WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2025 issue of *CERN Courier.*

Particle physicists are always doing things that have never been done before. So says the subject of this month's interview, Mark Thomson, who in December was given a five-year mandate to be Director-General of CERN, starting in January 2026 (p38). "Unfolding" with artificial intelligence is a great example, allowing experimenters to remove detector distortions from complex multidimensional data rather than just a couple of variables (p20).

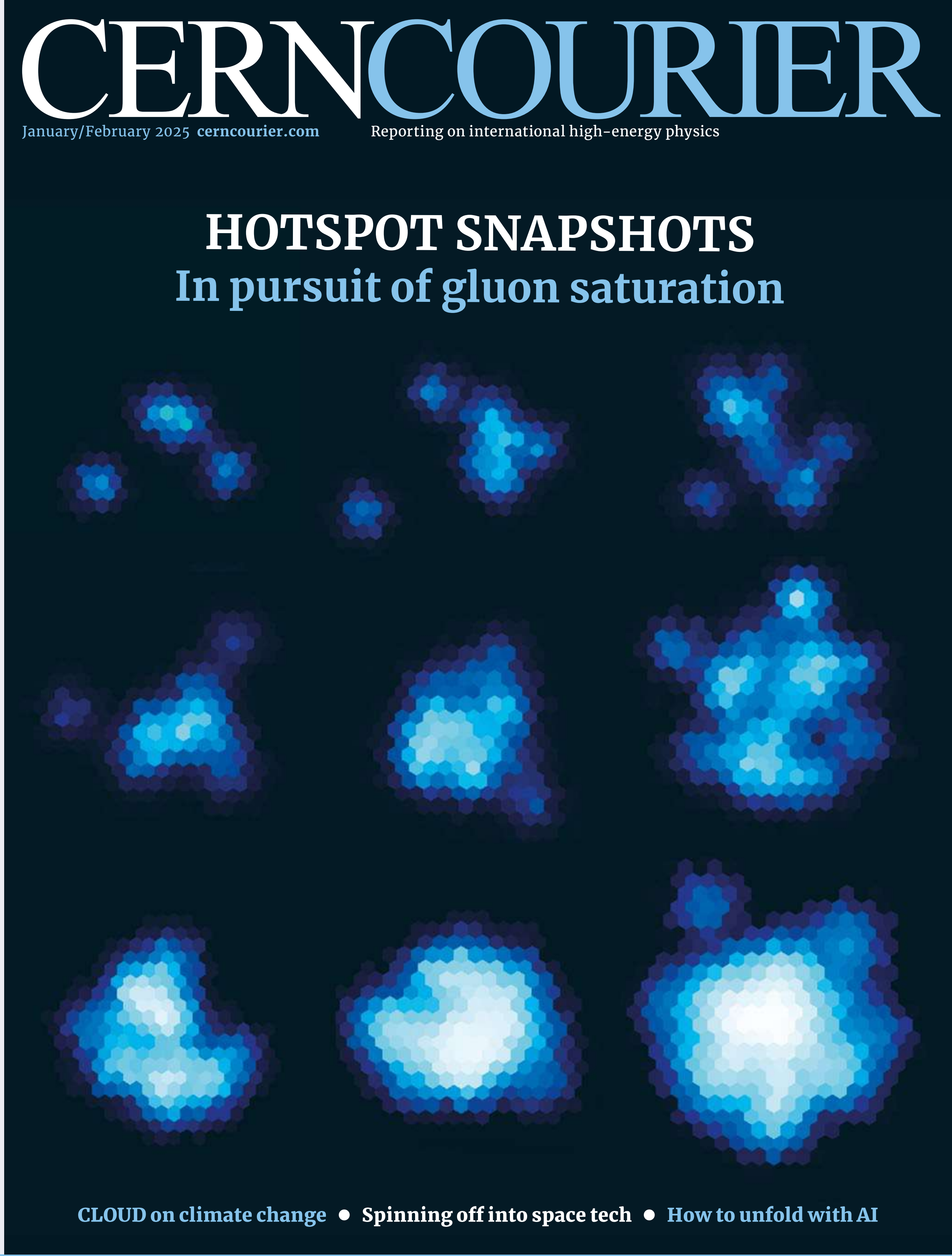
In his interview, Thomson also champions fluidity between academia and industry. This month's careers article explores entrepreneurship that embodies the ideals of academia (p44), and our feature on space technologies highlights how CERN and the European Space Agency collaborate to spark the growing space economy (p26).

Alexandra Ridziková's stunning cover highlights the experimental pursuit of a fundamental feature of gluon dynamics, showing the proton entering the regime of "gluon saturation". The first proton shows a handful of so-called gluonic hotspots carrying roughly 1% of the proton's momentum. The following eight delve down to a Bjorken x of 10^{-6}, where more than 70 hotspots overlap and gluons recombine as often as they split in two. Gluon saturation could be discovered as soon as the next run of the LHC (p31).

Elsewhere on these pages: a new project to demonstrate muon cooling kicks-off at Fermilab (p13); Sheldon Glashow recalls a remarkable decade of discovery (p35); and how energy-efficient RF will reduce electricity bills at colliders (p16).

To subscribe to the magazine, please visit:
https://cerncourier.com/p/about-cern-courier

EDITOR: MARK RAYNER



CERNCOURIER
January/February 2025 cerncourier.com Reporting on international high-energy physics

HOTSPOT SNAPSHOTS

In pursuit of gluon saturation

CLOUD on climate change ● Spinning off into space tech ● How to unfold with AI

CERNCOURIER
Volume 65 Number 1 January/February 2025

IN THIS ISSUE

Volume 65 Number 1 January/February 2025


C Malone

Getting real *The line between science communication and public relations has become blurred, argues Claire Malone.* **19**


ESA/NASA

Spinning off into space *Technologies developed for high-energy physics find diverse applications in space.* **26**


M Brice/CERN

Future DG *Mark Thomson's vision for innovation, early-career researchers and the future of the field.* **38**

NEWS

ANALYSIS

ENERGY FRONTIERS

FIELD NOTES

PEOPLE

CAREERS

OBITUARIES

FEATURES

STATISTICS

SPACE TECHNOLOGY


Planck Collaboration

GLUON SATURATION

SHELDON GLASHOW

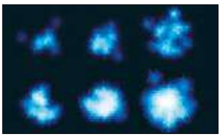
OPINION

VIEWPOINT

INTERVIEW

REVIEWS

DEPARTMENTS


A Ridzikova

On the cover *Simulated colour-charge distributions in protons as Bjorken x decreases from* 10^{-2} *to* 10^{-6}. **31**

FROM THE EDITOR

Spinning off into space

Mark Rayner
Editor

CERN Courier supports international collaboration in high-energy physics by openly communicating fundamental research and its applications. It's a mission that comes straight from CERN's convention – and there's never a shortage of great work to report on. Highlights from this edition include a pioneering new statistical technique, the experimental pursuit of a fundamental feature of gluon dynamics, and seven ways particle-physics technologies are spun-off into space science.

The magazine is written by and for the international community of physicists, engineers and policymakers, and edited at CERN. For the past 26 of the *Courier*'s 65 years, advertising, production, printing and distribution were managed by Institute of Physics Publishing (IOPP) in the UK. This is no longer the case, with the *Courier*'s full machinery now returning to Geneva.

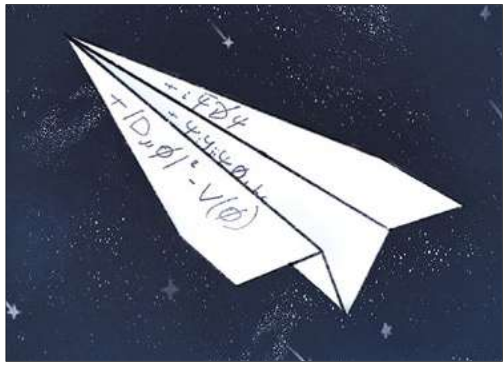
IOPP made significant contributions to the *Courier*'s presence online and in print. Much changed right away in October 1998. The magazine appeared in full colour. The Astrowatch column brought "news from the heavens" (p7). And the *Courier*'s first regular opinion section carried a viewpoint by then Director-General Chris Llewellyn Smith. In this edition, we interview another Briton, Mark Thomson, who in December was given a five-year mandate to be Director-General, starting in January 2026 (p38).

As Thomson points out, particle physicists are always doing things that have never been done before. "Unfolding" with artificial intelligence is a great example, allowing experimenters to remove detector distortions from complex multidimensional data rather than just a couple of variables. A handful of analyses have now been published, with the ATLAS collaboration this month publishing the first unbinned dataset with detector effects unfolded (p20). Elsewhere, the LHCb collaboration is offering theorists a new open-data tool (p14) and AI developed at CERN is being used to diagnose strokes (p16).

The *Courier*'s mission comes straight from CERN's convention – and there's never a shortage of great work to report on

There and back again

Thomson also champions fluidity between academia and industry. This month's careers article contains a great example of entrepreneurship that embodies the ideals of academia (p44), and our feature on space technologies highlights how CERN and the European Space Agency collaborate to spark the growing space economy (p26). In a neat parallel, the cover of the October 1998 edition showed the trailblazing Alpha Magnetic Spectrometer being delivered to the International Space Station by the space shuttle *Discovery*. This month's cover is no less exciting, showing the proton entering the regime of "gluon saturation" in simulations by Alexandra Ridziková of the Czech Technical University in Prague and colleagues. The first proton shows a handful of so-called gluonic hotspots carrying roughly 1% of the proton's momentum. The following eight delve down to a Bjorken x of 10^{-6}, where more than 70 hotspots overlap and gluons recombine as often as they split in two. Gluon saturation could be discovered as soon as the next run of the LHC (p31).


A Epshtein

Folding space *This issue's highlights include open-data unfolding and applications in space tech.*

Elsewhere on these pages: a new project to demonstrate muon cooling kicks-off at Fermilab (p13); Sheldon Glashow recalls a remarkable decade of discovery (p35); and how energy-efficient RF will reduce electricity bills at colliders (p16).

Reporting on international high-energy physics

CERN Courier is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

Editor Mark Rayner
Editorial assistant Alex Epshtein
Astrowatch contributor Merlin Kole
Archive contributor Peggie Rimmer
Publishing manager Matthew Chalmers
Content and production manager Ruth Leopold
Advertising sales and marketing officer Céline Belkadi

E-mail cern.courier@cern.ch

Advisory board Gianluigi Arduini, Philippe Bloch, Roger Forty, Peter Jenni, Joachim Kopp, Christine Sutton

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
DESY Laboratory Thomas Zoufal
Fermilab Madeleine J O'Keefe
Forschungszentrum Jülich Markus Buescher
GSI Darmstadt I Peter
IHEP, Beijing Shanzhen Chen
INFN Antonella Varaschin
Jefferson Laboratory Kandice Carter
KEK Toshihiko Katsuda
Lawrence Berkeley Laboratory Spencer Klein
Los Alamos National Lab Rajan Gupta
NSCL Ken Kingery
Nikhef Robert Fleischer
IJCLab Sabine Starita
PSI Laboratory P-R Kettle
Saclay Laboratory Elisabeth Locci
UK STFC Stephanie Hills
SLAC National Accelerator Laboratory Melinda Lee
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

Advertising Tel +41 (0) 754 118 645; e-mail celine.belkadi@cern.ch

General distribution Courrier Adressage, CERN, 1211 Geneva 23, Switzerland; e-mail courrier-adressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

ISSN 0304-288X

NEWS ANALYSIS

ATMOSPHERIC PHYSICS

CLOUD explains Amazon aerosols

In a paper published in the journal *Nature*, the CLOUD collaboration at CERN has revealed a new source of atmospheric aerosol particles that could help scientists to refine climate models.

Aerosols are microscopic particles suspended in the atmosphere that arise from both natural sources and human activities. They play an important role in Earth's climate system because they seed clouds and influence their reflectivity and coverage. Most aerosols arise from the spontaneous condensation of molecules that are present in the atmosphere only in minute concentrations. However, the vapours responsible for their formation are not well understood, particularly in the remote upper troposphere.

The CLOUD (Cosmics Leaving Outdoor Droplets) experiment at CERN is designed to investigate the formation and growth of atmospheric aerosol particles in a controlled laboratory environment. CLOUD comprises a 26 m³ ultra-clean chamber and a suite of advanced instruments that continuously analyse its contents. The chamber contains a precisely selected mixture of gases under atmospheric conditions, into which beams of charged pions are fired from CERN's Proton Synchrotron to mimic the influence of galactic cosmic rays.

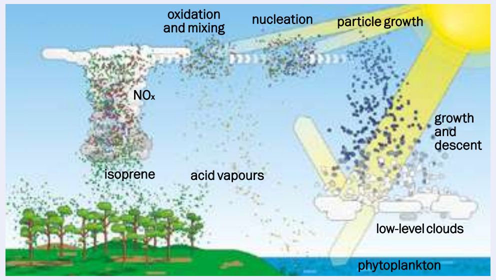
"Large concentrations of aerosol particles have been observed high over the Amazon rainforest for the past 20 years, but their source has remained a puzzle until now," says CLOUD spokesperson Jasper Kirkby. "Our latest study shows that the source is isoprene emitted by the rainforest and lofted in deep convective clouds to high altitudes, where it is oxidised to form highly condensable vapours. Isoprene represents a vast source of biogenic particles in both the present-day and pre-industrial atmospheres that is currently missing in atmospheric chemistry and climate models."

Isoprene is a hydrocarbon containing five carbon atoms and eight hydrogen atoms. It is emitted by broad-leaved trees and other vegetation and is the most abundant non-methane hydrocarbon released into the atmosphere. Until now, isoprene's ability to form new particles has been considered negligible.

The CLOUD results change this picture.


M Brice/CERN-PHOTO-202204-064-2

The CLOUD experiment *CERN's Proton Synchrotron mimics the effect of cosmic rays on atmospheric gases.*



D Dominguez/CERN-GRAPHICS-2024-002-1

Seeding clouds *Isoprene from forests is efficiently transported at night by deep convective clouds into the upper troposphere. During daylight, the isoprene that has accumulated overnight, together with daytime-convected isoprene, reacts with hydroxyl radicals and* NO_x *from lightning to produce isoprene-oxygenated organic molecules. These combine with trace amounts of acids to produce high particle concentrations at temperatures below –30 °C. The newly formed particles grow rapidly over several hours and days while following the descending air masses. This mechanism may provide an extensive source of cloud condensation nuclei for shallow continental and marine clouds, which influence Earth's radiative balance.*

By studying the reaction of hydroxyl radicals with isoprene at upper tropospheric temperatures of –30 °C and –50 °C, the collaboration discovered that isoprene oxidation products form copious particles at ambient isoprene concentrations. This new source of aerosol particles does not require any additional vapours. However, when minute concentrations of sulphuric acid or iodine oxoacids were introduced into the CLOUD chamber, a 100-fold increase in aerosol formation rate was observed. Although sulphuric acid derives mainly from anthropogenic sulphur dioxide emissions, the acid concentrations used in CLOUD can also arise from natural sources.

In addition, the team found that isoprene oxidation products drive rapid growth of particles to sizes at which they can seed clouds and influence the climate – a behaviour that persists in the presence of nitrogen oxides produced by lightning at upper-tropospheric concentrations. After continued growth and descent to lower altitudes, these particles may provide a globally important source for seeding shallow continental and marine clouds, which influence Earth's radiative balance – the amount of incoming solar radiation compared to outgoing longwave radiation (see "Seeding clouds" figure).

"This new source of biogenic particles in the upper troposphere may impact estimates of Earth's climate sensitivity, since it implies that more aerosol particles were produced in the pristine pre-industrial atmosphere than previously thought," adds Kirkby. "However, until our findings have been evaluated in global climate models, it's not possible to quantify the effect."

The CLOUD findings are consistent with aircraft observations over the Amazon, as reported in an accompanying paper in the same issue of *Nature*. Together, the two papers provide a compelling picture of the importance of isoprene-driven aerosol formation and its relevance for the atmosphere.

Since it began operation in 2009, the CLOUD experiment has unearthed several mechanisms by which aerosol particles form and grow in different regions of Earth's atmosphere. "In addition to helping climate researchers understand the critical role of aerosols in Earth's climate, the new CLOUD result demonstrates the rich diversity of CERN's scientific programme and the power of accelerator-based science to address societal challenges," says CERN Director for Research and Computing, Joachim Mnich.

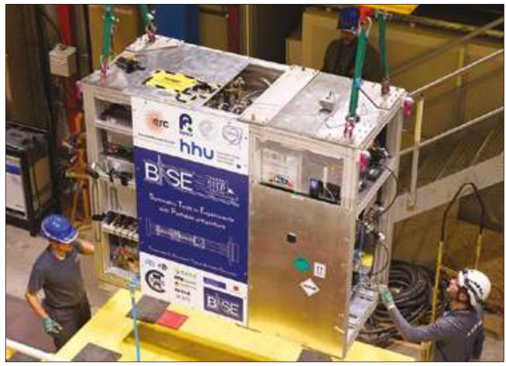
Further reading

J Shen *et al.* 2024 *Nature* **636** 115.
J Curtius *et al.* 2024 *Nature* **636** 124.

CERNCOURIER
VOLUME 65 NUMBER 1 JANUARY/FEBRUARY 2025

ANTIMATTER

Trial trap on a truck


Transportable antimatter trap *The BASE-STEP experiment is on track to transport antiprotons to Germany next year.*

CERN-PHOTO-202410-259-53

Thirty years ago, physicists from Harvard University set out to build a portable antiproton trap. They tested it on electrons, transporting them 5000 km from Nebraska to Massachusetts, but it was never used to transport antimatter. Now, a spin-off project of the Baryon Antibaryon Symmetry Experiment (BASE) at CERN has tested their own antiproton trap, this time using protons. The ultimate goal is to deliver antiprotons to labs beyond CERN's reach.

"For studying the fundamental properties of protons and antiprotons, you need to take extremely precise measurements – as precise as you can possibly make it," explains principal investigator Christian Smorra. "This level of precision is extremely difficult to achieve in the antimatter factory, and can only be reached when the accelerator is shut down. This is why we need to relocate the measurements – so we can get rid of these problems and measure anytime."

The team has made considerable strides to miniaturise their apparatus. BASE-STEP is far and away the most compact design for an antiproton trap yet built, measuring just 2 metres in length, 1.58 metres in height and 0.87 metres across. Weighing in at 1 tonne, transportation is nevertheless a complex operation. On 24 October, 70 protons were introduced into the trap and lifted onto a truck using two overhead cranes. The protons made a round trip through CERN's main site before returning home to the antimatter factory. All 70 protons were safely transported and the experiment with these particles continued seemlessly, successfully demonstrating the trap's performance.

Antimatter needs to be handled carefully, to avoid it annihilating with the walls of the trap. This is hard to achieve in the controlled environment of a laboratory, let alone on a moving truck. Just like in the BASE laboratory, BASE-STEP uses a Penning trap with two electrode stacks inside a single solenoid. The magnetic field confines charged particles radially, and the electric fields trap them axially. The first electrode stack collects antiprotons from CERN's antimatter factory and serves as an "airlock" by protecting antiprotons from annihilation with the molecules of external gases. The second is used for long-term storage. While in transit, non-destructive image-current detection monitors the particles and makes sure they have not hit the walls of the trap.

"We originally wanted a system that you can put in the back of your car," says Smorra. "Next, we want to try using permanent magnets instead of a superconducting solenoid. This would make the trap even smaller and save CHF 300,000. With this technology, there will be so much more potential for future experiments at CERN and beyond."

With or without a superconducting magnet, continuous cooling is essential to prevent heat from degrading the trap's ultra-high vacuum. Penning traps conventionally require two separate cooling systems – one for the trap and one for the superconducting magnet. BASE-STEP combines the cooling systems into one, as the Harvard team proposed in 1993. Ultimately, the transport system will have a cryocooler that is attached to a mobile power generator with a liquid-helium buffer tank present as a backup. Should the power generator be interrupted, the back-up cooling system provides a grace period of four hours to fix it and save the precious cargo of antiprotons. But such a scenario carries no safety risk given the miniscule amount of antimatter being transported. "The worst that can happen is the antiprotons annihilate, and you have to go back to the antimatter factory to refill the trap," explains Smorra.

With the proton trial-run a success, the team are confident they will be able to use this apparatus to successfully deliver antiprotons to precision laboratories in Europe. Next summer, BASE-STEP will load up the trap with 1000 antiprotons and hit the road. Their first stop is scheduled to be Heinrich Heine University in Germany.

"We can use the same apparatus for the antiproton transport," says Smorra. "All we need to do is switch the polarity of the electrodes."

HEAVY-ION PHYSICS

First signs of antihyperhelium-4

Heaviest antihypernucleus at the LHC *An artist's impression of antihyperhelium-4 being created in a lead–lead collision.*

J Ditzel

Heavy-ion collisions at the LHC create suitable conditions for the production of atomic nuclei and exotic hypernuclei, as well as their antimatter counterparts, antinuclei and antihypernuclei. Measurements of these forms of matter are important for understanding the formation of hadrons from the quark–gluon plasma and studying the matter–antimatter asymmetry seen in the present-day universe.

Hypernuclei are exotic nuclei formed by a mix of protons, neutrons and hyperons, the latter being unstable particles containing one or more strange quarks. More than 70 years since their discovery in cosmic rays, hypernuclei remain a source of fascination for physicists due to their rarity in nature and the challenge of creating and studying them in the laboratory.

In heavy-ion collisions, hypernuclei are created in significant quantities, but only the lightest hypernucleus, hypertriton, and its antimatter partner, antihypertriton, have been observed. Hypertriton is composed of a proton, a neutron and a lambda hyperon containing one strange quark. Antihypertriton is made up of an antiproton, an antineutron and an antilambda. ▷

Following hot on the heels of the observation of antihyperhydrogen-4 (a bound state of an antiproton, two antineutrons and an antilambda) earlier this year by the STAR collaboration at the Relativistic Heavy Ion Collider (RHIC), the ALICE collaboration at the LHC has now seen the first ever evidence for antihyperhelium-4, which is composed of two antiprotons, an antineutron and an antilambda. The result has a significance of 3.5 standard deviations. If confirmed, antihyperhelium-4 would be the heaviest antimatter hypernucleus yet seen at the LHC.

The ALICE measurement is based on lead–lead collision data taken in 2018 at a centre-of-mass energy of 5.02 TeV for each colliding pair of nucleons, be they protons or neutrons. Using a machine-learning technique that outperforms conventional hypernuclei search techniques, the ALICE researchers looked at the data for signals of hyperhydrogen-4, hyperhelium-4 and their antimatter partners. Candidates for (anti)hyperhydrogen-4 were identified by looking for the (anti)helium-4 nucleus and the charged pion into which it decays, whereas candidates for (anti) hyperhelium-4 were identified via its decay into an (anti)helium-3 nucleus, an (anti)proton and a charged pion.

In addition to finding evidence of antihyperhelium-4 with a significance of 3.5 standard deviations, and evidence of antihyperhydrogen-4 with a significance of 4.5 standard deviations, the ALICE team measured the production yields and masses of both hypernuclei.

For both hypernuclei, the measured masses are compatible with the current world-average values. The measured production yields were compared with predictions from the statistical hadronisation model, which provides a good description of the formation of hadrons and nuclei in heavy-ion collisions. This comparison shows that the model's predictions agree closely with the data if both excited hypernuclear states and ground states are included in the predictions. The results confirm that the statistical hadronisation model can also provide a good description of the production of hypernuclei modelled to be compact objects with sizes of around 2 femtometres.

The researchers also determined the antiparticle-to-particle yield ratios for both hypernuclei and found that they agree with unity within the experimental uncertainties. This agreement is consistent with ALICE's observation of the equal production of matter and antimatter at LHC energies and adds to the ongoing research into the matter–antimatter imbalance in the universe.

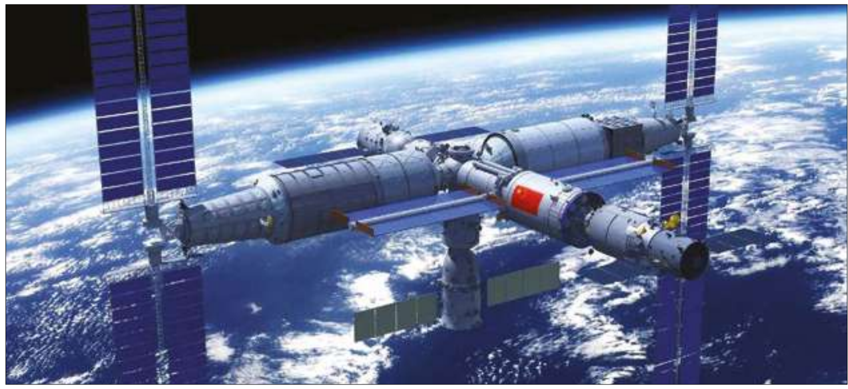
Hypernuclei remain a source of fascination due to their rarity in nature and the challenge of creating and studying them in the lab

Further reading

ALICE Collab. 2024 arXiv:2410.17769.

ASTROWATCH

Chinese space station gears up for astrophysics


Flying high *China's permanently crewed space station, Tiangong, which can be translated as "sky palace", orbits at an altitude of 340 to 450 km and was completed in 2022 following its precursors Tiangong-1 and Tiangong-2.*

China Manned Space Engineering Office

Completed in 2022, China's Tiangong space station represents one of the biggest projects in space exploration in recent decades. Like the International Space Station, its ability to provide large amounts of power, support heavy payloads and access powerful communication and computing facilities give it many advantages over typical satellite platforms. As such, both Chinese and international collaborations have been developing a number of science missions ranging from optical astronomy to the detection of cosmic rays with PeV energies.

For optical astronomy, the space station will be accompanied by the Xuntian telescope, which can be translated to "survey the heavens". Xuntian is currently planned to be launched in mid-2025 to fly alongside Tiangong, thereby allowing for regular maintenance. Although its spatial resolution will be similar to that of the Hubble Space Telescope, Xuntian's field of view will be about 300 times larger, allowing the observation of many objects at the same time. In addition to producing impressive images similar to those sent by Hubble, the instrument will be important for cosmological studies where large statistics for astronomical objects are typically required to study their evolution.

Another instrument that will observe large portions of the sky is LyRIC (Lyman UV Radiation from Interstellar medium and Circum-galactic medium). After being placed on the space station in the coming years, LyRIC will probe the poorly studied far-ultraviolet regime that contains emission lines from neutral hydrogen and other elements. While difficult to measure, this allows studies of baryonic matter in the universe, which can be used to answer important questions such as why only about half of the total baryons in the standard "ΛCDM" cosmological model can be accounted for.

At slightly higher energies, the Diffuse X-ray Explorer (DIXE) aims to use a novel type of X-ray detector to reach an energy resolution better than 1% in the 0.1 to 10 keV energy range. It achieves this using cryogenic transition-edge sensors (TESs), which exploit the rapid change in resistance that occurs during a superconducting phase transition. In this regime, the resistivity of the material is highly dependent on its temperature, allowing the detection of minuscule temperature increases resulting from X-rays being absorbed by the material. Positioned to scan the sky above the Tiangong space station, DIXE will be able, among other things, to measure the velocity of material that appears to have been emitted by the Milky Way during an active stage of its central black hole. Its high-energy resolution will allow Doppler shifts of the order of several eV to be measured, requiring the TES detectors to operate at 50 mK. Achieving such temperatures demands a cooling system of 640 W – a ▷

power level that is difficult to achieve on a satellite, but relatively easy to acquire on a space station. As such, DIXE will be one of the first detectors using this new technology when it launches in 2025, leading the way for missions such as the European ATHENA mission that plans to use it starting in 2037.

POLAR-2 was accepted as an international payload on the China space station through the United Nations Office for Outer Space Affairs and has since become a CERN-recognised experiment. The mission started as a Swiss, German, Polish and Chinese collaboration building on the success of POLAR, which flew on the space station's predecessor Tiangong-2. Like its earlier incarnation, POLAR-2 measures the polarisation of high-energy X rays or gamma rays to provide insights into, for example, the magnetic fields that produced the emission. As one of the most sensitive gamma-ray detectors in the sky, POLAR-2 can also play an important role in alerting other instruments when a bright gamma-ray transient, such as a gamma-ray burst, appears. The importance of such alerts has resulted in the expansion of POLAR-2 to include an accompanying imaging spectrometer, which will provide detailed spectral and location information on any gamma-ray transient. Also now foreseen for this second payload is an additional wide-field-of-view X-ray polarimeter. The international team developing the three instruments, which are scheduled to be launched in 2027, is led by the Institute of High Energy Physics in Beijing.

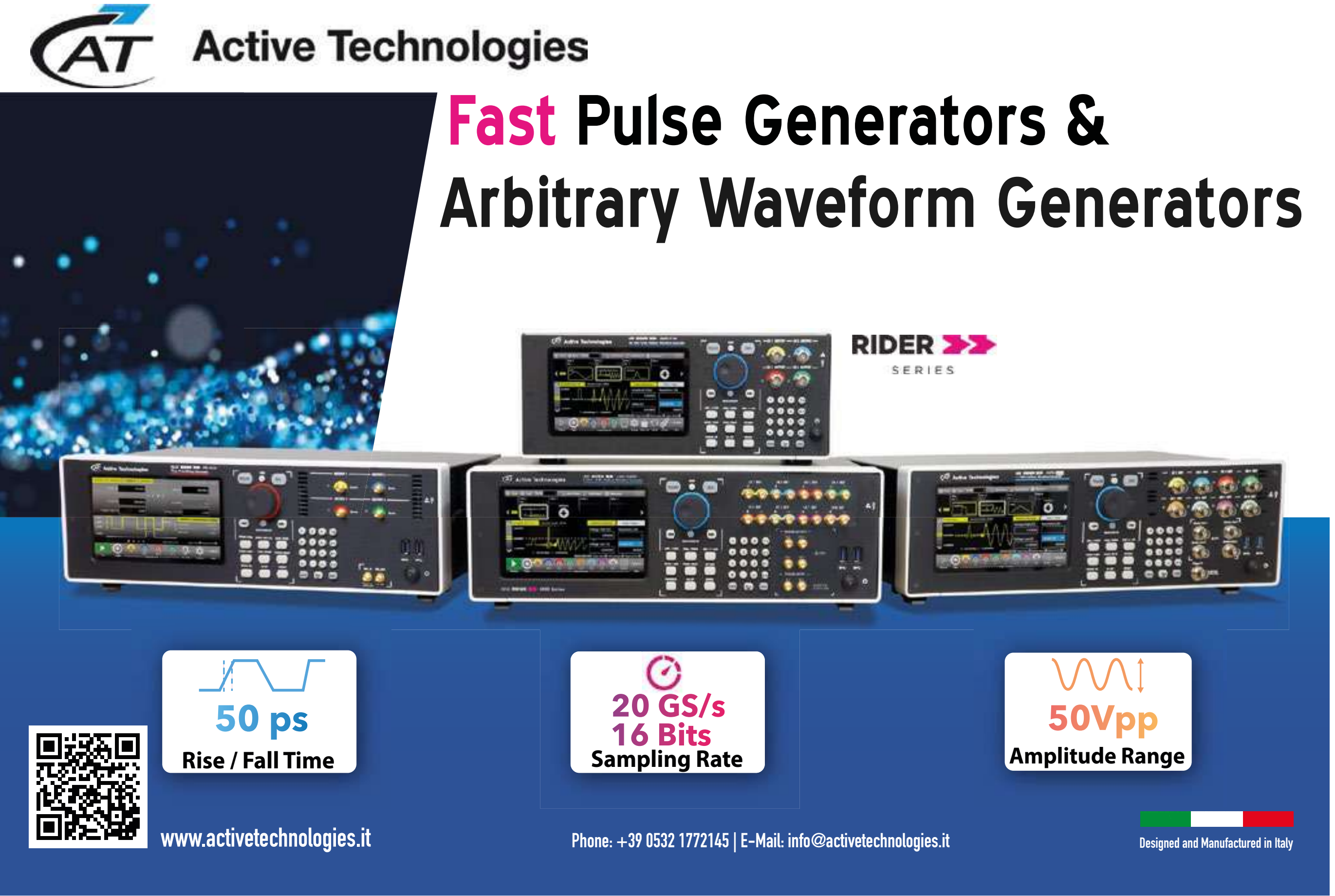
For studying the universe using even higher energy emissions, the space station will host the High Energy cosmic-Radiation Detection Facility (HERD). HERD is designed to study both cosmic rays and gamma rays at energies beyond those accessible to instruments like AMS-02, CALET (*CERN Courier* July/August 2024 p24) and DAMPE. It aims to achieve this, in part, by simply being larger, resulting in a mass that is currently only possible to support on a space station. The HERD calorimeter will be 55 radiation lengths long and consist of several tonnes of scintillating cubic LYSO crystals. The instrument will also use high-precision silicon trackers, which in combination with the deep calorimeter, will provide a better angular resolution and a geometrical acceptance 30 times larger than the present AMS-02 (which is due to be upgraded next year). This will allow HERD to probe the cosmic-ray spectrum up to PeV energies, filling in the energy gap between current space missions and ground-based detectors. HERD started out as an international mission with a large European contribution, however delays on the European side regarding participation, in combination with a launch requirement of 2027, mean that it is currently foreseen to be a fully Chinese mission.

Although not as large or mature as the International Space Station, Tiangong's capacity to host cutting-edge astrophysics missions is catching up

Although not as large or mature as the International Space Station, Tiangong's capacity to host cutting-edge astrophysics missions is catching up. As well as providing researchers with a pristine view of the electromagnetic universe, instruments such as HERD will enable vital cross-checks of data from AMS-02 and other unique experiments in space.

Further reading

H Jin *et al.* 2024 arXiv:2406.09813.



NEWS DIGEST


Yuexiang Liu

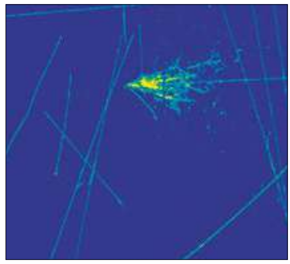
The two-month process of filling JUNO with water has begun.

JUNO complete, being filled
On 20 November, the last photomultiplier tube of the Jiangmen Underground Neutrino Observatory (JUNO) was installed 700 metres below the surface in Guangdong, China. On 18 December, the detector and its pool began filling with water. Water in the outer pool will shield JUNO from gamma rays from the surrounding rock and act as a Cherenkov detector to veto cosmic rays; water in the inner tank will displace air and dust before being replaced with liquid scintillator. JUNO is designed to resolve the neutrino mass hierarchy by measuring the neutrino energy spectrum from the Yangjiang and Taishan nuclear power plants with an unprecedented energy resolution of 3% at 1 MeV, as well as to study supernova, atmospheric, solar and geo-neutrinos.

BESIII pinpoints vertices
The Beijing Spectrometer III (BESIII) experiment boasts a brand new inner tracker. Thanks to the European "FEST" project led by INFN, its new cylindrical gas-electron multiplier will improve vertexing resolution from 1.5 to 0.5 mm and will tolerate data-collection rates over 10^4 Hz/cm^2 in high-intensity radiation environments – as required by an upcoming threefold luminosity upgrade to the BEPCII e^+e^- collider. BESIII began studying tau-charm physics in 2008. Over 15 years, the experiment has made notable contributions to the study of light hadron spectroscopy, charmonium-like exotic hadrons and CP violation in the hyperon sector. The collaboration now plans to branch out further. "We expect to perform the first study of entangled charmed baryon pairs at an electron-positron collider," says spokesperson Haibo Li (IHEP).

CERN on time
A new optical-fibre link between CERN and the French National Metrological Institute in Paris, established on 23 October, will help physicists to measure the energy levels of antihydrogen atoms with orders of magnitude greater precision. The ultra-stable laser signal, received via the REFIMEVE optical-fibre network, will help synchronise clocks in CERN's Antimatter Factory for spectroscopic comparisons between antihydrogen and hydrogen. Such measurements have so far relied on a simple quartz oscillator, enabling a precision on transitions between energy levels of 12 decimal places. In conjunction with a caesium fountain clock delivered to CERN in late 2022, and specialised equipment such as an optical frequency comb, the new signal will increase precision to 15 decimal places and beyond for fundamental tests of CPT invariance.

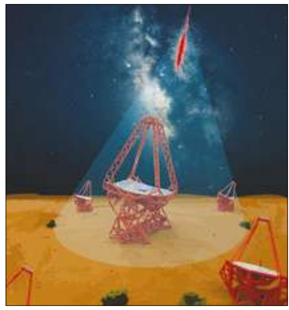
Second life for DUNE prototypes
Recently it was pointed out that CERN's "protoDUNE" detectors stand in the shadow of secondary particles from the T2 target in CERN's North Hall, which receives 400 GeV protons from the Super Proton Synchrotron: T2 could serve as a mini beam dump, potentially generating heavy neutral leptons, axion-like particles and other BSM particles (P Coloma *et al.* 2023 arXiv:2304.06765). Produced for the Deep Underground Neutrino Experiment in the US, the two 750 tonne prototype liquid-argon TPCs began reconstructing low-energy hadron and electron beams in 2018. "A real demonstration of the feasibility of reconstructing BSM events is to observe a well known weakly interacting particle: the neutrino!" says Albert De Roeck (CERN). First accelerator neutrinos were recorded in the "single-phase" NP04 prototype at the end of 2024.


D Pullia

A muon–neutrino interaction candidate.

French, Canadian physicists fuse
On 4 November, the French research organisation CNRS and TRIUMF, Canada's particle accelerator centre, signed a partnership agreement to create an international research laboratory for Nuclear Physics, Nuclear Astrophysics and Accelerator Technologies (NPAT) on the grounds of the University of British Columbia in Vancouver. The laboratory will bring together the Canadian and French nuclear-physics communities around two key themes: research on exotic nuclei to explore the mechanisms of nuclear cohesion, and research into nuclear astrophysics, which links extreme astrophysical objects such as neutron stars with the behaviour of nuclear matter. The lab's field of investigation will also cover R&D for ion accelerators – the key tool for studying exotic nuclei. NPAT will open its doors on 1 January 2025.

A break in Namibia
The High Energy Stereoscopic System (HESS) collaboration, operating five gamma-ray telescopes in Namibia, has observed cosmic-ray electrons and positrons at energies reaching up to 40 TeV – the highest ever recorded. A decade of data reveals an unforeseen break in the spectrum at 1 TeV, which the team surmises may be due to energy losses in propagation (HESS Collab. 2024 *Phys. Rev. Lett.* **133** 221001). "The measured cosmic-ray electrons most likely originate from very few sources in the vicinity of our own solar system, up to a maximum of a few 1000 light years away," says Kathrin Egberts (University of Potsdam).


Collaboration MPIK/H.E.S.S.

An illustration of the HESS telescope array.

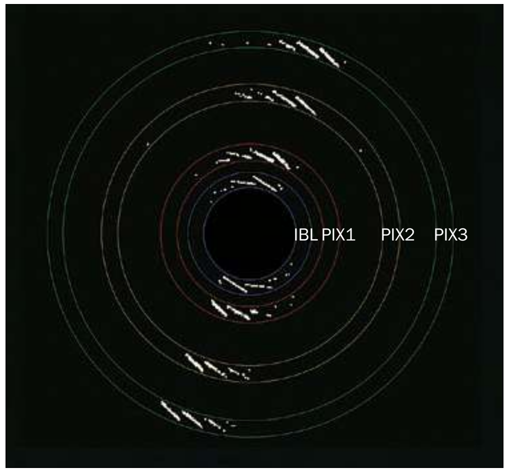
KOTO on kaons
The KOTO experiment at Japan's J-PARC laboratory reports a new upper limit on the branching ratio of the ultra-rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ (KOTO Collab. 2024 arXiv:2411.11237). With newly installed counters and analysis techniques to suppress charged-kaon backgrounds and model K_L in the beam halo, the expected background was suppressed to $0.252 \pm 0.055\,(\text{stat.})^{+0.052}_{-0.067}\,(\text{syst.})$ events. No events were observed in the signal region and an upper limit on the branching fraction for the decay was set to be 2.2×10^{-9} at 90% confidence. Though well above the Standard Model prediction of $(2.94 \pm 0.15) \times 10^{-11}$, this channel is one of the most promising ultra-rare decays that could reveal new physics beyond the energy frontier this decade (*CERN Courier* July/August 2024 p30).

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

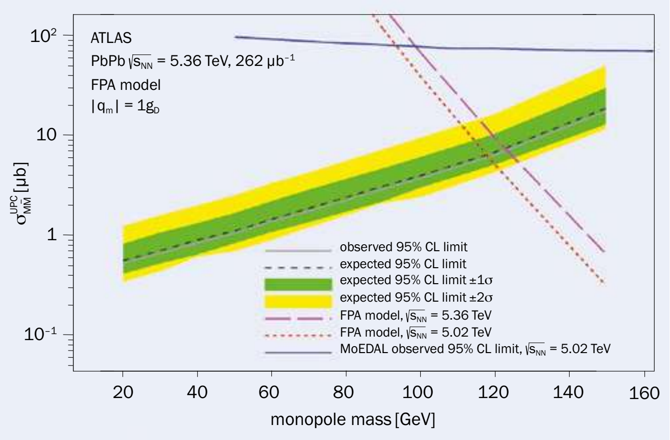
ATLAS

Taking the lead in the monopole hunt



ATLAS Collab./CERN

Fig. 1. *Simulated monopole pair-production signature for PbPb ultraperipheral collisions in the ATLAS pixel detector.*



ATLAS Collab./CERN

Fig. 2. *95% confidence upper limits on the monopole pair-production cross-section in PbPb ultraperipheral collisions at 5.36 TeV. The limits are compared with model predictions and limits from the MoEDAL experiment.*

Magnetic monopoles are hypothetical particles that would carry magnetic charge, a concept first proposed by Paul Dirac in 1931. He pointed out that if monopoles exist, electric charge must be quantised, meaning that particle charges must be integer multiples of a fundamental charge. Electric charge quantisation is indeed observed in nature, with no other known explanation for this striking phenomenon. The ATLAS collaboration performed a search for these elusive particles using lead–lead (PbPb) collisions at 5.36 TeV from Run 3 of the Large Hadron Collider.

The search targeted the production of monopole–antimonopole pairs via photon–photon interactions, a process enhanced in heavy-ion collisions due to the strong electromagnetic fields ($\propto Z^2$) generated by the $Z = 82$ lead nuclei. Ultraperipheral collisions are ideal for this search, as they feature electromagnetic interactions without direct nuclear contact, allowing rare processes like monopole production to dominate in visible signatures. The ATLAS study employed a novel detection technique exploiting the expected highly ionising nature of these particles, leaving a characteristic signal in the innermost silicon detectors of the ATLAS experiment (figure 1).

The analysis employed a non-perturbative semiclassical model to estimate monopole production. Traditional perturbative models, which rely on Feynman diagrams, are inadequate due to the large coupling constant of magnetic monopoles. Instead, the study used a model based on the Schwinger mechanism, adapted for magnetic fields, to predict monopole production in the ultraperipheral collisions' strong magnetic fields. This approach offers a more robust theoretical framework for the search.

The experiment's trigger system was critical to the search. Given the high ionisation signature of monopoles, traditional calorimeter-based triggers were unsuitable, as even high-momentum monopoles lose energy rapidly through ionisation and do not reach the calorimeter. Instead, the trigger, newly introduced for the 2023 PbPb data-taking campaign, focused on detecting the forward neutrons emitted during electromagnetic interactions. The level-1 trigger system identified neutrons using the Zero-Degree Calorimeter, while the high-level trigger required more than 100 clusters of pixel-detector hits in the inner detector – an approach sensitive to monopoles due to their high ionisation signatures.

The analysis set new upper limits on the cross-section for magnetic monopole production

Additionally, the analysis examined the topology of pixel clusters to further refine the search, as a more aligned azimuthal distribution in the data would indicate a signature consistent with monopoles (figure 1), while the uniform distribution typically associated with beam-induced backgrounds could be identified and suppressed.

No significant monopole signal is observed beyond the expected background, with the latter being estimated using a data-driven technique. Consequently, the analysis set new upper limits on the cross-section for magnetic monopole production (figure 2), significantly improving existing limits for low-mass monopoles in the 20–150 GeV range. Assuming a non-perturbative semiclassical model, the search excludes monopoles with a single Dirac magnetic charge and masses below 120 GeV. The techniques developed in this search will open new possibilities to study other highly ionising particles that may emerge from beyond-Standard Model physics.

Further reading

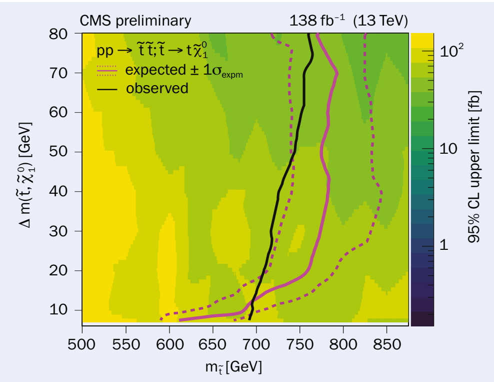
ATLAS Collab. 2024 arXiv:2408.11035.

CMS

Cornering compressed SUSY

Since the LHC began operations in 2008, the CMS experiment has been searching for signs of supersymmetry (SUSY) – the only remaining spacetime symmetry not yet observed to have consequences for physics. It has explored higher and higher masses of supersymmetric particles (sparticles) with increasing collision energies and growing datasets. No evidence has been observed so far. A new CMS analysis using data recorded between 2016 and 2018 continues this search in an often overlooked, difficult corner of SUSY manifestations: compressed sparticle mass spectra.

The masses of SUSY sparticles have very important implications for both the physics of our universe and how they could be potentially produced and observed at experiments like CMS. The heavier the sparticle, the rarer its appearance. On the other hand, when heavy sparticles decay, their mass is converted to the masses and momenta of SM particles, like leptons and jets. These particles are detected by CMS, with large masses leaving potentially spectacular (and conspicuous) signatures. Each heavy sparticle is expected to continue to decay to lighter ones, ending with the lightest SUSY particles (LSPs). LSPs, though massive, are stable and do not decay in the detector. Instead, they appear as missing momentum. In cases of *compressed* sparticle mass spectra, the mass difference between the initially produced sparticles and LSPs is small. This means the low rates of production of massive sparticles are not accompanied by high-momentum decay products in the detector. Most of their mass ends up escaping in the form of invisible particles, significantly complicating observation.



CMS-PAS-SUS-23-003

Fig. 1. *Limits on stop pair production with decays through top quarks and LSPs. The colour scale shows 95% CL upper limits on the product of the cross-section and branching fractions as a function of stop mass and stop–LSP mass difference. The expected (magenta line) and observed (black line) lower mass limits are indicated assuming 100% branching fractions.*

This new CMS result turns this difficulty on its head, using a kinematic observable R_{ISR}, which is directly sensitive to the mass of LSPs as opposed to the mass difference between parent sparticles and LSPs. The result is even better discrimination between SUSY and SM backgrounds when sparticle spectra are more compressed.

This approach focuses on events where putative SUSY candidates receive a significant "kick" from initial-state radiation (ISR) – additional jets recoiling opposite the system of sparticles. When the sparticle masses are highly compressed, the invisible, massive LSPs receive most of the ISR momentum-kick, with this fraction telling us about the LSP masses through the R_{ISR} observable.

Given the generic applicability of the approach, the analysis is able to systematically probe a large class of possible scenarios. This includes events with various numbers of leptons (0, 1, 2 or 3) and jets (including those from heavy-flavour quarks), with a focus on objects with low momentum. These multiplicities, along with R_{ISR} and other selected discriminating variables, are used to categorise recorded events and a comprehensive fit is performed to all these regions. Compressed SUSY signals would appear at larger values of R_{ISR}, while bins at lower values are used to model and constrain SM backgrounds. With more than 2000 different bins in R_{ISR}, over several hundred object-based categories, a significant fraction of the experimental phase space in which compressed SUSY could hide is scrutinised.

In the absence of significant observed deviations in data yields from SM expectations, a large collection of SUSY scenarios can be excluded at high confidence level (CL), including those with the production of stop quarks, EWKinos and sleptons. As can be seen in the results for stop quarks (figure 1), the analysis is able to achieve excellent sensitivity to compressed SUSY. Here, as for many of the SUSY scenarios considered, the analysis provides the world's most stringent constraints on compressed SUSY, further narrowing the space it could be hiding.

Further reading

CMS Collab. 2024 CMS-PAS-SUS-23-003.

LHCb

R(D) ratios in line at LHCb

The accidental symmetries observed between the three generations of leptons are poorly understood, with no compelling theoretical motivation in the framework of the Standard Model (SM). The $b \to c\tau^-\bar{\nu}_\tau$ transition has the potential to reveal new particles or forces that interact primarily with third-generation particles, which are subject to the less stringent experimental constraints at present. As a tree-level SM process mediated by W-boson exchange, its amplitude is large, resulting in large branching fractions and significant data samples to analyse.

The observable under scrutiny is the ratio of decay rates between the signal mode involving τ and ν_τ leptons from the third generation of fermions and the normalisation mode containing μ and ν_μ leptons from the second generation. Within the SM, this lepton flavour universality (LFU) ratio deviates from unity only due to the different mass of the charged leptons – but new contributions could change the value of the ratios. A longstanding tension exists between the SM prediction and the experimental measurements, requiring further input to clarify the source of the discrepancy.

This constitutes the world's second most precise measurement of R(D)

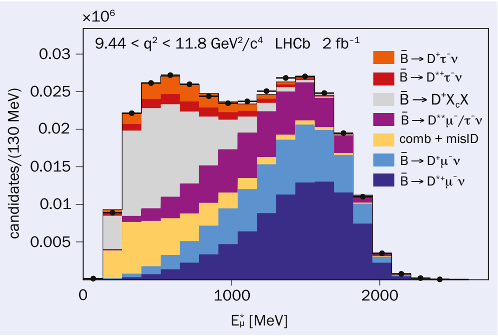
The LHCb collaboration analysed four decay modes: $\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell$, with ℓ representing τ or μ. Each is selected using the same visible final state of one muon and light hadrons from the decay of the charm meson. In the normalisation mode, the muon originates directly from the B-hadron decay, while in the signal mode, it arises from the decay of the τ lepton. The four contributions are analysed simultaneously, yielding two LFU ratios between taus and muons – one using the ground state of the D^+ meson and one the excited state D^{*+}.

The control of the background contributions is particularly complicated in this analysis as the final state is not fully reconstructible, limiting the resolution on some of the discriminating variables. Instead, a three-dimensional template fit separates the signal and the normalisation from the background versus: the momentum transferred to the lepton pair (q^2); the energy of the muon in the rest frame of the B meson (E^*_μ); and the invariant mass missing from the visible system. Each contribution is modelled ▷

using a template histogram derived either from simulation or from selected control samples in data.

To prevent the simulated data sample size from becoming a limiting factor in the precision of the measurement, a fast tracker-only simulation technique was exploited for the first time in LHCb. Another novel aspect of this work is the use of the HAMMER software tool during the minimisation procedure of the likelihood fit, which enables a fast, but exact, variation of a template as a function of the decay-model parameters. This variation is important to allow the form factors of both the signal and normalisation channels to vary as the constraints derived from the predictions that use precise lattice calculations can have larger uncertainties than those obtained from the fit.

The fit projection over one of the discriminating variables is shown in figure 1, illustrating the complexity of the analysed data sample but nonetheless showcasing LHCb's ability to distinguish the signal modes (red and orange) from the normalisation modes (two shades of blue) and background contributions.



LHCb Collab. 2024 arXiv:2406.03387

Fig. 1. *Fit projection as a function of the energy of the muon in the rest frame of the B meson in the signal-enriched region for all four decays used in the analysis.*

The measured LFU ratios are in good agreement with the current world average and the predictions of the SM: $R(D^+) = 0.249 \pm 0.043$ (stat.) $\pm\, 0.047$ (syst.) and $R(D^{*+}) = 0.402 \pm 0.081$ (stat.) $\pm\, 0.085$ (syst.). Under isospin symmetry assumptions, this constitutes the world's second most precise measurement of R(D), following a 2019 measurement by the Belle collaboration. This analysis complements other ongoing efforts at LHCb and other experiments to test LFU across different decay channels. The precision of the measurements reported here is primarily limited by the size of the signal and control samples, so more precise measurements are expected with future LHCb datasets.

Further reading

LHCb Collab. 2024 arXiv:2406.03387.

F Bernlochner *et al.* 2020 *Eur. Phys. J. C* **80** 883.

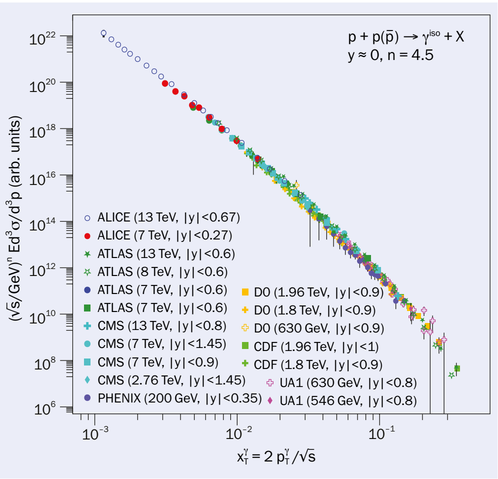
ALICE

Isolating photons at low Bjorken x

In high-energy collisions at the LHC, prompt photons are those that do not originate from particle decays and are instead directly produced by the hard scattering of quarks and gluons (partons). Due to their early production, they provide a clean method to probe the partons inside the colliding nucleons, and in particular the fraction of the momentum of the nucleon carried by each parton (Bjorken x). The distribution of each parton in Bjorken x is known as its parton distribution function (PDF).

Theoretical models of particle production rely on the precise knowledge of PDFs, which are derived from vast amounts of experimental data. The high centre-of-mass energies ($\sqrt{s}$) at the LHC probe very small values of the momentum fraction, Bjorken x. At "midrapidity", when a parton scatters with a large angle with respect to the beam axis, and a prompt photon is produced in the final state, a useful approximation to Bjorken x is provided by the dimensionless variable $x_T = 2p_T/\sqrt{s}$, where p_T is the transverse momentum of the prompt photon.

Prompt photons can also be produced by next-to-leading order processes such as parton fragmentation or bremsstrahlung. A clean separation of the different prompt photon sources is difficult experimentally, but fragmentation can be suppressed by selecting "isolated photons". For a photon to be considered isolated, the sum of the transverse energies or transverse momenta of the particles produced in a cone around the photon must be smaller than some threshold – a selection that can be done both in the experimental measurement and theoretical calculations. An isolation requirement also helps to reduce the background of decay photons, since hadrons that can decay to photons are often produced in jet fragmentation.



D D'Enterria/ALICE Collab.

Fig. 1. *World compilation of the isolated-photon cross-section at midrapidity, scaled by* $(\sqrt{s})^n$ *to approximately reveal the gluon PDF.* $n = 4.5$.

The ALICE collaboration now reports the measurement of the differential cross-section for isolated photons in proton–proton collisions at $\sqrt{s} = 13$ TeV at midrapidity. The photon measurement is performed by the electromagnetic calorimeter, and the isolated photons are selected by combining with the data from the central inner tracking system and time-projection chamber, requiring that the summed p_T of the charged particles in a cone of angular radius 0.4 radians centred on the photon candidate be smaller than 1.5 GeV/c. The isolated photon cross-sections are obtained within the transverse momentum range from 7 to 200 GeV/c, corresponding to $1.1 \times 10^{-3} < x_T < 30.8 \times 10^{-3}$.

Figure 1 shows the new ALICE results alongside those from ATLAS, CMS and prior measurements in proton–proton and proton–antiproton collisions at lower values of $\sqrt{s}$. The figure spans more than 15 orders of magnitude on the y-axis, representing the cross-section, over a wide range of x_T. The present measurement probes the smallest Bjorken x with isolated photons at midrapidity to date. The experimental data points show an agreement between all the measurements when scaled with the collision energy to the power $n = 4.5$. Such a scaling is designed to cancel the predicted $1/(p_T)^n$ dependence of partonic $2 \rightarrow 2$ scattering cross-sections in perturbative QCD and reveal insights into the gluon PDF (see p31).

This measurement will help to constrain the gluon PDF and will play a crucial role in exploring medium-induced modifications of hard probes in nucleus–nucleus collisions.

Further reading

ALICE Collab. 2024 arXiv:2407.01165.

FIELD NOTES

Reports from events, conferences and meetings

MUON COOLING DEMONSTRATOR WORKSHOP

Muon cooling kickoff at Fermilab

More than 100 accelerator scientists, engineers and particle physicists gathered in person and remotely at Fermilab from 30 October to 1 November for the first of a new series of workshops to discuss the future of beam-cooling technology for a muon collider. High-energy muon colliders offer a unique combination of discovery potential and precision. Unlike protons, muons are point-like particles that can achieve comparable physics outcomes at lower centre-of-mass energies. The large mass of the muon also suppresses synchrotron radiation, making muon colliders promising candidates for exploration at the energy frontier.

Fermilab

Demonstrably cool *Participants of the 2024 Muon Cooling Demonstrator Workshop at Fermilab.*

The International Muon Collider Collaboration (IMCC), supported by the EU MuCol study, is working to assess the potential of a muon collider as a future facility, along with the R&D needed to make it a reality. European engagement in this effort crystalised following the 2020 update to the European Strategy for Particle Physics (ESPPU), which identified the development of bright muon beams as a high-priority initiative. Worldwide interest in a muon collider is quickly growing: the 2023 Particle Physics Project Prioritization Panel (P5) recently identified it as an important future possibility for the US particle-physics community; Japanese colleagues have proposed a muon-collider concept, muTRISTAN (*CERN Courier* July/August 2024 p8); and Chinese colleagues have actively contributed to IMCC efforts as collaboration members.

Lighting the way

The workshop focused on reviewing the scope and design progress of a muon-cooling demonstrator facility, identifying potential host sites and timelines, and exploring science programmes that could be developed alongside it. Diktys Stratakis (Fermilab) began by reviewing the requirements and challenges of muon cooling. Delivering a high-brightness muon beam will be essential to achieving the luminosity needed for a muon collider. The technique proposed for this is ionisation cooling, wherein the phase-space volume of the muon beam decreases as it traverses a sequence of cells, each containing an energy-absorbing material and accelerating radiofrequency (RF) cavities.

Worldwide interest in a muon collider is quickly growing

Roberto Losito (CERN) called for a careful balance between ambition and practicality – the programme must be executed in a timely way if a muon collider is to be a viable next-generation facility. The Muon Cooling Demonstrator programme was conceived to prove that this technology can be developed, built and reliably operated. This is a critical step for any muon-collider programme, as highlighted in the ESPPU–LDG Accelerator R&D Roadmap published in 2022. The plan is to pursue a staged approach, starting with the development of the magnet, RF and absorber technology, and demonstrating the robust operation of high-gradient RF cavities in high magnetic fields. The components will then be integrated into a prototype cooling cell. The programme will conclude with a demonstration of the operation of a multi-cell cooling system with a beam, building on the cooling proof of principle made by the Muon Ionisation Cooling Experiment.

Chris Rogers (STFC RAL) summarised an emerging consensus that it is critical to demonstrate the reliable operation of a cooling lattice formed of multiple cells. While the technological complexity of the cooling-cell prototype will undergo further review, the preliminary choice presents a moderately challenging performance that could be achieved within five to seven years with reasonable investment. The target cooling performance of a whole cooling lattice remains to be established and depends on future funding levels. However, delegates agreed that a timely demonstration is more important than an ambitious cooling target.

The workshop also provided an opportunity to assess progress in designing the cooling-cell prototype. Given that the muon beam originates from hadron decays and is initially the size of a watermelon, solenoid magnets were chosen as they can contain large beams in a compact lattice and provide focusing in both horizontal and vertical planes simultaneously. Marco Statera (INFN LASA) presented preliminary solutions for the solenoid coil configuration based on high-temperature superconductors operating at 20 K: the challenge is to deliver the target magnetic field profile given axial forces, coil stresses and compact integration.

In ionisation cooling, low-Z absorbers are used to reduce the transverse momenta of the muons while keeping the multiple scattering at manageable levels. Candidate materials are lithium hydride and liquid hydrogen. Chris Rogers discussed the need to test absorbers and containment windows at the highest intensities. The potential for performance tests using muons or intensity tests using another particle species such as protons was considered to verify understanding of the collective interaction between the beam and the absorber. RF cavities are ▷

required to replace longitudinal energy lost in the absorbers. Dario Giove (INFN LASA) introduced the prototype of an RF structure based on three coupled 704 MHz cavities and presented a proposal to use existing INFN capabilities to carry out a test programme for materials and cavities in magnetic fields. The use of cavity windows was also discussed, as it would enable greater accelerating gradients, though at the cost of beam degradation, increased thermal loads and possible cavity detuning. The first steps in integrating these latest hardware designs into a compact cooling cell were presented by Lucio Rossi (INFN LASA and UMIL). Future work needs to address the management of the axial forces and cryogenic heat loads, Rossi observed.

Many institutes presented a strong interest in contributing to the programme, both in the hardware R&D and hosting the eventual demonstrator. The final sessions of the workshop focused on potential host laboratories.

At CERN, two potential sites were discussed, with ongoing studies focusing on the TT7 tunnel, where a moderate-power 10 kW proton beam from the Proton Synchrotron could be used for muon production. Preliminary beam physics studies of muon beam production and transport are already underway. Lukasz Krzempek (CERN) and Paul Jurj (Imperial College London) presented the first integration and beam-physics studies of the demonstrator facility in the TT7 tunnel, highlighting civil engineering and beamline design requirements, logistical challenges and safety considerations, finding no apparent showstoppers.

Jeff Eldred (Fermilab) gave an overview of Fermilab’s broad range of candidate sites and proton-beam energies. While further feasibility studies are required, Eldred highlighted that using 8 GeV protons from the Booster is an attractive option due to the favourable existing infrastructure and its alignment with Fermilab’s muon-collider scenario, which envisions a proton driver based on the same Booster proton energy.

The event underscored the critical need for sustained innovation, timely implementation and global cooperation

The Fermilab workshop represented a significant milestone in advancing the Muon Cooling Demonstrator, highlighting enthusiasm from the US community to join forces with the IMCC and growing interest in Asia. As Mark Palmer (BNL) observed in his closing remarks, the event underscored the critical need for sustained innovation, timely implementation and global cooperation to make the muon collider a reality.

Paul-Bogdan Jurj *Imperial College and*
Chris Rogers *STFC RAL.*

IMPLICATIONS OF LHCb MEASUREMENTS AND FUTURE PROSPECTS

The B’s Ke^+e^-s

The Implications of LHCb measurements and future prospects workshop series drew together more than 200 theorists and experimentalists from across the world to CERN from 23 to 25 October 2024. Patrick Koppenburg (Nikhef) began the meeting by looking back 10 years, when three and four sigma anomalies abounded: the inclusive/exclusive puzzles; the illuminatingly named P'_5 observable; and the lepton-universality ratios for rare B decays. While LHCb measurements have mostly eliminated the anomalies seen in the lepton-universality ratios, many of the other anomalies persist – most notably, the corresponding branching fractions for rare B-meson decays still appear to be suppressed significantly below Standard Model (SM) theory predictions. Sara Celani (Heidelberg) reinforced this picture with new results for $B_s \to \phi\mu^+\mu^-$ and $B_s \to \phi e^+e^-$, showing the continued importance of new-physics searches in these modes.


M Brice/CERN-PHOTO-202403-050-12

The bee’s knees *The view from the LHCb cavern.*

Changing flavour

The discussion on rare B decays continued in the session on flavour-changing neutral-currents. With new lattice-QCD results pinning down short-distance local hadronic contributions, the discussion focused on understanding the long-distance contributions arising from hadronic resonances and charm rescattering. Arianna Tinari (Zurich) and Martin Hoferichter (Bern) judged the latter not to be dramatic in magnitude. Lakshan Madhan (Cambridge) presented a new amplitude analysis in which the long and short-distance contributions are separated via the kinematic dependence of the decay amplitudes. New theoretical analyses of the nonlocal form factors for $B \to K^{(*)}\mu^+\mu^-$ and $B \to K^{(*)}e^+e^-$ were representative of the workshop as a whole: truly the bee’s knees.

Another challenge to accurate theory predictions for rare decays, the widths of vector final states, snuck its way into the flavour-changing charged-currents session, where Luka Leskovec (Ljubljana) presented a comprehensive overview of lattice methods for decays to resonances. Leskovec’s optimistic outlook for semileptonic decays with two mesons in the final state stood in contrast to prospects for applying lattice methods to D–$\bar{D}$ mixing: such studies are currently limited to the SU(3)-flavour symmetric point of equal light-quark masses, explained Felix Erben (CERN), though he offered a glimmer of hope in the form of spectral reconstruction methods currently under development.

LHCb’s beauty and charm physics programme reported substantial progress. Novel techniques have been implemented in the most recent CP-violation studies, potentially leading to an impressive uncertainty of just 1° in future measurements of the CKM angle gamma. LHCb has recently placed a special emphasis on beauty and charm baryons, where the experiment offers unique capabilities to perform many interesting measurements ranging from CP violation to searches for very rare decays and their form factors. Going from three quarks to four and five, the spectroscopy session illustrated the rich and complex debate around tetraquark and pentaquark states with a big open discussion on the underlying structure of the 20 or so discovered at LHCb: which are bound states of quarks and which are simply meson molecules? (*CERN Courier* November/December 2024 p26 and p33.)

LHCb’s ability to do unique physics was further highlighted in the QCD, electroweak (EW) and exotica session, where the collaboration has shown the most recent publicly available measurement of the weak-mixing angle in conjunction with W/Z-boson production cross-sections and other EW observables. LHCb have put an emphasis on combined QCD + QED and effective-field-theory calculations, and the interplay between EW precision observables and new-physics effects in couplings to the third generation. By studying phase space inaccessible to any other experiment, a study of hypothetical dark photons decaying to electrons showed the LHCb experiment to be a unique environment for direct searches for long-lived and low-mass particles.

Parallel to Implications 2024, the inaugural LHCb Open Data and Ntuple Wizard Workshop, took place on 22 October as a satellite event, providing theorists and phenomenologists with a first look at a novel software application for on-demand access to custom ntuples from the experiment’s open data. The LHCb Ntupling Service will offer a step-by-step wizard for requesting custom ntuples and a dashboard to monitor the status of requests, communicate with the LHCb open data team and retrieve data. The beta version was released at the workshop in advance of the anticipated public release of the application in 2025, which promises open access to LHCb’s Run 2 dataset for the first time.

A recurring satellite event features lectures by theorists on topics following LHCb’s scientific output. This year, Simon Kuberski (CERN) and Saša Prelovšek (Ljubljana) took the audience on a guided tour through lattice QCD and spectroscopy.

Attendees left the workshop with a fresh perspective

With LHCb’s integrated luminosity in 2024 exceeding all previous years combined, excitement was heightened. Attendees left the workshop with a fresh perspective on how to approach the challenges faced by our community.

Judd Harrison *Glasgow and*
Miguel Ramos Pernas *Warwick.*

IUPAP GENERAL ASSEMBLY

Emphasising the free circulation of scientists

Physics is a universal language that unites scientists worldwide. No event illustrates this more vividly than the general assembly of the International Union of Pure and Applied Physics (IUPAP). The 33rd assembly convened 100 delegates representing territories around the world in Haikou, China, from 10 to 14 October 2024. Amid today’s polarised global landscape, one clear commitment emerged: to uphold the universality of science and ensure the free movement of scientists.


Chinese Physical Society

General assembly *The International Union of Pure and Applied Physics met in Haikou, China.*

IUPAP was established in 1922 in the aftermath of World War I to coordinate international efforts in physics. Its logo is recognisable from conferences and proceedings, but its mission is less widely understood. IUPAP is the only worldwide organisation dedicated to the advancement of all fields of physics. Its goals include promoting global development and cooperation in physics by sponsoring international meetings; strengthening physics education, especially in developing countries; increasing diversity and inclusion in physics; advancing the participation and recognition of women and of people from under-represented groups; enhancing the visibility of early-career talents; and promoting international agreements on symbols, units, nomenclature and standards. At the 33rd assembly, 300 physicists were elected to the executive council and specialised commissions for a period of three years.

Global scientific initiatives were highlighted, including the International Year of Quantum Science and Technology (IYQ2025) and the International Decade on Science for Sustainable Development (IDSSD) from 2024 to 2033, which was adopted by the United Nations General Assembly in August 2023. A key session addressed the importance of industry partnerships, with delegates exploring strategies to engage companies in IYQ2025 and IDSSD to further IUPAP’s mission of using physics to drive societal progress. Nobel laureate Giorgio Parisi discussed the role of physics in promoting a sustainable future, and public lectures by fellow laureates Barry Barish, Takaaki Kajita and Samuel Ting filled the 1820-seat Oriental Universal Theater with enthusiastic students.

A key focus of the meeting was visa-related issues affecting international conferences. Delegates reaffirmed the union’s commitment to scientists’ freedom of movement. IUPAP stands against any discrimination in physics and will continue to sponsor events only in locations that uphold this value – a stance that is orthogonal to the policy of countries imposing sanctions on scientists affiliated with specific institutions.

A joint session with the fall meeting of the Chinese Physical Society celebrated the 25th anniversary of the IUPAP working group “Women in Physics” and emphasised diversity, equity and inclusion in the field. Since 2002, IUPAP has established precise guidelines for the sponsorship of conferences to ensure that women are fairly represented among participants, speakers and committee members, and has actively monitored the data ever since. This has contributed to a significant change in the participation of women in IUPAP-sponsored conferences. IUPAP is now building on this still-necessary work on gender by focusing on discrimination on the grounds of disability and ethnicity.

The closing ceremony brought together the themes of continuity and change. Incoming president Silvina Ponce Dawson (University of Buenos Aires) and president-designate Sunil Gupta (Tata Institute) outlined their joint commitment to maintaining an open dialogue among all physicists in an increasingly fragmented world, and to promoting physics as an essential tool for development and sustainability. Outgoing leaders Michel Spiro (CNRS) and Bruce McKellar (University of Melbourne) were honoured for their contributions, and the ceremonial handover symbolised a smooth transition of leadership.

As the general assembly concluded, there was a palpable sense of momentum. From strategic modernisation to deeper engagement with global issues, IUPAP is well-positioned to make physics more relevant and accessible. The resounding message was one of unity and purpose: the physics community is dedicated to leveraging science for a brighter, more sustainable future.

Monica Pepe Altarelli *INFN–LNF and*
Jens Vigen *CERN.*

CERNCOURIER
VOLUME 65 NUMBER 1 JANUARY/FEBRUARY 2025

UMBRELLA KICKOFF

AI treatments for stroke survivors


UMBRELLA

Stroke prevention *The UMBRELLA project kicked off in Barcelona last October.*

Data on strokes is plentiful but fragmented, making it difficult to exploit in data-driven treatment strategies. The toolbox of the high-energy physicist is well adapted to the task. To amplify CERN's societal contributions through technological innovation, the Unleashing a Comprehensive, Holistic and Patient-Centric Stroke Management for a Better, Rapid, Advanced and Personalised Stroke Diagnosis, Treatment and Outcome Prediction (UMBRELLA) project – co-led by Vall d'Hebron Research Institute and Siemens Healthineers – was officially launched on 1 October 2024. The kickoff meeting in Barcelona, Spain, convened more than 20 partners, including Philips, AstraZeneca, KU Leuven and EATRIS. Backed by nearly €27 million from the EU's Innovative Health Initiative and industry collaborators, the project aims to transform stroke care across Europe.

The meeting highlighted the urgent need to address stroke as a pressing health challenge in Europe. Each year, more than one million acute stroke cases occur in Europe, with nearly 10 million survivors facing long-term consequences. In 2017, the economic burden of stroke treatments was estimated to be €60 billion – a figure that continues to grow. UMBRELLA's partners outlined their collective ambition to translate a vast and fragmented stroke data set into actionable care innovations through standardisation and integration.

UMBRELLA will utilise advanced digital technologies to develop AI-powered predictive models for stroke management. By standardising real-world stroke data and leveraging tools like imaging technologies, wearable devices and virtual rehabilitation platforms, UMBRELLA aims to refine every stage of care – from diagnosis to recovery. Based on post-stroke data, AI-driven insights will empower clinicians to uncover root causes of strokes, improve treatment precision and predict patient outcomes, reshaping how stroke care is delivered.

Central to this effort is the integration of CERN's federated-learning platform, CAFEIN. A decentralised approach to training machine-learning algorithms without exchanging data, it was initiated thanks to seed funding from CERN's knowledge transfer budget for the benefit of medical applications: now CAFEIN promises to enhance diagnosis, treatment and prevention strategies for stroke victims, ultimately saving countless lives. A main topic of the kickoff meeting was the development of the "U-platform" – a federated data ecosystem co-designed by Siemens Healthineers and CERN. Based on CAFEIN, the infrastructure will enable the secure and privacy preserving training of advanced AI algorithms for personalised stroke diagnostics, risk prediction and treatment decisions without sharing sensitive patient data between institutions. Building on CERN's expertise, including its success in federated AI modelling for brain pathologies under the EU TRUSTroke project, the CAFEIN team is poised to handle the increasing complexity and scale of data sets required by UMBRELLA.

Beyond technological advancements, the UMBRELLA consortium discussed a plan to establish standardised protocols for acute stroke management, with an emphasis on integrating these protocols into European healthcare guidelines. By improving data collection and facilitating outcome predictions, these standards will particularly benefit patients in remote and underserved regions. The project also aims to advance research into the causes of strokes, a quarter of which remain undetermined – a statistic UMBRELLA seeks to change.

This ambitious initiative not only showcases CERN's role in pioneering federated-learning technologies but also underscores the broader societal benefits brought by basic science. By pushing technologies beyond the state-of-the-art, CERN and other particle-physics laboratories have fuelled innovations that have an impact on our everyday lives. As UMBRELLA begins its journey, its success holds the potential to redefine stroke care, delivering life-saving advancements to millions and paving the way for a healthier, more equitable future.

Amedeo Habsburg *and* **Luigi Serio** *CERN.*

EFFICIENT RF SOURCES

Unprecedented progress in energy-efficient RF

Forty-five experts from industry and academia met in the magnificent city of Toledo, Spain from 23 to 25 September 2024 for the second workshop on efficient RF sources. Part of the I.FAST initiative on sustainable concepts and technologies (*CERN Courier* July/August 2024 p20), the event focused on recent advances in energy-efficient technology for RF sources essential to accelerators. Progress in the last two years has been unprecedented, with new initiatives and accomplishments around the world fuelled by the ambitious goals of new, high-energy particle-physics projects.

Out of more than 30 presentations, a significant number featured pulsed, high-peak-power RF sources working at frequencies above 3 GHz in the S, C and X bands. These involve high-efficiency klystrons that are being designed, built and tested for the KEK e^-/e^+ Injector, the new EuPRAXIA@SPARC_LAB linac, the CLIC testing facilities, muon collider R&D, the CEPC injector linac and the C^3 project. Reported increases in beam-to-RF power efficiency range from 15 percentage points for the retrofit prototype for CLIC to more than 25 points (expected) for a new greenfield ▷ klystron design that can be used across most new projects.


N Catalan Lasheras

Industry meets academia *Experts discussed energy-efficient RF in beautiful Toledo.*

A very dynamic area for R&D is the search of efficient sources for the continuous wave (CW) and long-pulse RF needed for circular accelerators. Typically working in the L-band, existing devices deliver less than 3 MW in peak power. Solid-state amplifiers, inductive output tubes, klystrons, magnetrons, triodes and exotic newly rediscovered vacuum tubes called "tristrons" compete in this arena. Successful prototypes have been built for the High-Luminosity LHC and CEPC with power efficiency gains of 10 to 20 points. In the case of the LHC, this will allow 15% more power without an impact on the electricity bill; in the case of a circular Higgs factory, this will allow a 30% reduction. CERN and SLAC are also investigating very-high-efficiency vacuum tubes for the Future Circular Collider with a potential reduction of close to 50% on the final electricity bill. A collaboration between academia and industry would certainly be required to bring this exciting new technology to light.

Besides the astounding advances in vacuum-tube technology, solid-state amplifiers based on cheap transistors are undergoing a major transformation thanks to the adoption of gallium-nitride technology. Commercial amplifiers are now capable of delivering kilowatts of power at low duty cycles with a power efficiency of 80%, while Uppsala University and the European Spallation Source have demonstrated the same efficiency for combined systems working in CW.

The search for energy efficiency does not stop at designing and building more efficient RF sources. All aspects of operation, power combination and using permanent magnets and efficient modulators need to be folded in, as described by many concrete examples during the workshop. The field is thriving.

Nuria Catalan Lasheras *CERN.*

EOSC SYMPOSIUM

Open-science cloud takes shape in Berlin

Findable. Accessible. Interoperable. Reusable. That's the dream scenario for scientific data and tools. The European Open Science Cloud (EOSC) is a pan-European initiative to develop a web of "FAIR" data services across all scientific fields. EOSC's vision is to put in place a system for researchers in Europe to store, share, process, analyse and reuse research outputs such as data, publications and software across disciplines and borders.

EOSC's sixth symposium attracted 450 delegates to Berlin from 21 to 23 October 2024, with a further 900 participating online. Since its launch in 2017, EOSC activities have focused on conceptualisation, prototyping and planning. In order to develop a trusted federation of research data and services for research and innovation, EOSC is being deployed as a network of nodes. With the launch during the symposium of the EOSC EU node, this year marked a transition from design to deployment.


A Grauman

Liftoff *The European Open Science Cloud Symposium reported the launch of the initiative's first node.*

While EOSC is a flagship science initiative of the European Commission, FAIR concerns researchers and stakeholders globally. Via the multiple projects under the wings of EOSC that collaborate with software and data institutes around the world, a pan-European effort can be made to ensure a research landscape that encourages knowledge sharing while recognising work and training the next generation in best practices in research. The EU node – funded by the European Commission, and the first to be implemented – will serve as a reference for roughly 10 additional nodes to be deployed in a first wave, with more to follow. They are accessible using any institutional credentials based on GÉANT's MyAccess or with an EU login. A first operational implementation of the EOSC Federation is expected by the end of 2025.

A thematic focus of this year's symposium was the need for clear guidelines on the adaption of FAIR governance for artificial intelligence (AI), which relies on the accessibility of large and high-quality datasets. It is often the case that AI models are trained with synthetic data, large-scale simulations and first-principles mathematical models, although these may only provide an incomplete description of complex and highly nonlinear real-world phenomena. Once AI models are calibrated against experimental data, their predictions become increasingly accurate. Adopting FAIR principles for the production, collection and curation of scientific datasets will streamline the design, training, validation and testing of AI models (see, for example, Y Chen *et al.* 2021 arXiv:2108.02214).

EOSC includes five science clusters, from natural sciences to social sciences, with a dedicated cluster for particle physics and astronomy called ESCAPE: the European Science Cluster of Astronomy and Particle Physics. The future deployment of the ESCAPE Virtual Research Environment across multiple nodes will provide users with tools to bring together diverse experimental results, for example, in the search for evidence of dark matter, and to perform new analyses incorporating data from complementary searches.

Bob Jones *and* **Sanje Fenkart** *CERN.*

CERNCOURIER
VOLUME 65 NUMBER 1 JANUARY/FEBRUARY 2025

HIGH PRECISION FOR HARD PROCESSES

Rapid developments in precision predictions

L Magnea

HP2 participants *High Precision for Hard Processes 2024 took place in Turin, Italy.*

Achieving a theoretical uncertainty of only a few per cent in the measurement of physical observables is a vastly challenging task in the complex environment of hadronic collisions. To keep pace with experimental observations at the LHC and elsewhere, precision computing has had to develop rapidly in recent years – efforts that have been monitored and driven by the biennial High Precision for Hard Processes (HP2) conference for almost two decades now. The latest edition attracted 120 participants to the University of Torino from 10 to 13 September 2024.

All speakers addressed the same basic question: how can we achieve the most precise theoretical description for a wide variety of scattering processes at colliders?

The recipe for precise prediction involves many ingredients, so the talks in Torino probed several research directions. Advanced methods for the calculation of scattering amplitudes were discussed, among others, by Stephen Jones (IPPP Durham). These methods can be applied to detailed high-order phenomenological calculations for QCD, electroweak processes and BSM physics, as illustrated by Ramona Groeber (Padua) and Eleni Vryonidou (Manchester). Progress in parton showers – a crucial tool to bridge amplitude calculations and experimental results – was presented by Silvia Ferrario Ravasio (CERN). Dedicated methods to deal with the delicate issue of infrared divergences in high-order cross-section calculations were reviewed by Chiara Signorile-Signorile (Max Planck Institute, Munich).

The Torino conference was dedicated to the memory of Stefano Catani, a towering figure in the field of high-energy physics, who suddenly passed away at the beginning of this year. Starting from the early 1980s, and for the whole of his career, Catani made groundbreaking contributions in every facet of HP2. He was an inspiration to a whole generation of physicists working in high-energy phenomenology. We remember him as a generous and kind person, and a scientist of great rigour and vision. He will be sorely missed.

Leonardo Vernazza *INFN Torino and* **Lorenzo Magnea** *University of Torino.*

HIGGS HUNTING 2024

Painting Higgs' portrait in Paris

L Fayard

Higgs hunters *At the Laboratoire Astroparticule et Cosmologie in Paris.*

The 14th Higgs Hunting workshop took place from 23 to 25 September 2024 at Orsay's IJCLab and Paris's Laboratoire Astroparticule et Cosmologie. More than 100 participants joined lively discussions to decipher the latest developments in theory and results from the ATLAS and CMS experiments.

The portrait of the Higgs boson painted by experimental data is becoming more and more precise. Many new Run 2 and first Run 3 results have developed the picture this year. Highlights included the latest di-Higgs combinations with cross-section upper limits reaching down to 2.5 times the Standard Model (SM) expectations. A few excesses seen in various analyses were also discussed. The CMS collaboration reported a brand new excess of top–antitop events near the top–antitop production threshold, with a local significance of more than 5σ above the background described by perturbative quantum chromodynamics (QCD) only, that could be due to a pseudoscalar top–antitop bound state. A new W-boson mass measurement by the CMS collaboration – a subject deeply connected to electroweak symmetry breaking – was also presented, reporting a value consistent with the SM prediction with a very accurate precision of 9.9 MeV (*CERN Courier* November/December 2024 p7).

Parton shower event generators were in the spotlight. Historical talks by Torbjörn Sjöstrand (Lund University) and Bryan Webber (University of Cambridge) described the evolution of the PYTHIA and HERWIG generators, the crucial role they played in the discovery of the Higgs boson, and the role they now play in the LHC's physics programme. Differences in the modelling of the parton-shower systematics by the ATLAS and CMS collaborations led to lively discussions!

The vision talk was given by Lance Dixon (SLAC) about the reconstruction of scattering amplitudes directly from analytic properties, as a complementary approach to Lagrangians and Feynman diagrams. Oliver Bruning (CERN) conveyed the message that the HL-LHC accelerator project is well on track, and Patricia McBride (Fermilab) reached a similar conclusion regarding ATLAS and CMS's Phase-2 upgrades, enjoining new and young people to join the effort, to ensure they are ready and commissioned for the start of Run 4.

The next Higgs Hunting workshop will be held in Orsay and Paris from 15 to 17 July 2025, following EPS-HEP in Marseille from 7 to 11 July.

Nicolas Berger *LAPP,* **Luca Cadamuro** *IJCLab,* **Anne-Catherine Le Bihan** *IPHC and* **Thomas Strebler** *CPPM.*

The value of being messy

Claire Malone argues that science communicators should not stray too far into public-relations territory.

C Malone

Claire Malone *is a science journalist and communicator.*

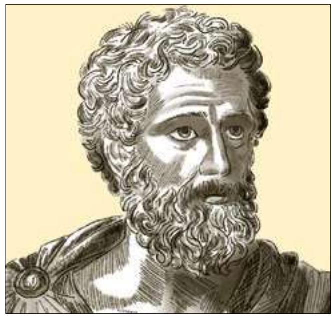
The line between science communication and public relations has become increasingly blurred. On one side, scientific press officers highlight institutional success, secure funding and showcase breakthrough discoveries. On the other, science communicators and journalists present scientific findings in a way that educates and entertains readers – acknowledging both the triumphs and the inherent uncertainties of the scientific process.

The core difference between these approaches lies in how they handle the inevitable messiness of science. Science isn't a smooth, linear path of consistent triumphs; it's an uncertain, trial-and-error journey. This uncertainty, and our willingness to discuss it openly, is what distinguishes authentic science communication from a polished public relations (PR) pitch. By necessity, PR often strives to present a neat narrative, free of controversy or doubt, but this risks creating a distorted perception of what science actually is.

Finding your voice

Take, for example, the situation in particle physics. Experiments probing the fundamental laws of physics are often critiqued in the press for their hefty price tags – particularly when people are eager to see resources directed towards solving global crises like climate change or preventing future pandemics. When researchers and science communicators are finding their voice, a pressing question is how much messiness to communicate in uncertain times.

After completing my PhD as part of the ATLAS collaboration, I became a science journalist and communicator, connecting audiences across Europe and America with the joy of learning about fundamental physics. After a recent talk at the Royal Institution in London, in which I explained how ATLAS measures fundamental particles, I received an email from a colleague. The only question the talk prompted him to ask was about the safety of colliding protons, aiming to create undiscovered particles. This reaction reflects how scientific misinformation – such as the idea that experiments at CERN could endanger the planet – can be persistent and difficult to eradicate.



A Epshtein

Evolving understanding *From Democritus to the Standard Model, scientific progress has not been serene.*

In response to such criticisms and concerns, I have argued many times for the value of fundamental physics research, often highlighting the vast number of technological advancements it enables, from touch screens to healthcare advances. However, we must be wary not to only rely on this PR tactic of stressing the tangible benefits of research, as it can sometimes sidestep the uncertainties and iterative nature of scientific investigation, presenting an oversimplified version of scientific progress.

This PR-driven approach risks undermining public understanding and trust in science in the long run. When science is framed solely as a series of grand successes without any setbacks, people may become confused or disillusioned when they inevitably encounter controversies or failures. Instead, this is where honest science communication shines – admitting that our understanding evolves, that we make mistakes and that uncertainties are an integral part of the process.

Our evolving understanding of particle physics is a perfect illustration of this. From Democritus' concept of "indivisible atoms" to the development of the Standard Model, every new discovery has refined or even overhauled our previous understanding. This is the essence of science – always refining, never perfect – and it's exactly what we should be communicating to the public.

Acknowledging the existence of different scientific perspectives helps the public understand that science is a dynamic process

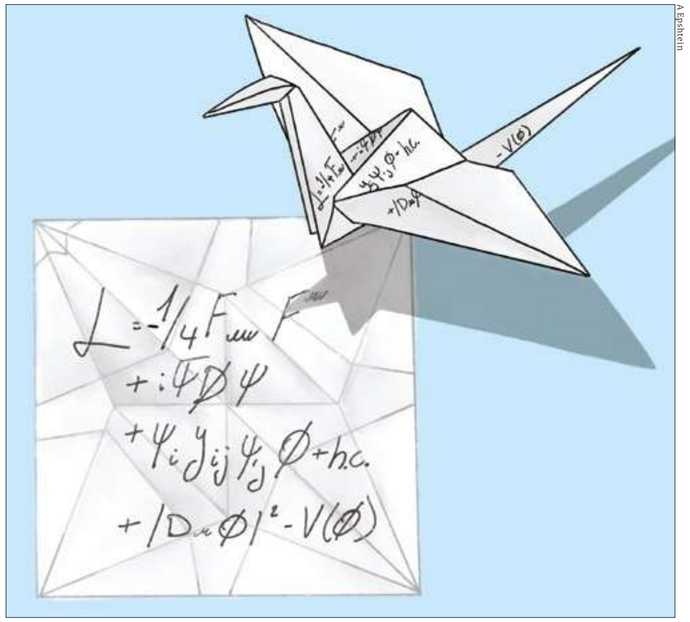
Embracing this messiness doesn't necessarily reduce public trust. When presenting scientific results to the public, it's important to remember that uncertainty can take many forms, and how we communicate these forms can significantly affect credibility. Technical uncertainty – expressing complexity or incomplete information – often increases audience trust, as it communicates the real intricacies of scientific research. Conversely, consensus uncertainty – spotlighting disagreements or controversies among experts – can have a negative impact on credibility. When it comes to genuine disagreements among scientists, effectively communicating uncertainty to the public requires a thoughtful balance. Transparency is key: acknowledging the existence of different scientific perspectives helps the public understand that science is a dynamic process. Providing context about why disagreements exist, whether due to limited data or competing theoretical frameworks, also helps in making the uncertainty comprehensible.

Embrace errors

In other words, the next time you present your latest results on social media, don't shy away from including the error bars. And if you must have a public argument with a colleague about what the results mean, context is essential!

No one knows where the next breakthrough will come from or how it might solve the challenges we face. In an information ecosystem increasingly filled with misinformation, scientists and science communicators must help people understand the iterative, uncertain and evolving nature of science. As science communicators, we should be cautious not to stray too far into PR territory. Authentic communication doesn't mean glossing over uncertainties but rather embracing them as an essential part of the story. This way, the public can appreciate science not just as a collection of established facts, but as an ongoing, dynamic process – messy, yet ultimately satisfying.

HOW TO UNFOLD WITH AI



A Epshtein

Inspired by high-dimensional data and the ideals of open science, high-energy physicists are using artificial intelligence to reimagine the statistical technique of 'unfolding'.

All scientific measurements are affected by the limitations of measuring devices. To make a fair comparison between data and a scientific hypothesis, theoretical predictions must typically be smeared to approximate the known distortions of the detector. Data is then compared with theory at the level of the detector's response. This works well for targeted measurements, but the detector simulation must be reapplied to the underlying physics model for every new hypothesis.

The alternative is to try to remove detector distortions from the data, and compare with theoretical predictions at the level of the theory. Once detector effects have been "unfolded" from the data, analysts can test any number of hypotheses without having to resimulate or re-estimate detector effects – a huge advantage for open science and data preservation that allows comparisons between datasets from different detectors. Physicists without access to the smearing functions can only use unfolded data.

No simple task

But unfolding detector distortions is no simple task. If the mathematical problem is solved through a straightforward inversion, using linear algebra, noisy fluctuations are amplified, resulting in large uncertainties. Some sort of "regularisation" must be imposed to smooth the fluctuations, but algorithms vary substantively and none is preeminent. Their scope has remained limited for decades. No traditional algorithm is capable of reliably unfolding detector distortions from data relative to more than a few observables at a time.

In the past few years, a new technique has emerged. Rather than unfolding detector effects from only one or two observables, it can unfold detector effects from multiple observables in a high-dimensional space; and rather than unfolding detector effects from binned histograms, it unfolds detector effects from an unbinned distribution of events. This technique is inspired by both artificial-intelligence techniques and the uniquely sparse and high-dimensional data sets of the LHC.

Open-science unfolding
AI-based unfolding exploits the strengths of deep learning to remove detector-specific distortions without reducing the dimensionality of the data set.

An ill-posed problem

Unfolding is used in many fields. Astronomers unfold point-spread functions to reveal true sky distributions. Medical physicists unfold detector distortions from CT and MRI scans. Geophysicists use unfolding to infer the Earth's internal structure from seismic-wave data. Economists attempt to unfold the true distribution of opinions from incomplete survey samples. Engineers use deconvolution methods for noise reduction in signal processing. But in recent decades, no field has had a greater need to innovate unfolding techniques than high-energy physics, given its complex detectors, sparse datasets and stringent standards for statistical rigour.

In traditional unfolding algorithms, analysers first choose which quantity they are interested in measuring. An event generator then creates a histogram of the true values of this observable for a large sample of events in their detector. Next, a Monte Carlo simulation simulates the detector response, accounting for noise, background modelling, acceptance effects, reconstruction errors, misidentification errors and energy smearing. A matrix is constructed that transforms the histogram of the true values of the observable into the histogram of detector-level events. Finally, analysts "invert" the matrix and apply it to data, to unfold detector effects from the measurement.

At this point in the analysis, the ill-posed nature of the problem presents a major challenge. A simple matrix inversion seldom suffices as statistical noise produces large changes in the estimated input. Several algorithms have been proposed to regularise these fluctuations. Each comes with caveats and constraints, and there is no consensus on a single method that outperforms the rest (see "How to unfold traditionally" panel).

THE AUTHORS
Ben Nachman *and* **Mariel Pettee** *LBNL*, **Kyle Cormier** *University of Zurich and* **Sookhyun Lee** *University of Tennessee.*

While these approaches have been successfully applied to thousands of measurements at the LHC and beyond, they have limitations. Histogramming is an efficient way to describe the distributions of one or two observables, but the number of bins grows exponentially with the number of parameters, restricting the number of observables that can be simultaneously unfolded. When unfolding only a few observables, model dependence can creep in, for example due to acceptance effects, and if another scientist wants to change the bin sizes or measure a different observable, they will have to redo the entire process.

How to unfold traditionally

Diverse algorithms have been invented to unfold distortions from data, with none yet achieving preeminence.

- Developed by Soviet mathematician Andrey Tikhonov in the late 1940s, **Tikhonov regularisation** (TR) frames unfolding as a minimisation problem with a penalty term added to suppress fluctuations in the solution.
- In the 1950s, statistical mechanic Edwin Jaynes took inspiration from information theory to seek solutions with **maximum entropy**, seeking to minimise bias beyond the data constraints.
- Between the 1960s and the 1990s, high-energy physicists increasingly drew on the linear algebra of 19th-century mathematicians Eugenio Beltrami and Camille Jordan to develop **singular value decomposition** as a pragmatic way to suppress noisy fluctuations.
- In the 1990s, Giulio D'Agostini and other high-energy physicists developed **iterative Bayesian unfolding** (IBU) – a similar technique to Lucy–Richardson deconvolution, which was developed independently in astronomy in the 1970s. An explicitly probabilistic approach well suited to complex detectors, IBU may be considered a forerunner of the neural-network-based technique described in this article.

IBU and TR are the most widely-used approaches in high-energy physics today, with the RooUnfold tool started by Tim Adye serving countless analysts.

New possibilities

AI opens up new possibilities for unfolding particle-physics data. Choosing good parameterisations in a high-dimensional space is difficult for humans, and binning is a way to limit the number of degrees of freedom in the problem, making it more tractable. Machine learning (ML) offers flexibility due to the large number of parameters in a deep neural network. Dozens of observables can be unfolded at once, and unfolded datasets can be published as an unbinned collection of individual events that have been corrected for detector distortions as an ensemble.

One way to represent the result is as a set of simulated events with weights that encode information from the data. For example, if there are 10 times as many simulated events as real events, the average weight would be about 0.1, with the distribution of weights correcting the simulation to match reality, and errors on the weights reflecting the uncertainties inherent in the unfolding process. This approach gives maximum flexibility to future analysts, who can recombine them into any binning or combination they desire. The weights can be used to build histograms or compute statistics. The full covariance matrix can also be extracted from the weights, which is important for downstream fits.

But how do we know the unfolded values are capturing the truth, and not just "hallucinations" from the AI model?

An important validation step for these analyses are tests performed on synthetic data with a known answer. Analysts take new simulation models, different from the one being used for the primary analysis, and treat them as if they were real data. By unfolding these alternative simulations, researchers are able to compare their results to a known answer. If the biases are large, analysts will need to refine their methods to reduce the model-dependency. If the biases are small compared to the other uncertainties then this remaining difference can be added into the total uncertainty estimate, which is calculated in the traditional way using hundreds of simulations. In unfolding problems, the choice of regularisation method and strength always involves some tradeoff between bias and variance.

Just as unfolding in two dimensions instead of one with traditional methods can reduce model dependence by incorporating more aspects of the detector response, ML methods use the same underlying principle to include as much of the detector response as possible. Learning differences between data and simulation in high-dimensional spaces is the kind of task that ML excels at, and the results are competitive with established methods (see "Better performance" figure).

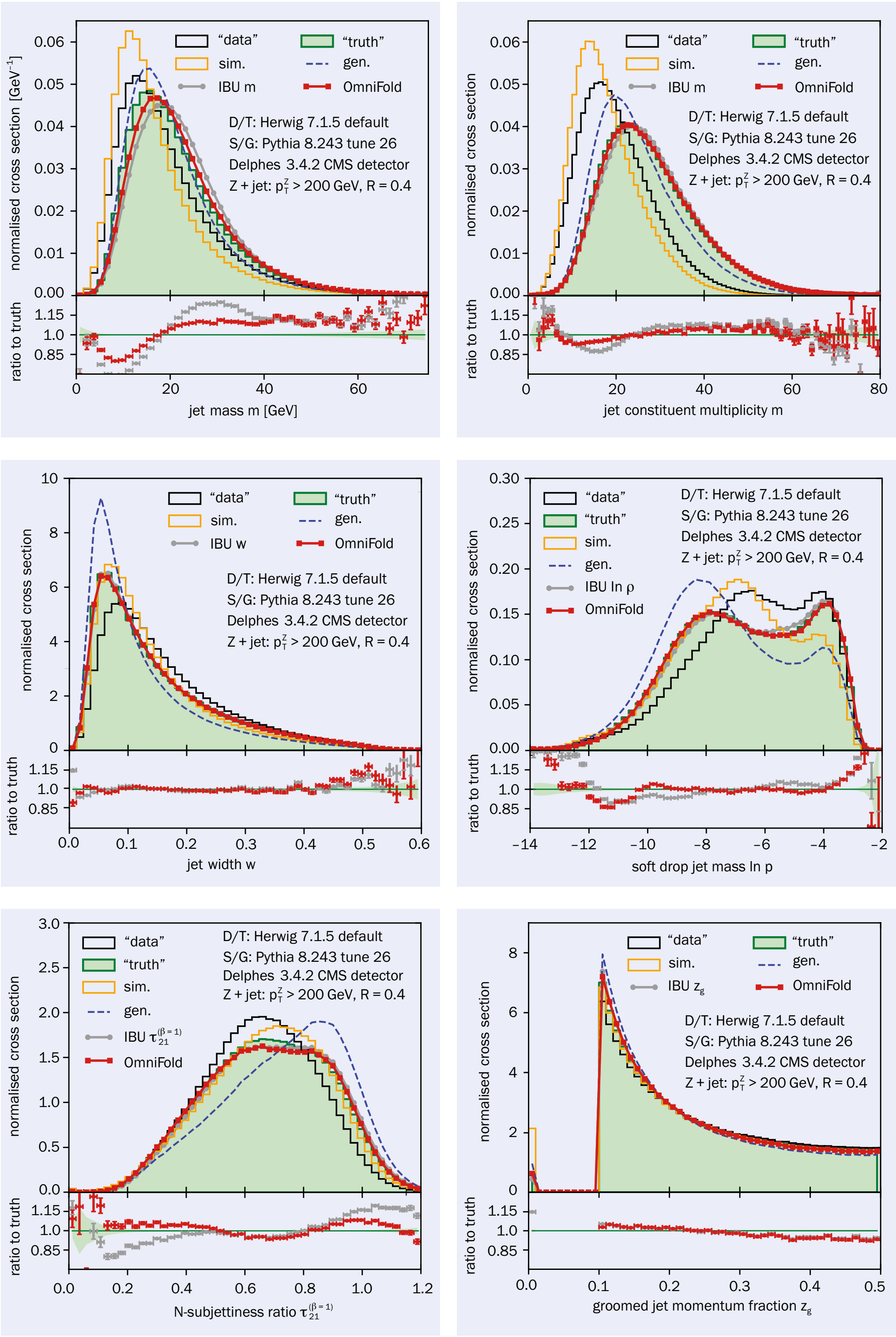
Neural learning

In the past few years, AI techniques have proven to be useful in practice, yielding publications from the LHC experiments, the H1 experiment at HERA and the STAR experiment at RHIC. The key idea underpinning the strategies used in each of these results is to use neural networks to learn a function that can reweight simulated events to look like data. The neural network is given a list of relevant features about an event such as the masses, energies and momenta of reconstructed objects, and trained to output the probability that it is from a Monte Carlo simulation or the data itself. Neural connections that reweight and combine the inputs across multiple layers are iteratively adjusted depending on the network's performance. The network thereby learns the relative densities of the simulation and data throughout phase space. The ratio of these densities is used to transform the simulated distribution into one that more closely resembles real events (see "OmniFold" figure).

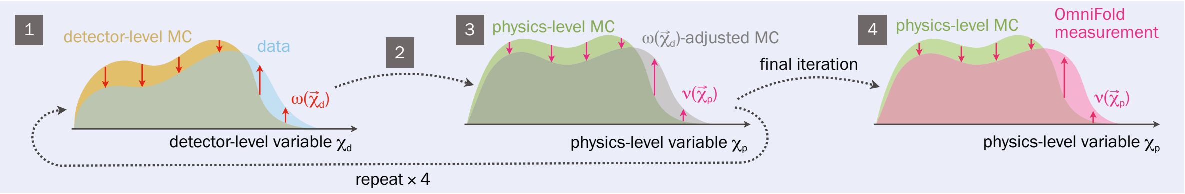
As this is a recently-developed technique, there are plenty of opportunities for new developments and improvements. These strategies are in principle capable of handling significant levels of background subtraction as well as acceptance and efficiency effects, but existing LHC measurements using AI-based unfolding generally have small backgrounds. And as with traditional methods, there is a risk in trying to estimate too many parameters from not

Machine learning offers flexibility due to the large number of parameters in a deep neural network

Better performance *The AI unfolding algorithm OmniFold (red) outperforms iterative Bayesian unfolding (IBU, grey) in unfolding synthetic data for six jet-substructure observables in a simulation of the CMS detector. Physics-level observables from the Herwig generator (green) are smeared with detector effects to generate the synthetic data (black). Both unfolding algorithms are then trained by physics-level (blue) and detector-level (yellow) events originating from the Pythia generator. OmniFold unfolds each observable simultaneously, while IBU must unfold each observable separately.*



A Andreassen et al. 2020 Phys. Rev. Lett. 124 182001



ATLAS Collab. 2024 arXiv:2405.20041

OmniFold *Illustration of AI unfolding using the OmniFold algorithm. Reconstructed events are reweighted to match the data, and the corresponding reweighting of Monte Carlo truth is inferred. The procedure iterates and the final reweighted Monte Carlo truth distribution serves as the unfolded measurement. This figure is based on a diagram in the ATLAS collaboration's recent paper in* Physical Review Letters *– the first analysis to be published unbinned, allowing readers to make their own derivative measurements.*

enough data. This is typically controlled by stopping the training of the neural network early, combining multiple trainings into a single result, and performing cross validations on different subsets of the data.

Beyond the "OmniFold" methods we are developing, an active community is also working on alternative techniques, including ones based on generative AI. Researchers are also considering creative new ways to use these unfolded results that aren't possible with traditional methods. One possibility in development is unfolding not just a selection of observables, but the full event. Another intriguing direction could be to generate new events with the corrections learnt by the network built-in. At present, the result of the unfolding is a reweighted set of simulated events, but once the neural network has been trained, its reweighting function could be used to simulate the unfolded sample from scratch, simplifying the output. ●

An active community is also working on alternative techniques

Further reading

A Andreassen *et al.* 2020 *Phys. Rev. Lett.* **124** 182001.
H1 Collab. 2023 *Phys. Lett. B* **844** 138101.
LHCb Collab. 2023 *Phys. Rev. D* **108** L031103.
CMS Collab. 2024 CMS-PAS-SMP-23-008.
ATLAS Collab. 2024 *Phys. Rev. Lett.* **133** 261803.

CERNCOURIER
Volume 65 Number 1 January/February 2025

TEAMBEST GLOBAL®
One World • One Source • The Best!
healthcare for everyone
TeamBest®
Your True Partner
www.teambest.com

Best™ Cyclotron Systems
A TEAMBEST GLOBAL COMPANY

Best™ medical international
A TEAMBEST GLOBAL COMPANY

Best Model B25p Cyclotron

Best Model 6-15 MeV Compact High Current/Variable Energy Proton Cyclotron

Best B 100p, BG 95p and B 11p Sub-Compact Self-Shielded Cyclotron with Optional Second Chemistry Module

Best Model B35ADP Alpha/Deuteron/Proton Cyclotron

Installation of B70 MeV Cyclotron at INFN, Legnaro, Italy.

Best Particle Therapy 400 MeV ion Rapid Cycling Medical Synchrotron (iRCMS)

NEW!
Best Model 200p Cyclotron—Variable Energy Proton Beam for Radiation Therapy
(patent pending)

Flash Therapy in 1975

Flash Therapy Now

Robotic Flash Therapy Linac System

X-Beam™ Robotic Radiosurgery System

X-Beam™ Image-Guided Multi-Energy Linac System

Best™ GammaBeam™ 300-100 CM Equinox™ Teletherapy System with Avanza 6D Patient Positioning Table

BE PART OF OUR TEAM

TBG is currently hiring talented engineers manufacturing/computer/software programmers, magnet physicists, scientists, and others. Please email Krish Suthanthiran at Krish@teambest.com or Jignasha Patel at Jignasha@teambest.com.

TBG Expansion Plans

TeamBest Global Companies (TBG), in partnership with Best Cure Foundation, plan to manufacture and establish 1000s of medical centers around the globe. These centers will include Best Cure Proactive, Preventive, Primary, Medical, Dental and Eye Care Wellness Centers, as well as treatment centers for cardiac, cancer, diabetes, and infectious diseases.

TBG Companies are expanding operations in the United States and India to meet the increasing demand for manufacturing advanced medical equipment such as cyclotrons, Linacs, MRI, CT, PET CT, X-ray, Ultrasound, and other technologies. The goal is to sell and provide these technologies globally as part of the Best Cure Global Healthcare Delivery.

TEAMBEST GLOBAL®
One World • One Source • The Best!
healthcare for everyone
TeamBest®
Your True Partner
www.teambest.com

Best Cyclotron Systems, Inc. | 3024 Topside Business Park Drive | Louisville, Tennessee 37777 USA
tel: 613 591 2100 866 792 8598 www.theratronics.com www.teambest.com
AFRICA | ASIA | EUROPE | LATIN AMERICA | MIDDLE EAST | NORTH AMERICA
*Certain products shown are not available for sale currently. TeamBest Global Companies ©2025

Best Medical International, Inc. | 7643 Fullerton Road | Springfield, VA 22153 USA
tel: 703 451 2378 800 336 4970 www.besttotalsolutions.com www.teambest.com
AFRICA | ASIA | EUROPE | LATIN AMERICA | MIDDLE EAST | NORTH AMERICA
*Certain products shown are not available for sale currently. TeamBest Global Companies ©2025

CERN AND ESA: A DECADE OF INNOVATION

Enrico Chesta, Véronique Ferlet-Cavrois and Markus Brugger highlight seven ways CERN and ESA are working together to further fundamental exploration and innovation in space technologies.

THE AUTHORS
Véronique Ferlet-Cavrois ESA;
Markus Brugger and **Enrico Chesta** CERN.

Particle accelerators and spacecraft both operate in harsh radiation environments, extreme temperatures and high vacuum. Each must process large amounts of data quickly and autonomously. Much can be gained from cooperation between scientists and engineers in each field.

Ten years ago, the European Space Agency (ESA) and CERN signed a bilateral cooperation agreement to share expertise and facilities. The goal was to expand the limits of human knowledge and keep Europe at the leading edge of progress, innovation and growth. A decade on, CERN and ESA have collaborated on projects ranging from cosmology and planetary exploration to Earth observation and human spaceflight, supporting new space-tech ventures and developing electronic systems, radiation-monitoring instruments and irradiation facilities.

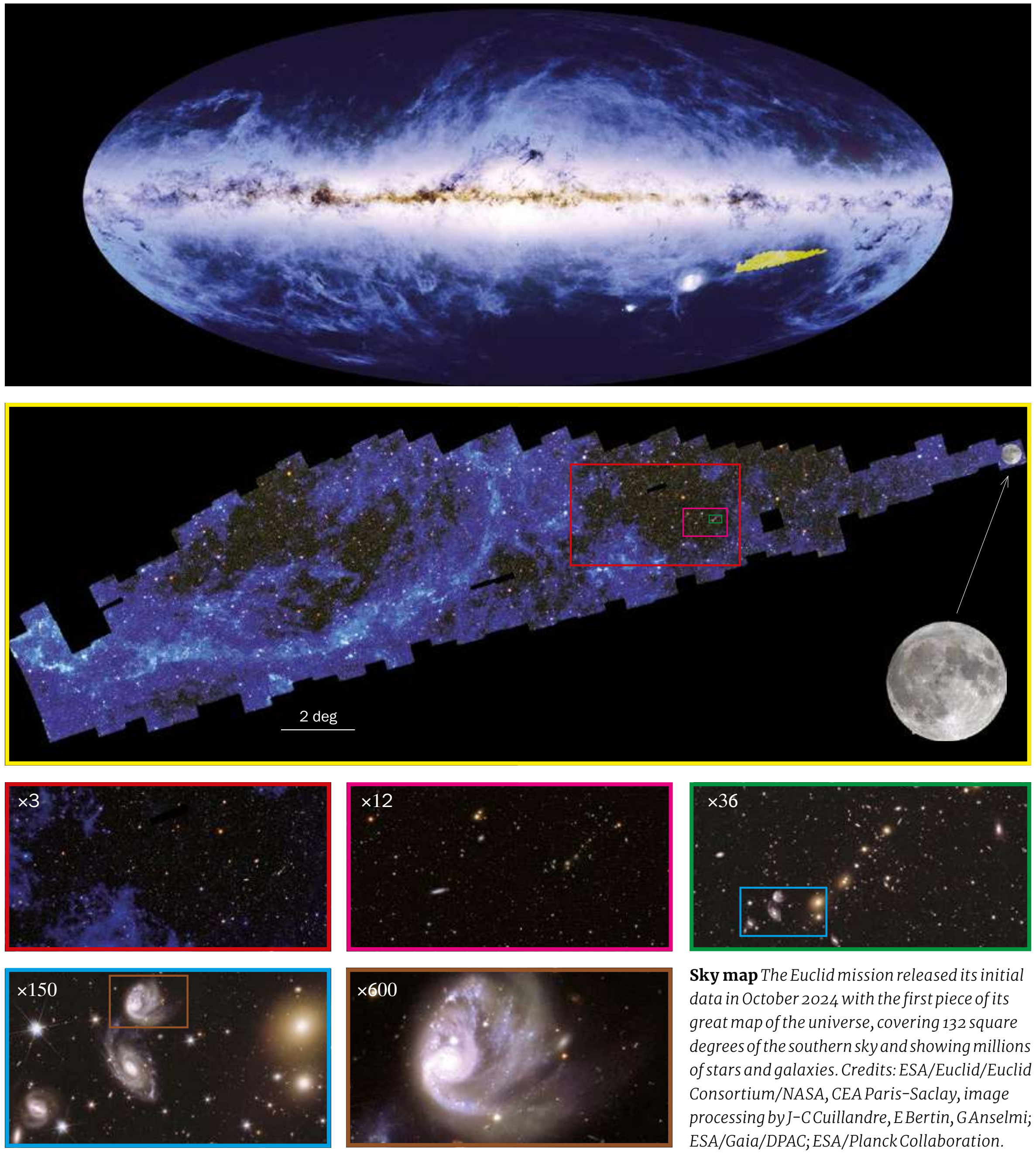
1. Mapping the universe

The Euclid space telescope is exploring the dark universe by mapping the large-scale structure of billions of galaxies out to 10 billion light-years across more than a third of the sky. With tens of petabytes expected in its final data set – already a substantial reduction of the 850 billion bits of compressed images Euclid processes each day – it will generate more data than any other ESA mission by far.

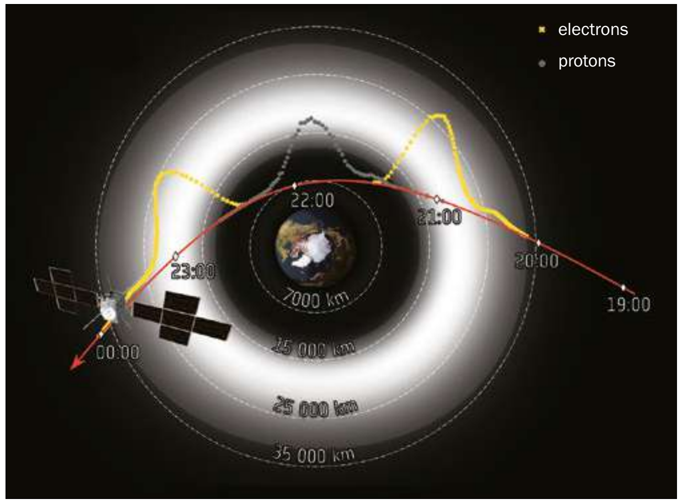
With many CERN cosmologists involved in testing theories of beyond-the-Standard-Model physics, Euclid first became a CERN-recognised experiment in 2015. CERN also contributes to the development of Euclid's "science ground segment" (SGS), which processes raw data received from the Euclid spacecraft into usable scientific products such as galaxy catalogues and dark-matter maps. CERN's virtual-machine file system (CernVM-FS) has been integrated into the SGS to allow continuous software deployment across Euclid's nine data centres and on developers' laptops.

The telescope was launched in July 2023 and began observations in February 2024. The first piece of its great map of the universe was released in October 2024, showing millions of stars and galaxies from observations and covering 132 square degrees of the southern sky (see "Sky map" figure). Based on just two weeks of observations, it accounts for just 1% of project's six-year survey, which will be the largest cosmic map ever made.

Future CERN–ESA collaborations on cosmology, astrophysics and multimessenger astronomy are likely to include the Laser Interferometer Space Antenna (LISA) and the NewAthena X-ray observatory. LISA will be the first space-based observatory to study gravitational waves. NewAthena will study the most energetic phenomena in the universe. Both projects are expected to be ready to launch about 10 years from now.



Sky map *The Euclid mission released its initial data in October 2024 with the first piece of its great map of the universe, covering 132 square degrees of the southern sky and showing millions of stars and galaxies. Credits: ESA/Euclid/Euclid Consortium/NASA, CEA Paris-Saclay, image processing by J-C Cuillandre, E Bertin, G Anselmi; ESA/Gaia/DPAC; ESA/Planck Collaboration.*



ESA/M Pinto

Flyby *Radiation-monitor measurements made during JUICE's flight through Earth's radiation belts in August 2024.*

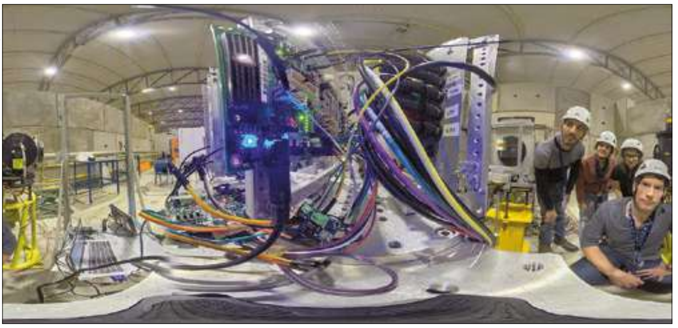
2. Planetary exploration

Though planetary exploration is conceptually far from fundamental physics, its technical demands require similar expertise. A good example is the Jupiter Icy Moons Explorer (JUICE) mission, which will make detailed observations of the gas giant and its three large ocean-bearing moons Ganymede, Callisto and Europa.

Jupiter's magnetic field is a million times greater in volume than Earth's magnetosphere, trapping large fluxes of highly energetic electrons and protons. Before JUICE, the direct and indirect impact of high-energy electrons on modern electronic devices, and in particular their ability to cause "single event effects", had never been studied before. Two test campaigns took place in the VESPER facility, which is part of the CERN Linear Electron Accelerator for Research (CLEAR) project. Components were tested with tuneable beam energies between 60 and 200 MeV, and average fluxes of roughly 10^8 electrons per square centimetre per second, mirroring expected radiation levels in the Jovian system.

JUICE was successfully launched in April 2023, starting an epic eight-year journey to Jupiter including several flyby manoeuvres that will be used to commission the onboard instruments (see "Flyby" figure). JUICE should reach Jupiter in July 2031. It remains to be seen whether test results obtained at CERN have successfully de-risked the mission.

Another interesting example of cooperation on planetary exploration is the Mars Sample Return mission, which must operate in low temperatures during eclipse phases. CERN supported the main industrial partner, Thales Alenia Space, in qualifying the orbiter's thermal-protection systems in cryogenic conditions.



CERN/M Brice

Space AI *Intel's Myriad 2 chip being tested at CERN by ESA and Ubotica.*

ESA/NASA

Space dosimetry *ESA astronaut Thomas Pesquet with the LUMINA experiment onboard the ISS.*

> **It's no mean feat to ensure that CERN's accelerator infrastructure functions in increasingly challenging radiation environments**

3. Earth observation

Earth observation from orbit has applications ranging from environmental monitoring to weather forecasting. CERN and ESA collaborate both on developing the advanced technologies required by these applications and ensuring they can operate in the harsh radiation environment of space.

In 2017 and 2018, ESA teams came to CERN's North Area with several partner companies to test the performance of radiation monitors, field-programmable gate arrays (FPGAs) and electronics chips in ultra-high-energy ion beams at the Super Proton Synchrotron. The tests mimicked the ultra-high-energy part of the galactic cosmic-ray spectrum, whose effects had never previously been measured on the ground beyond 10 GeV/nucleon. In 2017, ESA's standard radiation-environment monitor and several FPGAs and multiprocessor chips were tested with xenon ions. In 2018, the highlight of the campaign was the testing of Intel's Myriad-2 artificial intelligence (AI) chip with lead ions (see "Space AI" figure). Following its radiation characterisation and qualification, in 2020 the chip embarked on the ϕ-sat-1 mission to autonomously detect clouds using images from a hyperspectral camera.

More recently, CERN joined Edge SpAIce – an EU project to monitor ecosystems onboard the Balkan-1 satellite and track plastic pollution in the oceans. The project will use CERN's high-level synthesis for machine learning (hls4ml) AI technology to run inference models on an FPGA that will be launched in 2025.

Looking further ahead, ESA's ϕ-lab and CERN's Quantum Technology Initiative are sponsoring two PhD programmes to study the potential of quantum machine learning, generative models and time-series processing to advance Earth observation. Applications may accelerate the task of extracting features from images to monitor natural disasters, deforestation and the impact of environmental effects on the lifecycle of crops.

4. Dosimetry for human spaceflight

In space, nothing is more important than astronauts' safety and wellbeing. To this end, in August 2021 ESA astronaut Thomas Pesquet activated the LUMINA experiment inside the International Space Station (ISS), as part of the ALPHA mission (see "Space dosimetry" figure). Developed under the coordination of the French Space Agency and the Laboratoire Hubert Curien at the Université Jean-Monnet-Saint-Étienne and iXblue, LUMINA uses two several-kilometre-long phosphorous-doped optical fibres as active dosimeters to measure ionising radiation aboard the ISS.

When exposed to radiation, optical fibres experience a partial loss of transmitted power. Using a reference control channel, radiation-induced attenuation can be accurately measured related to the total ionising dose, with the sensitivity of the device primarily governed by the length of the fibre. Having studied optical-fibre-based technologies for many years, CERN helped optimise the architecture of the dosimeters and performed irradiation tests to calibrate the instrument, which will operate on the ISS for a period of up to five years.

LUMINA complements dosimetry measurements performed on the ISS using CERN's Timepix technology – an offshoot of the hybrid-pixel-detector technology developed for the LHC experiments (*CERN Courier* September/October 2024 p37). Timepix dosimeters have been integrated in multiple NASA payloads since 2012.

5. Radiation-hardness assurance

It's no mean feat to ensure that CERN's accelerator infrastructure functions in increasingly challenging radiation environments. Similar challenges are found in space. Damage can be caused by accumulating ionising doses, single-event effects (SEEs) or so-called displacement damage dose, which dislodges atoms within a material's crystal lattice rather than ionising them. Radiation-hardness assurance (RHA) reduces radiation-induced failures in space through environment simulations, part selection and testing, radiation-tolerant design, worst-case analysis and shielding definition.

Since its creation in 2008, CERN's Radiation to Electronics project has amplified the work of many equipment and service groups in modelling, mitigating and testing the effect of radiation on electronics. A decade later, joint test campaigns with ESA demonstrated the value of CERN's facilities and expertise to RHA for spaceflight. This led to the signing of a joint protocol on radiation environments, technologies and facilities in 2019, which also included radiation detectors and radiation-tolerant systems, and components and simulation tools.

Among CERN's facilities is CHARM: the CERN high-energy-accelerator mixed-field facility, which offers an innovative approach to low-cost RHA. CHARM's radiation field is generated by the interaction between a 24 GeV/c beam from the Proton Synchrotron and a metallic target. CHARM offers a uniquely wide spectrum of radiation types and energies, the possibility to adjust the environment using mobile shielding, and enough space to test a medium-sized satellite in full operating conditions.

CERN-PHOTO-202101-002-2

CHIMERA *CERN's CHARM facility has been upgraded to enable high-energy heavy-ion tests.*

CERN-PHOTO-202101-002-6

CubeSat *A full-scale radiation-testing model of the CELESTA satellite.*

> **Space technology is a fast-growing industry replete with opportunities for public–private cooperation**

Radiation testing is particularly challenging for the new generation of rapidly developed and often privately funded "new space" projects, which frequently make use of commercial and off-the-shelf (COTS) components. Here, RHA relies on testing and mitigation rather than radiation hardening by design. For "flip chip" configurations, which have their active circuitry facing inward toward the substrate, and dense three-dimensional structures that cannot be directly exposed without compromising their performance, heavy-ion beams accelerated to between 10 and 100 MeV/nucleon are the only way to induce SEE in the sensitive semiconductor volumes of the devices.

To enable testing of highly integrated electronic components, ESA supported studies to develop the CHARM heavy ions for micro-electronics reliability-assurance facility – CHIMERA for short (see "CHIMERA" figure). ESA has sponsored key feasibility activities such as: tuning the ion flux in a large dynamic range; tuning the beam size for board-level testing; and reducing beam energy to maximise the frequency of SEE while maintaining a penetration depth of a few millimetres in silicon.

6. In-orbit demonstrators

Weighing 1 kg and measuring just 10 cm on each side – a nanosatellite standard – the CELESTA satellite was designed to study the effects of cosmic radiation on electronics (see "CubeSat" figure). Initiated in partnership with the University of Montpellier and ESA, and launched in July 2022, CELESTA was CERN's first in-orbit technology demonstrator.

As well as providing the first opportunity for CHARM to test a full satellite, CELESTA offered the opportunity to flight-qualify SpaceRadMon, which counts single-event upsets (SEUs) and single-event latchups (SELs) in static random-access memory while using a field-effect transistor for dose monitoring. (SEUs are temporary errors caused by a high-energy particle flipping a bit and SELs are short circuits induced by high-energy particles.) More than 30 students contributed to the mission development, partially in the frame of ESA's Fly Your Satellite Programme. Built from COTS components calibrated in CHARM, SpaceRadMon has since been adopted by other ESA missions such as Trisat and GENA-OT, and could be used in the future as a low-cost predictive maintenance tool to reduce space debris and improve space sustainability.

The maiden flight of the Vega-C launcher placed CELESTA on an atypical quasi-circular medium-Earth orbit in the middle of the inner Van Allen proton belt at roughly 6000 km. Two months of flight data sufficed to validate the performance of the payload and the ground-testing procedure in CHARM, though CELESTA will fly for thousands of years in a region of space where debris is not a problem due to the harsh radiation environment.

The CELESTA approach has since been adopted by industrial partners to develop radiation-tolerant cameras, radios and on-board computers.

7. Stimulating the space economy

Space technology is a fast-growing industry replete with opportunities for public–private cooperation. The global space economy will be worth $1.8 trillion by 2035, according to the World Economic Forum – up from $630 billion in 2023 and growing at double the projected rate for global GDP.

Whether spun off from space exploration or particle physics, ESA and CERN look to support start-up companies and high-tech ventures in bringing to market technologies with positive societal and economic impacts (see "Spin offs" figure). The use of CERN's Timepix technology in space missions is a prime example. Private company Advacam collaborated with the Czech Technical University to provide a Timepix-based radiation-monitoring payload called SATRAM to ESA's Proba-V mission to map land cover and vegetation growth across the entire planet every two days.

E Chesta/CERN

Spin offs *CERN and ESA first co-exhibited with associated spin-off companies in 2014 at the Hannover Messe – one of the world's biggest industrial fairs.*

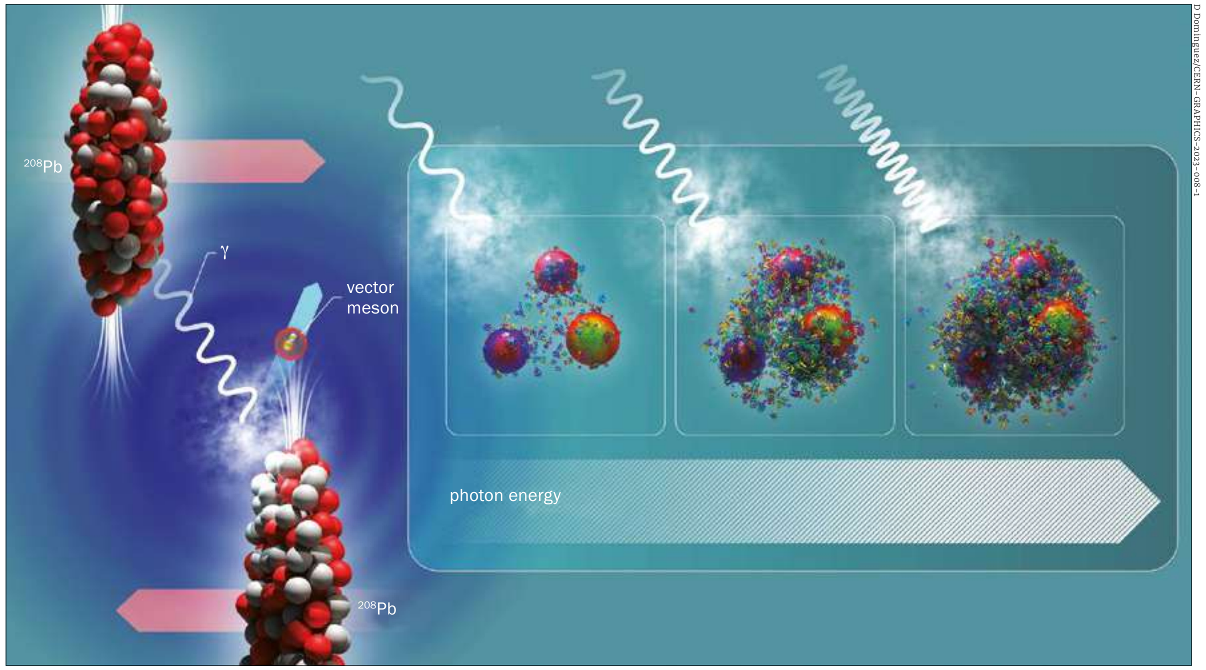
Advacam is now testing a pixel-detector instrument on JoeySat – an ESA-sponsored technology demonstrator for OneWeb's next-generation constellation of satellites designed to expand global connectivity. Advacam is also working with ESA on radiation monitors for Space Rider and NASA's Lunar Gateway. Space Rider is a reusable spacecraft whose maiden voyage is scheduled for the coming years, and Lunar Gateway is a planned space station in lunar orbit that could act as a staging post for Mars exploration.

Another promising example is SigmaLabs – a Polish startup founded by CERN alumni specialising in radiation detectors and predictive-maintenance R&D for space applications. SigmaLabs was recently selected by ESA and the Polish Space Agency to provide one of the experiments expected to fly on Axiom Mission 4 – a private spaceflight to the ISS in 2025 that will include Polish astronaut and CERN engineer Sławosz Uznański (*CERN Courier* May/June 2024 p55). The experiment will assess the scalability and versatility of the SpaceRadMon radiation-monitoring technology initially developed at CERN for the LHC and flight tested on the CELESTA CubeSat.

In radiation-hardness assurance, the CHIMERA facility is associated with the High-Energy Accelerators for Radiation Testing and Shielding (HEARTS) programme sponsored by the European Commission. Its 2024 pilot user run is already stimulating private innovation, with high-energy heavy ions used to perform business-critical research on electronic components for a dozen aerospace companies. ●

Further reading

A Coronetti *et al.* 2024 *IEEE Trans. Nucl. Sci.* **71** 1623.
K Bilko *et al.* 2024 *IEEE Trans. Nucl. Sci.* **71** 1549.
D Di Francesca *et al.* 2023 *Appl. Opt. E* **62** E43.
R Secondo *et al.* 2018 *IEEE Trans. Nucl. Sci.* **65** 1694.



D Dominguez/CERN-GRAPHICS-2023-008-1

Sensitivity to saturation *In ultraperipheral collisions at the LHC, photons serve as a clean probe of gluon dynamics as a function of energy scale.*

THE OTHER 99%

Daniel Tapia Takaki describes how ultraperipheral collisions mediated by high-energy photons are shedding light on gluon saturation, gluonic hotspots and nuclear shadowing.

Quarks contribute less than 1% to the mass of protons and neutrons. This provokes an astonishing question: where does the other 99% of the mass of the visible universe come from? The answer lies in the gluon, and how it interacts with itself to bind quarks together inside hadrons.

Much remains to be understood about gluon dynamics. At present, the chief experimental challenge is to observe the onset of gluon saturation – a dynamic equilibrium between gluon splitting and recombination predicted by QCD. The experimental key looks likely to be a rare but intriguing type of LHC interaction known as an ultraperipheral collision (UPC), and the breakthrough may come as soon as the next experimental run.

Gluon saturation is expected to end the rapid growth in gluon density measured at the HERA electron–proton collider at DESY in the 1990s and 2000s. HERA observed this growth as the energy of interactions increased and as the fraction of the proton's momentum borne by the gluons (Bjorken x) decreased.

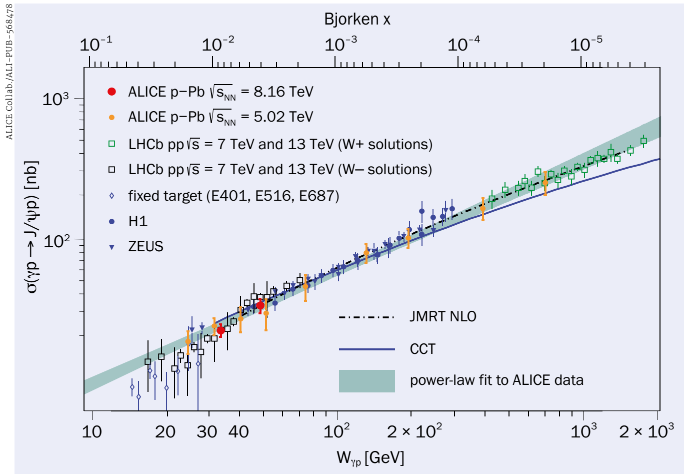
So gluons become more numerous in hadrons as their energy decreases – but to what end?

Nonlinear effects are expected to arise due to processes like gluon recombination, wherein two gluons combine to become one. When gluon recombination becomes a significant factor in QCD dynamics, gluon saturation sets in – an emergent phenomenon whose energy scale is a critical parameter to determine experimentally. At this scale, gluons begin to act like classical fields and gluon density plateaus. A dilute partonic picture transitions to a dense, saturated state. For recombination to take precedence over splitting, gluon momenta must be very small, corresponding to low values of Bjorken x. The saturation scale should also be directly proportional to the colour-charge density, making heavy nuclei like lead ideal for studying nonlinear QCD phenomena.

But despite strong theoretical reasoning and tantalising experimental hints, direct evidence for gluon saturation

THE AUTHOR

Daniel Tapia Takaki *University of Kansas.*



ALICE Collab./ALI-PUB-568478

Approaching the plateau? *The H1 and ZEUS experiments at HERA and the ALICE and LHCb experiments at the LHC have observed a power law in the cross section for γp → J/ψp. Theoretical models (dashed and blue curves) predict a plateau caused by gluon saturation that could be accessible in the next run of the LHC.*

Gluonic hotspots are now being probed with unprecedented precision at the LHC and are central to understanding the high-energy regime of QCD

remains elusive.

Since the conclusion of the HERA programme, the quest to explore gluon saturation has shifted focus to the LHC. But with no point-like electron to probe the hadronic target, LHC physicists had to find a new point-like probe: light itself. UPCs at the LHC exploit the flux of quasi-real high-energy photons generated by ultra-relativistic particles. For heavy ions like lead, this flux of photons is enhanced by the square of the nuclear charge, enabling studies of photon–proton (γp) and photon–nucleus interactions at centre-of-mass energies reaching the TeV scale.

Keeping it clean

What really sets UPCs apart is their clean environment. UPCs occur at large impact parameters well outside the range of the strong nuclear force, allowing the nuclei to remain intact. Unlike hadronic collisions, which can produce thousands of particles, UPCs often involve only a few final-state particles, for example a single J/ψ, providing an ideal laboratory for gluon saturation. J/ψ are produced when a $c\bar{c}$ pair created by two or more gluons from one nucleus is brought on-shell by interacting with a quasi-real photon from the other nucleus (see "Sensitivity to saturation" figure).

Gluon saturation models predict deviations in the γp → J/ψp cross section from the power-law behaviour observed at HERA. The LHC experiments are placing a significant focus on investigating the energy dependence of this process to identify potential signatures of saturation, with ALICE and LHCb extending studies to higher γp centre-of-mass energies ($W_{\gamma p}$) and lower Bjorken x than HERA. The results so far reveal that the cross-section continues to increase with energy, consistent with the power-law trend (see "Approaching the plateau?" figure).

The symmetric nature of pp collisions introduces significant challenges. In pp collisions, either proton can act as the photon source, leading to an intrinsic ambiguity in identifying the photon emitter. In proton–lead (pPb) collisions, the lead nucleus overwhelmingly dominates photon emission, eliminating this ambiguity. This makes pPb collisions an ideal environment for precise studies of the photoproduction of J/ψ by protons.

During LHC Run 1, the ALICE experiment probed $W_{\gamma p}$ up to 706 GeV in pPb collisions, more than doubling HERA's maximum reach of 300 GeV. This translates to probing Bjorken-x values as low as 10^{-5}, significantly beyond the regime explored at HERA. LHCb took a different approach. The collaboration inferred the behaviour of pp collisions at high energies ("W+ solutions") by assuming knowledge of their energy dependence at low energies ("W- solutions"), allowing LHCb to probe gluon energies as small as 10^{-6} in Bjorken x and $W_{\gamma p}$ up to 2 TeV.

There is not yet any theoretical consensus on whether LHC data align with gluon-saturation predictions, and the measurements remain statistically limited, leaving room for further exploration. Theoretical challenges include incomplete next-to-leading-order calculations and the reliance of some models on fits to HERA data. Progress will depend on robust and model-independent calculations and high-quality UPC data from pPb collisions in LHC Run 3 and Run 4.

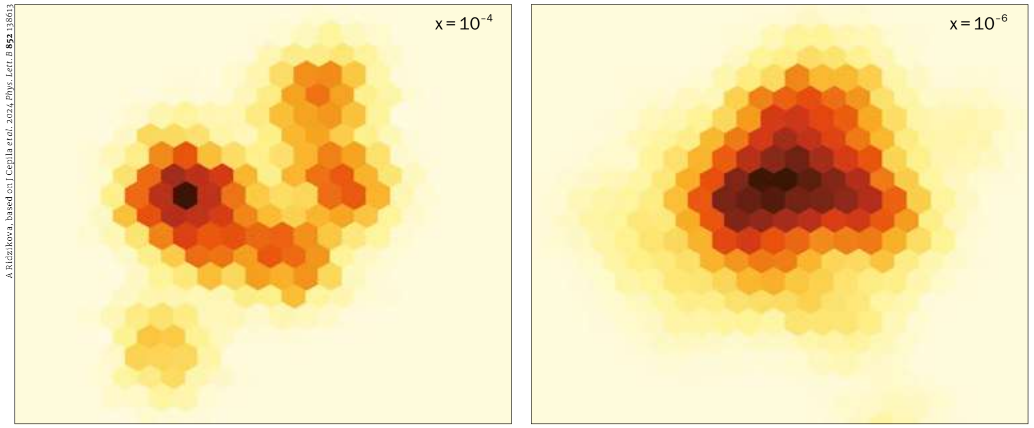
Some models predict a slowing increase in the γp → J/ψp cross section with energy at small Bjorken x. If these models are correct, gluon saturation will likely be discovered in LHC Run 4, where we expect to see a clear observation of whether pPb data deviate from the power law observed so far.

Gluonic hotspots

If a UPC photon interacts with the collective colour field of a nucleus – coherent scattering – it probes its overall distribution of gluons. If a UPC photon interacts with individual nucleons or smaller sub-nucleonic structures – *incoherent* scattering – it can probe smaller-scale gluon fluctuations.

These fluctuations, known as gluonic hotspots, are theorised to become more numerous and overlap in the regime of gluon saturation (see "Onset of saturation" figure). Now being probed with unprecedented precision at the LHC, they are central to understanding the high-energy regime of QCD.

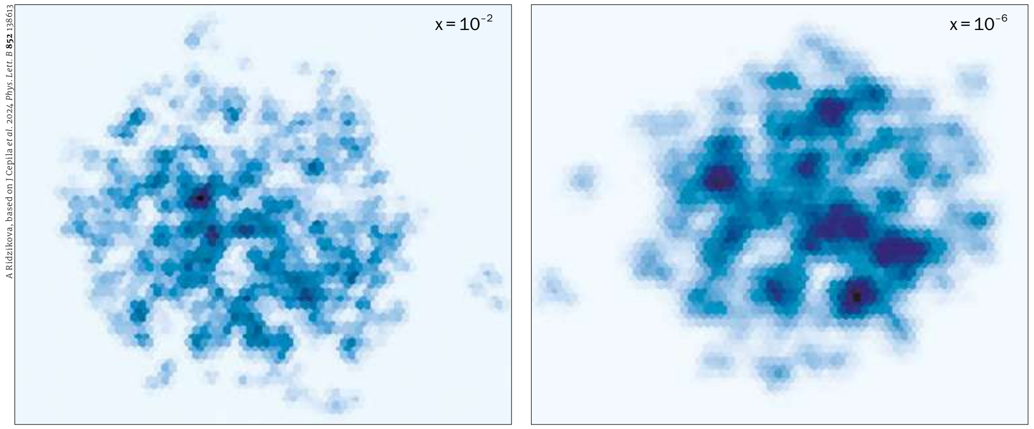
Gluonic hotspots are used to model the internal transverse structure of colliding protons or nuclei (see "Hotspot snapshots" figure). The saturation scale is inherently impact-parameter dependent, with the densest colour charge densities concentrated at the core of the proton or nucleus, and diminishing toward the periphery, though subject to fluctuations. Researchers are increasingly interested in exploring how these fluctuations depend on the impact parameter of collisions to better characterise the spatial dynamics of colour charge. Future analyses will pinpoint contributions from localised hotspots where saturation effects are most likely to be observed.



A Ridzikova, based on J Cepila *et al.* 2024 *Phys. Lett. B* **852** 138613

Onset of saturation *Simulations of the transverse density of gluons in protons at Bjorken x of 10^{-4} (left) and 10^{-6} (right). The colour shows the probability of a gluonic hotspot in each bin, with both distributions spanning a diameter of roughly 1.5 fm. The number of gluonic hotspots increases from 12 to 67 as x drops by a factor of 100 from left to right, with gluon saturation increasingly evident in the overlapping of the hotspots. A Bjorken x of 10^{-6} is experimentally within reach at LHC energies.*

The observation that sub-nucleonic structures impart the greatest momentum transfer is compelling evidence for gluonic quantum fluctuations at the sub-nucleon level



A Ridzikova, based on J Cepila *et al.* 2024 *Phys. Lett. B* **852** 138613

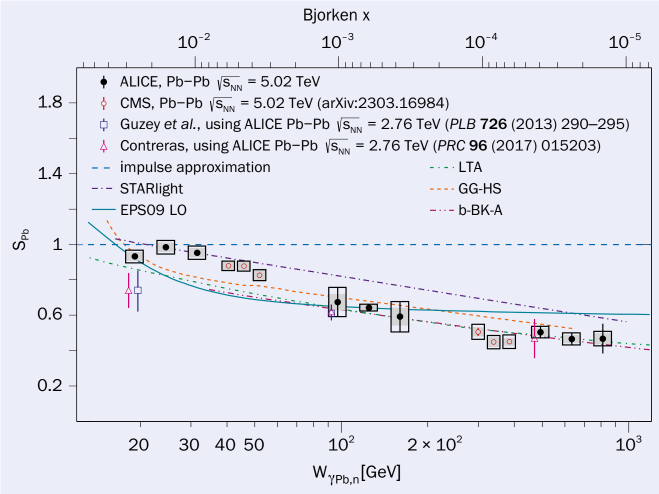
Hotspot snapshots *Simulations of the transverse density of gluons in lead nuclei at Bjorken x of 10^{-2} (left) and 10^{-6} (right). The distributions are 10 times broader than for protons and span almost 15 fm. The number of gluonic hotspots increases from 1,400 to 12,000 as x drops by a factor of 10,000, from left to right.*

The energy dependence of incoherent or dissociative photoproduction promises a clear signature for gluon saturation, independent of the coherent power-law method described above. As saturation sets in, all gluon configurations in the target converge to similar densities, causing the variance of the gluon field to decrease, and with it the dissociative cross section. Detecting a peak and a decline in the incoherent cross-section as a function of energy would represent a clear signature of gluon saturation.

The ALICE collaboration has taken significant steps in exploring this quantum terrain, demonstrating the possibility of studying different geometrical configurations of quantum fluctuations in processes where protons or lead nucleons dissociate. The results highlight a striking correlation between momentum transfer, which is inversely proportional to the impact parameter, and the size of the target structure. The observation that sub-nucleonic structures impart the greatest momentum transfer is compelling evidence for gluonic quantum fluctuations at the sub-nucleon level.

Into the shadows

In 1982 the European Muon Collaboration observed an intriguing phenomenon: nuclei appeared to contain fewer gluons than expected based on the contribu-



Nuclear shadowing *The nuclear suppression factor for lead relative to protons (S_{Pb}) as a function of energy and Bjorken x. No model can yet describe saturation and shadowing over the measured kinematic domain.*

Saturation specific *ALICE's new high-granularity forward calorimeter is designed to study gluon saturation.*

tions from their individual protons and neutrons. This effect, known as nuclear shadowing, was observed in experiments conducted at CERN at moderate values of Bjorken x. It is now known to occur because the interaction of a probe with one gluon reduces the likelihood of the probe interacting with other gluons within the nucleus – the gluons hiding behind them, in their shadow, so to speak. At smaller values of Bjorken x, saturation further suppresses the number of gluons contributing to the interaction.

The relationship between gluon saturation and nuclear shadowing is poorly understood, and separating their effects remains an open challenge. The situation is further complicated by an experimental reliance on lead–lead (PbPb) collisions, which, like pp collisions, suffer from ambiguity in identifying the interacting nucleus, unless the interaction is accompanied by an ejected neutron.

The ALICE, CMS and LHCb experiments have extensively studied nuclear shadowing via the exclusive production of vector mesons such as J/ψ in ultraperipheral PbPb collisions. Results span photon–nucleus collision energies from 10 to 1000 GeV. The onset of nuclear shadowing, or another nonlinear QCD phenomenon like saturation, is clearly visible as a function of energy and Bjorken x (see "Nuclear shadowing" figure).

The LHC's unparalleled energy reach and diverse colliding systems offers unique opportunities to explore gluon dynamics at the highest energies

Multidimensional maps

While both saturation-based and gluon shadowing models describe the data reasonably well at high energies, neither framework captures the observed trends across the entire kinematic range. Future efforts must go beyond energy dependence by being differential in momentum transfer and studying a range of vector mesons with complementary sensitivities to the saturation scale.

Soon to be constructed at Brookhaven National Laboratory, the Electron-Ion Collider (EIC) promises to transform our understanding of gluonic matter. Designed specifically for QCD research, the EIC will probe gluon saturation and shadowing in unprecedented detail, using a broad array of reactions, collision species and energy levels. By providing a multidimensional map of gluonic behaviour, the EIC will address fundamental questions such as the origin of mass and nuclear spin.

Before then, a tenfold increase in PbPb statistics in LHC Runs 3 and 4 will allow a transformative leap in low Bjorken-x physics. Though not originally designed for low Bjorken-x physics, the LHC's unparalleled energy reach and diverse range of colliding systems offers unique opportunities to explore gluon dynamics at the highest energies.

Enhanced capabilities

Surpassing the gains from increased luminosity alone, ALICE's new triggerless detector readout mode will offer a vast improvement over previous runs, which were constrained by dedicated triggers and bandwidth limitations. Subdetector upgrades will also play an important role. The muon forward tracker has already enhanced ALICE's capabilities, and the high-granularity forward calorimeter set to be installed in time for Run 4 is specifically designed to improve sensitivity to small Bjorken-x physics (see "Saturation specific" figure).

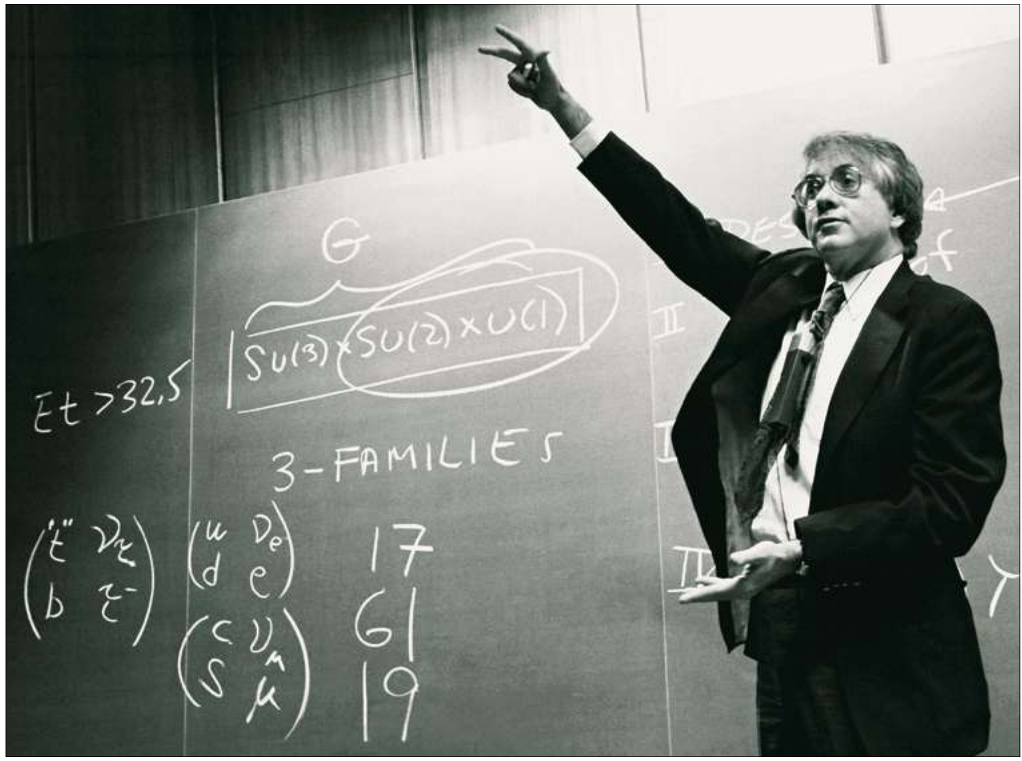
Ultraperipheral-collision physics at the LHC is far more than a technical exploration of QCD. Gluons govern the structure of all visible matter. Saturation, hotspots and shadowing shed light on the origin of 99% of the mass of the visible universe. ●

Further reading

ALICE Collab. 2024 *Phys. Rev. Lett.* **132** 162302.
CMS Collab. 2023 *Phys. Rev. Lett.* **131** 262301.
ALICE Collab. 2023 *JHEP* **10** 119.
LHCb Collab. 2018 *JHEP* **10** 167.

CHARM AND SYNTHESIS

Sheldon Glashow recalls the events surrounding a remarkable decade of model building and discovery between 1964 and 1974.



Electroweak unification *Sheldon Glashow lectures at CERN in 1979.*

In 1955, after a year of graduate study at Harvard, I joined a group of a dozen or so students committed to studying elementary particle theory. We approached Julian Schwinger, one of the founders of quantum electrodynamics, hoping to become his thesis students – and we all did.

Schwinger lined us up in his office, and spent several hours assigning thesis subjects. It was a remarkable performance. I was the last in line. Having run out of well-defined thesis problems, he explained to me that weak and electromagnetic interactions share two remarkable features: both are vectorial and both display aspects of universality. Schwinger suggested that I create a unified theory of the two interactions – an electroweak synthesis. How I was to do this he did not say, aside from slyly hinting at the Yang–Mills gauge theory.

By the summer of 1958, I had convinced myself that weak and electromagnetic interactions might be described by a badly broken gauge theory, and Schwinger that I deserved a PhD. I had hoped to partly spend a postdoctoral fellowship in Moscow at the invitation of the recent Russian Nobel laureate Igor Tamm, and sought to visit Niels Bohr's institute in Copenhagen while awaiting my Soviet visa. With Bohr's enthusiastic consent, I boarded the SS Île de France with my friend Jack Schnepps. Following a memorable and luxurious crossing – one of the great ship's last – Jack drove south to Padova to work with Milla Baldo-Ceolin's emulsion group in Padova, and I took the slow train north to Copenhagen. Thankfully, my Soviet visa never arrived. I found the $SU(2) \times U(1)$ structure of the electroweak model in the spring of 1960 at Bohr's famous institute at Blegsdamvej 19, and wrote the paper that would earn my share of the 1979 Nobel Prize.

A year earlier, in 1959, Augusto Gamba, Bob Marshak and Susumo Okubo had proposed lepton–hadron symmetry, which regarded protons, neutrons and lambda hyperons as the building blocks of all hadrons, to match the three known leptons at the time: neutrinos, electrons

THE AUTHOR
Sheldon Lee Glashow *Boston University and Harvard University.*

CERNCOURIER
Volume 65 Number 1 January/February 2025

Four intractable problems of early 1964

How could the W and Z bosons acquire masses while leaving the photon massless?
Steven Weinberg, my friend from both high-school and college, brilliantly solved this problem in 1967 by subjecting the electroweak gauge group to spontaneous symmetry breaking, initiating the half-century-long search for the Higgs boson. Salam published the same solution in 1968.

Was the spontaneously broken electroweak gauge model mathematically consistent?
Gerard 't Hooft announced in 1971 that he had proven Steven Weinberg's electroweak model to be renormalisable. In 1972, Claude Bouchiat, John Iliopoulos and Philippe Meyer demonstrated the electroweak model to be free of Adler anomalies provided that lepton–quark symmetry is maintained.

How could an electroweak model of leptons be extended to describe the weak interactions of hadrons?
John Iliopoulos, Luciano Maiani and I solved this problem in 1970 by introducing charm and quark–lepton symmetry to avoid unobserved strangeness-changing neutral currents.

Could the electroweak model describe CP violation without invoking additional spinless fields?
In 1973, Makoto Kobayashi and Toshihide Maskawa showed that the electroweak model could easily and naturally violate CP if there are more than four quark flavours.

> **We called the new quark flavour "charm", completing two weak doublets of quarks to match two weak doublets of leptons, and establishing lepton–quark symmetry, which holds to this day**

and muons. The idea was falsified by the discovery of a second neutrino in 1962, and superseded in 1964 by the invention of fractionally charged hadron constituents, first by George Zweig and André Petermann, and then decisively by Murray Gell-Mann with his three flavours of quarks. Later in 1964, while on sabbatical in Copenhagen, James Bjorken and I realised that lepton–hadron symmetry could be revived simply by adding a fourth quark flavour to Gell-Mann's three. We called the new quark flavour "charm", completing two weak doublets of quarks to match two weak doublets of leptons, and establishing lepton–*quark* symmetry, which holds to this day.

Annus mirabilis

1964 was a remarkable year. In addition to the invention of quarks, Nick Samios spotted the triply strange Ω^- baryon, and Oscar Greenberg devised what became the critical notion of colour. Arno Penzias and Robert Wilson stumbled on the cosmic microwave background radiation. James Cronin, Val Fitch and others discovered CP violation. Robert Brout, François Englert, Peter Higgs and others invented spontaneously broken non-Abelian gauge theories. And to top off the year, Abdus Salam rediscovered and published my $SU(2) \times U(1)$ model, after I had more-or-less abandoned electroweak thoughts due to four seemingly intractable problems.

Much to my surprise and delight, all of them would be solved within just a few years, with the last theoretical obstacle removed by Makoto Kobayashi and Toshihide Maskawa in 1973 (see "Four intractable problems" panel). A few months later, Paul Musset announced that CERN's Gargamelle detector had won the race to detect weak neutral-current interactions, giving the electroweak model the status of a predictive theory. Remarkably, the year had begun with Gell-Mann, Harald Fritzsch and Heinrich Leutwyler proposing QCD, and David Gross, Frank Wilczek and David Politzer showing it to be asymptotically free. The Standard Model of particle physics was born.

Charmed findings

But where were the charmed quarks? Early on Monday morning on 11 November, 1974, I was awakened by a phone call from Sam Ting, who asked me to come to his MIT office as soon as possible. He and Ulrich Becker were waiting for me impatiently. They showed me an amazingly sharp resonance. Could it be a vector meson like the ρ or ω and be so narrow, or was it something quite different? I hopped in my car and drove to Harvard, where my colleagues Alvaro de Rújula and Howard Georgi excitedly regaled me about the Californian side of the story. A few days later, experimenters in Frascati confirmed the BNL–SLAC discovery, and de Rújula and I submitted our paper "Is Bound Charm Found?" – one of two papers on the J/ψ discovery printed in *Physical Review Letters* on 5 July 1965 that would prove to be correct. Among five false papers was one written by my beloved mentor, Julian Schwinger.

The second correct paper was by Tom Appelquist and David Politzer. Well before that November, they had realised (without publishing) that bound states of a charmed quark and its antiquark lying below the charm threshold would be exceptionally narrow due the asymptotic freedom of QCD. De Rújula suggested to them that such a system be called charmonium in an analogy with positronium. His term made it into the dictionary. Shortly afterward, the 1976 Nobel Prize in Physics was jointly awarded to Burton Richter and Sam Ting for "their pioneering work in the discovery of a heavy elementary particle of a new kind" – evidence that charm was not yet a universally accepted explanation. Over the next few years, experimenters worked hard to confirm the predictions of theorists at Harvard and Cornell by detecting and measuring the masses, spins and transitions among the eight sub-threshold charmonium states. Later on, they would do the same for 14 relatively narrow states of bottomonium.


CERN

Spiky resonance *Sam Ting at CERN's Intersecting Storage Rings in 1976.*


CERN

Theory and experiment *Abdus Salam, Tom Ball and Paul Musset at CERN in 1979.*


Photopress/*CERN Courier* December 1979 p395

Inspiration and execution *Sheldon Glashow and Steven Weinberg at Harvard in 1979.*

Other experimenters were searching for particles containing just one charmed quark or antiquark. In our 1975 paper "Hadron Masses in a Gauge Theory", de Rújula, Georgi and I included predictions of the masses of several not-yet-discovered charmed mesons and baryons. The first claim to have detected charmed particles was made in 1975 by Robert Palmer and Nick Samios at Brookhaven, again with a bubble-chamber event. It seemed to show a cascade decay process in which one charmed baryon decays into another charmed baryon, which itself decays. The measured masses of both of the charmed baryons were in excellent agreement with our predictions. Though the claim was not widely accepted, I believe to this day that Samios and Palmer were the first to detect charmed particles.

The SLAC electron–positron collider, operating well above charm threshold, was certainly producing charmed particles copiously. Why were they not being detected? I recall attending a conference in Wisconsin that was largely dedicated to this question. On the flight home, I met my old friend Gerson Goldhaber, who had been struggling unsuccessfully to find them. I think I convinced him to try a bit harder. A couple of weeks later in 1976, Goldhaber and François Pierre succeeded. My role in charm physics had come to a happy ending. ●

● *This article is adapted from a presentation given at the Institute of High-Energy Physics in Beijing on 20 October 2024 to celebrate the 50th anniversary of the discovery of the J/ψ.*

OPINION
INTERVIEW

A word with CERN's next Director-General

Mark Thomson is professor of experimental particle physics at the University of Cambridge and was executive chair of the UK's Science and Technology Facilities Council (STFC) until his confirmation as CERN's next Director-General by the CERN Council in December. His five-year mandate will begin in January 2026.


M Brice/CERN

What motivates you to be CERN's next Director-General?
CERN is an incredibly important organisation. I believe my deep passion for particle physics, coupled with the experience I have accumulated in recent years, including leading the Deep Underground Neutrino Experiment, DUNE, through a formative phase, and running the Science and Technology Facilities Council in the UK, has equipped me with the right skill set to lead CERN though a particularly important period.

How would you describe your management style?
That's a good question. My overarching approach is built around delegating and trusting my team. This has two advantages. First, it builds an empowering culture, which in my experience provides the right environment for people to thrive. Second, it frees me up to focus on strategic planning and engagement with numerous key stakeholders. I like to focus on transparency and openness, to build trust both internally and externally.

How will you spend your familiarisation year before you take over in 2026?
First, by getting a deep understanding of CERN "from within", to plan how I want to approach my mandate. Second, by lending my voice to the scientific discussion that will underpin the third update to the European strategy for particle physics. The European strategy process is a key opportunity for the particle-physics community to provide genuine bottom-up input and shape the future. This is going to be a really varied and exciting year.

What open question in fundamental physics would you most like to see answered in your lifetime?
I am going to have to pick two. I would really like to understand the nature of dark matter. There are a wide range of possibilities, and we are addressing this question from multiple angles; the search for dark matter is an area where the collider and non-collider experiments can both contribute enormously. The second question is the nature of the Higgs field. The Higgs boson is just so different from anything else we've ever seen. It's not just unique – it's unique and very strange. There are just so many deep questions, such as whether it is fundamental or composite. I am confident that we will make progress in the coming years. I believe the High-Luminosity LHC will be able to make meaningful measurements of the self-coupling at the heart of the Higgs potential. If you'd asked me five years ago whether this was possible, I would have been doubtful. But today I am very optimistic because of the rapid progress with advanced analysis techniques being developed by the brilliant scientists on the LHC experiments.

> **My overarching approach is built around delegating and trusting my team**

What areas of R&D are most in need of innovation to meet our science goals?
Artificial intelligence is changing how we look at data in all areas of science. Particle physics is the ideal testing ground for artificial intelligence, because our data is complex there are none of the issues around the sensitive nature of the data that exist in other fields. Complex multidimensional datasets are where you'll benefit the most from artificial intelligence. I'm also excited by the emergence of new quantum technologies, which will open up fresh opportunities for our detector systems and also new ways of doing experiments in fundamental physics. We've only scratched the surface of what can be achieved with entangled quantum systems.

How about in accelerator R&D?
There are two areas that I would like to highlight: making our current technologies more sustainable, and the development of high-field magnets based on high-temperature superconductivity. This connects to the question of innovation more broadly. To quote one example among many, high-temperature superconducting magnets are likely to be an important component of fusion reactors just as much as particle accelerators, making this a very exciting area where CERN can deploy its engineering expertise and really push that programme forward. That's not just a benefit for particle physics, but a benefit for wider society.

How has CERN changed since you were a fellow back in 1994?
The biggest change is that the collider experiments are larger and more complex, and the scientific and technical skills required have become more specialised. When I first came to CERN, I worked on the OPAL experiment at LEP – a collaboration of less than 400 people. Everybody knew everybody, and it was relatively easy to understand the science of the whole experiment.

But I don't think the scientific culture of CERN and the particle-physics community has changed much. When I visit CERN and meet with the younger scientists, I see the same levels of excitement and enthusiasm. People are driven by the wonderful mission of discovery. When planning the future, we need to ensure that early-career researchers can see a clear way forward with opportunities in all periods of their career. This is essential for the long-term health of particle physics. Today we have an amazing machine that's running beautifully: the LHC. I also don't think it is possible to overstate the excitement of the High-Luminosity LHC. So there's a clear and exciting future out to the early 2040s for today's early-career researchers. The question is what happens beyond that? This is one reason to ensure that there is not a large gap between the end of the High-Luminosity LHC and the start of whatever comes next.

> **We need to ensure that early-career researchers can see a clear way forward with opportunities in all periods of their career. This is essential for the long-term health of particle physics**

Should the world be aligning on a single project?
Given the increasing scale of investment, we do have to focus as a global community, but that doesn't necessarily mean a single project. We saw something similar about 10 years ago when the global neutrino community decided to focus its efforts on two complementary long-baseline projects, DUNE and Hyper-Kamiokande. From the perspective of today's European strategy, the Future Circular Collider (FCC) is an extremely appealing project that would map out an exciting future for CERN for many decades. I think we'll see this come through strongly in an open and science-driven European strategy process.

How do you see the scientific case for the FCC?
For me, there are two key points. First, gaining a deep understanding of the Higgs boson is the natural next step in our field. We have discovered something truly unique, and we should now explore its properties to gain deeper insights into fundamental physics. Scientifically, the FCC provides everything you want from a Higgs factory, both in terms of luminosity and the opportunity to support multiple experiments.

Second, investment in the FCC tunnel will provide a route to hadron–hadron collisions at the 100 TeV scale. I find it difficult to foresee a future where we will not want this capability.

These two aspects make the FCC a very attractive proposition.

How successful do you believe particle physics is in communicating science and societal impacts to the public and to policymakers?
I think we communicate science well. After all, we've got a great story. People get the idea that we work to understand the universe at its most basic level. It's a simple and profound message.

Going beyond the science, the way we communicate the wider industrial and societal impact is probably equally important. Here we also have a good story. In our experiments we are always pushing beyond the limits of current technology, doing things that have not been done before. The technologies we develop to do this almost always find their way back into something that will have wider applications. Of course, when we start, we don't know what the impact will be. That's the strength and beauty of pushing the boundaries of technology for science.

Would the FCC give a strong return on investment to the member states?
Absolutely. Part of the return is the science, part is the investment in technology, and we should not underestimate the importance of the training opportunities for young people across Europe. CERN provides such an amazing and inspiring environment for young people. The scale of the FCC will provide a huge number of opportunities for young scientists and engineers.

In terms of technology development, the detectors for the electron–positron collider will provide an opportunity for pushing forward and deploying new, advanced technologies to deliver the precision required for the science programme. In parallel, the development of the magnet technologies for the future hadron collider will be really exciting, particularly the potential use of high-temperature superconductors, as I said before.

It is always difficult to predict the specific "return on investment" on the technologies for big scientific research infrastructure. Part of this challenge is that some of that benefits might be 20, 30, 40 years down the line. Nevertheless, every retrospective that has tried, has demonstrated that you get a huge downstream benefit.

Do we reward technical innovation well enough in high-energy physics?

There needs to be a bit of a culture shift within our community. Engineering and technology innovation are critical to the future of science and critical to the prosperity of Europe. We should be striving to reward individuals working in these areas.

Should the field make it more flexible for physicists and engineers to work in industry and return to the field having worked there?

This is an important question. I actually think things are changing. The fluidity between academia and industry is increasing in both directions. For example, an early-career researcher in particle physics with a background in deep artificial-intelligence techniques is valued incredibly highly by industry. It also works the other way around, and I experienced this myself in my career when one of my post-doctoral researchers joined from an industry background after a PhD in particle physics. The software skills they picked up from industry were incredibly impactful.

I don't think there is much we need to do to directly increase flexibility – it's more about culture change, to recognise that fluidity between industry and academia is important and beneficial. Career trajectories are evolving across many sectors. People move around much more than they did in the past.

Does CERN have a future as a global laboratory?

CERN already is a global laboratory. The amazing range of nationalities working here is both inspiring and a huge benefit to CERN.

How can we open up opportunities in low- and middle-income countries?

I am really passionate about the importance of diversity in all its forms and this includes national and regional inclusivity. It is an agenda that I pursued in my last two positions. At the Deep Underground Neutrino Experiment, I was really keen to engage the scientific community from Latin America, and I believe this has been mutually beneficial. At STFC, we used physics as a way to provide opportunities for people across Africa to gain high-tech skills. Going beyond the training, one of the challenges is to ensure that people use these skills in their home nations. Otherwise, you're not really helping low- and middle-income countries to develop.

What message would you like to leave with readers?

That we have really only just started the LHC programme. With more than a factor of 10 increase in data to come, coupled with new data tools and upgraded detectors, the High-Luminosity LHC represents a major opportunity for a new discovery. Its nature could be a complete surprise. That's the whole point of exploring the unknown: you don't know what's out there. This alone is incredibly exciting, and it is just a part of CERN's amazing future.

Interview by **Mark Rayner** *editor.*

Intensely focused on physics

The High Luminosity Large Hadron Collider

Edited by Oliver Brüning and Lucio Rossi

World Scientific

The High Luminosity Large Hadron Collider, edited by Oliver Brüning and Lucio Rossi, is a comprehensive review of an upgrade project designed to boost the total event statistics of CERN's Large Hadron Collider (LHC) by nearly an order of magnitude. The LHC is the world's largest and, in many respects, most performant particle accelerator. It may well represent the most complex infrastructure ever built for scientific research. The increase in event rate is achieved by higher beam intensities and smaller beam sizes at the collision points.

Brüning and Rossi's book offers a comprehensive overview of this work across 31 chapters authored by more than 150 contributors. Due to the mentioned complexity of the HL-LHC, it is advisable to read the excellent introductory chapter first to obtain an overview on the various physics aspects, different components and project structure. After coverage of the physics case and the upgrades to the LHC experiments, the operational experiences with the LHC and its performance development are described.

The LHC's upgrade is a significant project, as evidenced by the involvement of nine collaborating countries including China and the US, a materials budget that exceeds one billion Swiss Francs, more than 2200 years of integrated work, and the complexity of the physics and engineering. The safe operation of the enormous beam intensity represented a major challenge for the original LHC, and will be even more challenging with the upgraded beam parameters. For example, the instantaneous power carried by the circulating beam will be 7.6 TW, while the total beam energy is then 680 MJ – enough energy to boil two tonnes of water. Such numbers should be compared with the extremely low power density of 30 mW/cm^3, which is sufficient to quench a superconducting magnet coil and interrupt the operation of the entire facility.


CERN

Testing, one, two, three *The High-Luminosity LHC test stand in November 2024.*


World Scientific

The book continues with descriptions of the two subsystems of greatest importance for the luminosity increase: the superconducting magnets and the RF systems including the crab cavities.

Besides the increase in intensity, the primary factor for instantaneous luminosity gain is obtained by a reduction in beam size at the interaction points (IPs), partly through a smaller emittance but mainly through improved beam optics. This change results in a larger beam in the superconducting quadrupoles beside the IP. To accommodate the upgraded beam and to shield the magnet coils from radiation, the aperture of these magnets is increased by more than a factor of two to 150 mm. New quadrupoles have been developed, utilising the superconductor material Nb_3Sn, allowing higher fields at the location of the coils. Further measures include the cancellation of the beam crossing angle during collision by dynamic tilting of the bunch orientation using the superconducting crab cavities that were designed for this special application in the LHC. The authors make fascinating observations, for example regarding the enhanced sensitivity to errors due to the extreme beam demagnification at the IPs: a typical relative error of 10^{-4} in the strength of the IP quadrupoles results in a significant distortion in beam optics, a so-called beta-beat of 7%.

Chapter eight describes the upgrade to the beam-collimation system, which is of particular importance for the safe operation of high-intensity beams. For ion collimation, halo particles are extracted most efficiently using collimators made from bent crystals.

The book continues with a description of the magnet-powering circuits. For the new superconducting magnets CERN is using "superconducting links" for the first time: cable sets made of a high-temperature superconductor that can carry enormous currents on many circuits in parallel in a small cross section; it suffices to cool them to temperatures of around 20 to 30 K with gaseous helium by evaporating some of the liquid helium that is used for cooling the superconducting magnets in the accelerator.

Magnetic efforts

The next chapters cover machine protection, the interface with the detectors and the cryogenic system. Chapter 15 is dedicated to the effects of beam-induced stray radiation, in particular on electronics – an effect that has become quite important at high intensities in recent years. Another chapter covers the development of an 11 Tesla dipole magnet that was intended to replace a regular superconducting magnet, thereby gaining space for additional collimators in the arc of the ring. Despite considerable effort, this programme was eventually dropped from the project because the new magnet technology could not be mastered with the required reliability for routine operation; and, most importantly, alternative collimation solutions were identified.

Other chapters describe virtually all the remaining technical subsystems and beam-dynamics aspects of the collider, as well as the extensive test infrastructure required before installation in the LHC. A whole chapter is dedicated to high-field-magnet R&D – a field of utmost importance to the development of a next-generation hadron collider beyond the LHC.

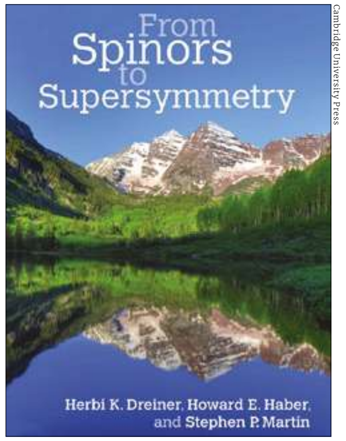
Brüning and Rossi's book will interest accelerator physicists in that it describes many outstanding beam-physics aspects of the HL-LHC. Engineers and readers with an interest in technology will also find many technical details on its subsystems.

Mike Seidel *PSI.*

From Spinors to Supersymmetry

By Herbi Dreiner, Howard Haber and Stephen Martin

Cambridge University Press


Cambridge University Press

This text is a hefty volume of around 1000 pages describing the two-component formalism of spinors and its applications to particle physics, quantum field theory and supersymmetry. The authors of this volume, Herbi Dreiner, Howard Haber and Stephen Martin, are household names in the phenomenology of particle physics with many original contributions in the topics that are covered in the book. Haber is also well known at CERN as a co-author of the legendary *Higgs Hunter's Guide* (Perseus Books, 1990), a book that most collider physicists of the pre and early LHC eras are very familiar with.

A valuable resource for all those who are interested in the extensions of the SM, especially if they include supersymmetry

The book starts with a 250-page introduction (chapters one to five) to the Standard Model (SM), covering more or less the theory material that one finds in standard advanced textbooks. The emphasis is on the theoretical side, with no discussion on experimental results, providing a succinct discussion of topics ranging from how to obtain Feynman rules to anomaly-cancellation calculations. In chapter six, extensions of the SM are discussed, starting with the seesaw-extended SM, moving on to a very detailed exposition of the two-Higgs-doublet model and finishing with grand unification theories (GUTs).

The second part of the book (from chapter seven onwards) is about supersymmetry in general. It begins with an accessible introduction that is also applicable to other beyond-SM-physics scenarios. This gentle and very pedagogical pattern continues to chapter eight, before proceeding to a more demanding supersymmetry-algebra discussion in chapter nine. Superfields, supersymmetric radiative corrections and supersymmetry symmetry breaking, which are discussed in the subsequent chapters, are more advanced topics that will be of interest to specialists in these areas.

The third part (chapter 13 onwards) discusses realistic supersymmetric models starting from the minimal supersymmetric SM (MSSM). After some preliminaries, chapter 15 provides a general presentation of MSSM phenomenology, discussing signatures relevant for proton–proton and electron–positron collisions, as well as direct dark-matter searches. A short discussion on beyond-MSSM scenarios is given in chapter 16, including NMSSM, seesaw, GUTs and R-parity violating theories. Phenomenological implications, for example their impact on proton decay, are also discussed.

Part four includes basic Feynman diagram calculations in the SM and MSSM using two-component spinor formalism. Starting from very simple tree-level SM processes, like Bhabha scattering and Z-boson decays, it proceeds with tree-level supersymmetric processes, standard one-loop calculations and their supersymmetric counterparts, and Higgs-boson mass corrections. The presentation of this is very practical and useful for those who want to see how to perform easy calculations in SM or MSSM using two-component spinor formalism. The material is accessible and detailed enough to be used for teaching master's or graduate-level students.

The book finishes with almost 200 pages of appendices covering all sorts of useful topics, from notation to commonly used identity lists and group theory.

The book requires some familiarity with master's-level particle-physics concepts, for example via Halzen and Martin's *Quarks and Leptons* or Paganini's *Fundamentals of Particle Physics*. Some familiarity with quantum field theory is helpful but not needed for large parts of the book. No effort is made to be brief: two-component spinor formalism is discussed in all its detail in a very pedagogic and clear way. Parts two and three are a significant enhancement to the well known *A Supersymmetry Primer* (arXiv:hep-ph/9709356), which is very popular among beginners to supersymmetry and written by Stephen Martin, one of authors of this volume. A rich collection of exercises is included in every chapter, and the appendix chapters are no exception to this.

Do not let the word supersymmetry in the title to fool you: even if you are not interested in supersymmetric extensions you can find a detailed exposition on two-component formalism for spinors, SM calculations with this formalism and a detailed discussion on how to design extensions of the scalar sector of the SM. Chapter three is particularly useful, describing in 54 pages how to get from the two-component to the four-component spinor formalism that is more familiar to many of us.

This is a book for advanced graduate students and researchers in particle-physics phenomenology, which nevertheless contains much that will be of interest to advanced physics students and particle-physics researchers in both theory and experiment. This is because the size of the volume allows the authors to start from the basics and dwell in topics that most other books of that type cover in less detail, making them less accessible. I expect that Dreiner, Haber and Martin will become a valuable resource for all those who are interested in the extensions of the SM, especially if they include supersymmetry.

Nikolaos Rompotis *University of Liverpool.*

Dark Matter: Evidence, Theory and Constraints

By David J E Marsh, David Ellis and Viraf M Mehta

Princeton University Press

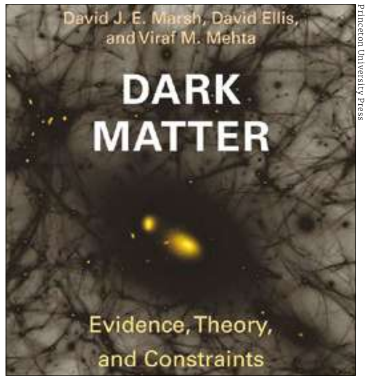
Cold non-baryonic dark matter appears to make up 85% of the matter and 25% of the energy in our universe. However, we don't yet know what it is. As the opening of many research proposals state, "The nature of dark matter is one of the major open questions in physics."

Dark-matter research spans a broad range of topics and methods, making it a challenging field to master

The evidence for dark matter comes from astronomical and cosmological observations. Theoretical particle physics provides us with various well motivated candidates, such as weakly interacting massive particles (WIMPs), axions and primordial black holes. Each has different experimental and observational signatures and a wide range of searches are taking place. Dark-matter research spans a very broad range of topics and methods. This makes it a challenging research field to enter and master. *Dark Matter: Evidence, Theory and Constraints* by David Marsh, David Ellis and Viraf Mehta, the latest addition to the Princeton Series in Astrophysics, clearly presents the relevant essentials of all of these areas.

The book starts with a brief history ▷ of dark matter and some warm-up calculations involving units. Part one outlines the evidence for dark matter, on scales ranging from individual galaxies to the entire universe. It compactly summarises the essential background material, including cosmological perturbation theory.

Part two focuses on theories of dark matter. After an overview of the Standard Model of particle physics, it covers three candidates with very different motivations, properties and phenomenology: WIMPs, axions and primordial black holes. Part three then covers both direct and indirect searches for these candidates. I particularly like the schematic illustrations of experiments; they should be helpful for theorists who want to (and should!) understand the essentials of experimental searches.


Princeton University Press

The main content finishes with a brief overview of other dark-matter candidates. Some of these arguably merit more extensive coverage, in particular sterile neutrinos. The book ends with extensive recommendations for further reading, including textbooks, review papers and key research papers.

The one thing I would argue with is the claim in the introduction that dark matter has already been discovered. I agree with the authors that the evidence for dark matter is strong and currently cannot all be explained by modified gravity theories. However, given that all of the evidence for dark matter comes from its gravitational effects, I'm open to the possibility that our understanding of gravity is incorrect or incomplete. The authors are also more positive than I am about the prospects for dark-matter detection in the near future, claiming that we will soon know which dark-matter candidates exist "in the real pantheon of nature". Optimism is a good thing, but this is a promise that dark-matter researchers (myself included…) have now been making for several decades.

The conversational writing style is engaging and easy to read. The annotation of equations with explanatory text is novel and helpful, and the inclusion of numerous diagrams – simple and illustrative where possible and complex when called for – aids understanding. The attention to detail is impressive. I reviewed a draft copy for the publishers, and all of my comments and suggestions have been addressed in detail.

This book will be extremely useful to newcomers to the field, and I recommend it strongly to PhD students and undergraduate research students. It is particularly well suited as a companion to a lecture course, with numerous quizzes, problems and online materials, including numerical calculations and plots using Jupyter notebooks. It will also be useful to those who wish to broaden or extend their research interests, for instance to a different dark-matter candidate.

Anne Green *University of Nottingham.*

PEOPLE CAREERS

The new hackerpreneur

Hackathons can kick-start your career, says hacker and entrepreneur Jiannan Zhang.

The World Wide Web, AI and quantum computing – what do these technologies have in common? They all started out as "hacks", says Jiannan Zhang, founder of the open-source community platform DoraHacks. "When the Web was invented at CERN, it demonstrated that in order to fundamentally change how people live and work, you have to think of new ways to use existing technology," says Zhang. "Progress cannot be made if you always start from scratch. That's what hackathons are for."

Ten years ago, Zhang helped organise the first CERN Webfest, a hackathon that explores creative uses of technology for science and society. Webfest helped Zhang develop his coding skills and knowledge of physics by applying it to something beyond his own discipline. He also made long-lasting connections with teammates, who were from different academic backgrounds and all over the world. After participating in more hackathons, Zhang's growing "hacker spirit" inspired him to start his own company. In 2024 Zhang returned to Webfest not as a participant, but as the CEO of DoraHacks.

Hackathons are social coding events often spanning multiple days. They are inclusive and open – no academic institution or corporate backing is required – making them accessible to a diverse range of talented individuals. Participants work in teams, pooling their skills to tackle technical problems through software, hardware or a business plan for a new product. Physicists, computer scientists, engineers and entrepreneurs all bring their strengths to the table. Young scientists can pursue work that may not fit within typical research structures, develop their skills, and build portfolios and professional networks.

"If you're really passionate about something, you should be able to jump on a project and work on it," says Zhang. "You shouldn't need to be associated with a university or have a PhD to pursue it."

For early-career researchers, hackathons offer more than just technical challenges. They provide an alternative entry point into research and industry, bridging the gap between academia and real-world applications. University-run hackathons often attract corporate sponsors, giving them the budget to rent out stadiums with hundreds, sometimes thousands, of attendees.


J Zhang

Open-source entrepreneur *Jiannan Zhang.*

"These large-scale hackathons really capture the attention of headhunters and mentors from industry," explains Zhang. "They see the events as a recruitment pool. It can be a really effective way to advance careers and speak to representatives of big companies, as well as enhancing your coding skills."

In the 2010s, weekend hackathons served as Zhang's stepping stone into entrepreneurship. "I used to sit in the computer-science common room and work on my hacks. That's how I met most of my friends," recalled Zhang. "But later I realised that to build something great, I had to effectively organise people and capital. So I started to skip my computer-science classes and sneak into the business classrooms." Zhang would hide in the back row of the business lectures, plotting his plan towards entrepreneurship. He networked with peers to evaluate different business models each day. "It was fun to combine our knowledge of engineering and business theory," he added. "It made the journey a lot less stressful."

But the transition from science to entrepreneurship was hard. "At the start you must learn and do everything yourself. The good thing is you're exposed to lots of new skills and new people, but you also have to force yourself to do things you're not usually good at."

This is a dilemma many entrepreneurs face: whether to learn new skills from scratch, or to find business partners and delegate tasks. But finding trustworthy business partners is not always easy, and making the wrong decision can hinder the start up's progress. That's why planning the company's vision and mission from the start is so important.

"The solution is actually pretty straightforward," says Zhang. "You need to spend more time completing the important milestones yourself, to ensure you have a feasible product. Once you make the business plan and vision clear, you get support from everywhere."

Decentralised community governance

Rather than hackathon participants competing for a week before abandoning their code, Zhang started DoraHacks to give teams from all over the world a chance to turn their ideas into fully developed products. "I want hackathons to be more than a recruitment tool," he explains. "They should foster open-source development and decentralised community governance. Today, a hacker from Tanzania can collaborate virtually with a team in the US, and teams gain support to develop real products. This helps make tech fields much more diverse and accessible."

Zhang's company enables this by reducing logistical costs for organisers and providing funding mechanisms for participants, making hackathons accessible to aspiring researchers beyond academic institutions. As the community expands, new doors open for young scientists at the start of their careers.

"The business model is changing," says Zhang. Hackathons are becoming fundamental to emerging technologies, particularly in areas like quantum computing, blockchain and AI, which often start out open source. "There will be a major shift in the process of product creation. Instead of building products in isolation, new technologies rely on platforms and infrastructure where hackers can contribute."

Today, hackathons aren't just about coding or networking – they're about pushing the boundaries of what's possible, creating meaningful solutions and launching new career paths. They act as incubators for ideas with lasting impact. Zhang wants to help these ideas become reality. "The future of innovation is collaborative and open source," he says. "The old world relies on corporations building moats around closed-source technology, which is inefficient and inaccessible. The new world is centred around open platform technology, where people can build on top of old projects. This collaborative spirit is what makes the hacker movement so important."

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

Appointments and awards


CERN

Next CERN Director-General

On 6 November 2024 the CERN Council selected Mark Thomson to be the next Director-General of CERN. The appointment was formalised at the Council's December session, with Thomson's five-year mandate to begin on 1 January 2026. A professor of experimental particle physics at the University of Cambridge and until last month executive chair of the UK Science and Technology Facilities Council, Thomson has dedicated much of his career to CERN. He initially contributed to precision measurements of the W and Z bosons at the OPAL experiment at LEP, and has been a member of the ATLAS collaboration at the LHC. In neutrino physics, he served as co-spokesperson for the DUNE collaboration from 2015 to 2018. An expert in high-granularity particle-flow calorimetry, he has also played an important role in the design and optimisation of detectors for future colliders, particularly for the proposed ILC and CLIC projects. "This is an important time for CERN," said Thomson during a press briefing, highlighting two main challenges ahead. "We are currently working through a significant upgrade of the LHC. This in itself is an incredibly ambitious and exciting project. The second main challenge is reaching consensus and conclusion on the project that comes after the LHC. One of the nice things about the process we have at CERN is that there is a one-year run-in period to my taking on the role." *Interview on p38.*

Panofsky Prize 2025

The American Physical Society will award the 2025 W.K.H Panofsky Prize in Experimental Particle Physics to Eckhard Elsen (DESY) and Robert Klanner (University of Hamburg) for their central contributions to experiments at the HERA collider, which was in operation from 1992 to 2007. Klanner was involved in the construction, operation and analysis of the ZEUS experiment and was DESY research director from 1999 to 2005. Elsen was spokesperson for the H1 experiment and spent 25 years as a scientist at DESY, before taking up the post of CERN research director from 2016 to 2020. Their work at HERA enabled more precise tracking of particle decay paths using advanced silicon trackers, which are now the standard for many experiments in accelerator labs around the world, as well as for medical applications such as PET.

New IHEP director

Experimental particle physicist Jun Cao has taken over as director of the Institute of High Energy Physics (IHEP) in Beijing, succeeding Yi-Fang Wang, who held the position since 2011. Since joining IHEP in 2004, Cao has played a leading role in the Daya Bay reactor-neutrino experiment, serving as co-spokesperson since 2013. Since 2014, Cao has been the deputy spokesperson of Daya Bay's successor, the Jiangmen Underground Neutrino Observatory, and proposed the Taishan Antineutrino Observatory (p9). Cao's term as the new IHEP director started in October.


IHEP

Royal recognition for Virdee

The Royal Society has awarded a 2024 Royal Medal to Tejinder Singh Virdee (Imperial College London) for his "extraordinary leadership and profound impact on all phases of the monumental CMS experiment at the CERN Large Hadron Collider, including the crucial discovery of the Higgs boson through its decays to two photons". Virdee has played a major role in all phases of the CMS experiment, from conception and design, through construction to the extraction of science. "I believe that the medal not only celebrates fundamental science but also recognises the audacious undertaking of the many scientists, engineers and technicians from around the world," he said.


Imperial College London

Rare searches rewarded

Danielle Speller (Johns Hopkins) has received the 2024 Joseph A. Johnson Award for her research on neutrinoless double-beta decay and axion-like dark matter. Speller works on the HAYSTAC (Haloscope At Yale Sensitive To Axion CDM) experiment and the CUORE (Cryogenic Underground Observatory for Rare Events) experiment, and is helping to develop the next-generation ALPHA (Axion Longitudinal Plasma Haloscope) experiment. The Joseph A. Johnson Award has been granted each year since 2021 via a partnership between the American Institute of Physics and the National Society of Black Physicists.


AIP

Wiik Prize for Higgs physics

DESY has awarded the Bjørn H. Wiik Prize to Ludovica Aperio Bella from the DESY ATLAS group, for her work on studying di-Higgs production. Her team recently achieved a precision of 0.09% on the Higgs-boson mass by refining photon energy calibration techniques, which is crucial for studies involving rare decay processes such as Higgs-boson pair production. "With her outstanding analyses of precision tests of the Standard Model of particle physics, Ludovica Aperio Bella has achieved the world's best results in areas that no one would have expected the LHC to do," said Jörg Rossbach, chairman of the Wiik Prize Committee. The €3000 prize, which is granted every two to three years to early-career scientists and engineers at DESY, was awarded on DESY Day, 13 November 2024.


DESY

Shaw Prize for pulsars

The Shaw Prize in Astronomy 2024 goes to Shrinivas R Kulkarni (Caltech) for his discoveries involving millisecond pulsars, gamma-ray bursts and supernovae, among other variable or transient astronomical objects. His contributions to time-domain astronomy culminated in the conception, construction and leadership of the Palomar Transient Factory and its successor, the Zwicky Transient Facility, which have both enhanced the field's understanding of the time-variable optical sky.

PEOPLE OBITUARIES

Tsung-Dao Lee 1926–2024

Master of symmetries

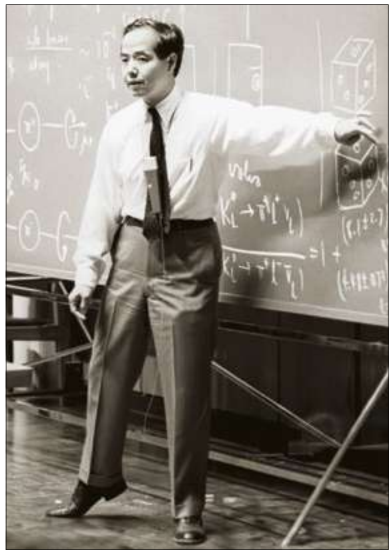
On 4 August 2024, the great physicist Tsung-Dao Lee (also known as T D Lee) passed away at his home in San Francisco, aged 97.

Born in 1926 to an intellectual family in Shanghai, Lee's education was disrupted several times by the war against Japan. He neither completed high school nor graduated from university. In 1943, however, he took the national entrance exam and, with outstanding scores, was admitted to the chemical engineering department of Zhejiang University. He then transferred to the physics department of Southwest Associated University, a temporary setup during the war for Peking, Tsinghua and Nankai universities. In the autumn of 1946, under the recommendation of Ta-You Wu, Lee went to study at the University of Chicago under the supervision of Enrico Fermi, earning his PhD in June 1950.

From 1950 to 1953 Lee conducted research at the University of Chicago, the University of California, Berkeley and the Institute for Advanced Study at Princeton. During this period, he made significant contributions to particle physics, statistical mechanics, field theory, astrophysics, condensed-matter physics and turbulence theory, demonstrating a wide range of interests and deep insights in several frontiers of physics. In a 1952 paper on turbulence, for example, Lee pointed out the significant difference between fluid dynamics in two-dimensional and three-dimensional spaces, namely, there is no turbulence in two dimensions. This finding provided essential conditions for John von Neumann's model, which used supercomputers to simulate weather.

Profound impact

During this period, Lee and Chen-Ning Yang collaborated on two foundational works in statistical physics concerning phase transitions, discovering the famous "unit circle theorem" on lattice gases, which had a profound impact on statistical mechanics and phase-transition theory.


CERN 33-8-68

T D Lee lecturing on symmetry principles at CERN in 1968.

Between 1952 and 1953, during a visit to the University of Illinois at Urbana-Champaign, Lee was inspired by discussions with John Bardeen (winner, with Leon Neil Cooper and John Robert Schrieffer, of the 1972 Nobel Prize in Physics for developing the first successful microscopic theory of superconductivity). Lee applied field-theory methods to study the motion of slow electrons in polar crystals, pioneering the use of field theory to investigate condensed matter systems. According to Schrieffer, Lee's work directly influenced the development of their "BCS" theory of superconductivity.

In 1953, after taking an assistant professor position at Columbia University, Lee proposed a renormalisable field-theory model, widely known as the "Lee Model," which had a substantial impact on the study of renormalisation in quantum field theory.

On 1 October 1956, Lee and Yang's theory of parity non-conservation in weak interactions was published in *Physical Review*. It was quickly confirmed by the experiments of Chien-Shiung Wu and others, earning Lee and Yang the 1957 Nobel Prize in Physics – one of the fastest recognitions in the history of the Nobel Prize. The discovery of parity violation significantly challenged the established understanding of fundamental physical laws and directly led to the establishment of the universal V–A theory of weak interactions in 1958. It also laid the groundwork for the unified theory of weak and electromagnetic interactions developed a decade later.

In 1957, Lee, Oehme and Yang extended symmetry studies to combined charge–parity (CP) transformations. The CP non-conservation discovered in neutral K-meson decays in 1964 validated the importance of Lee and his colleagues' theoretical work, as well as the later establishment of CP violation theories. The same year, Lee was appointed the Fermi Professor of Physics at Columbia.

In the 1970s, Lee published papers exploring the origins of CP violation, suggesting that it might stem from spontaneous symmetry breaking in the vacuum and predicting several significant phenomenological consequences. In 1974, Lee and G C Wick investigated whether spontaneously broken symmetries in the vacuum could be partially restored under certain conditions. They found that heavy-ion collisions could achieve this restoration and produce observable effects. This work pioneered the study of the quantum chromodynamics (QCD) vacuum, phase transitions and quark–gluon plasma. It also laid the theoretical and experimental foundation for relativistic heavy-ion collision physics.

From 1982, Lee devoted significant efforts to solving non-perturbative QCD using lattice-QCD methods. Together with Norman Christ and Fred Friedberg, he developed stochastic lattice field theory and promoted first-principle lattice simulations on supercomputers, greatly advancing lattice QCD research.

Immense respect

In 2011 Lee retired as a professor emeritus from Columbia at the age of 85. In China, he enjoyed immense respect, not only for being the first Chinese scientist (with Chen-Ning Yang) to win a Nobel Prize, but also for enhancing the level of science and education in China and promoting the Sino-American collaboration in high-energy physics. This led to the establishment and successful construction of China's first major high-energy physics facility, the Beijing Electron–Positron Collider (BEPC). At the beginning of this century, Lee supported and personally helped the upgrade of BEPC, the Daya Bay reactor neutrino experiment and others. In addition, he initiated, promoted and executed the China–US Physics Examination and Application plan, the National Natural Science Foundation of China, and the postdoctoral system in China.

Tsung-Dao Lee's contributions to an extraordinarily wide range of fields profoundly shaped humanity's understanding of the basic laws of the universe.

His friends and colleagues in China.

James D Bjorken 1934–2024

Scaling the heights of the strong force

Theoretical physicist James D "BJ" Bjorken, whose work played a key role in revealing the existence of quarks, passed away on 6 August aged 90. Part of a wave of young physicists who came to Stanford in the mid-1950s, Bjorken also made important contributions to the design of experiments and the efficient operation of accelerators.

Born in Chicago on 22 June 1934, James Daniel Bjorken grew up in Park Ridge, Illinois, where he was drawn to mathematics and chemistry. His father, who had immigrated from Sweden in 1923, was an electrical engineer who repaired industrial motors and generators. After earning a bachelor's degree at MIT, he went to Stanford University as a graduate student in 1956. He was one of half a dozen MIT physicists, including his adviser Sidney Drell and future director of the SLAC National Accelerator Laboratory Burton Richter, who were drawn by new facilities on the Stanford campus. This included an early linear accelerator that scattered electrons off targets to explore the nature of the neutron and proton.

Ten years later those experiments moved to SLAC, where the newly constructed Stanford Linear Collider would boost electrons to much higher energies. By that time, theorists had proposed that protons and neutrons contained fundamental particles. But no one knew much about their properties or how to go about proving they were there. Bjorken, who joined the Stanford faculty in 1961, wrote an influential 1969 paper in which he suggested that electrons were bouncing off point-like particles within the proton, a process known as deep inelastic scattering. He started lobbying experimentalists to test it with the SLAC accelerator.


Fermilab/wikicommons

James Bjorken invented an analytical approach called Bjorken scaling.

Carrying out the experiments would require a new mathematical language and Bjorken contributed to its development, with simplifications and improvements from two of his students (John Kogut and Davison Soper) and Caltech physicist Richard Feynman. In the late 1960s and early 1970s, those experiments confirmed that the proton does indeed consist of fundamental particles – a discovery honoured with the 1990 Nobel Prize in Physics for SLAC's Richard Taylor and MIT's Henry Kendall and Jerome Friedman. Bjorken's role was later recognised by the prestigious Wolf Prize in Physics and the 2015 High Energy and Particle Physics Prize of the European Physical Society.

While the invention of "Bjorken scaling" was his most famous scientific achievement, Bjorken was also known for identifying a wide variety of interesting problems and tackling them in novel ways. He was somewhat iconoclastic. He also had colourful and often distinctly visual ways of thinking about physics – for instance, describing physics concepts in terms of plumbing or a baked Alaska. He never sought recognition for himself and was very generous in recognising the contributions of others.

In 1979 Bjorken headed east to become associate director for physics at Fermilab. He returned to SLAC in 1989, where he continued to innovate. Over the course of his career, among other things, he invented ideas related to the existence of the charm quark and the circulation of protons in a storage ring. He helped popularise the unitarity triangle and, along with Drell, co-wrote the widely used graduate-level textbooks *Relativistic Quantum Mechanics* and *Relativistic Quantum Fields*. In 2009 Bjorken contributed to an influential paper by three younger theorists suggesting approaches for searching for "dark" photons, hypothetical carriers of a new fundamental force.

He was also awarded the American Physical Society's Dannie Heineman Prize, the Department of Energy's Ernest Orlando Lawrence Award, and the Dirac Medal from the International Center for Theoretical Physics. In 2017 he shared the Robert R Wilson Prize for Achievement in the Physics of Particle Accelerators for groundbreaking theoretical work he did at Fermilab that helped to sharpen the focus of particle beams in many types of accelerators.

Known for his warmth, generosity and collaborative spirit, Bjorken passionately pursued many interests outside physics, from mountain climbing, skiing, cycling and windsurfing to listening to classical music. He divided his time between homes in Woodside, California and Driggs, Idaho, and thought nothing of driving long distances to see an opera in Chicago or dropping in unannounced at the office of some fellow physicist for deep conversations about general relativity, dark matter or dark energy – once remarking: "I've found the most efficient way to test ideas and get hard criticism is one-on-one conversation with people who know more than I do."

His friends and colleagues at Stanford.

Max Klein 1951–2024

Journeying to the heart of the proton

Experimental particle physicist Max Klein, whose exceptional career spanned theory, detectors, accelerators and data analysis, passed away on 23 August 2024.

A strong advocate for the responsibility of scientists toward their societies

Born in Berlin in 1951, Max earned his diploma in physics in 1973 from Humboldt University of Berlin (HUB, East-Germany, GDR) with a thesis on low-energy heavy-ion physics. He received his PhD in 1977 from the Institute for High Energy Physics (IHEP) of the Academy of Sciences of the GDR in Zeuthen (now part of DESY) on the subject of multiparticle production, and his habilitation degree in 1984 from HUB. From 1973 to 1991 he conducted research at IHEP Zeuthen, spending several years from 1977 at the Joint Institute for Nuclear Research in Dubna, and from the 1980s at DESY and CERN. For his role in determining the asymmetry of the interaction of polarised positive and negative muons with the NA4 muon spectrometer at CERN's SPS M2 muon beam, he was awarded the Max von Laue Medal by the Academy of Sciences of the GDR in 1985.

Max worked as a scientist at DESY from 1992 to 2006. As a member of the H1 experiment at the lepton–proton collider HERA since 1985, his research focused on investigating the internal structure of protons using deep inelastic scat- ▷

tering. He served as spokesperson of the H1 collaboration from 2002 to 2006 for two mandates.

Max became a professor at the University of Liverpool in 2006, and the following year he joined the ATLAS collaboration. He served as chair of the ATLAS publication committee and as editorial-board chair of the ATLAS detector paper and other important works. Max made key contributions to data analysis, notably on the high-precision 7 TeV inclusive W and Z boson production cross sections and associated properties, and was a convener of the PDF forum in 2015–2016. From 2017 to 2019, Max was chair of the ATLAS collaboration board, during which he made invaluable contributions to the experiment and collaboration life. He led the Liverpool ATLAS team from 2009 to 2017. Under his guidance, the 30-strong group contributed to the maintenance of the SCT detector, as well as to ATLAS data preparation and physics analyses. The group also developed hybrids, mechanics and software for the new ITk pixel and strip detectors.

In recent years, Max's scientific contributions extended well beyond ATLAS. He was a strong advocate for the development of an electron-beam upgrade of the LHC, the LHeC, and collaborated closely with the CERN accelerator group and international teams on the development of energy-recovery linacs. Here, he was influential in the development of the PERLE demonstrator accelerator at IJCLab, for which he acted as spokesperson until 2023.

M D'Onofrio

Max Klein worked across theory, detectors, accelerators and data analysis.

In 2013 Max was awarded the Max Born Prize by the Deutsche Physikalische Gesellschaft and the UK Institute of Physics for his fundamental experimental contributions to the elucidation of the proton structure using deep-inelastic scattering. The prize citation stands as a testament to his scientific stature: "In the last 40 years, Max Klein has dedicated himself to the study of the innermost structure of the proton. In the 1990s he was a leading figure in the discovery that gluons form a surprisingly large component of proton structure. These gluons play an important role in the production of Higgs bosons in proton–proton collisions for which experiments at CERN have recently found promising candidates."

Besides being a distinguished scientist, Max was a man of unwavering principles, grounded in his selfless interactions with others and his deep sense of humanity. Drawing from his experience as a bridge between East and West, he was a strong advocate for international scientific collaboration and the responsibility of scientists toward their societies. He had a strong desire and ability to mentor and support students, postdocs and early-career researchers, and an admirably wise and calm approach to problem solving.

Max Klein had a profound knowledge of physics and a tireless dedication to ATLAS and to experimental particle physics in general. His passing is a profound loss for the entire community, but his legacy will endure.

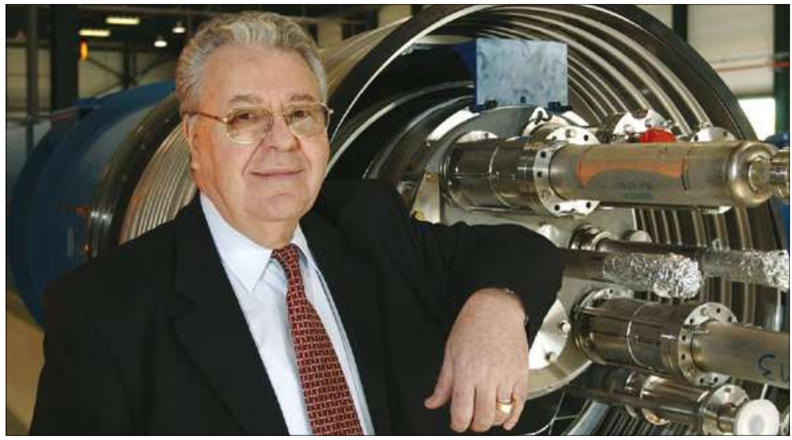
His friends and colleagues.

ROBERT AYMAR 1936–2024

Leadership in big science

Robert Aymar, CERN Director-General from January 2004 to December 2008, passed away on 23 September at the age of 88. An inspirational leader in big-science projects for several decades, including the International Thermonuclear Experimental Reactor (ITER), his term of office at CERN was marked by the completion of construction and the first commissioning of the Large Hadron Collider (LHC). His experience of complex industrial projects proved to be crucial, as the CERN teams had to overcome numerous challenges linked to the LHC's innovative technologies and their industrial production.

Robert Aymar was educated at École Polytechnique in Paris. He started his career in plasma physics at the Commissariat à l'Énergie Atomique (CEA), since renamed the Commissariat à l'Énergie Atomique et aux Énergies Alternatives, at the time when thermonuclear fusion was declassified and research started on its application to energy production. After being involved in several studies at CEA, Aymar contributed to the design of the Joint European Torus, the European tokamak project based on conventional magnet technology, built in Culham, UK in the late 1970s. In the same period, CEA was considering a compact tokamak project based on superconducting magnet technology, for which Aymar decided to use pressurised superfluid helium cooling – a technology then recently developed by Gérard Claudet and his team at CEA Grenoble. Aymar was naturally appointed head of the Tore Supra tokamak project, built at CEA Cadarache from 1977 to 1988. The successful project served *inter alia* as an industrial-sized demonstrator of superfluid helium cryogenics, which became a key technology of the LHC.



CERN-GE-0401007-01

Former CERN Director-General Robert Aymar in front of a LHC dipole magnet in 2004.

As head of the Département des Sciences de la Matière at CEA from 1990 to 1994, Aymar set out to bring together the physics of the infinitely large and the infinitely small, as well as the associated instrumentation, in a department that has now become the Institut de Recherche sur les Lois Fondamentales de l'Univers. In that position, he actively supported CEA–CERN collaboration agreements on R&D for the LHC and served on many national and international ▷

committees. In 1993 he chaired the LHC external review committee, whose recommendation proved decisive in the project's approval. From 1994 to 2003 he led the ITER engineering design activities under the auspices of the International Atomic Energy Agency, establishing the basic design and validity of the project that would be approved for construction in 2006. In 2001, the CERN Council called on his expertise once again by entrusting him to chair the external review committee for CERN's activities.

When Robert Aymar took over as Director-General of CERN in 2004, the construction of the LHC was well under way. But there were many industrial and financial challenges, and a few production crises still to overcome. During his tenure, which saw the ramp-up, series production and installation of major components, the machine was completed and the first beams circulated. That first start-up in 2008 was followed by a major technical problem that led to a shutdown lasting several months. But the LHC had demonstrated that it could run, and in 2009 the machine was successfully restarted. Aymar's term of office also saw a simplification of CERN's structure and procedures, aimed at making the laboratory more efficient. He also set about reducing costs and secured additional funding to complete the construction and optimise the operation of the LHC. After retirement, he remained active as a scientific advisor to the head of the CEA, occasionally visiting CERN and the ITER construction site in Cadarache.

Robert Aymar was a dedicated and demanding leader, with a strong drive and search for pragmatic solutions in the activities he undertook or supervised. CERN and the LHC project owe much to his efforts. He was also a man of culture with a marked interest in history. It was a privilege to serve under his direction.

Philippe Lebrun *European Scientific Institute.*

IAN SHIPSEY 1959–2024

A remarkable leader and individual

Experimental particle physicist Ian Shipsey, a remarkable leader and individual, passed away suddenly and unexpectedly in Oxford on 7 October.

Ian was educated at Queen Mary University of London and the University of Edinburgh, where he earned his PhD in 1986 for his work on the NA31 experiment at CERN. Moving to the US, he joined Syracuse as a post-doc and then became a faculty member at Purdue, where, in 2007, he was elected Julian Schwinger Distinguished Professor of Physics. In 2013 he was appointed the Henry Moseley Centenary Professor of Experimental Physics at the University of Oxford.

Ian was a central figure behind the success of the CLEO experiment at Cornell, which was for many years the world's pre-eminent detector in flavour physics. He led many analyses, most notably in semi-leptonic decays, from which he measured four different CKM matrix elements, and oversaw the construction of the silicon vertex detector for the CLEO III phase of the experiment. He served as co-spokesperson between 2001 and 2004, and was one of the intellectual leaders that saw the opportunity to re-configure the detector and the CESR accelerator as a facility for making precise exploration of physics at the charm threshold. The resulting CLEO-c programme yielded many important measurements in the charm system and enabled critical experimental validations of lattice-QCD predictions.

Influential voice

At CMS, Ian played a leading role in the construction of the forward-pixel detector, exploiting the silicon laboratory he had established at Purdue. His contributions to CMS physics analyses were no less significant. These included the observation of upsilon suppression in heavy-ion collisions (a smoking gun for the production of quark–gluon plasma) and the discovery, reported in a joint *Nature* paper with the LHCb collaboration, of the ultra-rare decay $B_s \rightarrow \mu^+\mu^-$. He was also an influential voice as CMS collaboration board chair (2013–2014).

University of Oxford

Ian Shipsey had remarkable optimism.

After moving to the University of Oxford and, in 2015, joining the ATLAS collaboration, Ian became Oxford's ATLAS team leader and established state-of-the-art cleanrooms, which are used for the construction of the future inner tracker (ITk) pixel end-cap modules. Together with his students, he contributed to measurements of the Higgs boson mass and width, and to the search for its rare di-muon decay. Ian also led the UK's involvement in LSST (now the Vera Rubin Observatory), where Oxford is providing deep expertise for the CCD cameras.

Following his tenure as the dynamic head of the particle physics sub-department, Ian was elected head of Oxford physics in 2018 and re-elected in 2023. Among his many successful initiatives, he played a leading role in establishing the £40 million UKRI "Quantum Technologies for Fundamental Physics" programme, which is advancing quantum-based applications across various areas of physics. With the support of this programme, he led the development of novel atom interferometers for light dark matter searches and gravitational-wave detection.

Ian took a central role in establishing roadmaps for detector R&D both in the US and (via ECFA) in Europe. He was one of the coordinators and driving force of the ECFA R&D roadmap panel, and co-chair of the US effort to define the basic research needs in this area. As chair of the ICFA instrumentation, innovation and development panel, he promoted R&D in instrumentation for particle physics and the recognition of excellence in this field.

Among his many prestigious honours, Ian was elected a Fellow of the Royal Society in 2022 and received the James Chadwick Medal and Prize from the Institute of Physics in 2019. He served on numerous collaboration boards, panels, and advisory and decision-making committees shaping national and international science strategies.

The success of Ian's career is even more remarkable given that he lost his hearing in 1989. He received a cochlear implant, which restored limited auditory ability, and gave unforgettable talks on this subject, explaining the technology and its impact on his life.

Ian was an outstanding physicist and also a remarkable individual. His legacy is not only an extensive body of transformative scientific results, but also the impact that he had on all who met him. He was equally charming, whether speaking to graduate students or lab directors. Everyone felt better after talking to Ian. His success derived from a remarkable combination of optimism and limitless energy. Once he had identified the correct course of action, he would not allow himself to be dissuaded by cautious pessimists who worried about the challenges ahead. His colleagues and many graduate students will continue to benefit for many years from the projects he initiated. The example he set as a physicist, and the memories he leaves as friend, will endure still longer.

Alan Barr, Tony Weidberg *and* **Guy Wilkinson** *University of Oxford.*

BACKGROUND

Notes and observations from the high-energy physics community

High-school HEP


CERN

How to teach *The course is informed by the well established framework of "educational reconstruction".*

CERN education gurus wife-and-husband-team Julia Woithe and Jeff Wiener have launched an interactive online introduction to particle physics for high-school students. Sixteen chapters whizz through videos, quizzes and DIY experiments that can be performed at home. Woithe and Wiener mix childlike wonder with exceptionally clear exposition – a salutary reminder to the rest of us to start at the beginning, with questions like "do we even know what a particle is?" Try it out yourself at cern.ch/PPC.

N Hüsken *et al.* 2024 arXiv:2410.06923

Pentaquark in the park *Exotic hadrons and the experiments studying them.*

Hot on the heels of the *Courier*'s exploration of exotic hadrons in the November/December issue, Nils Hüsken (Mainz), Elisabetta Spadaro Norella (Genoa) and Ivan Polyakov (CERN) have uploaded their own brief guide to exotic hadrons to the preprint archive, featuring "an almost zoological field guide" and winning artwork (arXiv:2410.06923).

Media corner

"He is a person who values what the FCC can bring to CERN, but who is also aware of the reservations some people might have. I think he will really act in a quite transparent way to come to a decision."

Former CERN Council president **Ursula Bassler** on the appointment of Mark Thomson as CERN's next Director-General (*Nature*, 7 November).

"Now that we face this existential threat, we need to find a way to relate to science appropriately. We have to restore a discourse about what options are available to us. I want to thank CERN for showing the rest of the world how this can be done in the best way possible."

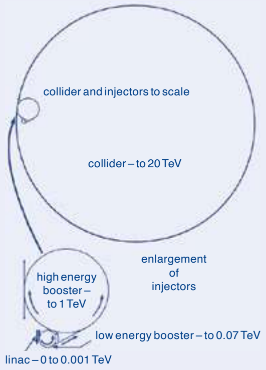
Former US vice president **Al Gore** on the importance of making science transparent and understandable (CERN, 8 November).

"Hawking said gravity started the universe. So he's not saying there is no God. He's saying gravity is God. And at least that would explain why Catholics celebrate Mass."

Director of the Vatican Observatory **Guy Consolmagno** on the orthogonal questions posed by science and religion (*The Times*, 17 November).

From the archive: January/February 1985

What goes around comes around



A possible SSC injection scheme.

In summer 1983, the US High Energy Physics Advisory Panel HEPAP took the important decision to place its eggs in a single basket, the Superconducting Super Collider SSC, to enter the TeV range by colliding protons at energies up to 20 TeV. The hope is to have the SSC conceptual design and site selection in place for April 1986. Actual construction would start in October 1987 with first beams scheduled for 1993. It is a project of great vision that would open a region of physics where theoreticians promise much.

The major part of CERN's research equipment is beyond the manufacturing capabilities of CERN's workshops and must be supplied by industry. Specifications and requirements are often beyond currently available "know-how", producing quality improvements, increased productivity, new products, etc. A survey finds that one CERN franc spent in the high technology sector has generated three useful francs for the suppliers, a bonus for a major European Laboratory whose basic objective remains pure scientific research. CERN's scientific achievements may well go on to revolutionise the 21st century, just as today's technology results from breakthroughs in electrodynamics by Faraday, Maxwell, Hertz and others, 19th-century research that did not require multinational budgets.

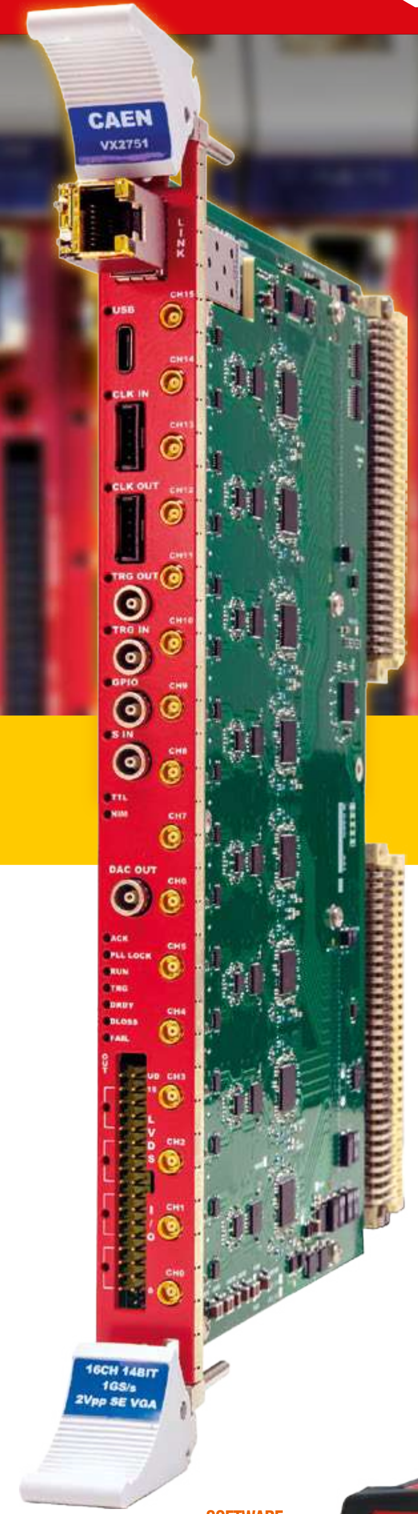
- Text adapted from *CERN Courier* January/February 1985 pp 3, 4, 8.

Compiler's note

With over a quarter of the 87 km SSC tunnel excavated in Waxahachie, Texas, construction was cancelled in 1993, leaving the stage empty for CERN's TeV-scale Large Hadron Collider. Built in the existing LEP 27 km tunnel, the LHC started up in 2008 and delivered the Higgs boson in 2012. Soon after, feasibility studies started for a near 100 km Future Circular Collider, to collide leptons in a first stage and hadrons in a later stage, pushing the energy frontier to 100 TeV. A conceptual design report was published in 2018 and the study should complete in 2025. Studies by economists show that the FCC would deliver benefits that outweigh its cost, with an estimated benefit/cost ratio of 1.66 from impacts on industry, training, software, spin-off companies, cultural goods and other factors.

130,000

The number of gold nuclei produced each second in lead–lead collisions at the LHC, amounting to 4×10^{-11} grams so far (ALICE Collab. 2024 arXiv:2411.07058)


CAEN
VX2751
16CH 14BIT
1GS/s
2Vpp SE VGA


CAEN Tools for Discovery
DT2751 16ch 14bit 1GS/s Digitizer