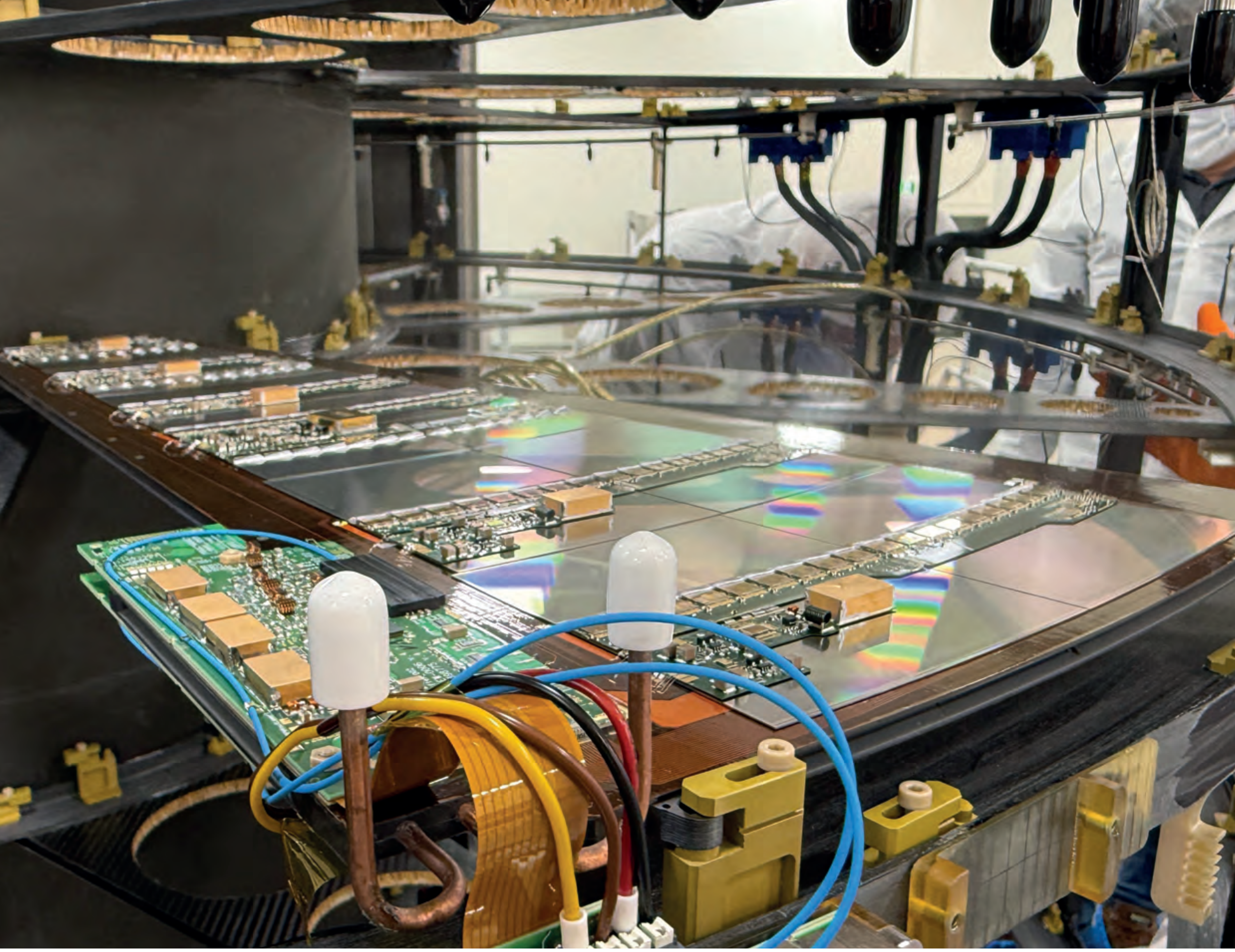


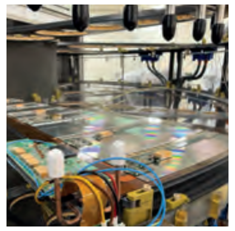
PARTICLE PHYSICS 2025.

Highlights and Annual Report

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

PARTICLE PHYSICS 2025.

Highlights and Annual Report



Cover
Detector construction for the ATLAS experiment at the LHC: First full petal with silicon modules produced at both DESY sites, installed in the ATLAS endcap in the Detector Assembly Facility (DAF) at DESY.

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The year 2025 at DESY

Dear Colleagues and Friends of DESY

As I reflect on the year 2025, I am proud to present this annual report of DESY. It is the first time that I have the honour to do this, having started as Chair of the DESY Board of Directors on 1 April. I have very much enjoyed this first half year in my new job, most of all as every day I learn something new about DESY, and I get to work with so many talented and committed people.

In 2025, there were many changes in the Directorate: Britta Redlich started on 1 January as the new Director in charge of Photon Science, taking over from Franz X. Kärtner, who had filled this role ad interim for a year after Edgar Weckert's term finished at the end of 2023.

On 1 April, Iris Wilhelm took up her position as Administrative Director. And, on 1 November, Ulrich Husemann started as new Director in charge of Particle Physics. My deep gratitude goes to the former and interim directors, Christian Harringa, Edgar Weckert, Arik Willner, Ties Behnke and in particular Helmut Dosch, for their tireless commitment to advance DESY. Together with the experienced directors Wim Leemans and Christian Stegmann, we form a team that is steering DESY – in collaboration with the deputy directors, group and team leaders, all employees as well as the members of our advisory boards and the funding agencies – through these somewhat turbulent times.

Figure 1

Ceremonial transition at DESY on 31 March 2025: Outgoing Chair of the DESY Board of Directors Helmut Dosch (right) transfers leadership to Beate Heinemann (left), with Manja Schüle (Minister of Science, Brandenburg) and Katharina Fegebank (Senator and Second Mayor of Hamburg) in attendance.

Figure 2

The DESY Board of Directors with newly appointed members in November 2025 (from left): Miriam Hufnagl (Delegate of the Directorate for Innovation, CTO (interim)), Iris Wilhelm (Director of Administration), Christian Stegman (Director in charge of Astroparticle Physics), Wim Leemans (Director of the Accelerator Division), Britta Redlich (Director in charge of Photon Science), Beate Heinemann (Chair of the DESY Board of Directors) and Ulrich Husemann (Director in charge of Particle Physics)

Science faces profound challenges in today's world. The pace of technological and geopolitical change has blurred the lines between open knowledge and strategic competition. Global crises, such as pandemics, climate change, conflicts and wars, underscore the need for international collaboration, and simultaneously trust and cooperation across borders are eroding. At the same time, the spread of misinformation and the politicisation of scientific facts threaten public confidence in evidence-based decision and policy making. Researchers must balance openness with responsibility – safeguarding integrity, transparency and security while ensuring that science continues to serve humanity as a shared, global endeavour.

DESY as a premier research institution plays an important role in the national and international science landscape. Each year, thousands of scientists from around the world come to us to perform measurements, attend workshops and conferences or collaborate with colleagues on our sites in Zeuthen and Hamburg. We have collaborations with institutions across Europe and the entire world, and our scientists travel across the globe to advance their research.

The success of DESY is founded on the design, construction and operation of fantastic research infrastructures, on cutting-edge contributions to science, on the thriving of many scientists at all career levels, who pursue their ideas and engage in collaborations worldwide, and – above all – on the skilled and dedicated employees of DESY, who enable all this at a technical and administrative level.

This year, DESY has once again demonstrated its scientific excellence. In February 2025, a panel of international scientists appointed by the Helmholtz Association visited and reviewed DESY. All areas of our research and of the operation of our facilities were rated with the highest marks, and many useful recommendations were given for the next funding period of the Helmholtz Association's programme-oriented funding (PoF V). The panel was also impressed by our activities in the areas of diversity, international cooperation, sustainability, innovation and talent development. Later in the year, we were thrilled that six Clusters of Excellence with DESY contributions were selected for funding by the German Research Foundation (DFG), and at the European level one European Research Council (ERC) Starting Grant and two Synergy Grants were awarded.

A major achievement this year has been the completion of the upgrade project FLASH2020+. The implementation of external seeding and the newly installed variable-gap undulators will significantly enhance the capabilities of the FLASH free-electron laser facility, so that it remains at the forefront of extreme ultraviolet and soft X-ray science. In Zeuthen, a key accomplishment has been the completion of the construction of new sensor modules (mDOMs) for the upgrade of the IceCube neutrino detector at the South Pole: 201 mDOMs were shipped to Antarctica to be installed there during the Antarctic summer. During the second half of 2025, the accelerator of the European XFEL X-ray laser was warmed up for the first time since its start-up in 2017 to allow the mandatory inspection of helium valves, perform maintenance tasks and install a new electron source at the beginning of the accelerator, which was newly developed at DESY's photoinjector test facility (PITZ) in Zeuthen. DESY's efforts for on-site experiments in particle physics are also beginning to pay off: The results of the search for very light dark matter particles from the ALPS II experiment have been published.

2025 has also seen DESY at the forefront of critical political and strategic initiatives. The selection of our two future projects, IceCube-Gen2 and PETRA IV, in the "National Prioritisation Process for Extensive Research Infrastructures", alongside seven other large research infrastructures in Germany, underscores our important role in shaping the national and European research agendas. In 2026, we expect to get the final go-ahead for the PETRA IV project and continue to advance the detailed planning, with the goal of delivering the project on time and on budget. 2026 will also bring an update of the European Strategy for Particle Physics, to which DESY scientists are contributing significantly; the update might shape the future of the field for a long time.

Figure 3

Celebrating a milestone for German science: On 8 July 2025, DESY employees gathered in the auditorium to mark the BMFTR's decision to prioritise IceCube-Gen2 and PETRA IV as key research infrastructures. In the front row (from left): new directors Iris Wilhelm and Britta Redlich.

It is particularly important to attract young talents to DESY. At any time, we have about 130 apprentices, 250 doctoral students and 250 postdoctoral researchers at DESY. Among the PhD students and postdoctoral researchers, about two thirds are not from Germany, and our International Office plays a key role in ensuring that these young people are supported during the first weeks, so that they quickly feel at home. This year, we also welcomed three new lead scientists, who bring fresh perspectives and expertise to DESY: Elina Fuchs in theoretical particle physics, Samaya Nissanke in gravitational and multi-messenger astrophysics and Nønne Prisle in physical chemistry and aerosol research.

Innovation is a very important part of DESY's mission. We want to contribute to ensuring that science also results in making life better for society at large. The successful participation in the Startup Factories competition of the Federal Ministry for Economic Affairs and Energy, resulting in the "Impossible Founders", which strengthen the innovation ecosystem in Hamburg, as well as our strategic cooperation with the Fraunhofer-Gesellschaft exemplify our commitment to translating research into practical applications. These collaborations, along with our many regional, national and global partnerships with industry partners and academic institutions, position DESY as a leader in both scientific and industrial innovation.

Our campuses in Hamburg and Zeuthen continue to evolve. We had three topping-out ceremonies this year, celebrating the structural completion of the Centre for Accelerator Science and Technology (CAST) building and the two DESY Innovation Factory buildings. The new visitor centre DESYUM in Hamburg will open in spring 2026. Together with our campus partners, we are striving to make our campuses more sustainable and greener, and we have been awarded prizes this year: for the roof terrace of the Max Planck Institute for the Structure and Dynamics of Matter and the DESY Building 36, a big hall from 1977 on the Hamburg campus.

In an increasingly interconnected world, international collaboration is more important than ever. Our partnerships with institutions such as the SESAME synchrotron light source in Jordan and our engagement in science diplomacy reflect our belief in the power of global cooperation. As we navigate geopolitical challenges, DESY remains committed to fostering transparency, exchange and collaboration on both local and international levels.

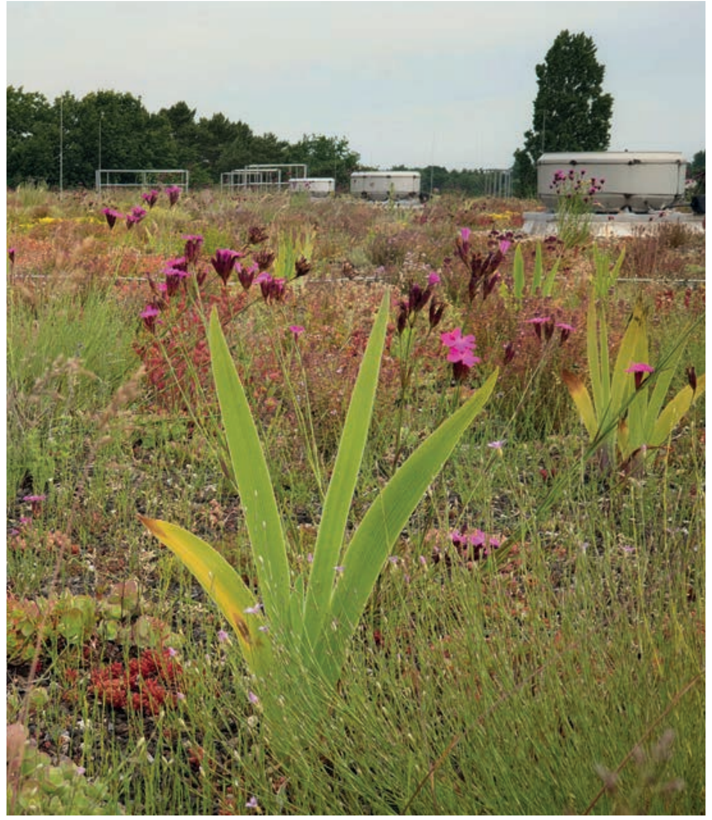


Figure 4

Impression of the roof of DESY's award-winning Building 36

In closing, I would like to express my gratitude to the entire DESY community – our experienced and early-career scientists, engineers, technicians, administrators, users and partners – for their dedication and hard work. My special thanks go to the funding agencies – the Federal Ministry of Research, Technology and Space (BMFTR) and the Science Ministries in Hamburg and Brandenburg (BWFG and BMWK) – which have been supporting DESY for many decades. I would also like to extend my heartfelt thanks to my predecessor Helmut Dosch for his outstanding leadership and long-standing commitment to DESY, which have laid the foundations for much of what we are building on today. Together, we continue to push the boundaries of knowledge and innovation, ensuring that DESY remains at the forefront of global research.

Warm regards,

Yours Beate

Beate Heinemann
Chairperson of the DESY Board of Directors

Particle physics at DESY

Introduction

Dear Colleagues and Friends of DESY,

It is my great pleasure to address you for the first time in my new capacity as DESY's Director of Particle Physics. Having arrived at DESY only in November 2025, let me take this foreword as an opportunity to sketch my impressions from – and insights into – the Particle Physics Division so far. First of all, I am deeply impressed by your dedication to our division's mission – that is, to the goals of enabling great science and delivering outstanding results.

Let me start with the "physics harvest" and my short, personal and very biased collection of highlight results of the past year – apologies to all those whose beautiful results I do not mention!

The ALPS and ALPS II axion search experiments have been in preparation at DESY for close to 15 years, and after the first data run in early 2024, expectations for results from the experiments were high. Now, the first publication of ALPS II results is out. And although ALPS II did not (yet) find axions, the experiment improved the limit for the diphoton coupling of such light-weight particles by a factor of more than 20, down to values of 1.5×10^{-9} GeV^{-1}. A further improvement of the sensitivity by two orders of magnitude will become possible with upgrades to the experiment that are currently under way. This result – together with, for example, first limits derived with prototype setups of the MADMAX experiment on axions and dark photons – underlines DESY's ambition to be an international axion "hotspot".

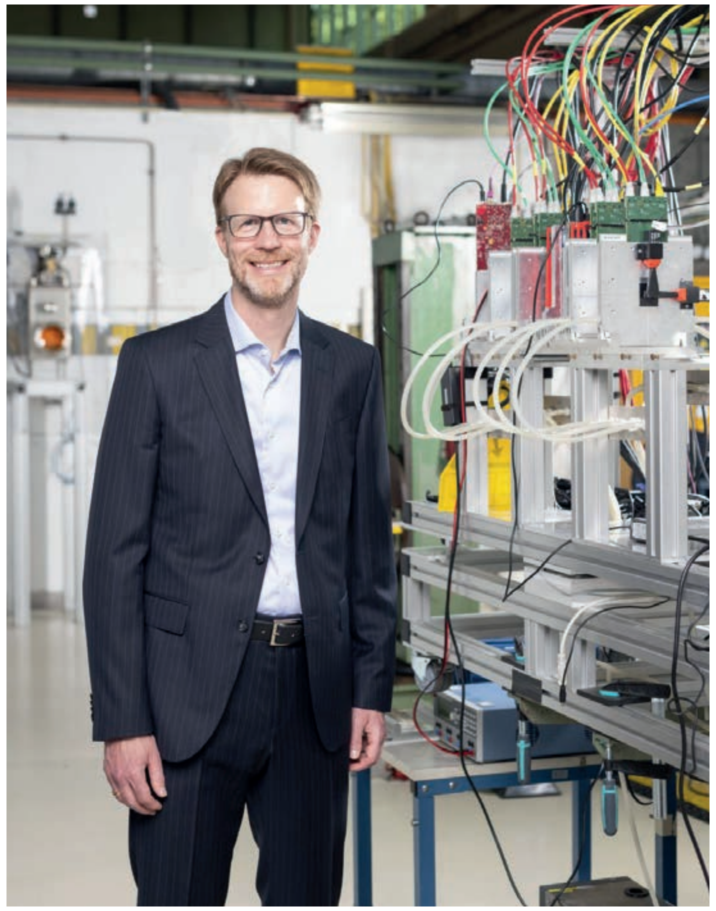


Figure 1

Ulrich Husemann took over DESY's Particle Physics Division in November 2025.

Another exciting result with major DESY contributions is the unexpected observation of toponium – an extremely short-lived bound state of a top quark and antiquark – by the CMS and ATLAS experiments at the Large Hadron Collider (LHC) at CERN. While the precise interpretation of the small peak at the top quark–antiquark production threshold remains open – and theorists are working flat out on this! – the result shows that the combination of high energy, high luminosity and innovative data analysis methods at the LHC is a very successful recipe for surprising results. We can thus confidently expect more exciting news to come from the Geneva area in the years to come!

Our Theory group has also been overwhelmingly productive in the past year. One absolutely noteworthy result is the first calculation of baryon number violation at 0 K from collisions of bubbles in the Higgs field – a result that opens up new approaches to solving the puzzle of the matter–antimatter imbalance in our universe.

These and all the other results would not have been possible without technical and infrastructural groundwork, and without appropriate funding. In this respect, the amount of third-party funding acquired by the division through our scientists' tireless effort is impressive. Particularly important are the Cluster of Excellence "Quantum Universe" together with Universität Hamburg, which will receive funding for a second seven-year period, the European Research Council (ERC) grants for Elina Fuchs and for Jenny List and colleagues, and the ELBEX EU grant for the construction of an extraction beamline at the European XFEL X-ray laser facility for the LUXE strong-field quantum electrodynamics experiment. Not to be forgotten are the many third-party funds that the Theory group has raised. In addition, for some of our activities, important decisions have been taken: The planned location of the BabyIAXO axion search experiment was shifted from the hall of the former ZEUS experiment (HERA South) to the hill between Building 1 and Hall 1, making the site much more accessible. The designated location of the ELBEX beamline and the LUXE experiment was also moved to a different European XFEL tunnel.

The upgrades for the High-Luminosity LHC (HL-LHC) are the number-one priority for particle physics in Europe, and for our division. The development work towards constructing endcaps for the ATLAS and CMS silicon tracking detectors and producing the CMS high-granularity calorimeter (HGCAL) is basically done, and much of the pre-series production work is ready. However, production progress has experienced several significant setbacks beyond the scope of DESY's responsibility in the past years, challenging the HL-LHC schedule, not least with the now all too familiar bPOL12V application-specific integrated circuit (ASIC). DESY is deeply involved in tackling these issues – and solving them! It is very clear that we have to go "all in" in the coming years to "deliver" and make the upgrades a success.

I gratefully acknowledge the full support that the HL-LHC upgrade projects – and all of our development and construction work – receive from our technical groups, be it the Electronics Development (FE) group or the Service Centre Electronics (ZE), the DESY II Test Beam team, the Library, the IT group and others. It is clear that we all rely on these important contributions for our scientific progress.

From virus-free PCs to massive compute power for science, the DESY campus could not be operated without the IT group. At the same time, IT has strengthened their own research in scientific computing, for the benefit of the entire community of the Research Field *Helmholtz Matter*.

Our world seems to be full of challenges, and recent years have seen a tremendous rise of difficult developments. Geopolitical turmoil affects the way we engage in international cooperation. We have a very tight budget situation at DESY, and fundamental research appears to be under pressure from several sides. But there are also new opportunities: DESY and our division have a lot to offer for

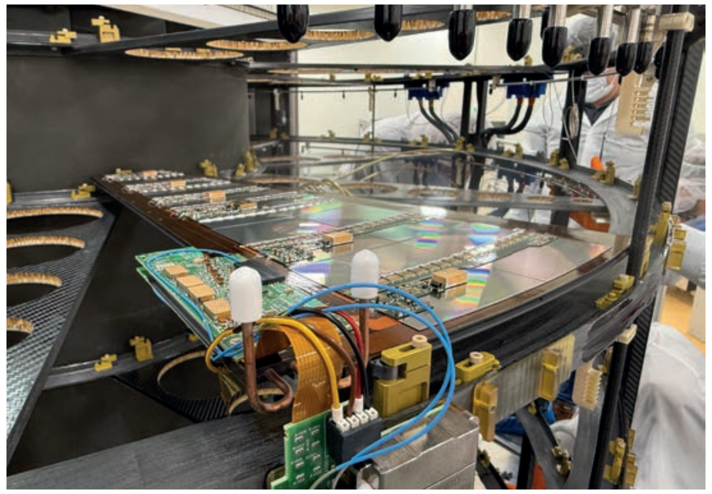


Figure 2

First full petal with silicon modules produced at both DESY sites, installed in the ATLAS endcap in the Detector Assembly Facility (DAF) at DESY

the new High-Tech Agenda Germany. In this context, it is excellent news that DESY's main priority for the next few years – PETRA IV, the upgrade of the PETRA III synchrotron radiation source – was prioritised in the national planning for large research infrastructures and received undivided support from the Science and Humanities Council (*Wissenschaftsrat*) of the German federal government.

It is also a significant step forward for our field that, in December 2025, the European Strategy Group, which I had the privilege of joining last fall, came forward with a recommendation to the CERN Council for an update of the European Strategy for Particle Physics. The clear vote of the European particle physics community for the electron–positron Future Circular Collider (FCC-ee) as the future flagship project at CERN now allows us to focus our efforts on a detailed investigation of the project – with a decision expected as early as 2028! Any decision taken will be a great opportunity for us to shape the future of our division and show once again what we can achieve together.

In this spirit, I would like to thank you all – at DESY, at our partner institutions and at our funding agencies – for your continued and untiring commitment to our endeavours. I am very much looking forward to working with you and to shaping particle physics with you. I am sure that, together, we can accomplish a lot – also under challenging circumstances. Maybe you can draw some inspiration from this annual report and the great achievements described in it. Enjoy reading!

With kind regards,

Ulrich Husemann
Director of Particle Physics

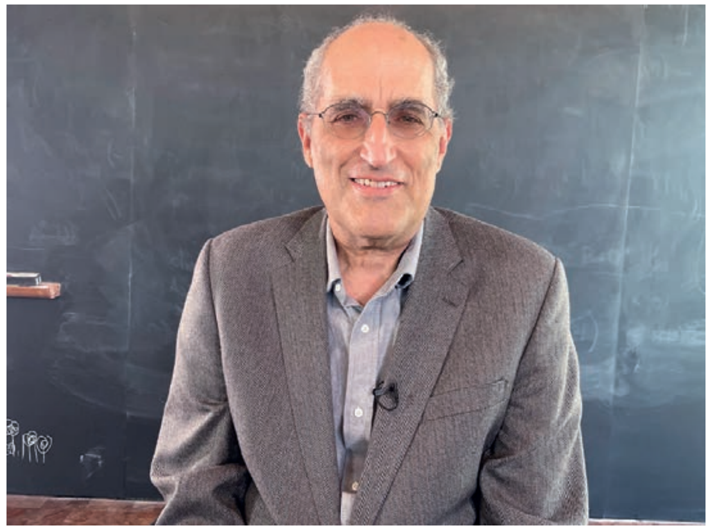
News and events

A busy year 2025

January

Edward Witten leads masterclass in Hamburg

The Wolfgang Pauli Centre for Theoretical Physics (WPC), a joint institution of DESY and Universität Hamburg, hosted a groundbreaking masterclass on "Invitation to Black Hole Thermodynamics" led by Edward Witten, one of the most influential physicists of our time. Held at DESY from 14 to 17 January, the event attracted more than 300 registered participants from around the world, underscoring the global interest in Witten's pioneering contributions to theoretical physics.

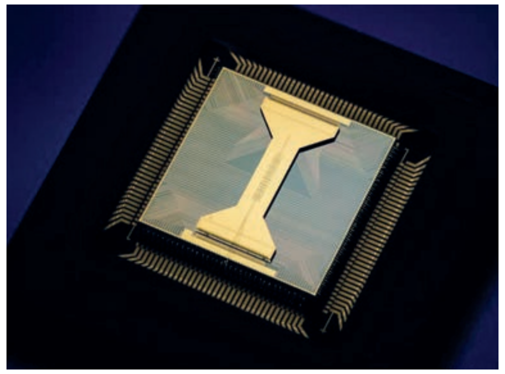


Edward Witten gave a masterclass about the thermodynamics of black holes.

Foundation stone laid for new accelerator centre

On 17 January, Eva Gümbel, Hamburg State Councillor for Science, Research and Equality, DESY Director Helmut Dosch, Accelerator Director Wim Leemans and other guests of honour laid the foundation stone for DESY's Centre for Accelerator Science and Technology (CAST). By enabling different research groups from the Accelerator Division to work side by side, the new centre for accelerator research – one of DESY's strategic core areas – will be "a place where technologies are developed, innovation is created, and knowledge is shared," as Wim Leemans emphasised on the occasion.

Visualisation of CAST



The core of Quantinuum's H1 quantum computer system

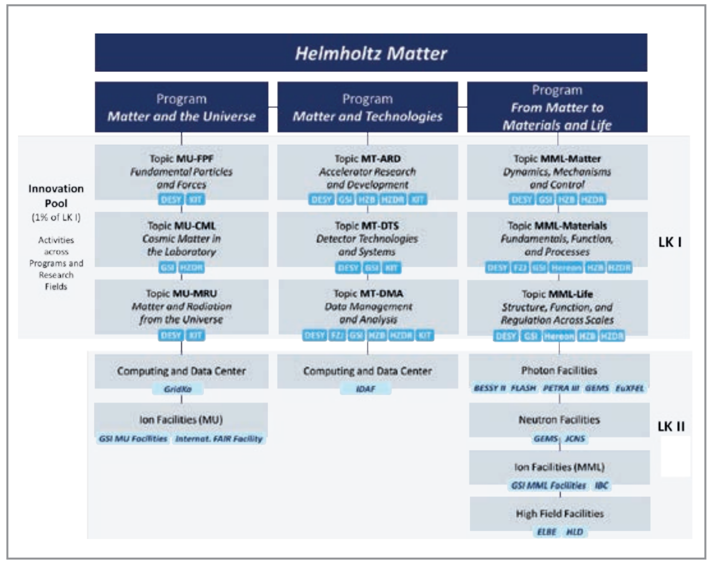
DESY and Quantinuum: breakthrough in quantum physics

The quantum computing company Quantinuum and a DESY team led by Karl Jansen, head of the Centre of Quantum Technology and Applications (CQTA) at DESY, achieved an important milestone. Using Quantinuum's H1 quantum computer, they studied a model in lattice gauge theory – a mathematical tool used to understand fundamental processes in nature. For the first time, they were able to compute the full wavefunction of a two-dimensional confinement system in quantum electrodynamics on a quantum processor.

February

Scientific evaluation of DESY

In February, a committee of 23 leading scientists in their field carried out a comprehensive evaluation of DESY, which examined the international scientific excellence of the research programmes, the role of DESY within the Helmholtz Association and in the international science landscape as well as the DESY user facilities. Particular attention was paid to the importance of DESY's unique research infrastructures for groundbreaking science. The committee analysed and assessed DESY's contributions in recent years to the Research Field *Helmholtz Matter*, in which DESY is involved in eight of nine Programme Topics. At the end of the DESY evaluation, Daniel Zajfman, Chair of the Evaluation Committee, concluded: "If I were 30 years old, I would clearly consider this place."



Structure of the Research Field *Helmholtz Matter* of the Helmholtz Association

"Jugend forscht" science competition at DESY

Soil bacteria studies of climate impacts, optimised plant behaviour, artificial intelligence in supermarkets or a prototype robot dog: These were some of the topics explored at DESY during the regional "Jugend forscht" competition. The Germany-wide science competition gives pupils the opportunity to conduct actual research and pit their findings. At the Hamburg-Bahrenfeld regional competition, which was held at DESY for the 13th time, the young research groups competed for the coveted first places, which qualified them to participate in the state competition.

DESY hosted the Hamburg-Bahrenfeld regional part of the Germany-wide "Jugend forscht" science competition.

Quarks experience forces equivalent to the weight of ten elephants

An international team of theoretical physicists led by DESY emeritus scientist Gerrit Schierholz calculated the force felt by individual quarks inside the proton, one of the building blocks of the atomic nucleus. The value and direction of this force can now be determined for each quark, which could have implications for how experiments at future particle colliders are conducted and interpreted. The forces that confine the quarks to the protons were found to be on the order of 3 GeV/fm, or about half a million newtons: roughly equivalent to the weight of ten elephants – all within the tiny space of the proton. The result was selected as a research highlight by the prestigious scientific journal *Physical Review Letters.*

March

openCost – the next stage

The DESY Library's project openCost, funded by the German Research Foundation (DFG), was approved for a second phase of another three years. The primary focus at this stage of the project is on a generalised storage format for cost data – an area in which the Library's expertise already had a significant impact in the initial phase of the project. This format serves as the foundation for the subsequent version of the cost management tool in DESY's publication database PubDB. A second key element addresses cost data for additional publication formats, some of which are not text-based.

openCost

April

Beate Heinemann leads the DESY Board of Directors

On 1 April, Beate Heinemann became the new head of DESY. She took over as Chair of the DESY Board of Directors, to which she already belonged as Director in charge of Particle Physics. Beate Heinemann succeeded Helmut Dosch, who headed DESY for 16 years. She is the first woman to lead the research centre.

Beate Heinemann

Throughout her career, Beate Heinemann made significant contributions to particle physics through her research and leadership positions in international experiments, such as H1 at DESY, CDF at Fermilab in the USA and ATLAS at CERN. In 2016, she joined DESY as lead scientist and became a professor at the University of Freiburg. She was appointed DESY Director in charge of Particle Physics in 2022 and professor at Universität Hamburg in 2023.

Iris Wilhelm

Iris Wilhelm is new Administrative Director at DESY

On 1 April, Iris Wilhelm took over the position of Administrative Director at DESY. She brought with her extensive experience in research centre management: After studying business administration, she started her career at the Helmholtz Centre Hereon as a controller in finance and accounting, then headed the finance and purchasing department. After some years in the private sector, where she held management positions in various branches of industry, she now returned to the world of research.

Ties, please take over!

For the second time, Ties Behnke, lead scientist at DESY in experimental particle physics, successfully bridged the gap between the outgoing and new Directors in charge of Particle Physics. From 1 April to 31 October, he took over as interim director, ensuring the continuation of ongoing business operations and guaranteeing a smooth transition from Beate Heinemann to Ulrich Husemann, who assumed office on 1 November.

Ulrich Husemann and Ties Behnke in the process of knowledge transfer

Kick-off for new Collaborative Research Centre in mathematical physics

With an international conference on "Higher Structures, Moduli Spaces and Integrability", the Collaborative Research Centre (*Sonderforschungsbereich, SFB*) of the same name, organised by DESY and Universität Hamburg, was officially opened at the beginning of April. On the occasion, leading scientists from the field of mathematical physics from all over the world came to Hamburg to discuss the latest developments in algebra and geometry and their connection with quantum field and string theory. This work on the foundations of the quantum world will initially be funded by the German Research Foundation (DFG) for a period of almost four years.

More than 150 researchers met for the kick-off of the new Collaborative Research Centre in Hamburg.

And the Oscar of Science goes to...

DESY scientists were among the recipients of the prestigious Breakthrough Prizes. Sometimes referred to as the "Oscars of Science", they are awarded by the Breakthrough Prize Foundation in different scientific disciplines. The 2025 breakthrough Prize for Fundamental Physics, worth three million US dollars, recognised the over 13 000 scientists from around the world working on the four experiments ALICE, ATLAS, CMS and LHCb at the LHC at CERN in Geneva – and thus some 200 scientists in the ATLAS and CMS groups at DESY.

The spokespersons of the four LHC experiments at the awarding ceremony

The 2024 winners of BL4S at DESY came from the USA.

EPS Outreach Prize for Beamline for Schools

The project Beamline for Schools (BL4S) has been turning high-school students into temporary scientists for over ten years. More than 20 000 students aged 16 to 19 from around the world came in touch with it over the course of its existence. So far, 25 teams of students have performed their experiments at a real beamline at a real physics lab. The High Energy and Particle Physics Division of the European Physical Society (EPS) awarded the project the 2025 EPS Outreach Prize "for its original, innovative and successful outreach program of global competitions for high-school teams".

May

Cluster of Excellence "Quantum Universe" extended for second funding period

The spokespersons of the Cluster of Excellence "Quantum Universe" (from left): Géraldine Servant, Erika Garutti and Timo Weigand

The Cluster of Excellence "Quantum Universe" at Universität Hamburg in collaboration with DESY will receive funding for another seven years. The German Research Foundation (DFG) and the German Science and Humanities Council (*Wissenschaftsrat, WR*) announced the positive decision on further funding for the Cluster as part of the Excellence Strategy of the German federal and state governments at a joint press conference. The Cluster will receive funding from 2026 until 2032.

May

Science takes over Hamburg's pubs for an evening

Are we immersed in dark matter? How do you reveal 5000-year-old secrets in letters? Is climate protection a private commitment or a national goal? And does the language I use influence my identity? At the yearly "Science on Tap" event, researchers from Universität Hamburg and DESY once again provided answers to exciting and topical questions in Hamburg's bars and pubs.

June

Gravity cavity

It is quite common for research equipment to end up in display cases and exhibition rooms: Discarded prototypes help to explain science and serve as technological "eye witnesses". Rarely are exhibits dusted off and moved from the glass cabinet back into the research centre. At DESY, however, one exhibit has begun its second life: a cavity that was previously on display in Genoa, Italy, is now helping to find gravitational waves and axions.

New life for an exhibit: Krisztian Peters, Marc Wenskat (both DESY) and Bianca Giaccone (Fermilab, USA) want to measure gravitational waves with the help of cavities.

July

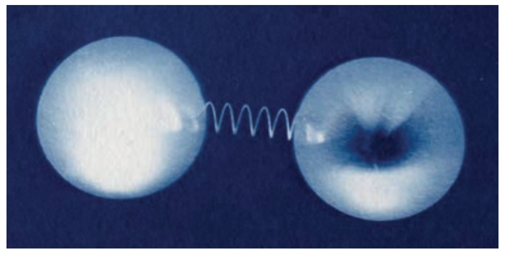
PETRA IV: for Europe from Hamburg

Two projects with DESY participation were selected in the "National Prioritisation Process for Extensive Research Infrastructures" of the Federal Ministry of Research, Technology and Space (BMFTR): Federal Research Minister Dorothee Bär announced that both projects submitted by DESY were classified as research infrastructures of national importance. The PETRA IV X-ray light source and the IceCube-Gen2 neutrino telescope were thus attested high scientific excellence, innovation and transfer potential as well as well-thought-out planning.

From left: Director in charge of Photon Science Britta Redlich, Chair of the DESY Directorate Beate Heinemann and Director of the Accelerator Division Wim Leemans with a model of the experimental hall for PETRA IV

Do top quarks combine to form a new particle called toponium?

When researchers from DESY and Universität Hamburg noticed something new in the data from the CMS experiment at the LHC in 2024, they chose their words very carefully, saying that they had seen an interesting effect in the data that could point to something that had never been seen before. In early July 2025, their colleagues from the competing ATLAS experiment reported at a meeting of the European Physical Society in Marseille, France, that they had observed the same effect. The results suggest that top quarks and their antiparticles may be able to combine into a short-lived bound state known as "toponium". DESY researchers also played a leading role in the ATLAS analysis.



Artist's impression of a connection between a top quark and its antiparticle

DESY welcomes 100 summer students from all over the world

In July and August, DESY hosted 100 students from 33 countries as part of its summer student programme – an international programme full of research projects, lectures, campus tours and culture. In Hamburg and Zeuthen, participants experienced first-hand how cutting-edge research works and gained experience for their scientific future. Tours through tunnels and laboratories, networking events and excursions into the surrounding area made the summer an unforgettable experience.

The 2025 summer students at the campus Hamburg (top) and Zeuthen (bottom)

August

DESY mourns the loss of Herwig Schopper

DESY and the physics community mourn the loss of a great scientist, science manager, diplomat and visionary. The physicist and former DESY and CERN Director General Herwig Schopper passed away in Hamburg on 19 August at the age of 101. "We have lost a giant," said DESY Director Beate Heinemann. "With his vision of science without borders in order to unravel the mysteries of the world, Herwig shaped the physics landscape in Europe and Germany like no other. He also paved the way for DESY to become the international research centre it is today. We are eternally grateful for the many projects and accelerators whose approval and construction he achieved. All our sympathy goes out to his family." Herwig Schopper chaired the DESY Board of Directors from 1973 to 1980.

Herwig Schopper (1924–2025)

September

Two Beamline for Schools winning teams perform experiments in Hamburg

From Mexico City and Montreal to Hamburg! For the first time, not one but two winning teams of the international Beamline for Schools (BL4S) competition conducted their self-designed experiments at the DESY II Test Beam Facility in Hamburg. The Canadian experiment aimed to observe the trajectories of muons with a three-dimensional scintillator-based detector. The Mexican project explored the use of kidneywood pigment and fluorite as potential scintillators in order to build less expensive detectors.

The BL4S winning teams in the HERA tunnel

October

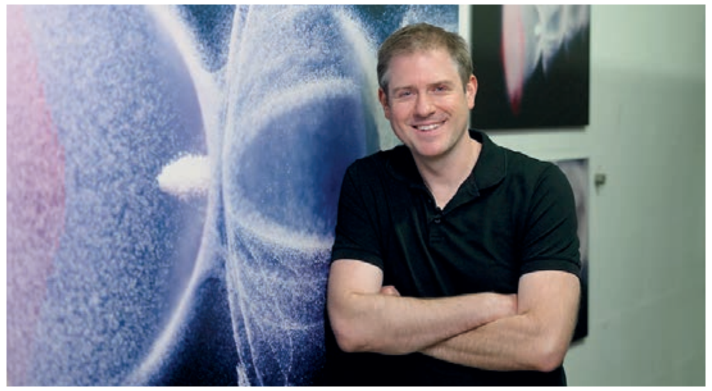
DESY wins award for green campus buildings

On 14 October, the Hamburg Environment Agency honoured DESY's project to green its Building 36 with the Hamburg Prize for Green Buildings, which recognises the best greening measures for roofs, façades and interiors in the city. Built in 1977, Building 36 has been part of a pilot project to green buildings since 2021. With a façade infrastructure that helps climbing plants and other vegetation to settle on the sides and roof of the building, it has become a model for how other buildings on the DESY campus can be greened. The aim is to improve the climate control of the buildings themselves and to bring more plants and biodiversity to the campus.

October

Andreas Maier wins 2025 Bjørn H. Wiik Prize

DESY physicist Andreas Maier is one of the world's leading experts in laser plasma acceleration. Under his leadership, the LUX experiment succeeded in generating an electron beam of high quality and stability, reaching a level of operational reliability comparable to that of conventional accelerators. More recently, an outstanding result was achieved by implementing external energy stabilisation in the LUX beamline, leading to an energy spread and stability better than 0.1%. In recognition for these achievements, which have attracted considerable international attention, Andreas Maier was honoured with DESY's most important science award, the Bjørn H. Wiik Prize.



Andreas Maier

November

Ulrich Husemann takes over the DESY Particle Physics Division

Ulrich Husemann

On 1 November, Ulrich Husemann became the new DESY Director in charge of Particle Physics. DESY is familiar territory for the particle physicist: Ulrich Husemann worked on DESY experiments during his diploma and doctoral theses and was a junior research group leader in the ATLAS group at DESY in Zeuthen, where he worked in cooperation with Humboldt University of Berlin to prepare for the upgrade of the ATLAS detector at the LHC. In 2011, he was appointed professor at the Karlsruhe Institute of Technology (KIT) and switched to the CMS experiment at the LHC. He was a member of DESY's Physics Research Committee (PRC) from 2019 to 2024. As one of Germany's representatives for the update of the European Strategy for Particle Physics, he is actively involved in shaping the international physics research landscape of the future.

PhD Thesis Prize 2025

The Association of the Friends and Sponsors of DESY (VFFD) awarded its 2025 PhD Thesis Prize in equal parts to Ke Li and Benoît Richard. Ke Li received the award for her groundbreaking work on mixed-reality interfaces for operating complex accelerator facilities. Benoît Richard was honoured for his new methods of molecular imaging. The award, which is worth 3000 euros, recognises outstanding doctoral theses that make a special contribution to research at DESY.

PhD Thesis Prize winner Ke Li joined the awarding ceremony via video link on DESY DAY.

DESY Director Beate Heinemann (left) and VFFD Chairman Franz Kärtner (right) congratulated Benoît Richard on winning the PhD Thesis Prize.

DESY scientists awarded prestigious ERC Synergy Grants

Six DESY scientists were awarded the highly competitive European Research Council (ERC) Synergy Grants for two ambitious research programmes. One team is a collaboration between DESY scientist Jenny List and lead scientist Andreas Maier alongside Henri Vincenti from the French research organisation CEA and Antonino Di Piazza from the University of Rochester in the USA. This programme, funded with 14 million euros, of which 5.3 million are allocated to DESY, will investigate the quantum fundamentals of the electromagnetic interaction by generating extremely high electric fields using plasma accelerators and high-power lasers. The other team, comprising the DESY lead scientists Saša Bajt, Francesca Calegari, Henry Chapman and Nina Rohringer, was awarded 14 million euros for DESY and will combine atomic-scale imaging with attosecond science.

The NP-QED team (from left): Andreas Maier and Jenny List from DESY, Henri Vincenti from CEA and Antonino Di Piazza from the University of Rochester

December

DESY publishes its second Sustainability Report

"Advancing ideas. Designing solutions." is the title of DESY's second Sustainability Report, published at the beginning of December, which covers the reporting period from 2022 to 2024. Featuring ideas and initiatives, achievements and figures, it also offers inspiring stories about the people on campus who are driving sustainable projects and strategies. "We are sticking to our sustainability strategy, especially in times of global political and economic uncertainty," said DESY Director Beate Heinemann. "Having laid important foundations up until 2022, we are now focusing on our energy-intensive large-scale research facilities and equipment. We want to demonstrate that scientific excellence and sustainability can reinforce one another."

DESY's second Sustainability Report

Experimental particle physics

Physics with protons has been at the heart of DESY's particle physics activities since the start-up of its former electron–proton collider HERA in 1992. Today, the cornerstones of DESY's proton physics programme are its ATLAS and CMS groups, which are involved in a large variety of developments at the Large Hadron Collider (LHC) at CERN, from hardware design to data analysis.

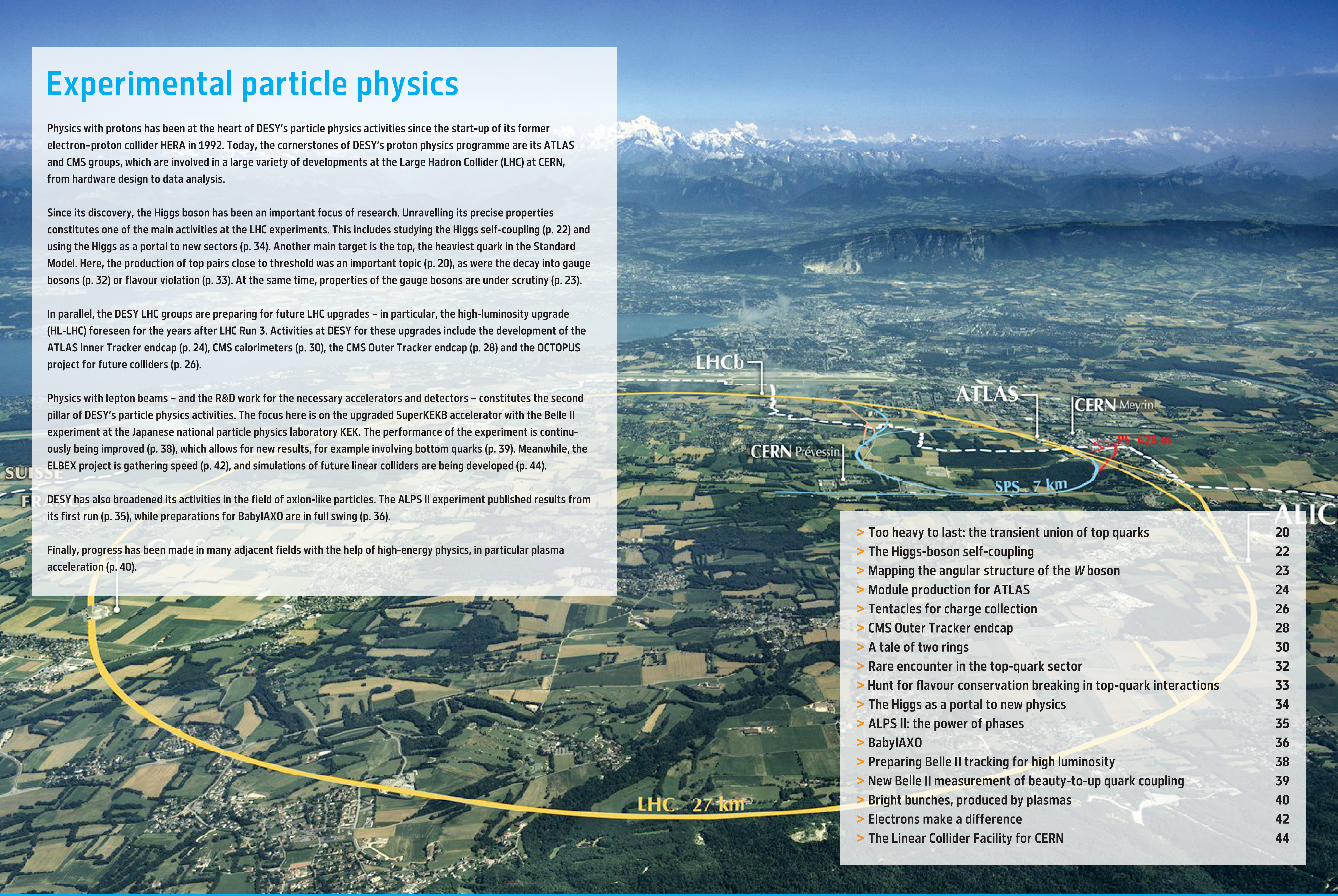
Since its discovery, the Higgs boson has been an important focus of research. Unravelling its precise properties constitutes one of the main activities at the LHC experiments. This includes studying the Higgs self-coupling (p. 22) and using the Higgs as a portal to new sectors (p. 34). Another main target is the top, the heaviest quark in the Standard Model. Here, the production of top pairs close to threshold was an important topic (p. 20), as were the decay into gauge bosons (p. 32) or flavour violation (p. 33). At the same time, properties of the gauge bosons are under scrutiny (p. 23).

In parallel, the DESY LHC groups are preparing for future LHC upgrades – in particular, the high-luminosity upgrade (HL-LHC) foreseen for the years after LHC Run 3. Activities at DESY for these upgrades include the development of the ATLAS Inner Tracker endcap (p. 24), CMS calorimeters (p. 30), the CMS Outer Tracker endcap (p. 28) and the OCTOPUS project for future colliders (p. 26).

Physics with lepton beams – and the R&D work for the necessary accelerators and detectors – constitutes the second pillar of DESY's particle physics activities. The focus here is on the upgraded SuperKEKB accelerator with the Belle II experiment at the Japanese national particle physics laboratory KEK. The performance of the experiment is continuously being improved (p. 38), which allows for new results, for example involving bottom quarks (p. 39). Meanwhile, the ELBEX project is gathering speed (p. 42), and simulations of future linear colliders are being developed (p. 44).

DESY has also broadened its activities in the field of axion-like particles. The ALPS II experiment published results from its first run (p. 35), while preparations for BabyIAXO are in full swing (p. 36).

Finally, progress has been made in many adjacent fields with the help of high-energy physics, in particular plasma acceleration (p. 40).



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Too heavy to last: the transient union of top quarks

An unexpected discovery

DESY physicists have revealed an excess of events near the production threshold of slow-moving top and antitop quarks at both the CMS and ATLAS experiment at the LHC. The observed deviations are consistent with expectations for a short-lived bound configuration, forming what would be the smallest hadron in nature. Owing to the extremely short lifetime of the top quark, this fleeting union ends when one of the particles decays before their connection can flourish into a full-blown "relationship". Once thought impossible to observe at the LHC, this effect has become accessible through cutting-edge analysis techniques. Although theoretical uncertainties remain and alternative interpretations cannot be excluded, the results demonstrate a new sensitivity to heavy-quark dynamics and provide a novel probe of the strong force at the shortest distances.

Observing top–antitop pairs...

DESY researchers working on the ATLAS and CMS experiments at the LHC at CERN have reported intriguing signs that top quarks may briefly form an unfamiliar type of matter. The study examined how pairs of top quarks and their antimatter partners are created in proton–proton collisions at an energy of 13 TeV, using the entire data samples recorded from 2016 to 2018.

Top quarks stand out because of their enormous mass and extremely short lifetime: They decay almost as soon as they appear. For this reason, physicists long assumed that a top quark and an antitop quark would not survive long enough to be able to observe binding effects due to their strong interaction with one another at the LHC. Until now, no experimental evidence suggested otherwise.

The two teams concentrated on events in which both particles decay into charged leptons – electrons or muons – accompanied by several particle jets. By reconstructing the combined mass of the top–antitop system ($m_{t\bar{t}}$) and studying how the spins of the two particles are correlated (c_{hel}, c_{han}), see Fig. 2, the researchers compared the measurements with standard theoretical calculations for ordinary, non-resonant top-pair production based on fixed-order perturbative quantum chromodynamics (FO pQCD), which is what physicists normally use to calculate how quarks behave according to the Standard Model of particle physics.

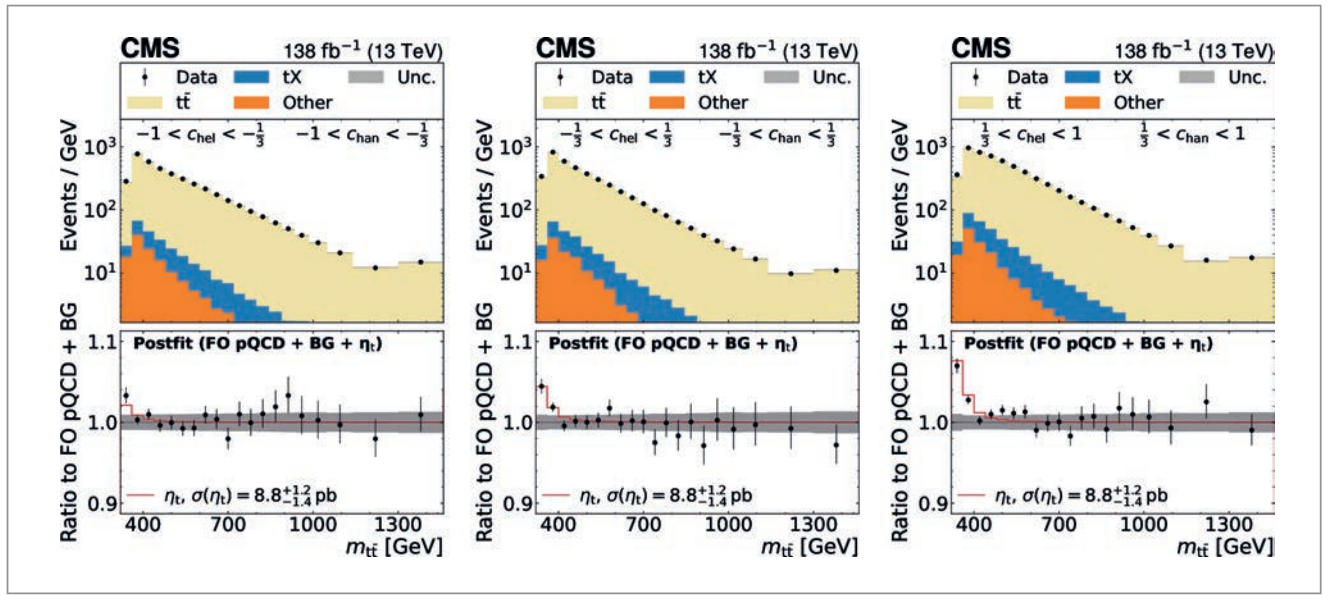

Figure 1

Observed (points with statistical error bars) and predicted (stacked coloured histograms) $m_{t\bar{t}}$ distribution in three out of nine (c_{hel}, c_{han}) bins. In the upper panels, the $t\bar{t}$ histogram shows the FO pQCD prediction after the fit to the data that includes the η_t signal model (whose contribution is not drawn), and the shown event rates are divided by the bin width. The lower panels display the ratio of the data to the FO pQCD + background prediction, with the η_t signal overlaid at its best-fit η_t cross section (red line). The grey band indicates the postfit uncertainty. The first and last $m_{t\bar{t}}$ bins include all events with reconstructed $m_{t\bar{t}}$ below 360 and above 1300 GeV, respectively, and the drawn bin width is used for the normalisation in these bins. From [1].

... with CMS

A striking deviation appears close to the minimum energy required to produce the pair. In this threshold region, the DESY CMS team observed more events than predicted by conventional calculations [1], depending on the investigated $t\bar{t}$ spin correlation variables (Fig. 1). The observed surplus of events can be expressed as an effective production rate. Within a simplified framework tuned to non-relativistic QCD (η_t signal model), the excess corresponds to an estimated cross section of about 8.8 pb, with an uncertainty of approximately +1.2/–1.4 pb. The characteristics of the signal, including its distinctive spin correlation pattern, are compatible with the formation of a colour-singlet pseudo-scalar state – a top–antitop pair in the $^1S_0$ configuration, representing the lowest-energy bound state – and thus agree with non-relativistic QCD expectations near the $t\bar{t}$ threshold. With a statistical significance exceeding 5 σ, the result is highly unlikely to arise from a random fluctuation.

... and with ATLAS

The excess has been confirmed by the DESY ATLAS team in an independent measurement. This measurement relies on a new Monte Carlo model of top–antitop production close to its threshold, in which the top-quark kinematics are derived directly from first principles, using the non-relativistic QCD potential as a starting point. With this model, the excess corresponds to an estimated cross section of about 9.3 pb, with an uncertainty of approximately +1.4/–1.3 pb. The statistical significance of the effect is greater than 8 σ, firmly establishing the robustness of the excess. When using the same simplified model as in the CMS measurement, the ATLAS analysis yields a larger cross section of 13.1 pb with an uncertainty of approximately ±1.8 pb. This demonstrates the continued need for both improved models of non-relativistic QCD effects and FO pQCD predictions close to the top–antitop production threshold for future precision measurements of this exciting kinematic regime.

A "toponium-like" state?

Both excesses are statistically robust, making a random fluctuation extremely unlikely. If confirmed as a genuine bound system, such a "toponium-like" state would offer a unique way to explore the strong nuclear force at extreme energies and to test theoretical descriptions of heavy quarks, with possible implications beyond the Standard Model.

The researchers caution that the threshold region is difficult to describe precisely and that additional contributions, for example through exotic physics beyond the Standard Model, cannot yet be ruled out. Even so, the observation is consistent with long-standing theoretical ideas and demonstrates that spin correlation measurements can uncover phenomena once thought experimentally inaccessible. As the DESY ATLAS and CMS groups make similar observations, the result has triggered renewed theoretical and experimental interest in transient bound states of heavy quarks and the behaviour of the strong force under extreme conditions.

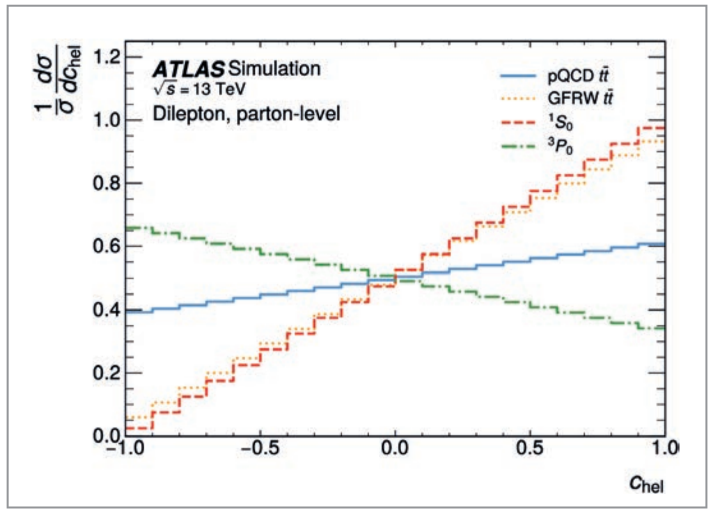

Figure 2

Parton-level distributions of the spin correlation observable c_{hel} for the FO pQCD $t\bar{t}$ and non-relativistic QCD $t\bar{t}$ production, emphasising their different shapes. The distributions for a pure spin-singlet state ($^1S_0$) and a pure spin-triplet state ($^1P_0$), obtained analytically, are shown as well for comparison. From [2].

Summary

To summarise, analyses by the DESY ATLAS and CMS groups revealed an unexpected excess of top–antitop events produced near their kinematic threshold in proton–proton collisions at the LHC. The properties of this excess, including characteristic spin correlations, are consistent with the brief formation of a bound top–antitop state as predicted by non-relativistic QCD. Although the top quark is known for its extremely short lifetime, the result suggests that it may still interact strongly enough to produce effects of a transient composite system. If confirmed, this state would represent the smallest composite particle ever observed. The observation, which reaches high statistical significance, demonstrates the precision of modern collider experiments and opens a new avenue for studying heavy-quark dynamics and the strong force at the smallest distances.

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[1] CMS Collaboration, Rep. Prog. Phys. 88 087801 (2025)
[2] ATLAS Collaboration, arXiv:2601.11780 (submitted to Rep. Prog. Phys.)

The Higgs-boson self-coupling

Search for Higgs-boson pairs using new data taken with the ATLAS detector

Higgs-boson pair (*HH*) production is 1000 times rarer than single Higgs-boson production. Members of the DESY ATLAS group have participated in the most recent *HH* analysis of the data taken with the ATLAS detector from 2015 to 2024. The analysis improves our understanding of the *HH* production process, which has still not been observed experimentally. New results were obtained in the *HH* final state of two *b* quarks and two photons. This *HH* measurement is the first that includes 2022–2024 data from the third operational run of the LHC (Run 3), and the resulting sensitivity competes with the one obtained by the combination of all channels using Run 2 data.

Although our understanding of the Higgs boson has advanced since its discovery in 2012, the self-coupling (λ) remains almost unconstrained experimentally. This fundamental parameter determines the shape of the Higgs-boson potential, which is central to electroweak symmetry breaking. At the LHC, λ is probed through *HH* production, where it affects both the event rate and the kinematics of this still unobserved process. The DESY ATLAS group searched for *HH* in the $bb\gamma\gamma$ decay channel: $H \to bb$ provides a large signal yield, given the large branching fraction; $H \to \gamma\gamma$ helps in background rejection, thanks to a clean detector signature and excellent diphoton invariant-mass ($m_{\gamma\gamma}$) resolution.

The analysis strategy relies on splitting events into low and high regions of the *HH* invariant mass (m_{HH}), an observable that is sensitive to λ. Selected candidate events are categorised using a boosted decision tree (BDT) classifier, which exploits characteristics of the final-state objects to separate signal (*HH*) from background. Then, the signal is extracted with a simultaneous maximum likelihood fit to $m_{\gamma\gamma}$ in all event categories. Members of the DESY ATLAS group contributed to the optimisation of the analysis using a kinematic fit to improve the m_{HH} and $m_{\gamma\gamma}$ resolutions, consequently improving the splitting and categorisation of the events in the analysis. Other contributions include photon identification, systematic uncertainty estimation and a leading role in the editing of the publication.

The analysis established an observed 95% CL upper limit on the *HH* cross section of 3.7 times the Standard Model (SM) prediction, with an observed statistical significance of 0.78 σ (compared to an expected 1.01 σ), as shown in Fig. 1. Additionally, the Higgs self-coupling modifier, $\kappa_\lambda = \lambda_{obs}/\lambda_{SM}$, was constrained to the interval [-1.6, 6.6]. For comparison, the full ATLAS Run 2 combination, integrating all available channels, achieved an upper limit on the *HH* cross section of 2.9 × SM and a κ_λ interval of [-1.2, 7.2].

While much of the improvement (60%) stems from the new Run 3 data, the strategy yielded a 25% intrinsic sensitivity gain. Overall, this led to a 85% better expected limit.

The analysis achieved the best single-channel sensitivity to the Higgs-boson self-coupling to this date.

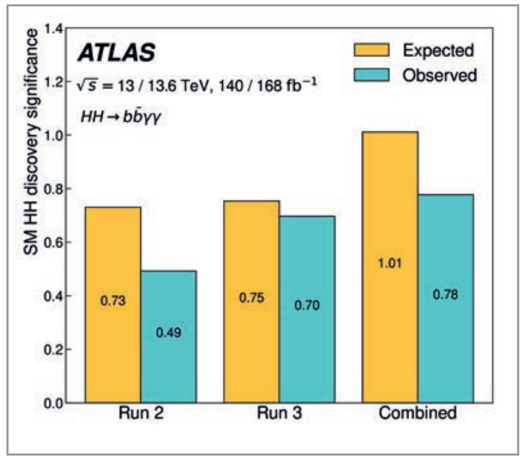

Figure 1
Observed and expected statistical significance of *HH* production obtained with separate fits to Run 2 and Run 3 data as well as their combination

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[1] ATLAS Collaboration, arXiv:2507.03495
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Mapping the angular structure of the *W* boson

First-of-its-kind measurement of the full angular structure of *W*-boson production with ATLAS

The LHC offers a unique opportunity to probe the fundamental forces of nature with unprecedented precision. Using data collected during special operating periods with minimal background from overlapping collisions, together with novel analysis techniques, the DESY ATLAS group has achieved, for the first time at the LHC, a complete measurement of the angular structure of *W*-boson production. This result enables new, stringent tests of the strong and electroweak interactions, strengthens the foundations of the Standard Model and establishes a new benchmark for precision studies of *W* bosons at the LHC.

The production of *W* bosons at the LHC offers a unique opportunity to explore the fundamental laws of nature. The DESY ATLAS group developed a new analysis focusing on events in which the *W* boson decays into a charged particle and a neutrino. These studies were carried out using special data collected during LHC Run 2, when the accelerator was operated under quieter conditions than usual, with far fewer overlapping collisions. These so-called low-μ runs greatly reduce background noise and allow much cleaner measurements.

The goal of the analysis was to measure the directions in which the charged particle is emitted. In fact, the directions of the charged lepton encode detailed information about how the *W* boson is produced and how the strong force influences the process. This information can be summarised by a set of seven quantities, called angular coefficients, which provide a clear and model-independent way to describe the underlying physics process. Until now, measuring all of these coefficients had not been possible, because the neutrino escapes the detector and obscures part of the decay geometry.
By combining innovative analysis techniques with the exceptionally clean low-μ data, the new work resolved this ambiguity and, for the first time, achieved a complete measurement of the *W* boson angular structure together with its production rate over the full angular and momentum phase space. The results open a new window on precision studies of the Standard Model and the search for new physics.

The results agree well with state-of-the-art theoretical predictions and provide crucial input for precision measurements such as the measurement of the *W* boson mass, where modelling uncertainties remain a key limitation. This work sets a new benchmark for electroweak precision physics at the LHC and enables even more sensitive studies in the future.

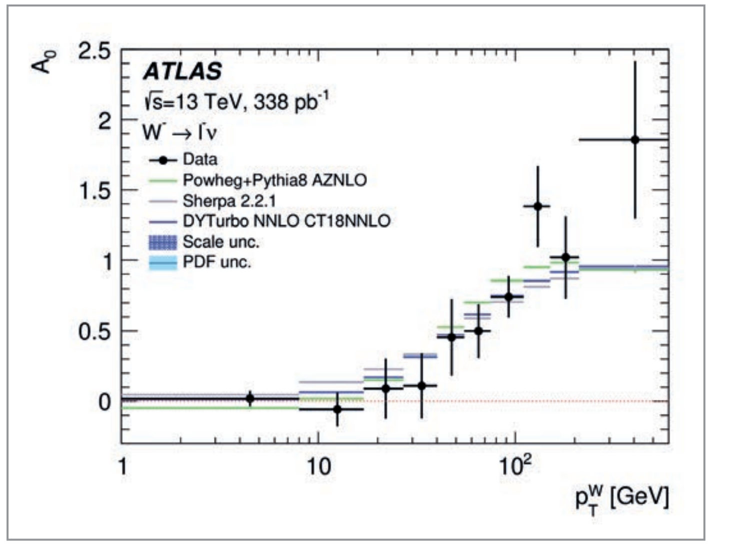

Figure 1
The *W*-boson angular coefficient A_0 as a function of the *W*-boson transverse momentum, measured for negatively charged *W* bosons and compared with modern theoretical predictions. Data points show total experimental uncertainties; shaded bands indicate theoretical uncertainties. From [1].

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Reference:
[1] ATLAS Collaboration, arXiv:2509.13759 (accepted by EPJ C)

Module production for ATLAS

Inner Tracker upgrade for the High-Luminosity LHC

The DESY ATLAS group is leading and contributing to a large number of tasks for the upgrade of the Inner Tracker (ITk) of the ATLAS detector. Among those activities, group members in Zeuthen and Hamburg have begun production of the first of around 2000 silicon strip modules – their share for the endcaps of the future ATLAS tracking detector, one of which will be fully assembled in Hamburg. The start of production was challenging in parts, because of sensor fractures observed when operating the modules at cold temperatures. Engineers and scientists at DESY have been at the forefront of surpassing those difficulties.

The ATLAS Inner Tracker upgrade

The High-Luminosity LHC (HL-LHC) [1] is the next step of the world's most powerful particle collider to date. Starting in 2030, the HL-LHC is expected to deliver a data set that is one order of magnitude larger than what has been produced by the LHC so far. The high collision intensities required to achieve this goal will result in up to 200 simultaneous collisions during one bunch crossing, which places high demands on detector performance. To provide optimal conditions e.g. for searches for rare Standard Model (SM) processes, such as diboson scattering [2], or to perform sensitive searches for new physics, such as searches for dark matter [3], a nearly hermetic coverage of the tracking detector is needed that reaches as closely as possible to the beam pipe. This close to the beam, radiation levels are particularly high, requiring the sensors and electronics to be radiation-hard. To keep radiation-induced sensor dark currents and thus the particle detection noise as low as possible, the sensors are operated at temperatures of -35°C. The ATLAS ITk [4] was designed to fulfil all those requirements. In collaboration with many other institutes worldwide, the DESY ATLAS group is working towards the construction, delivery and use of the "strip" part of the future ATLAS detector.

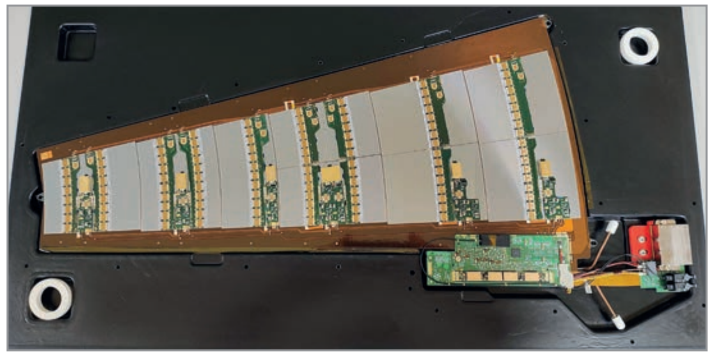


Figure 1
Fully loaded side of a petal with six ring modules and a total of nine sensors

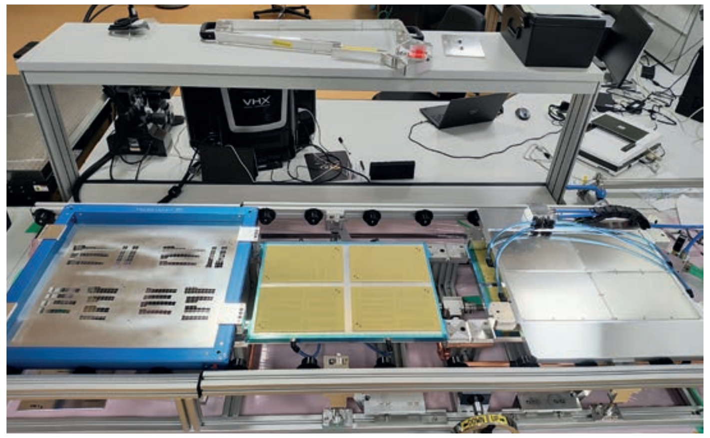
An ITk strip detector endcap consists of six discs, each with 32 petals (Fig. 1). Petals are structures onto which six ring modules with a total of nine sensors are mounted on each side. To optimise the coverage of the area with active sensor material, the modules differ in shape and number of readout channels. They also come with different electronic boards for the readout, called "hybrids" in the following, and for powering the modules, called "power boards". The hybrids and power boards are glued with the help of high-precision tools on top of the sensors with an epoxy glue. The required precision of the placement is approximately 200 µm in lateral direction and 50 µm in height. Those criteria have to be met to, for example, avoid problems when neighbouring modules are loaded on a petal and to achieve correct glue placement, ensuring that the sensors can reach the high voltage levels required for operation.

Overcoming sensor fractures at cold temperatures

During modules preproduction, it was observed that modules can experience high mechanical stress when mounted on petals and operated at very low temperatures. This stress was caused by the different thermal expansion of the sensor and the powered electronics, along with the properties of the epoxy glue used to attach the electronics to the sensor (as a result of the Covid pandemic, the original glue producer became unavailable and a new adhesive had to be found). The mechanical stress was sufficient to cause crack formation in some sensors, typically in areas close to the electronic boards. Although this damage was observed mostly at temperatures below the future operating temperature, the risk was considered too high and a mitigation strategy was developed.

Two main approaches were considered: The first one was to optimise glue patterns to reduce the stress. Together with other institutes, DESY built a series of such modules, which were assembled onto petals. While the risk was reduced, some sensor cracks were still observed. The second approach, which was later chosen as the primary solution, was to add a layer of "soft" glue, separated from the sensor by a thin layer of polyimide foil below the electronics boards. This process, called interposing, was developed and validated for all the different electrical components. The DESY ATLAS group led this effort for the hybrids and developed tools (Fig. 2) to enable arrays of different printed circuit board flexes to be interposed even in industry. Recently, the interposing process was successfully outsourced to an industrial partner, with the tooling provided by DESY.

Figure 2
Tooling for hybrid array interposing, developed by DESY



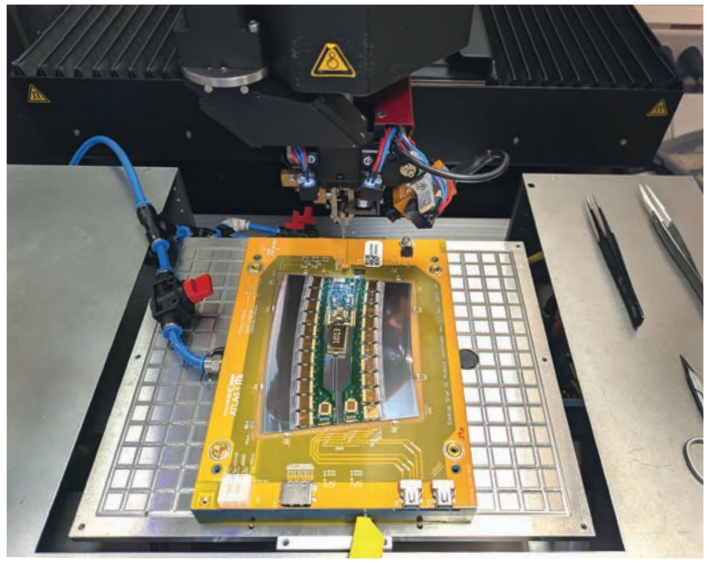


Figure 3
Module in a wire bonding machine

Additional challenges

After the sensor crack issue had been solved, the upgrade suffered another setback when DESY's partners at the University of Freiburg im Breisgau discovered that a central electronic component, the DC–DC converter, had a design flaw. Fortunately, after an intense experimentation phase, a very simple solution to the problem was found (consisting of configuring the DC–DC converter so that just one power-up option is disabled), which is currently being implemented.

The DESY ITk group used the resulting lull in production to track down a source of noise found in modules at larger radius in the detector and devised a solution to the problem. By adding a capacitor between the sensor high-voltage lines and the electronics low-voltage ground, the noise was significantly reduced, which could lead to a wider operating range of the modules in the future detector.

Towards module production

Overall, both DESY sites in Zeuthen and Hamburg are now ready to ramp up the production rate of ITk endcap modules. Optimised and partially automated workflows for component reception testing, module assembly using automatic glue dispensing, wire bonding (Fig. 3) as well as electrical performance tests of the finished modules at alternating "high" (20°C) and "low" temperatures (-35°C) are in place. As of February 2026, a total of more than 120 modules of all types have been assembled with the final production processes, and the yield of good modules exceeds the targeted minimum value of 85%.

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[3] ATLAS and CMS Collaborations, CERN-LPCC-2019-01 (2019)
[4] ATLAS Collaboration, ATLAS-TDR-025 (2017)

Tentacles for charge collection

Novel sensor layout for the OCTOPUS project

Within the OCTOPUS project, DESY scientists are driving the development of a novel monolithic active pixel sensor (MAPS) layout for next-generation silicon detectors at future collider experiments. The "N-Cross" MAPS layout extends like tentacles of an octopus inside each pixel, shaping the electric field to finely balance charge collection efficiency and spatial resolution. By carefully optimising the geometry of the deep N-implant, the sensor performance can be fine-tuned to the specific application requirements. Extensive finite element and Monte Carlo simulations demonstrate the flexibility and performance of the concept, and dedicated prototypes are in preparation for production to validate the design.

The OCTOPUS project

The Optimised CMOS Technology for Precision in Ultra-thin Silicon (OCTOPUS) project is developing technologies for future particle physics detectors. It is part of the newly formed international Detector Research & Development collaboration on semiconductors (DRD3), and the 13 member institutes cover the full chain of silicon detector development, from simulations and application-specific integrated circuit (ASIC) design to data acquisition systems and prototype characterisation. OCTOPUS builds on the achievements of the successful Helmholtz Innovation Pool project TANGERINE and continues the sensor development that began there.

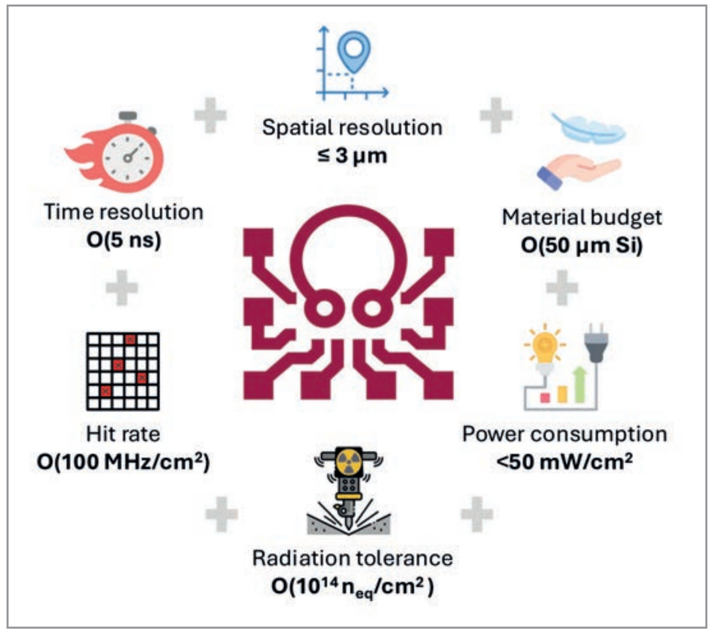

Figure 1

Target requirements for the OCTOPUS demonstrator detector for applications in vertex detectors at future lepton colliders

The main objective of the project is the development of a demonstrator sensor tailored to the vertex detectors of future experiments, targeting the requirements for future lepton colliders in line with the detector R&D roadmap of the European Committee for Future Accelerators (ECFA) [1]. Figure 1 summarises the demanding performance goals. As an intermediate milestone, the OCTOPUS project aims to develop a next-generation sensor for beam telescopes by 2030. Beam telescopes are an essential infrastructure for the characterisation of prototypes at test beam facilities such as the DESY II Test Beam Facility.

MAPS technology and sensor layouts

The technology of choice for OCTOPUS is MAPS, implemented in a state-of-the-art commercial 65 nm CMOS imaging process. This process has been evaluated for use in particle physics and currently sees its first large-scale application in the ALICE ITS3 detector at the LHC. Within OCTOPUS, the relevant studies have been reviewed, indicating that the technology has the potential to meet the stringent requirements of the project [2].

A single pixel of a MAPS sensor is illustrated schematically in Fig. 2 (left). The substrate (blue) consists of bulk silicon used as mechanical support during fabrication. Above the substrate is an epitaxially grown silicon layer (green), which forms the sensitive volume in which the traversing particle generates free charge carriers (electron–hole pairs). By applying a bias voltage, an electric field is created that drives the charges towards the collection electrode (red), thereby inducing a detectable signal. This signal is then processed internally by the integrated CMOS electronics, shielded from the sensor volume (light blue).

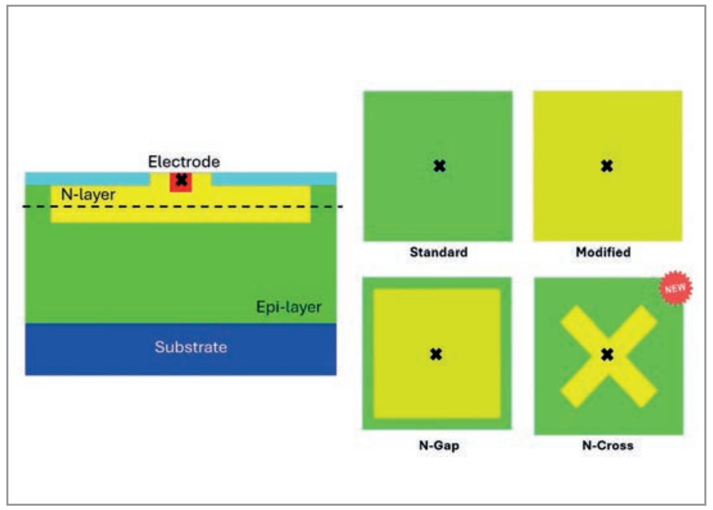

Figure 2

Left: Schematic cross section of a MAPS pixel. Right: Top view of pixel layout variations.

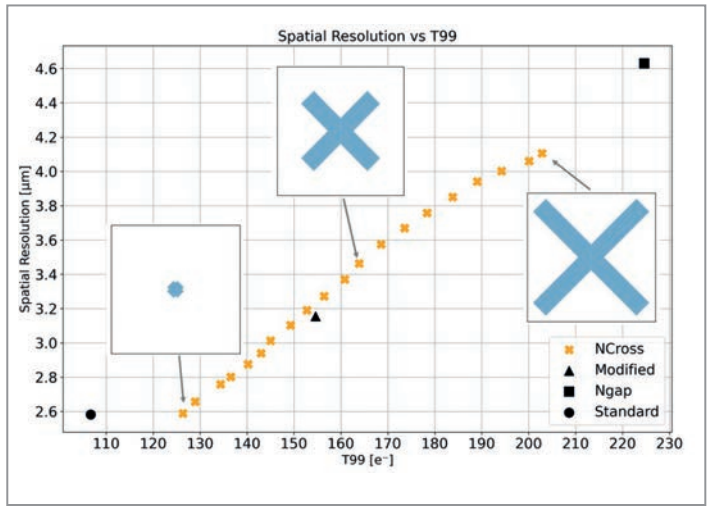

Figure 3

Simulated spatial resolution and efficiency for different sensor layouts. Selected N-Cross configurations are illustrated.

The yellow region in Fig. 2 indicates a modification to the standard process, achieved by adding a deep N-doped layer, which regulates the strength, shape and direction of the electric field within the epitaxial layer, thereby influencing the charge carriers' path, hence the efficiency and spatial resolution of particle detection [3].

Different N-layer implant shapes define alternative sensor layouts, as shown in Fig. 2 (right). Detailed studies have been carried out on the so-called "Standard", "Modified" and "N-Gap" layouts, while the novel "N-Cross" layout is currently under development at DESY within the framework of the OCTOPUS project.

Flexibility in performance

The performance differences among the layouts are determined by the extent and geometry of the p–n junction, namely the interface between the p-doped epitaxial layer and the n-implants: the collection electrode and/or the N-layer. In the Standard layout, the junction is created around the collection electrode. This results in a weaker electric field, smaller depletion volume and therefore reduced charge collection efficiency. However, the slower charge transport towards the electrode has a beneficial impact on spatial resolution. By distributing the signal over more than one pixel, the particle position can be interpolated by charge weighting.

By contrast, in the N-Gap layout, the junction reaches its maximum extension and introduces a lateral electric-field component. This increases the particle detection efficiency towards the pixel edges. At the same time, it leads to a degradation of the spatial resolution, as most of the charge is collected by a single pixel.

The new N-Cross layout, which is currently under development at DESY, aims to provide a flexible solution that can balance the performance of the existing Standard and N-Gap layouts and be adapted to specific application requirements. By adjusting the thickness and length of the cross-shaped N-implant, the new layout allows the sensor efficiency and spatial resolution to be tuned over a wide parameter range.

Figure 3 shows simulation results of the N-Cross MAPS layout with a pixel size of 20 µm, demonstrating this flexibility. The study was carried out using the MAPS simulation methods developed at DESY in the context of the TANGERINE project [4]. For the different simulated layouts, the spatial resolution is presented as a function of the average signal threshold required to achieve a detection efficiency of 99% (T99). Higher T99 values indicate improved charge collection performance and a larger operational range of the threshold.

The simulations confirm the flexibility of the new N-Cross layout, and dedicated sensor test chips based on the layout are currently being planned.

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CMS Outer Tracker endcap

Production begins

The DESY CMS group has launched the production of 1250 silicon modules that DESY has committed to supplying for the upgrade of the CMS Outer Tracker. At DESY, these modules, along with additional modules manufactured at other institutes, will undergo final tests and be integrated onto local mechanical structures, which comprise the Double-Disks that will form the tracker endcaps of the upgraded CMS detector for the High-Luminosity LHC (HL-LHC).

The CMS detector will receive a major upgrade to cope with the challenges of the HL-LHC. Among other features, the Outer Tracker will provide tracking information to the Level 1 trigger. Silicon sensor modules composed of two layers of sensors have been designed for this purpose. The Outer Tracker will be equipped with two types of modules: pixel strip (PS) modules and two-strip (2S) modules. The DESY CMS group is committed to producing PS modules and to testing and integrating both PS and 2S modules for the Tracker Endcap Double-Disks.

CMS PS module production

DESY has started production of the first PS modules out of the total of 1250 modules it has committed to manufacturing. The assembly of sensor sandwiches with the commissioned 3D stage robot built by DESY is ramping up fast. The subsequent assembly steps and their respective tests, which are also carried out at DESY, consist of wire-bonding the front-end hybrids and encapsulating the wire bonds.

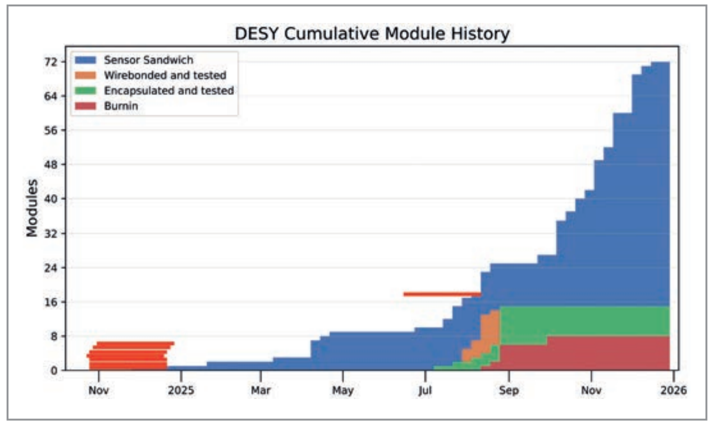

Figure 1

PS module production history in 2025. The graph shows the cumulative number of sensor sandwiches produced and of modules wire-bonded, encapsulated and burned in.

Recently, tests of a DC–DC converter of the power hybrid revealed unexpected problems after irradiation. While further investigations are ongoing, the PS modules are being assembled only up to the sensor sandwich step and then stored, waiting for completion until a solution is found. To compensate for possible delays, the CMS collaboration suggested speeding up the production of 2S modules. In cooperation with RWTH Aachen University, DESY technicians will also wire bond and encapsulate, in-house, 2S modules assembled in Aachen. In the 2S modules, DC–DC converter chips are mounted on service hybrids that can be replaced if needed; thus, fully operational 2S modules are being produced.

In 2025, DESY produced and tested about 70 PS module sensor sandwiches (Fig. 1). Of these sensor sandwiches produced so far, 15 had been fully assembled before the DC–DC converter problem became known. The burn-in test was performed on eight of the fully assembled PS modules.

Burn-in tests

The DESY CMS group has built and commissioned two identical burn-in test setups. Each setup consists of a commercial refrigerator with internal support structures capable of accommodating up to 10 PS or 10 2S modules and equipped with temperature and humidity monitoring, power supplies for the modules and electronics to read out the data from the modules (Fig. 2).

The burn-in procedure is the ultimate test of the fully assembled modules, ensuring the robustness of their electrical and mechanical components. It consists of operating the modules inside the refrigerators while they undergo several temperature cycles ranging from +20°C to -35°C (Fig. 3) and evaluating their performance during the test. The time span of the cycles is optimised to maximise the number of cycles. Once the modules pass the test, they are ready to be integrated onto the local support structures.

Figure 2

Burn-in test setup with modules to be tested on the support structure inside the refrigerator. The second setup is identical.

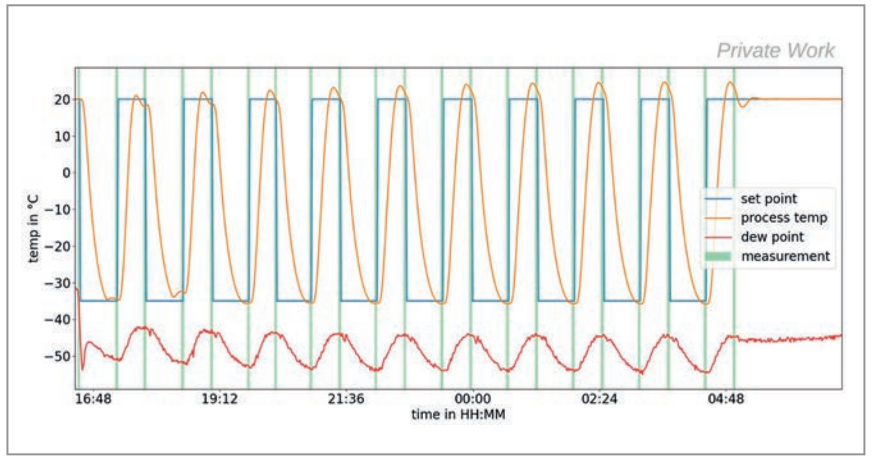

Figure 3

Temperature cycles during a burn-in test. The time span of the cycles is optimised to maximise the number of cycles.

In 2025, the DESY CMS group tested 50 of the Aachen 2S modules in addition to the eight fully assembled PS modules produced at DESY.

Dee production

The largest possible local mechanical support structures, called Dees, onto which the PS and 2S modules will be integrated, are being produced by an external company. The Dees incorporate cooling pipes, carbon foam blocks and aluminium inserts to cool the modules. At DESY, quality control of the Dees is performed, including pressure and leakage tests of the cooling pipes as well as tests of thermal performance, flatness of the Dees' surface and position of the inserts. In 2025, DESY received eight production Dees of good quality. The remaining Dees will be delivered by August 2026.

Double-Disk assembly exercises

The DESY CMS group is also responsible for the integration of modules onto the Dees. Up to 182 modules will be integrated onto each Dee. Once four Dees have been integrated, they will be assembled into Double-Disks (DDs) and shipped to CERN. Each disk has a diameter of 2.2 m. The distance between the surfaces of the two disks in a DD is about 21 mm, and the distance between modules on opposing disks is approximately 10 mm. Five DDs, including cooling manifolds and patch panels, will be assembled at DESY – a major endeavour for the research centre.

In 2025, members of the DESY CMS group carried out exercises using real mechanical structures – the four pre-production Dees delivered in 2024 – to successfully assemble a DD mechanically for the first time (Fig. 4). The exercises led to minor improvements to the tooling and identified issues in the procedures developed previously using dummies and prototypes. The necessary improvements were implemented, and updates to the procedure were included in the documentation. The metrology of the DD showed a flatness of 1.1 mm, close to the 1 mm goal.

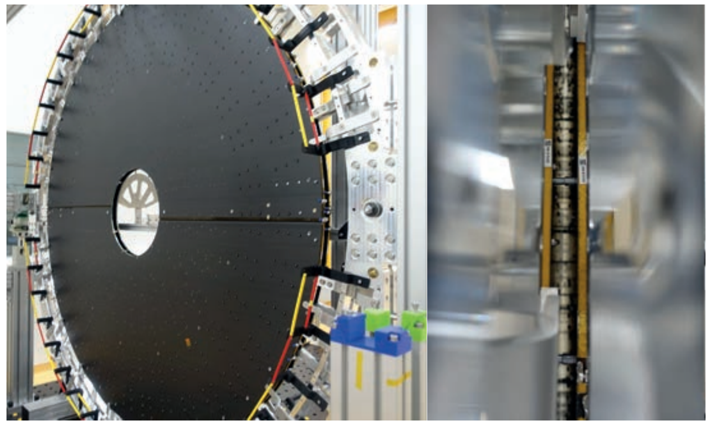

Figure 4

Left: Assembled Double-Disk. Right: Gap between the disks of the same Double-Disk, showing the good alignment of the disk-to-disk connectors.

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A tale of two rings

Assembly of CMS HGCAL tilemodules has started

The large numbers of particles produced during the high-luminosity phase of the LHC require upgrades to the current detectors. The CMS collaboration will replace the experiment's endcap calorimeters with an entirely new high-granularity calorimeter (HGCAL). DESY is involved in the SiPM-on-tile part of the HGCAL, which consists of small scintillator tiles directly read out by silicon photomultipliers (SiPMs). The production and testing of about 2000 SiPM-on-tile modules is a joint effort of the FE, ZE, CMS and FTX groups at DESY.

The high-luminosity phase of the LHC is planned to start in 2030. The increased luminosity will lead to unprecedented rates of particle production in proton–proton collisions, requiring upgrades to the current detectors of the LHC experiments. One of these is the upgrade of the CMS experiment's calorimeter endcap [1], which will be replaced by the HGCAL. This will make it possible to disentangle particles produced in different proton–proton collisions in the same bunch crossing ("pile-up").

The front part of the HGCAL and the areas closest to the beam pipe, which are most strongly affected by radiation, will be based on silicon pad sensors. In contrast, the rear part will consist of small scintillator tiles that are directly read out by silicon photomultipliers (Fig. 1). This SiPM-on-tile technology has been developed over many years in a fruitful collaboration between DESY and international partners within the CALICE collaboration. The basic detector unit in the SiPM-on-tile section is a tilemodule, consisting of a tileboard – the electronics board holding the SiPMs, the tiles and the readout application-specific integrated circuit (ASIC) – and the tiles (Fig. 2).

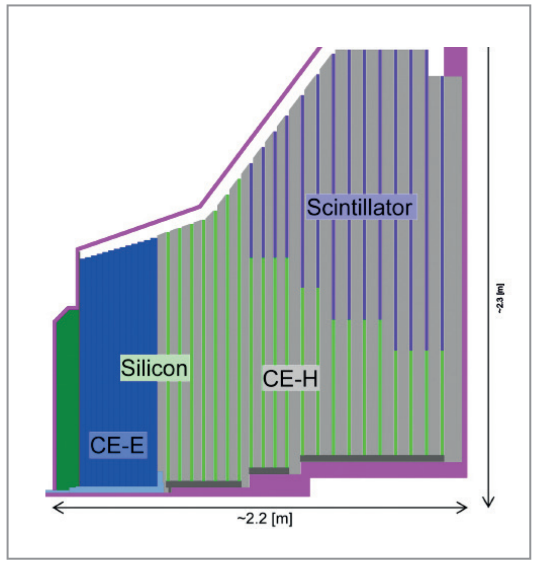

Figure 1
Schematic side view of the CMS HGCAL with the silicon part indicated in blue and green and the SiPM-on-tile part in purple

After a long period of developing and testing prototype modules for the CMS HGCAL, series production is now in full swing. At DESY, this means that about 2000 tilemodules will be produced and tested before being sent to the USA, where they will be integrated into larger units, the cassettes.

The production at DESY includes several steps: 1) the electrical assembly of the tileboards, 2) the wrapping of more than 160 000 scintillator tiles in reflective foil, 3) the glueing of the tiles to the tileboards, as well as various tests at different stages to ensure the quality of the final product, the tilemodules. Undergraduate students from Universität Hamburg play a crucial role in this process, which involves a lot of intricate work.

The peculiar geometry of the existing CMS endcap calorimeters, which the HGCAL will replace, requires a wide variety of tile and module sizes. In total, more than 30 tile sizes and eight module types are needed to achieve complete coverage across all layers. The individual tilemodules cover an angular range of 10°, so 36 modules form a full circle. The production of the module types is shared roughly equally between US institutes and DESY.

Figure 2
Two types of tilemodules produced at DESY. Top: A-type module shown from the top (left, wrapped tiles visible) and bottom (right, readout ASIC and other electronic components visible). Bottom: Larger E-type module.

The construction of modules has started with the most backward layers. For these layers, two module types are being built at DESY. The first 72 DESY modules for the last layer, forming two concentric rings, are shown in Fig. 3.

In October 2025, DESY hosted a workshop gathering scientists from all institutes involved in the construction of the SiPM-on-tile part of the detector. Live demonstrations of the procedures at DESY, from assembly to testing, helped synchronise the production efforts on both sides of the Atlantic.

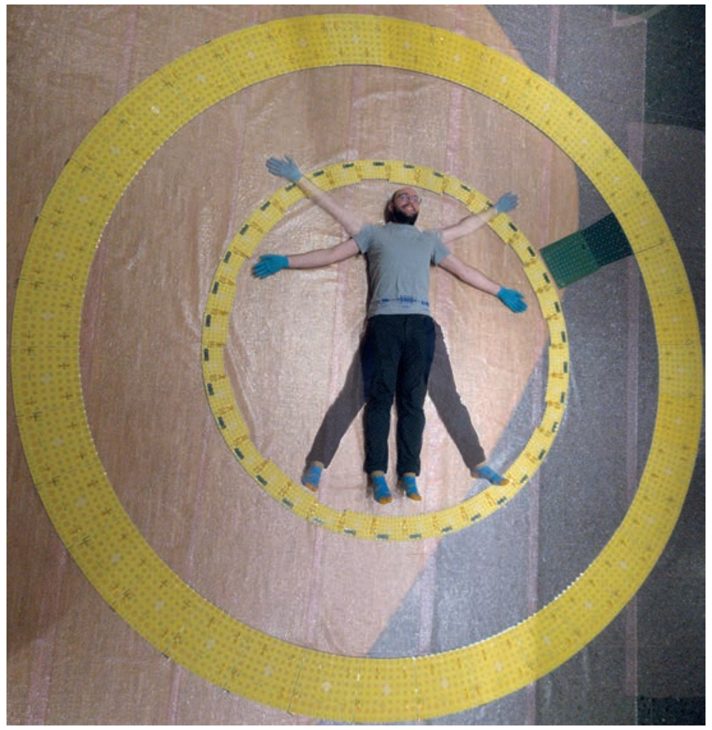

Figure 3
Two rings of 36 tilemodules each, with a human (DESY postdoc A. Laudrain) for size comparison

Since the beginning of production, over 300 tileboards have been assembled, and more than 20 000 tiles have been wrapped. We are looking forward to many more rings of tilemodules!

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Rare encounter in the top-quark sector

CMS collaboration reports first observation of the *tWZ* process

Researchers from the DESY CMS group carried out an analysis that resulted in the first observation of the creation of a top quark, a *W* boson and a *Z* boson, known as *tWZ* production. The large data set recorded with the CMS detector between 2018 and 2023 as well as advanced machine learning algorithms were needed for an observation with a significance of more than five standard deviations. This process opens up a new window to better understand the electroweak interaction of the top quark and its interaction with the Higgs field.

The DESY CMS group has longstanding expertise in analyses of top-quark pair production ($t\bar{t}$), also in association with additional bosons (*W*, *Z*, *H*, photon), and single top-quark (*t*) production. Measurements of these processes are sensitive probes of the strong force, top-quark properties and the top-quark interaction with the electroweak force. However, probing neutral-current interactions of the top quark is very difficult and can only be achieved through the measurement of rare processes, such as $t\bar{t}Z$ production.

While the rate of $t\bar{t}Z$ production at the LHC is already very small, the rate of *tWZ* production is predicted to be smaller by a factor of 7, still. However, it provides a more powerful probe of how the top quark couples to the electroweak sector and may reveal subtle effects from physics beyond the Standard Model. DESY researchers started the endeavour of measuring this elusive process in 2020 using data recorded with the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1}. This analysis resulted in a first hint in 2024 that this process is realised in nature [1], shown by the green contours in Fig. 1.

Since then, the group has improved the analysis considerably. Among the developments are a state-of-the-art machine learning algorithm, a new method to estimate the background from misidentified leptons and an optimised event selection. The analysis of 200 fb^{-1} of CMS data from LHC Run 2 and Run 3 resulted in an observed significance of 5.8 standard deviations (σ) [2], shown by the blue contours in Fig. 1.

The improvements to the analysis resulted in an enhancement of the expected sensitivity by more than a factor of 2, visible by the much smaller allowed region for the signal strengths in the new measurement. The observed *tWZ* signal strength is higher than the prediction by 2.3 σ. As more data is taken with the CMS detector at the LHC, future measurements of this process will provide us with more information on this discrepancy.

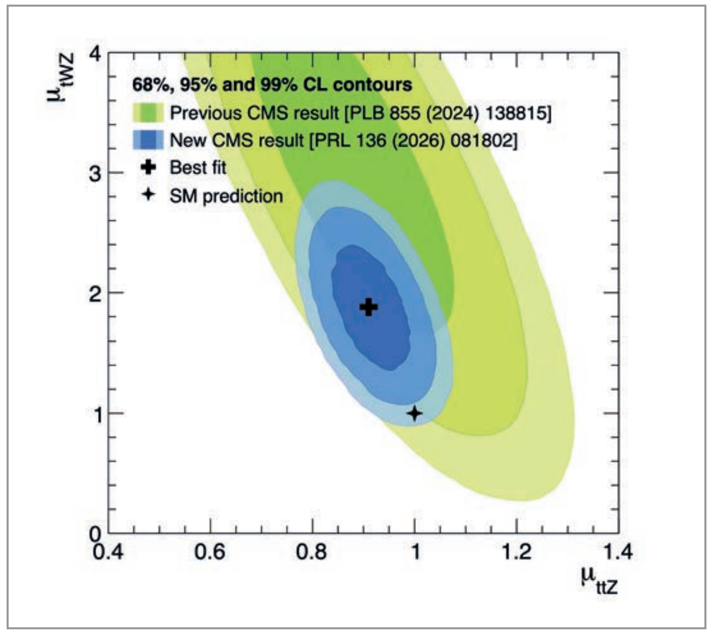

Figure 1

Strength of the simultaneously measured $t\bar{t}Z$ and *tWZ* processes relative to the predictions from the Standard Model (SM)

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Hunt for flavour conservation breaking in top-quark interactions

Exploring lepton-flavour-violating interactions between top quark and tau lepton

Researchers from DESY, in collaboration with other institutions in the CMS experiment, have delivered the most sensitive test to date of charged-lepton flavour-violating (CLFV) interactions of top quarks involving a muon and a tau lepton. Using effective field theory (EFT), the branching fractions of CLFV top quarks are excluded up to the order of 10^{-8}.

Deviations reported in the *b* meson branching-fraction ratios involving different lepton flavours [1] fuelled further investigations into lepton universality. As an analogy to the anomalies involving tau leptons, DESY researchers performed a search for CLFV interactions of top quarks by analysing the proton–proton collision data at 13 TeV collected by the CMS experiment.

The analysis probed EFT interactions in which a top quark couples to a muon, a tau lepton and an up-type quark (*u* or *c*), leading to single top-quark production or to top-quark decays (Fig. 1). Scalar, vector and tensor-like EFT operators were considered with different predicted cross sections. A deep neural network (DNN) algorithm was introduced to discriminate CLFV signal events from the Standard Model predictions.

From the multivariate analysis with DNN, no significant excess was observed above the Standard Model prediction, and upper limits on the signal cross section were set at 95% confidence level (CL). The upper limits ranged from 2 to 8 fb, depending on the EFT operators considered. These were translated into upper limits on the branching fraction (*B*) of CLFV top-quark decays, ranging from 2×10^{-6} to 4×10^{-8}. Furthermore, exclusion contours (Fig. 2) were obtained from up- and charm-quark channel results using an interpolation that assumes a linear relationship between the limits on branching fractions. This search provided the most stringent upper limits on top-quark CLFV interactions involving a muon and a tau lepton.

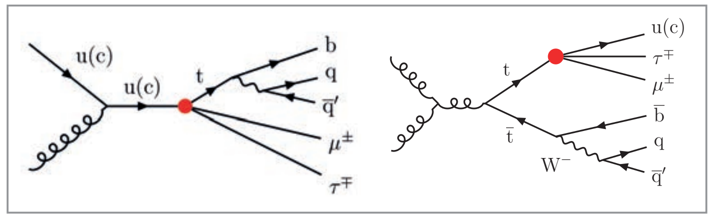

Figure 1

Example Feynman diagrams for the CLFV production of a single top quark (left) and for top-quark pair production followed by a CLFV decay (right)

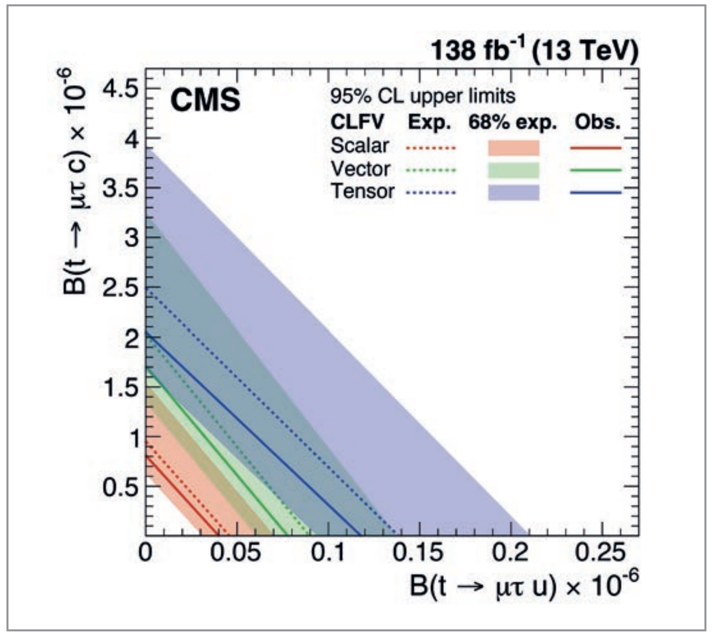

Figure 2

Observed and expected upper limit contours at 95% CL and central probability intervals containing 68% of the expected upper limits for the branching fractions

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The Higgs as a portal to new physics

Does the discovered scalar have little siblings?

Since its discovery in 2012, the Higgs boson has been studied with increasing precision at the LHC, and its properties so far agree with Standard Model (SM) predictions. Yet one very exciting possibility remains open: The Higgs boson could decay into particles beyond the SM. Using data collected during Run 2 of the LHC, the DESY CMS group performed a search for decays of the Higgs boson into a pair of light neutral bosons, each further decaying into two tau leptons. While no evidence for this process was found, the study set the most stringent limits to date on the cross section times branching ratio for this decay, relative to the SM Higgs production cross section.

The discovery of the Higgs boson (H) marked the final piece of the SM, our best description of elementary particles and their interactions to date. But what if the Higgs boson could also provide a first glimpse of what lies beyond it? Many well-motivated theories predict that the Higgs could decay into new particles. Such "exotic" decays would be difficult to observe, but their discovery would provide a direct sign of new physics.

One particularly compelling scenario, predicted for example in the next-to-minimal supersymmetric Standard Model and in two-Higgs-doublet models extended by a singlet, is the decay of the Higgs boson into a pair of light neutral bosons (a_1) that are part of an extended Higgs sector. Members of the DESY CMS group carried out a search for this process, with each a_1 further decaying into two tau leptons (τ).

A primary challenge in this study, which focuses on the a_1 mass range from 4 to 15 GeV, is the large Lorentz boost of the a_1 bosons. This causes the two taus from each decay to be so close together that their decay products partially overlap in the detector, complicating their identification. To address this, dedicated selection techniques were developed that exploit two of CMS's most precisely reconstructed objects – muons and charged-particle tracks – to identify the tau decays. Another difficulty arises from the enormous rate of quantum chromodynamics multijet events, which can mimic the signal. As standard simulations fail to model this background accurately, a dedicated data-driven method was used to obtain a reliable estimate.

Although no evidence of a_1 bosons or exotic Higgs decays was found, 95% confidence level upper limits were set on the cross section times branching ratio for $H \rightarrow a_1 a_1 \rightarrow 4\tau$, as shown in Fig. 1. These are the most stringent constraints to date in this final state, narrowing down where new physics could still be hiding and guiding where future searches should focus as more data become available.

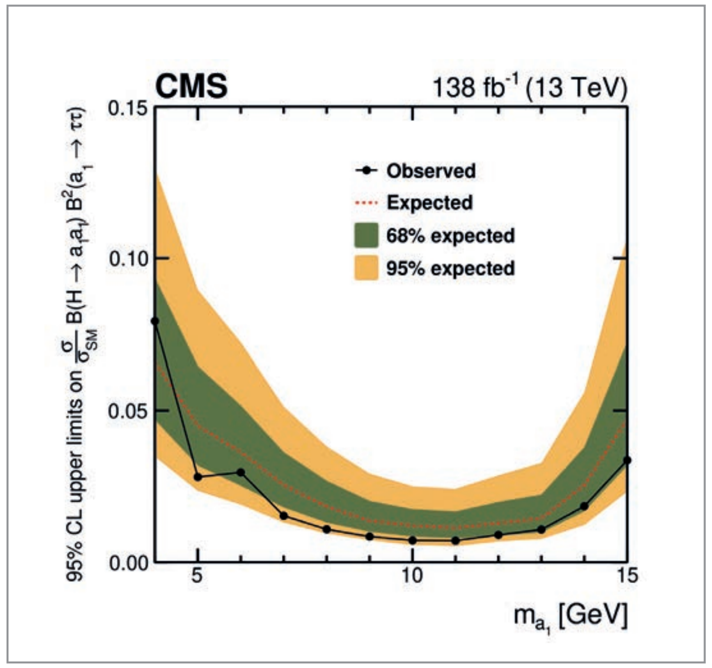

Figure 1

Observed and expected upper limits on the cross section times branching ratio for $H \rightarrow a_1 a_1 \rightarrow 4\tau$ relative to the SM Higgs production cross section [1]

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Alexei Raspereza, alexei.raspereza@desy.de

Reference:

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ALPS II: the power of phases

Beyond-the-Standard-Model searches focusing on phases and amplitudes of fields

As described in *DESY Particle Physics 2024*, the first data-taking campaign of the ALPS II experiment in the tunnel of DESY's former HERA accelerator was very successful, demonstrating a signal-to-noise sensitivity five orders of magnitude beyond previous experiments. Time to take a glimpse at the ALPS II engine.

Under the ALPS II hood

The collaboration is well on track to reach the sensitivities lined out in the ALPS II Technical Design Report (TDR) [1] published in 2013. However, a closer look under the hood reveals major technological differences in the optics system installed at ALPS II compared to plans in 2013. The ALPS II TDR foresaw counting photons seemingly passing a light-tight wall. Only in eight places does the TDR refer to the phases of the light fields. In contrast, the recent publication [2] on the data analysis of the first ALPS II science campaign mentions such phases 104 times.

This emphasis highlights the application of precision interferometry at ALPS II: The experiment is calibrated and controlled by light fields with powers of a few 10^{-18} W and aims for sensing a physics signal of 10^{-24} W. Such sensitivities are achieved by overlaying the light field to be analysed with a reference light field of exactly known frequency difference and controlled phase relation: After integrating for some time – up to 20 days at ALPS II – a signal shows up at the frequency difference of the reference light and the signal light. Figure 1 gives an impression of the complexity of the optics implemented to find a dark matter candidate.

Beyond light-shining-through-a-wall

Motivated by the necessity to precisely measure the properties of high-precision long-baseline optical resonators, A. Spector (head of the optics team) and T. Kozlowski (then fellow in the optics team) developed a new, very robust characterisation scheme [3]. Besides being very beneficial for ALPS II [4], it also paves the way towards purely polarimetric dark matter and high-frequency gravitational wave searches [5] as well as towards a first-time measurement of the vacuum magnetic birefringence [6] (VMB), a quantum electrodynamics (QED) effect predicted more than 90 years ago. According to the present planning, the VMB measurement will take place in 2029/2030 after the light-shining-through-a-wall programme at ALPS II has been completed. The VMB physics signal is a tiny difference in the refractive index n of light polarised perpendicular and parallel to a magnetic dipole field of $\Delta n = 4.0 \times 10^{-24}\,(B[\mathrm{T}])^2$, with the magnetic field strength B expressed in units of tesla. In addition to dedicated complex optics, this experiment also requires upgrading the ALPS II magnet string to allow faster and technically safe cycling of the magnet field strength.

Laura Roberts, PhD student of the Albert Einstein Institute in Hannover working at ALPS II, recently received an Enrico Fermi Fellowship [7] to further study the sensitivity of VMB measurements to heavier axions out of reach at ALPS II and to the modification of QED by string theories, for example. Thus, VMB@ALPS may not only probe QED in new regimes, but also point to physics beyond the Standard Model.

Figure 1

Members of the ALPS II optics team in the central cleanroom of the experiment in the HERA North hall area

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BabyIAXO

Looking at the sun through dark radiation

BabyIAXO is a next-generation helioscope aimed at discovering axions and similar hypothetical elementary particles emitted by the sun. Featuring a 10 m superconducting dipole magnet, advanced X-ray optics and ultralow-background detectors, it also serves as a prototype for the International Axion Observatory (IAXO). DESY is planned to be the host laboratory, and as such, a DESY team is coordinating the design, future construction and eventual operation of the experiment.

Axions were originally proposed to solve the strong charge–parity (CP) problem in quantum chromodynamics (QCD) and have since become leading candidates to explain the dark-matter content of the universe. More broadly, axion-like particles are predicted by many extensions of the Standard Model, including string theory, and may even play a role in dark energy. Detecting these extremely weakly interacting particles is therefore a major goal of modern particle physics. One of the most promising approaches to their discovery is the helioscope method, in which axions produced in the sun are converted into X-ray photons inside a strong laboratory magnetic field (Fig. 1). This technique offers high sensitivity with relatively few theoretical assumptions and can probe regions of parameter space inaccessible to other experimental strategies (Fig. 2).

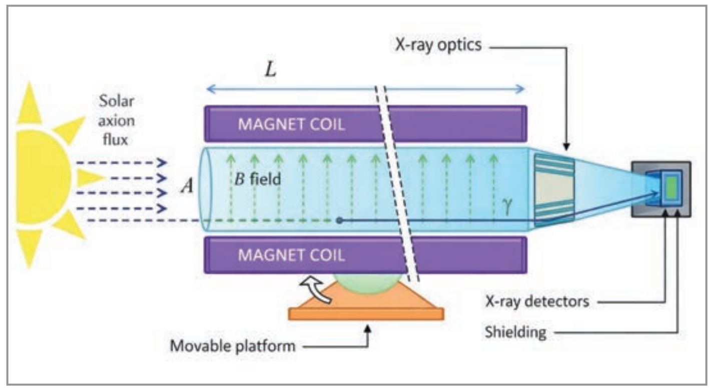

Figure 1

Conceptual sketch of an axion helioscope. Solar axions are converted into photons by the transverse magnetic field inside the bore of a powerful dipole magnet. The resulting quasi-parallel beam of photons of cross-sectional area *A* is concentrated by appropriate X-ray optics onto a small spot area in a low-background detector.

The next-generation helioscope BabyIAXO [1] is designed to significantly improve detection sensitivity and explore parameter regions hinted at by astrophysical anomalies. In addition to looking for solar axions, it will provide a versatile platform to search for axions from supernovae, dark-matter axions and even high-frequency gravitational waves. At the same time, BabyIAXO serves as a technological and operational prototype for the much larger IAXO helioscope [2], reducing risks and enabling the collaboration to gain experience with full experimental operation while already producing competitive physics results.

The prototype of the positioner developed at DESY in Zeuthen for the Medium-Sized Telescopes of the Cherenkov Telescope Array Observatory (CTAO) and used in Berlin-Adlershof serves as the basis for the solar observatory. The experiment features an over 10 m long superconducting "common coil" dipole magnet with two 70 cm diameter bores, each equipped with X-ray optics and ultralow-background detectors representative of those planned for IAXO. The use of an available 70 cm spare optics for the XMM-Newton X-ray space telescope of the European Space Agency (ESA) further strengthens the physics reach while providing practical experience in operating large-scale optical systems. At the focal points, highly radiopure micromegas X-ray detectors, developed for the CAST experiment at CERN and refined afterward, will be deployed together with extensive passive and active shielding. Additional technologies, such as GridPix detectors, silicon drift detectors and cryogenic calorimeters (metallic magnetic calorimeters and transition edge sensors) are under development to further improve energy thresholds and resolution and to be prepared for spectral measurements of the axion energy after discovery. With current detector technologies, expected background levels are extremely low, below roughly one spurious hit per month. Beyond hardware, BabyIAXO will also validate software, data-taking procedures and collaboration infrastructure that will later be extended to IAXO. DESY's contribution, as already approved by the DESY Foundation Council, would focus on the infrastructure.

The superconducting magnet is one of the most technically demanding components. Once built, it will be the largest superconducting dipole of its kind, about 10 m long and weighing roughly 50 t, producing a peak field of around 2 T in its bores. Its cryogenic concept is particularly innovative, relying on cryo-coolers to drastically reduce helium consumption and potentially setting a precedent for future large-scale magnet systems. A viable procurement path for the required niobium–titanium aluminium-stabilised superconducting cable has been established, with successful sample production and testing in collaboration with international partners and part of the Rutherford cable already in production. The magnet design is being developed by experts from DESY and CERN together with an industrial partner and has undergone multiple successful reviews by international magnet specialists. These reviews concluded that the conceptual design is mature, recommended further prototyping and encouraged preparation of a technical design report while clarifying the construction strategy, which could involve either industrial procurement or construction at a major research laboratory.

The experiment requires a footprint of roughly 35 m × 35 m and a height of at least 13 m, supported by a reinforced concrete base capable of carrying a total weight of about 120 t. While an underground installation in the HERA South hall was initially considered and technically viable, refurbishment costs prompted a reassessment. On-surface installation on the DESY campus emerged as a more cost-effective solution, with fewer infrastructure constraints. The preferred site lies between Building 1 and the DESY II accelerator ring, offering sufficient space (Fig. 3). Although an outdoor setup is technically more challenging, the collaboration concluded that it is feasible and would have only limited impact on the achievable physics performance.

The project timeline foresees completion of the experimental infrastructure by early 2027, followed by installation of the support structure and drive system by mid-2027. In parallel, magnet design, procurement and construction will proceed, enabling installation and commissioning between 2029 and 2030. Scientific data taking with the full system is expected to begin around 2031 and could continue until approximately 2041, depending on results. Through this staged approach, BabyIAXO will both advance the search for axions and establish the technological, operational and organisational foundations for the next major step: the realisation of the full International Axion Observatory.

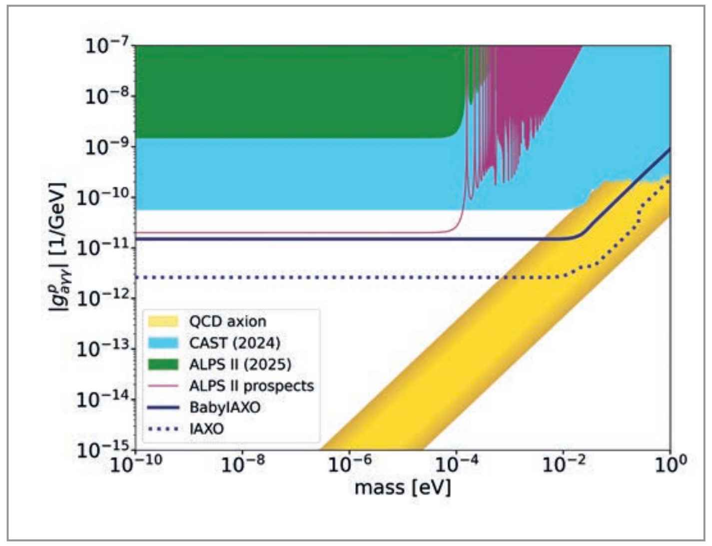

Figure 2

Sensitivity plot of BabyIAXO (blue line) in the primary $g_{a\gamma\gamma}$–m_a parameter space, compared with the QCD axion (yellow) band and other current (filled) experimental limits. The IAXO prospects are displayed as a dotted line.

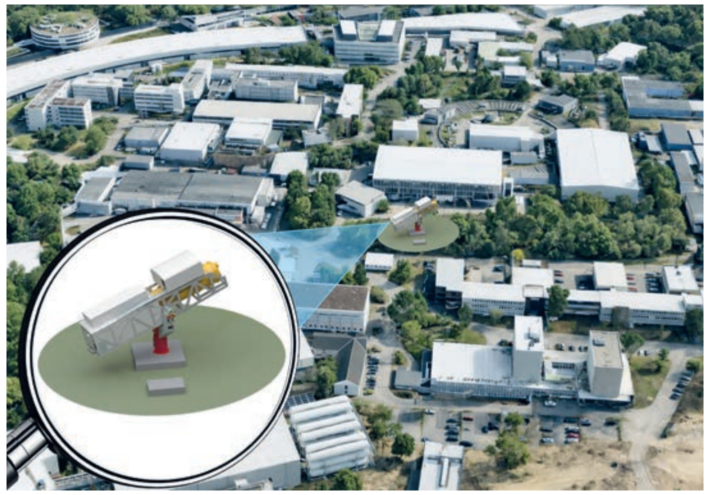

Figure 3

Aerial view of the DESY campus including the BabyIAXO experiment, fully instrumented and located on surface

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Preparing Belle II tracking for high luminosity

Improved operation of the Central Drift Chamber

To prepare the Belle II experiment at the SuperKEKB accelerator in Japan for higher luminosities – which will be accompanied by harsher beam background conditions – systematic studies of the operation of the Central Drift Chamber (CDC) were performed. These included a dedicated cosmic-ray run during the 2025 shutdown. Significant changes to the way the CDC gas system is operated, a reduced high voltage in the most exposed regions and improved reconstruction algorithms will ensure more robust tracking performance in the future.

The Belle II detector has been designed to study rare processes that might offer insight into physics beyond the Standard Model. These measurements rely critically on the ability to accurately reconstruct the trajectories of charged particles and determine their momenta. The main tracking device of Belle II is the CDC, which is used both for online event selection and for offline reconstruction. The DESY Belle II group has made key contributions to the CDC reconstruction software and continues to play an active role in adapting it to evolving data-taking conditions. As the luminosity of SuperKEKB increases, background levels in the detector also rise, resulting in varying CDC performance and making the operation of the CDC more demanding. The interplay between background levels and operating parameters, such as the precise gas decomposition within the detector, has been a puzzle since the beginning of CDC operation at SuperKEKB.

In a systematic study of the 2024 data, the DESY group was able to shed light on this complex mutual dependence for the first time. To verify these observed dependencies in a controlled way, a series of dedicated tests were carried out during the 2025 spring–summer shutdown of the accelerator using cosmic-ray data. Several performance indicators were considered, including the efficiency of hit detection, track reconstruction efficiency and the measured charge deposition (expressed in analogue-to-digital converter counts). The latter is directly related to the gas amplification (gain) of the chamber. A higher gain generally improves performance, but it also increases the electric current in the detector and accelerates ageing effects. Finding the optimal balance between gain and long-term stability was therefore a key goal of this study.

Further studies explored operating at reduced gain by lowering the chamber's high voltage in order to increase its resilience against ageing effects, such as the Malter effect. It was found that the resulting loss in tracking efficiency could be partially offset by optimising the software background filters (Fig. 1).

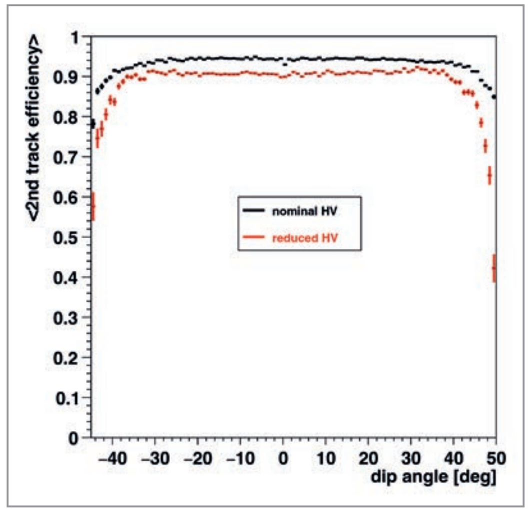

Figure 1
Tracking efficiency as a function of charged-track incident angle for nominal and reduced high-voltage conditions and with improved software filters

Based on these studies, the CDC is now operated with a significantly increased flow rate of fresh gas, a higher concentration of water vapour and oxygen, and reduced high voltage in the two innermost super-layers. These changes reduce stress on the detector hardware while maintaining good tracking performance through improved reconstruction algorithms developed at DESY.

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New Belle II measurement of beauty-to-up quark coupling

Measuring the least precisely known Cabibbo–Kobayashi–Maskawa element

The DESY Belle II group has measured the magnitude of the least precisely known Cabibbo–Kobayashi–Maskawa element (V_{ub}) from inclusive charmless semileptonic beauty meson decays using 365 fb^{-1} of data. This is the first determination of $|V_{ub}|$ in inclusive *B*-meson decays performed at the Belle II experiment. The result, $|V_{ub}| = (4.01 \pm 0.21) \times 10^{-3}$, has an uncertainty that is competitive with previous measurements performed by the BABAR and Belle experiments with larger data sets.

In the Standard Model (SM), the untitary Cabibbo–Kobayashi–Maskawa (CKM) matrix governs the mixing between quarks of different generations. Precise determinations of its elements provide essential tests of the theory. The least precisely known element is V_{ub}, which governs $b \to u$ transitions, and its uncertainty limits CKM unitarity tests and sensitivity to possible non-SM effects [1]. $|V_{ub}|$ is extracted from semileptonic $B \to X_u \ell \nu$ decays (Fig. 1) using two strategies: Exclusive measurements reconstruct specific X_u hadrons, while inclusive measurements place no requirement on the X_u final states. These approaches yield values of $|V_{ub}|$ that differ by about three standard deviations [1]. It is therefore crucial to perform these measurements at Belle II to further investigate possible reasons for this discrepancy.

The DESY Belle II group recently measured $|V_{ub}|$ using inclusive decays with 365 fb^{-1} of data [2]. Isolating $b \to u$ transitions is challenging, as $b \to c$ transitions are about 50 times more abundant. To suppress and control this background, the group used a neural network and performed a simultaneous fit to signal regions and background-enriched control regions. The partner B meson was reconstructed fully in hadronic decay channels to constrain the signal-side kinematics despite the undetected neutrino, improving resolution and background rejection [3].

The DESY Belle II group measured the partial branching fraction $\Delta B(B \to X_u \ell \nu) = (1.54 \pm 0.08(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-3}$ for lepton energies above 1 GeV, corresponding to $|V_{ub}| = (4.01 \pm 0.19^{+0.07}_{-0.08}) \times 10^{-3}$, where the first uncertainty is experimental and the second theoretical [2]. This value is compatible with the inclusive world average, $(4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$ [1], as shown in Fig. 2. The obtained uncertainty is competitive with the most precise measurement performed by the BABAR collaboration [4].

This measurement confirms the maturity of inclusive methods at Belle II and establishes a strong foundation for future precision studies of flavour physics and CKM unitarity.

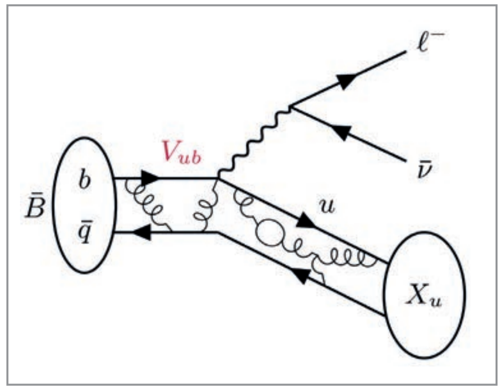

Figure 1
Feynman diagram of the $B \to X_u \ell \nu$ decay

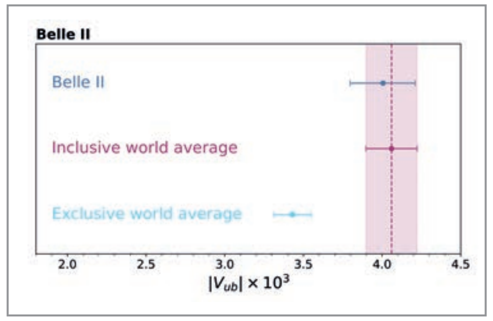

Figure 2
Comparison between $|V_{ub}|$ obtained from the Belle II measurement (blue) [2] and the inclusive (purple) and exclusive (cyan) world averages [1]

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Bright bunches, produced by plasmas

Cold electrons get caught in a plasma wakefield and then rapidly accelerated

Bright electron bunches, with high current, low energy spread and low emittance, are in demand for photon science. Low-emittance bunches in radio frequency accelerators are rapidly degraded by space charge forces once they are produced, and this continues until they are accelerated to relativistic energies. In a plasma, the acceleration happens more quickly, meaning plasma accelerators have the potential to produce truly ultralow-emittance bunches. Using a technique called density down-ramp injection, the FLASHForward team at DESY showed strong progress in this direction, reliably producing micrometre normalised emittance bunches with spectral densities on the order of 10 pC/MeV.

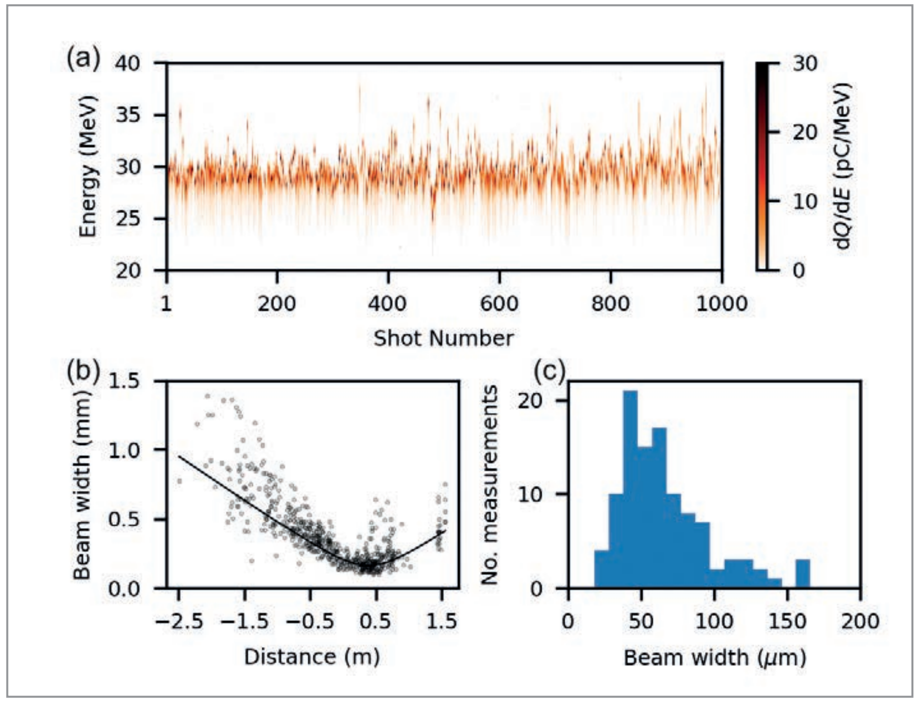

Figure 2

Electron acceleration results. a) Energy spectra from 1000 consecutive events. b) Evolution of the bunch width with distance. c) Histogram of bunch widths.

Motivation and experiment

In a plasma wakefield accelerator (PWFA), a short, high-energy electron bunch is focused into a plasma of density n_e. The strong electric field from the space charge of this driver bunch pushes the plasma electrons away from it, while on short time scales the heavier ions remain stationary. In this way, an electron density wave (the wakefield) with longitudinal and transverse fields of 1–10 GV/m is created, which follows the driver [1, 2]. The radius and length of this wakefield increase with n_e. Regions of the wakefield have both an accelerating and a focusing effect on electrons, so a trailing bunch placed in the wakefield can rapidly gain energy. By tailoring the properties of the trailing bunch, its energy spread and emittance can be preserved [3, 4].

These strong fields can rapidly accelerate a bunch from rest, minimising space-charge-driven emittance growth.

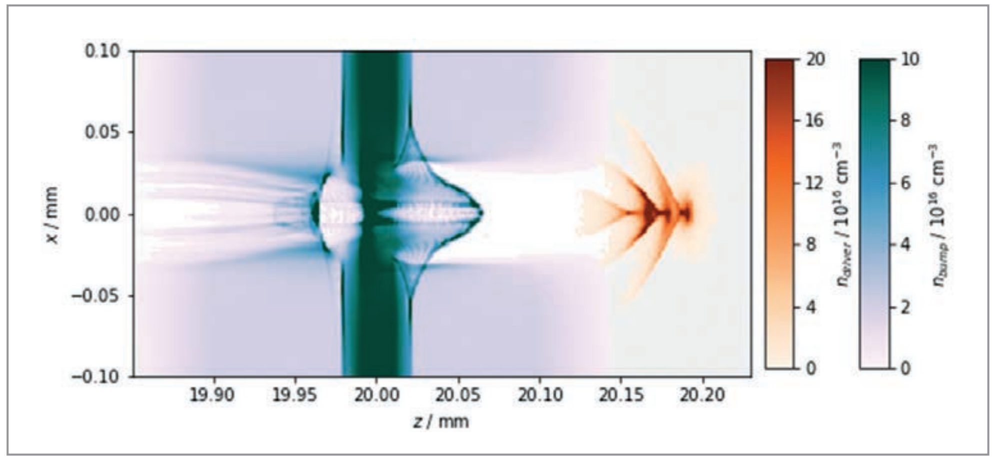

Figure 1

Snapshot of the beam and plasma densities from particle-in-cell simulation at the moment of injection

The challenge is to place an ultralow-emittance bunch inside the wakefield. A practical source of electrons turns out to be those electrons that make up the wakefield itself. These gain large longitudinal velocities from the driver. If the driver propagates through a plasma that decreases in density with distance (a down-ramp), then the wakefield elongates, reducing its velocity below that of some plasma electrons [5]. This solves the problem of injecting electrons into the wakefield, but not how to give them a small emittance, as they still have large transverse momenta from their interaction with the driver. Fortunately, a strong magnetic field generated at the back of the wakefield resists their motion, arresting their momentum [6]. The resulting normalised emittance can, in simulations, be as low as tens of nanometres [7].

A simulation of this process is depicted in Fig. 1. Similar to the experiment at FLASHForward, a focused ~2 kA driver bunch (orange) drives a plasma wakefield in a low-density plasma (purple). In the experiment, this low-density plasma was generated by a moderate-intensity laser pulse. A secondary laser pulse travelling transversely to the driver was focused to higher intensity in the plasma, forming a narrow column with high n_e (green in Fig. 1). The down-ramp at the column edge was used for injection.

Results and discussion

Once this interaction was set up in the experiment, it was optimised by varying the focal position of the driver bunch, the relative transverse positions of the bunch and the transverse laser pulse, the bunch compression and the delay between the creation of the plasma column and the arrival of the driver. The latter tuned the height and length of the down-ramp. Simulations showed that the maximum charge was injected when the peak density of the narrow plasma column was equal to the bunch density, which drove rapid charge injection all along the ramp. Here, the optimal peak density was 12 times the background n_e, whereas previous work used a factor of less than 2 [8, 9].

The properties of the optimised, experimentally injected bunch are shown in Fig. 2. An imaging spectrometer measured the energy spectra of the bunches. 1000 consecutive shots are plotted in Fig. 2a. The injection probability was > 99%, the mean energy and energy spread were (30 ± 2) MeV and 1.3%, the mean charge was (19 ± 7) pC, and the mean spectral density was (14 ± 6) pC/MeV.

By varying the spectrometer object plane (Fig. 2b), a low divergence of 0.32 mrad was measured. Combining this with the beam size measured on a higher-resolution detector (histogram in Fig. 2c), a mean emittance of (1.2 ± 0.1) mm•mrad was determined, which is comparable to modern linear accelerators. At 11.3 pC/MeV/mm•mrad, the brightness of the injected beam was around five times higher than that of the driver bunch.

In this experiment, bunches were internally injected into a PWFA with simultaneously high charge per MeV and low emittance for the first time. The low final energy was due to the short plasma source. In a simulation study with a similar driver, a 37 pC density-down-ramp-injected bunch was accelerated to 635 MeV in 20 cm of plasma. During acceleration, the charge remained constant, as did the normalised emittance at 0.4 mm•mrad, while the energy spread stayed below 1%.

More details can be found in [10].

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Electrons make a difference

ELBEX project gathers speed towards providing electron beam at the European XFEL

ELBEX, short for Extracted Lepton Beam at the European XFEL, is a project to prepare exactly that – an extracted lepton beam at the European XFEL X-ray free-electron laser in Schenefeld. The proposed facility is designed to deliver electrons of up to 17.6 GeV energy into an experimental area. This beam of excellent quality and high energy will open up new avenues of research at the European XFEL, most notably in high-precision quantum electrodynamics (QED) experiments, in beam-driven plasma acceleration and in studies of detector materials and setups. ELBEX is a collaborative effort of DESY, European XFEL, INFN Padova in Italy, IFIC Valencia in Spain and the University of Manchester in the UK. ELBEX is partially funded by the European Commission under Grant Agreement 101130174.

The ELBEX facility

The ELBEX facility (Fig. 1) is proposed for installation in XTD8, one of the currently unused tunnels of the European XFEL. Electron bunches will be extracted from the XFEL and then guided into the XTD8 tunnel via a dedicated beamline. The XTD8 tunnel will be shared with another new instrument at the European XFEL dedicated to fusion energy research. ELBEX will occupy the first 150 m or so of the tunnel, with the fusion instrument utilising the remainder, next to the experimental hall in Schenefeld. ELBEX will be run parasitically alongside the rest of the XFEL operation and in such a way that the downstream part of the XTD8 tunnel will not be affected by its operation.

ELBEX is designed as a user facility that will provide beam to a number of experiments [1]. Currently, three communities are discussing the possibility to perform experiments at ELBEX: The LUXE collaboration proposes to use the electron beam for a precision test of QED [2]. For this experiment, a high-intensity laser beam will additionally need to be transported into the user area, where it will be made to collide with the electron beam. The high energy of the electron beam, combined with a high-power laser in the petawatt regime, will enable the experiment to reach energy densities approaching and passing the Schwinger limit.

The second community wants to use the electron beam to perform beam-based plasma acceleration experiments. The high quality and extreme reproducibility of the beam parameters at the European XFEL make it an ideal environment in which energy boosting of the electron beam in a plasma cell at high energies could be demonstrated. This is of high interest to the FEL community, but also to the particle physics community as a platform for proof-of-concept experiments leading towards a plasma-based high-energy accelerator.

The third community proposes to use the electron beam in a setup to test detectors under varying conditions. The high energy of the electrons in ELBEX make them very well suited for fundamental studies of properties of detectors in an energy regime where multiple scattering does not play an important role any more. Due to the high energy, this use case would ideally complement the already existing test beam setup at the 6 GeV DESY II electron synchrotron.

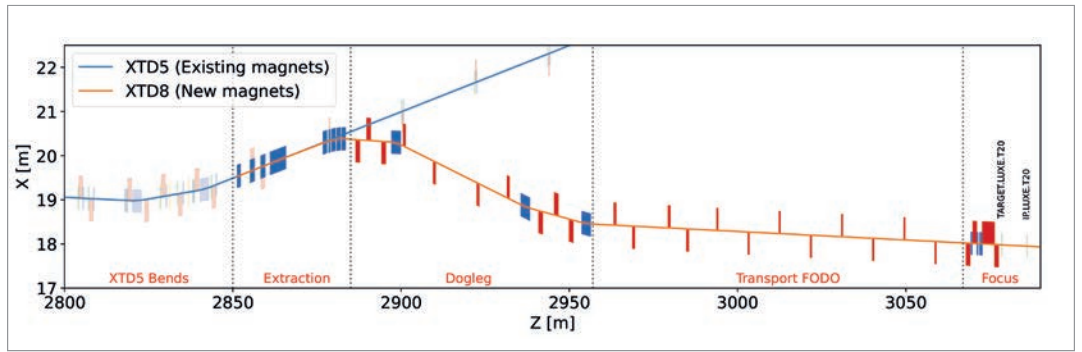

Figure 1

Conceptual layout of the ELBEX extracted-electron beamline at the European XFEL. Shown are the existing beam elements (faint blue and red) and the new elements to be installed for ELBEX. The length of the beam transport section is still under discussion.

Figure 2

View into the XTD8 tunnel, in which the ELBEX beamline is to be installed

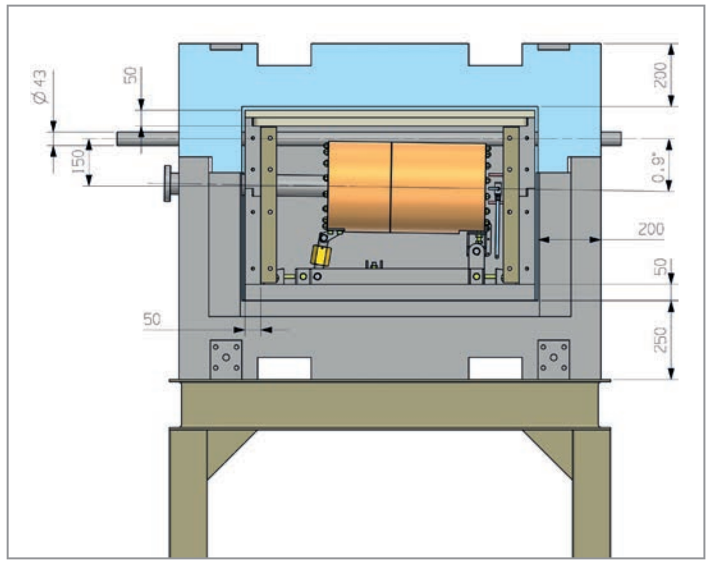

Figure 3

Design of the beam dump for the ELBEX beamline. The dump is mounted at a slight angle to point away from the rest of the tunnel. The dump will be enclosed in a concrete housing to shield the surrounding area.

Over the past year, the ELBEX facility underwent a major redesign. The location of the facility was moved within the European XFEL complex from the XS1 hall to the XS4 hall and XTD8 tunnel. This new location (Fig. 2) offers much better accessibility. During the past few months, extensive studies have been carried out to demonstrate the feasibility of the new location and, in particular, to study the coexistence of ELBEX with the fusion instrument.

The ELBEX beamline

After passing through the SASE2 undulator, the European XFEL electron beam is transported through the XS4 hall to an electron dump. ELBEX will kick out a small number of electron bunches into the new beamline. The bunches will be separated from the European XFEL beam and then guided through a “dog-leg”-like beam transport into the XTD8 tunnel (Fig. 1). There, a system of magnetic elements will focus the beam down to a spot size of 10 µm.

For LUXE, the focus will be located inside an interaction chamber, in which the electron beam and the laser beam will be brought into collision. The electron beam that exits the interaction chamber will then be transported towards an electron dump, where it will be disposed of. A small fraction of the beam will interact with the laser and be measured in great detail in the LUXE experiment, before being dumped as well.

A design of the lattice needed to transport the beam into the XTD8 tunnel has been developed. Simulations have shown that it is possible to achieve a beam spot size of less than 10 µm in the vertical direction, as required by the LUXE experiment.

Inside the XTD8 tunnel, a beam pipe will be installed to transport high-energy X-ray photons from the SASE2 undulator towards the fusion instrument. The design of ELBEX needs to be done in such a way as to not interfere with this installation and to provide a clean path for the photons throughout the area.

European XFEL requires that the operation of ELBEX and of the fusion instrument be decoupled as much as possible. In particular, access to the fusion part of the tunnel should be possible at all times, regardless of the status of ELBEX. Studies are currently ongoing to develop a radiation protection scheme that will allow safe access to the fusion instrument independent of the operation of ELBEX. This will most likely require an optimised design of the ELBEX beam dump and the insertion of a radiation protection chicane in the tunnel to separate the two instruments.

The beam dump will be oriented at a slight downwards angle of a few degrees to ensure that any leakage from the beam dump is oriented away from the rest of the tunnel (Fig. 3). Simulations and design efforts are currently under way to optimise the dump design and demonstrate that the ELBEX facility can operate in parallel to the fusion instrument.

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The Linear Collider Facility for CERN

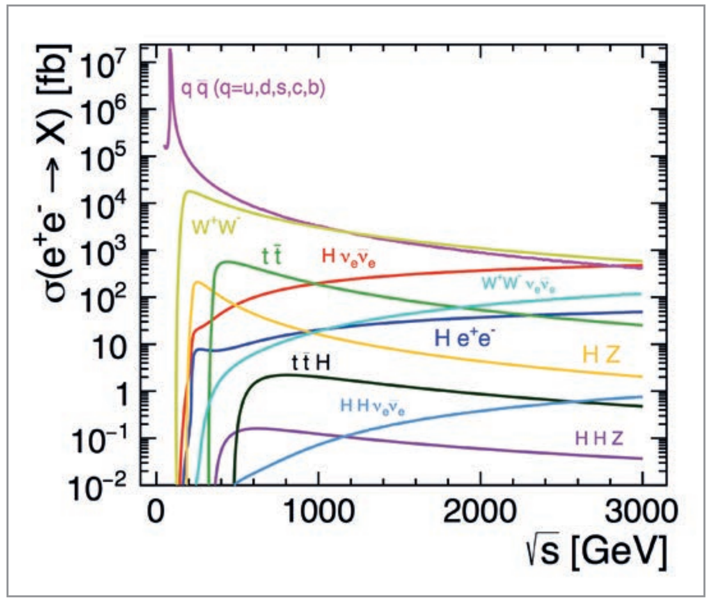
A flexible exploration tool for the next era of particle physics

In March 2025, DESY scientists – together with many colleagues from around the globe – proposed a Linear Collider Facility (LCF) as a future flagship project for CERN, aiming to unravel the mysteries of the Higgs boson and its closest relatives with measurements beyond the capabilities of the High-Luminosity LHC (HL-LHC). The LCF proposal is a contribution to the currently ongoing update of the European Strategy for Particle Physics, which will conclude in May 2026 with a special session of the CERN Council in Budapest, Hungary. While there is a strong preference in the particle physics community for the Future Circular Collider as a next project for CERN, the LCF could be an interesting alternative that offers not only an attractive science programme but also staged construction and operation and flexible upgrade paths, including opportunities to employ advanced accelerator technologies.

Beyond the HL-LHC

The discovery of the Higgs boson in 2012 at the LHC was a huge triumph, harvesting on decades of theoretical and experimental progress. This discovery raises many questions, however, about the mechanism by which particles acquire their mass and the role the Higgs boson played in the evolution of our universe since the Big Bang. The LHC and its high-luminosity phase, the HL-LHC, will continue to advance our knowledge for many years to come – and maybe even yield further striking discoveries. Yet we know already today that we can only unravel the mysteries of the Higgs boson and the heaviest known elementary particle, the top quark, when adding complementary measurements uniquely accessible through electron–positron collisions.

The Higgs boson and the top quark can be produced in electron–positron collisions through many different reactions, which all contribute their own pieces of information to the big puzzle. Figure 1 shows their rates (or cross sections), as predicted by the Standard Model of particle physics, as a function of the centre-of-mass energy of the collisions. At different energies between 200 and 1000 GeV, the production rates rise steeply, rendering the corresponding process observable: While the production of single Higgs bosons starts around 230 GeV, the production of top–antitop pairs requires about 350 GeV, and the production of two Higgs bosons requires at least 500 GeV or even 1000 GeV, depending on the exact production mechanism.



Linear colliders

The higher of these centre-of-mass energies can only be reached by linear colliders, which do not suffer from the exploding losses due to synchrotron radiation that occur in circular colliders when their beam energies are increased. Linear colliders can also collide spin-polarised beams, adding important degrees of freedom that provide additional information. On the downside, linear facilities collide particles only once, thus they require highly efficient particle production and acceleration techniques as well as excellent focusing of the beams.

Figure 1

Production rates of various processes in electron–positron collisions as a function of the centre-of-mass energy. Between centre-of-mass energies of 200 and 1000 GeV, several processes involving Higgs bosons and top quarks become kinematically accessible. [CERN, https://clic.cern/physics-processes]

However, a key advantage of linear colliders lies in the possibility to construct them stepwise in stages: Their energy can be increased by adding more accelerator modules at their outer ends, replacing the existing accelerator modules at some point by improved ones, or even using radically new approaches such as plasma wakefield acceleration. The luminosity could be increased by up to two orders of magnitude with energy recovery technology, and even upgrades to provide photon–photon collisions are conceivable. Thanks to these opportunities, linear colliders are ideally suited to starting with moderate scope and mature technology while being intrinsically open to later upgrades with advanced technologies, making it possible to react flexibly to scientific discoveries and/or technological breakthroughs.

The Linear Collider Facility for CERN

In this spirit, the Linear Collider Facility (LCF) for CERN [1] has been proposed as part of an input to the currently ongoing update of the European Strategy for Particle Physics, complemented by a more comprehensive review of linear colliders and their upgrade scenarios [2]. The LCF would have a site length of 33.5 km, including a 5 km beam delivery region sized for up to 3 TeV collisions. It would accommodate two interaction points, which would share the collider luminosity. Superconducting cavities with an accelerating gradient of 31.5 MV/m, as developed for the International Linear Collider (ILC), would serve as the initial technology.

In its first stage, this facility would be equipped to reach a centre-of-mass energy of 250 GeV, with both beams polarised ($|P(e^-, e^+)| = (80\%, 30\%)$), leaving part of the tunnel equipped only with a transfer line. This would make it possible to flexibly increase the centre-of-mass energy up to 550 GeV by installing more accelerator modules at any time, at a pace adjustable to the availability of resources and scientific competition. The radio frequency and cooling systems would provide for trains of 1312 bunches ($N_e = 2 \times 10^{10}$ per bunch) with a repetition rate of 10 Hz, resulting in an instantaneous luminosity of 2.7×10^{34} cm^{-2}s^{-1}, a factor of 2 higher than for the ILC as proposed in Japan.

The construction cost of this baseline configuration, without the detectors, would be 8.3 billion CHF, the total required alternating-current (AC) site power 143 MW. The upgrade to 550 GeV would require an additional 5.5 billion CHF, assuming that the same production facilities as for the initial-stage cryomodules can be reused. With a total AC power of 322 MW, an instantaneous luminosity of 7.7×10^{34} cm^{-2}s^{-1} would be achieved, with the positron polarisation increased to $|P(e^+)| = 60\%$.

Figure 2 illustrates a possible run plan for the LCF. Besides the main operation at 250 and 550 GeV, shorter dedicated runs at the *Z* pole (91 GeV) and the top–antitop production threshold (350 GeV) are included. This also shows that the second chunk of substantial investment, for the 550 GeV upgrade, would only be needed about 10 years after the construction of the first stage.

The expected science output of the LCF is to a large extend quite similar to that of other Higgs factory proposals, in particular with regard to measurements of single-Higgs production and the electroweak precision measurements required for the interpretation of the Higgs data. It would deliver this programme at substantially reduced resource budget, though. In other aspects, the LCF is complementary to circular colliders: While it does not enable precision studies of *B* hadrons beyond what Belle II and LHCb will achieve over the next decade, the 550 GeV stage of LCF offers a superior programme in top physics and unique measurements of di-Higgs production, providing important insights into the role of the Higgs boson and the top quark in the early universe. Beyond the 550 GeV stage, it offers many attractive long-term opportunities and the flexibility to choose between them based on the scientific and technological advances of the next decades.

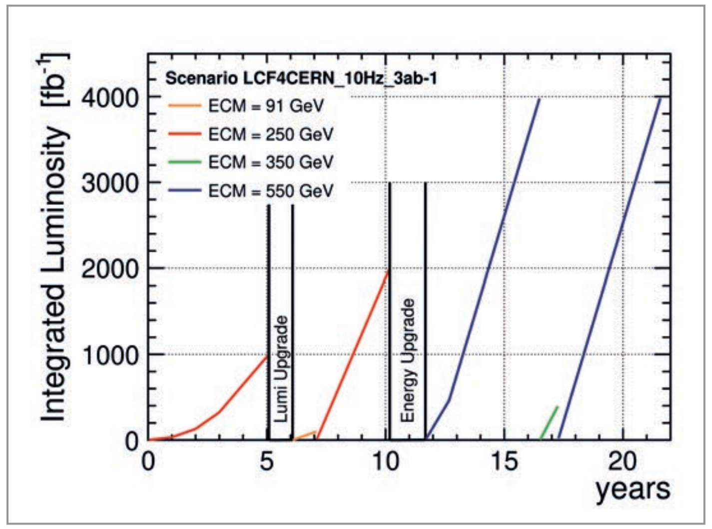


Figure 2

Possible operating scenario for the LCF: A first operating stage at centre-of-mass energies up to 250 GeV, costed at 8.3 billion CHF, could be followed by a second stage reaching up to 550 GeV by investing another 5.5 billion CHF about 10 years later.

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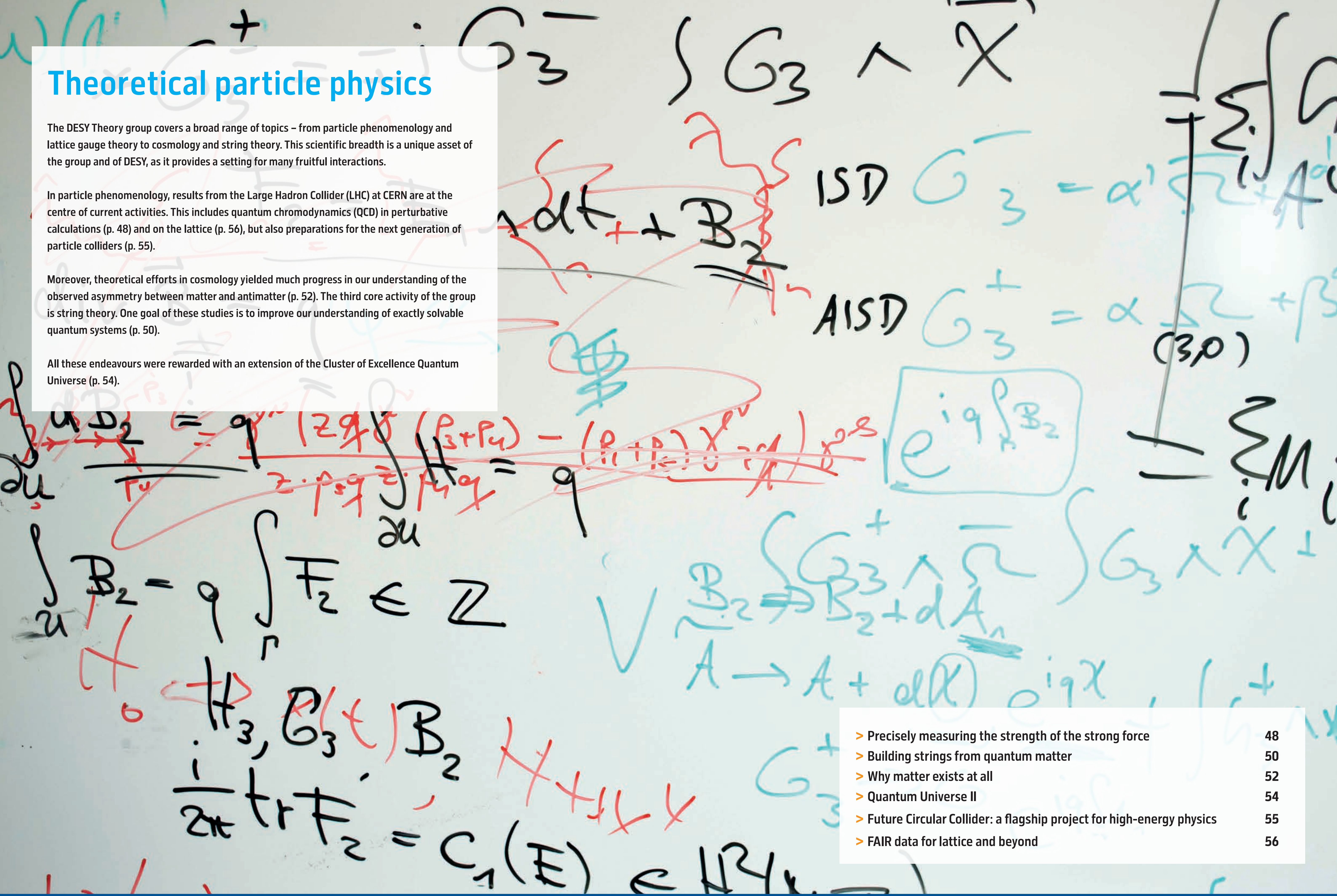
Theoretical particle physics

The DESY Theory group covers a broad range of topics – from particle phenomenology and lattice gauge theory to cosmology and string theory. This scientific breadth is a unique asset of the group and of DESY, as it provides a setting for many fruitful interactions.

In particle phenomenology, results from the Large Hadron Collider (LHC) at CERN are at the centre of current activities. This includes quantum chromodynamics (QCD) in perturbative calculations (p. 48) and on the lattice (p. 56), but also preparations for the next generation of particle colliders (p. 55).

Moreover, theoretical efforts in cosmology yielded much progress in our understanding of the observed asymmetry between matter and antimatter (p. 52). The third core activity of the group is string theory. One goal of these studies is to improve our understanding of exactly solvable quantum systems (p. 50).

All these endeavours were rewarded with an extension of the Cluster of Excellence Quantum Universe (p. 54).



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Precisely measuring the strength of the strong force

Making theory uncertainties reliable and robust

Theoretical physicists at DESY have developed a novel strategy to determine the strong coupling constant α_s from the *Z*-boson transverse-momentum spectrum at the LHC. By introducing theory nuisance parameters to consistently treat correlated theory uncertainties, the method enables a statistically robust extraction at percent-level precision. This framework paves the way for a new generation of high-precision quantum chromodynamics studies and fundamental parameter determinations at the LHC and beyond.

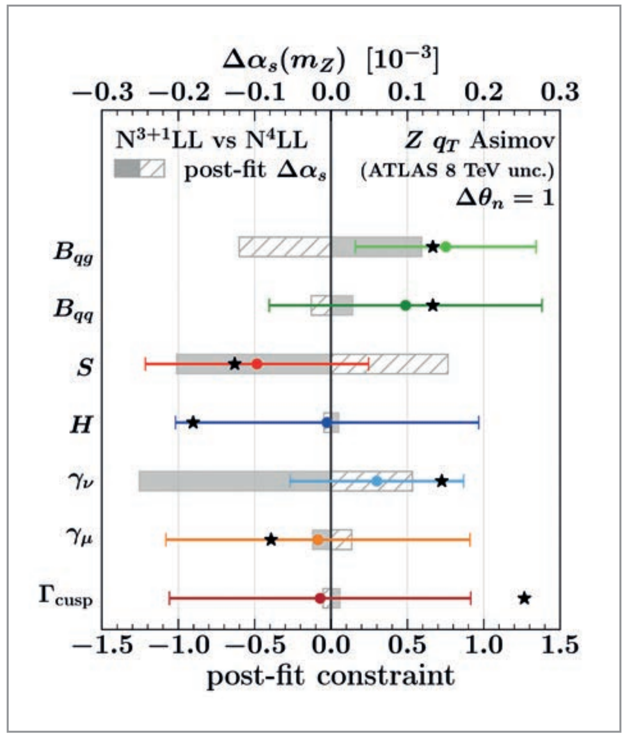

Figure 2

Post-fit constraints on the TNPs (error bars) and their impact on $\alpha_s(m_Z)$, with the solid (dashed) grey band showing the impact of the post-fit downward (upward) TNP variations

The strong coupling

Most processes at the LHC are governed by the strong interaction. Its strength is set by a fundamental parameter, the strong coupling constant α_s. Its precise value is a crucial input for many predictions in particle physics, yet it remains one of the least well-known fundamental constants. A precise determination of α_s is essential for stringent tests of the Standard Model.

Determining α_s at the LHC

A powerful observable to determine α_s at the LHC is the transverse-momentum (q_T) spectrum of the *Z* boson in the Drell–Yan process. It has been measured with remarkable precision by the ATLAS and CMS experiments, reaching permille-level accuracy. At small q_T, the shape of the spectrum is especially sensitive to the dynamics of the strong interaction, making it an ideal laboratory for precision studies. Theoretically, this region can be described with very high accuracy using state-of-the-art resummed calculations. However, extracting α_s is not only a question of precision, but also of how reliably we are able to estimate theory uncertainties.

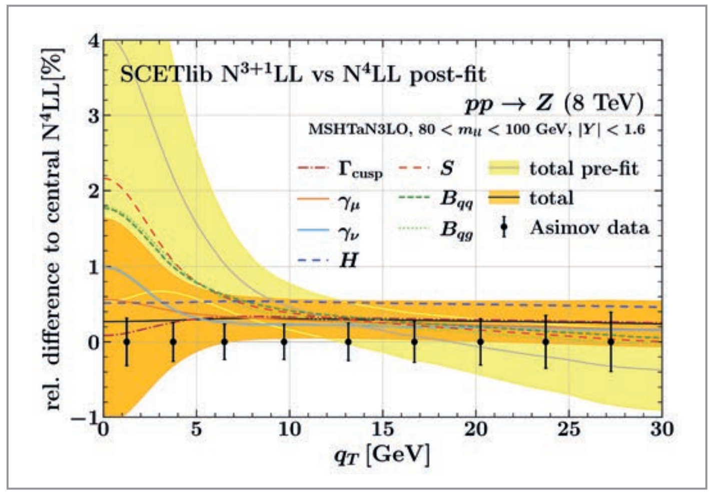

Figure 1

Uncertainties in the q_T spectrum at N^{3+1}LL relative to N^{4}LL, before (yellow band) and after (orange band) profiling the TNPs

In perturbation theory, calculations are performed order by order in α_s and are therefore intrinsically approximate. The associated theory uncertainties are traditionally estimated by varying unphysical scales in the calculation. While widely used, this method is well known to have severe limitations: It does not provide a statistically meaningful uncertainty, and it fails to correctly describe correlations across the q_T spectrum.

This is crucial: The information on α_s is encoded in the shape of the distribution. If correlations are not treated properly, the shape uncertainty is not correctly accounted for, preventing a reliable uncertainty in the extracted value of α_s.

A new strategy: theory nuisance parameters

To overcome these limitations, the DESY physicists exploited a novel framework based on theory nuisance parameters (TNPs) [1]. Instead of estimating uncertainties through scale variations, the missing higher-order terms are promoted to well-defined nuisance parameters with associated uncertainties. These parameters encode distinct sources of theory uncertainty and correctly capture theory correlations across the spectrum.

Using an Asimov data set based on the highest available perturbative accuracy (N^{4}LL), the team tested how well α_s can be extracted when theory uncertainties are treated in this way [2].

Figure 1 shows the uncertainty decomposition for the q_T spectrum in terms of seven independent TNP components. Their combined effect gives the total pre-fit uncertainty (yellow band). A key advantage of this approach is that the TNPs can be consistently constrained by the data itself, i.e. profiled in the fit to data. The result is an even lower theory uncertainty (orange band).

Figure 2 illustrates how each TNP behaves in the fit and quantifies its impact on the extracted value of α_s. It shows that the TNPs are pulled by the data towards their correct true values at N^{4}LL (represented by the stars).

In addition to these perturbative uncertainties, the team also investigated the role of non-perturbative effects, which become relevant at very low q_T where most of the sensitivity to α_s resides. With the perturbative uncertainties under control, it becomes possible to reliably determine the non-perturbative effects alongside α_s from the data.

The analysis demonstrated that a robust treatment of correlated theory uncertainties is both essential and possible, setting the stage for a reliable precision determination of α_s, with an expected uncertainty at or below 1%, competitive with the current world average. For a full extraction of α_s, additional theory inputs and sub-leading effects need to be incorporated and their uncertainties carefully assessed.

The TNP framework thus provides a method to quantify theory uncertainties and their correlations in a systematic, robust and statistically meaningful way. It was also successfully applied in the recent CMS measurement of the *W*-boson mass [3], where it played the same role in controlling theory systematics. This confirms that the method is not only conceptually well motivated, but also experimentally viable at the highest level of precision.

By enabling a more faithful treatment of theory uncertainties, this framework has opened the door to a new generation of precision studies at the LHC and beyond, allowing fundamental parameters to be extracted both at the highest possible accuracy and with reliable theory uncertainty.

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Building strings from quantum matter

A systematic route to holography

Understanding strongly interacting quantum systems remains a central challenge, particularly in quantum chromodynamics where key phenomena resist standard methods. Holographic dualities with string theories in higher dimensions offer a powerful handle but are so far limited to idealised models. For the first time, researchers at DESY engineered a string-theoretic dual for a family of 1+1-dimensional quantum systems: They showed how correlation functions can be reinterpreted as string interactions, enabling a direct translation of quantum data into a string framework. The work provides new insights into holography and advances efforts to connect it to realistic physical systems.

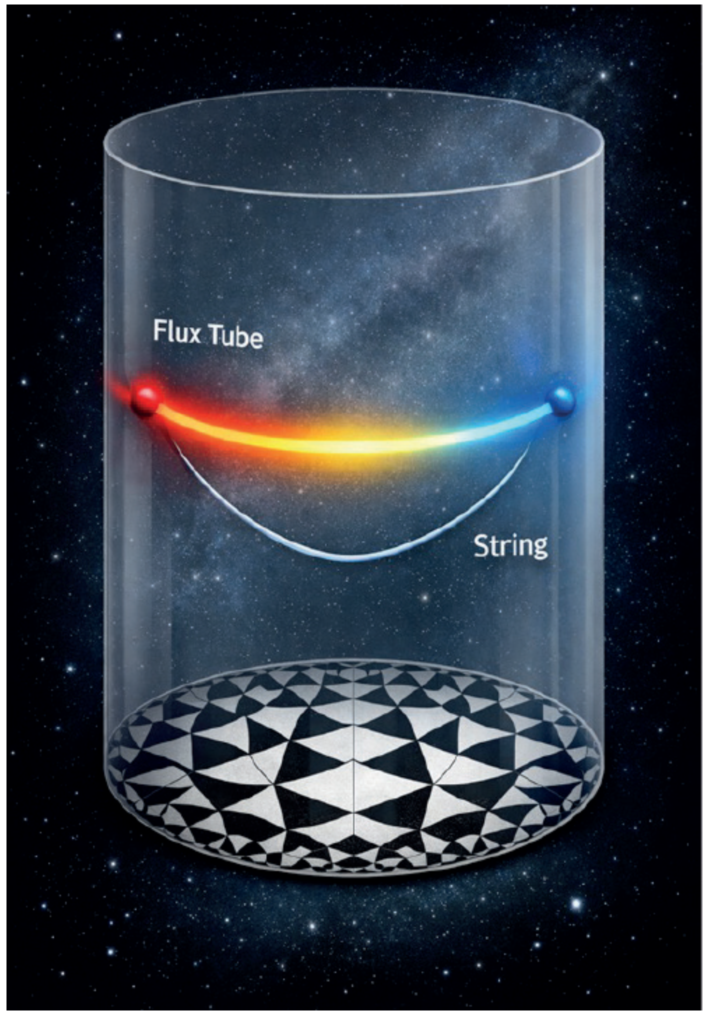

Figure 1

Holography offers an intriguing alternative to understand strongly coupled quantum systems in terms of some dual string theory. Typical features of the strongly coupled theory, such as the confining flux tube of QCD, are modelled by strings in some carefully chosen background. The latter is represented by the image at the bottom of the cylinder. For the first time, researchers at DESY were now able to engineer the string-theoretic background directly from correlations of some quantum theory that lives on the 1+1-dimensional mantle of the cylinder.

Understanding strongly interacting quantum systems is one of the major challenges in modern physics. This is especially important in particle physics, where the strong force – described by quantum chromodynamics (QCD) – governs how quarks and gluons form protons, neutrons and other particles. Although QCD is well established, many of its key phenomena, such as confinement, occur in regimes where standard calculation methods fail.

One powerful way to study such systems is through large-scale numerical simulations. However, these methods have important limitations, for example when describing real-time processes. An alternative approach is holography, a surprising idea suggesting that certain quantum systems can be equivalently described by theories of strings in higher dimensions. The quantum systems thereby appear as a hologram of a string theory that lives in one dimension higher (Fig. 1). Holography indeed provides powerful new tools to tackle otherwise intractable problems.

So far, however, holographic descriptions are only known for some highly idealised theories that differ significantly from real-world systems such as QCD. No direct way is known of how to systematically engineer string theories directly from our conventional models of quantum matter. For example, it is not known which string theory describes the confining flux tube of QCD (Fig. 1). Finding such a systematic route that applies to large families of quantum systems and in particular to QCD is a "holy grail" of modern theoretical physics.

This is exactly what was achieved by members of DESY's String Theory group, though in a low-dimensional context in which the quantum matter lives in 1+1 space-time dimensions. There exists a class of models in 1+1 dimensions that bears many striking similarities with the gauge theories we use to model quantum matter in our 3+1-dimensional world. These 1+1-dimensional analogues of gauge theories are called symmetric product orbifolds (SPOs), which is a reference to the way they are constructed, by taking many identical copies of the same underlying theory and identifying states that differ by a permutation, i.e. by an exchange of the individual copies.

In some special cases, SPOs are known to possess a string-theoretic description in terms of "tensionless" strings, meaning that it costs no energy to stretch or excite such strings. This deeply stringy nature implies that tensionless strings do not perceive the bulk of the cylinder in Fig. 1 as a smooth space-time geometry. Instead, they describe a highly quantum, non-geometric phase of the dual gravitational theory.

A team of researchers at DESY joined forces with colleagues in Japan to understand how such a tensionless string theory emerges from the usual formulation of SPOs. In particular, they showed that the most basic observables describing the quantum system – so-called correlation functions – can be systematically reorganised and reinterpreted as interactions of tensionless strings in a dual theory. Extensions to other quantities, including the SPO version of quark–antiquark potentials in QCD, are also being investigated [2, 3].

What makes the construction in [1] so remarkable is that it does not rely on solving the theory in detail. Instead, it provides a method to translate quantum-field-theoretic data directly into a string-theoretic language. In this way, the structure of the dual string theory can be "read off" from the original quantum system. This offers a new and more systematic understanding of how holography works.

These insights bring researchers closer to the long-term goal of applying holography to more realistic systems, including those relevant for particle physics. While such applications are still far away, the conceptual advances are significant. They provide new tools and ideas for understanding how space-time and gravity might arise from fundamental quantum processes.

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Why matter exists at all

Simulations suggest matter may have arisen from Higgs bubble collisions

One of cosmology's deepest mysteries is why the universe contains far more matter than antimatter. The hot Big Bang theory, based on the Standard Model (SM), predicts equal amounts of both. Explaining this baryon asymmetry requires new processes that created more protons and neutrons than their antiparticles. New simulations by the DESY Cosmology group indicate that such conditions could have arisen in the universe's first instants, during a spectacular first-order phase transition of the Higgs field. As Higgs bubbles formed and violently collided, they may have generated the excess of baryons we observe today. These results significantly impact standard calculations of baryon asymmetry at the electroweak scale.

Baryon asymmetry at the electroweak transition

Without a mechanism for baryogenesis, matter and antimatter in the early universe would have completely annihilated each other, leaving only light. Surprisingly, the SM already contains part of the solution. While the number of baryons seems conserved in everyday reactions, this conservation is not exact at the quantum level. Because of the unusual structure of the fields linked to the *W* and *Z* bosons, the vacuum has multiple possible configurations. Transitions between them change the number of baryons.

In the hot thermal plasma of the early universe, such transitions occurred frequently. Violent thermal fluctuations allowed the fields to "hop" between different vacuum configurations, changing the baryon number in processes known as thermal sphalerons.

As sphalerons and their inverse processes (anti-sphalerons) are equally probable, this alone cannot explain why matter dominates. Additional ingredients to violate the symmetry between matter and antimatter – possibly new, heavy particles – should have played a role. Besides, departure from equilibrium is required for baryons to dominate over antibaryons. If the new particles' interactions with the Higgs are strong, the universe could have undergone a dramatic phase transition, nucleating bubbles of the true Higgs phase that expand (Fig. 1a). Near the bubble walls, subtle differences between matter and antimatter interactions could have tipped the balance between sphalerons and anti-sphalerons – producing a tiny excess of baryons.

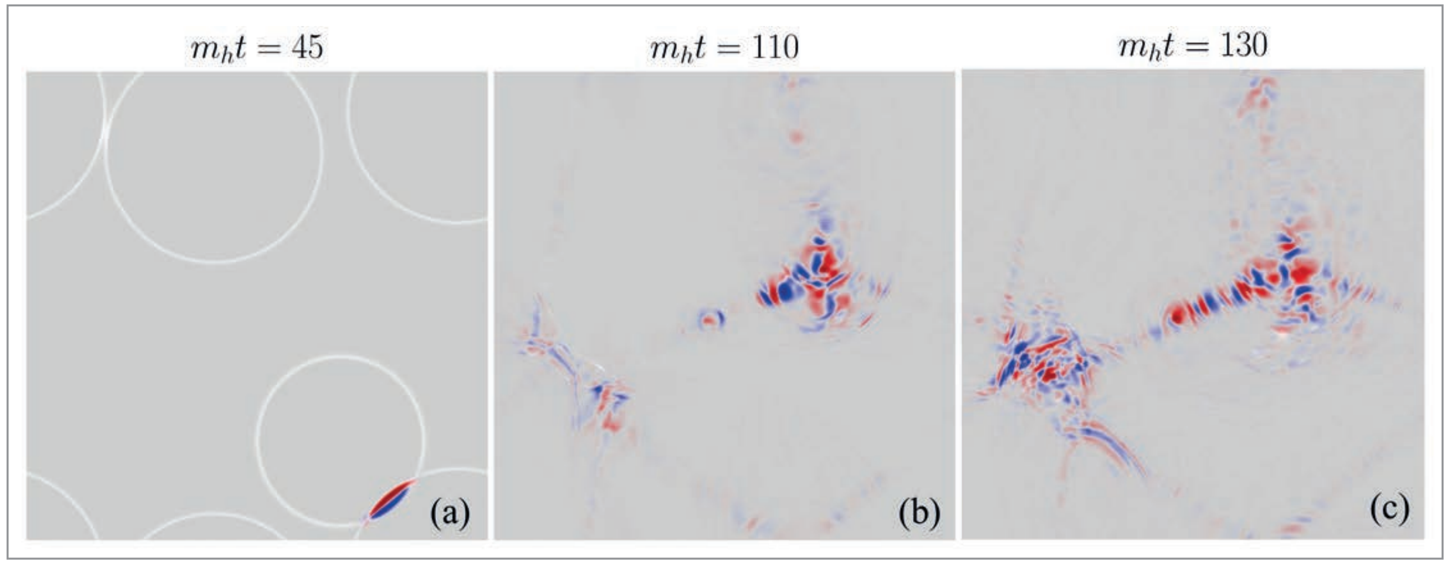

Figure 1

Expansion and collision of Higgs bubbles. The bubble walls are shown in white, while the regions where the new, additional sphaleron processes – and thus baryon number generation – occur are highlighted in blue and red.

Supercooling

In fact, in motivated theories of new physics, a more dramatic phase transition occurs. In many, the transition happens unusually slowly, and the universe cools far below the electroweak temperature (~100 GeV) before bubbles of the new phase begin to form. This "supercooling" can happen for example if the Higgs is composite, i.e. built from smaller constituents bound by a new strong force – as the LHC is testing in collaboration with DESY researchers.

In these cases, the thermal fluctuations in the hot plasma are strongly reduced. The expanding bubble walls can then accelerate to speeds close to that of light. But this seems problematic: The usual mechanism for baryogenesis relies on slow-moving walls and thermal sphalerons in front of them. If the walls move too fast, there is simply no time for the usual mechanism to build up the baryon asymmetry.

A new source of baryon number: dynamics over heat

Researchers at DESY have found a way around this problem. Instead of relying on thermal fluctuations, they suggested that baryon number violation could arise from the violent, out-of-equilibrium dynamics of the Higgs field itself when the rapidly expanding bubbles collide [1]. Specifically, as bubbles crash into each other, the Higgs field oscillates strongly. Its energy is efficiently transferred to the *W* and *Z* bosons, which explore multiple vacuum configurations dynamically, leading to additional sphaleron transitions (blue and red in Fig. 1b, 1c). Here, it is not active thermal hopping but the classical field dynamics that drives baryon number violation.

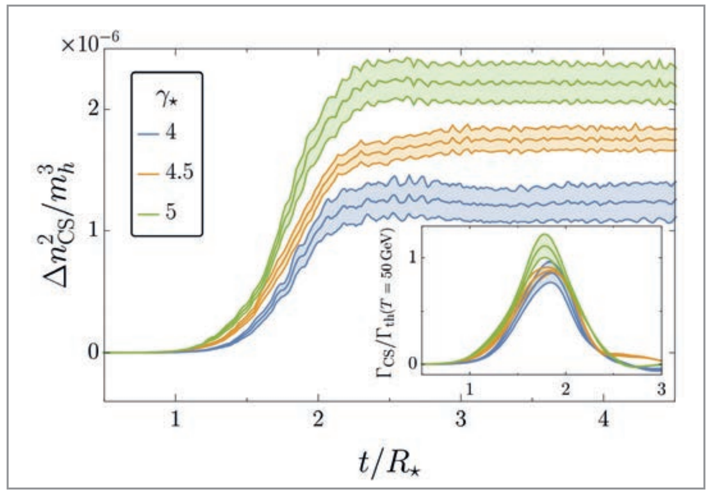

Figure 2

Variance of the baryon number generated by bubble collisions as a function of time, shown for different bubble wall γ^* factors at the moment of collision. Here, R^* denotes the bubble radius at this moment. The inset displays the corresponding effective sphaleron rate.

Simulating Higgs bubble collisions

A recent study by scientists from DESY and Universität Hamburg provides the first concrete evidence that this new mechanism could really work [2]. The equations describing the Higgs and the *W* and *Z* bosons are highly complex, so the team carried out large-scale computer simulations. These encode the full evolution of the fields, including the expansion and collision of bubbles.

The key quantity – the rate of sphaleron transitions, linked to baryon number change – is large as the bubbles collide. The time evolution of these transitions is shown in Fig. 2 for different values of the bubble wall γ factor – i.e. different collision velocities. Strikingly, the resulting transition rate is comparable to the well-known thermal sphaleron rate in a hot plasma (inset of Fig. 2). In other words, even without high temperatures, the sole violent bubble collisions in a supercooled phase transition can efficiently change the baryon number.

For particle physicists, this changes the picture. In theories that predict supercooled first-order transitions, the apparent failure of the standard, heat-driven mechanism is not the end of the story. Instead, the dramatic collision of bubbles may open a new path to explaining why matter dominates over antimatter. Moreover, this extra source of baryon number violation could play an important role even in conventional first-order phase transitions.

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Quantum Universe II

Understanding mass and gravity at the interface between quantum physics and cosmology

The Cluster of Excellence Quantum Universe (QU), which has been running at Universität Hamburg in collaboration with DESY since 2019, will receive funding from the German Research Foundation (DFG) for another seven years. Its unique scientific breadth and core expertise span astrophysics, cosmology, particle physics and mathematics.

For the second funding phase of the Cluster starting in 2026, QU scientists will seek to advance our understanding of the fundamental laws of nature from the earliest quantum era of cosmological history to the largest gravitational structures of today's universe.

The programme has been structured around the main research areas featured in Fig. 1. QU II will push the boundaries of our understanding of Higgs physics. The uniqueness of the Cluster lies in the strong interplay between theory and experiment and the strong involvement in shaping a future Higgs factory. In the quest for dark matter, QU II builds on a unique experimental on-site programme, in particular through the "axion hub" of Hamburg experiments, such as WISPLC, BRASS, MADMAX, BabyIAXO, WISPFI and ALPS II. QU II will also exploit the rich interplay with cosmology and gravitational-wave production.

The next big question addressed by the Cluster is that of gravity. QU I established gravitational waves as a new scientific pillar in Hamburg. Building on this success, QU II will work on the development of next-generation gravitational-wave detectors, in order to increase the sensitivity and extend the frequency range, with the goal of discovering completely new sources. Another important activity consists in pushing to a record the theoretical prediction of gravitational waves from astrophysical compact objects and from the early universe, in order to show that gravitational-wave detectors teach us not only about gravity and astrophysics but also about particle physics at very high energy scales, up to the Big Bang.

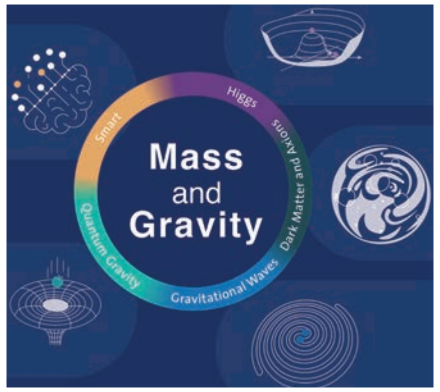

Figure 1
Main research areas of the Cluster of Excellence Quantum Universe II

To understand quantum gravity and black holes and to develop important theoretical guidance for particle physics and cosmology, new ideas in theoretical physics and novel geometric and algebraic structures will be explored, thanks to the unique expertise in formal quantum field theory, holography, string theory and its underlying mathematics gathered in the DESY Theory group and at the University, united under the umbrella of the Wolfgang Pauli Centre and the Center for Mathematical Physics Hamburg.

To harvest the unprecedented amount of new data in experiments and theory, QU II will develop new artificial intelligence techniques, creating major synergies across our individual research fields and enabling powerful applications throughout the Cluster. The ambitious programme of QU II is carried not only by the 25 Principal Investigators (PIs) who signed the proposal, but by the complete team of 46 PIs currently active in QU. Additionally, 38 key researchers strengthen the portfolio of the Cluster. All in all, QU is inspiring and training over 200 early-career researchers.

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Future Circular Collider: a flagship project for high-energy physics

Creating opportunities for fundamental science and enabling new technologies

The Future Circular Collider (FCC) is set to become the next worldwide flagship project after the LHC era. Its ambitious programme will be a unique opportunity to fuel the field of high-energy physics for several decades to come. Be it for testing the Standard Model predictions with unprecedented precision or for searching directly and indirectly for new particles at high and low energy scales, the machine is being designed with versatility and diversity at the heart of its multistage programme. The FCC accelerator complex will build on the expertise acquired over the last 70 years, and it will benefit from a combination of technological improvements that will enhance its efficiency by more than five orders of magnitude compared to the previous electron–positron collider, the Large Electron–Positron Collider (LEP) at CERN.

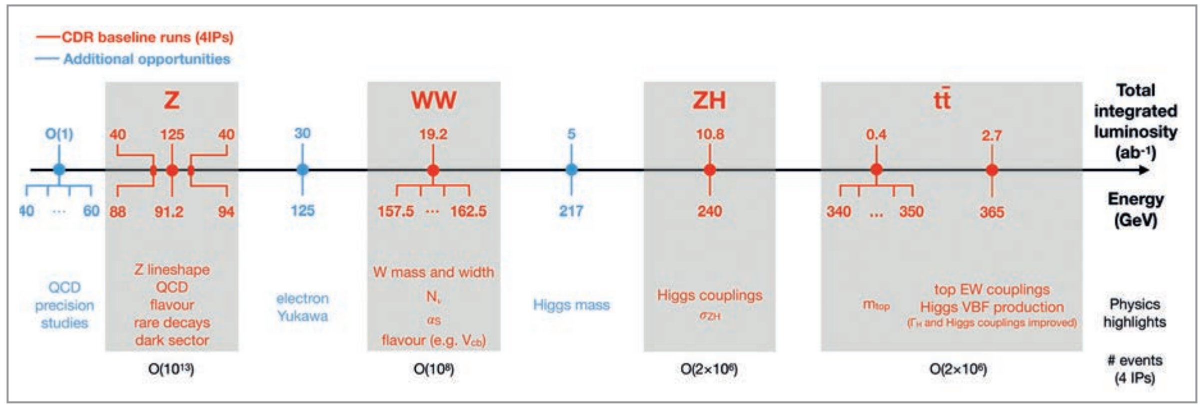

Figure 1
Potential physics programme for the FCC-ee electron–positron collider, ordered by increasing centre-of-mass energy. Red indicates the minimal programme with 15 years of running. Blue indicates a possible wider physics programme.

In 2024, the CERN Council initiated a process to develop a visionary and concrete plan that greatly advances human knowledge in fundamental physics through the realisation of the next flagship project at CERN. The whole community was asked to submit contributions, alongside national inputs, such as the one prepared by the German Committee for Particle Physics (KET) [1]. These contributions were reviewed and synthesised in the Physics Briefing Book [2]. Two DESY groups, FTX and Theory, were particularly active in this process, advocating the physics motivations as well as the design options for a circular or linear electron–positron Higgs factory.

Taking into account the technical readiness, the physics potential and the long-term prospects of reaching beyond the 10 TeV partonic centre-of-mass energy scale, the European Strategy Group issued a set of recommendations in December 2025 [3], identifying the FCC as the preferred option. These recommendations will be reviewed in a special session of the CERN Council in May 2026 in Budapest, Hungary.

The FCC science programme, developed in [4] and illustrated in Fig. 1, is broad and optimal in terms of its environmental impact. It will enable outstanding discoveries throughout the Higgs, electroweak, flavour and top sectors as well as advances in quantum chromodynamics. It will also open up a unique opportunity to realise a hadron collider by reusing the 91 km tunnel and much of the infrastructure, thus providing a direct discovery reach at energies about one order of magnitude higher than at the LHC. Beyond its use as a collider, the FCC complex, through its numerous assets (abundant positron production, low-emittance beams and high-power beamstrahlung) could also serve as a powerful light source for very hard X-rays of 100 keV energies.

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FAIR data for lattice and beyond

ILDG as a blueprint for a distributed FAIR-compliant data management framework

The International Lattice Data Grid (ILDG) is a community effort to enable and organise the worldwide sharing of precious data from lattice quantum chromodynamics (QCD) simulations [1]. Members of the Zeuthen Particle Physics Theory (ZPPT) group and the IT groups have been making important contributions to the creation and operation of ILDG for more than two decades. DESY also played a leading role in recent efforts to modernise and extend ILDG to make it a modular, flexible and fully FAIR-compliant data management framework. Features such as the freely configurable metadata catalogue and fine-grained token-based access control make an ILDG-like setup also interesting for other data management use cases at DESY and beyond.

FAIR data principles

Many research fields rely on large and valuable data sets produced e.g. by complex experimental facilities or through expensive numerical simulations. The management and sharing of such precious research data require more attention than just providing a sufficient amount of storage space.

Making data "findable, accessible, interoperable and re-usable" (FAIR) is an essential guiding principle for scientific data management and stewardship [2]. These FAIR data principles are also a cornerstone of DESY's research data policy, and they are becoming an increasingly important requirement of funding agencies.

Rich metadata, which describes e.g. content, provenance and other important properties of the data, is a key aspect of FAIR data. From a logical point of view, this requires some kind of database, where data objects are stored as entries with three fields: a persistent unique identifier, metadata and the actual data, as illustrated in Fig. 1.

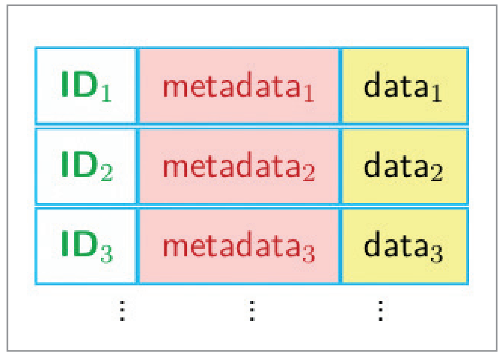

Figure 1
Logical organisation of FAIR data as a database. Each data object is represented as an entry (row) with three fields: an identifier (ID), metadata and data.

However, the practical implementation of a FAIR data management ecosystem may strongly depend on specific characteristics of the data sets and of the research community. The naive setup of Fig. 1 might only be adequate in very simple cases, such as the local management of data for a stand-alone research project (e.g. a PhD thesis) on a single computer by a single researcher.

Lattice data and ILDG

In theoretical physics, petabytes of extensive data sets arise in lattice QCD. They are called "ensembles" and consist of Monte Carlo samples of the gluon field on a space-time lattice. These ensembles are produced by large-scale simulations, which may take years even on high-performance computers, and are then used – possibly many years after their production and by different research groups – to compute physical quantities of interest.

To enable and organise the worldwide sharing of these precious ensembles, lattice physicists founded the International Lattice Data Grid (ILDG) more than 20 years ago [3, 4]. Since then, members of the DESY Theory and IT groups have made important contributions to ILDG, e.g. to establish a community-wide metadata schema and to define or operate services such as the global user registration, metadata and file catalogues, or storage elements.

A natural strategy of the early ILDG has been to leverage grid technologies, such as those used for the LHC grid at that time. This includes user authentication by certificates and distributed storage elements indexed via a file catalogue.

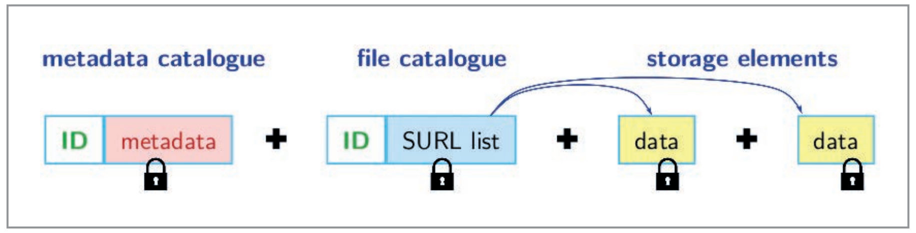

Figure 2
Logical organisation of FAIR data and metadata in a setup with a separate metadata catalogue and with multiple storage elements for large data objects. Their distributed and possibly replicated storage locations (SURL) are registered in the file catalogue. The padlock symbol indicates fine-grained access control.

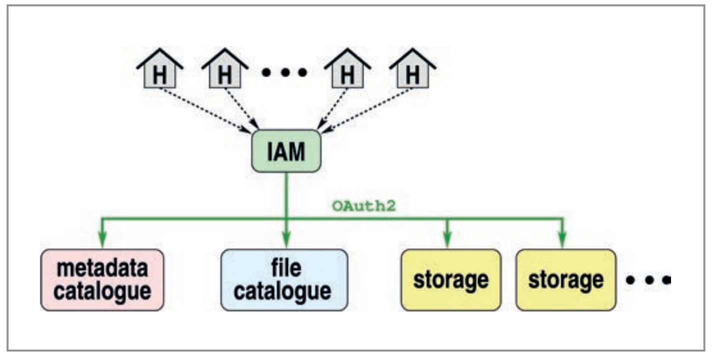

Figure 3
Architecture and interplay of ILDG services: Users authenticate through their home institutions (H) at the Identity and Access Management (IAM) service. In turn, the IAM issues OAuth2 access tokens with fine-grained permissions to access specific (meta-)data objects in the distributed infrastructure (metadata and file catalogues, storage elements).

In addition, ILDG mandates a dedicated metadata catalogue to register and handle the rich metadata that is essential in any FAIR-compliant data management. Due to the large size of the data objects, the metadata needs to be stored separately from the actual data in order to support complex and efficient search operations.

ILDG implements a very generic FAIR-compliant and federated data management framework for the distributed and possibly replicated storage of large data objects. Its logical organisation is shown in Fig. 2.

In contrast to a monolithic framework, the modular architecture of ILDG allows each sub-community (called regional grid) to choose its own technical implementation of the catalogue and storage services. They are only required to respect the ILDG-wide interface specifications to guarantee interoperability and consistent access.

ILDG 2.0 and beyond

During the past three years, members of the DESY Theory and IT groups have led a major effort to modernise and extend ILDG [5, 6], with the following aims:

- Setup of a new global user management using a dedicated INDIGO Identity and Access Management (IAM) instance [7] and supporting all eduGAIN identity providers
- Token-based authentication and authorisation to completely eliminate the use of grid certificates
- Containerised implementation of metadata and file catalogues that support multiple, freely configurable metadata schemas and can be easily deployed for different sub-communities or use cases
- Fine-grained and consistent (capability-based) access control for all catalogue and storage services to impose reliable embargo restrictions
- Revision of the QCDml metadata schema to take into account all known user requests

These ambitious developments became possible thanks to synergies with and funding from the PUNCH4NFDI project [8]. ILDG 2.0, the modernised version of ILDG, is now fully operational. It features an innovative token-based access control, and the catalogues developed by DESY have meanwhile been deployed in three of the regional grids. Figure 3 shows the flexible and modular architecture of the data management framework of ILDG, which is also interesting for non-lattice use cases and is currently being evaluated as a solution for data from axion experiments and other sources at DESY.

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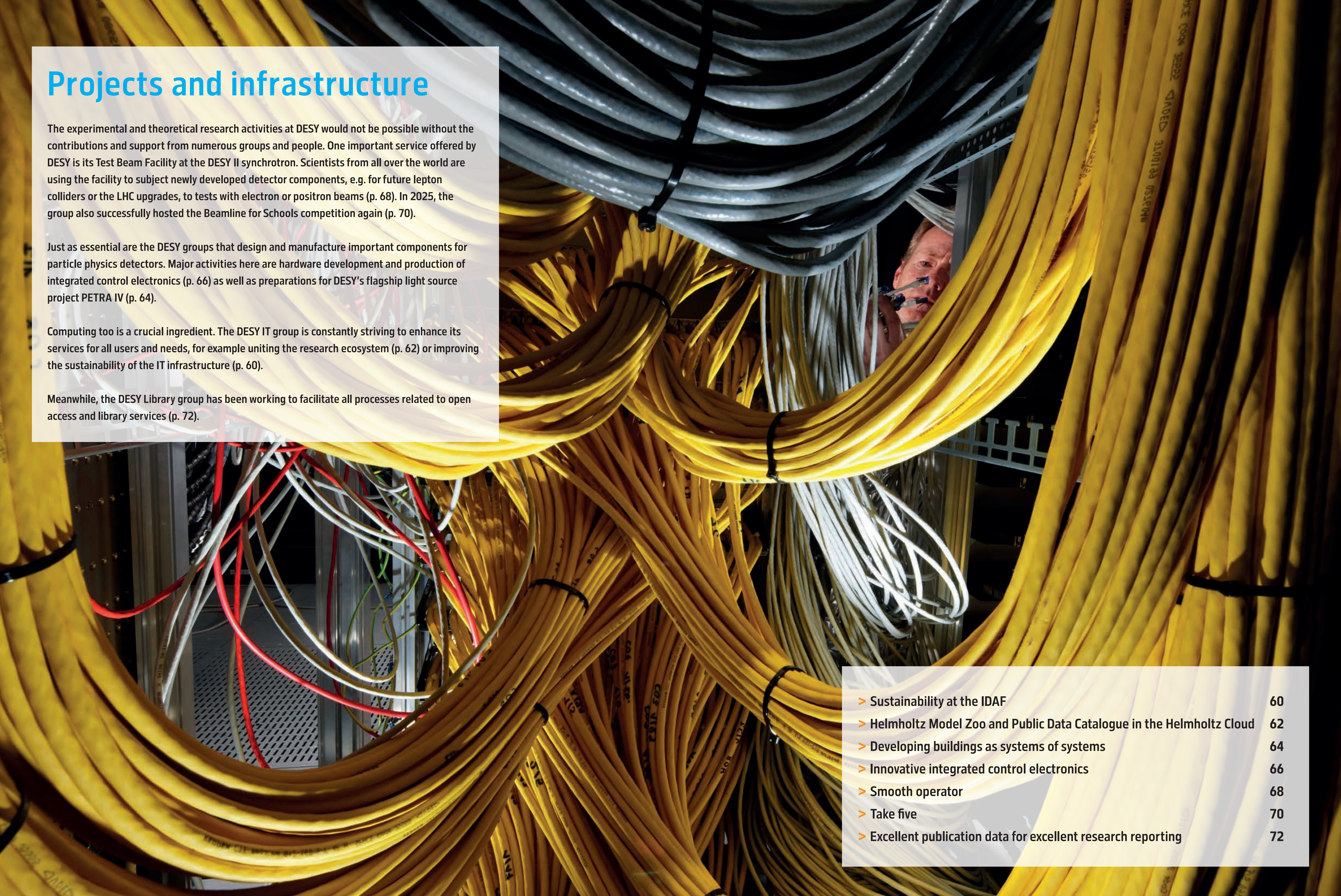

Projects and infrastructure

The experimental and theoretical research activities at DESY would not be possible without the contributions and support from numerous groups and people. One important service offered by DESY is its Test Beam Facility at the DESY II synchrotron. Scientists from all over the world are using the facility to subject newly developed detector components, e.g. for future lepton colliders or the LHC upgrades, to tests with electron or positron beams (p. 68). In 2025, the group also successfully hosted the Beamline for Schools competition again (p. 70).

Just as essential are the DESY groups that design and manufacture important components for particle physics detectors. Major activities here are hardware development and production of integrated control electronics (p. 66) as well as preparations for DESY's flagship light source project PETRA IV (p. 64).

Computing too is a crucial ingredient. The DESY IT group is constantly striving to enhance its services for all users and needs, for example uniting the research ecosystem (p. 62) or improving the sustainability of the IT infrastructure (p. 60).

Meanwhile, the DESY Library group has been working to facilitate all processes related to open access and library services (p. 72).

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Sustainability at the IDAF

Optimisation and other energy-saving measures

DESY advances sustainable computing at its Interdisciplinary Data and Analysis Facility (IDAF), which includes three main computing clusters and several storage clusters for data processing, through training, energy-aware cluster operation, automated benchmarking and workload optimisation. A digital twin of the facility based on system data and simulation enables evaluation of strategies to improve efficiency and reduce energy consumption.

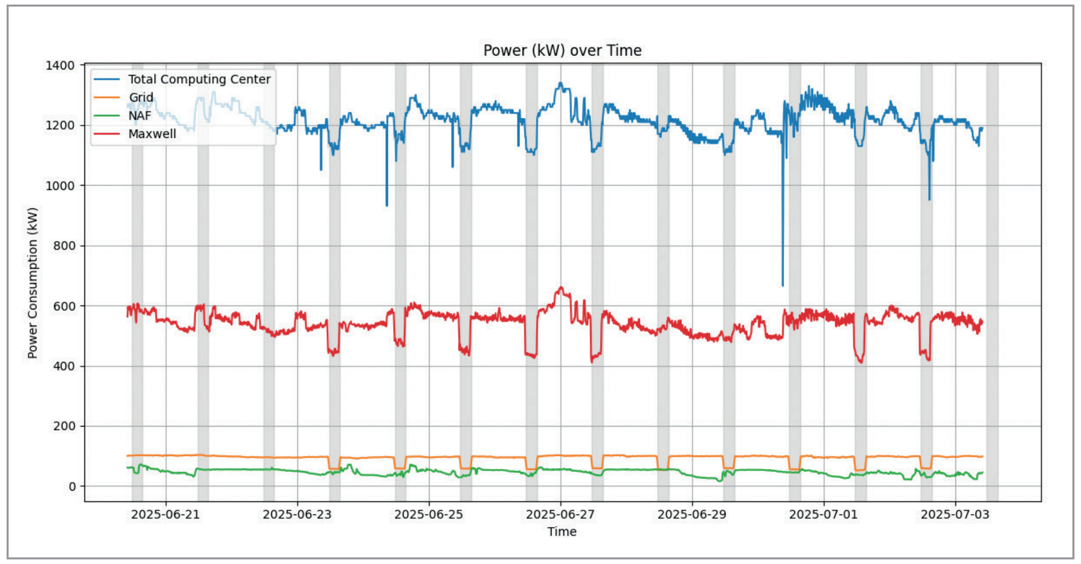

Figure 1
Power consumption of the different systems during the summer 2025 power-saving effort

Training people for sustainability

To encourage students and postdocs to think more critically about sustainability in everyday computing, DESY launched the Sustainable Computing Workshop series. The workshops introduce core concepts of sustainable computing and provide hands-on training in system basics, best practices, sustainable coding, software maintenance, efficient batch computing and resource optimisation. Each workshop combines short lectures with practical exercises and offers individual support; participation is therefore limited to 30 people.

The series is jointly organised by the Sustainability Forum of the Particle Physics Division and DESY computing experts in particle physics and IT. A general workshop for newcomers is offered annually, alongside advanced topical sessions. Six workshops have been held since September 2023, including a container-focused workshop in March 2025 and a general workshop in November 2025. The programme is now being expanded beyond the Particle Physics Division to include scientists in the Photon Science Division, fostering cross-divisional collaboration and strengthening the DESY computing community.

Modulating power consumption of a cluster

In 2025, two situations required active modulation of compute cluster power consumption: reduced demand during the year-end holiday season and daily peak load constraints in summer.

Several strategies were evaluated. Adjusting CPU frequency is the simplest method and allows predictable power savings while keeping jobs running, though with longer runtimes. Alternatively, nodes can be shut down either immediately – terminating jobs – or by draining them, which avoids job loss but can be slow and inefficient if nodes remain underutilised.

The optimal approach depends on the cluster. For the Grid cluster, with stable workloads, frequency scaling is effective. In the National Analysis Facility (NAF) cluster, where job runtimes are constrained, scheduled downtimes are preferable. On the Maxwell High-Performance Computing (HPC) cluster, where jobs occupy full nodes with GPUs, reservations enable planned shutdowns without disrupting workloads.

Automation of performance benchmarks in the compute clusters

Within the Research Facilities 2.0 (RF2.0) project, DESY aims to improve the energy and resource efficiency of its computing infrastructure by prioritising efficient machines, shutting down unused systems and adapting utilisation to renewable-energy availability.

As a foundation, an inventory of server energy consumption was created and automated benchmarking and power measurements were implemented, to be extended across all DESY IT systems.

Benchmark results are stored in a central database, and new benchmarks are triggered automatically if a system reboots and its last test is older than one year. Beyond enabling energy-aware modelling, this automation allows for rapid identification of misconfigurations and performance bottlenecks.

Optimising utilisation

User-driven clusters such as NAF and Maxwell show fluctuating demand, unlike consistently utilised Grid resources. To improve efficiency, workloads are compacted and underutilised servers are shut down during low-demand periods, though draining nodes can temporarily reduce efficiency. Conversely, periods of excess renewable energy require rapid scaling of compute workloads.

To address both challenges, workload consolidation is balanced with responsiveness to energy availability. Compacting jobs reduces idle capacity, while flexible scheduling enables rapid ramp-up when additional energy is available.

In collaboration with the ATLAS group, the IT group implemented backfill jobs – short, scalable tasks with high resource utilisation. These jobs run on draining nodes to utilise otherwise idle capacity and can also be quickly deployed when additional compute power is needed, improving both efficiency and responsiveness.

Towards a digital twin of the IDAF

As part of RF2.0, methods are being developed to operate the DESY computing infrastructure more efficiently using data-driven analysis and simulation. As part of this effort, a comprehensive survey of the data centre was conducted. The IT group evaluated operational strategies for energy-aware scheduling, resource utilisation and hardware efficiency.

These strategies are parameterised and incorporated into the simulation to evaluate their impact on energy consumption and carbon footprint. Building on the automated benchmarking and inventory described above, these data provide performance and energy profiles for all systems and enable the identification of inefficiencies. These data form the basis of the Optimised Resource Analysis and Carbon Legacy Estimator for Data centres (ORACLE-D) simulation framework, which enables rapid evaluation of optimisation strategies and has been validated against real-world energy-saving measures.

IDAF – Status in a nutshell

Maxwell HPC cluster: ~45 000 CPU cores, ~400 GPUs, ~2700 registered users, mostly photon science, incl. European XFEL, as well as accelerator R&D and operations. 119 publications citing Maxwell HPC.
Grid cluster: 20 000 CPU cores, integrated into federated Worldwide LHC Computing Grid (WLCG) experiment production frameworks, mostly serving ATLAS, CMS and Belle II.
NAF – National Analysis Facility: ~9000 CPU cores, serving experiments of the Terascale Alliance as well as smaller DESY-based communities, optimised for fast turn-around times.
Data – dCache systems: ~25 PB for particle physics, ~140 PB for photon science, incl. European XFEL.
Data – GPFS systems: Speed optimised for integration into data-taking and project space: ~80 PB (incl. European XFEL)
Network: WAN: up to 2 x 100 Gbit/s. Internally: InfiniBand in Maxwell HPC cluster for ultrafast data access and parallel jobs.
Services: Scientific software provisioning, Jupyter portal availability, remote graphical login and desktop sharing, container execution in batch systems, extensive documentation, support and consulting.

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Helmholtz Model Zoo and Public Data Catalogue in the Helmholtz Cloud

Services that connect data, AI models and computing

The Helmholtz Cloud is a decentralised digital platform that enables Helmholtz researchers to access web-based and collaborative services, streamlining workflows for users across Helmholtz and their international partners. It recently onboarded two DESY services: the Helmholtz Model Zoo, a compute-enabled artificial intelligence (AI) model repository that allows sharing and execution of trained models, and the Public Data Catalogue, a FAIR-compliant data platform for publishing data sets with digital object identifiers, metadata curation and community-driven quality control. By integrating AI-driven research tools and structured data sharing, the Helmholtz Cloud enhances collaboration and open science while reducing administrative barriers.

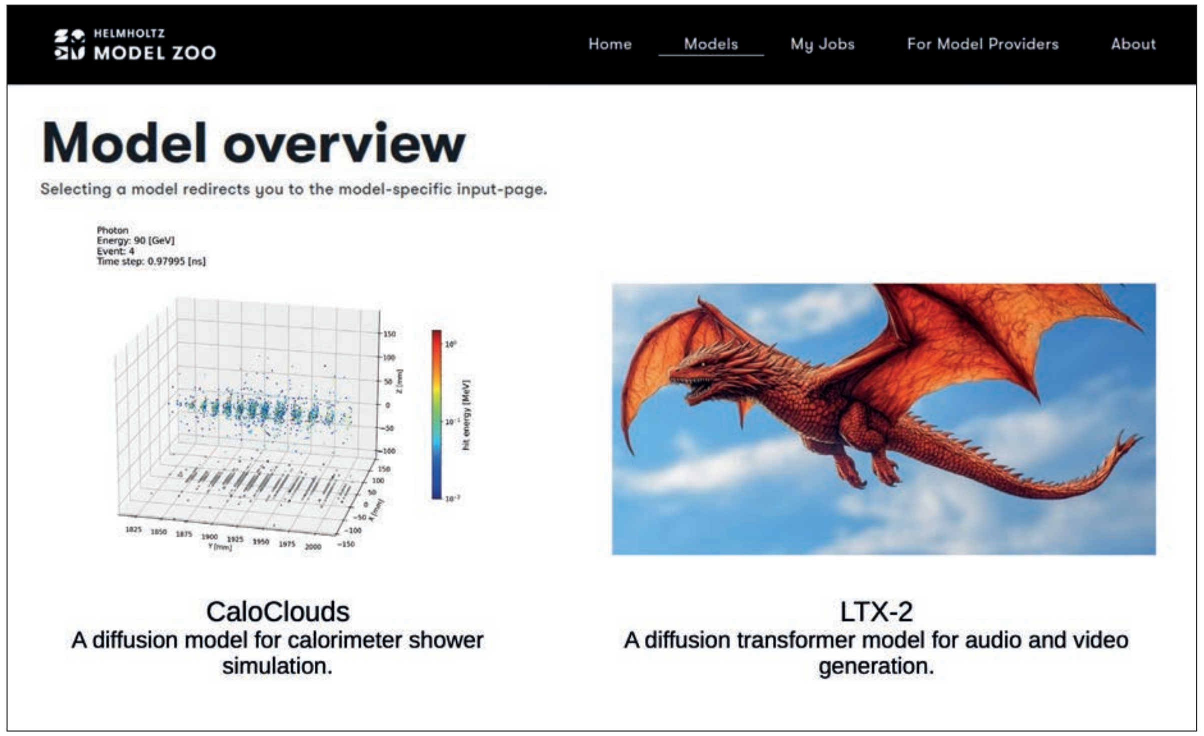

Figure 1

The HEP CaloClouds [10] and the LTX-2 [11] text-to-video models, provided through the Helmholtz Model Zoo

The Helmholtz Cloud [1], set up and maintained by the Helmholtz Incubator platform Helmholtz Federated IT Services (HIFIS) [2], represents a cornerstone of modern digital infrastructure within the Helmholtz Association, which provides researchers across all Helmholtz centres with seamless access to a comprehensive suite of collaborative and scientific services. Designed to streamline scientific workflows, the platform eliminates the need for redundant account creation by leveraging existing institutional credentials, allowing users to authenticate with their home username and password. This unified access model not only enhances usability but also significantly reduces the administrative burden associated with managing multiple accounts, thereby fostering a more efficient and secure research environment.

Since its inception, the Helmholtz Cloud has undergone continuous refinement and expansion, driven by a commitment to scalability, interoperability and user-centric design. Today, it supports a total of over 50 000 user accounts, with approximately 6000 active users each week. This represents a roughly 9 to 10-fold increase compared to 2022. These numbers include researchers from Helmholtz centres, European institutions and international scientific collaborations. The growth and coverage underscore the platform's role as an indispensable tool in modern research, enabling cross-disciplinary collaboration while adhering to open science principles.

DESY has recently added two more services to the Helmholtz Cloud, further enriching its service catalogue and reinforcing its position as a leading research infrastructure.

The Helmholtz Model Zoo [3, 4], developed by the Helmholtz Imaging platform [5], rethinks how trained AI models are shared and used within research infrastructures. Conventional repositories, such as Hugging Face, store and distribute models, but researchers still need their own computational resources to run them. The Model Zoo integrates computational resources directly, so researchers can (Fig. 1):

- Upload trained AI models in a standardised, reusable format,
- Access pre-trained models from other scientists or publicly available ones through an easy-to-use frontend or a representational state transfer application programming interface (REST API),
- Generate inference outputs by running models against their own data sets.

This matters because limited access to high-performance computing (HPC) often prevents researchers from using models that are, in principle, freely available. The Helmholtz Model Zoo removes that barrier by letting researchers run shared models on their own data without needing their own HPC resources. This is especially relevant in compute-intensive fields such as high-energy physics, materials science and biomedical research, where access to shared models can directly shorten the path from training to results.

The Public Data Catalogue [6], built on the SciCat scientific metadata catalogue framework, addresses a fundamental challenge in modern research: the need for structured, discoverable and reusable data. As scientific data sets grow in volume, complexity and diversity, ensuring their long-term accessibility and interoperability becomes paramount. The Public Data Catalogue provides a robust solution by enabling researchers to:

- Upload data sets annotated with bibliographic and scientific metadata, ensuring rich contextual information is preserved,
- Obtain a digital object identifier (DOI) for each data set, facilitating citation and long-term referencing,
- Publish data [7] in compliance with the FAIR data principles – a set of guidelines designed to maximise the reusability and impact of research outputs.

The FAIR data principles (findable, accessible, interoperable, reusable) [8] serve as the gold standard for modern data management, and the Public Data Catalogue ensures adherence to these principles.

To maintain high data quality, the platform lets community-appointed data stewards curate and validate data sets to ensure they meet expected standards. Data deposition is facilitated through a user-friendly portal [9] that enforces adherence to metadata schemas agreed on by the respective scientific community, thereby reducing ambiguity and enhancing reproducibility.

By consolidating access to essential services, eliminating redundant administrative processes and introducing innovative tools such as the Helmholtz Model Zoo and Public Data Catalogue, the Helmholtz Cloud platform empowers researchers to focus on discovery rather than logistics.

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Developing buildings as systems of systems

RFLP in the AEC industry

Buildings are usually turnkey products. They are readily constructed and then handed over to the owners, who move in and make the inside comfortable. But not in a research centre: We need to arrange the facilities inside first and then make the buildings fit them like a coat.

Civil construction is performed in highly standardised, so-called engineering-to-order projects. The building is defined in an upfront specification, detailing spatial needs, size, required rooms and appearance. The project is then contracted to a construction company, which produces the building according to that specification.

The approach works well for common buildings, such as homes, convention centres, or schools. They can be created largely independently of their future users. The buildings are delivered, and then the users move in. The method reaches its limit for large-scale infrastructures, however, where the building is an integral part of a complex facility.

A building is more than just a building

In research facilities, civil construction is interwoven with technical infrastructure in many aspects: Space needs to be coordinated. Certain components may only be accessible at specific phases of the construction sequence. Construction and installation procedures of different systems need to be coordinated to ensure constructability of the facility. Technical safety requirements of the instrumentation may impact the building safety systems, and so on. Research facilities need to be treated as a system of systems, with civil construction as one of many equal-righted subsystems.

Thus, for planning the new X-ray light source PETRA IV, DESY has introduced RFLP to AEC projects: Requirements–Functional–Logical–Physical (RFLP) is a state-of-the-art design process in Model-Based Systems Engineering (MBSE). RFLP systematically evolves stakeholder needs into compliant physical products in complex settings (Fig. 1). For Architecture, Engineering and Construction (AEC) planners, the formal treatment of functional and logical models and the stringent inclusion of user facilities in the planning process of a building constitute a novel approach.

Make a wish

First, expectations and needs are collected from all stakeholders: This includes the various user groups planning installations in the building, such as experimental facilities and labs; the many building services, such as transportation, supplies, air conditioning as well as safety, health and environmental concerns; various kinds of administrative constraints; and, of course, the people who are expected to work in the building. Stakeholder needs are elaborated into a requirements document, the R in RFLP (Fig. 1a).

The building welcomes you in

The requirements are then evolved into a functional definition of the building, the F in RFLP, expressed as a

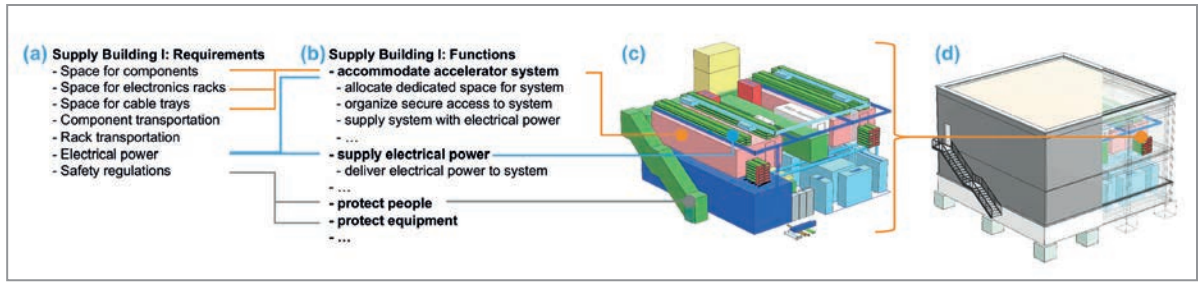
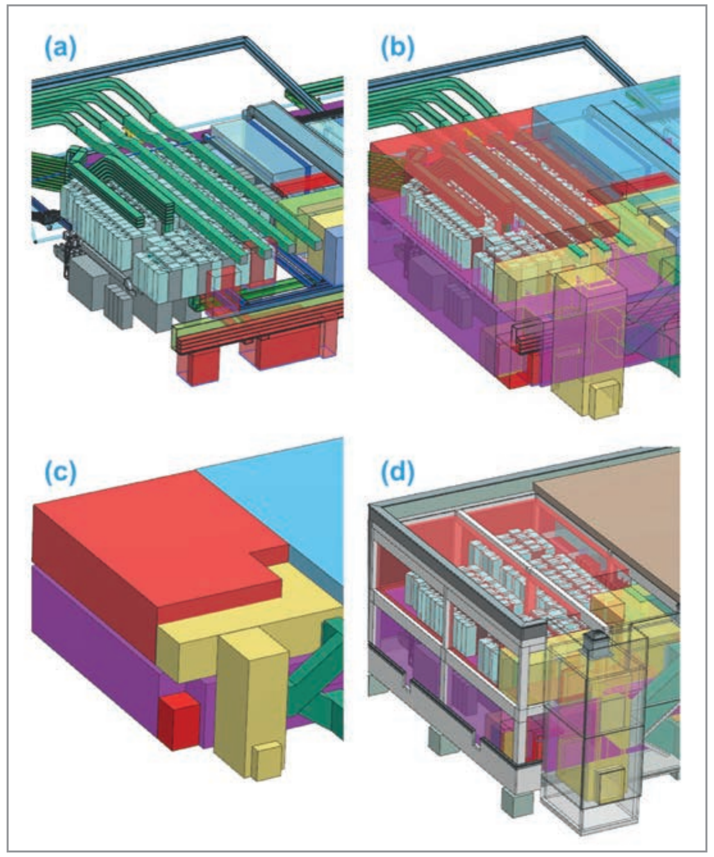


Figure 1

Overview of the RFLP process: a) Stakeholder requirements, b) corresponding functions, c) logical building usage concept and d) fitting physical building.

Figure 2

Different configurations of the logical model:
a) Installations and temporary working spaces in detail,
b) technical subsystem details and envelopes,
c) envelopes for coordination and
d) envelopes and fitting physical building.



function tree (Fig. 1b): For example, buildings foreseen to accommodate certain technical installations have to provide space, control access, protect people and facilities, regulate the internal environment, ensure safety, supply power and consumables and enable the installation and servicing of components. Other buildings may promote scientific collaboration by inviting people in, encouraging communication, inspiring creativity, fostering community and endorsing multilingualism. They have to provide places of work, meeting facilities and access to communication services.

Associating buildings with functions, i.e. with active behaviour, is still uncommon and something to get used to. Radios can play music, planes can fly in the air, and buildings can invite people in. Well, somehow. Functions can condense large amounts of requirements into compact and meaningful expressions.

Tetris

The functions are allocated to building elements, which are scoped, sized and arranged in the logical (layout) model, the L in RFLP. The logical model includes installations, such as scientific infrastructure, building services, media routing, and safety equipment, as well as space reservations, such as free access and transportation routes or clearance for cranes. It places the elements and optimises their arrangement. Eventually, the logical model contains the entire interior of the planned building as well as all major building elements (Fig. 1c).

The functions are driving the logical building design in an intuitive way: Transporting items, installing parts, enabling or preventing access etc. can easily be imagined and simulated, helping to evolve the design to support every scenario as well as possible.

The logical model is configurable in its level of detail, offering detailed representations of the various subsystems for facility planning as well as subsystem envelopes for cross-disciplinary coordination (Fig. 2).

Let's get physical, physical

The building elements are elaborated and detailed into the physical building model, the P in RFLP, which is the final technical definition of the construction project. It specifies all the components that are needed for the building, their geometry, properties and material as well as their integration. It shows the building as it will be erected (Fig. 1d).

Interdisciplinary model-based engineering lifecycle collaboration

The RFLP process offers a sound, systematic and straightforward approach to a fully integrated facility design, which understands buildings and their interior as integrated systems of systems. RFLP establishes vision sharing and offers a profound basis for interdisciplinary collaboration, also between groups that are not already used to working together from previous projects.

Yet, the true strength of the process becomes apparent when it comes to mastering the construction project's dynamics, where changes are induced from everywhere: Physical modelling may reveal technical constraints, which may ripple all the way back to the layout. And of course, scientists are permanently optimising the planned facilities, which may inject new requirements to be taken into account all the way through to the physical design. Based on its model-based nature and bidirectional tracing, the RFLP process can incorporate such dynamics quickly in a methodical, robust and reliable manner.

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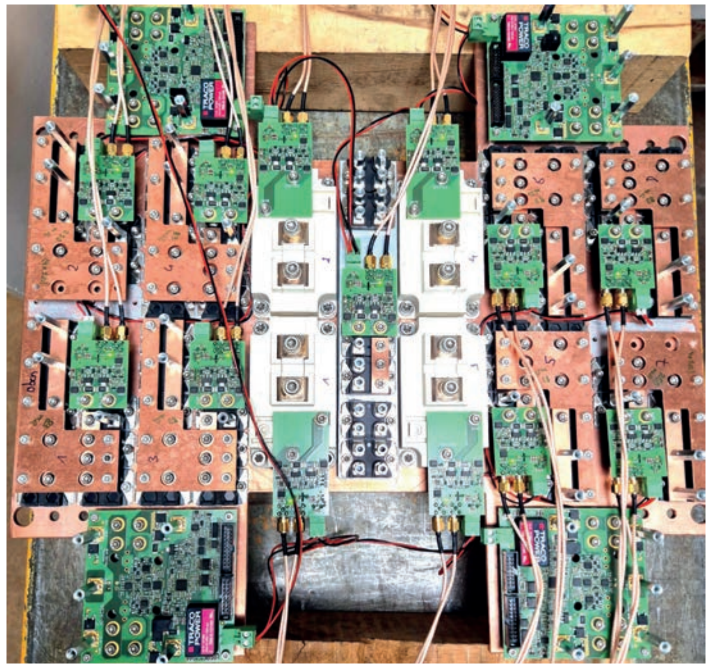
Innovative integrated control electronics

Universal FPGA-based board for versatile applications

Modern particle accelerators operated at DESY and European XFEL require control electronics that go beyond usual industrial requirements. DESY's central Electronics Development (FE) group developed a cost-efficient field-programmable gate array (FPGA)-based system that fulfils almost all conceivable requirements in this field. The result is a standardisable solution that offers a lot of new possibilities for users.

Based on a request from the DESY Injection (MIN) group, FE was commissioned to develop an FPGA-based control system for a new kicker magnet required for the European XFEL injector (Fig. 1). The magnet coil was to be designed to operate with currents of up to 2500 A, with precise regulation. Additionally, it was to control all associated peripherals.

As there was a general need for such control electronics, FE decided to create a solution that could also be reused for other tasks. The reason for focusing on an FPGA-based solution was mainly the necessity to handle fast signals in the nanosecond range, which is impossible with a pure processor-based solution. In short, something like a programmable logic controller (PLC) was needed, but about a million times faster – operating on the scale of nano-seconds instead of milliseconds.



In similar cases, project leaders often choose existing standards, such as µTCA-based systems. Because of the high number of control signals and the need for short cables, however, µTCA cards were not a good solution in this situation. The control board needed to be embedded directly into the device.

When discussing the specifications of such a versatile and standardisable solution, it was hard to estimate the amount and type of interfaces required. In the early phase of projects requiring such control boards, it is often not clear what functionality is needed, as project specifications change on the fly, sometimes even in the end phase of the projects or later. Developed printed circuit boards (PCBs) may become unusable if additional features are required subsequently. A lot of work has to be done twice, and time is wasted in producing a new PCB.

Thus, the idea came up to develop an interface-independent baseboard with the possibility of adding function-specific modules. Similar commercial development/evolution boards available on the market are often unsuitable either for mechanical reasons or simply because essential features are missing.

Thinking as far ahead as possible and taking into account experience with versatile control electronics and their general requirements, the result is a baseboard with only a limited number of basic peripherals, but with many connectors, which are directly linked to the FPGA input/output pins (I/Os). Unlike a large FPGA mezzanine card (FMC) connector, each connector contains only eight I/Os and some supply voltages. This enables a large number of different interfaces. It is possible to use multiple connectors in parallel.

Figure 1

2500 A kicker magnet power switches

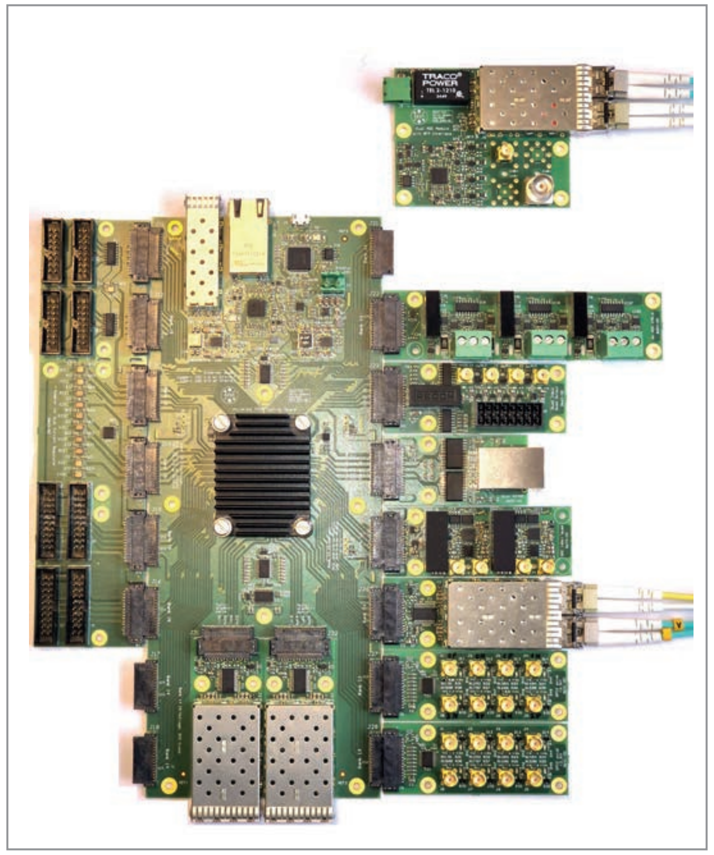


Figure 2

FPGA baseboard with some connected modules

The system is designed to be mechanically flat with edge-connected PCBs (Fig. 2). The core of the system is an off-the-shelf XILINX 7-Series FPGA module, which saves a lot of development time compared to populating an FPGA directly on the developed PCB. The main board includes a Gigabit Ethernet interface (copper and fibre), power control and all required programming and debugging functions. For all other functionalities, small external PCB modules are used.

To date, many versatile interface modules are available, such as simple digital I/O drivers and several high-speed and/or high-precision analogue-to-digital converter (ADC) modules with galvanic isolation. That makes the developed control board a good choice also for safety-related systems. Special interfaces, such as SFP+, RS-485 or isolated digital-to-analogue converters (DACs), are also available. The modular solution allows users to develop their own modules with special functionality, without having in-depth knowledge of design with FPGAs.

Besides the hardware, a considerable set of software and FPGA IP cores has also been developed. These modules are verified and ready to be used in a block design. They offer a solid basis of predeveloped functionality that is often needed, and they save a lot of development time. Using them allows ready-to-use solutions to be created within just a few weeks, as was actually done for a future transmission line kicker project and is planned for DESY's PIA accelerator. Users also benefit from a rich collection of control and analysis software tools for easy debugging of specific peripheral setups.

For example, Data Scope (Fig. 3) is an oscilloscope-style software tool and a corresponding FPGA core. It can be used to analyse the interface signals remotely and independently over a network without the need for an external oscilloscope. It helps with debugging during the development and commissioning phase, as well as with diagnostics during runtime.

The OPC UA industry standard is implemented as the main control protocol, allowing a direct connection to DESY's Distributed Object Oriented Control System (DOOCS).

FE thus offers an embedded solution that fits perfectly to DESY's needs, for a very good price of just a few hundred euros for the baseboard, compared to standard µTCA components. In this context, it should be mentioned that all required developing tools (except the PCB development tool) are free of charge.

An additional big advantage of the in-house development is that FE has "everything in its hands". This means that FE is flexible regarding further developments and does not depend on the disclosure of electronic schematics or any commercial software. FE is also able to enhance and adapt the system if needed. The system is kept as simple as possible, and the hurdle for training new colleagues in the details is low – another important prerequisite for operating such a system for decades.

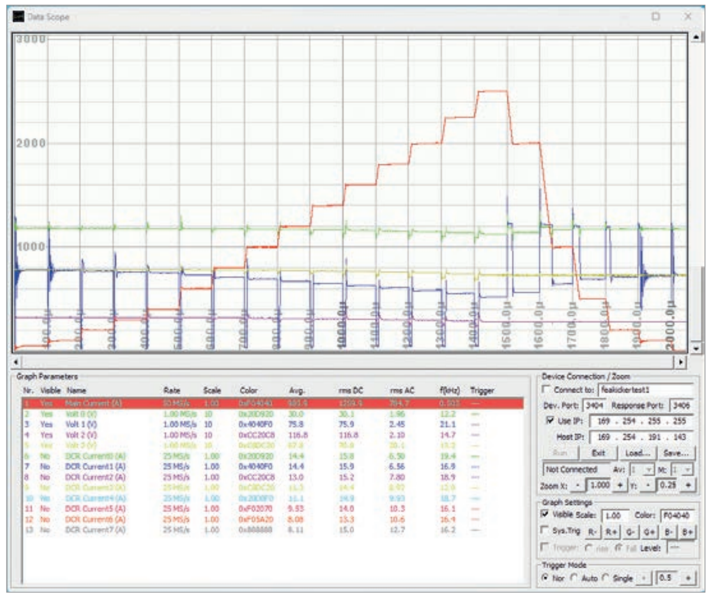


Figure 3

Data Scope with signals measured at the 2500 A kicker

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Smooth operator

The DESY II Test Beam Facility keeps running like a well-oiled machine

In 2025, the DESY II Test Beam Facility once again very reliably delivered electron and positron beams with energies of up to 6 GeV. The three beamlines were used by more than 440 users from experiments and R&D projects of the global particle detector community and beyond. The efforts of the test beam team to update and extend the world-class infrastructure continued, with the beam telescopes in particular nearing a major update. In addition, the development of a new type of beamline that provides the full DESY II electron beam made huge steps forward.

The DESY II Test Beam Facility

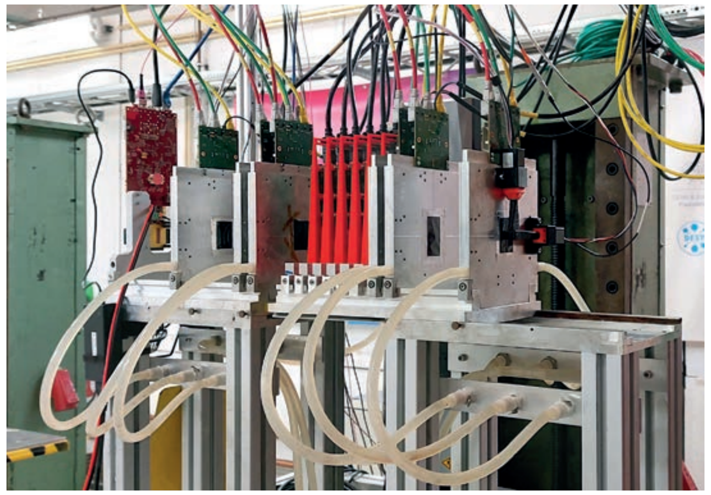
The DESY II Test Beam Facility [1] comprises three beamlines in Hall 2 at the centre of the DESY campus in Hamburg. At three stations, electron beams are extracted from the DESY II synchrotron, delivering single electron or positron beams in the energy range from 1 to 6 GeV with repetition rates of up to several 10 kHz to three individually controllable beamlines.

The facility's international user groups employ the electron beams to test prototypes of particle detectors. They are supported by the local test beam crew, which is constantly working to improve and expand the beamlines and infrastructure in order to keep the facility a world-class venue for detector characterisation.

2025 in numbers

After the winter shutdown 2024/25, user operation started as usual in mid-February and stopped shortly before Christmas. Of the 76 planned beamtimes, 17 had to be cancelled, mostly due to unforeseen delays in supplies and the preparatory R&D. This resulted in 59 beamtimes that used 86 of the available 105 weeks, i.e. a booking rate of 82%. The more than excellent availability of 99.76% of the DESY II synchrotron ensured that the 600 days of booked beamtime could be efficiently used by 441 users from 24 countries.

With 42%, the largest fraction of user groups carried out work for generic detector R&D. For the first time since years, this was larger than the fraction of groups working for the detector upgrades at the LHC at CERN, that reached 28% last year. The fraction of international users increased in 2025, reaching close to 60%.



A close look at the beams

So-called beam telescopes are installed at each beamline. They are essential reference instruments that allow the extrapolation of the precise position where the beam traverses the detector under test.

After nearly 20 years in operation, the EUDET-type beam telescopes with MIMOSA26 sensors [2] will be replaced. Since 2022, a new telescope using ALPIDE sensors [3] has been running in user operation. After the positive experience with this telescope, a new prototype has been developed for "mass production". This prototype was successfully tested in 2025 (Fig. 1), including first operation in a user setup. The production of several copies of this telescope is under way.

Figure 1

The new ALPIDE telescope (six red frames) mounted for studies inside an EUDET-type telescope (six aluminium frames), including a TimePix4 timing layer (red printed circuit board on the left) and a beam trigger system (two black "fingers" on the right)

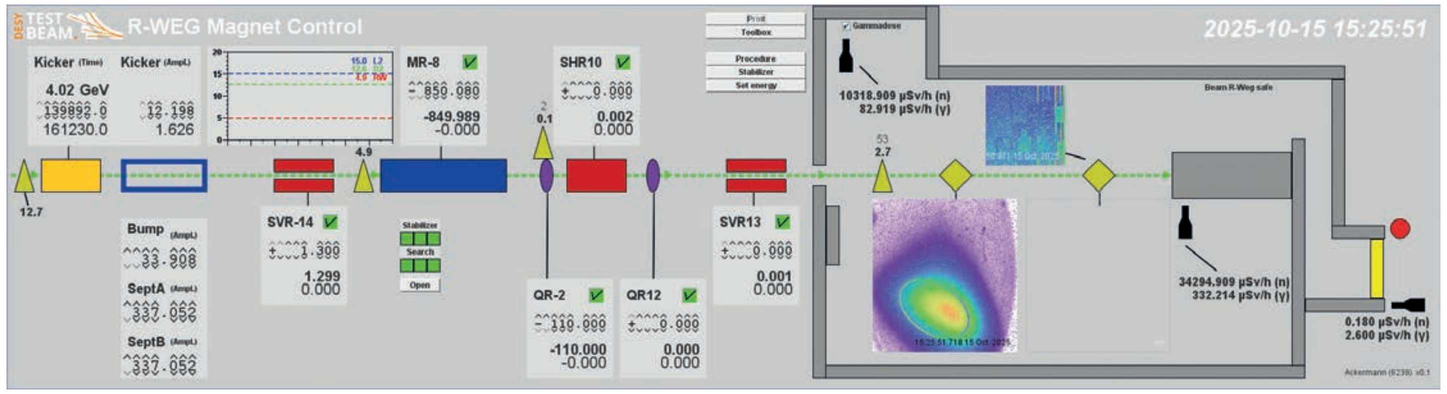


Figure 2

Overview for the accelerator operator crew, showing the "R-Weg" beam delivery system and the PRIMA experimental area. The installations inside the DESY II tunnel, including all magnets that guide and shape the beam, are displayed on the left. The PRIMA installation inside the R-Weg tunnel can be seen on the right inside the grey walls, including, on the bottom left, the image of the camera that records the beam profile for the beam stabilisation system.

Whole lotta beam

The studies and commissioning of a beamline that uses the full, direct DESY II electron bunch made great progress in the past year. Since 2021, the PRIMA experimental facility allows the extraction of full DESY II bunches with up to 10^{10} electrons at an energy of up to 6.1 GeV and a repetition rate of 6.25 Hz. This new beamline is now very well understood, and in 2025, the operating tools for the accelerator shift crew received a major improvement, including an automatic beam stabilisation system (Fig. 2).

In 2025, the test beam team performed irradiation studies of silicon chips to prove the usability of the facility for tests of radiation hardness. This is a real asset for the international R&D community, as beamlines that offer irradiation with an electron beam are very rare.

In addition, a first industry user group made use of the PRIMA facility: Muon tomography experts from the start-up company MuRayTech, collaborating with muography company Gscan, successfully measured artificially generated muons with Gscan's muFLUX Infra detector system. The goal of this R&D effort is rapid, safe and accurate 3D imaging of the chemical composition of scanned objects for industrial quality control and medical diagnostics. The next step is an optimised muon tracker system capable of tolerating a muon flux up to 10 000 times higher than the natural cosmic-ray background – an intensity that today's cosmic-ray muon systems cannot handle.

The muon beam was created by directing the electron beam of PRIMA onto a heavy tungsten target. This creates a mixed shower of muons, neutrons, electrons and gamma rays. Large concrete shielding elements filter out most particles, allowing only a relatively pure muon beam to pass through to the detector.

Hello, goodbye

In May 2025, our colleague Norbert Meyners, who had been coordinator of the facility since 1990, retired and left the test beam team after 35 years. We will miss him not only for his profound and extensive knowledge of the facility and beyond, but even more for his very friendly and calm personality. We wish him health, happiness and wonderful new experiences on his way.

Sven Ackermann, who joined the test beam team in June 2023, took over the vacant coordinator position.

Summary

2025 was another successful year in which the DESY II Test Beam Facility provided much-needed beam to the international detector R&D community. It also marks a big step forward for the new beam telescope family and the direct electron beamline of the PRIMA facility.

The success of the DESY II Test Beam Facility would not have been possible without the support of many individuals and groups from many DESY divisions, and we would like to take this opportunity to thank everybody who supported us.

Contact:
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Take five

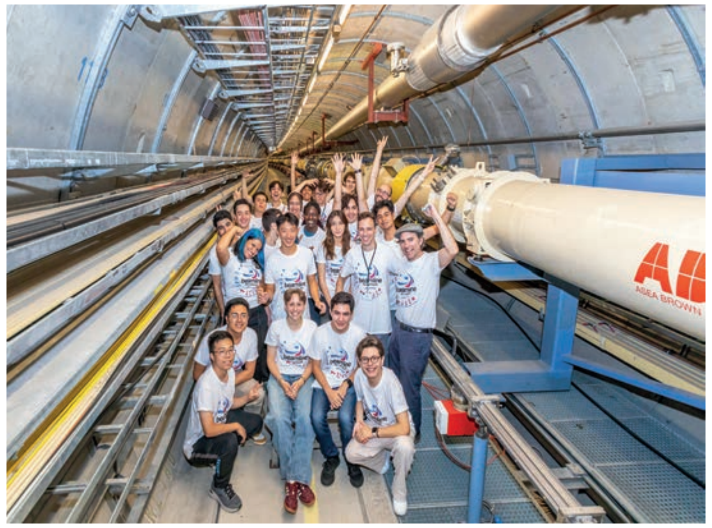
Beamline for Schools competition invited five student teams in 2025

In autumn 2025, CERN's Beamline for Schools competition invited high-school students to perform their experiments at a real beamline for the 12th time. This year, the University of Bonn took part for the first time, meaning that a total of five winning teams could be invited: one to the ELSA electron accelerator in Bonn and two to the Proton Synchrotron (PS) at CERN. The DESY II Test Beam Facility welcomed the two teams Pumas in Kollision from Mexico City and Dawson Technicolor from Montreal.

If you invite them, they will come

The first Beamline for Schools (BL4S) competition [1] took place in 2014. In this competition, teams of high-school students propose fixed-target experiments to be performed at a real beamline. The winning teams are invited for two weeks to carry out their experiments like real scientists.

Until 2018, two experiments each year were performed at the PS test beam facility at CERN. During a long shutdown of the CERN accelerator complex, DESY took over as host from 2019 to 2021. Since the end of the shutdown in 2022, CERN and DESY have been running the experiments in parallel, allowing for three winning teams. And since 2025, five winning teams have been invited, two to the test beamlines at the PS at CERN, two to the beamlines of the DESY II Test Beam Facility and one to the test beam at the ELSA accelerator at the University of Bonn. In 2025, the effort and enthusiasm shown over these years were rewarded with the Outreach Prize of the High Energy and Particle Physics Division of the European Physical Society (EPS) for this "inspiring global outreach and education program for high-school students".



In 2025, more than 3500 high-school students from 72 countries followed the call and formed 508 teams. The winning teams included the team Physical from Turkey and the Spallateam from Belgium, who went to CERN, both studying nuclear spallation and proposing new target designs to optimise the production of neutrons from the PS proton beam. The team XTReme from the USA was invited to the University of Bonn to investigate transition radiation with several multilayer targets made of different materials.

The world is Hamburg's guest

And DESY hosted the team Dawson Technicolor from Montreal, Canada, and the team Pumas in Kollision from Mexico City (Fig. 1).

The team Dawson Technicolor from the Dawson College in Montreal conceptualised and built a three-dimensional, scintillator-based detector from scratch, including the mechanical support and a readout system as well as the necessary software (Fig. 2). The students were looking forward to test their system at the DESY beamlines. The detector was designed to measure muons from cosmic rays and can therefore change its orientation. At DESY, electrons were used to mimic the trajectories and signals of cosmic muons.

The team Pumas in Kollision from the Escuela Nacional Preparatoria N° 6 "Antonio Caso" in Mexico City studied the suitability of an extract from a tree native to Mexico, called kidneywood, and of fluorite from their hometown as scintillator material. The kidneywood pigment is luminescent and glows when excited by bright light, particularly

Figure 1
The two winning teams at DESY: Pumas in Kollision and Dawson Technicolor together with their teachers and the two DESY support scientists in the tunnel of the former HERA accelerator

Figure 2
Setup of the experiments at Beamline T21. The muon detector setup of the team Dawson Technicolor, including the rotatable support structure, can be seen at the bottom right.

when mixed with the organic solvent toluene. As its scintillation capabilities were hitherto unknown, the student team decided to experimentally investigate whether it would also be a suitable candidate for a scintillation detector (Fig. 3).

The teams arrived at DESY on 11 September, and the first days were filled with introductory and safety sessions, as well as a tour of Hamburg and a welcome dinner. As usual, the students were very eager to start and began setting up their experiments at the first opportunity. Just like real scientists working at a beamline, they faced several hurdles, as experiments rarely work as planned out of the box. But luckily, there were no show-stoppers, and the students worked hard as a team to solve all the issues they encountered on their way to successful measurements. Figure 4 shows a typical example of what this looked like.

The Sponsors' (VIP) Day took place in the middle of their stay. On this day, the students met with scientists, sponsors and directors to present their experiments to the visitors and the other teams, both on site and in a video conference between all participating institutes. At DESY, the day ended with the traditional barbecue, to which everyone on site was invited – a perfect opportunity for the teams to continue their discussions and share their experiences in a relaxed atmosphere.

At the end of their two weeks of living the life of a physicist, both teams had obtained exciting results, which were presented in a final session together with the other teams at CERN and Bonn on 23 September.

Acknowledgements

We would like to extend our heartfelt thanks to everyone at DESY and beyond who supports us and helps make this programme possible. Special thanks go to our two on-site support scientists, Antoine Laudrain and Antonios Athanassiadis, who once again did a tremendous job in helping to prepare the experiments and supervising the students during their two weeks at DESY.

Beamline for Schools is an education and outreach project supported by donors and partners through the CERN & Society Foundation. The Foundation works with partners and donors to advance initiatives in education, innovation and culture that connect CERN's science, creativity and innovation with society to help unlock solutions to global challenges. This 12th edition was supported notably by Rolex through its Perpetual Planet Initiative and by the Wilhelm and Else Heraeus Foundation.

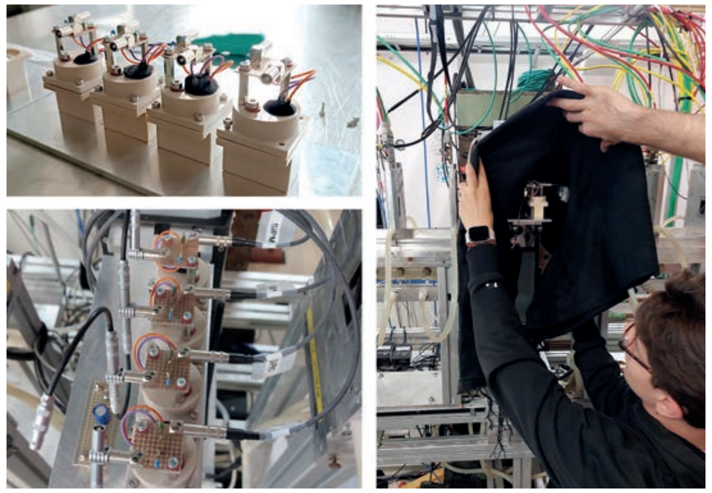


Figure 3
Top left: Containers made of PEEK, a material with excellent chemical resistance properties, in which the kidneywood solution was filled. Bottom left: Silicon photomultipliers on top of the containers, used to detect the scintillation light. Right: A light-tight cover is put over the setup at the beamline.

Figure 4
Hut H23 of the DESY II Test Beam Facility, usually used for quiet working, meetings and coffee breaks, was turned into an impromptu lab space.

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Excellent publication data for excellent research reporting

The publication database PubDB as DESY's central repository

Scientific publications at DESY are much more than just specialist articles – they document research achievements, create international visibility and form the basis for future collaborations and funding. To ensure that these results remain permanently accessible and reliably evaluable, the DESY Library operates the publication database PubDB as a central repository. It records not only publications by DESY authors, but also user publications that were produced at DESY's large-scale research facilities. Quality-assured metadata, open-access checks and long-term archiving make research transparent and accessible in a sustainable way. PubDB thus supports strategic reporting, compliance with funding requirements and efficient monitoring of publication costs. In this way, the database makes a decisive contribution to highlighting the scientific impact of DESY.

Publications as a strategic resource

Publications are the most visible result of scientific work. They show what research is being conducted at DESY, make successes internationally comprehensible and form the basis for reputation, collaborations and funding.

To ensure the reliable documentation of this research, the DESY Library operates the publication database PubDB [1] (Fig. 1). It serves as the central repository for all scientific publications at DESY, offering permanent archiving, quality assurance and global accessibility.

As a large research centre with user facilities such as PETRA III or FLASH, it is crucial to record not only publications with DESY authors, but also user publications, i.e. work by (possibly only external) researchers produced using DESY's infrastructure. These publications may appear in commercial databases, but without the important attribution to FLASH or PETRA III. It is evident that, in the absence of PubDB, it would be challenging to obtain a comprehensive and accurate representation of the scientific impact of DESY.

Why complete data matters

Today, providing a reliable and timely publication database is no longer just a library service. It is a prerequisite for strategic research reporting, compliance with funding requirements, transparency towards the DESY Directorate, Foundation Council and funders, robust monitoring of publication costs and international visibility of DESY research.

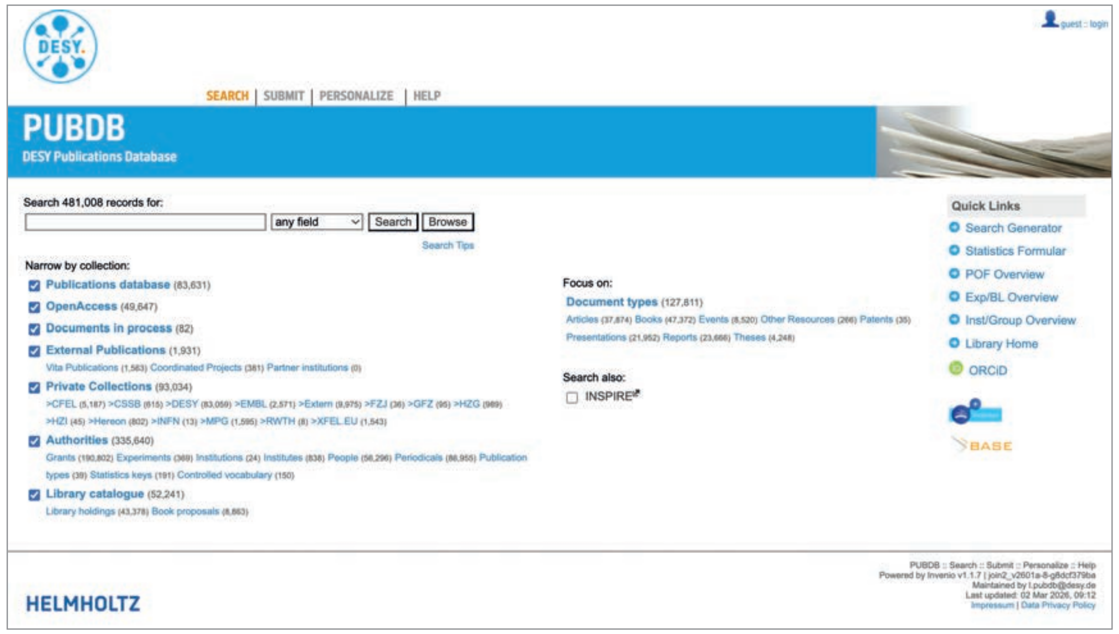

Figure 1
DESY Publication database PubDB

Figure 2
Involvement of DESY authors and assignment of PETRA III user publications to Clusters of Excellence in Germany (as of October 2025)

For PubDB to fulfil this role, it is essential that researchers provide their support and that completed publications are recorded promptly. This approach ensures comprehensive and current reporting, which in turn has a direct impact on funding.

What the DESY Library provides

All publications in PubDB are subject to a quality assurance process. The DESY Library verifies and updates accurate affiliation information, ensures complete and standardised funder and grant acknowledgements, facilitates both green and gold open-access options and addresses legal aspects, such as image rights. It also takes into account warning signals for problematic journals.

Additionally, abstracts, keywords and further metadata are enriched to promote visibility. Where possible, full texts are permanently archived in PubDB and thus remain accessible even in the subsequent absence of a journal subscription.

A key benefit is the seamless integration with the electronic invoicing workflow. First and foremost, this frees up DESY scientists to focus on their core scientific tasks rather than being tied up with the administrative burden of handling invoices. It is important to note that this system connects publications directly to their costs, enabling continuous cost monitoring while ensuring that cost subsidies can be fully exploited.

Greater visibility for research and infrastructure

PubDB has been shown to increase the international discoverability of DESY research. Content is indexed in search engines, open-access versions are available, and publication lists on beamline websites highlight the attractiveness of the infrastructure for new user communities.

Career achievements, including dissertations, cover images, lectures, software, data sets, etc., can also be reliably documented. This information can be used as additional information for advanced research assessment [2]. PubDB's primary function is twofold: It contributes to reporting and fulfils a central mission by ensuring that research results remain accessible in the long term.

Example: Clusters of Excellence

The strategic importance of a complete data basis is illustrated by the example of the Clusters of Excellence established through the Excellence Strategy of the German federal and state governments. During the initial funding period (2019–2025), 44 of the 57 clusters used DESY's infrastructure (Fig. 2). Publications involving measurements at PETRA III could even be assigned to 23 clusters.

Such analyses are only possible because publications are systematically recorded, user publications are specifically researched, and metadata is carefully curated. The example illustrates how high-quality publication data leads to increased visibility and funding opportunities and forms the basis for future excellent research.

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Imprint

Publishing and contact
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A Research Centre of the Helmholtz Association

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ISBN 978-3-945931-60-8
DOI 10.3204/PUBDB-2026-01277

Editing
Ilka Flegel, Manfred Fleischer, Thomas Konstandin, Stephanie Krause

Layout
Sabine Kuhls-Dawideit, Büro für Grafik und Design, Halstenbek

Printing
EHS Druck GmbH, Schenefeld

Editorial deadline
28 February 2026

Editorial note
The authors of the individual scientific contributions published in this report are fully responsible for the contents.

Acknowledgement
We would like to thank all authors and everyone who helped in the creation of this annual report.

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