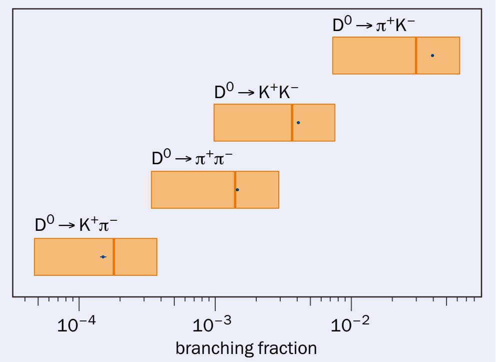
Matter–antimatter mixing *D^0–$\bar{D}^0$ oscillations involving virtual down and strange quarks. Including bottom quarks adds a further eight permutations.*

D King et al. 2022 JHEP **08** 241



Charmed life *Theoretical attempts (orange) to reproduce experimental measurements (blue) of the widths (Γ), lifetimes (τ) and branching fractions (B), sometimes semi-leptonic, of charmed mesons. All observables are normalised to experiment, for which errors are small by comparison to theory.*

A Lenz 2024 JHEP **03** 151



Two body *Theoretical calculations and uncertainties (orange) and experimental measurements (blue) of the branching fractions of non-leptonic two-body D^0 decays. Experimental uncertainties are too small to be visible.*

A difference in the behaviour of matter and antimatter particles, CP violation can be expressed directly in charm decays, indirectly in the matter–antimatter oscillations of charmed particles, or in a quantum admixture of both effects. To isolate direct CP violation, LHCb proved that the difference in matter–antimatter asymmetries seen in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays (ΔA_{CP}) is nonzero. Though the observed CP violation is tiny, it is nevertheless approximately a factor 10 larger than the best available SM predictions. Currently the big question is whether these naive SM expectations can be enhanced by a factor of 10 due to non-perturbative effects, or whether the measurement of ΔA_{CP} is a first glimpse of physics beyond the SM, perhaps also answering the question of why there is more matter than antimatter in the universe.

Two years later, LHCb definitively demonstrated the transformation of neutral D^0 mesons into their antiparticles (D^0–$\bar{D}^0$ mixing). These transitions only involve virtual down-type quarks (down, strange and bottom), causing extreme GIM cancellations as m_d^2/M_W^2, m_s^2/M_W^2 and m_b^2/M_W^2 are all negligible (see "Matter–antimatter mixing" figure). Theory calculations are preliminary here too, but naive SM predictions of the mass splitting between the mass eigenstates of the neutral D-meson system are at present several orders of magnitude below the experimental value.

The charm system has often proved to be more experimentally challenging than the bottom system, with matter–antimatter oscillations and direct and indirect CP violation all discovered first for the bottom quark, and indirect CP violation still awaiting confirmation in charm. The theoretical description of the charm system also presents several interesting features by comparison to the bottom system. They may be regarded as challenges, peculiarities, or even opportunities.

A challenge is the use of perturbation theory. The strong coupling at the scale of the charm-quark mass is quite large – $\alpha_s(m_c) \approx 0.35$ – and perturbative expansions in the strong coupling only converge as (1, 0.35, 0.12, …). The charm quark is also not particularly heavy, and perturbative expansions in Λ/m_c only converge as roughly (1, 0.33, 0.11, …), assuming Λ is an energy scale of the order of the hadronic scale of the strong interaction. If the coefficients being multiplied are of similar sizes, then these series may converge.

Numerical cancellations are a peculiarity, and often classified as strong or even crazy in cases such as D^0–$\bar{D}^0$ mixing, where contributions cancel to one part in 10^5.

The fact that CKM couplings involving the charm quark (V_{cd}, V_{cs} and V_{cb}) have almost vanishing imaginary parts is an opportunity. With CP-violating effects in charm systems expected to be tiny, any measurement of sizable CP violating effects would indicate the presence of physics beyond the SM (BSM).

A final peculiarity is that loop-induced charm decays and D-mixing both proceed exclusively via virtual down-type quarks, presenting opportunities to extend sensitivity to BSM physics via joint analyses with complementary bottom and strange decays.

At first sight, these effects complicate the theoretical treatment of the charm system. Many approaches are therefore based on approximations such as $SU(3)_F$ flavour symmetry or U-spin symmetry (see p15). On the other hand, these properties can also be a virtue, making some observables very sensitive to higher orders in our expansions and providing an ideal testing ground for QCD tools.

The charm system has often proved to be more experimentally challenging than the bottom system

Thanks to many theoretical improvements, we are now in a position to start answering the question of whether perturbative expansions in the strong coupling and the inverse of the quark mass are applicable in the charm system. Recently, progress has been made with observables that are free from severe cancellations: a double expansion in Λ/m_c and α_s (the heavy-quark expansion) seems to be able to reproduce the D^0 lifetime (see "Charmed life" figure); and theoretical calculations of branching fractions for non-leptonic two-body D^0 decays seem to be in good agreement with experimental values (see "Two body" figure).

All these theory predictions still suffer from large uncertainties, but they can be systematically improved. Demonstrating the validity of these theory tools with higher precision could imply that the measured value of CP violation in the charm system (ΔA_{CP}) has a BSM origin.

The future

Charm physics therefore has a bright future. Many of the current theory approaches can be systematically improved with currently available technologies by adding higher-order perturbative corrections. A full lattice-QCD description of D-mixing and non-leptonic D-meson decays requires new ideas, but first steps have already been taken. These theory developments should give us deeper insights into the question of whether ΔA_{CP} and D^0–$\bar{D}^0$ mixing can be described within the SM.

Maybe the charm quark will in the end provide the ultimate clue to explain our existence

More precise experimental data can also help in answering these questions. The BESIII experiment at IHEP in China and the Belle II experiment at KEK in Japan can investigate inclusive semileptonic charm decays and measure parameters that are needed for the heavy-quark expansion. LHCb and Belle II can investigate CP-violating effects in D^0–$\bar{D}^0$ mixing and in channels other than $D^0 \to K^+K^-$ and $\pi^+\pi^-$. The super tau–charm factory proposed by China could contribute further precise data and a future e^+e^- collider running as an ultimate Z factory could provide an independent experimental cross-check for ΔA_{CP}.

Another exciting field is that of rare charm decays such as $D^+ \to \pi^+\mu^+\mu^-$ and $D^+ \to \pi^+ \nu\bar{\nu}$, which proceed via loop diagrams similar to those in $K^0 \to \mu^+\mu^-$ decays and D^0–$\bar{D}^0$ oscillations. Here, null tests can be constructed using observables that vanish precisely in the SM, allowing future experimental data to unambiguously probe BSM effects.

Maybe the charm quark will in the end provide the ultimate clue to explain our existence. Wouldn't that be charming? ●

Further reading

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● Fifty years ago, the discovery of the J/ψ and its excitations sparked the November Revolution in particle physics, giving fresh experimental impetus to the theoretical ideas that would become the Standard Model. Here, we reproduce in full the Courier*'s report from December 1974, describing the excitement and confusion that surrounded the new particles and their interpretation. The J/ψ is now known to be a bound state of a charm quark and a charm antiquark – entities for which there was only indirect evidence at the time of the discoveries.*

THE NEW PARTICLES

Anyone in touch with the world of high-energy physics will be well aware of the ferment created by the news from Brookhaven and Stanford, followed by Frascati and DESY, of the existence of new particles. But new particles have been unearthed in profusion by high-energy accelerators during the past 20 years. Why the excitement over the new discoveries?

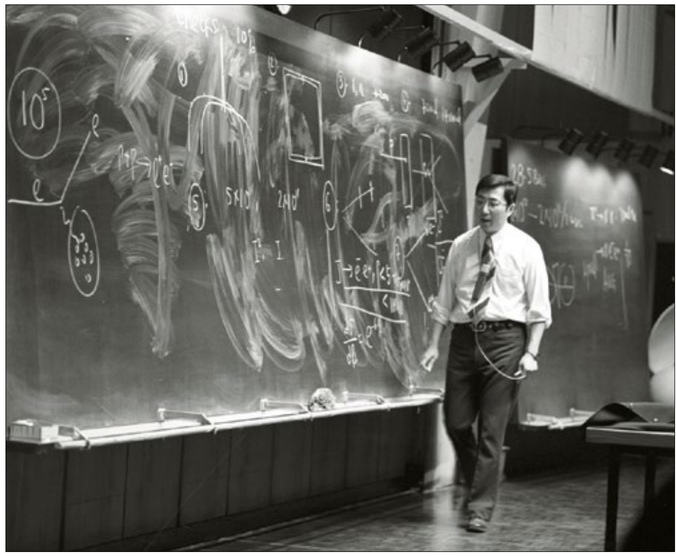
A brief answer is that the particles have been found in a mass region where they were completely unexpected with stability properties which, at this stage of the game, are completely inexplicable. In this article we will first describe the discoveries and then discuss some of the speculations as to what the discoveries might mean.

We begin at the Brookhaven National Laboratory where, since the Spring of this year, a MIT/Brookhaven team have been looking at collisions between two protons which yielded (amongst other things) an electron and a positron. A series of experiments on the production of electron–positron pairs in particle collisions has been going on for about eight years in groups led by Sam Ting, mainly at the DESY synchrotron in Hamburg. The aim is to study some of the electromagnetic features of particles where energy is manifest in the form of a photon which materialises in an electron–positron pair. The experiments are not easy to do because the probability that the collisions will yield such a pair is very low. The detection system has to be capable of picking out an event from a million or more other types of event.

Beryllium bombardment

It was with long experience of such problems behind them that the MIT/Brookhaven team led by Ting, J J Aubert, U J Becker and P J Biggs brought into action a detection system with a double arm spectrometer in a slow ejected proton beam at the Brookhaven 33 GeV synchrotron. They used beams of 28.5 GeV bombarding a beryllium target. The two spectrometer arms span out at 15° either side of the incident beam direction and have magnets, Cherenkov counters, multiwire proportional chambers, scintillation counters and lead glass counters. With this array, it is possible to identify electrons and positrons coming from the same source and to measure their energy.

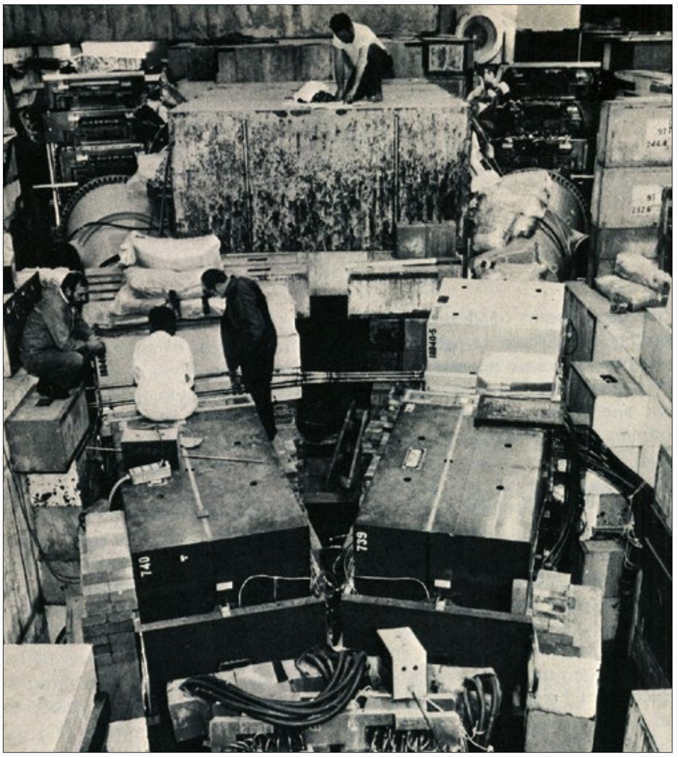
From about August, the realisation that they were on to something important began slowly to grow. The spectrometer was totting up an unusually large number of events where the combined energies of the electron and positron were equal to 3.1 GeV.


CERN 118.11.74

50 years ago *Sam Ting telling the new particle story in an auditorium packed with an enthusiastic audience at CERN on 21 November 1974.*

This is the classic way of spotting a resonance. An unstable particle, which breaks up too quickly to be seen itself, is identified by adding up the energies of more stable particles which emerge from its decay. Looking at many interactions, if energies repeatedly add up to the same figure (as opposed to the other possible figures all around it), they indicate that the measured particles are coming from the break up of an unseen particle whose mass is equal to the measured sum.

The team went through extraordinary contortions to check their apparatus to be sure that nothing was biasing their results. The particle decaying into the electron and positron they were measuring was a difficult one to swallow. The energy region had been scoured before, even if not so thoroughly, without anything being seen. Also the resonance was looking "narrow" – this means that the energy sums were coming out at 3.1 GeV with great precision rather than, for example, spanning from 2.9 to 3.3 GeV. The width is a measure of the stability of the particle (from Heisenberg's Uncertainty Principle, which requires only that the product of the average lifetime and the width be a constant). A narrow width means that the



Brookhaven

Fork in the path *The detection system of the experiment at Brookhaven that spotted the new particle. It consists of two symmetrical spectrometer arms, 20 m long. In the foreground in each arm are three magnets. They are followed by Cherenkov counters (looking like cement mixers) to identify particles (in addition to Cherenkovs in the magnets) and, finally, multiwire proportional chambers which determine precise particle positions.*

particle lives a long time. No other particle of such a heavy mass (over three times the mass of the proton) has anything like that stability.

By the end of October, the team had about 500 events from a 3.1 GeV particle. They were keen to extend their search to the maximum mass their detection system could pin down (about 5.5 GeV) but were prodded into print mid-November by dramatic news from the other coast of America. They baptised the particle J, which is a letter close to the Chinese symbol for "ting". From then on, the experiment has had top priority. Sam Ting said that the Director of the Laboratory, George Vineyard, asked him how much time on the machine he would need – which is not the way such conversations usually go.

The apparition of the particle at the Stanford Linear Accelerator Center on 10 November was nothing short of shattering. Burt Richter described it as "the most exciting and frantic week-end in particle physics I have ever been through". It followed an upgrading of the electron–positron storage ring SPEAR during the late Summer.

Until June, SPEAR was operating with beams of energy up to 2.5 GeV so that the total energy in the collision was up to a peak of 5 GeV. The ring was shut down during the late summer to install a new RF system and new power supplies so as to reach about 4.5 GeV per beam. It was switched on again in September and within two days beams were orbiting the storage ring again. Only three of the four new RF cavities were in action so the beams could only be taken to 3.8 GeV. Within two weeks the luminosity had climbed to 5×10^{30} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (the luminosity dictates the number of interactions the physicists can see) and time began to be allocated to experimental teams to bring their detection systems into trim.

It was the Berkeley/Stanford team led by Richter, M Perl, W Chinowsky, G Goldhaber and G H Trilling who went into action during the week-end 9–10 November to check back on some "funny" readings they had seen in June. They were using a detection system consisting of a large solenoid magnet, wire chambers, scintillation counters and shower counters, almost completely surrounding one of the two intersection regions where the electrons and positrons are brought into head-on collision.

Put through its paces

During the first series of measurements with SPEAR, when it went through its energy paces, the cross-section (or probability of an interaction between an electron and positron occurring) was a little high at 1.6 GeV beam energy (3.2 GeV collision energy) compared with at the neighbouring beam energies. The June exercise, which gave the funny readings, was a look over this energy region again. Cross-sections were measured with electrons and positrons at 1.5, 1.55, 1.6 and 1.65 GeV. Again 1.6 GeV was a little high but 1.55 GeV was even more peculiar. In eight runs, six measurements agreed with the 1.5 GeV data while two were higher (one of them five-times higher). So, obviously, a gremlin had crept in to the apparatus. While meditating during the transformation from SPEAR I to SPEAR II, the gremlin was looked for but not found. It was then that the suspicion grew that between 3.1 and 3.2 GeV collision energies could lie a resonance.

During the night of 9–10 November the hunt began, changing the beam energies in 0.5 MeV steps. By 11.00 a.m. Sunday morning the new particle had been unequivocally found. A set of cross-section measurements around 3.1 GeV showed that the probability of interaction jumped by a factor of 10 from 20 to 200 nanobarns. In a state of euphoria, the champagne was cracked open and the team began celebrating an important discovery. Gerson Goldhaber retired in search of peace and quiet to write the findings for immediate publication.

While he was away, it was decided to polish up the data by going slowly over the resonance again. The beams were nudged from 1.55 to 1.57 and everything went crazy. The interaction probability soared higher; from around 20 nanobarns the cross-section jumped to 2000 nanobarns and the detector was flooded with events producing hadrons. Pief Panofsky, the Director of SLAC, arrived and paced around invoking the Deity in utter amazement at what was being seen. Gerson Goldhaber then emerged with his paper proudly announcing the 200 nanobarn resonance and had to start again, writing 10 times more proudly.

Within hours of the SPEAR measurements, the telephone wires across the Atlantic were humming as information enquiries and rumours were exchanged. As soon as it became clear what had happened, the European Laboratories looked to see how they could contribute to the excitement. The obvious candidates, to be in on the act quickly, were the electron–positron storage rings at Frascati and DESY.

They baptised the particle J, which is a letter close to the Chinese symbol for "ting"

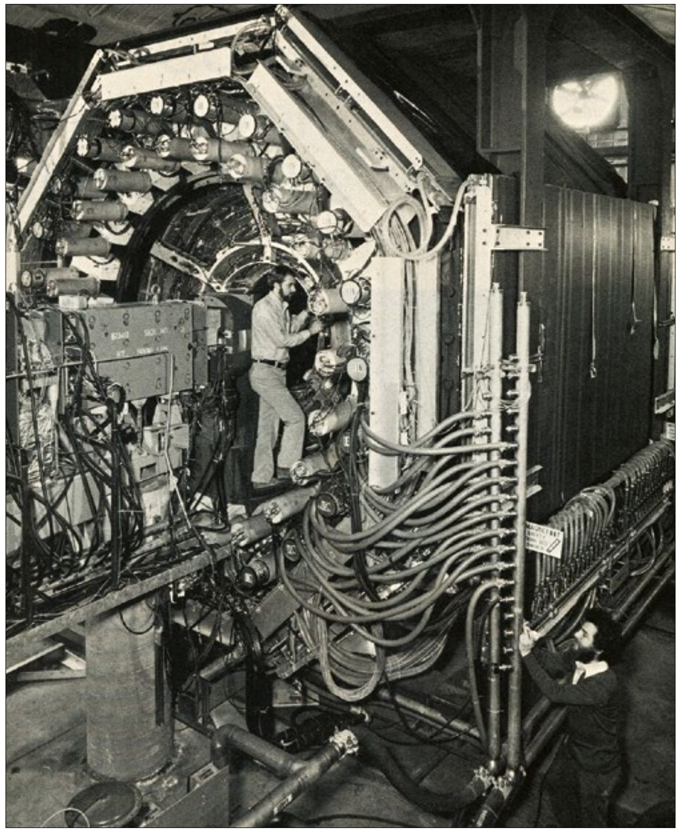
From 13 November, the experimental teams on the ADONE storage ring (from Frascati and the INFN sections of the universities of Naples, Padua, Pisa and Rome) began to search in the same energy region. They have detection systems for three experiments known as gamma–gamma (wide solid angle detector with high efficiency for detecting neutral particles), MEA (solenoidal magnetic spectrometer with wide gap spark chambers and shower detectors) and baryon–antibaryon (coaxial hodoscopes of scintillators covering a wide solid angle). The ADONE operators were able to jack the beam energy up a little above its normal peak of 1.5 GeV and on 15 November the new particle was seen in all three detection systems. The data confirmed the mass and the high stability. The experiments are continuing using the complementary abilities of the detectors to gather as much information as possible on the nature of the particle.

At DESY, the DORIS storage ring was brought into action with the PLUTO and DASP detection systems described later in this issue on page 427. During the week-end of 23–24 November, a clear signal at about 3.1 GeV total energy was seen in both detectors, with PLUTO measuring events with many emerging hadrons and DASP measuring two emerging particles. The angular distribution of elastic electron–positron scattering was measured at 3.1 GeV, and around it, and a distinct change was seen. The detectors are now concentrating on measuring branching ratios – the relative rate at which the particle decays in different ways.

Excitation times

In the meantime, SPEAR II had struck again. On 21 November, another particle was seen at 3.7 GeV. Like the first it is a very narrow resonance indicating the same high stability. The Berkeley/Stanford team have called the particles psi (3105) and psi (3695).

No-one had written the recipe for these particles and that is part of what all the excitement is about. At this stage, we can only speculate about what they might mean. First of all, for the past year, something has been expected in the hadron–lepton relationship. The leptons are particles, like the electron, which we believe do not feel the strong force. Their interactions, such as are initiated in an electron–positron storage ring, can produce hadrons



SLAC

On a high *The famous detection system at the SPEAR storage ring at Stanford, which already has the high hadron production rate to its credit, now adds the identification of new particles.*

(or strong force particles) via their common electromagnetic features. On the basis of the theory that hadrons are built up of quarks (a theory that has a growing weight of experimental support – see *CERN Courier* October 1974 pp331–333), it is possible to calculate relative rates at which the electron–positron interaction will yield hadrons and the rate should decrease as the energy goes higher. The results from the Cambridge bypass and SPEAR about a year ago showed hadrons being produced much more profusely than these predictions.

What seems to be the inverse of this observation is seen at the CERN Intersecting Storage Rings and the 400 GeV synchrotron at the FermiLab. In interactions between hadrons, such as proton–proton collisions, leptons are seen coming off at much higher relative rates than could be predicted. Are the new particles behind this hadron–lepton mystery? And if so, how?

Other speculations are that the particles have new properties to add to the familiar ones like charge, spin, parity… As the complexity of particle behaviour has been uncovered, names have had to be selected to describe different aspects. These names are linked, in the mathematical description of what is going on, to quantum numbers. When particles

Signs of a revolution *Above left: The dramatic signal of the 3.1 GeV particle as seen at SPEAR. The vertical axis measures the cross-section in nanobarns for producing hadrons (in other words the probability that an interaction between an electron and positron will take place, producing strongly interacting particles). Along the horizontal axis is the energy showing that the probability jumps a hundred times at 3.1 GeV. Above right: Hadron production events at 3.1 GeV from: (left) the gamma–gamma group on the ADONE storage ring at Frascati where a large spark chamber array spots an event giving at least three charged particles plus an electromagnetic shower (bottom right); (right) the PLUTO detector on the DORIS storage ring at DESY where three projections of an event with five charged particles are displayed together via the computer.*

interact, the quantum numbers are generally conserved – the properties of the particles going into the interaction are carried away, in some perhaps very different combination, by the particles which emerge. If there are new properties, they also will influence what interactions can take place.

To explain what might be happening, we can consider the property called "strangeness". This was assigned to particles like the neutral kaon and lambda to explain why they were always produced in pairs – the strangeness quantum number is then conserved, the kaon carrying +1, the lambda carrying –1. It is because the kaon has strangeness that it is a very stable particle. It will not readily break up into other particles which do not have this property.

Two new properties have recently been invoked by the theorists – colour and charm. Colour is a suggested property of quarks which makes sense of the statistics used to calculate the consequences of their existence. This gives us nine basic quarks – three coloured varieties of each of the three familiar ones. Charm is a suggested property which makes sense of some observations concerning neutral current interactions (discussed below).

It is the remarkable stability of the new particles which makes it so attractive to invoke colour or charm. From the measured width of the resonances they seem to live for about 10^{-20} seconds and do not decay rapidly like all the other resonances in their mass range. Perhaps they carry a new quantum number?

Unfortunately, even if the new particles are coloured, since they are formed electromagnetically they should be able to decay the same way and the sums do not give their high stability. In addition, the sums say that there is not enough energy around for them to be built up of charmed constituents. The answer may lie in new properties but not in a way that we can easily calculate.

Yet another possibility is that we are, at last, seeing the intermediate boson. This particle was proposed many years ago as an intermediary of the weak force. Just as the strong force is communicated between hadrons by passing mesons around and the electromagnetic force is communicated between charged particles by passing photons around, it is thought that the weak force could also act via the exchange of a particle rather than "at a point".

When it was believed that the weak interactions always involved a change of electric charge between the lepton going into the interaction and the lepton going out, the intermediate boson (often referred to as the W particle) was always envisaged as a charged particle. The CERN discovery of neutral currents in 1973 revealed that a charge change between the leptons need not take place; there could also be a neutral version of the intermediate boson (often referred to as the Z particle). The Z particle can also be treated in the theory which has had encouraging success in uniting the interpretations of the weak and electromagnetic forces.

This work has taken the Z mass into the 70 GeV region and its appearance around 3 GeV would damage some of the beautiful features of the reunification theories. A strong clue could come from looking for asymmetries in the decays of the new particles because, if they are of the Z variety, parity violation should occur.

1974 has been one of the most fascinating years ever experienced in high-energy physics. Still reeling from the neutral current discovery, the year began with the SPEAR hadron production mystery, continued with new high-energy information from the FermiLab and the CERN ISR, including the high lepton production rate, and finished with the discovery of the new particles. And all this against a background of feverish theoretical activity trying to keep pace with what the new accelerators and storage rings have been uncovering. ●

Perhaps the new particles carry a new quantum number?

- *For further details and an account of current challenges and opportunities in charm physics, see "Charming clues for existence" (p37).*

OPINION VIEWPOINT

An obligation to engage

As the CERN & Society Foundation turns 10, founding Director-General Rolf-Dieter Heuer argues that physicists have a duty to promote curiosity and evidence-based critical thinking.

M Brice

Rolf-Dieter Heuer *was Director-General of CERN from 2009 to 2015.*

Science is for everyone, and everyone depends on science, so why not bring more of it to society? That was the idea behind the CERN & Society Foundation, established 10 years ago.

The longer I work in science, and the more people I talk to about science, the more I become convinced that everyone is interested in science whether they realise it or not. Many have emerged from their school education with a belief that science is hard and not for them, but they nevertheless ask the very same questions that those at the cutting edge of fundamental physics research ask, and that people have been asking since time immemorial: what is the universe made of, where did we come from and where are we going? Such curiosity is part of what it is to be human. On a more prosaic level, science and technology play an ever-growing role in modern society, and it is incumbent on all of us to understand its consequences and engage on the debate about its uses.

The power to inspire

When I tell people about CERN, more often than not their eyes light up with excitement and they want to know more. Experiences like this show that the scientific community needs to do all it can to engage with society at large in a fast-changing world. We need to bring people closer to an understanding of science, of how science works and why critical evidence-based thinking is vital in every walk of life, not only in science.

When I tell people about CERN, more often than not their eyes light up with excitement and they want to know more

Laboratories like CERN are extraordinary places where people from all over the world come together to explore nature's mysteries. I believe that when we come together like this, we have the power to inspire and an obligation to use this power to address the critical challenge of public engagement in science and technology. CERN has always taken this responsibility seriously. Ten years ago, it added a new string to its bow in the form of the CERN & Society Foundation. Through philanthropy, the foundation spreads CERN's spirit of scientific curiosity.

E Prado Felgueiras/ATLAS-PHOTO-2023-059-19

Next generation *Summer students working on the ATLAS experiment.*

The CERN & Society Foundation helps the laboratory to deepen its impact beyond the core mission of fundamental physics research. Projects supported by the foundation encourage talented young people from around the globe to follow STEM careers, catalyse innovation for the benefit of all, and inspire wide and diverse audiences. From training high-school teachers to producing medical isotopes, donors' generosity brings research excellence to all corners of society.

The foundation's work rests on three pillars: education and outreach, innovation and knowledge exchange, and culture and creativity. Allow me to highlight one example from each pillar that I particularly like.

One of the flagships of the education and outreach pillar is the Beamline for Schools (BL4S) competition. Launched in 2014, BL4S invites groups of high-school students from around the world to submit a proposal for an experiment at CERN. The winning teams are invited to come to CERN to carry out their experiment under expert supervision from CERN scientists. More recently, the DESY laboratory has joined the programme and also welcomes high-school groups to work on a beamline there. Project proposals have ranged from fundamental physics to projects aimed at enabling cosmic-ray tomography of the pyramids by measuring muon transmission through limestone (p49). To date, some 20,000 students have taken part in the competition, with 25 winning teams coming to CERN or DESY to carry out their experiments (p51).

Zenodo is a great example of the innovation and knowledge-exchange pillar. It provides a repository for free and easy access to research results, data and analysis code, thereby promoting the ideal of open science, which is at the very heart of scientific progress. Zenodo taps into CERN's long-standing tradition and know-how in sharing and preserving scientific knowledge for the benefit of all. The scientific community can now store data in a non-commercial environment, freely available for society at large. Zenodo goes far beyond high-energy physics and played an important role during the COVID-19 pandemic.

Mutual inspiration

Our flagship culture-and-creativity initiative is the world-leading Arts at CERN programme, which recognises the creativity inherent in both the arts and the sciences, and harnesses them to generate benefits for both. Participating artists and scientists find mutual inspiration, going on to inspire audiences around the world.

"In an era where society needs science more than ever, inspiring new generations to believe in their dreams and giving them the tools and space to change the world is essential," said one donor recently. It is encouraging to hear such sentiments, and there's no doubt that the CERN & Society Foundation should feel satisfied with its first decade. Through the examples I have cited above, and many more that I have not mentioned, the foundation has made a tangible difference. It is, however, but one voice. Scientists and scientific organisations in prominent positions should take inspiration from the foundation: the world needs more ambassadors for science. On that note, all that remains is for me to say happy birthday, CERN & Society Foundation.

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OPINION
INTERVIEW

Exploding misconceptions

Cosmologist Katie Mack talks to the *Courier* about how high-energy physics can succeed in #scicomm by throwing open the doors to academia.

What role does science communication play in your academic career?

When I was a postdoc I started to realise that the science communication side of my life was really important to me. It felt like I was having a big impact – and in research, you don't always feel like you're having that big impact. When you're a grad student or postdoc, you spend a lot of time dealing with rejection, feeling like you're not making progress or you're not good enough. I realised that with science communication, I was able to really feel like I did know something, and I was able to share that with people.

When I began to apply for faculty jobs, I realised I didn't want to just do science writing as a nights and weekends job, I wanted it to be integrated into my career. Partially because I didn't want to give up the opportunity to have that kind of impact, but also because I really enjoyed it. It was energising for me and helped me contextualise the work I was doing as a scientist.

How did you begin your career in science communication?

I've always enjoyed writing stories and poetry. At some point I figured out that I could write about science. When I went to grad school I took a class on science journalism and the professor helped me pitch some stories to magazines, and I started to do freelance science writing. Then I discovered Twitter. That was even better because I could share every little idea I had with a big audience. Between Twitter and freelance science writing, I garnered quite a large profile in science communication and that led to opportunities to speak and do more writing. At some point I was approached by agents and publishers about writing books.

Who is your audience?

When I'm not talking to other scientists, my main community is generally those who have a high-school education, but not necessarily a university education. I don't tailor things to people who aren't interested in science, or try to change people's minds on whether science is a good idea. I try to help people who don't have a science background feel empowered to learn about science. I think there are a lot of people who don't see themselves as "science people". I think that's a silly concept but a lot of people conceptualise it that way. They feel like science is closed to them.

The more that science communicators can give people a moment of understanding, an insight into science, I think they can really help people get more involved in science. The best feedback I've ever gotten is when students have come up to me and said "I started studying physics because I followed you on Twitter and I saw that I could do this," or they read my book and that inspired them. That's absolutely the best thing that comes out of this. It is possible to have a big impact on individuals by doing social media and science communication – and hopefully change the situation in science itself over time.

Perimeter Institute

Cosmologist, communicator *Katie Mack is the Hawking Chair in Cosmology and Science Communication at the Perimeter Institute.*

What were your own preconceptions of academia?

I have been excited about science since I was a little kid. I saw that Stephen Hawking was called a cosmologist, so I decided I wanted to be a cosmologist too. I had this vision in my head that I would be a theoretical physicist. I thought that involved a lot of standing alone in a small room with a blackboard, writing equations and having eureka moments. That's what was always depicted on TV: you just sit by yourself and think real hard. When I actually got into academia, I was surprised by how collaborative and social it is. That was probably the biggest difference between expectation and reality.

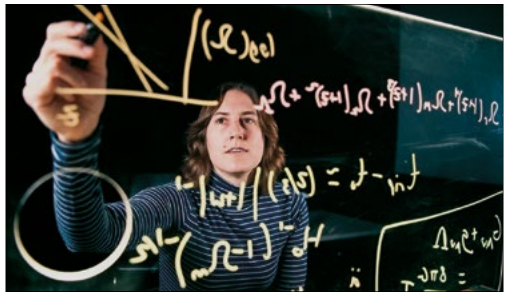
How do you communicate the challenges of academia, alongside the awe-inspiring discoveries and eureka moments?

I think it's important to talk about what it's really like to be an academic, in both good ways and bad. Most people outside of academia have no idea what we do, so it's really valuable to share our experiences, both because it challenges stereotypes in terms of what we're really motivated by and how we spend our time, but also because there are a lot of people who have the same impression I did: where you just sit alone in a room with a chalkboard. I believe it's important to be clear about what you actually do in academia, so more people can see themselves happy in the job.

At the same time, there are challenges. Academia is hard and can be very isolating. My advice for early-career researchers is to have things other than science in your life. As a student you're working on something that potentially no one else cares very much about, except maybe your supervisor. You're going to be the world-expert on it for a while. It can be hard to go through that and not have anybody to talk to about your work. I think it's important to acknowledge what people go through and encourage them to get support.

There are of course other parts of academia that can be really challenging, like moving all the time. I went from West coast to East coast between undergrad and grad school, and then from the US to the UK, from the UK to Australia, back to the US and then to Canada. That's a lot. It's hard. They're all big moves so you lose whatever local support system you had and you have to start over in a new place, make new friends and get used to a whole new government bureaucracy.

So there are a whole lot of things that are difficult about academia, and you do need to acknowledge those because a lot of them affect equity. Some of these make it more challenging to have diversity in the field, and they disproportionately affect some groups more than others. It is important to talk about these issues instead of just sweeping people under the rug.


G Secara

Writing on the wall *"I thought being a theoretical physicist involved a lot of standing alone in a small room with a blackboard, writing equations and having eureka moments."*

Do you think that social media can help to diversify science and research?

Yes! I think that a large reason why people from underrepresented groups leave science is because they lack the feeling of belonging. If you get into a field and don't feel like you belong, it's hard to power through that. It makes it very unpleasant to be there. So I think that one of the ways social media can really help is by letting people see scientists who are not the stereotypical old white men. Talking about what being a scientist is really like, what the lifestyle is like, is really helpful for dismantling those stereotypes.

Your first book, *The End of Everything*, explored astrophysics but your next will popularise particle physics. Have you had to change your strategy when communicating different subjects?

This book is definitely a lot harder to write. The first one was very big and dramatic: the universe is ending! In this one, I'm really trying to get deeper into how fundamental physics works, which is a more challenging story to tell. The way I'm framing it is through "how to build a universe". It's about how fundamental physics connects with the structure of reality, both in terms of what we experience in our daily lives, but also the structure of the universe, and how physicists are working to understand that. I also want to highlight some of the scientists who are doing that work.

So yes, it's much harder to find a catchy hook, but I think the subject matter and topics are things that people are curious about and have a hunger to understand. There really is a desire amongst the public to understand what the point of studying particle physics is.

Is high-energy physics succeeding when it comes to communicating with the public?

I think that there are some aspects where high-energy physics does a fantastic job. When the Higgs boson was discovered in 2012, it was all over the news and everybody was talking about it. Even though it's a really tough concept to explain, a lot of people got some inkling of its importance.

A lot of science communication in high-energy physics relies on big discoveries, however recently there have not been that many discoveries at the level of international news. There have been many interesting anomalies in recent years, however in terms of discoveries we had the Higgs and the neutrino mass in 1998, but I'm not sure that there are many others that would really grab your attention if you're not already invested in physics.

Part of the challenge is just the phase of discovery that particle physics is in right now. We have a model, and we're trying to find the edges of validity of that model. We see some anomalies and then we fix them, and some might stick around. We have some ideas and theories but they might not pan out. That's kind of the story we're working with right now, whereas if you're looking at astronomy, we had gravitational waves and dark energy. We get new telescopes with beautiful pictures all the time, so it's easier to communicate and get people excited than it is in particle physics, where we're constantly refining the model and learning new things. It's a fantastically exciting time, but there have been no big paradigm shifts recently.

How can you keep people engaged in a subject where big discoveries aren't constantly being made?

I think it's hard. There are a few ways to go about it. You can talk about the really massive journey we're on: this hugely consequential and difficult challenge we're facing in high-energy physics. It's a huge task of massive global effort, so you can help people feel involved in the quest to go beyond the Standard Model of particle physics.

You need to acknowledge it's going to be a long journey before we make any big discoveries. There's much work to be done, and we're learning lots of amazing things along the way. We're getting much higher precision. The process of discovery is also hugely consequential outside of high-energy physics: there are so many technological spin-offs that tie into other fields, like cosmology. Discoveries are being made between particle and cosmological physics that are really exciting.

We don't know what the end of the story looks like. There aren't a lot of big signposts along the way where we can say "we've made so much progress, we're halfway there!" Highlighting the purpose of discovery, the little exciting things that we accomplish along the way such as new experimental achievements, and the people who are involved and what they're excited about – this is how we can get around this communication challenge.

Every little milestone is an achievement to be celebrated

Every little milestone is an achievement to be celebrated. CERN is the biggest laboratory in the world. It's one of humanity's crowning achievements in terms of technology and international collaboration – I don't think that's an exaggeration. CERN and the International Space Station. Those two labs are examples of where a bunch of different countries, which may or may not get along, collaborate to achieve something that they can't do alone. Seeing how everyone works together on these projects is really inspiring. If more people were able to get a glimpse of the excitement and enthusiasm around these experiments, it would make a big difference.

Interview by **Alex Epshtein** *editorial assistant.*

OPINION REVIEWS

Inside pyramids, underneath glaciers

Cosmic Ray Muography

Edited by Paola Scampoli and Akitaka Ariga

World Scientific


HIP Institute

Natural probes *Cosmic-ray muons can non-destructively map precious or impenetrable objects.*

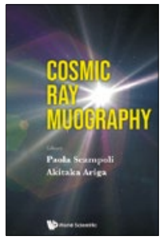
Muon radiography – muography for short – uses cosmic-ray muons to probe and image large, dense objects. Coordinated by editors Paola Scampoli and Akitaka Ariga of the University of Bern, the authors of this book provide an invaluable snapshot of this booming research area. From muon detectors, which differ significantly from those used in fundamental physics research, to applications of muography in scientific, cultural, industrial and societal scenarios, a broad cross section of experts describe the physical principles that underpin modern muography.

Hiroyuki Tanaka of the University of Tokyo begins the book with historical developments and perspectives. He guides readers from the first documented use of cosmic-ray muons in 1955 for rock overburden estimation, to current studies of the sea-level dynamics in Tokyo Bay using muon detectors laid on the seafloor and visionary ideas to bring muography to other planets using teleguided rovers.

Scattering methods

Tanaka limits his discussion to the muon-absorption approach to muography, which images an object by comparing the muon flux before and after – or with and without – an object. The muon-scattering approach, which was invented two decades ago, instead exploits the deflection of muons passing through matter that is due to electromagnetic interactions with nuclei. The interested reader will find several examples of the application of muon scattering in other chapters, particularly that on civil and industrial applications by Davide Pagano (Pavia) and Altea Lorenzon (Padova). Scattering methods have an edge in these fields thanks to their sensitivity to the atomic number of the materials under investigation.

A broad cross section of experts describe the physical principles that underpin modern muography



World Scientific

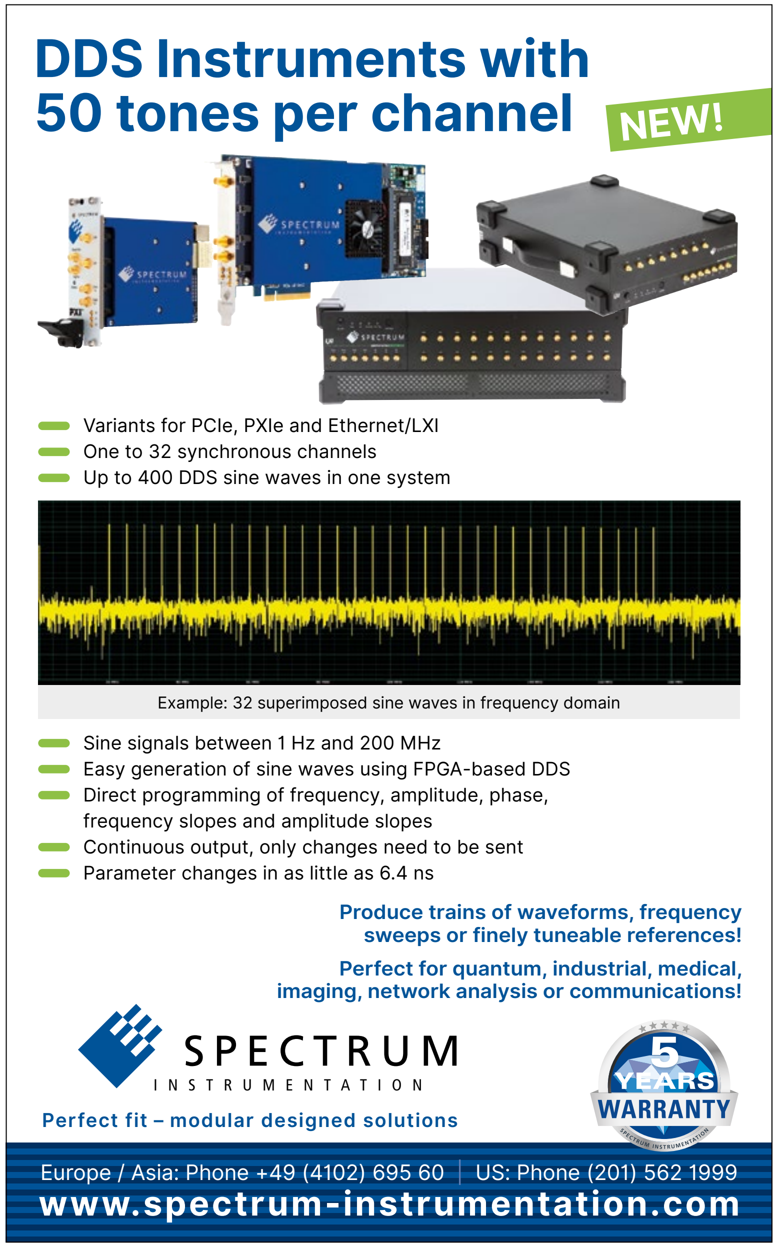
Peter Grieder (Bern), who sadly passed away shortly before the publication of the book, gives an excellent and concise introduction to the physics of cosmic rays, which Paolo Checchia (Padova) expands on, delving into the physics of interactions between muons and matter. Akira Nishio (Nagoya University) describes the history and physical principles of nuclear emulsions. These detectors played an important role in the history of particle physics, but are not very popular now as they cannot provide real-time information. Though modern detectors are a more common choice today, nuclear emulsions still find a niche in muography thanks to their portability. The large accumulation of data from muography experiments requires automatic analysis, for which dedicated scanning systems have been developed. Nishio includes a long and insightful discussion on how the nuclear-emulsions community reacted to supply-chain evolution. The transition from analogue to digital cameras meant that most film-producing firms changed their core business or simply disappeared, and researchers had to take a large part of the production process into their own hands.

Fabio Ambrosino and Giulio Saracino of INFN Napoli next take on the task of providing an overview of the much broader and more popular category of real-time detectors, such as those commonly used in experiments at particle colliders. Elaborating on the requirements set by the cosmic rate and environmental factors, their chapter explains why scintillator and gas-based tracking devices are the most popular options in muography. They also touch on more exotic detector options, including Cherenkov telescopes and cylindrical tracking detectors that fit in boreholes.

In spite of their superficial similarity, methods that are common in X-ray imaging need quite a lot of ingenuity to be adapted to the context of muography. For example, the source cannot be controlled in muography, and is not monochromatic. Both energy and direction are random and have a very broad distribution, and one cannot afford to take data from more than a few viewpoints. Shogo Nagahara and Seigo Miyamoto of the University of Tokyo provide a specialised but intriguing insight into 3D image reconstruction using filtered back-projection.

Geoscience is among the most mature applications of muography. While Jacques Marteau (Claude Bernard University Lyon 1) provides a broad overview of decades of activities spanning from volcano studies to the exploration of natural caves, Ryuichi Nishiyama (Tokyo) explores recent studies where muography provided unique data on the shape of the bedrock underneath two major glaciers in the Swiss Alps.

One of the greatest successes of muography is the study of pyramids



One of the greatest successes of muography is the study of pyramids, which is given ample space in the chapter on archaeology by Kunihiro Morishima (Nagoya). In 1971, Nobel-laureate Luis Alvarez's team pioneered the use of muography in archaeology during an investigation at the pyramid of Khafre in Giza, Egypt, motivated by his hunch that an unknown large chamber could be hiding in the pyramid. Their data convincingly excluded that possibility, but the attempt can be regarded as launching modern muography (*CERN Courier* May/June 2023 p32). Half a century later, muography was reintroduced to the exploration of Egyptian pyramids thanks to ScanPyramids – an international project led by particle-physics teams in France and Japan under the supervision of the Heritage Innovation and Preservation Institute. ScanPyramids aims at systematically surveying all of the main pyramids in the Giza complex, and recently made headlines by finding a previously unknown corridor-shaped cavity in Khufu's Great Pyramid, which is the second largest pyramid in the world. To support the claim, which was initially based on muography alone, the finding was cross-checked with the more traditional surveying method based on ground penetrating radar, and finally confirmed via visual inspection through an endoscope.

Pedagogical focus

This book is a precious resource for anyone approaching muography, from students to senior scientists, and potential practitioners from both academic and industrial communities. There are some other excellent books that have already been published on the same topic, and that have showcased original research, but *Cosmic Ray Muography*'s pedagogical focus, which prioritises the explanation of timeless first principles, will not become outdated any time soon. Given each chapter was written independently, there is a certain degree of overlap and some incoherence in terminology, but this gives the reader valuable exposure to different perspectives about what matters most in this type of research.

Andrea Giammanco
Université catholique de Louvain.

From blackboard to beamline

To celebrate the 10th anniversary of Beamline for Schools, the *Courier* caught up with past winners whose lives were impacted by the competition.

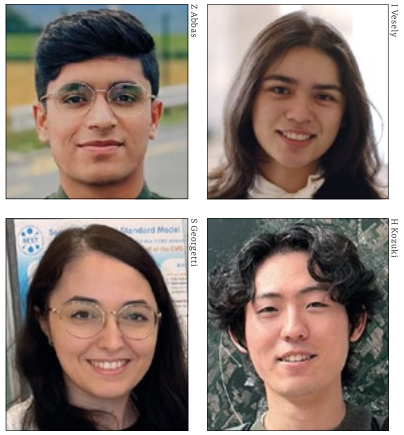
High-school physics curricula don't include much particle physics. The Beamline for Schools (BL4S) competition seeks to remedy this by offering high-school students the chance to turn CERN or DESY into their own laboratory. Since 2014, more than 20,000 students from 2750 teams in 108 countries have competed in BL4S, with 25 winning teams coming to the labs to perform experiments they planned from blackboard to beamline. Though, at 10 years old, the competition is still young, multiple career trajectories have already been influenced, with the impact radiating out into participants' communities of origin.

For Hiroki Kozuki, a member of a winning team from Switzerland in 2020, learning the fundamentals of particle physics while constructing his team's project proposal was what first sparked his interest in the subject.

"Our mentor gave us after-school classes on particle physics, fundamentals, quantum mechanics and special relativity," says Kozuki. "I really felt as though there was so much more depth to physics. I still remember this one lecture where he taught us about the fundamental forces and quarks… It's like he just pulled the tablecloth out from under my feet. I thought: nature is so much more beautiful when I see all these mechanisms underneath it that I didn't know existed. That's the moment where I got hooked on particle physics." Kozuki will soon graduate from Imperial College London, and hopes to pursue a career in research.

Sabrina Giorgetti, from an Italian team, tells a similar story. "I can say confidently that the reason I chose physics for my bachelor's, master's and PhD was because of this experience." One of the competition's earliest winners from back in 2015, Giorgetti is now working on the CMS experiment for her PhD. One of her most memorable experiences from BL4S was getting to know the other winning team, who were from South Africa. This solidified her decision to pursue a career in academia.

"You really feel like you can reach out and collaborate with people all over the world, which is something I find truly amazing," she says. "Now it's even more international than it was nine years ago. I learnt at BL4S that if you're interested in research at a place like CERN, it's not only about physics. It may look like that from the outside, but it's also engineering, IT and science communication – it's a very broad world."


Z Abbas
I Vesely
S Georgetti
H Kozuki

BL4S alumni *Former winners Zohaib Abbas, Isabella Vesely, Hiroki Kozuki and Sabrina Georgetti (clockwise from top left) aspire to careers in physics.*

The power of collaboration

As well as getting hands-on with the equipment, one of the primary aims of BL4S is to encourage students to collaborate in a way they wouldn't in a typical high-school context. While physics experiments in school are usually conducted in pairs, BL4S allows students to work in larger teams, as is common in professional and research environments. The competition provides the chance to explore uncharted territory, rather than repeating timeworn experiments in school.

2023 winner Isabella Vesely from the US is now majoring in physics, electrical engineering and computer science at MIT. Alongside trying to fix their experiment prior to running it on the beamline, her most impactful memories involve collaborating with the other winning team from Pakistan. "We overcame so many challenges with collaboration," explains Vesely. "They were from a completely different background to us, and it was very cool to talk to them about the experiment, our shared interest in physics and get to know each other personally. I'm still in touch with them now."

One fellow 2023 winner is just down the road at Harvard. Zohaib Abbas, a member of the winning Pakistan team that year, is now majoring in physics. "In Pakistan, there weren't any physical laboratories, so nothing was hands-on and all the physics was theoretical," he says, recalling his shock at the US team's technical skills, which included 3D printing and coding. After his education, Abbas wants to bring some of this knowledge back to Pakistan in the hopes of growing the physics community in his hometown. "After I got into BL4S, there have been hundreds of people in Pakistan who have been reaching out to me because they didn't know about this opportunity. I think that BL4S is doing a really great job at exposing people to particle physics."

All of the students recalled the significant challenge of ensuring the functionality of their instruments across one of CERN's or DESY's beamlines. While the project seemed a daunting task at first, the participants enjoyed following the process from start to finish, from the initial idea through to the data collection and analysis.

"It was really exciting to see the whole process in such a short timescale," said Vesely. "It's pretty complicated seeing all the work that's already been done at these experiments, so it's really cool to contribute a small piece of data and integrate that with everything else."

Kozuki concurs. Though only he went on to study physics, with teammates branching off into subjects ranging from mathematics to law and medicine, they still plan to get together and take another crack at the data they compiled in 2020. "We want to take another look and see if we find anything we didn't see before. These projects go on far beyond those two weeks, and the team that you worked with are forever connected."

For Kozuki, it's all about collaboration. "I want to be in a field where everyone shares this fundamental desire to crack open some mysteries about the universe. I think that this incremental contribution to science is a very noble motivation. It's one I really felt when working at CERN. Everyone is genuinely so excited to do their work, and it's such an encouraging environment. I learnt so much about particle physics, the accelerators and the detectors, but I think those are somewhat secondary compared to the interpersonal connections I developed at BL4S. These are the sorts of international collaborations that accelerate science, and it's something I want to be a part of."

Interview by **Alex Epshtein** *editorial assistant.*

Appointments and awards


M Brice/CERN-PHOTO-202409-220-1

25th Council president

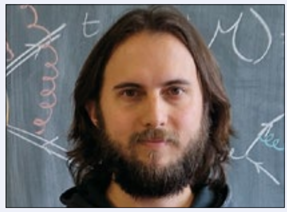
On 27 September, the CERN Council elected Costas Fountas (University of Ioannina) as its 25th president for a period of one year, renewable twice, with a mandate starting on 1 January 2025. He will take over from Eliezer Rabinovici, who concludes his three-year-long term at the end of December. After completing his PhD at Columbia University in 1989, Fountas worked on data-acquisition electronics at Fermilab and then moved to the University of Wisconsin, where he developed the trigger system for ZEUS at DESY. In 2000 he went to Imperial College London and joined the CMS collaboration where, among several roles, he has taken responsibility for the design and implementation of the global calorimeter trigger and the barrel muon track finder. He was appointed Greek scientific delegate to the Council in 2016 and vice president of Council in 2022. “My focus will be to support the CERN management and the experiments so as to ensure that the High-Luminosity LHC is completed successfully and in a timely manner,” said Fountas. “I will also make sure that discussions on the next major project at CERN are held in such a way that everybody has a voice. It is a critical time for CERN, and as president of Council, my commitment will be to do everything I can to bring consensus and guarantee the brightest future possible for the Organization.”

New director at Nikhef

In July, experimentalist Jorgen D’Hondt (Vrije Universiteit Brussel) was appointed director of the National Institute for Subatomic Physics – Nikhef – for a period of five years. He succeeds current director Stan Bentvelsen, whose second term expires at the end of this year. D’Hondt started out at LEP before moving to the LHC and working on the CMS experiment, where he develops techniques to determine the coupling between charm quarks and Higgs bosons. Between 2014 and 2017, he chaired the CMS collaboration board and from 2018 to 2020 he chaired the European Committee for Future Accelerators. “As the new Nikhef director, I will maintain the vision that future advances in particle and astroparticle physics will continue to be closely linked to technological innovations to make the invisible visible,” he said.

2024 Altarelli Award

Javier Mazzitelli (PSI) has been awarded the 2024 Guido Altarelli Award in acknowledgement of his distinguished contributions to particle physics. The Guido Altarelli Award honours the memory of the late CERN theorist Guido Altarelli, one of the founders of QCD, and is awarded every year to junior scientists for outstanding scientific contributions to the field of deep inelastic scattering. Mazzitelli has carried out next-to-next-to-leading order QCD calculations for the production of single and double Higgs-bosons, of top-quark pairs and of the associated production of Higgs and electroweak gauge bosons with heavy-quark pairs, paving the way to precision measurements of heavy particles at the LHC.


PSI

ESRF director general

Soft-matter physicist and synchrotron-radiation expert Jean Daillant started his five-year mandate as director general of the European Synchrotron Radiation Facility (ESRF) on 2 September, taking over from Francesco Sette, who has led the Grenoble-based facility since 2009. Daillant was director general of the SOLEIL synchrotron near Paris for the past 13 years, during which time it has become a leading facility among the medium-energy synchrotron radiation sources. After serving as chair, he is also now vice-chair of the League of European Accelerator-based Photon Sources, which aims to promote scientific excellence and strengthen the cooperation between synchrotron and X-ray free electron laser facilities to support an innovative and sustainable European research area.

WIPAC director

Theorist Dan Hooper (Fermilab/University of Chicago) took over as director of the Wisconsin IceCube Particle Astrophysics Center (WIPAC) on 9 September, succeeding interim director Jim Madsen. WIPAC manages and operates the IceCube Observatory and leads the IceCube upgrade scheduled for completion in 2026, which will dramatically enhance the low-energy sensitivity of the facility to enable higher precision measurements of neutrino oscillation parameters. Hooper, who is also the author of several popular books, works on dark matter, high-energy neutrino astronomy, gamma-ray astronomy and cosmic-rays. “I’m fully dedicated to working as hard as I can to ensure the successful implementation of the IceCube upgrade and IceCube-Gen2,” he said.

Thuréus Prize 2024

Stefano Moretti (University of Southampton) has been awarded the 2024 Thuréus Prize in the Physical-Mathematical class from the Royal Society of Sciences in Uppsala for his contributions to particle phenomenology in collider physics, in particular involving supersymmetric models. Moretti, who is a member of the CMS collaboration, also has research interests in non-minimal Higgs models, higher order corrections and Monte Carlo event generators. The prize, which comes with a sum of SEK 100,000, originates from a donation by the late doctor and Uppsala student Sven Thuréus.

IOP awards 2024

The 2024 awards of the UK Institute of Physics (IOP) were announced on 14 October. Alison Bruce (below, University of Brighton) received the Ernest Rutherford medal and prize for her contributions to understanding the shapes and dynamical symmetries in atomic nuclei. Janne Ruostekoski (University of Lancaster) was awarded the Joseph Thomson medal and prize for theoretical contributions that have reshaped the understanding of cooperative interactions between light and atomic ensembles. Isabelle Baraffe (University of Exeter) received the Fred Hoyle medal and prize for her research into the structure and evolution of stars and planets. The Lawrence Bragg medal and prize was awarded to Stephen Blundell (University of Oxford) for his outstanding work in science communication.


A Bruce

Pride of Wales

Rhodri Jones, head of CERN’s beams department, has been awarded the Eisteddfod 2024 Science and Technology Medal for his work on the LHC. The annual award recognises an individual’s special contribution to science and technology “through the medium of Welsh”. Jones was born in Carmarthenshire and studied at Swansea University, joining CERN in 1996 to contribute to the design and construction of diagnostic systems for the LHC.

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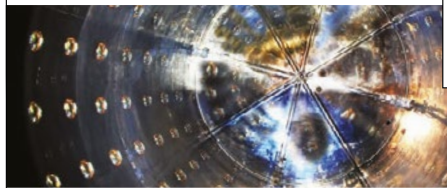

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PEOPLE OBITUARIES

Werner Beusch 1930–2024

The soul of the OMEGA spectrometer

Werner Beusch, who played a pioneering role in the OMEGA spectrometer at CERN, passed away after a short illness on 4 May 2024.

A student of Paul Scherrer at ETH Zurich, Werner obtained his PhD in 1960 with a thesis on two-photon transitions in barium-137 and moved to CERN, joining the "Groupe Chambre Wilson" (a collaboration of teams from CERN, ETH Zurich and Imperial College London). Around that time, cloud chambers were being replaced with spark chambers. Werner, already very experienced in electronics despite his young age, designed and built the entire trigger system for spark chambers from scratch using discrete components (NIM modules were not yet available at the time!).


Family photograph

Werner Beusch on his 90th birthday.

In the late 1960s Werner started working on the OMEGA project – a high-aperture electronic spectrometer to be installed on a PS beam line in the West Area. The spectrometer was envisioned to operate as a facility, with a standard suite of detectors that could be complemented by experiment-specific apparatus provided by the individual collaborations. This was achieved by a large (3 m diameter) superconducting magnet equipped with spark chambers, a triggering system and data acquisition. The original programme included missing-mass experiments, the study of baryon-exchange processes and leptonic hyperon decays, and experiments with hyperon beams and with polarised targets. After a few years, interest moved to new topics, such as photoproduction, charm production and QCD studies.

In 1976 the OMEGA spectrometer was moved to its final position in the West Area on a beam line from the newly built SPS. In 1979, under Werner's supervision, the spectrometer – until then equipped with spark chambers and plumbicon cameras – was instrumented with the new, much faster and higher resolution multi-wire proportional chambers. The refurbished OMEGA quickly became the go-to facility for a wide range of experiments. Over the years, under Werner's stewardship, the facility was continuously upgraded with new equipment such as drift chambers, ring-imaging Cherenkov detectors, silicon microstrips and silicon pixel detectors (which were deployed at OMEGA for the first time). Triggering and data acquisition were also continuously updated such that, throughout its 25-year lifetime, OMEGA remained at the forefront of technology. It hosted some 50 experiments, with achievements ranging from its essential role in the establishment of non-$q\bar{q}$ mesons, to the detection of a (so-far unexplained) excess in the production of soft photons, to the observation of clear violations of factorisation in charm hadroproduction. The OMEGA scientific programme culminated in a key contribution to the discovery of quark–gluon plasma (QGP), with the detection of the signature enhancement pattern of strange and multi-strange hadrons in lead–lead collisions.

Werner retired from CERN in 1995, one year before OMEGA was closed, not because it had reached its time (QGP studies, then in full blossom, had to be hastily moved to the North Area), but to make room for an assembly and test facility for the LHC magnets. Throughout its lifetime, Werner truly was the "soul" of the OMEGA experiment, always present and ready to help. Swapping from one layout to the next (and from one experimental group to the next) was the standard way of operating, and Werner and his team had the heavy responsibility of keeping the spectrometer in good shape and guaranteeing a prompt and efficient restart of the experiments. Werner's kind and thoughtful attitude was key to this and the many other OMEGA successes. His impassioned, matter-of-fact and selfless way of doing science influenced generations of physicists whose careers were forged at OMEGA. Werner coming into the control room and offering a basket of fruits from his garden remains vivid in the memory. We miss him dearly.

His friends and colleagues.

Hans Joachim Specht 1936–2024

Pioneer of heavy-ion physics and ion cancer therapy

Hans Joachim Specht, one of the founders of ultra-relativistic heavy-ion physics and a pioneering figure in hadron cancer therapy, passed away on 20 May 2024 at the age of 87. A graduate of the University of Munich and ETH Zurich, and full professor at the University of Heidelberg for more than 30 years, his career was distinguished by important contributions across a spectrum of scientific domains.

> **Hans was a brilliant experimentalist with a keen eye for cutting-edge detector concepts**

Hans started his academic career in atomic and nuclear physics in Munich, under the guidance of Heinz Maier-Leibnitz. A highlight was the discovery and precise measurement of shape isomerism in heavy nuclei. His observation of distinct rotational bands in plutonium-240 showed, for the first time, that nuclei can be in a strongly deformed cigar-shaped state shortly before fission, confirming the concept of a "double-humped" fission barrier. In Munich, and later in Heidelberg, he developed several innovative large-scale detectors for fission fragments and reaction products of heavy-ion collisions, becoming one of the leading experimentalists in the new field of heavy-ion physics, with experiments at the MPI for Nuclear Physics in Heidelberg and at the newly founded GSI in Darmstadt.

In the early 1980s, Hans reoriented his research towards the higher energies available at CERN. His contributions and advocacy, alongside a handful of other enthusiastic proponents, were instrumental in establishing CERN's ultra-relativistic heavy-ion programme at the SPS, which was approved in 1984. He became the spokesperson of a first-generation heavy-ion experiment (Helios/NA34-2), initiator and ▷

spokesperson of a second-generation experiment (CERES/NA45), and a crucial supporter of the third-generation ALICE experiment at the LHC.

Hans was a brilliant experimentalist with a keen eye for cutting-edge detector concepts and how to apply them in a minimalistic approach. This was apparent in his masterpiece, the dilepton experiment CERES, which used a "hadron blind" double Cherenkov detector and a specially crafted magnetic field configuration to pick out and measure the rare electrons from the haystack of hadrons.

Initially with CERES, and later as a leading force within NA60, Hans succeeded in detecting, for the first time, thermally produced lepton pairs in heavy-ion collisions; the original discovery with NA45 remains one of the most cited papers from the SPS heavy-ion programme. The high-precision measurements at NA60 of what is arguably one of the most challenging signals (the Planck-like spectrum of thermal radiation at higher masses), and the precise characterisation of the in-medium modification of the ρ meson at lower masses, proved to be crucial in establishing the existence and properties of quark–gluon plasma. The enduring quality and relevance of these measurements remain unsurpassed almost two decades later.


H Specht

Hans Specht also worked on the intersection of physics, music and neuroscience.

Throughout his career, Hans held numerous positions in the realm of science policy at a variety of German and international research institutes. At CERN, he served as chair of the PSCC committee and as a member of the SPC. He was also a founding member of the first board of directors of the theory institute ECT* in Trento, a place that held special significance for him.

As scientific director of GSI from 1992 to 1999, Hans set the course for the development and application of a groundbreaking innovation in radiation medicine: ion-beam cancer therapy. A pilot project at GSI for the irradiation of tumours with carbon-12 ions successfully treated 450 patients and led to the establishment of the Heidelberg Ion-Beam Therapy Center, the first European ion-beam therapy facility. Reflecting on his achievements, he was most proud of his contributions to ion-beam therapy. Additionally, Hans initiated discussions on the long-term future of GSI, which eventually led to the proposal for the international FAIR facility.

Hans also had a profound interest in the intersection of physics, music and neuroscience, collaborating with Hans-Günter Dosch on understanding perception of music and its physiological bases. This transdisciplinary approach produced highly cited publications on the differences in the auditory cortex between musicians and non-musicians, expanding the boundaries of how we understand the brain and its response to music.

Hans was an outstanding teacher, a prolific mentor, a successful science manager, but foremost, he was someone who profoundly loved physics, with a relentless drive to follow wherever his interests and research would lead him. His frequent and spirited commutes between Heidelberg and CERN in his iconic green Lotus Elan will be fondly remembered. His critical guidance and profound questions will be deeply missed by all who had the privilege of knowing him.

His friends and colleagues.

Sachio Komamiya 1952–2024

Bridging science and politics

Sachio Komamiya, a prominent figure in the Japanese and International Linear Collider communities, passed away on 5 June 2024 at the age of 71.

Born in Yokohama, Japan in 1952, Komamiya graduated from the University of Tokyo in 1976. He remained there as a graduate student, under the mentorship of Masatoshi Koshiba. Komamiya began his diverse international career by proposing an experiment using the PETRA electron–positron collider at DESY in collaboration with Heidelberg University and the University of Manchester. This collaboration led to the JADE experiment. Koshiba's laboratory took charge of developing the lead-glass electromagnetic shower detector, which operated reliably and contributed to the discovery of gluons.


KEK

Sachio Komamiya in 2013, when he was appointed as chair of the Linear Collider Board.

After obtaining his PhD for his work at DESY, Komamiya took up a postdoc position at the University of Heidelberg, joining the group of Joachim Heintze. He quickly integrated himself into the group and to the JADE collaboration in general, and was one of the first to perform searches for supersymmetric particles – his enthusiasm for this type of analysis earning him the nickname "SachiNo".

In 1986 Komamiya's interest in the highest-energy experiments led him to SLAC as a staff physicist. The construction of the SLAC Linear Collider (SLC) – the first linear collider – was underway. The SLC was a single-pass collider that used a linac to accelerate both electrons and positrons, a design that was highly complex. Komamiya worked on developing the arcs that bent the beams at the end of the linac, which was one of the most complicated parts of the machine. Physics measurements at the SLC started in 1988 with the Mark II detector, and in 1990 Komamiya moved to Europe to join the OPAL experiment at the Large Electron Positron Collider.

Komamiya returned to Japan in 1999 and became a director of the International Center for Elementary Particle Physics at the University of Tokyo in 2000. While leading research and experiments there, he led Japan's high-energy physics community, serving four terms as the chairman of the Japan Association of High Energy Physics and as a Japanese representative for the International Committee for Future Accelerators from 2000. His leadership and extensive international experience have been precious in advancing the International Linear Collider (ILC) project. In December 2012, a technical design report for the ILC was completed. Shortly afterwards, the ILC project was reorganised under the umbrellas of the Linear Collider Collaboration (LCC), led by Lyn Evans for project development, and the Linear Collider Board, which oversaw the LCC's activity and was chaired by Komamiya.

Komamiya was eager to see the ILC become Japan's first globally hosted project. He served as a diplomat to advance this vision, and was calm and patient when explaining to others the often-complex relations involved. Sachio thus fulfilled a critical and essential role bridging science and politics – a talent that, alongside his physics expertise, will be sorely missed.

His friends and colleagues.
- Originally published in *ILC NewsLine*.

OLAV ULLALAND 1944–2024

A rich career in detectors

Olav Ullaland, a brilliant detector physicist who spent his career at CERN, passed away on 16 June 2024.

Olav obtained his degree in particle physics at the University of Bergen in 1971. After a short period at Rutherford Appleton Laboratory in the UK, he went to CERN as a fellow in 1973, following which he was awarded a staff contract. He worked as a detector physicist at CERN until he retired in 2009, remaining active for several years as an emeritus. One of his last scientific articles dates from 2020.

Alongside detector R&D, Olav participated in several key CERN experiments. For the Split Field Magnet Detector, located at CERN's Intersecting Storage Rings, he was in charge of the multi-wire proportional chambers and worked on the prototype of a novel electromagnetic calorimeter that was later adopted by the DELPHI experiment.

After contributing to the UA1 upgrade, he was asked to take a leading role in the complex barrel ring-imaging Cherenkov (RICH) project of DELPHI, which was the first attempt to integrate an imaging Cherenkov detector into a cylindrical collider experiment. The challenges were immense, as it was necessary to operate a gas and liquid radiator, together with a photosensitive gas, at different temperatures in a confined space. Thanks to Olav's perseverance and the loyalty he inspired in his team, he was able to bring the apparatus to a level where it could be used in physics analysis, for example in the tagging of strange jets from Z and W decays. This was a critical milestone in the history of RICH detectors.


Family photograph

Olav Ullaland was also passionate in his support of students and fellows.

Around 1997 Olav joined LHCb and became a leader in the international effort to make its two RICH detectors a reality. Thanks to his deep knowledge of the many facets of detector physics and techniques, and his ability to remain calm, he and his team managed to find solutions to potential showstoppers. It is testament to Olav's efforts that the particle identification system of LHCb works so impressively in the study of CP violation and heavy-flavour rare decays. In addition, Olav was the LHCb resource coordinator for several years, taking impeccable control of delicate LHCb financial matters at the beginning of the experiment operations. His expertise in leading many project reviews and trouble-shooting several wide-ranging detector subsystems was also in high demand both within and outside LHCb.

Olav was a wonderful collaborator. He was passionate in his support of students and fellows, and encouraged young people to give presentations and international talks, always graciously stepping away from the limelight himself. His dedication to student training was highlighted by his running of the CERN summer student programme, with both lectures and laboratory courses.

For Olav, work did not finish at CERN, but would be continued in any possible meeting place. These unconventional settings provided a conducive atmosphere to explore, discuss and challenge new projects and ideas, with the goal of promoting cohesion in a critical, constructive and friendly fashion.

Olav Ullaland was not only an outstanding researcher, but also a unique human being who left a deep impression on all those with whom he came into contact. We will never forget him.

His collaborators and friends.

CRISTIANA PERONI 1949–2024

A determined leader

Cristiana Peroni, former team leader of the Torino group of the CMS collaboration, passed away on 19 June 2024.

Peroni obtained her degree in physics in 1974 at the University of Torino. She worked at an experiment on low-energy proton–antiproton collisions at the CERN Proton Synchrotron, before joining the European Muon Collaboration and, later, the New Muon Collaboration. After this, she moved to ZEUS at DESY and then CMS at the LHC, and was appointed full professor at the University of Torino in 2001.

Thanks to Cristiana's initiative, in collaboration with Fabrizio Gasparini (project manager of the drift-tube project of CMS's muon system), the Torino group joined the CMS collaboration in the late 1990s. The group took responsibility for the construction of the MB4 muon chambers, together with groups at Padua, Madrid and Aachen, which were responsible for the construction of the MB3, MB2 and MB1 layers of CMS's drift-tube system, respectively.


Family photograph

Cristiana Peroni led the CMS Torino group.

At the same time, Cristiana started a collaboration with the JINR–Dubna group led by Igor Golutvin to realise a critical part of the system: the deposition of the field electrodes on the aluminium planes that form the structural element of the chambers. This was a very successful collaboration, in spite of the crucial issues related to complex logistics, which worked extremely well, guaranteeing the construction of the system within the required timeframe. Alongside hardware commitments, the team coordinated by Cristiana took on important roles of responsibility in the physics groups of the collaboration (in particular in the Higgs sector), and soon saw its expansion with the addition and merger of other groups in Torino, which added activities related to the tracker, electromagnetic calorimeter and precision proton spectrometer.

"Cris" was a determined and capable leader, highly appreciated for the attention she always paid to the professional growth of her collaborators, the career development of early-stage researchers, as well as the team building and mutual support that made her group united and coherent.

In the last part of her professional life, Cris turned her attention to research in medical physics, leaving the management of the CMS group to her collaborators, and carrying out research on hadron therapy. In this field, not only did she establish a new course on medical physics at Torino, but she was instrumental to the CNAO hadron-therapy facility in Pavia, which has been treating cancer patients for more than a decade.

Her CMS Torino colleagues.

ARNAU BROSSA GONZALO 1993–2024

A rising star in LHCb

Arnau Brossa Gonzalo, a postdoctoral researcher at the Galician Institute of High Energy Physics (IGFAE) working on the LHCb experiment, died in Santiago on 21 July 2024 following complications from a climbing accident.

Arnau obtained his degree in physics at the University of Barcelona in 2016, specialising in theoretical physics. He continued there for his master's in astrophysics, particle physics and cosmology, with a thesis on the LHCb experiment.

In 2017 he embarked on his PhD studies in particle physics at the University of Warwick. His thesis, entitled "First observation of $B^0 \to \bar{D}^*(2007)^0K^+\pi^-$ and $B_s^0 \to \bar{D}^*(2007)^0K^-\pi^+$ decays in LHCb", won the Springer Thesis Prize for outstanding PhD research. This was the first LHCb measurement of B decays involving fully reconstructed neutral D^* mesons, which are particularly challenging due to the soft neutral particles emitted in the $D^* \to D\pi^0$ and $D^* \to D\gamma$ decays. These modes are nonetheless extremely important to understand as they are backgrounds to a wide range of other studies, including those used for precision measurements of the CKM angle γ.


A Hobson

Arnau Brossa Gonzalo carried out important tests of lepton flavour universality at LHCb.

Following the completion of his PhD, Arnau joined the LHCb group at IGFAE in 2022 to work further on the LHCb experiment, first as a postdoctoral researcher and later as a Juan de la Cierva researcher. He then joined the lepton-flavour-universality group at IGFAE, taking on a leading role in the measurement of the ratios of semileptonic-decay branching fractions to final states with tau leptons relative to muons, denoted R(D) and R(D^*). Arnau had rapidly established himself as an expert in this area, and in early 2024 he had taken on convenership of the LHCb subgroup that was dedicated to this and to similar charged-current lepton-flavour-universality tests.

Arnau's warmth, kindness, dedication, intelligence and competence will be deeply missed by his many friends at the institute in Santiago and in the LHCb collaboration.

His friends and colleagues.

BACKGROUND

Notes and observations from the high-energy physics community

Flashes, glows and flickers

A lightning strike lasts a few milliseconds, releasing an avalanche of relativistic electrons. These electrons are accompanied by intense, short-lived bursts of gamma radiation called terrestrial gamma-ray flashes (TGFs), which last a fraction of a millisecond. The subsequent rumble of thunder lasts longer and often occurs alongside gamma-ray glows, which are much less intense than TGFs, and last from a few seconds to a minute. To study these phenomena, researchers from the University of Bergen collaborated with NASA to convert an ex-cold-war spy plane into an aircraft capable of weathering the storm. What they discovered was unexpected: a third type of gamma radiation, which they called flickering gamma-ray flashes (FGFs). FGFs have characteristics of both phenomena. Lasting between 20 to 250 milliseconds, they have more pulses than typical TGFs, and lack the radio and optical signals associated with lightning. Instead, FGFs begin as a glow and suddenly intensify, transitioning into a flicker (N Østgaard *et al.* 2024 *Nature* **634** 53).

The ALOFT team/Mount Visual (CC BY 4.0)

Lightning fast *Illustration of an aircraft monitoring gamma-ray glows.*

300 PB

Data-storage milestone for Brookhaven National Laboratory. Its fully accessible tape archive largely originates in data from the Relativistic Heavy-Ion Collider and the ATLAS experiment at the LHC. Written history, from Sanskrit to today, would fill just 50 petabytes, claim the lab.

Media corner

"People have been reviewing how we've done it, and we haven't received any clear indication that any flaw has been noticed. The same has to be done for CMS."

Ashutosh Kotwal (Duke University), leader of the CDF W-mass analysis (*Nature* 17 September).

"Particle physicists and cosmologists may be 'frothing a bit', but neural networks have long been considered a part of statistical physics."

Statistical physicist **Austen Lamacraft** (University of Cambridge) on the 2024 Nobel Prize in Physics (*Science* 8 October).

"People are excited. I expect in a few weeks, you will find many new papers [attempting to explain the result], and each one will claim something different."

Theorist **Andrzej Buras** (TUM) on NA62's observation of a super-rare kaon decay (*Scientific American* 1 October).

"If China were to win this race and its circular collider were to start working before CERN's, Europe would risk losing its leadership in particle physics, potentially jeopardizing CERN's future."

Former European Central Bank president **Mario Draghi** (*Business Standard* 29 September).

From the archive: September/October 1984

Looking back and heading forwards

At the 1971 inauguration of CERN's Intersecting Storage Rings, ISR, the key was passed from Werner Heisenberg (a theorist) to Edoardo Amaldi (an experimentalist). At the closure in 1984, the key was returned from Giorgio Bellettini (the last Chairman of the ISR Experiments Committee) to Viki Weisskopf (doyen of theorists), who as CERN's Director-General in the early 60s did much to promote the construction of the ISR.

In 1976, the International Committee for Future Accelerators, ICFA, was set up by the International Union of Pure and Applied Physics – "to organize workshops to study the construction and use of an international super-high-energy accelerator complex, to exchange information on future plans of regional facilities, and formulate advice on joint studies and uses."

● Text adapted from *CERN Courier* Sep/Oct 1984 pp 287, 319.

On the platform were, left to right: Herwig Schopper, Kjell Johnsen, Viki Weisskopf, Giorgio Bellettini and Gunther Plass.

A M Stepanets

At the 1981 ICFA meeting in Protvino, USSR, were left to right: K Myznikov, V Yarba, J H Mulvey, V P Dzelephov, V Telegdi, R Wilson, J B Adams, L Lederman, K Lanius, W O Lock and Y Yamaguchi.

Compiler's note

Five years before ICFA was established, the ISR had already triggered CERN's expansion beyond the Swiss border into France, with a 940 m circular tunnel buried in a hill. Recently, the International Tunnelling and Underground Space Association named CERN's 27 km LEP/LHC tunnel as one of the 50 most iconic tunnels in the world. As the particle-physics community develops plans for a Future Circular Collider, some 90 km in circumference, or an International Linear Collider, some 20 km in length, an ICFA panel is studying energy-efficient technologies for a Strategy on Sustainable Accelerators and Colliders, chaired by Thomas Roser of Brookhaven National Laboratory.

CERN rocks out

CERN

Colliding worlds *Les Horribles Cernettes.*

On 17 September, CERN celebrated its 70th birthday by throwing a music festival for 8000 guests. Supertramp saxophonist John Helliwell and the Orchestre des Nations were joined by home-grown bands including Les Horribles Cernettes, Diracula, and Miss Proper and the Moving Targets – a chance for physicists to take off their lab coats and don electric guitars, becoming rockstars for a night.