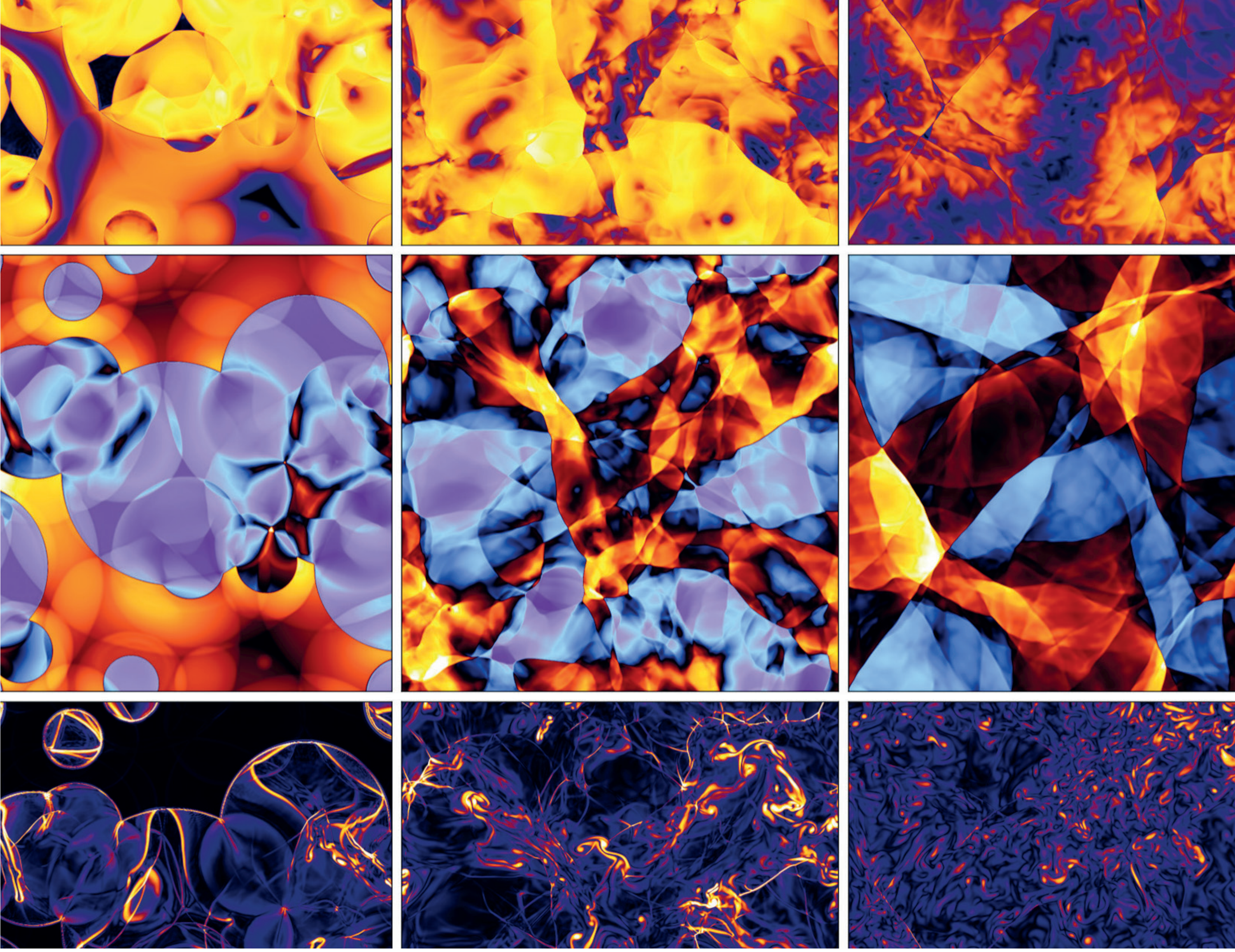
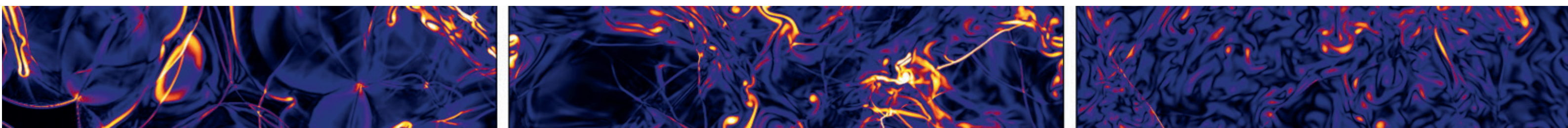


PARTICLE PHYSICS 2024.

Highlights and Annual Report

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

DESY.



PARTICLE PHYSICS 2024.

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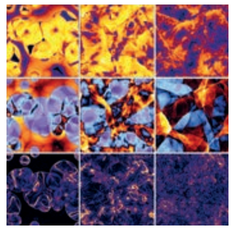


Cover
Three snapshots of a simulation of kinetic energy, enthalpy and vorticity during a cosmological phase transition.

Contents

The year 2024 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

In a time of significant challenges – financial constraints, geopolitical instabilities and heightened international competition – DESY faces a demanding landscape. Rising personnel costs, volatile energy prices and inflation-driven reductions in purchasing power put us under considerable pressure, and the priority is to lead DESY safely into the future.

At the heart of our strategy stands the ambitious PETRA IV upgrade project. The conversion of PETRA III into a state of-the-art fourth generation X-ray light source is essential not only for DESY's advancement but also for strengthening international research and securing Germany's technological sovereignty. As the world's most advanced and brilliant X-ray source, PETRA IV will enable unprecedented precision in studying materials and biological macromolecules, paving the way for pioneering innovations, such as AI-driven material design.

The DESY infrastructure focus also includes transformative projects. The new DESYUM visitor centre, whose construction is progressing according to plan, will soon be a public landmark and could become the iconic symbol of the Hamburg-Bahrenfeld campus. Through our Centre for Accelerator Science and Technology (CAST) and the DESY Innovation Factory, an integrated technology and start-up centre, we are expanding the "Bahrenfeld ecosystem" by linking research and innovation to drive technological and economic development.

This is my last foreword for an annual report as the chairman of the DESY Board of Directors, and I would like to take this opportunity to make a few personal remarks: It has been an honour to serve in this role. I would like to thank all DESY employees and our national and international partners for their trust over the past 15 years, and especially the Board members for their unique team spirit and constructive cooperation. Together, we have achieved numerous successes, including the remarkable construction of the European XFEL from 2009 to 2017, a masterpiece "made by DESY", the establishment of the Astroparticle Physics Division, the strategic expansion of nanoscience and laser plasma research and the successful operation of PETRA III, FLASH and the European XFEL as Hamburg's flagship photon sources. We are continuing a long tradition: Since the commissioning of its first particle accelerator in 1964, DESY has been one of the pioneers of research with synchrotron radiation worldwide.

Figure 1
Celebrating 60 years of research with synchrotron light at DESY: (from left to right) Robert Feidenhans'l, Poul Nissen, Edgar Weckert, Sasa Bajt, Massimo Altarelli, Jerome Hastings, Jochen Schneider, Tetsuya Ishikawa, Laurent Chapon, Francesco Sette, Harald Reichert, Rolf Heuer and Helmut Dosch

Figure 2
Visualisation of the DESY Centre for Accelerator Science and Technology (CAST), close to the PETRA III experimental hall "Max von Laue" (right)

I reflect with pride on the growth of the two DESY sites in Hamburg and Zeuthen together with our partners. The new interdisciplinary research centres – CFEL, CSSB and CXNS for photon science, the recently opened Science Data Management Centre (SDMC) for astroparticle physics, the ongoing projects mentioned above as well as the planned Wolfgang Pauli Centre for theoretical physics (WPC) and Centre for Molecular Water Science (CMWS) – are visionary initiatives that will contribute to strengthening Germany's research landscape as a whole and the innovation regions of Hamburg and Zeuthen in particular.

A highlight of my time at DESY has been the recruitment of renowned scientists. With the appointment of over 30 W3 professorships, including 15 women, and close collaborations with universities in Hamburg, Schleswig-Holstein, Berlin, Brandenburg and beyond, we have enhanced our scientific network and supported our university partners' excellence. Particularly noteworthy are the new members on the DESY Board of Directors in 2025: Beate Heinemann, Wim Leemans, Britta Redlich, Christian Stegmann and Arik Willner, bringing science, innovation and technology transfer expertise. With this exceptional team, DESY is well equipped to master future challenges.

When I will hand over the helm to Beate Heinemann in spring 2025, I will do so in a turbulent time not only for DESY. Research and social issues can no longer be addressed only on the national level. Sharing expertise and infrastructures and thereby strengthening international cooperations is becoming more important: Innovation is the key for our future. Therefore, the pending political decision for PETRA IV is crucial for DESY and our national and international partners and users, and I hope for swift action in the next period.

Figure 3
The Science Data Management Centre (SDMC) building for the CTAO gamma-ray observatory on the DESY campus in Zeuthen

I extend my best wishes to all DESY staff, hoping you will continue to lead this remarkable research centre into a bright future. Thank you all and also our partners for constant support and excellent cooperation over the years. I wish DESY continued success and that essential extra bit of luck.

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Particle physics at DESY

Introduction

Dear Colleagues and Friends of DESY,

This is my last foreword to a *DESY Particle Physics* highlights brochure in my function as director in charge of particle physics, and it is thus with even greater pride that I am looking back at the achievements of our Particle Physics Division in the past year 2024!

There were a few! Let me start with our flagship – the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN in Geneva: The LHC – again – hit a new luminosity record in 2024, with more than 120 fb^{-1} per experiment, and consequently, while finishing Run 2 analyses, Run 3 analyses are being ramped up. From both data taking periods, significant results have been derived by DESY scientists. To mention but a few: a new measurement of the *W*-boson mass, in agreement with previous measurements and the world average, and supported by strong DESY theory contributions; di-Higgs analyses that start to constrain the Higgs potential; and a measurement of the effective weak mixing angle from *Z* bosons, in agreement with the Standard Model and reconciling the long-standing 3 σ discrepancy between results from the LEP collider at CERN and the SLD experiment at SLAC in the USA.

In parallel to the data analyses and operation work at the LHC experiments, the construction of the tracker endcaps for ATLAS and CMS at DESY is progressing, on schedule for a timely delivery to CERN at the end of this decade.

In the context of the LHC, I also want to mention the physics coordination roles of DESY physicists Kerstin Tackmann and Andreas Meyer in ATLAS and CMS, respectively. These – and numerous other – important leadership positions in the large experiments underline the high reputation of DESY's work at the LHC.

At the Belle II experiment at the SuperKEKB collider at KEK in Japan, the complete two-layer pixel vertex detector (PXD2) was taken into operation at the beginning of the year and successfully demonstrated its abilities. In the meantime, more and more results are produced from Belle II data, certainly surpassing the precision and reach that was anticipated for the still rather limited luminosity accumulated so far. DESY scientists take on important responsibilities in leadership roles also at Belle II.

Figure 1
Meeting of the German Committee for Particle Physics (KET) at DESY in November 2024

Looking closer at our own DESY campus in Hamburg, we also saw progress on many fronts – in particular with our axion platform experiments: ALPS II has taken first data, and publications are imminent. MADMAX has delivered first competitive results on dark photons and on axion dark matter with a prototype setup, and the discussions on a complete funding for MADMAX and BabyIAXO are progressing.

For the LUXE strong-field quantum electrodynamics experiment, we could secure an EU infrastructure grant called ELBEX, which will enable the construction of the necessary transfer line for the experiment. With the latest developments in view, we hope to be able to set up LUXE in the not too distant future.

In the meantime, the process for the update of the European Strategy for Particle Physics has started, and it is supposed to conclude with the approval of the strategy by the CERN Council in summer 2026. DESY is making contributions to this process in many places – also in line with the strategy update remit from 2020, which explicitly emphasised the role of the big labs: in the field of collider physics with contributions to the FCC, ILC, LCF, muon collider and HALHF (a first conceptual design that involves beam-driven plasma wakefield acceleration) ideas, but also in the field of axions, of dark matter, etc. We are looking forward to the outcome of the strategy and will ensure that DESY plays a role commensurate to its size and position as a national hub! I am also a member of the European Strategy Group, which will meet for final deliberations in December 2025.

All these achievements have been obtained by the members of the DESY Particle Physics Division, and there would be many stories to tell about the individuals, but also about the group spirit and the excellent level of teamwork in our division. There is not enough space here to do justice to all these important contributions – please see this report for a few highlights!

Figure 2
Beate Heinemann with the former Chairmen of the DESY Board of Directors, Herwig Schopper (left) and Albrecht Wagner (centre)

We are living in difficult times, and some of you may look anxiously to the future: The COVID-19 pandemic has demonstrated our vulnerability as humans and as a society. The Russian war on Ukraine threatens freedom in Europe, and scientific freedom is challenged by recent developments in the USA.

It is thus all the more important that we stand by our values, such as freedom in science and otherwise, international cooperation, respect for all people and fact-based decisions. The role of science cannot be overstated, and I look forward to continue working with all of you, at DESY and at our partner institutes around the world, to advocate for science and technology locally, nationally and internationally.

Beate Heinemann
Director in charge of Particle Physics

News and events

A busy year 2024

January

Nobel laureate Anne L'Huillier visits DESY

Anne L'Huillier from the University of Lund in Sweden visited DESY in Hamburg and the Center for Free-Electron Laser Science (CFEL). After a tour of the attosecond and laser research laboratories at DESY and CFEL, the Nobel laureate, who is also a senior scientist at the Helmholtz–Lund International Graduate School (HELIOS), gave a lecture in the DESY auditorium.

Anne L'Huillier (centre left) in the attosecond laboratory at PETRA III

Topping-out celebrated for DESYUM visitor centre

The topping-out ceremony was held for the building that will house the DESY visitor centre, called DESYUM. Since its foundation stone was laid in May 2023, six storeys have been constructed near the Notkestraße entrance on the DESY site in Hamburg. With 3250 m^2 of usable space, DESYUM will accommodate a two-storey exhibition area, meeting rooms, offices, an auditorium, a cafeteria and a green roof with rooftop terrace. DESYUM will open to the public in 2025. Some 150 guests, including Hamburg Senator for Science Katharina Fegebank as guest of honour, attended the ceremony.

The DESYUM visitor centre almost completely scaffolded

February

ERC Starting Grant for Priscilla Pani

Priscilla Pani, a scientist in the ATLAS group at DESY, was awarded a European Research Council (ERC) Starting Grant for a new method to search for dark matter candidates using colliders. She will use the ATLAS experiment at the Large Hadron Collider (LHC) at CERN in Geneva to find hints of new light particles that could interact with more massive versions of some of the particles that make up matter. The grant, worth 1.5 million euros for a project that will last five years, will allow Pani to set up her own working group on the subject at DESY in Zeuthen.

Priscilla Pani

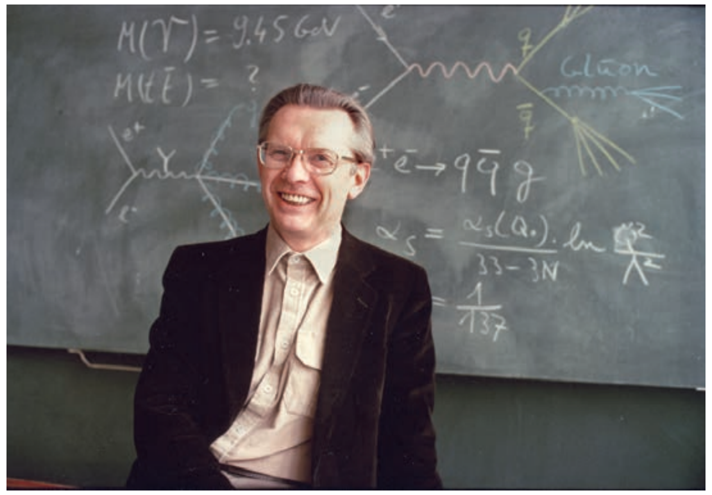
EURIZON fellowship programme for Ukraine begins

On 1 February, the EU project EURIZON kicked off its fellowship programme for scientists in Ukraine. These fellowships are designed to support scientific research in Ukraine, especially during the ongoing Russian invasion. EURIZON is an EU-funded project that is coordinated by DESY and involves 27 European research institutes. Their main aim is to encourage collaboration among European research centres and to support research efforts in Ukraine. A total of 18 fellowships were allocated in the first round, with more to follow from a large pool of applications.

Locations of the 780 applications for fellowships across Ukraine

One hundred years of living physics history

A life marked by scientific milestones, major decisions, ever larger accelerators and a great deal of science diplomacy: Herwig Schopper, former DESY and CERN Director General, turned 100 years old on 28 February and was honoured at a festive symposium at CERN on 1 March. DESY, which he headed as Chairman of the Board of Directors from 1972 to 1980, owes him a lot. Congratulations from DESY on completing a century!



Herwig Schopper was Chairman of the DESY Board of Directors in the 1970s

March

Kerstin Tackmann appointed physics coordinator of ATLAS

The international ATLAS collaboration at the LHC at CERN elected Kerstin Tackmann, leading scientist at DESY and professor at Universität Hamburg, as its next physics coordinator. Physics coordination is a key task in the collaboration, and DESY is one of the few institutions to hold the post for the second time: DESY scientist Klaus Mönig was physics coordinator of ATLAS from October 2018 to September 2020.

Kerstin Tackmann

DESY–IonQ collaboration shows potential benefits of quantum computing

DESY and IonQ, a leading firm in the quantum computing industry, presented early results from their cooperation to run combinatorial optimisation problems on IonQ's quantum system. The results demonstrate the potential of quantum computing as a more effective solution than traditional classical computing when tackling equations with multiple variables in a dense environment – e.g. the flight gate assignment problem at a bustling airport. Quantum techniques have also been used for particle reconstruction in high-energy physics at DESY. An article explaining the project, which is part of DESY's quantum technology initiative, was published on the arXiv preprint server.

Tackling complex problems with quantum computing

DESY and Helmut Schmidt University expand collaboration

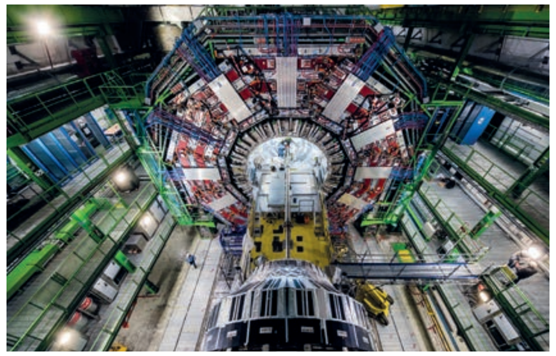
DESY and Helmut Schmidt University (HSU) in Hamburg will expand their strategic and operative cooperation. DESY Director Helmut Dosch and HSU President Klaus Beckmann signed a corresponding agreement on the occasion of the Day of Research at HSU on 26 March.

Klaus Beckmann (HSU, second from left) with Wim Leemans, Helmut Dosch and Beate Heinemann from DESY at Helmut Schmidt University

April

CMS measures crucial parameter of the Standard Model

At the annual "Rencontres de Moriond" conference, the international CMS collaboration at the LHC at CERN presented a measurement of the effective leptonic electroweak mixing angle. The result is the most precise measurement of its kind performed at a hadron collider to date and is in good agreement with the prediction of the Standard Model. Researchers from DESY played a key role in the preparation of the result. The measurement brings new insights to an old mystery: how the forces of nature become mixed when symmetry is broken in our universe.



The CMS detector during maintenance work

Israeli high-school students visit DESY

A group of 23 Israeli students visited DESY in Hamburg for a week. The students came from the Israeli Schwartz/Reisman Science Education Centers, a unique platform for physics enthusiasts in Rehovot and other cities in Israel and an institution under the umbrella of the renowned Weizmann Institute of Science.

A group of students from the Schwartz/Reisman Science Education Centers visited DESY.

Future Day for girls and boys

25 April was Future Day for girls and boys throughout Germany. Pupils were invited to the DESY campuses in Hamburg and Zeuthen to gain their first practical insights into the world of work and familiarise themselves with the variety of apprenticeships and study opportunities. This annual day of action for initial career orientation successfully contributes to overcoming the traditional, gender-specific categorisation of professions.

VR applications are fun.

In Zeuthen, apprentice Denise gave the young guests a demonstration of her work in the mechanical workshop.

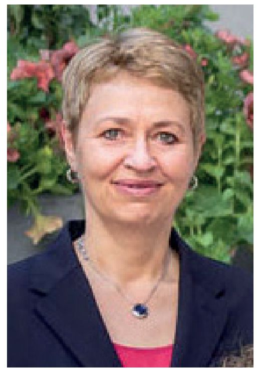
Andreas Meyer

Andreas Meyer appointed physics coordinator of CMS

No physics analysis at the LHC without DESY involvement: The CMS collaboration elected DESY scientist Andreas Meyer as CMS physics coordinator from September 2024 to August 2026. The posts of physics coordinator for the two LHC experiments ATLAS and CMS are thus currently held by senior scientists from DESY.

Honorary doctorate for Beate Heinemann

Beate Heinemann, DESY Director in charge of Particle Physics, received an honorary doctorate from the University of Zurich in Switzerland. The university honoured her "for her outstanding scientific achievements in experimental elementary particle physics, for her pioneering role in the search for new particles and phenomena and for her associated contributions to the planning of future particle accelerators".



Beate Heinemann

May

Science on tap: Cutting-edge science in a cosy atmosphere

Can cancer be cured in a fraction of a second? How do you unravel a 5000-year-old letter secret? And how do you trick artificial intelligence with maths? Once again, the "Science on tap" event brought researchers from all disciplines to Hamburg's bars and pubs. On 2 May, curious visitors were given insights into the world of science in entertaining lectures and then had the chance to chat with the speakers over a drink.

May

MADMAX achieves major milestones and first physics results

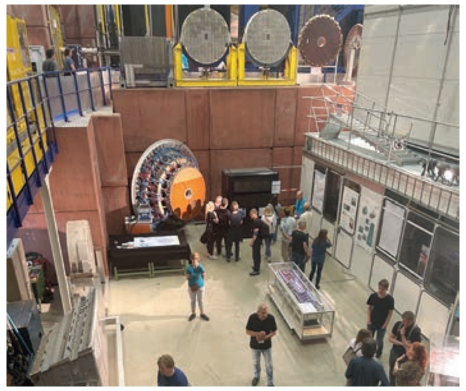
Many different experiments around the world are on the chase for dark matter, including the ALPS II experiment at DESY, which started taking data in 2024, and an experiment called MADMAX (MAgnetized Disc and Mirror Axion eXperiment). The MADMAX collaboration conducted experiments with three prototypes that differ in complexity and size, providing convincing answers for future reviews. MADMAX is an international collaboration initiated and led by the Max Planck Institute for Physics in Munich that was formally launched at DESY in 2017.

The MADMAX team during tests at CERN

June

Science City Day: Welcome to DESY!

On 1 June, DESY opened the doors to the future. On the occasion of the Science City Day, the research centre invited the public to a big open day on the campus in Hamburg-Bahrenfeld. Visitors were able to enter the huge experimental halls and experience science up close, understandable and hands-on, in more than 100 events, activities and lectures. In total, around 15 000 people were given an insight into DESY research! Around 10% visited the HERA West hall to see an exhibition of old and current detector components in the detector lab of the Particle Physics Division.



Visitors in the detector lab in the HERA West hall

Network "Kleine Forscher Hamburg" celebrates fifth birthday

On 18 June, the network "Kleine Forscher Hamburg" – now called "Neugier ahoi!" – celebrated its fifth birthday at DESY. The network primarily offers training courses aimed at educational specialists and teachers in Hamburg's day-care centres and primary schools. The topics range from maths, computer science, natural sciences and technology to education for sustainable development and are always based on children's everyday lives. Since its launch at DESY, the network has processed almost 2000 applications. Nearly 200 day-care centres and primary schools have taken part in a training course for the first time, and many specialists return to the training courses again to continue their education.

Celebrating five years of "Kleine Forscher Hamburg" (from left): Bettina Schmidt ("Kleine Forscher Hamburg"), Margret Lohmann ("Kinder forschen" Foundation), Kay Petersen (Hamburg Authority for Labour, Health, Social Affairs, Family and Integration), Beate Heinemann (DESY) and Inken Stobbe ("Kinder forschen" Foundation)

Transatlantic Big Science Conference 2024 kicks off in Berlin

The second Transatlantic Big Science Conference took place in Berlin on 27–28 June, bringing together key figures from the realms of science and politics from across the USA, Europe and beyond. This landmark event aims to enhance transatlantic cooperation in research and technology, fostering sustainable and reliable partnerships to address global challenges and set the groundwork for common research policies. As one of the hosts of the conference, DESY Director Helmut Dosch was delighted to welcome an exceptional assembly of scientific minds and policy leaders: "In an era of unprecedented global challenges, it is imperative that we strengthen our transatlantic partnerships to drive forward science and innovation. This conference represents a unique opportunity to forge sustainable collaborations that will shape the future of science and innovation."

Opening ceremony of the Transatlantic Big Science Conference 2024

July

Philipp Neumann new leading scientist and head of DESY IT

DESY has a new head of IT: Philipp Neumann, who was also named leading scientist and appointed professor for high-performance computing (HPC) and data science at Universität Hamburg. Neumann brings extensive experience on data- and HPC-driven research and on running and managing HPC infrastructures. He took over from Volker Gülzow, who retired in 2023.

Philipp Neumann

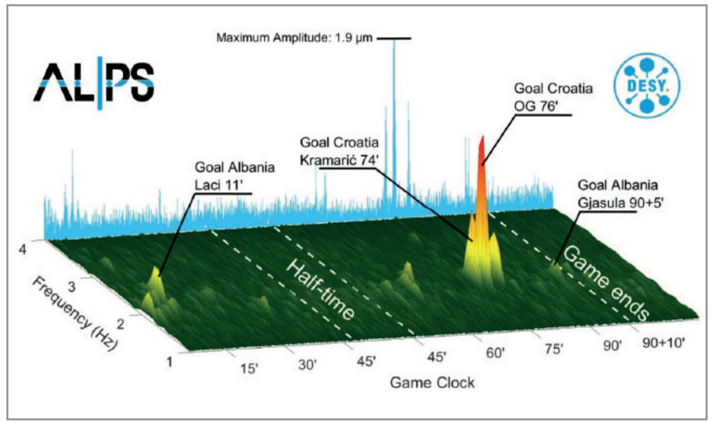
Summer student programme and Ukraine summer school begin at DESY

In summer 2024, a total of 112 participants from 27 countries performed research on the Hamburg and Zeuthen campuses for seven weeks as part of the DESY summer student programme. This year's novelty: For the first time, a DESY–Ukraine summer school was held simultaneously, with 14 participants coming from Ukraine. Due to the many positive responses from participants of the earlier DESY–Ukraine winter school, the organisers around Olaf Behnke had decided to offer even more places for Ukrainian students this year.

The 2024 summer students at the DESY campus in Hamburg

Croatia vs. Albania or the great hopping

The team of the ALPS experiment at DESY took advantage of the European Football Championship to measure seismic motion caused by crowds, using the 122 m long ALPS II regeneration cavity in the HERA North hall, which is located 26 m underground and around 1 km from the Volksparkstadion, where Croatia played Albania. By monitoring changes in the absolute length of the cavity during the match, it was possible to clearly identify crowd-induced seismic noise when goals were scored by either team as well-defined features both in the time series and in the spectrogram. The observed primary frequencies between 2 and 3 Hz are associated with the frequency of fans jumping in unison. This is a demonstration of the high sensitivity of the optical systems in the ALPS II experiment, which completed its first axion search campaign in 2024.



Seismic motion caused by fans hopping during the match Croatia vs. Albania of the European Football Championship, as measured by the ALPS II experiment

September

Berlin, CERN and Fragments of Creation

Questions about the beginning and the infinite nature of existence have preoccupied humankind for thousands of years. The search for answers provides comfort, expands knowledge and advances technology, but sometimes brings people to the brink of despair. All these elements could be found in the opera "Creazione/Creation" by Gloria Bruni, which was performed in the Kaiser Wilhelm Memorial Church in Berlin on 1 September as part of the German celebrations for the 70th anniversary of CERN. The actors were the Hamburg Symphonic Orchestra and the Berlin Vocalconsort conducted by Wolf Kerschek and supported by an enthusiastic choir of scientists from DESY and Universität Hamburg.

CERN School of Computing held in Hamburg

DESY hosted the 2024 CERN School of Computing, a two-week school designed for computer scientists and physicists with an interest in computing. A total of 70 students from 32 countries were trained by computing experts from CERN and elsewhere in lectures and hands-on exercises – and enjoyed Hamburg for two weeks.

Participants of the CERN School of Computing

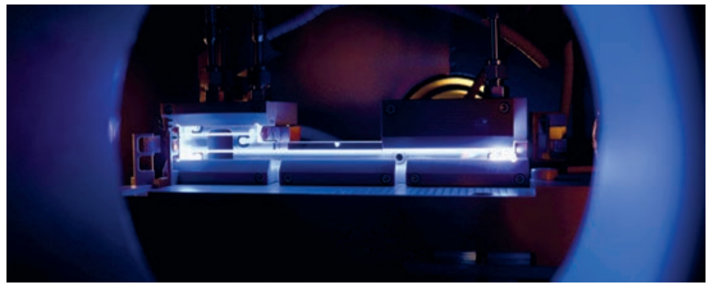
2024 Beamline for Schools winners begin experiments

The SPEEDers team on their first day in Hamburg

In September, DESY welcomed eight students of the SPEEDers team from Andover High School in Massachusetts, USA, to its campus. The teenagers used the DESY II Test Beam Facility to carry out an experiment they had proposed as part of the 2024 Beamline for Schools competition and which had prevailed among 461 applications from students around the world. Their research could help to define a novel way of measuring a particle beam without interfering with it – an important issue for the seamless operation of accelerators. Two further teams from Estonia and Japan performed experiments at CERN in Geneva, which organises the competition.

FLASHForward achieves critical acceleration quality

For the first time, a research team at DESY's FLASHForward plasma accelerator experiment has been able to preserve an important parameter of the particle beam during the plasma acceleration process. The researchers kept the emittance of the high-quality electron bunches from the FLASH linear accelerator at the same level during acceleration. The team published their results in *Nature Communications*.



The FLASHForward plasma cell at work

October

DESY sends strong signal of solidarity with science in Ukraine

A delegation from DESY led by DESY Director Helmut Dosch travelled to Kyiv to demonstrate its solidarity with the Ukrainian scientific community. The exchange with students of Taras Shevchenko National University, including participants of the EU-funded EURIZON project, clearly showed the challenges that young Ukrainian scientists are facing in times of war. Dosch emphasised that freedom of science and international cooperation are the cornerstones of every democratic society. Peaceful coexistence on the basis of international law is an indispensable prerequisite.

Helmut Dosch during the meeting with students at Taras Shevchenko National University, Kyiv

New hub for high-energy astrophysics

DESY and the Cherenkov Telescope Array Observatory (CTAO) celebrated the official opening of the new CTAO Science Data Management Centre (SDMC) building on the DESY campus in Zeuthen. The event brought together key figures from the international CTAO community, political representatives, regional partners as well as DESY and CTAO staff members to celebrate an important milestone in the further exploration of the high-energy processes in the universe.

The Science Data Management Centre building for CTAO at DESY in Zeuthen

APS Panofsky Prize for Eckhard Elsen and Robert Klanner

Former DESY scientists Eckhard Elsen and Robert Klanner will be awarded the W.K.H. Panofsky Prize in Experimental Particle Physics by the American Physical Society (APS) in spring 2025, the APS announced in October. The two particle physicists receive the award for "pioneering work in establishing the HERA physics program and detectors, leadership in HERA physics exploitation resulting in the measurement of the proton's structure in new kinematic regions of vital importance in confronting new aspects of quantum chromodynamics, and enabling discoveries at the LHC".

Robert Klanner and Eckhard Elsen

DESY hosts QBN expert workshop on the future of quantum computing

On 29 and 30 October, DESY hosted the workshop of the Working Group Quantum Computing and Applications on "Use cases in Key Verticals" organised by the Quantum Business Network (QBN). The event brought together national and international experts from academia and industry to discuss latest developments and practical applications of quantum computing in academic research and key industries, such as logistics, aerospace, energy and materials science, as well as the development of new algorithms. The event underlines DESY's central role in the broad quantum ecosystem and the Hamburg metropolitan area. DESY promotes the development and knowledge transfer of quantum technologies through close cooperation with the Hamburg Quantum Innovation Capital (hqic) coordination office set up by the Hamburg Senate and through contact with universities, research institutions and companies.

Participants of the QBN workshop

November

Bjørn H. Wiik Prize 2024 goes to Ludovica Aperio Bella

On her way to the next big discovery, Ludovica Aperio Bella, particle physicist in the DESY ATLAS group, searches for the unknown with immense precision and boundless enthusiasm: “My focus is on analysing the data from the ATLAS experiment at CERN,” says the Italian scientist. “My research concentrates on precision measurements of fundamental particles and their interactions at the high-energy precision limit.” This year, she was honoured with the Bjørn H. Wiik Prize for her work.

Ludovica Aperio Bella

PhD Thesis Prize 2024

The PhD Thesis Prize of the Association of the Friends and Sponsors of DESY (VFFD) was awarded in equal parts to Sören Jalas for his thesis “Machine-learning-based optimisation of laser-plasma accelerators” and to Florian Lorkowski for his thesis “Measurement and NNLO QCD analysis of jet production in deep inelastic scattering at ZEUS”.

Sören Jalas

Florian Lorkowski

Katharina Behr wins Hertha Sponer Prize

DESY scientist and Helmholtz Young Investigator Group leader Katharina Behr received the Hertha Sponer Prize of the German Physical Society (DPG) for her outstanding experimental contributions to the search for an extended Higgs sector through decays of heavy Higgs bosons into top quarks.

Katharina Behr

PETRA IV – moving forward towards funding

The German Federal Ministry of Education and Research (BMBF) officially confirmed the inclusion of PETRA IV in the “National Prioritisation Procedure for Large-scale Research Infrastructures”. A team from DESY had submitted a corresponding concept, which is currently being evaluated. In addition to the expected gain in scientific knowledge, the concepts will be evaluated on their innovation and transfer potential, the sustainability of construction and operation as well as the costs and risks. The BMBF plans to publish a shortlist of the best projects in summer 2025.

Rendering of the tunnel of the proposed X-ray source PETRA IV

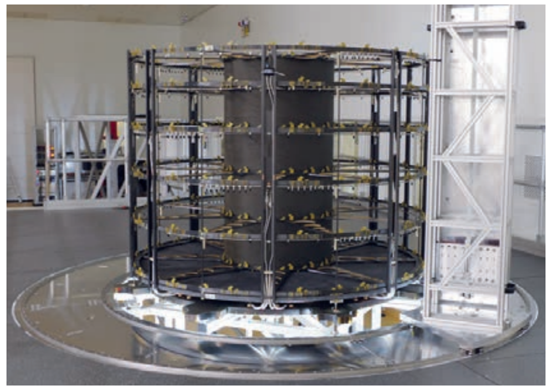
Breaking ground for new technology and start-up centre at DESY

A combined total of over 8500 m^2 of workspace for the new DESY Innovation Factory will be created in three years of construction at two locations: the main site on the DESY campus and a second close by in the Altona Innovation Park. Complex laboratories, offices and open working environments will be built to foster the flow and transfer of knowledge and technology from research to industry and society.

Breaking ground for the DESY Innovation Factory (from left): Helmut Dosch (DESY), Volkmar Dietz (Federal Ministry of Education and Research), Melanie Leonhard (Hamburg Senator for Economics), Eva Gümbel (Hamburg State Councillor for Science), Arik Willner and Hansjörg Wiese (both DESY)

Important detector component for ATLAS arrives in Hamburg

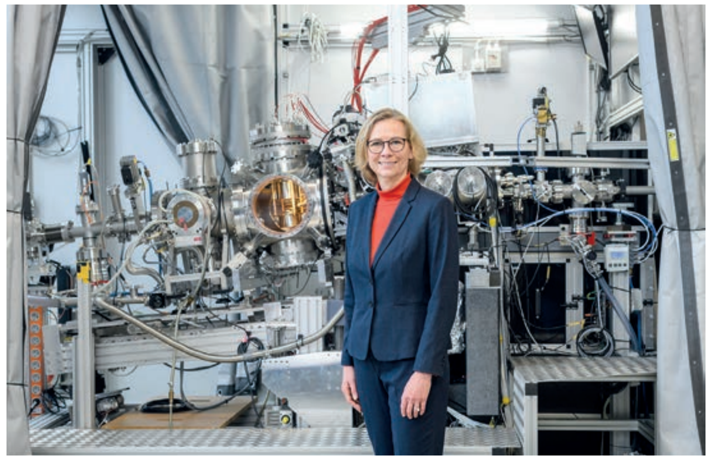
On 27 November, the DESY ATLAS group reached a major milestone in the construction of an endcap for the new silicon strip detector for the ATLAS experiment at CERN. The basic carbon fibre mechanical structure of the endcap (the “skeleton”), built at the Dutch national particle physics facility NIKHEF in Amsterdam, arrived in Hamburg for completion with 35 m^2 of silicon and many other components. The transport from Amsterdam to the Detector Assembly Facility (DAF) at DESY was carried out in a special transportation device that minimised mechanical and thermal influences.



The new ATLAS endcap skeleton

Britta Redlich to become new Director in charge of Photon Science at DESY

As of 1 January 2025, Britta Redlich will be the new Director in charge of Photon Science at DESY. The chemist and professor of experimental physics was previously the director of the FELIX free-electron laser facility and the High Field Magnet Laboratory of the Radboud University in Nijmegen, the Netherlands. She is a senator of the Helmholtz Association for the research field Helmholtz Matter and a member of international consortia, such as LEAPS, LaserLab Europe and FELs of Europe. Britta Redlich succeeds Edgar Weckert, who headed the Photon Science Division for 16 years.



Britta Redlich

December

ERC Starting Grant for Aditya Pathak

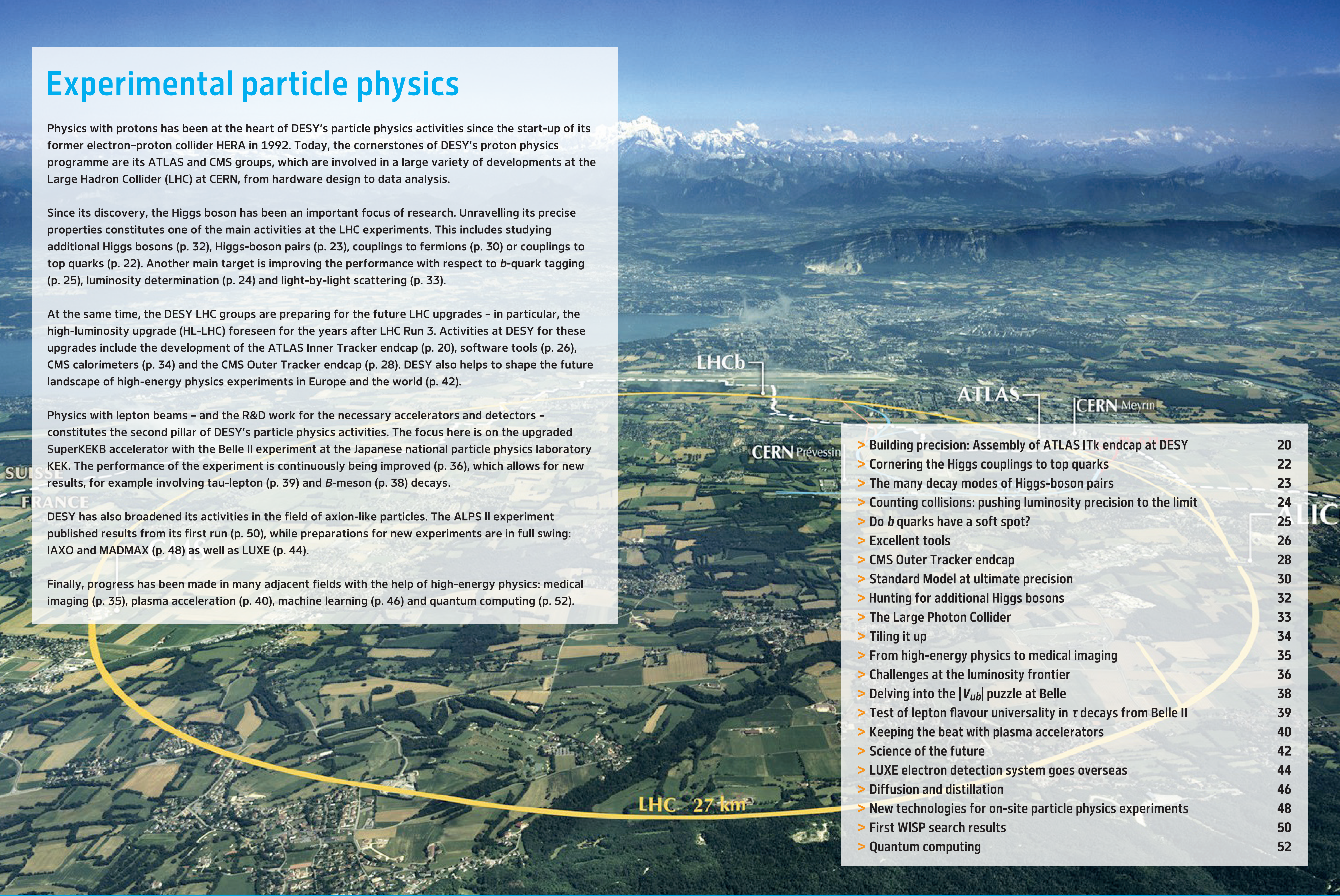
Aditya Pathak

DESY theorist Aditya Pathak was awarded a Starting Grant by the European Research Council (ERC) for his research project TOPMASS. Starting in September 2025, Pathak will lead a group that will work towards strengthening the precision of measurements of the top-quark mass. A precise determination of the top-quark mass and a systematic treatment of hadronisation are crucial for many other precision measurements in particle physics, but are currently strongly influenced by an overreliance on simulations of particle collisions. Pathak’s winning proposal aims to eliminate this dependence and make the mass of the top quark more precisely known.

Sarah Heim appointed professor at Universität Hamburg

Sarah Heim joined the Institute of Experimental Physics at Universität Hamburg as a professor of physics after successfully applying to the Helmholtz programme “Funding of first-time professorial appointments of highly talented female scientists”. She took up her joint professorship entitled “Physics – with a focus on dark matter and Higgs analysis at ATLAS” in December 2024, while retaining her position as DESY scientist.

Sarah Heim



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 additional Higgs bosons (p. 32), Higgs-boson pairs (p. 23), couplings to fermions (p. 30) or couplings to top quarks (p. 22). Another main target is improving the performance with respect to *b*-quark tagging (p. 25), luminosity determination (p. 24) and light-by-light scattering (p. 33).

At the same time, the DESY LHC groups are preparing for the 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. 20), software tools (p. 26), CMS calorimeters (p. 34) and the CMS Outer Tracker endcap (p. 28). DESY also helps to shape the future landscape of high-energy physics experiments in Europe and the world (p. 42).

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. 36), which allows for new results, for example involving tau-lepton (p. 39) and *B*-meson (p. 38) decays.

DESY has also broadened its activities in the field of axion-like particles. The ALPS II experiment published results from its first run (p. 50), while preparations for new experiments are in full swing: IAXO and MADMAX (p. 48) as well as LUXE (p. 44).

Finally, progress has been made in many adjacent fields with the help of high-energy physics: medical imaging (p. 35), plasma acceleration (p. 40), machine learning (p. 46) and quantum computing (p. 52).

Building precision: Assembly of ATLAS ITk endcap at DESY

From micrometre-scale silicon strips to a giant endcap detector

The ATLAS collaboration is preparing for the necessary upgrades of the ATLAS detector to address the high occupancy conditions of the High-Luminosity LHC (HL-LHC) phase. For this challenging project, the ATLAS group at DESY is heavily involved in the development, design, construction and installation of the new silicon tracking detector, called the ATLAS Inner Tracker (ITk). In 2024, several more detector components entered the production phase towards final delivery to CERN. The DESY ATLAS group, which comprises a highly motivated and well-trained team of physicists, engineers and technicians based in Hamburg and Zeuthen, plays a leading role in the production of one complete endcap detector for the ITk.

The new Inner Tracker for ATLAS

During the high-luminosity upgrade of the LHC, the ATLAS collaboration will also upgrade several of its detector systems. The DESY ATLAS group is significantly involved in the new ITk and has made leading contributions to the design and prototyping of the detector components for the strip endcap part of the ITk over the past decade.

This detector section consists of a cylindrical global support structure equipped with individual detector structures called petals. A petal is made up of a core support structure loaded with six different types of silicon strip modules glued on both sides and a data concentrator board at the end, called the end-of-substructure card. DESY's contribution covers almost all subcomponents of the detector up to the delivery of a completed endcap to CERN by 2028.

Petal core production in full swing

The mechanical support structures for the detector elements – called petal cores – are carbon-fibre-based sandwich structures with an embedded cooling pipe for dual-phase CO_2 cooling of the sensor modules. After extensive prototyping at DESY and other institutes, the manufacturing process was outsourced to a Spanish industry partner. Within the DESY ATLAS group, critical input elements for the structures – the prepared titanium cooling pipes, the carbon-based thermal conductive foam parts around the pipes and the electrical connectivity surface, called bus tapes – are produced in house. After manufacturing and quality testing, the material is sent in monthly batches to Spain for core production. In summer 2024, the industry partner entered series production with 20 cores per month. The produced objects are then shipped to IFIC in Valencia, Spain, and DESY in Hamburg for quality control checks (Fig. 1). These tests involve checks of geometrical precision, electrical properties, especially of the bus tape surfaces, and thermal performance. After passing all quality checks, the cores are sent to the four petal loading sites worldwide for the next assembly steps.

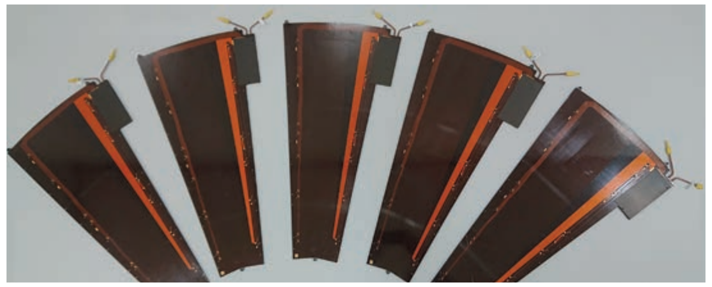


Figure 1
Delivery of a batch of petal cores from industry ready for quality testing at DESY

The production requires a well-organised workflow among the technicians, engineers and detector physicists in the DESY ATLAS group. The production team successfully demonstrated that the envisioned monthly throughput can be achieved, and the manufacturing and quality control techniques developed in house are working well.

In-house strip module production

Significant progress has been achieved in the in-house manufacturing of the strip detector modules and their assembly on the carbon fibre carrier structures. During module assembly (Fig. 2), the hybrid printed circuit boards containing the front-end readout electronics as well as components for module high-voltage operation are glued onto the silicon strip sensor with micrometre-level precision positioning. Connections with each individual sensor channel are established via wire bonds.

In total, there are nine flavours of modules (R0–R5, with R3–R5 split into two half-modules each) with different size and geometry, depending on their radial location in the endcap. DESY in Hamburg specialises in the assembly of R2 and R4 modules, while DESY in Zeuthen produces R0, R1, R3 and R5 modules. In 2024, DESY fully qualified as a module production site, demonstrating the team's ability to reliably produce high-quality strip modules and perform thermal and electrical quality control steps during mass production. One important milestone achieved at DESY is the successful commissioning of the module thermal cycling setup, which is used to perform electrical quality tests of up to four modules simultaneously at different operating temperatures between +20 and -40°C.

The petals as building blocks of the endcap

After a module has been built and passed quality control, the next step is the petal loading – the assembly of the modules on the core support structure. Each petal hosts 18 modules, with nine modules each instrumenting the front and back side of the petal. The modules are glued and placed on the petals using a robot gantry that dispenses the glue and subsequently picks up and places the module with a precision below 50 µm. After a petal is fully loaded with modules, the petal is bonded to ensure data and power connectivity via the end-of-substructure card to the outside of the endcap. Fully loaded petals undergo more thermal and electrical testing for quality assurance before being mounted in the endcap structure. DESY successfully completed the qualification as a petal production site in 2024, having produced three fully loaded petals (Fig. 3).

Arrival of the endcap global support structure

During the final integration of the endcap detector, the produced and thoroughly tested petals are inserted into the endcap skeleton – a carbon-fibre-based global support structure manufactured at Nikhef in Amsterdam. As this task is happening outside CERN, where the complete ITk detector will be integrated, the teams at the DESY and Nikhef integration sites have been preparing meticulously for these last steps of the detector assembly in 2024. A critical aspect is the careful planning of the transport between the different locations. As the endcap is an extremely delicate and expensive object, it has special transport

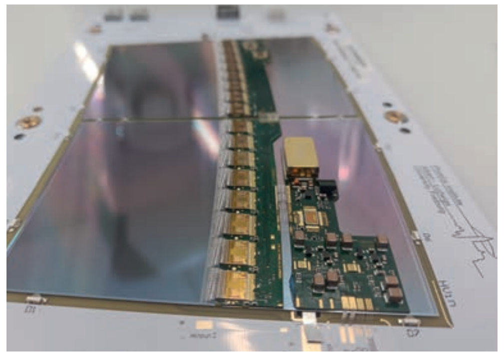


Figure 2
Finished R4 silicon sensor module in its electrical test frame, complete with front-end chips, power electronics and connecting wire bonds

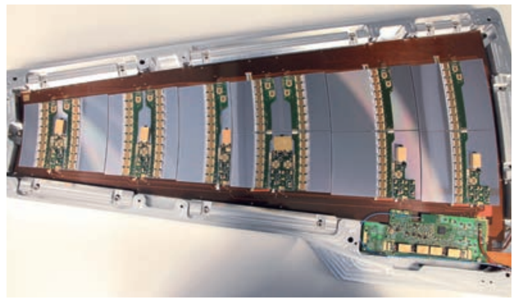


Figure 3
Petal fully loaded with silicon modules and interfaces on the core structure

requirements. DESY collaborates closely with a specialised logistics company to make sure the endcap will arrive in pristine condition at its final destination at CERN.

First, the empty skeleton structure needed to be brought from Amsterdam to Hamburg in December 2024. To learn as much as possible from this transport also for the final transports to CERN, the team handled everything under realistic conditions. The company provided a 3 x 3 x 3 m^3 large transport box with the capability to maintain stable climatic conditions over 72 h and equipped with a special dampening mechanism to protect the endcap from any vibrations or shocks during transport. For validation, several transport loggers were operated during the road trip. Within one week, the Nikhef and DESY teams, together with the logistics experts, successfully transported the endcap skeleton to its destination in the DESY cleanrooms.

For the DESY ATLAS group, achieving this milestone means we can now get ready for the installation of the petals and the completion of the endcap over the next three years. With a great team on site (Fig. 4) and in close collaboration with our international partners, we are set and ready for the challenge ahead.

Figure 4
The DESY ATLAS group looking forward to performing the integration work on the endcap structure delivered to the cleanrooms of the Detector Assembly Facility

Contact:
Jan-Hendrik Arling, jan-hendrik.arling@desy.de
Ruth Jacobs, ruth.jacobs@desy.de

Cornering the Higgs couplings to top quarks

Most precise *ttH* measurements with the help of machine learning

Anomalies in the coupling of the Higgs boson to the top quark could explain the asymmetry in the abundance of baryons and antibaryons observed in the universe. With the help of a state-of-the-art machine learning algorithm developed at DESY, the ATLAS collaboration released new results of unprecedented precision on top–Higgs interactions.

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

The DESY ATLAS group took a leading role in the recently released results by the ATLAS collaboration on the Higgs boson's interaction with top quarks based on the analysis of data collected during LHC Run 2 (2015–2018). The interaction with top quarks is probed in Higgs production in association with a top-quark pair (*ttH*) in events with $H \to bb$ decays. This analysis is extremely challenging due to large backgrounds and complex event topologies. Innovative analysis techniques, such as state-of-the-art transformers developed at DESY, were crucial for success. Thanks to the transformer, the classification of the signal from various background processes was enhanced, allowing a tripling of the number of selected *ttH*, $H \to bb$ events. The DESY team also improved the methods for estimating background processes, including new theoretical predictions and a refined assessment of related uncertainties – a key component to boost the *ttH*, $H \to bb$ sensitivity.

Thanks to these improvements, the sensitivity to *ttH*, $H \to bb$ production was doubled, leading to a measurement of the *ttH*, $H \to bb$ cross section with a precision of 24%, better than any single measurement before. The inclusive signal strength relative to the SM prediction was found to be 0.81 ± 0.21, consistent with the SM expectation of unity. This does not confirm previous results from ATLAS and CMS, which left room for a lower-than-expected *ttH* cross section, dispelling speculations of new physics in this process.

Notably, in the high transverse-momentum regime, where the sensitivity to new physics effects is especially large, the precision was nearly doubled. However, the analysis did not show significant deviations from SM predictions.

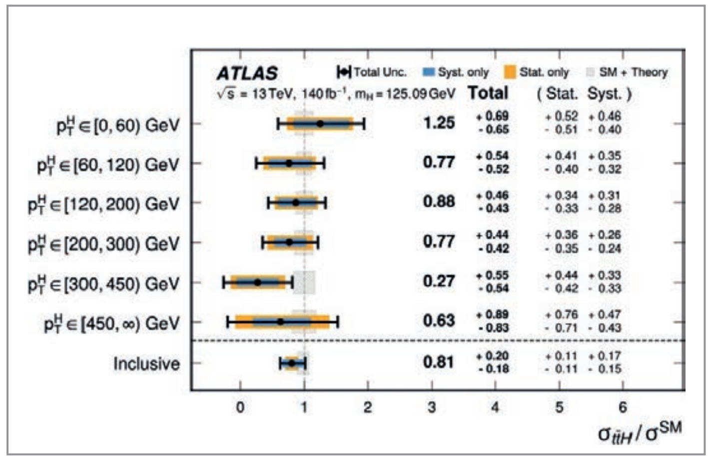


Figure 1

ttH cross section measured as a function of Higgs transverse momentum [1]

Contact:

Judith Katzy, judith.katzy@desy.de

Reference:

[1] ATLAS Collaboration, Eur. Phys. J. C 85, 210 (2025)

The many decay modes of Higgs-boson pairs

The search for Higgs-boson pairs in ATLAS continues

Higgs-boson pairs are an extremely rare phenomenon, which can currently only be studied with the LHC at CERN. Members of the DESY ATLAS group have assumed leading roles in multiple analyses of the data taken with the ATLAS detector in 2015–2018 to improve our understanding of this process, which has still not been observed experimentally. New results were obtained in the Higgs-boson pair final states of four *b* quarks or two *b* quarks and two τ leptons. Finally, a combination of all ATLAS searches for Higgs-boson pairs was conducted, yielding the strongest expected sensitivity to Higgs-boson pair production to date.

The Higgs self-coupling λ_{HHH}, related to the shape of the Higgs potential, is crucial for our understanding of electroweak symmetry breaking, but it remains unmeasured. The quartic coupling g_{HHVV} is also unconstrained. Higgs pair production (*HH*) via gluon–gluon fusion (ggF) and vector boson fusion (VBF) probes both couplings, affecting the kinematics at tree level. Using the full LHC Run 2 proton–proton data set (140 fb^{-1}), the DESY ATLAS group searched for non-resonant VBF $HH \to b\bar{b}b\bar{b}$ in a Lorentz-boosted topology, sensitive to $\kappa_{2V} = g_{HHVV} / g^{SM}_{HHVV}$ [1]. Because roughly one-third of *HH* events yield a $b\bar{b}b\bar{b}$ final state, it provides strong sensitivity. By combining this with a resolved analysis, the group obtained the observed 95% confidence level (CL) constraint of $0.5<\kappa_{2V}<1.5$, the most sensitive result in the ATLAS experiment.

Another focus of the DESY ATLAS group was the search for $HH \to b\bar{b}\tau^+\tau^-$ events [2]. This channel has an intermediate branching fraction of about 7%, but the relatively low rate of background events makes it very competitive with other decay channels. In fact, it is currently the most sensitive channel to the Standard Model (SM) *HH* production (Fig. 1). Using novel techniques, this analysis outperformed the previously quoted results on SM by about 15% and set 11% stronger constraints on the Higgs self-coupling modifier $\kappa_\lambda = \lambda_{HHH} / \lambda^{SM}_{HHH}$.

The DESY ATLAS group further combined results with $b\bar{b}\gamma\gamma$, multilepton and $b\bar{b}$ ll + E_T^{miss} channels, covering over half of all *HH* decays [3]. The group set an observed 95% CL upper limit on the *HH* cross section at 2.9 × SM prediction, with the interval of κ_λ in $-1.2<\kappa_\lambda<7.2$ and the interval of κ_{2V} in $0.6<\kappa_{2V}<1.5$. This combination represented the best expected sensitivities to the *HH* production cross section and the Higgs-boson self-coupling.

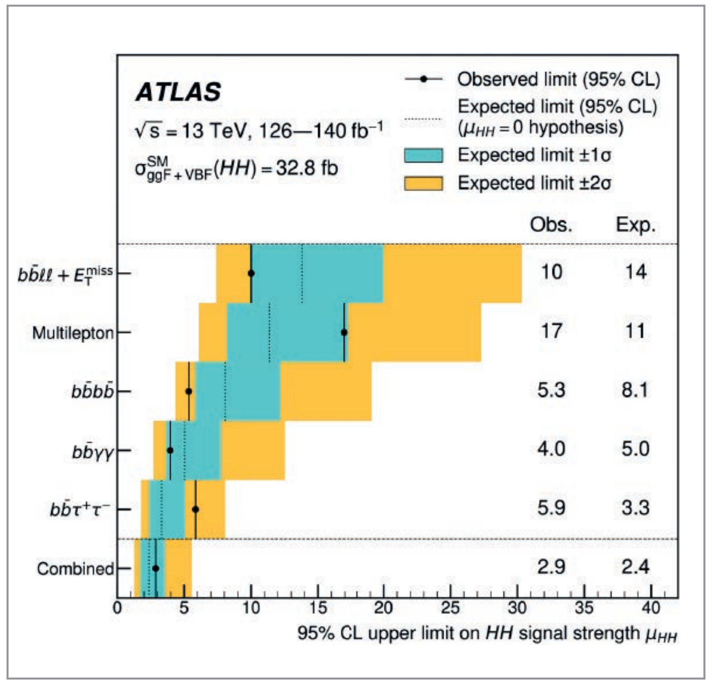


Figure 1

Observed and expected 95% CL upper limits on the signal strength for inclusive ggF *HH* and VBF *HH* production from the $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$, multilepton and $b\bar{b}$ ll + E_T^{miss} decay channels as well as their statistical combination.

Contact:

Serhat Ördek, serhat.oerdek@desy.de
Kunlin Ran, kunlin.ran@desy.de

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[3] ATLAS Collaboration, Phys. Rev. Lett. 133,101801 (2024)

Counting collisions: pushing luminosity precision to the limit

ATLAS sets the stage for ultraprecise luminosity measurement in LHC Run 3

Accurately determining the number of collisions in a collected data set is essential for nearly all measurements and searches for new phenomena at the LHC. To achieve this, a precise measurement of the integrated luminosity is required – a challenging task at hadron colliders. Members of the DESY ATLAS group play key roles in various aspects of the luminosity calibration process and pioneer innovative techniques in the quest for the ultimate precision in Run 3 of the LHC.

Luminosity is a fundamental parameter at any collider, linking measured event rates to cross sections of physics processes. Its accurate determination is therefore essential. ATLAS physicists achieved a record 0.83% uncertainty in the LHC Run 2 data set [1] and aim for sub-percent precision in Run 3.

The measurement involves three main steps: determining the absolute luminosity scale via van der Meer (vdM) scans [2], extrapolating the scale to physics data taking and ensuring long-term stability. ATLAS [3] determines luminosity with the LUCID-2 Cherenkov detector [4], supported by the inner detector and calorimeters.

In vdM scans, interaction rates are measured at different beam separations. The rate-versus-separation curve, corrected for effects like beam–beam interactions, is fitted to extract an absolute calibration. Traditional scans assume that particle density distributions factorise into horizontal (x) and vertical (y) components, but deviations challenge the model. To address this, the DESY ATLAS team developed two-dimensional vdM scans, fitting interaction rates as functions of both x and y separations (Fig. 1) [5].

DESY physicists also contribute to the transfer of the vdM calibration to normal running conditions by correcting the LUCID-2 response through independent track-counting measurements, linking reconstructed inner detector tracks to interaction rates.

Despite challenges, ATLAS achieved a preliminary luminosity uncertainty of 2.0% in 2022 and 2023. A large part of the uncertainty comes from the non-factorisation effect, and work is ongoing to understand this better.

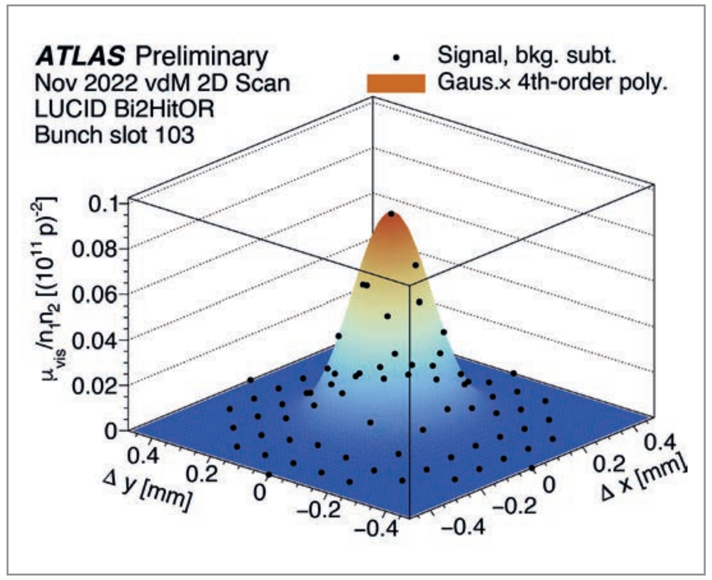

Figure 1

Visible interaction rate per unit bunch population product vs. beam separation in the two-dimensional vdM scan of November 2022, for bunch slot (BCID) 103, using the LUCID Bi2HitOR algorithm

Contact:

Cédrine Hügli, cedrine.huegli@desy.de
Filippo Dattola, filippo.dattola@desy.de

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Do *b* quarks have a soft spot?

Calibration of a soft secondary vertex tagger with ATLAS data

The identification of *b* quarks with very low momenta (soft *b*-jets) is a crucial element for improving ATLAS data analysis results, including searches for Higgs-boson partners and supersymmetry. These elusive and challenging particles require dedicated calibration to ensure accurate identification. In 2024, the DESY ATLAS group led the calibration of a new algorithm designed to enhance soft *b*-jet tagging performance.

Among the six known quark flavours, the bottom (*b*) quark holds a particularly important place in the Standard Model. Closely linked to the top quark, which predominantly decays into a *W* boson and a *b* quark, the *b* quark hadronises into *B* hadrons, which have a long lifetime and distinctive decay patterns. They play a central role in precision measurements of the Higgs boson, flavour physics and the search for physics beyond the Standard Model, including potential hints of dark matter and supersymmetry. This is why identifying *b*-jets [1] – collimated sprays of particles that contain a *B* hadron – is a crucial part of the LHC physics programme.

However, not all *b*-jets behave in the same way. Some carry lower energy and escape traditional jet-based identification methods (soft *b* quarks). To address this challenge, the ATLAS collaboration has developed the Track-Cluster-based Low-p_T Vertex Tagger (TC-LVT), an algorithm specifically designed to identify "soft secondary vertices" (SSVs) from *B* hadron decays outside reconstructed jets. It identifies displaced tracks, groups them into clusters and applies a vertex reconstruction technique to distinguish real decay vertices from random track crossings. The DESY ATLAS team led the calibration of this algorithm, ensuring its accuracy by comparing performance in simulation and real data to derive correction factors [2].

To achieve a robust calibration, a data set enriched in top-quark pair events was selected. Exploiting the topology of these events (i.e. events containing two *b* quarks) and categorising them based on the number of reconstructed SSVs and *b*-jets (Fig. 1), it was possible to isolate samples enriched in low-momentum *b* quarks and fake reconstructed secondary vertices. If both *b* quarks are identified by the standard *b*-tagging algorithm, the reconstructed SSV is likely fake due to random track crossings. Using 13 TeV proton–proton collision data, correction factors for both TC-LVT efficiency and fake rate were extracted, ensuring high precision and a full systematic uncertainty assessment. This approach improves TC-LVT reliability in physics analyses.

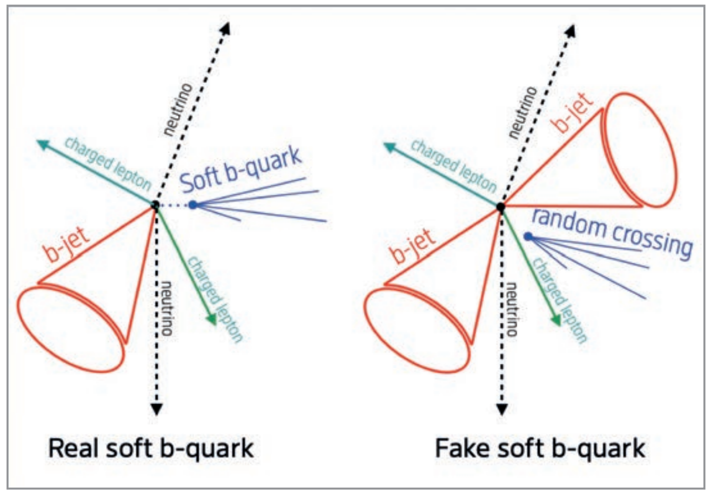

Figure 1

Schematic representation of event topologies used for the calibration of the soft *b*-tagging algorithm. Real and fake contributions are distinguished in top-quark pair production events based on categorisations.

Contact:

Claudia Seitz, claudia.seitz@desy.de
Priscilla Pani, priscilla.pani@desy.de

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Excellent tools

"You cannot mandate productivity, you must provide the tools to let people become their best" – Steve Jobs

Developing new particle detectors is a complex endeavour that requires a combination of detailed understanding of the device physics, deep technical knowledge and flexible analysis tools for the data the detectors produce. DESY lives up to its ambition of being a hub for detector development in particle physics, providing, developing and maintaining several software tools that are crucial to the entire development cycle of current and next-generation detectors. With Constellation, a new control and data acquisition system is being developed; Corryvreckan is the standard tool for analysis of test beam experiments; and Allpix² has become a stronghold in simulating semiconductor detectors across different fields of science and industry.

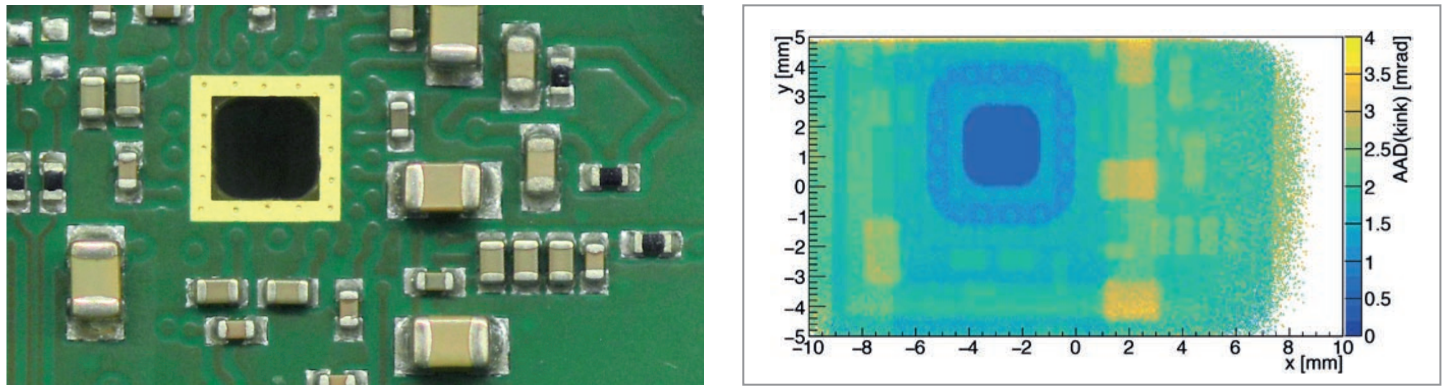

Figure 2
Left: Printed circuit board (PCB) with a hole underneath a silicon sensor and with surface-mounted device (SMD) components. Right: Average absolute deviation (AAD) of the track kink angle in the plane of the PCB. The position of the SMD components and the hole are clearly distinguishable. From [4].

Developing Constellation

Whenever a new detector prototype comes back from production, it undergoes rigorous testing. This involves different laboratory tests but also test beam experiments, where the detectors are placed in a beam of particles and characterised with the help of reference detectors. These experiments require synchronous operation of the different detector systems and a common distribution of commands and configuration information. This task is usually performed by control and data acquisition software.

Constellation is such a software framework, which targets small-scale experiments and experimental setups with volatile and dynamic constituents. It is currently being developed at DESY and aims at providing a system that is simultaneously easy to use by operators, flexible enough to keep up with ever-changing systems in lab and test beam environments and that makes the integration of new systems and detectors straightforward.

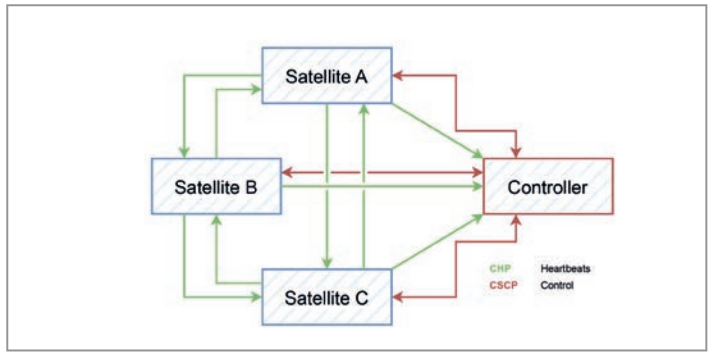

Figure 1
Diagram of the communication paths between satellites and a controller of a Constellation network. The satellites exchange status information via regular heartbeats, while the controller instance can send commands.

Its unique feature is the possibility of operating different instruments (dubbed "satellites") autonomously and without the need for a central control server or user interface. Status information and finite-state-machine (FSM) states are communicated between satellites using a decentralised "heartbeating" protocol, shown in Fig. 1. This protocol enables autonomous FSM transitions between states as well as error response in case of faults or connection losses.

Constellation has already been used in a number of application scenarios and is constantly improved and extended to serve e.g. the user community of the DESY II Test Beam Facility. More information is available alongside the documentation at [1].

Maintaining Corryvreckan

Corryvreckan [2, 3] is a modular framework dedicated to the reconstruction and analysis of data acquired in test beam experiments that test position-sensitive detectors for charged particles. Data from a reference system and the investigated detectors are combined to events, and particle tracks are reconstructed using the data from the reference system. If these tracks intercept the active area of an investigated detector, detector properties such as hit detection efficiency and spatial hit resolution can be inferred.

The framework profits from a thriving community of users at DESY and throughout the world. More than 50 authors and developers have written and reviewed close to 650 contributions to the framework, improving, maintaining and extending its functionality to meet the growing demands of detector R&D.

One of these extensions is a module that analyses the material budget of an object. This requires straight tracks to be reconstructed before and after a particle passes the object. The width of the distribution of kink angles between these track pairs is related to the amount and density of material in the investigated object. An example is shown in Fig. 2.

Using Allpix²

As the complexity of particle detectors increases, so does the interest in a detailed description of these detector as digital twins. Such digital twins enable optimisations during the design phase and facilitate a detailed understanding of phenomena observed in measurements. Since both the interaction of the particles with matter and the detection process itself are stochastic in nature, Monte Carlo (MC) simulations are an optimal solution to such problems.

The Allpix² MC simulation framework [5], developed and maintained at DESY, provides innovative solutions for complex simulations of semiconductor detectors. The tool not only offers the means to simulate detectors but also bridges communities working on radiation detectors in different fields. It has a wide user and developer base that comprises research facilities, universities and industry partners, with applications ranging from particle and nuclear physics to medical imaging and photon science.

At DESY, Allpix² was recently used to develop a technology-independent toolkit for the simulation of monolithic active pixel sensors (MAPS) [6], a crucial step in understanding and reproducing measurements from this type of detectors (Fig. 3).

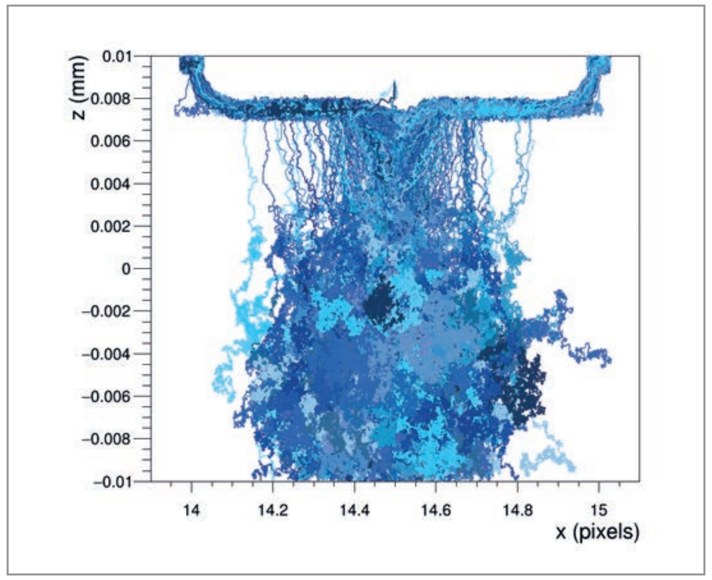

Figure 3
Line graph of electrons drifting in the sensitive volume of a MAPS sensor, simulated using Allpix². The individual pixels are located at the top of the image where the drift lines combine. From [6].

Contact:
Finn King, finn.king@desy.de
Simon Spannagel, simon.spannagel@desy.de

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CMS Outer Tracker endcap

Going towards full production

The DESY CMS group is taking the final steps to launch the production of 1250 modules for the upgraded Outer Tracker of the CMS detector and to integrate the modules onto an endcap. The main structures have been developed and are currently being manufactured. Integration procedures, tooling and quality assurance measures have been devised and are being put in place.

The CMS Phase 2 Outer Tracker is the foreseen upgrade of the tracking detector of the CMS experiment for the HL-LHC. The DESY CMS group is strongly engaged in the design, production and construction of the tracker endcap. The endcap comprises five double disks (DDs), with each DD having four surfaces with modules arranged to cover the full area with sensitive detector area, giving at least one hit from a traversing particle. One DD is built from four half disks (Dees), each carrying up to 180 detector modules of two different flavours. The outer radii are populated with two-strip (2S) modules, while the inner radii are populated with pixel strip (PS) modules.

CMS PS module assembly

The DESY CMS group has completed and tested the module production line and is ready for the imminent start of the production of 1250 PS modules for the upgraded CMS Outer Tracker. One of the setups now fully commissioned is the probe station for reception testing of the macro-pixel sub-assemblies – a stack made up of a pixelated sensor with bump-bonded readout chips. Figure 1 shows this setup with the needles of the probe card to be lowered onto the pads of the macro-pixel application-specific integrated circuit (ASIC).

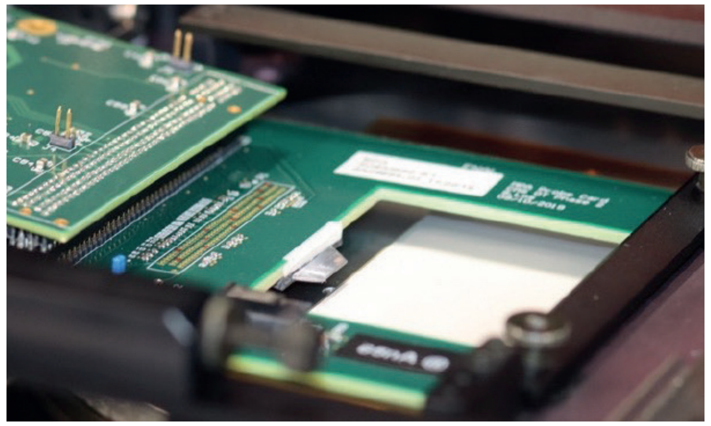

Figure 1

Macro-pixel sub-assembly about to be tested

The steps up to completion of a module include preparatory gluing steps on sensors and the carbon fibre base plate as well as the assembly of the bare module, for which the DESY group developed a robot-assisted setup that was adopted by two other CMS institutes. After gluing and wire-bonding of the electronic printed circuit boards for readout and powering, a module must undergo a final electrical test before being moved to the burn-in setup. There, modules are temperature-cycled between -35°C and room temperature and electrically tested between those cycles in order to find faulty modules prior to the integration onto the Dees.

Preproduction of Dees

The Dees are the local support structures on which the modules are mounted. They provide efficient bi-phase CO_2 cooling at -35°C to mitigate radiation-induced damage to the silicon sensors. They are also an integral part of the global mechanics to reduce the overall weight of the endcaps.

A set of four preproduction Dees was produced in 2024 and is being evaluated. Before the modules can be integrated, the Dees are tested for their mechanical and thermal properties. The mechanical inserts must be measured for dimensional accuracy to verify that the modules fit and can be positioned correctly. Figure 2 shows the metrology result of the PS module fixation inserts.

To verify the thermal performance, the surface of the Dee is surveyed using an infrared camera while actively cooling the Dee. Figure 3 shows the infrared picture of the PS module area. In the centre of each rectangle, representing a module position, thermally conductive carbon foam blocks inside the Dee enable heat transport from the Dee surface to the cooling pipes. Each module position is checked as to whether the cold spot is homogeneous, indicating proper thermal contact.

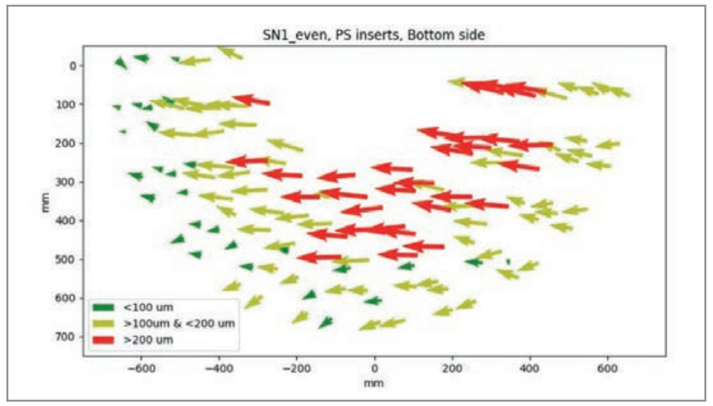

Figure 2

Position deviation of the PS module mounting inserts inside the Dee. A large deviation of a single insert is a production defect and can indicate that a module will not fit properly. Global shifts as seen in the figure are not problematic.

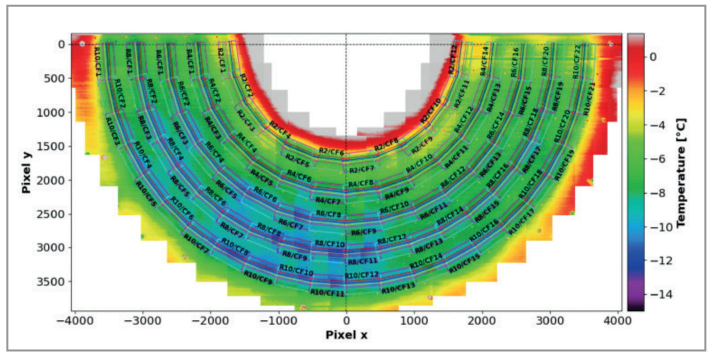

Figure 3

Infrared image of the Dee surface where the PS modules will be installed. Each square corresponds to one module. Each module position is evaluated for potential non-conformities.

During preproduction, several improvements were made to the production workflow. Given the confidence already gained in the production process, the serial production of Dees was launched at the end of the year.

Preparation of Dee integration

Integrating modules on a Dee is a complicated process. Not only the installation of the modules must be done carefully, but also the routing of services and the verification of the full functionality of the modules through dedicated tests. The focus in 2024 was on developing a method to thermally couple the PS modules to the Dee. The PS modules need to be cooled through their entire underside. A thermal interface material (TIM) is needed so that there is no thermally insulating air gap. Applying the TIM is not trivial, as a thin layer must be applied on a large area. The contact with the surface cannot be achieved by pressing on the fragile modules. A repetitive circular motion was developed as a suitable process. The beneficial function of the TIM was quantified by testing the application with a thermal dummy and with real modules equipped with temperature probes.

Figure 4 shows the thermal dummy mounted on a cooling structure for a single PS module that is designed to reflect the mechanics of a Dee. To demonstrate the thermal performance, measurement with the baseline TIM are compared with the use of a thermal pad and no interface material (dry contact). Figure 5 shows measurement results using different interfaces. The proposed TIM (gap filler) and application technique (massaging) yield the lowest temperatures on the dummy, implying the best thermal contact. While further tests are ongoing to optimise and quantify the thermal contact, a baseline module mounting procedure has been established.

Summary

The project is making remarkable progress in all activity areas. As module and Dee production are transitioning into full production, work on the integration of disks and double disks and their transport to CERN will be the main focus of the remaining R&D work in 2025.

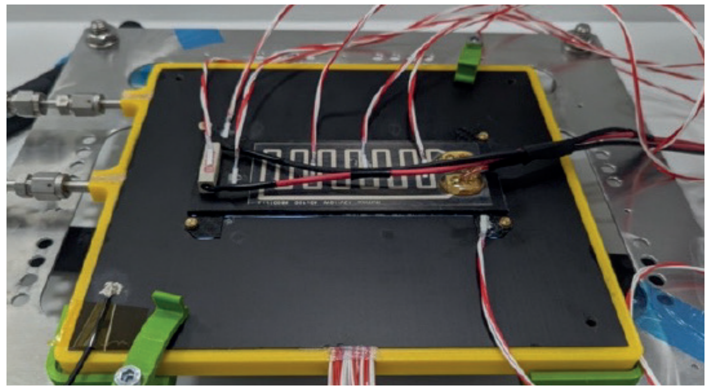

Figure 4

A thermal PS module dummy is equipped with heating resistors and temperature sensors mounted on a PS module cooling structure. A thermal interface material is applied between dummy and cooling structure.

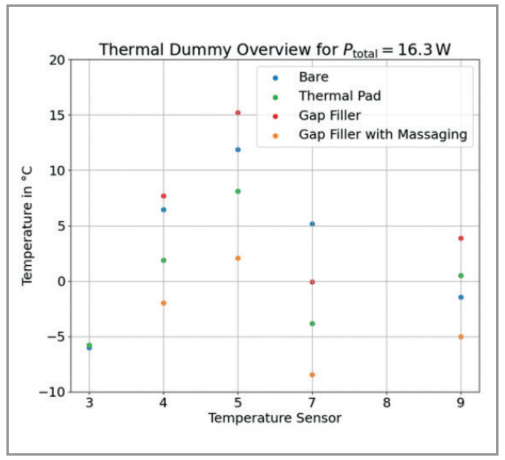

Figure 5

Measurement results using different thermal interfaces between PS module dummy and cooling structure

Contact:

Doris Eckstein, doris.eckstein@desy.de

Moritz Guthoff, moritz.guthoff@desy.de

Standard Model at ultimate precision

Testing our picture of matter

The Standard Model of particle physics describes the fundamental particles and forces shaping our universe, yet its key parameters – particle masses and interaction strengths – must be determined experimentally to unambiguously prove its validity. Furthermore, high-precision determinations are essential for probing potential deviations that could hint at new physics. The DESY CMS group plays a crucial role in the global effort at the LHC to achieve unprecedented accuracy in these measurements, advancing our understanding of nature's fundamental laws.

Two faces of the electroweak interaction

The electroweak interaction, a cornerstone of the Standard Model (SM), consists of two components: a charged-current interaction mediated by the *W* boson and a neutral-current interaction involving the *Z* boson and the photon. The fundamental parameters governing these interactions are closely linked to the mass of the *W* boson m_W and the effective electroweak mixing angle $sin^2\theta^l_{eff}$. The past experimental results have revealed intriguing tensions. The recent high-precision measurement of m_W by the CDF experiment at Fermilab deviates significantly from the SM prediction, challenging its validity. Additionally, the two most precise determinations of $sin^2\theta^l_{eff}$, one from the SLD experiment at SLAC, and another from the LEP collider at CERN, differ by several standard deviations, raising further questions. New measurements [1, 2] by the CMS experiment at the LHC provide crucial new insights, offering precise tests of the electroweak sector of the SM.

Achieving ultimate precision can take up to a decade and requires close collaboration between experimentalists and theorists. The recent CMS high-precision measurement of the *W*-boson mass [1] is based on a dedicated data sample of proton–proton collisions at 13 TeV, collected by CMS in 2016, and was achieved in a global effort by multiple institutes within the CMS collaboration, with significant contributions from DESY CMS scientists and valuable insights from the DESY Theory group [3]. At the LHC, *W* bosons are investigated in their decays into a muon and neutrino. The ultimate precision of the CMS m_W measurement relies on CMS high-performance muon kinematics reconstruction. The muons "inherit" the kinematic

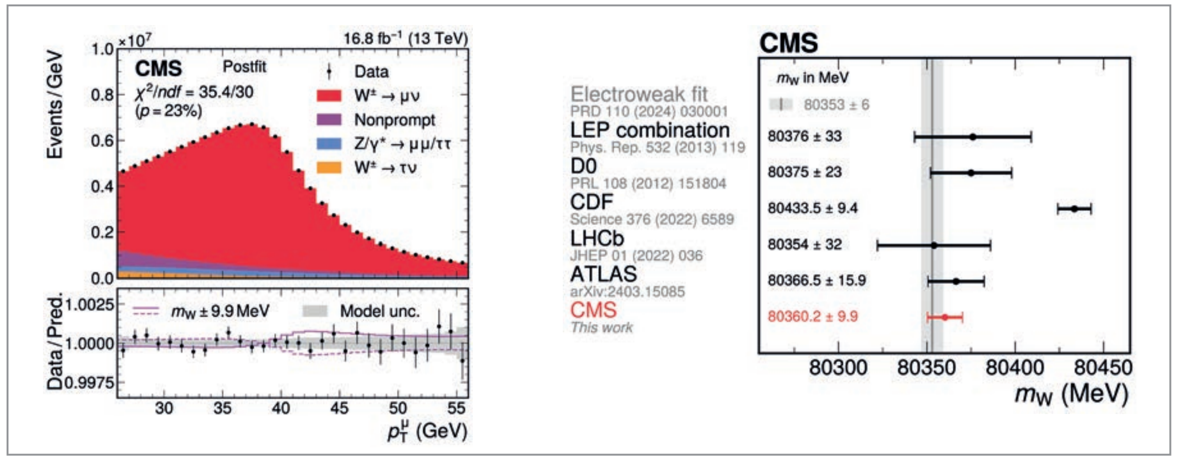

Figure 1

Left: Transverse momentum of the muon p_T^μ originating from the *W*-boson decay. The measurement (prediction) is shown by closed symbols (red histogram). The background contributions are shown in blue, purple and yellow. The bottom panel shows the ratio between the measurement (black symbols) and the predictions (magenta line), where the latter are obtained by varying the value of m_W by 9.9 MeV up (solid) and down (dashed). Right: The CMS m_W result (red symbol) with the SM prediction (grey band) and the results from other experiments (black symbols). The total uncertainty is shown by the grey band. From [1].

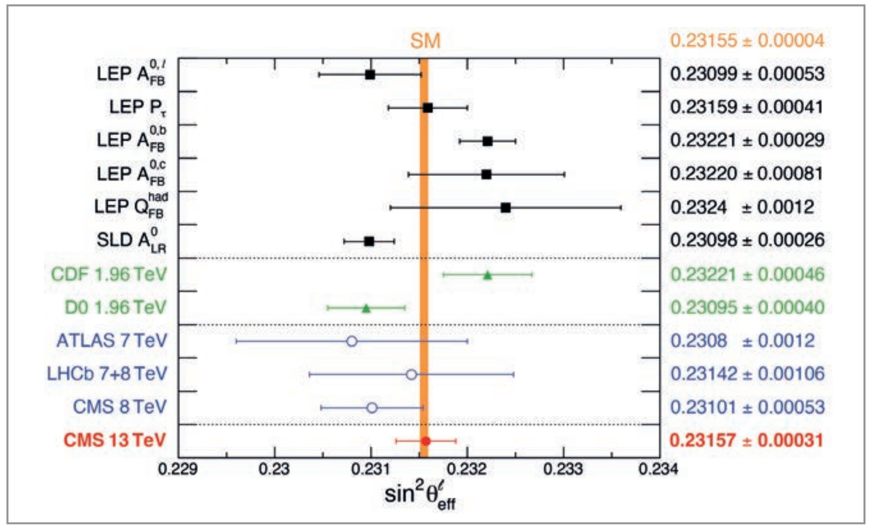

Figure 2

Recent result on $sin^2\theta^l_{eff}$ obtained by CMS (red symbol), compared to the results of other experiments (symbols of different colour) and the result of a SM global fit (orange band). From [2].

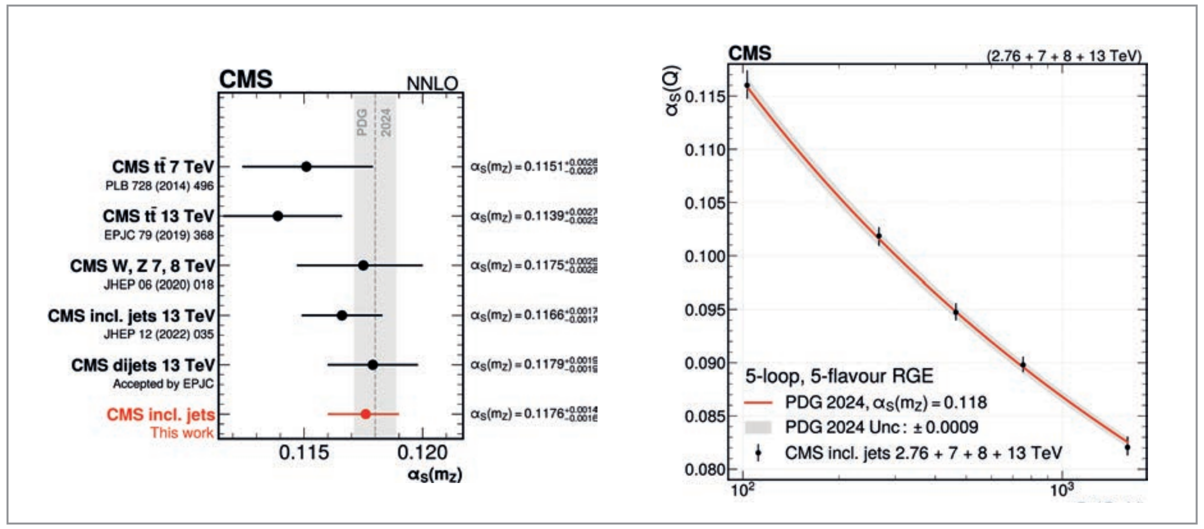

Figure 3

Most recent value of $\alpha_S\,(m_Z)$ (left) and illustration of α_S running (right), obtained by CMS by using jet rates. From [4].

properties of their original *W* boson, and their transverse momentum (Fig. 1) is driven by the value of m_W, which is extracted through detailed comparison of the measurement and the theory prediction, leading to the most precise result at the LHC, in good agreement with the SM.

The CMS measurement of the electroweak mixing angle [2] is based on proton collision data collected at a centre-of-mass energy of 13 TeV by CMS between 2016 and 2018. This analysis focuses on Drell–Yan events, in which a photon or *Z* boson is produced and subsequently decays into leptons. In the SM, a small forward–backward asymmetry of the leptons relative to the original boson's flight direction is expected, providing sensitivity to $sin^2\theta^l_{eff}$. By precisely measuring the angular distributions of electron and muon pairs, $sin^2\theta^l_{eff}$ is extracted. The DESY CMS team made essential contribution to this measurement by providing precise modelling, leveraging its expertise in determining the quark and gluon distributions within the proton. The new CMS result (Fig. 2) represents the most precise determination of its kind at a hadron collider. It is in excellent agreement with the SM prediction and marks a step towards resolving the long-standing discrepancy between the LEP and SLD measurements.

Strong coupling and its running at new precision

The strong coupling constant α_S is the least well-known coupling in the SM. Indeed, it is not a constant but varies with the energy at which matter is probed. The standard process for extracting α_S in proton collisions is hadronic jet production. However, a key challenge is the strong correlation between the quark and gluon distributions in the proton, which affect SM jet rate predictions. The DESY CMS team analysed CMS jet measurements at different centre-of-mass energies, simultaneously interpreting them in terms of both the strong coupling at the *Z*-boson mass $\alpha_S\,(m_Z)$ and the proton structure [4]. This yielded not only the most precise determination of $\alpha_S\,(m_Z)$ from jet measurements, but also a high-precision demonstration of a fundamental quantum effect – the running of the strong coupling (Fig. 3).

Contact:

Katerina Lipka, katerina.lipka@desy.de
Valentina Guglielmi, valentina.guglielmi@desy.de

References:

[1] CMS Collaboration, arxiv:2412.13872
[2] CMS Collaboration, arxiv:2408.07622
[3] F. J. Tackmann, arxiv:2411.18606
[4] CMS Collaboration, arxiv:2412.16665

Hunting for additional Higgs bosons

Through their interaction with bottom quarks

A search for additional neutral Higgs bosons in final states with bottom quarks was conducted with major contributions from the DESY CMS group. A significant challenge of this analysis is the overwhelming background from quantum chromodynamics multijet production at hadron colliders. To address this, a data-driven background estimation method was employed. In addition, two event categories were defined, optimised for analysis towards a high-mass and low-mass regime, respectively. While no evidence for additional Higgs bosons was found, the most stringent limits to date were set on the production cross section times the branching fraction of a neutral Higgs boson decaying into bottom quarks. These results represent a major advancement in the search for extended Higgs sectors.

A path to new physics

The Higgs sector, with a minimal formulation in the Standard Model (SM), provides a rich testing ground for theories beyond the SM. Among these, the Minimal Supersymmetric Extension of the Standard Model (MSSM) and the Two-Higgs Doublet Models (2HDM) predict an extended Higgs sector featuring multiple Higgs bosons that include both neutral and charged states. One of the most promising channels for detecting neutral Higgs bosons is through their decay into *b*-quark pairs and their production in association with *b* quarks. Researchers from the DESY CMS group conducted a search for these bosons in final states with *b* quarks [1]. In total, up to 126.9 fb^{-1} of data collected during proton–proton collisions at 13 TeV centre-of-mass energy were analysed.

The main challenge of this search arises from the large production at the LHC of quantum chromodynamics events with exactly the same final state. Simulation techniques fail to provide an accurate estimation of the background, so a data-driven approach was used instead. The background model in the signal region (SR) was built using a signal-depleted control region (CR) modified by a transfer function. This transfer function accounted for the differences between the CR and SR. The signal was then extracted in a simultaneous fit of the CR and SR.

In the search, two event categories were defined: one where at least three *b*-jets were identified, with the two most energetic originating from Higgs decay, and another where one of these *b*-jets contained a muon. The muon selection helped to reduce trigger thresholds, enabling sensitivity to masses as low as 125 GeV, with any potential overlap removed from the first category. While new Higgs bosons were not observed, upper 95% CL limits were set on the *b*-associated production cross section times the branching fraction of the decay into a *b*-quark pair. These limits, shown in Fig. 1, extend from 123 pb at a Higgs-boson mass of 125 GeV down to 0.77 pb at 1800 GeV. These results are the most stringent to date in the studied final state.

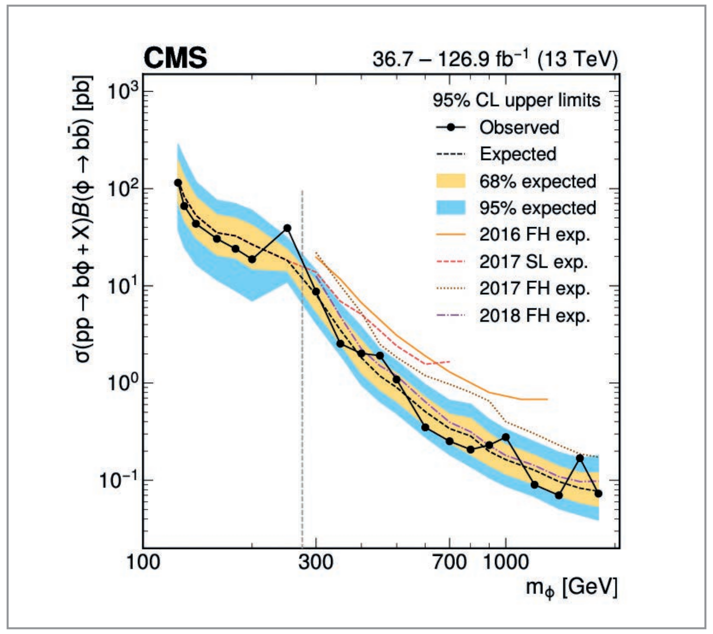

Figure 1

Expected and observed upper limits at 95% CL on the *b*-associated production of a Higgs boson ϕ times the branching fraction of the decay into a *b*-quark pair, as a function of the Higgs-boson mass [1]

Contact:
Daina Leyva Pernia, daina.leyva.pernia@desy.de
Rainer Mankel, rainer.mankel@desy.de

Reference:
[1] CMS Collaboration, arxiv:2502.06568 (submitted to JHEP)

The Large Photon Collider

CMS observes scattering of light by light at the LHC

DESY scientists, working in collaboration with other CMS institutes, discovered some of the rarest collisions that the LHC can produce – the scattering of light by light – while also learning more about the quantum nature of electromagnetism and searching for new particles.

Light-by-light scattering

In everyday life, crossing two beams of light does nothing – photons pass through each other. However, quantum mechanics predicts that, in very rare cases, photons can interact by creating intermediate, charged particles that annihilate back into two photons. This process is called light-by-light scattering. Finding and studying these elastic photon collisions at the LHC allows us to test quantum electrodynamics (QED) at high energies and search for new physics that could alter these collision rates. However, multiple rare conditions must align for light-by-light scattering to occur. Fast-moving charged particles can emit photons without breaking up – a rare event, but still millions of times more likely in lead ion collisions than in proton collisions. Even rarer is the case where two emitted photons meet without the lead ions touching, and finally, the chance of those photons bouncing off each other is tiny.

Adding to the challenge, other processes can mimic light-by-light scattering, producing two photons in the detector. Fortunately, QED predicts that these photons should be emitted almost exactly back-to-back, helping CMS physicists isolate the signal from background processes. The process is shown schematically in Fig. 1. This method also enables the study of a related phenomenon, the Breit–Wheeler process, in which two photons create an electron–positron pair. This process occurs about a thousand times more often than light-by-light scattering and provides another precise test of QED.

Recently, CMS physicists identified 26 lead ion collisions consistent with light-by-light scattering, with only 12 expected background events. The probability that all 26 are background is less than 1 in 10 million, surpassing the five-standard-deviation threshold for discovery [1]. This measurement complements an earlier ATLAS result [2], extending it to lower-energy photons.

New physics searches

Beyond testing QED, these collisions also help search for new particles that interact primarily with photons, such as axion-like particles (ALPs). The observed number of collisions provides constraints on ALP masses and photon couplings in an unexplored range. The result marks a major step in the study of fundamental quantum effects at the LHC. With future high-luminosity data, CMS will further explore these rare interactions, pushing the boundaries of our understanding of light and its interactions.

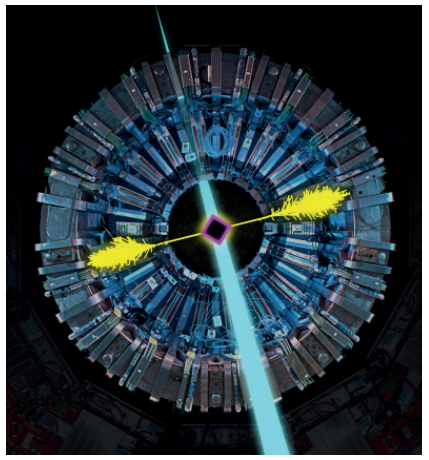

Figure 1

Schematic representation of a light-by-light scattering process in a lead ion collision at the LHC, registered by the CMS detector

Contact:
Jeremi Niedziela, jeremi.niedziela@desy.de

References:
[1] CMS Collaboration, arxiv:2412.15413 (submitted to JHEP)
[2] ATLAS Collaboration, JHEP 03, 243 (2021)

Tiling it up

New CMS calorimeter enters production at DESY

To meet the challenges posed by the high-luminosity upgrade of the Large Hadron Collider (HL-LHC), the CMS experiment will be equipped with an entirely new high-granularity calorimeter (HGCAL). Production has begun at DESY and will feature over 140 000 scintillating tiles glued onto 2000 printed circuit boards, with silicon photomultipliers (SiPMs) positioned beneath each tile for readout. Extensive testing of preseries modules using the DESY II Test Beam Facility has been crucial in reaching this milestone, made possible through the excellent collaboration between the DESY CMS, FTX, FE and ZE groups.

The HGCAL will be a new detector installed in the forward regions of the CMS experiment at the LHC at CERN. It will enable high-granularity 5D shower reconstruction, measuring a particle's energy, spatial position and time of arrival. These capabilities are essential to cope with the increased additional interactions (pile-up) per bunch crossing at the HL-LHC.

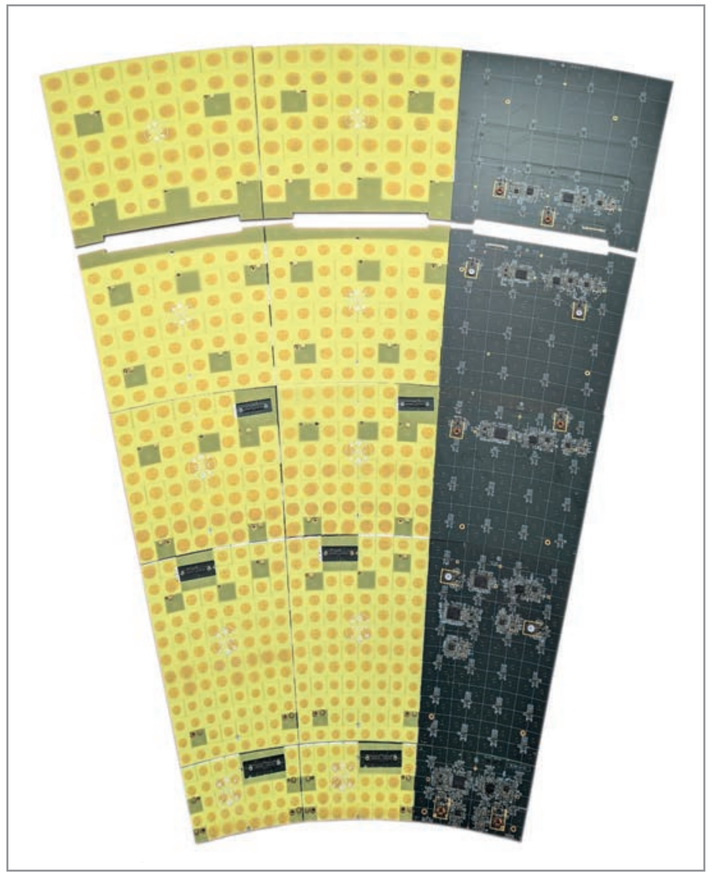

Figure 1

Laid-out 30° sector of SiPM-on-tile modules. The modules on the right have been flipped to show their rear side for demonstration purposes.

Parts of the HGCAL will consist of 14 layers of trapezoidal SiPM-on-tile modules, produced at DESY and Fermilab, with sizes ranging from 15 x 21 cm^2 to 42 x 45 cm^2. In 2024, the preseries phase – comprising prototype modules of the eight major geometrical form factors – was concluded after rigorous testing, finalising their designs (Fig. 1). In addition to validating the electrical assembly and operability, this phase involved using the DESY II Test Beam Facility to study the modules' response to a 3 GeV electron beam, corresponding to signals expected from minimum ionising particles (MIPs).

In January 2025, the first preproduction modules were assembled, marking the beginning of large-scale production, with a target of 150 modules per month at DESY. Automated quality control systems are being developed to ensure efficient and reliable testing. This production phase also presents an excellent opportunity for students to join the team and gain hands-on experience in experimental particle physics and detector operation.

Contact:
Freya Blekman, freya.blekman@desy.de
Matthias Komm, matthias.komm@desy.de
Katja Krüger, katja.krueger@desy.de
Felix Sefkow, felix.sefkow@desy.de

Reference:

[1] CMS Collaboration, CMS-TDR-019 (2017)

From high-energy physics to medical imaging

electronCT – Imaging with highly energetic electrons

Medical imaging is more related to high-energy physics than one might think. Imaging techniques always rely on the properties of particles and the matter these are located in. The most powerful and versatile techniques to date depend on the spin of atomic nuclei and the absorption of photons in the X-ray regime in matter. At DESY, a cross-divisional group of scientists is developing an imaging technique based on highly energetic electrons and has achieved proof-of-concept measurements for projectional (2D) and tomographic (3D) imaging.

When highly energetic particles traverse any material, they begin to interact with the atoms of the material. For example, highly energetic photons – or X-rays – can be absorbed in matter. The more and the larger the atoms present in the material, the higher the probability of absorption, which is the underlying concept of X-ray imaging. Charged particles, such as electrons, are not immediately absorbed but can change their direction of travel due to the electric fields of the atomic nuclei. This is the basic principle of electronCT, an imaging technique developed at DESY that seeks synergies with radiation therapy using highly energetic electrons.

Over the past years, a group of scientists, partly engaged in the development of particle detectors for high-energy physics and partly in the development of linear particle accelerators, worked together to perform first measurements using this method [1]. The technique is based on findings about a modality that was previously studied at DESY [2] and is intended to overcome its technical limitations, such as the long measurement time.

For electronCT, a linear particle accelerator is used in which only a few thousand electrons are accelerated and then directed onto an object under study. The electron beam widens as it traverses the object, and measuring the transverse profile of the scattered electron beam provides a measure of the amount of material in the beam path. The beam profile is determined using particle detectors developed and applied in particle physics.

Figure 1 shows a projectional image of a mouse phantom [3] alongside tomographic reconstructions at different positions, performed at DESY's linear accelerator ARES [4] – representing the first proof of concept of this technique.

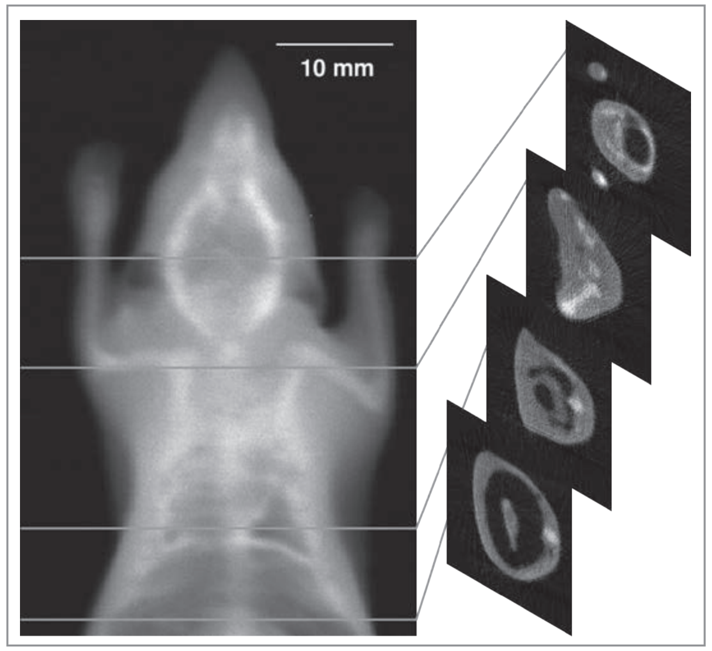

Figure 1

Two-dimensional image and tomographic reconstructions of a mouse phantom acquired using the electronCT technique. The tomographic reconstructions are interpreted as horizontal slices at the positions indicated by the orange lines.

Contact:
Paul Schütze, paul.schuetze@desy.de
Simon Spannagel, simon.spannagel@desy.de
Florian Burkart, florian.burkart@desy.de

References:

[1] P. Schütze et al., Front. Phys. 12, 1454854 (2024)
[2] H. Jansen, P. Schütze, Appl. Phys. Lett. 112, 144101 (2018)
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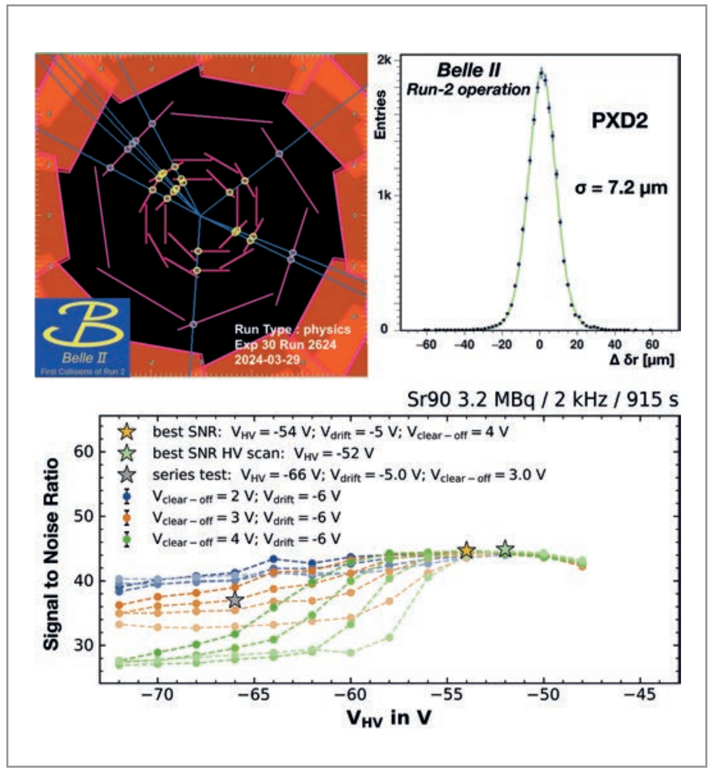
Challenges at the luminosity frontier

Critical time for SuperKEKB, Belle II and its pixel detector

Run-2 operation of the SuperKEKB accelerator at KEK in Tsukuba, Japan, commenced in early 2024. The new pixel vertex detector, which was pre-commissioned at DESY and installed at KEK for this run period, demonstrated its excellent performance, until two sudden beam losses resulted in damage to the readout channels and the detector was turned off while safe accelerator conditions had to be re-established. Despite various challenges in operation, SuperKEKB finally achieved a new world-record luminosity at the end of 2024. Further investigation and improvements are planned before the next operation period in late 2025.

Successful start of PXD2

After the first Long Shutdown (LS1) of the SuperKEKB accelerator with several improvements described in the *DESY Particle Physics 2023* report, the new operation period (Run-2) began in early 2024 with the aim to accumulate data at an unprecedented luminosity. With the successful installation and commissioning of the complete two-layer pixel vertex detector (PXD2) during LS1, which was largely undertaken by DESY physicists and engineers, the Belle II experiment was all set for collecting quality data.



The first layer of the PXD2, just 1.4 cm away from the beamline, offers a complete coverage in azimuthal angle. In the second layer, two out of a total of 12 ladders had to be turned off from the start due to extreme thermo-mechanical behaviour, which was identified and investigated extensively at DESY during commissioning. Additionally, one module (half of a ladder) with unstable operation performance was kept off. Nonetheless, the enhancement in Layer-2 coverage with respect to the previous PXD (PXD1) provided a better handle on selecting the correct signal hit in a high-luminosity environment, suppressing hit contamination from background beam particles. Measurements using the early Run-2 data demonstrated a high efficiency of signal detection of over 98% in the fiducial region and excellent position resolution (Fig. 1, top). The optimal performance of the PXD2 is largely attributed to the commissioning studies carried out by the DESY team (Fig. 1, bottom).

DESY provides a test facility to operate the PXD modules with exactly the same signal readout chain and data acquisition system as employed at KEK, making it the only place outside the experiment where the operation of the readout components can be practiced (Fig. 2). The facility was completely rebuilt after the PXD2 commissioning, with a new system design as well as environmental monitoring and interlocks to allow fully controlled operation of the PXD modules. The setup is used for developments and testing of operation software and firmware as well as for training exercises for the new members of the Belle II PXD group, both locally and remotely.

Figure 1

Top left: Event display from Run-2 operation showing several particle tracks leaving hits in the PXD2. Top right: Excellent pixel hit resolution represented by the difference in two hit positions measured with respect to the same single associated track going through two closely overlapping sensors.
Bottom: Optimisation of operation parameters during pre-commissioning at DESY, which improved PXD2 efficiency.

Sudden beam losses

Several weeks into Run-2 operation, two sudden beam losses (SBLs) with a large radiation dose at the beam interaction region resulted in damage to the PXD2. In an SBL event, a large fraction of the stored beam is lost without prior detectable signs that would enable a safe beam abort.

During Run-1, the PXD1 had also suffered from SBL damage. The mechanism of the damage lies in the custom readout chips on the pixel modules, where the voltage regulators are vulnerable to high radiation bursts. A comprehensive beam test examination was carried out and new, improved chips have since been developed, though too late to produce new modules within the timeline of the PXD2 preparation.

The damage to the PXD2 from the two SBLs amounts to 2% of non-functional pixel channels and a few percent of "hot" channels, the performance of which may still be recovered by rejecting noise hits with small signal charge. The total PXD2 damage is already equivalent to the level that the PXD1 received over three years of Run-1 operation. Furthermore, additional ladders in the second layer of the PXD2 had to be turned off to compensate for the higher heat load from the damaged chips. The Belle II collaboration therefore took the decision shortly after the second damage to turn off the PXD2 until safe conditions could be established.

Detailed analyses of data from beam monitors mostly installed during LS1 showed that first signs of beam loss and associated vacuum pressure bursts were detected at specific locations of the accelerator ring. A likely SBL mechanism was identified as dust particles present inside the beampipe coming into contact with the beam – a phenomenon that was reproduced by knocking at the suspected sections. One identified source of dust particles is the vacuum sealant used at the beampipe coupling joints, which has degraded under high radiation. By replacing and cleaning the parts at a location where pressure bursts occurred most frequently, further SBLs were significantly reduced, and the substance of the stain found on the inner surface of the beampipe was consistent with the vacuum sealant. The plan is to remove the sealant in other locations of the accelerator before the next run period.

The high frequency of SBLs, which increased with beam currents, not only significantly reduces the efficiency of SuperKEKB operation and slows down the ramp-up of luminosity, but also poses a significant threat to vital machine elements. Understanding and mitigating its root causes has therefore been recognised by KEK as a top priority for future beam periods. Further investigations are under way to understand the exact mechanism and identify other signs and possible causes of SBLs. The recently completed improvement to the beam abort trigger system enables a shorter delivery time of the abort signal by up to one turn of the beam around the accelerator ring and will help to mitigate possible damage from beam losses in the future.

Figure 2

PXD lab in the DESY HERA West hall. Two PXD ladders – one Layer-1 ladder and one Layer-2 ladder, each with a forward and a backward module – are installed to allow testing on all possible types of modules and readout sequences.

Road to the target luminosity

SuperKEKB faced several challenges throughout Run-2 operation. A fraction of the last run period in autumn 2024 was spent on investigating and trialling several schemes to increase the beam currents and reach higher luminosity. During this luminosity challenge, the Belle II detector was turned off when the observed beam background level exceeded the safety limit. Finally, in the last week of operation, the SuperKEKB team progressively renewed the previous luminosity record and achieved the present world record of 5.1 x 10^{34} $cm^{-2}s^{-1}$.

The next operation period of the accelerator is planned to start in autumn 2025 with an extended run time until the end of spring 2026. The SuperKEKB team, together with the international collaborators and the Belle II collaboration, are working on diagnosing the remaining issues and developing strategies for the next operation period.

Contact:
Maiko Takahashi, maiko.takahashi@desy.de
Carsten Niebuhr, carsten.niebuhr@desy.de
Daniel Pitzl, daniel.pitzl@desy.de
Fabian Becherer, fabian.becherer@desy.de
Anna Luisa Moreira de Carvalho, ana.luisa.carvalho@desy.de
Anselm Baur, anselm.baur@desy.de

Delving into the $|V_{ub}|$ puzzle at Belle

A fresh look at a long-standing discrepancy between complementary measurement techniques

The DESY Belle group has achieved the first determination of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{ub}|$ by simultaneously using exclusive and inclusive measurement techniques, offering a novel perspective on their long-standing discrepancy. The results of the two simultaneous measurements of $|V_{ub}|$ were found to be consistent within the current precision.

The CKM matrix governs the transitions between the three generations of quarks and plays a fundamental role in the Standard Model of particle physics. The matrix element $|V_{ub}|$, which governs transitions of *b* quarks into *u* quarks, can be measured through semileptonic *B*-meson decays, either in exclusive decays (e.g. $B \to \pi l \nu$) or in inclusive decays ($B \to X_u l \nu$) where the final state includes all possible hadrons arising from the hadronisation of the *u* quark from the $b \to u l \nu$ transition. However, results obtained from these two approaches have long shown a significant discrepancy, with their ratio deviating from unity by 3.7 σ. The reason underlying this tension is not understood. New physics explanations are challenging, leading to speculations about the existence of so far unconsidered systematic effects.

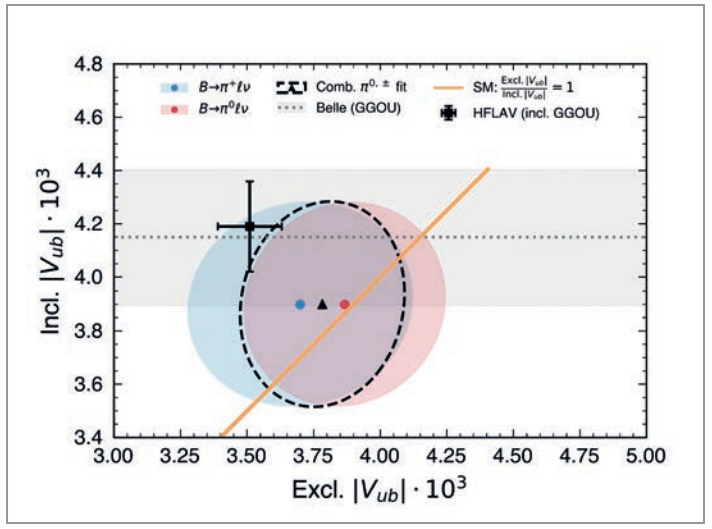


Figure 1

$|V_{ub}|$ values obtained in the simultaneous measurement with the separate exclusive modes of π^{+0} (blue or red) and the combined results (black dashed). The inclusive $|V_{ub}|$ value is based on the decay rate from the GGOU calculation [2]. The values obtained from the previous Belle measurement [3] (grey band) and the world averages from the Heavy Flavor Averaging Group (HFLAV) [4] (black marker) are also shown. The ellipses correspond to 39.3% confidence levels.

DESY researchers and collaborators from the University of Bonn analysed data collected by the Belle experiment at the former KEKB collider at the $\Upsilon(4S)$ resonance, corresponding to an integrated luminosity of 711 fb^{-1}. By fully reconstructing one *B* meson in hadronic decay modes, they were able to study the semileptonic decays of the accompanying *B* meson. Contrary to previous measurements, they performed a simultaneous analysis of both exclusive and inclusive decays within the same experimental analysis framework. They found the results of the exclusive and inclusive measurements to be in agreement: $|V_{ub}^{excl}|$ = (3.78 ± 0.23 (stat) ± 0.16 (syst) ± 0.14 (theo)) x 10^{-3}, $|V_{ub}^{incl}|$ = (3.88 ± 0.20 (stat) ± 0.31 (syst) ± 0.09 (theo)) x 10^{-3}, and their ratio 0.97 ± 0.12 compatible with unity (Fig. 1) [1]. Constraints from lattice quantum chromodynamics and experimental observations for the $B \to \pi l \nu$ form factor were considered in the fits. The averaged exclusive and inclusive $|V_{ub}|$ is (3.84 ± 0.26) x 10^{-3}, which aligns well with (3.64 ± 0.07) x 10^{-3} as obtained from imposing unitarity of the CKM matrix in a global fit.

While the current experimental precision is limited by the size of the data sample, this new simultaneous extraction approach provides a promising path to resolving the long-standing tensions in the measurements of $|V_{ub}|$. Future studies with the successor experiment Belle II, which will collect significantly larger data samples, are expected to further improve in precision and have the potential to settle this long-standing puzzle.

Contact:
Lu Cao, lu.cao@desy.de
Kerstin Tackmann, kerstin.tackmann@desy.de

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Test of lepton flavour universality in τ decays from Belle II

The Standard Model and the τ leptons

DESY researchers working on the Belle II experiment at the SuperKEKB electron–positron collider at KEK in Japan have performed the most precise test of lepton flavour universality in τ-lepton decays from a single measurement. They studied τ-lepton decays involving electrons and muons, taking advantage of the excellent lepton identification capabilities of the Belle II detector. The researchers determined the ratio of the weak coupling constants of muon and electron to be $|g_\mu/g_e|_\tau$ = 0.9974 ± 0.0019. This result enhances the understanding of fundamental particle interactions and further constrains possible extensions of the Standard Model.

SuperKEKB as τ factory

Lepton flavour universality is a fundamental principle of the Standard Model (SM) of particle physics, stating that the interactions of different types of leptons with the *W* weak gauge bosons should be identical when accounting for their mass differences. A recent study by researchers from DESY and HEPHY in Vienna, Austria, tested the flavour universality of the light leptons by analysing τ decays into electrons and muons and measuring the gauge coupling ratio. If lepton flavour universality holds, the g_μ/g_e ratio should be equal to 1. Any deviation could indicate the presence of new physics, such as interactions with undiscovered gauge bosons that couple to the three leptons differently, making searches of violation in lepton flavour universality compelling.

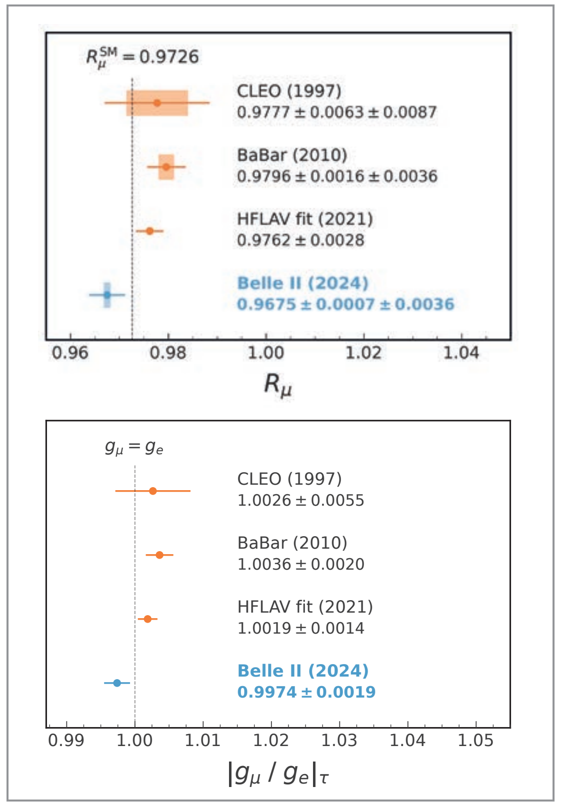

Figure 1

Determinations of R_μ (top) and $|g_\mu/g_e|_\tau$ (bottom) from previous experiments and fit from the Heavy Flavour Averaging Group (HFLAV) compared with the result of Belle II. The shaded areas represent the statistical uncertainties, while the error bars indicate the total uncertainties. The vertical dashed line indicates the SM prediction, including mass effects.

The study was based on approximately 333 million τ-pair events recorded by the Belle II detector. The data set, collected between 2019 and 2022, corresponds to an integrated luminosity of 362 fb^{-1}. The gauge coupling ratio g_μ/g_e was determined from the branching fraction ratio $R_\mu = B(\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu)/B(\tau^- \to e^- \nu_\tau \bar{\nu}_e)$ of the τ decays $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ and $\tau^- \to e^- \nu_\tau \bar{\nu}_e$ after applying a correction factor that accounts for the different lepton masses. The results [1] R_μ = 0.9675 ± 0.0036 and $|g_\mu/g_e|_\tau$ = 0.9974 ± 0.0019 enable the world's most precise test of light lepton flavour universality in τ decays performed by a single experiment, which is consistent with the SM. Interestingly, the slight discrepancy observed in previous measurements has decreased when combined with this result, $|g_\mu/g_e|_\tau$ = 1.0002 ± 0.0011 [2], reinforcing the validity of the SM. While no significant violation of lepton flavour universality was found with the current precision, the search for signs of new physics continues in the ever-evolving landscape of particle physics.

Contact:
Armine Rostomyan, armine.rostomyan@desy.de

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Keeping the beat with plasma accelerators

Mapping energy flows on the microsecond time scale in high-repetition-rate plasma wakefield accelerators

High-energy particle acceleration for particle physics and photon science is dissonant with our commitment to sustainable future goals. To come to a harmonious agreement between the two, accelerators should, among other requirements, be space-efficient. Plasma wakefield acceleration, researched at DESY, is a promising high-gradient technology that could reduce the size of accelerator facilities. However, to prove that it is a viable option for the future, high-repetition-rate operation must be demonstrated in plasma. In other words, plasma accelerators must keep up with the frequencies of conventional superconducting radio frequency (SRF) technology – as is being investigated at DESY's FLASHForward plasma accelerator experiment.

The potential showstoppers – ions

Future high-energy physics colliders are designed to operate with similar conventional (S)RF technology to presently running free-electron lasers, with a frequency of around MHz in burst mode. To illuminate whether plasma accelerators are compatible with the energy-efficient SRF cavities and their MHz bunch trains, the feasibility of accelerating in plasma after a microsecond or similar must be investigated.

When a driving electron bunch creates a wakefield in plasma, it deposits its energy: Some of it is transferred to the trailing accelerated bunch, and the rest stays in the plasma. The nanosecond–microsecond plasma evolution is dominated by ion motion [1, 2]. This motion of ions precludes the energy efficiency and quality preservation of plasma accelerators, necessitating some idle time before the next acceleration event. In 2022, the FLASHForward team measured the recovery time of a plasma accelerator at a specific operation point [3]. It was observed that one could achieve the same acceleration conditions in plasma after waiting for 63 ns for it to recover, thus fundamentally allowing MHz burst operation in plasma.

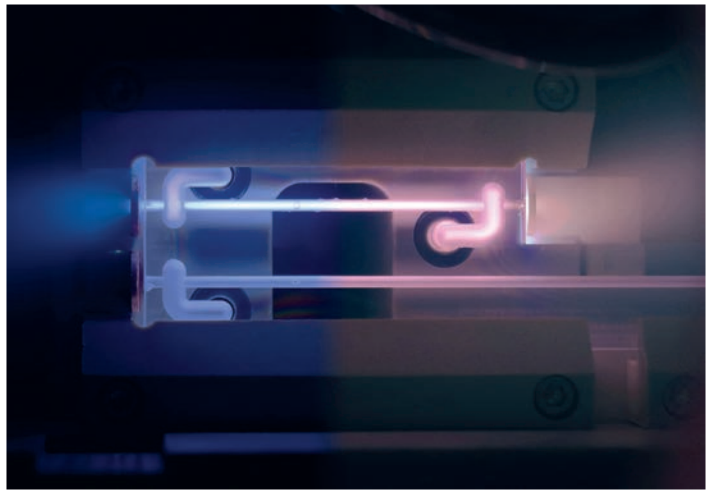

Figure 1
FLASHForward plasma capillary (50 mm, top). On the left-hand side of the image, argon plasma (blue) is operated, and a helium plasma (pink) image is spliced on the right. In this experiment, only argon, doped with 3% hydrogen, and pure hydrogen plasmas were operated.

Enter ionisation

It was experimentally observed in Ref. [2] that such ion motion can also drive a long-lasting ionisation front, where neutral atoms are impact-excited and -ionised by the electrons moving together with the ions. If more neutral atoms were present in the FLASHForward plasma capillary, shown in Fig. 1, such ionisation, lasting on the nanosecond–microsecond time scale, might be observed. This would lead to increased plasma density in the capillary, resulting in different wakefield and acceleration conditions.

To observe such global plasma density changes after the electron beam interaction with the plasma, optical emission spectroscopy (OES) was used at FLASHForward. In OES, the radially averaged plasma density is inferred from the broadening of the hydrogen Balmer-alpha line. In the FLASHForward capillaries, the initial atomic gas density is set by adjusting the flow rate and the buffer pressure of the gas system. Additionally, the initial plasma density at the arrival of the electron beam is set by selecting an electrical discharge timing that allows the plasma density to decay in the capillary to a desired value ("Beam off" data in Fig. 2). By choosing lower ratios of initial plasma density to initial atomic gas density in the capillary (denoted by α in Fig. 2), it was expected that more ion-motion-driven ionisation would be observed. In other words, there would be a higher probability for a neutral atom to be impact-excited and -ionised by a moving ion and electron and to set off near-exponential plasma density growth, as observed in Ref. [2].

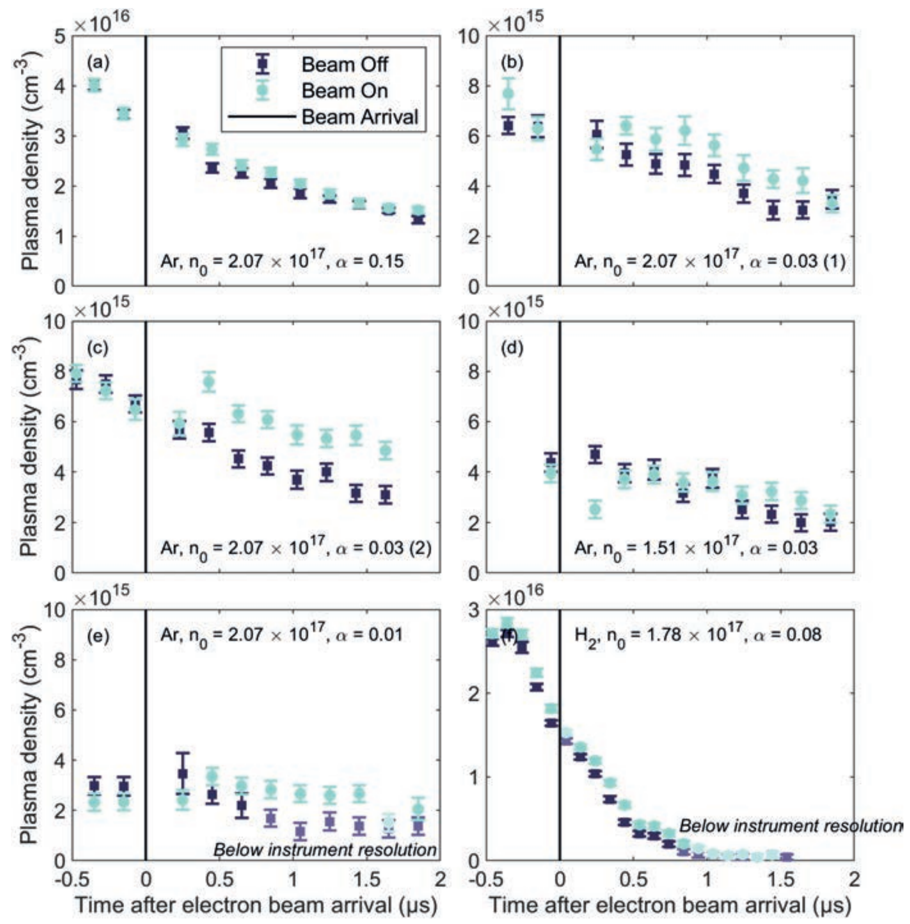

Figure 2
Plasma density with ("Beam on") and without ("Beam off") electron beam interaction with plasma (denoted by the vertical black bar). The ratio of initial plasma density and initial atomic gas density (n_0, in cm^{-3} units) in the capillary is denoted by α.

Indeed, as the initial plasma density was reduced and the initial atomic gas density was kept the same, the plasma density increased correspondingly (panels (a), (b), (c) and (e) in Fig. 2). While (b) and (c) were taken with the same plasma capillary conditions, the electron beam setup was different, potentially resulting in a different amount of deposited energy. For the measurement in panel (d), the initial atomic gas density in the capillary was reduced, resulting in much less additional ionisation and a much later onset. Additionally, the evolution of ion motion was investigated in hydrogen, whose much lighter ion mass could speed up the recovery process (Fig. 2(f)). A slight additional ionisation can still be seen between 300 and 500 ns; it was expected that, by going to even lower initial atomic gas densities, this would be suppressed. This indicates that ion-motion-driven ionisation precludes fast plasma recovery but could be reduced for lower initial atomic gas density in the capillary.

The show must go on

Without fast plasma recovery from ion motion and the additional ionisation, bunches in consecutive beats of conventional SRF frequencies would not be accelerated in temporally uniform plasma conditions. However, this investigation has shown the trend towards ionisation suppression: If the initial atomic gas density in the capillary is low and the initial plasma density is high, plasma may recover as fast as in Ref. [3]. Achieving such a working point would require operating with a gas that allows an electrical discharge of kilovolts to occur at low pressures. Additionally, achieving a high initial plasma density to atomic gas density ratio may be possible by using laser ionisation. Moreover, the ion-motion-driven ionisation effect may not persist if the plasma is replenished with MHz-frequency electric discharges. In general, the lifetime of ion-motion-driven ionisation and its dependencies are unknown; there could be an operation point compatible with MHz frequencies. This will be further explored experimentally and in simulations at FLASHForward.

Contact:
Judita Beinortaitė, judita.beinortaite@desy.de

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Science of the future

Sharpening the science case of future electron–positron colliders

In 2021, the European Committee for Future Accelerators (ECFA) launched a study on a new kind of particle collider called an electron–positron Higgs / Electroweak / Top factory. The study culminated in 2024 with a concluding workshop and a comprehensive final report. This report will be among the key inputs to the ongoing European Strategy for Particle Physics Update, which focuses on identifying the next collider project for CERN after the end of the HL-LHC. DESY scientists have shaped the ECFA study through their coordinating roles and numerous scientific contributions, some of which are summarised here.

The ECFA Higgs factory study

An electron–positron (e^+e^-) collider able to perform precision studies of the Higgs boson was identified as the highest-priority next collider by the last update of the European Strategy for Particle Physics in 2020. Several types of these colliders have been proposed, and the study launched by ECFA in 2021 [1] was charged to foster exchange between the proponents of these projects in the areas of the projects' science case, analytical methods and detectors as well as to trigger research on topics not sufficiently covered. As an integral part of assessing the physics case of future colliders, the reach of the HL-LHC and other current projects was also addressed. Two of the three top-level working groups were co-coordinated by DESY scientists from the FTX group, and many more contributed as conveners or members of subgroups.

In the course of the ECFA study, 14 "focus topics" were identified [2], all of which are of high relevance to planning the future of particle physics, but have not been sufficiently well addressed in previous studies. One of them concerns the development of AI-based algorithms for the identification of hadronic jets originating from strange and anti-strange quarks coming from the decay of either a Higgs or a *Z* boson. One of the most performant algorithms, based on a DeepJetTransformer architecture, was developed under the supervision of a DESY scientist [3]. This algorithm can identify *s*-quark jets with an efficiency of 40% at a *u*/*d*-quark jet misidentification rate of only 10%. With such a performance, it is expected that the forward–backward asymmetry of *s* quarks at the *Z* pole can be measured with a precision of 10^{-5} at the FCC-ee proposed by CERN [4].

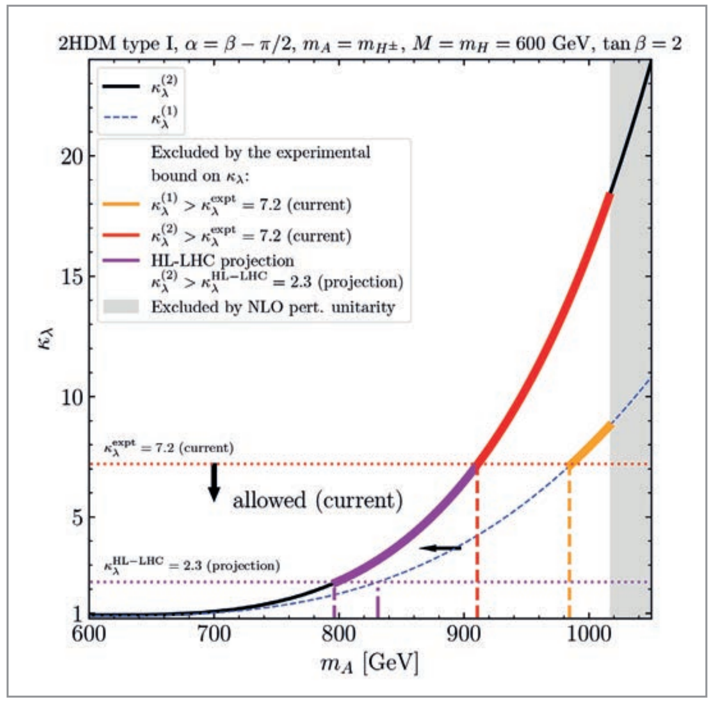

Figure 1

Case study on how measurements of the Higgs self-interaction (κ_λ) can constrain the parameter space of theories that extend the Standard Model of particle physics (here in terms of the mass of an extra Higgs boson m_A in a model with an additional Higgs doublet)

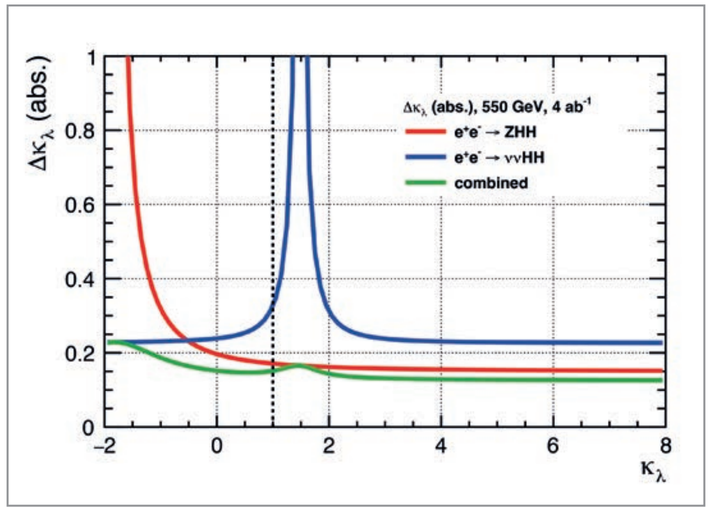

Figure 2

Expected precision on the self-coupling of the Higgs boson as a function of the centre-of-mass energy of a future e^+e^- collider. At an energy of 550 GeV, with an integrated luminosity of 4.4 ab^{-1}, 15% precision can be obtained when combining both production modes.

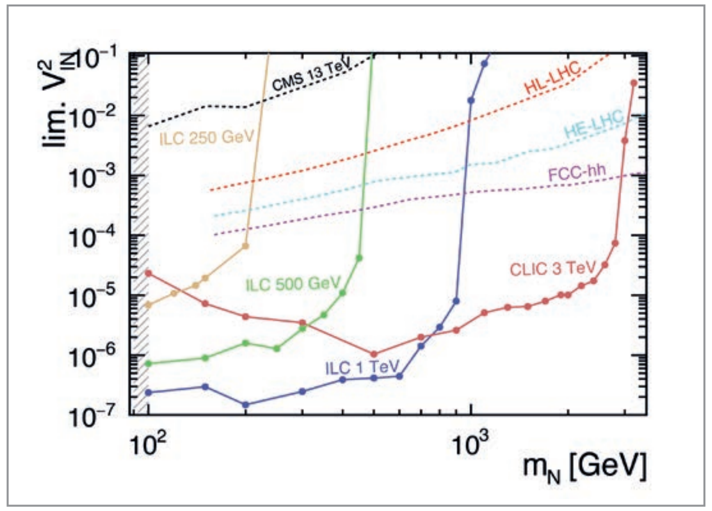

Figure 3

Sensitivity of different current and future colliders in the coupling-vs.-mass plane of a heavy neutral lepton, showing the complementarity of hadron and lepton colliders. Areas above and to the left of the curves can be probed.

The shape of the Higgs potential

Another focus topic addresses the potential of future Higgs factories to measure the self-interaction of the Higgs boson. Currently, the only information about this fundamental property, which is essential to explain how the Higgs boson gives mass to the gauge bosons and fermions, comes from the LHC, and it will still improve considerably with its high-luminosity phase. DESY scientists have studied how HL-LHC measurements will help to constrain theories with extended Higgs sectors [5]. An example is shown in Fig. 1.

Future e^+e^- colliders can provide additional information, either by exploiting quantum loop effects on the Higgs-strahlung process $e^+e^- \to Zh$, or through the much rarer production of two Higgs bosons in one collision event, which gives leading-order access to the self-interaction. In the context of the ECFA study, DESY scientists studied for the first time the prospects of measuring the Higgs self-coupling (λ) as a function of the centre-of-mass energy of a future e^+e^- collider [4]. The result is shown in Fig. 2. In contrast to earlier projections, this new study incorporates the drastically improved quark flavour identification performance based on AI tools like the one discussed above.

Discoveries of new particles?

Since the centre-of-mass energy of a future e^+e^- collider will be much lower than that of the HL-LHC, one is tempted to assume that it cannot discover new particles. However, this is not true at all for particles that have no or only very weak couplings to quarks and gluons but instead prefer to interact with leptons. DESY scientists analysed various such scenarios quantitatively and pointed out several discovery opportunities for e^+e^- colliders as contributions to the ECFA study.

As an example, Fig. 3 illustrates the complementarity of lepton and hadron colliders in the coupling-vs.-mass plane of a heavy neutral lepton [6] – a hypothetical massive sibling of the Standard Model neutrinos: While hadron colliders like the LHC or FCC-hh have sensitivity to large masses at large couplings, even the lowest-energy edition of a future e^+e^- collider (cf. curve labelled "ILC 250 GeV" in Fig. 3) can probe much lower values of the couplings.

The final report of the ECFA study [4] of course contains many more results beyond the selected examples highlighted here. It forms an important basis for the more strategic discussions on the future of particle physics and the choice of the next flagship collider project for CERN, and DESY scientists will continue to make leading contributions to these discussions.

Contact:

Jenny List, jenny.list@desy.de

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LUXE electron detection system goes overseas

...to make quantum electrodynamics strong again

A small team of young researchers from the LUXE collaboration at DESY went to the USA in 2024 to develop and test a novel type of detector for studies of strong-field quantum electrodynamics. This detector is designed to measure the energy spectra of electrons interacting with a high-intensity laser pulse. Following initial test and commissioning measurements, the team could successfully observe the effects of the non-linear Compton process in their detection system. These measurements pave the way for future developments in the LUXE experiment at DESY.

LUXE is a planned experiment at DESY that will collide electrons from the European XFEL X-ray free-electron laser with a high-intensity laser pulse [1, 2]. The main goal is to precisely test the transition from perturbative to non-perturbative quantum electrodynamics (QED). One important detection system that is being developed at DESY is the electron detection system (EDS). To test it in a comparable environment, the DESY team visited the existing strong-field QED experiment E-320 at the FACET-II accelerator at the SLAC National Accelerator Laboratory in Menlo Park, USA [3].

Strong-field QED is an emerging part of quantum electrodynamics that involves strong or high-intensity fields [4]. It is relevant to our fundamental understanding of light–matter and light–light interactions. It finds application in astrophysics, plasma physics, the interaction of charged particles with crystals and future high-energy lepton colliders. The theory can be precisely tested by colliding a high-energy electron beam with a high-intensity laser pulse. The two main effects that can be observed are the non-linear Compton process and non-linear Breit–Wheeler pair production. In the former, an electron scatters off many photons of the laser pulse simultaneously, thereby radiating new, high-energy photons. In the latter, such a high-energy photon interacts with many laser photons, producing an electron–positron pair, the lightest matter–antimatter pair.

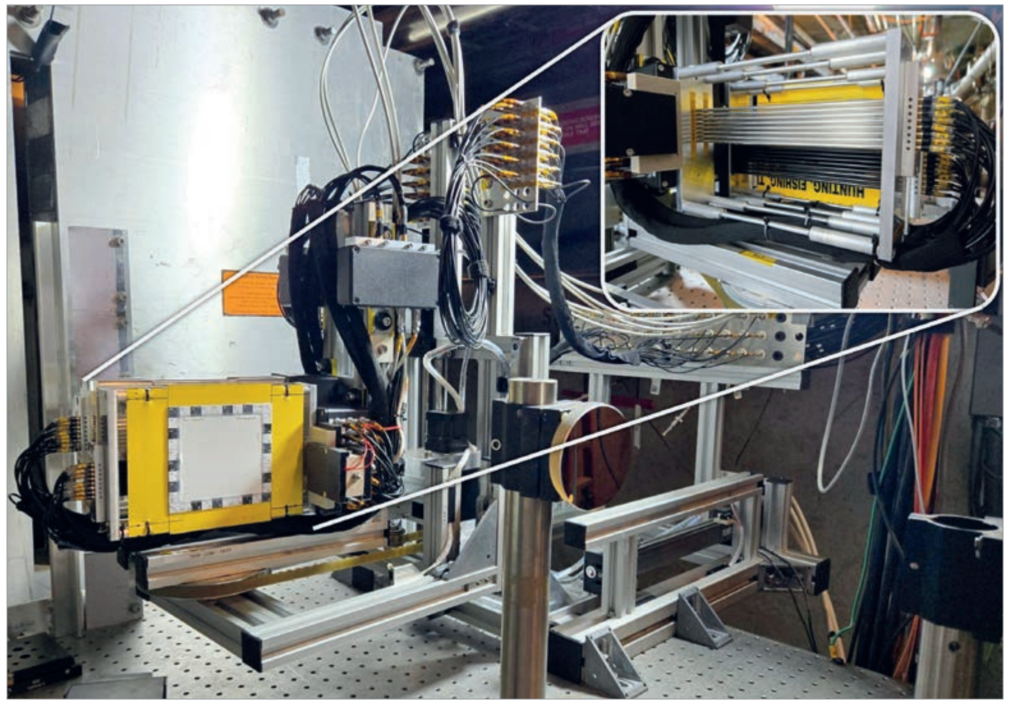

Figure 1
LUXE EDS prototype at the FACET-II accelerator at SLAC. The scintillating screen is surrounded by a yellow frame. The inset shows a view of the Cherenkov straws from the rear side.

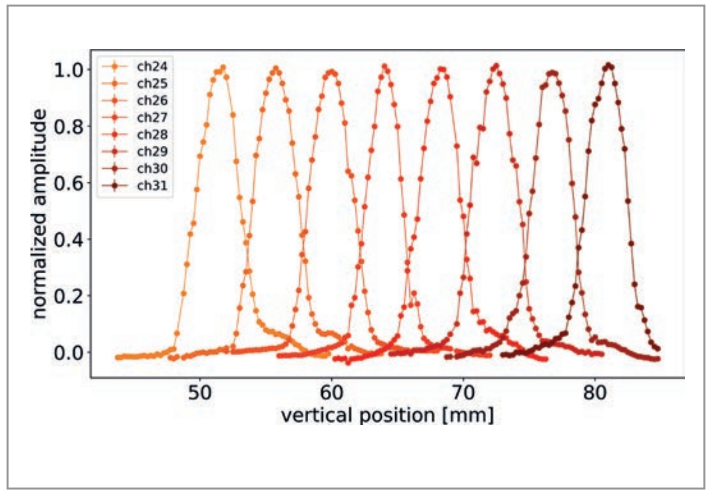

Figure 2
Signal measured with the Cherenkov straws of the EDS as a function of the vertical position, showing the signal in some straws (ch24 – ch31) when the detector is moved through a millimetre-sized beam.

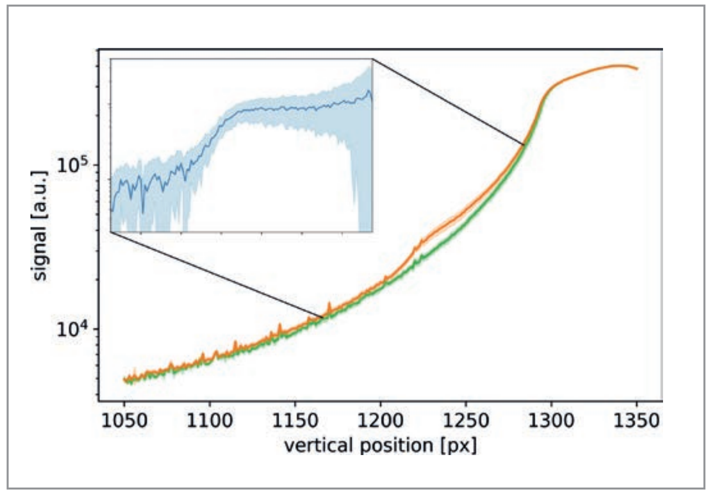

Figure 3
Signal measured with the scintillating screen of the EDS as a function of the vertical position, which is proportional to the particle energy. It shows the signal without electron–laser collisions (green) and with collisions (orange) as well as the difference between the two, which is only sensitive to the contribution from the Compton process (blue).

The main goal of the EDS is to measure the electron energy spectrum originating from the strong-field interaction. After the interaction, a dipole magnet spatially separates the different energies. A position-sensitive charge measurement provides the spectral information. The LUXE EDS is a dual detector system (Fig. 1). Electrons passing the screen (surrounded by the yellow frame in the image) produce light via the scintillation process. This light is detected with a CMOS camera. Behind the screen are straw detectors (shown from the back in the inset). Electrons passing through the straws produce light via the Cherenkov process, which is detected with silicon photomultipliers.

The DESY team made two research visits to SLAC in 2024. The first visit, in May and June, served to get to know the facility, install the detector and perform the first commissioning measurements. During the second research visit, in October and November, the team installed an upgraded detector designed from the lessons learned during the first research visit. New detector components were added, and others were rearranged. The new system was then commissioned and calibrated. Finally, the team could test interesting strong-field physics in a three-night-long experiment session.

The LUXE team commissioned the detection system with a millimetre-sized beam by moving the detector vertically through the beam, which corresponds to the direction of the energy dispersion. Figure 2 shows the normalised amplitude of a few signals in the Cherenkov straw detector. The shape of the signal emerges from the convolution of the beam and the straw profiles.

Collisions of the electron beam and laser pulse were eventually recorded in the final measurement shift. Figure 3 shows an example of such a measurement. When the monoenergetic electron beam collides with the laser, some electrons lose a part of their energy in the non-linear Compton process to produce high-energy photons. This leads to the edge-like structure in the electron spectrum.

The tests of the EDS prototype at the E-320 experiment at SLAC showed that this novel type of detector can measure the electron energy spectrum in the environment of a strong-field QED experiment. The next steps towards an EDS at the LUXE experiment involve a thorough analysis of all the data and a mechanical and electronic upgrade to meet LUXE’s specific needs.

Contact:
Ivo Schulthess, ivo.schulthess@desy.de

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Diffusion and distillation

Generative machine learning tools for collider simulation

Detectors at future colliders promise beautiful highly granular images of particle collisions. To make use of this data, we must be able to simulate a vast number of events with high precision. Generative machine learning (ML) is vital to keep up with the demand. At the same time, the requirements for collider simulation are rather strict – only a carefully chosen architecture will achieve the results with the fidelity needed. In DESY's FTX group, cutting-edge models are refined for this unique task. New ways to replicate the detector response with an inversion of entropy have been explored and distilled to reveal their potential at dramatically reduced computing time compared to standard simulation methods.

Much of life is an attempt to reverse entropy one way or another, which makes it both magical and sensible that teaching an ML model to reverse entropy works well. This is how a diffusion model generates new data. Beginning with a cloud of randomness, the diffusion model incrementally rearranges the points to resemble an example in the training set. The Stable Diffusion model inverts the entropy process to create beautiful images, such as imaginary landscapes, stylised portraits or cats (Fig. 1).

Collider physics heavily relies on very large simulated data sets. Theories often predict changes in the particle interactions that cannot be directly observed. Instead, the observables expected in the detector are simulated from those theoretical predictions. Enough simulation is needed to prevent statistical errors from dominating the final analysis. Many analyses are required, and luminosities are always rising, so a vast amount of simulation is needed. Of all the steps in the simulation chain, detector simulation is the slowest.

Geant4 is the gold standard for detector simulation in particle physics, accurately representing particle interactions in matter. Strongly established and well maintained, Geant4 is trusted by the community. So perhaps unsurprisingly, substituting it with generative ML attracts controversy. However, collider physics has required simulation optimisations for a long time, such as parametrised approximations of energy depositions in the detector or "frozen showers". Compute time is almost always a limiting factor. While such approximations were well understood, they were imprecise and only acceptable in special cases. Using generative ML, fast clones of Geant4 can surpass these approximations, improving analysis results while offering accuracy in a larger part of the parameter space. A more widespread substitution of Geant4 is not only faster but also more sustainable, meeting our scientific goals while reducing our impact on the planet.

Figure 1
Step by step, entropy is removed from the 3D point cloud, creating a cat.

Figure 2
Step by step, entropy is removed from the 4D point cloud, with the points having three spatial dimensions plus energy, creating a properly described photon shower.

Most generative architectures predict a grid of fixed size, representing the detector readout as a 3D image. Readouts are often sparse, so time is wasted simulating empty space. Diffusion models don't need to predict images. The input points can represent hits, rather than pixel values, so that the model only records non-empty space. This is a major advantage, particularly for the high-granularity calorimeters expected in future colliders.

The CaloClouds model was developed to showcase this approach (Fig. 2). As always, there is a catch. To train a diffusion model, you begin with an example of the points in the distribution you want to model. You add noise, a little at a time, creating a sequence between each training example and a cloud of uniform randomness. Then the model learns to remove the noise, again a little at a time, until it can walk all the way back to something that looks like a training example. Many little steps add up to a lot of operations, and the first CaloClouds model was only 20% faster than Geant4 on CPU. CaloClouds could gain some ground with a GPU; however, innovation was needed to become competitive with other generative solutions.

Like distilling vodka, distilling a model compresses it into something more potent. For a diffusion model, this means turning the input cloud to the target in a single step. At the time of writing, DeepSeek has made headlines for being a highly successful distillation of other models. DeepSeek was trained using input and output pairs created by complex models such as ChatGPT. The complex model has already learned good mapping between input and output, which has less noise than the original training data. The heavy lifting of interpolation and extrapolation is already done, and the complex model provides a smooth continuum of examples. With this guidance, the distillation model learns a simpler task, allowing a simpler design.

CaloClouds was distilled to CaloClouds II before DeepSeek had been released, and the strategy was rather unmapped. Further verification tests ensured that the model still reproduced the physics; Fig. 3 showcases basic examples. Additionally, the minimum size of the model was systematically investigated. The outcome was excellent; CaloClouds II is now 46 times faster than Geant4 on CPU and nearly two thousand times faster on GPU. It delivers all the power and flexibility of its predecessor with leading-edge speed. With this major challenge overcome, diffusion models offer ideal fast simulation for future high-granularity calorimeters.

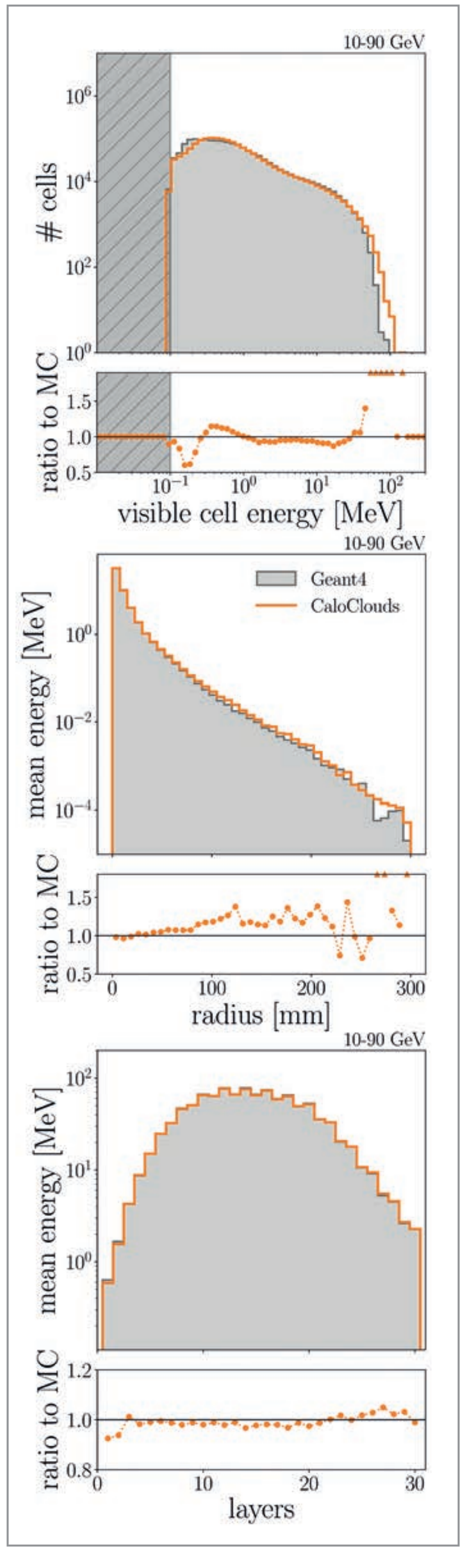

Figure 3
CaloClouds reproducing key physics distributions in photon showers, compared to a Geant4 simulation of the ILD calorimeter.
Top: Distribution of cell energies, showing good replication of the minimum ionising particle (MIP) peak at ~ 0.2 MeV.
Centre: Radial energy distribution of the shower.
Bottom: Distribution of energy in each layer along the path of the shower, showing good replication of the regular interleaving of thin and thick absorbers in the calorimeter.

Contact:

Henry Day-Hall, henry.day-hall@desy.de

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New technologies for on-site particle physics experiments

Quantum sensing, data handling and more

The new generation of particle physics experiments at DESY in Hamburg offers unique physics opportunities, but also poses new technological challenges. These range from data handling to new sensing schemes. This article gives a brief overview of some crucial aspects that are relevant for the search for axions and axion-like particles and the hunt for high-frequency gravitational waves. Our R&D activities have also opened up prospects for developing new commercial gas pressure sensors.

Optical high-precision interferometry

With the completion of the first science campaign of the ALPS II experiment in 2024, the ALPS optics team is pushing the limits of what is possible with precision interferometry. While the world-record optical storage time demonstrated by the ALPS II regeneration cavity is one of the team's most recognised achievements, the optical system is now also breaking new ground in sensing and background suppression. The heterodyne detection system is able to achieve sensitivities down to powers equivalent to a photon every few days, while backgrounds limited by the optical system amount to roughly a photon per hour at present.

Finally, the ALPS optics team is also developing new methods for the characterisation of optical cavities, including using a mode-matched heterodyne sensing scheme to perform *in-situ* measurements of the transmissivity of cavity optics [1]. The future looks promising as the team plans to use these techniques in a number of experiments beyond ALPS II, including searches for the vacuum magnetic birefringence effect, axion dark matter in our galactic halo and high-frequency gravitational waves (GWs).

Quantum sensing

As mentioned above, the sensing of extremely weak signals is of crucial importance for axion and high-frequency GW searches. At DESY, we are developing systems based on transition edge sensors (TES) for 1064 nm light, operated at temperatures below 100 mK. These TES combine extremely low background rates and high efficiencies with an excellent energy resolution of up to 5%. In the past years, the TES system essentially qualified for ALPS II (detection of a 10^{-24} W 1064 nm light signal within 20 days of data taking). Figure 1 shows the installation of a TES module. Meanwhile, new physics cases for the TES have emerged. A prime example is the search for sub-MeV-mass dark matter via its interaction in the TES [2], in collaboration with the Hebrew University of Jerusalem and MIT.

Superconducting radio frequency cavities for GW searches

In this detection concept, an electromagnetic resonator is designed with two nearly degenerate modes, where radio frequency (RF) power is injected into only one mode. An incoming GW can transfer power from the excited mode to the initially unexcited mode. This power transfer is maximised when the GW frequency matches the frequency difference between the two modes, thereby satisfying the resonant condition (heterodyne detection). The power transfer is indirectly driven by the deformation of the cavity walls, leading to mode mixing, which can be detected with appropriate instrumentation.

In collaboration with Fermilab, we conducted studies using a spherical two-cell cavity that was fabricated approximately

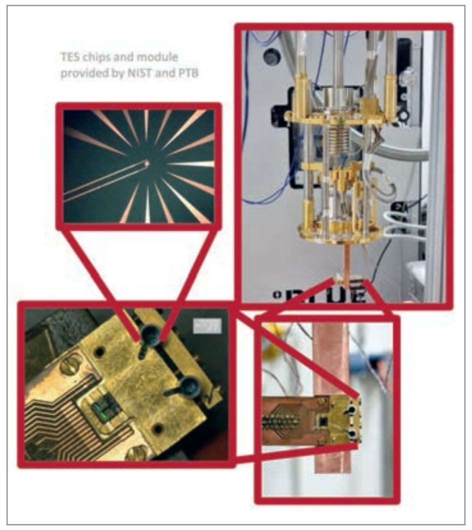

Figure 1

Experimental setup for a TES module (upper left) in one of two dilution refrigerators in the quantum sensing lab in the HERA West hall

20 years ago by the MAGO collaboration. We performed a mechanical survey followed by room-temperature plastic tuning (Fig. 2). To assess the cavity's GW-coupling potential, we carried out both mechanical resonance measurements and electromagnetic property simulations [3]. Based on these findings, we plan to extend these studies to a cryogenic environment. The cavity characterisation not only provides essential insights for the upcoming physics run, but also informs the design and optimisation of next-generation cavities with enhanced sensitivity.

FAIR data management

Efficient and future-oriented data management is an essential prerequisite for the success of new technologies in future on-site experiments. The use of modern metadata catalogues such as SciCat plays a crucial role in this process. These enable the structured collection, management and searchability of experimental data and their metadata. The publication of collected data follows the principles of FAIR (findable, accessible, interoperable, reusable) data to ensure sustainable and open use of research results.

Special attention is given to the collection and provision of both short and long measurement series. For example, at the DESY II Test Beam Facility, short but meaningful measurements are often taken, and their systematic cataloguing significantly facilitates reuse. The data is automatically processed and made available to the respective users in a centralised location. Longer, continuous data collections, such as those arising from experiments like ALPS or BabyIAXO, require especially careful data management to handle the complexity and volume of the data.

Additionally, efficient access management is indispensable, ensuring authorised access to data while simultaneously safeguarding data protection and the integrity of sensitive research data. A holistic data management system promotes knowledge exchange, increases transparency and ultimately accelerates scientific progress. Concrete projects and current work focus on creating metadata schemas to standardise input parameters for real devices and in DESY's Distributed Object Oriented Control System (DOOCS), such as MicroTCA hardware information, analogue-to-digital converter details (manufacturer, serial number, inputs) and more. Based on these schemas, data sets are being generated. ALPS DOOCS measurement data is being supplemented with metadata and stored in HDF5 files. The data is then integrated into SciCat as a metadata catalogue. Metadata schemas are also being prepared for doctoral students in the FTX group. Additionally, responsive web pages are being developed to facilitate data entry and validation through AI tools. Initial efforts are under way to incorporate the DESY test beam into the metadata concept [4].

Optomechanical sensors

Oscillating nanomechanical membranes are thin films

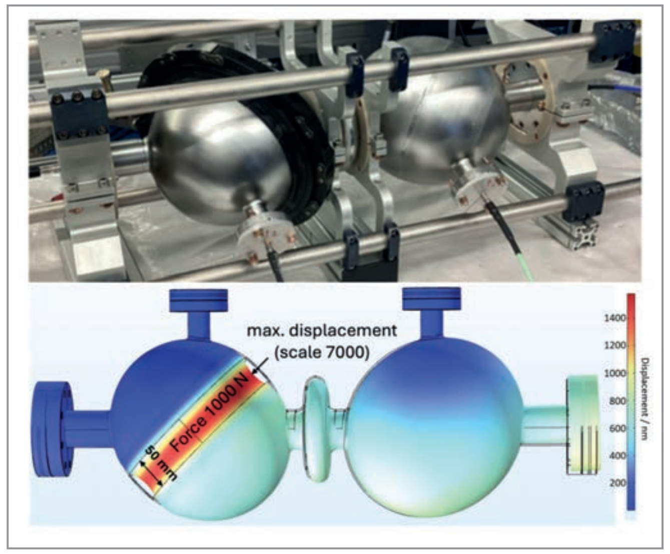

Figure 2

Top: Chain tuner installed around the minor axis of cell 1. Bottom: Deformation study on the RF cell, simulating the effect of the chain tuner. The planned strategy is to squeeze a waist around the minor axis of the ellipsoid.

suspended from a silicon chip, typically made of silicon nitride (Si_3N_4), which offer exceptionally low mechanical and optical loss. When combined with laser interferometric readout, they enable a wide range of applications, from fundamental quantum motion experiments and quantum information transduction to sensing. In the ALPS group, we focus on two main applications of these optomechanical sensors: gas pressure sensing and high-frequency GW detection.

The sensor offers an unprecedented ten-decade measurement range based on the pressure-dependent mechanical quality factor of the membrane [5]. It is compatible with scalable chip-based production, high magnetic fields and heated environments, requires no external calibration and can function as a primary pressure sensor. Placing the membrane near a surface induces periodic gas flow into the gap, increasing damping at low pressure and enabling gas mass measurement for gas identification [6]. As part of the DESY Generator Program, we are taking steps towards commercialising this sensor.

Contact:
Aaron Spector, aaron.spector@desy.de
Axel Lindner, axel.lindner@desy.de
Krisztian Peters, krisztian.peters@desy.de
Sven Karstensen, sven.karstensen@desy.de
Christoph Reinhardt, christoph.reinhardt@desy.de

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First WISP search results

ALPS II and MADMAX deliver science data

Experiments at DESY to search for axions and other bosons have been prepared for many years. In 2024, major milestones were achieved with first science results from ALPS II and MADMAX. Much more is expected for the years to come with increasing sensitivities.

Axions and other WISPs

Worldwide interest in axions and other weakly interacting slim particles (WISPs) as constituents of a dark sector of nature has strongly increased over the past years. A vibrant community is developing, constructing and operating corresponding experiments, so that most promising parameter regions will be probed within the next 15 years or so. Larger-scale projects are being pursued at DESY in Hamburg: The "light-shining-through-a-wall" experiment ALPS II in the tunnel of DESY's former HERA collider started data taking in 2024. The solar helioscope BabyIAXO is nearly ready to start construction, while the dark matter haloscope MADMAX is in the prototyping phase. In 2024, a first science campaign of ALPS II was successfully concluded, and first science results were published by the MADMAX collaboration from dark matter searches with prototype detectors.

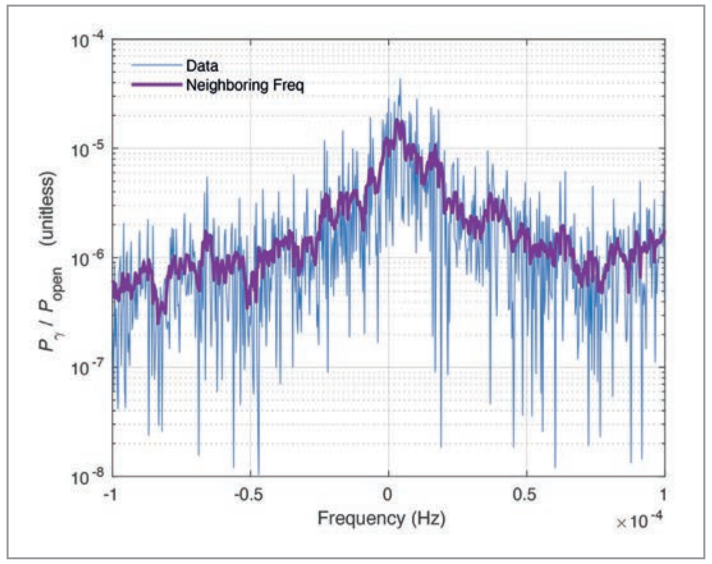

Figure 1
The plot shows the power of the light detected behind the wall as a function of the frequency difference relative to the correct demodulation frequency for the heterodyne sensing. A signal would show up in the single bin at zero. Data and an interpolation to estimate the background due to stray light are plotted.

ALPS II

In early 2024, ALPS II performed its first science campaign, representing the culmination of 12 years of work since the technical design report was published in 2012. More than 1.6 million seconds of data were taken over the course of three months to search for scalar and pseudoscalar WISPs. The optical system played a critical role in enhancing the sensitivity of the experiment, using a high-power laser to inject 30 W of light into the magnet string before the wall and an optical cavity after the wall to amplify the signal field by a factor of 7000 [1].

It is crucial to maintain the coupling of the high-power laser to the optical cavity while also suppressing background signals due to stray light. To check the performance and calibrate the optical system, a shutter in the wall can be opened, allowing a small amount of the laser power to impinge on the cavity. The power of this "open-shutter" calibration signal transmitted to the cavity was on the order of only 10 photons per second (few attowatts). To measure such low intensities as well as even lower powers when the shutter was closed, a heterodyne detection system was used. Measurements over the course of the science campaign showed an average coupling between the laser and the cavity of about 50%. The technical noise limit was found to be roughly a photon every two days. After some learning period, the whole system could be operated much more stably than previously hoped for.

In the first science campaign, the ALPS II sensitivity was limited by spurious stray light passing by the light-tight barrier. This is demonstrated in Fig. 1. A broad excess was observed around the expected frequency difference, which is not expected for a true signal but matches predictions for stray light. While the axion beam or the open shutter signal take a controlled path to the cavity, in which the optical system is able to compensate for any path length changes, the stray light takes an uncontrolled path. After many reflections from the walls of the beam tube, tanks and random components, slight changes in the positions of those reflections will cause a slight doppler shift in the signal and hence a broad bump, as observed.

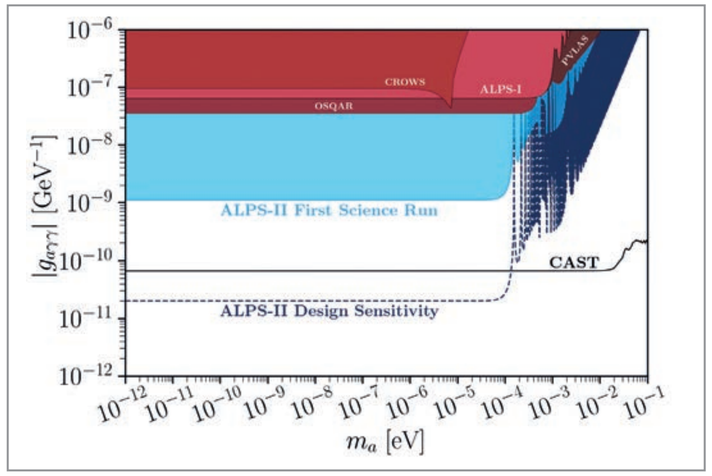

Figure 2
Limits from first ALPS II data for the coupling constant of pseudoscalar axions and axion-like particles compared to previous purely laboratory-based searches and the CERN Axion Solar Telescope (CAST). The dashed line will be reached in 2027.

This stray light intensity of a few 10^{-22} W presently limits the ALPS II sensitivity. While the ALPS II collaboration was not able to claim a discovery from this first science campaign, the results can be used to set new limits on the coupling strength of scalar and pseudoscalar axions to photons of roughly 10^{-9} GeV^{-1}. This goes well beyond the current limits from previous generations of light-shining-through-a-wall experiments by a factor of nearly 30 (Fig. 2). It should be noted that this is a very robust exclusion as it does not depend on any assumptions about the local dark matter density.

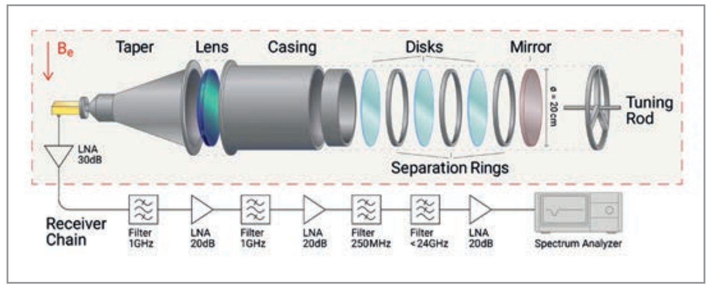

Figure 3
Exploded schematic view of the MADMAX prototype CB200 (200 mm disk diameter) and the receiver chain used for measurements at CERN. See [2] for details.

MADMAX

The MAgnetized Disc and Mirror Axion eXperiment (MADMAX) is dedicated to searching for dark matter in the form of axions and others WISPs. Targeting the 40–400 µeV mass range, MADMAX will explore a region beyond the reach of traditional resonant cavity experiments. This will be achieved using a stack of parallel dielectric discs, which enhance axion-to-photon conversion through resonance. By adjusting the distances between the discs, the resonance frequency and bandwidth can be flexibly tuned, offering significant scanning capabilities. The experiment will operate at cryogenic temperatures to minimise thermal noise and will be housed within a large dipole magnet, which is essential for axion–photon conversion. The year 2024 marked an important milestone for MADMAX, as the first experimental searches for axions (using the MORPURGO magnet at CERN) and dark photons (in the SHELL laboratories of Universität Hamburg) were conducted using different small-scale prototypes (Fig. 3). These efforts successfully explored previously uncharted parameter space (Fig. 4), unfortunately without a dark matter signal yet [2, 3].

With these proofs of concept now validated and a full analysis pipeline developed, upcoming searches will focus on significantly enhancing both sensitivity and mass range. The required progress on the technical front has also been made. One of the key achievements was the successful demonstration of motorised control of dielectric discs under cryogenic conditions and within a high magnetic field, an essential step toward scaling up the experiment [4]. At the same time, the construction of a large cryostat, designed to house future MADMAX prototypes, has nearly been completed, and it is expected to arrive at SHELL in spring 2025.

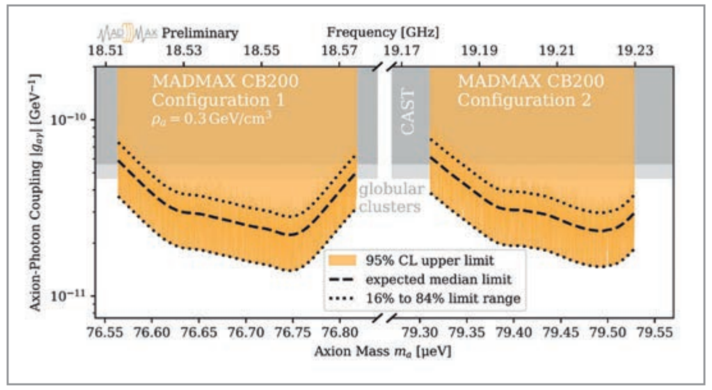

Figure 4
95% CL exclusion limits in 0.9 kHz bins (orange) from the 2024 MADMAX axion search with the CB200 prototype using the MORPURGO magnet at CERN, assuming a local axion DM density of ρ_a = 0.3 GeV cm^{-3}. Limits are compared to the helioscope experiment CAST (dark grey) as well as to globular cluster limits (light grey). See [2] for details.

Contact:
Axel Lindner, axel.lindner@desy.de
Aaron Spector, aaron.spector@desy.de (ALPS II)
Jacob M. Egge, jacob.mathias.egge@desy.de (MADMAX)

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Quantum computing

A novel tool with the potential for unprecedented computing

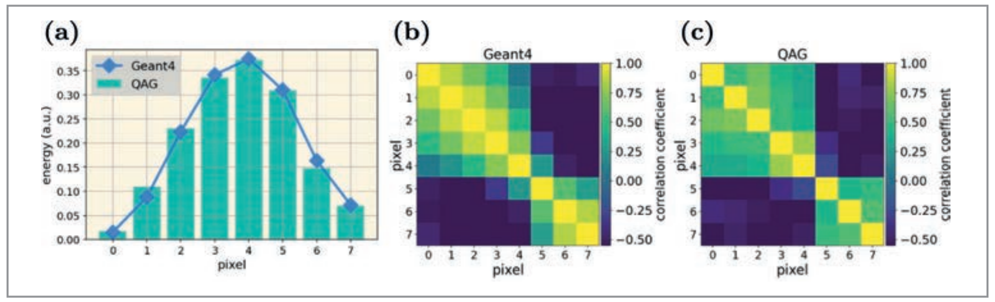

Figure 2

Condensed shower profile simulated with eight qubits (green histogram) and compared to a conventional simulation (blue curve)

Quantum computers utilise controllable quantum systems for performing computational tasks. By exploiting quantum properties, such as superposition and entanglement, they enable the solution of certain complex problems that conventional computers cannot address efficiently. Moreover, quantum systems may offer a more efficient way to represent correlations in experimental data. This makes them a promising tool for applications in theoretical and experimental particle physics, and beyond. With the availability of the first quantum computers, researchers at DESY are exploring the new opportunities these technologies offer for fundamental science.

Quantum technologies at DESY – a new strategic initiative

Quantum physics is at the heart of DESY's research, and quantum technologies open up a large variety of new opportunities for scientific excellence. A task force with members from all DESY research divisions has identified three activity areas: quantum computing, quantum materials and quantum sensing. The initiative DESY.Quantum [1] fills these areas with life in Hamburg and via the Centre for Quantum Technology and Applications (CQTA) [2] in Zeuthen.

QC4HEP working group

CERN, DESY and IBM established a joint working group to use quantum computing for high-energy physics (HEP). The group published a white paper [3] that identifies problems where quantum computing could help overcome current computational challenges. Under the co-leadership of CQTA and with contributions from DESY authors, a range of topics in HEP theory including real-time phenomena, lattice gauge theory and neutrino oscillations were addressed. On the experimental front, promising areas include jet and track reconstruction, the extraction of rare signals, parton showers and detector simulation. Applications also extend to other areas DESY is involved in, such as astroparticle physics observatories (e.g. IceCube) and the search for dark matter particle candidates (e.g. ALPS II).

Figure 1

Karl Jansen (second from right) handed over the strategy paper to Brandenburg's State Secretary Tobias Dünow (centre).

The Centre for Quantum Technology and Applications

CQTA was founded at DESY in Zeuthen in 2021. Led by Karl Jansen, who also holds the European Research Executive Agency (ERA) Chair for Quantum Computing at the Cyprus Institute, CQTA focuses on developing quantum algorithms for problems in fundamental science, health care and life science, as well as for industrial use cases. As an IBM Quantum Innovation Centre, it has access to IBM's latest superconducting quantum hardware, enabling researchers to test their methods on state-of-the art technology.

Scientists at CQTA engage in three main lines of research. First, they investigate how quantum computers can be used to numerically explore gauge theories which, in particular, provide the theoretical description of the Standard Model of particle physics. Gauge theories are inherently challenging and cannot be solved analytically for many relevant cases. Simulations on quantum computers provide a promising route for efficiently tackling them. A team of scientists from CQTA and IBM successfully made first steps to demonstrate this promise by developing a method to simulate scattering on a digital quantum computer [4]. Second, quantum machine learning (QML) as well as its application to various problems, ranging from data analysis from HEP experiments to health care and life science, are investigated. In particular, members of CQTA showed how quantum computers and their potential to represent complex correlations may offer an improvement for biomarker discovery [5]. Third, researchers at CQTA study the use of tensor networks (TNs), a quantum-inspired ansatz for wave functions of quantum many-body systems. Recently, members of CQTA investigated the use of TNs for matrix models, which provide insight into certain quantum field theories and string theories, and demonstrated that they can successfully be explored with TNs [6].

As a prominent centre for quantum technology in the region, CQTA partnered with the Optics and Photonics Cluster Berlin-Brandenburg to establish a network of stakeholders in the field of quantum technologies that includes academia, industry and government agencies. Under the leadership of CQTA, the network developed a roadmap that outlines strategic steps and development opportunities. The strategy document was presented to Brandenburg's State Secretary Tobias Dünow (Fig. 1).

Researchers at CQTA started developing training programmes in 2024 to help industry professionals acquire the knowledge and skills needed in the emerging quantum era. From early 2025, these trainings will be offered to the public. Furthermore, CQTA is dedicated to bridging the gap between research and society. Quantum computing opens new possibilities for music and visual arts, serving as a tool for artistic expression and as a medium to create curiosity. In 2024, members of CQTA engaged in various projects at the interface of science and art, bringing quantum concepts to a wider public in creative and engaging ways.

Quantum computing for LUXE

The LUXE experiment at DESY will probe the strong-field regime of quantum electrodynamics by studying the interactions of the high-energy electron beam delivered by the European XFEL with a high-power laser. These interactions generate up to 10^7 charged particles per laser shot that impinge on a tracking detector, leading to hit densities 100 times larger than those expected at any future collider facility. Such a challenging scenario is exploited to study the feasibility and performance of quantum algorithms to reconstruct the trajectories of the charged particles. Initial studies conducted by DESY scientists proved that quantum algorithms can deliver a performance competitive with that of classical tracking methods. The DESY team recently explored the use of quantum annealers [7] and the extension of the tracking formalism to time-sensitive detectors to develop a four-dimensional track reconstruction algorithm [8]. In both cases, the quantum algorithms were found to provide equal or better efficiency than classical tracking methods.

Simulating a calorimeter for the HL-LHC

After the upgrade, the High-Luminosity LHC will produce up to 200 overlay events in one bunch crossing. This poses a crucial challenge for simulations of the detector, especially the calorimeters that measure the energy of particles produced via shower generation. Generative models have been developed at DESY in cooperation with the CERN Quantum Technology Initiative (QTI) using QML. For small prototypes, the showers are condensed down to eight channels (Fig. 2). The quantum prototypes are a successful proof of principle. They are robust against the noise in present quantum computers because the neural net can learn and compensate for it. In addition, the models seem to be able to describe complex and highly correlated data with fewer parameters [9]. Figure 2 displays the accurate reproduction of the signals in the condensed profile via QML compared to classical computations. The prototypes are currently being scaled up and are used to benchmark various quantum computer platforms. Special funding from the City of Hamburg enables the exploration of ion trap quantum computers in cooperation with the manufacturer and a software company.

Contact:

Kerstin Borras, kerstin.borras@desy.de
Karl Jansen, karl.jansen@desy.de
Stefan Kühn, stefan.kuehn@desy.de
Federico Meloni, federico.meloni@desy.de

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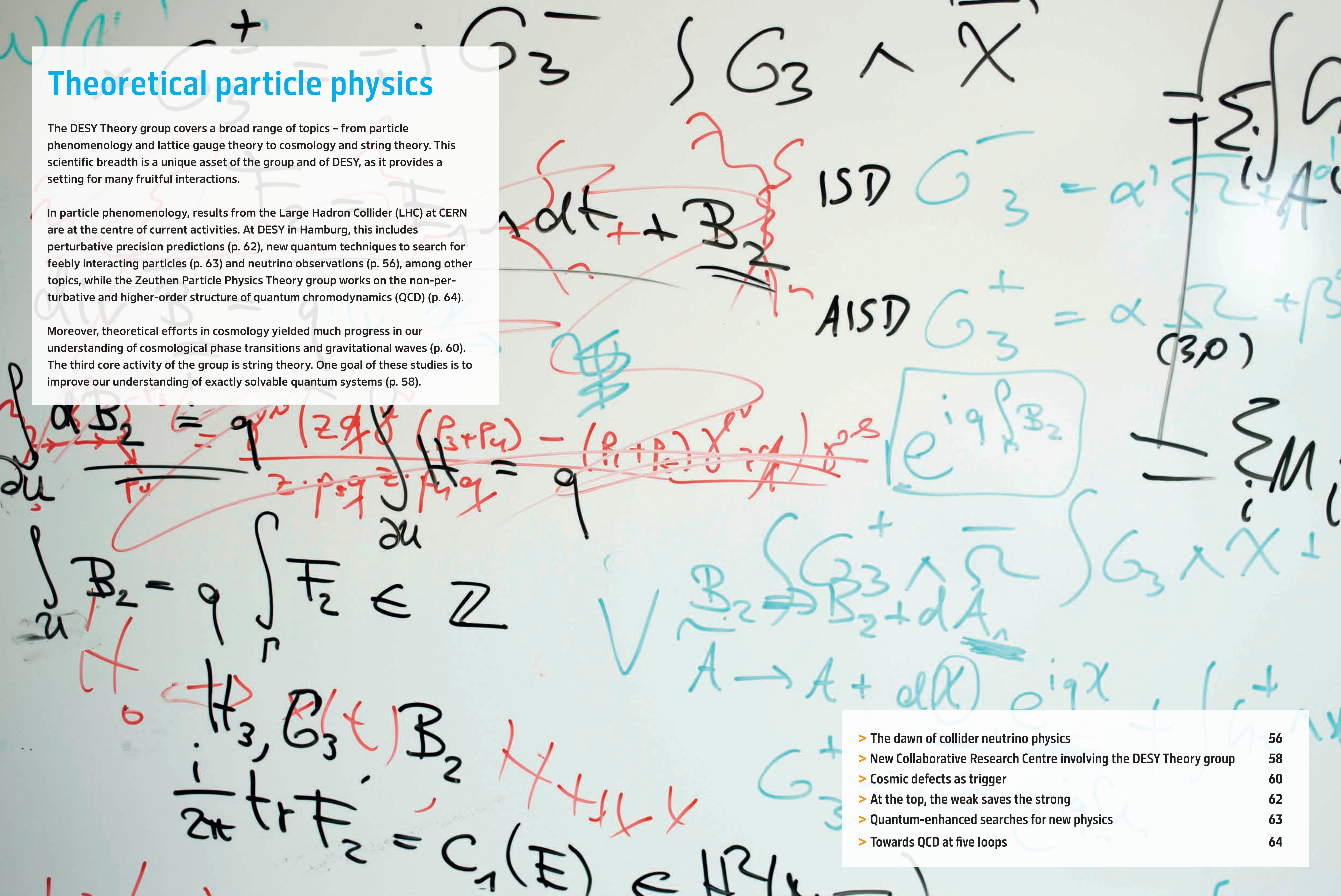

Theoretical particle physics

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. At DESY in Hamburg, this includes perturbative precision predictions (p. 62), new quantum techniques to search for feebly interacting particles (p. 63) and neutrino observations (p. 56), among other topics, while the Zeuthen Particle Physics Theory group works on the non-perturbative and higher-order structure of quantum chromodynamics (QCD) (p. 64).

Moreover, theoretical efforts in cosmology yielded much progress in our understanding of cosmological phase transitions and gravitational waves (p. 60). 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. 58).

The dawn of collider neutrino physics

Probing neutrinos at unprecedented energies

The LHC is not only the most powerful collider built thus far, but also the source of the most energetic neutrinos ever produced by humankind. After nearly 15 years of LHC operation, these neutrinos have been observed for the first time by the FASER experiment. This breakthrough marks the dawn of a new field: collider neutrino physics. Members of the DESY Theory group have played a crucial role in this endeavour and are leading the efforts to understand the opportunities this new field offers to advance neutrino physics, constrain the strong interaction in uncharted kinematic regimes, provide critical input to astroparticle physics and search for phenomena predicted by scenarios of physics beyond the Standard Model.

The LHC as neutrino source

The LHC at CERN is the most powerful particle collider built thus far, colliding counter-rotating beams of protons at multi-TeV energies. Its primary goal is to study known heavy particles, such as the Higgs boson, and to search for other heavy particles predicted by models of new physics, like those arising from supersymmetry. The main detectors, such as ATLAS and CMS, were optimised to capture such signals.

Already during the early planning stages in the 1980s, it was recognised that the LHC also produces a large number of neutrinos. Indeed, at each interaction point, the LHC generates an intense and strongly collimated beam of high-energy neutrinos in the forward region, i.e. along the direction of the colliding proton beams. However, the main LHC detectors do not cover this region and are therefore blind to this neutrino signal.

While the LHC tunnel eventually curves away, the neutrinos continue to propagate straight along the beam axis. As illustrated in the left panel of Fig. 1, roughly 480 m downstream of the ATLAS experiment, this beam axis intersects the existing tunnels that previously housed the injectors of the Large Electron–Positron (LEP) collider, but which have remained unused during the LHC era. This location provides a unique opportunity to access the beam collision axis and exploit the neutrino beam.

First detection of collider neutrinos at FASER

This opportunity has first been exploited by the FASER experiment, which began operation at the start of LHC Run 3 in 2022. FASER consists of two main components. Positioned at the front is the dedicated FASERν neutrino detector, comprising a tungsten target interleaved with emulsion films that enable the precise reconstruction of neutrino interactions. Located behind is the electronic detector, consisting of a few-metre-long magnetised tracking spectrometer and a calorimeter.

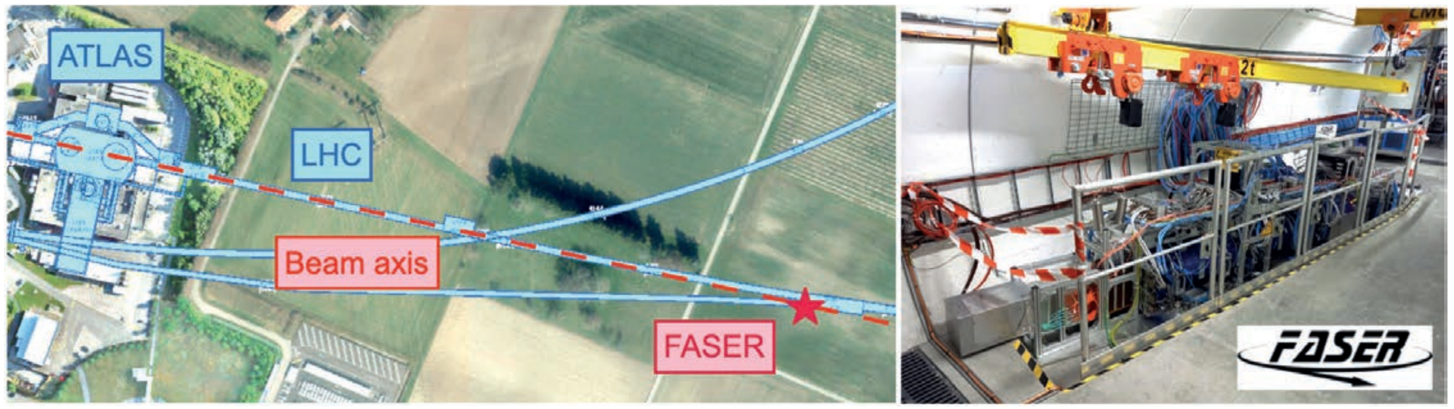

Figure 1

Left: The FASER experiment is located along the beam axis, about 480 m downstream downstream of the ATLAS interaction point. Right: Photo of FASER.

In March 2023, the FASER collaboration announced the first observation of neutrinos at the LHC [1]. This analysis relied solely on the electronic detector components to search for charged-current muon neutrino interactions via the appearance of an energetic muon. A total of 153 events were observed in the signal region, corresponding to a significance for muon neutrino detection of more than 15 σ.

In March 2024, the FASER collaboration released the first results based on a small subset of data collected by the FASERν emulsion detector [2]. After being removed from the FASERν detector, the emulsion films were developed, scanned and digitised, tracks were reconstructed and neutrino interactions were identified. Four electron-neutrino-like events were selected, in agreement with expectations, corresponding to a statistical significance of 5.2 σ. An example electron neutrino event is shown in Fig. 2.

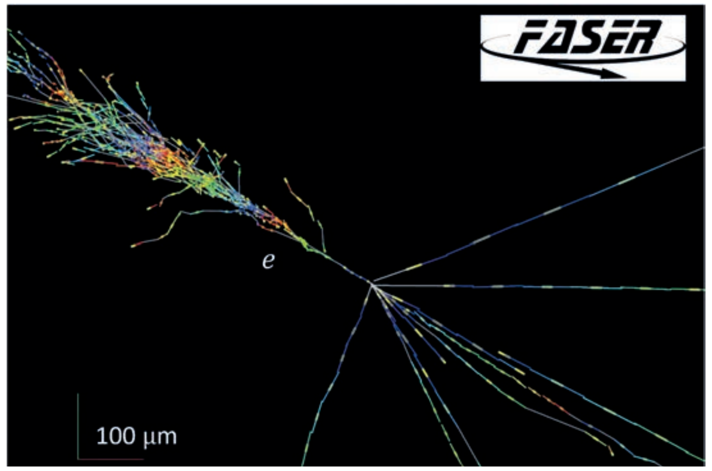

Figure 2

Observed electron neutrino candidate in FASERν

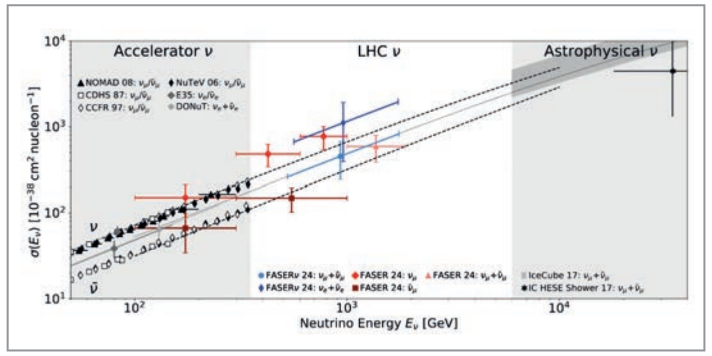

Figure 3

Measurements of the charged-current neutrino cross section as a function of the neutrino energy

A new era of collider neutrino physics

The first observation of neutrinos at the LHC marks the dawn of a new field of collider neutrino physics. While only a few hundred neutrinos have been detected so far, FASERν is projected to record around 10 000 neutrinos by the end of LHC Run 3. Upgraded detectors have the potential to collect significantly larger samples. Researchers from the DESY Theory group have played a leading role in developing this collider neutrino programme and understanding the associated physics opportunities.

The collider neutrino programme will enable precision measurements of neutrino interactions at the highest human-made energies. The first observations have already been used to constrain the neutrino cross section at previously unconstrained TeV energies (Fig. 3). More precise measurements will enable differential cross section studies to probe the proton structure, test lepton flavour universality and search for physics beyond the Standard Model.

Collider neutrinos originate from the decay of charged pions, kaons and charm mesons. Since the production of these particles at the LHC energies has not been measured before in the forward region, collider neutrino flux measurements provide a novel way to probe and constrain forward hadron production. This offers unique insights into the strong interaction in previously inaccessible kinematic regions, allowing researchers to constrain the proton structure at ultralow momentum fractions and to search for signs of gluon saturation.

Additionally, these measurements will provide crucial input for astroparticle physics, where they will shed light on the cosmic-ray muon puzzle – a long-standing discrepancy between measured and predicted muon counts in high-energy cosmic-ray air showers – and on the prompt atmospheric neutrino flux, which arises from charmed hadron decays in cosmic-ray collisions.

Contact:

Felix Kling, felix.kling@desy.de

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New Collaborative Research Centre involving the DESY Theory group

Connecting mathematics to quantum field theory and string theory

The Collaborative Research Centre CRC 1624 "Higher structures, moduli spaces and integrability" [1], which was launched in April 2024, is an interdisciplinary joint venture of the Faculties of Mathematics and Physics of Universität Hamburg with the DESY Theory group. It is funded by the German Research Foundation (DFG) and provides funding in particular for three postdocs and three PhD students. This article explains some of the basic questions that motivate us to develop completely new mathematical instruments for the theoretical challenges posed by the fundamental theories of nature. These tools will enable us to understand new aspects and new regimes of the fundamental interactions that cannot be computed with traditional Feynman diagram techniques.

Motivation

It is quite possible that we already know the most important basic principles and some of the main equations governing the fundamental theories of nature. But even well-established theories, such as the Standard Model, are poorly understood in many regimes where traditional computational methods based on Feynman diagrams fail. And to see whether promising candidates for theories of quantum gravity, such as string theory, can explain the observed universe, we will need completely new mathematical tools to extract the relevant predictions.

What are good observables in physical theories?

We are used to observables, such as field strengths, that can be measured in small regions, often idealised as points. In the past few years, however, we have learned that it may be very useful to consider extended observables that can be localised along curves or surfaces to describe the fundamental theories of nature (Fig. 1).

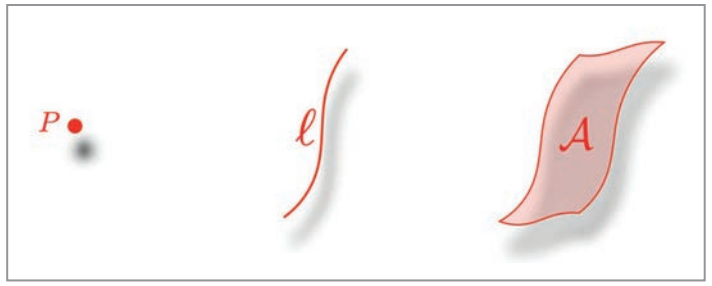

Figure 1

Observables can have supports of different dimensions.

A good example is Wilson lines. They can serve as a probe for a phenomenon called confinement, which refers to the fact that the strong interactions between quarks will never allow us to break bound states of quarks up into a collection of free particles. More generally, a lot of the physics is encoded in the dependence of the observed quantities on the geometry of the support of the observables. The resulting interplay between geometry and physics requires new mathematics, known as higher category theory. The higher structures encoded in the interplay between observables of varying dimensions represent an important area of research in our CRC.

How do fields encode the physical information?

Even the classical theory of electric fields often uses quantities that do not have a direct physical meaning, such as the electrostatic potential. As the electric field is the rate of change of the potential, modifying the potential by adding a constant will not change the electric field (Fig. 2).

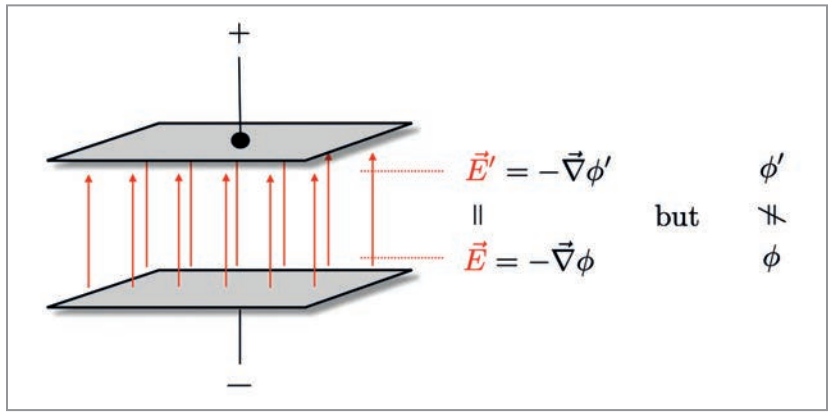

Figure 2

Different potentials may describe the same electric field.

All promising candidates for fundamental theories use similar auxiliary quantities. It is then crucial to understand which changes of the auxiliary quantities leave the physical content unchanged. Such changes are known as gauge transformations, and theories that are formulated using gauge transformations are called gauge theories.

The known fundamental theories of nature are gauge theories. To understand the predictions made by such theories, one needs powerful mathematical tools to classify all possible gauge transformations. Quantities that are unchanged under all gauge transformations reflect the physical content of the theory, but may be hard to compute in practice. A way out is provided by the concept of moduli spaces, which can describe the physically relevant quantities in geometric terms. We need new mathematics to make the geometry of moduli spaces computable.

How to solve the basic equations?

The basic equations of nature are non-linear. This implies that small changes of the initial conditions can get amplified very quickly, rapidly making numerical or other approximate solutions unreliable. To understand some of the most important effects predicted by such theories, it may help if one can find possibly idealised situations where only a part of the complicated interactions is relevant and where one has powerful tools for computing the non-linear effects.

A large family of theories where this is the case is known as integrable models. Such models can be solved exactly. Some spectacular developments of the past years have revealed that the solutions of integrable models can teach us a lot about the physics of quantum field theories that resemble the Standard Model in many ways. It has, for example, been suspected for a long time that such theories exhibit phenomena called dualities: Large "lumps" of elementary particles bound together by strong forces may behave like weakly coupled elementary particles of another type. In some idealised situations, it has been found that integrable models can allow us to analyse the mechanisms behind such dualities in detail. A part of our goals is to generalise these techniques to more realistic situations.

Contact:
Jörg Teschner, joerg.teschner@desy.de

Reference:

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Cosmic defects as trigger

Novel dynamics for phase transitions in the early universe

Cosmological phase transitions (PTs) are spectacular events that took place in the first instants after the big bang, involving the physics of matter under the most extreme conditions. New results from the DESY Cosmology group show that, much like PTs in everyday life initiate and spread out from impurities, the nucleation of bubbles in the early universe can be catalysed by highly energetic relics resulting from the breakdown of new fundamental symmetries, known as topological defects. This non-trivial interplay between bubbles and defects gives rise to novel dynamics with largely unexplored implications for the emission of gravitational waves (GWs) and other whispers from the cosmos.

Primordial plasma

According to the standard big bang picture, our universe started off hot and dense in a state of matter that was very different from what we observe today. As the temperature decreased while the universe expanded, such "exotic" phases became less and less favourable, and the primordial plasma underwent a series of PTs that ultimately led to the universe as we know it (see Fig. 1 for a schematic representation).

As these dynamics took place at temperatures that can be much higher than the energy reach of colliders and other terrestrial experiments, cosmologists and particle physicists at DESY study PTs as a unique opportunity to test our current understanding of fundamental interactions and to address the deepest mysteries of our universe, such as the origin of its matter–antimatter asymmetry (baryogenesis), which could in fact arise from one such dramatic event.

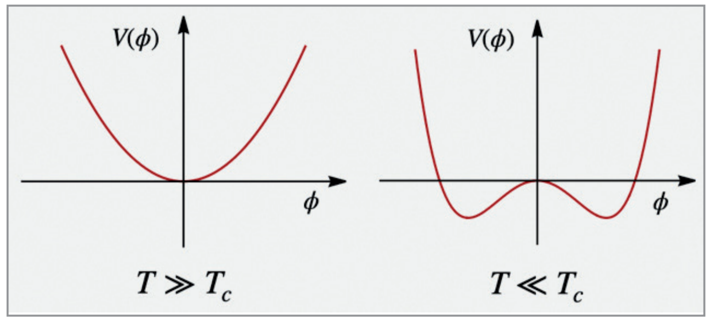

Figure 1

Effective potential at high (left) and low (right) temperatures, signalling a phase transition from the origin to either minimum at non-zero field value

Moreover, the energy suddenly released in the primordial plasma during a first-order PT through the nucleation and expansion of bubbles could be large enough to generate a background of GWs that should be detectable at current and future experiments, such as the space interferometer LISA. This background would contain invaluable information on the physics of its source, offering a glimpse at the most violent events in the history of the universe.

Topological defects

Another fascinating phenomenon that can take place in the early universe is the formation of topological defects. This occurs for systems containing a set of equivalent but physically distinct ground states related by symmetry transformations. In every region of space, only one among the possible states is ultimately selected, leading to spontaneous symmetry breaking, and uncorrelated patches will in general be marked by different outcomes. At the boundary where such regions merge, the system will be trapped in a high-energy configuration that interpolates between these different states.

Such configurations are known as topological defects, and they are stable despite their large energy density due to the underlying symmetry of the ground states. This implies that defects that formed in the very early universe can be extremely long-lived and thus affect the physics of processes taking place at much later times.

While the symmetry-breaking pattern mediated by the Standard Model (SM) Higgs boson discovered in 2012 does not lead to the formation of stable defects, several motivated extensions of the SM contain new symmetries and new "Higgs fields" that do support such configurations.

Among the most relevant examples are two-dimensional surfaces known as domain walls as well as line-like defects called cosmic strings or vortices. The former are often associated with models of baryogenesis, while strings are predicted by the quantum chromodynamics (QCD) axion solution to the strong CP problem, whose possible, groundbreaking discovery drives a large experimental effort at DESY.

Seeded electroweak phase transition

While the universe appears homogenous at large scales, the presence of topological defects at early times can break the isotropy of space and induce local variations in the energy density. In extensions of the SM, defects surviving until the time of the electroweak PT can act as impurities, or seeds, enhancing the probability for bubble nucleation in their vicinity.

These catalysed processes turn out to be exponentially faster than homogenous nucleation, which could still occur far from the defects, thus dictating the way the PT proceeds. This conclusion was reached in a series of papers involving researchers at DESY as well as international collaborations [1–3], by determining the detailed shape of the bubbles nucleated along the defects (see Fig. 2 for the case of QCD axion strings and [2] for domain wall seeds) as well as the corresponding nucleation rate.

A seeded PT is special not only for the shape of the nucleated bubbles, but also in terms of their size at collision, which is set by the distance between the seeding defects. Such dynamics were simulated for the first time with the hydrodynamical code developed in the DESY Cosmology group in [3], leading to a novel GW spectrum from a first-order electroweak PT that depends on the number density of the defects (Fig. 3).

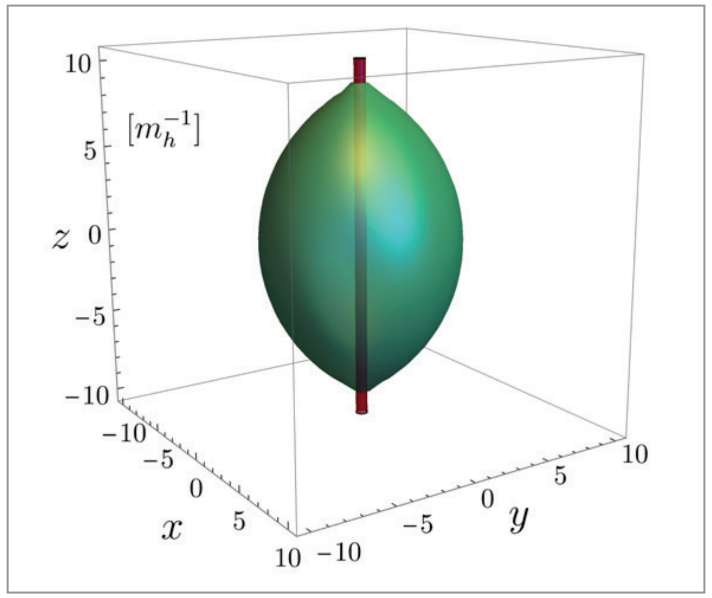

Figure 2

Nucleation of an electroweak bubble along a QCD axion string from [1], with a shape resembling a prolate ellipsoid

This work points towards novel processes in the early universe that actually resemble the familiar dynamics of PTs in our everyday life, paving the way for future investigations of their implications for GWs and fundamental physics.

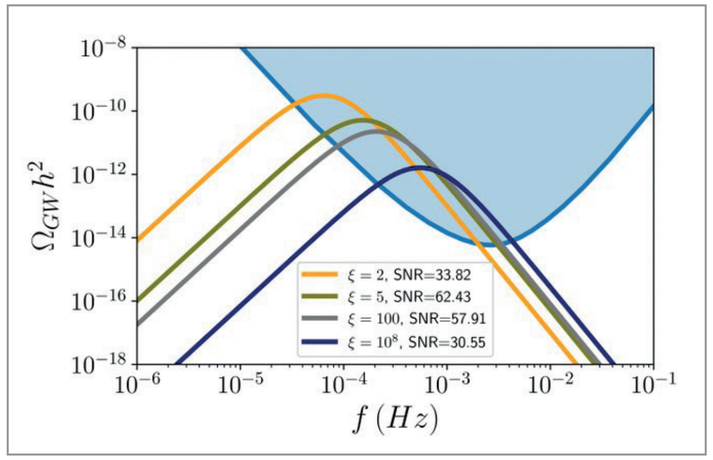

Figure 3

GW spectrum from a domain-wall-seeded electroweak phase transition for different domain wall number densities, overlaid with the LISA sensitivity band from [2]

Contact:

Simone Blasi, simone.blasi@desy.de

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At the top, the weak saves the strong

A new approach for measuring the top-quark mass

A precise determination of the top-quark mass is one of the prime goals of the LHC. While the masses of the Higgs, *Z* and *W* electroweak bosons have been measured within tens of MeVs, a sub-percent-level top-mass measurement has remained a notorious longstanding problem. The top quark experiences strong interactions, a short-range force whose non-perturbative confining nature at low energies makes achieving precise theoretical predictions challenging. A new Young Investigator Group (YIG) at DESY will develop new theoretical tools and strategies that hold the promise to finally resolve the top-mass problem while bringing new advancements in the field of precision collider measurements at large.

The strongly interacting top quark is accompanied by a messy haze of quarks and gluons that complicate experimental measurements and theoretical predictions alike. On the other hand, the electroweak interactions of the top quark result in a clean decay chain involving an intermediate *W* boson. The YIG will adopt a unique approach of measuring "energy-weighted angular correlations" in the final particles resulting from these decays [1]. Such correlations can be robustly measured at the LHC while being amenable to precise field-theoretic predictions.

The top quark and its daughter *W* imprint their electroweak decays as enhancements in these correlations at characteristic angles $\zeta_t \sim m_t^2 / p_T^2$ and $\zeta_W \sim m_W^2 / p_T^2$, yielding a direct relation of the top mass m_t in terms of the much more precisely known *W* mass m_W, with the transverse momentum p_T being a shared energy scale that drops out (Fig. 1).

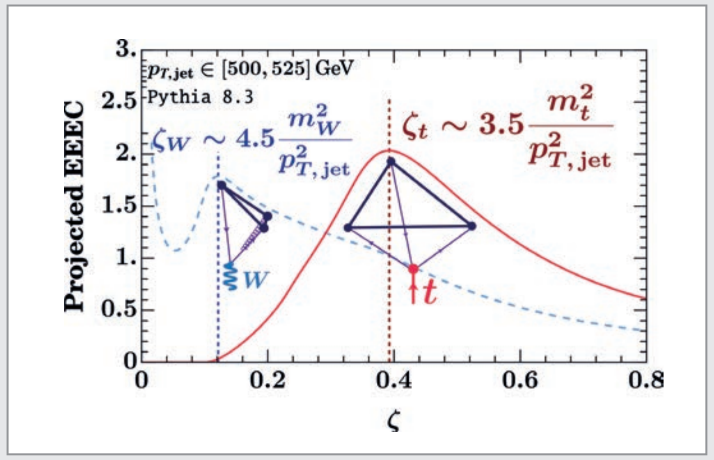

Figure 1
The imprint of the three-body top-quark and associated two-body *W*-boson decay in three-point energy correlations measured on boosted top-quark jets [1]. The two highly correlated peak locations enable a precise determination of m_t from the ζ_t / ζ_W ratio.

To achieve precise predictions, it is crucial to describe the effects of hadronisation, the non-perturbative process by which quarks and gluons at the end of the decay chain bind into hadrons. Existing measurements of m_t suffer from conceptual uncertainties that stem from modelling this process. By exploiting state-of-the-art tools of effective theories of quantum chromodynamics (QCD), the YIG will advance a new data-driven approach to capture the impact of hadronisation through a small set of non-perturbative functions and constants that can be fit from the data. This approach, if successful, will impact all kinds of precision collider QCD measurements.

ERC Grant
"TOMPASS – A new paradigm for high-precision top mass and jet substructure measurements at the LHC"

Contact:
Aditya Pathak, aditya.pathak@desy.de

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Quantum-enhanced searches for new physics

Particle physics beyond the Standard Model between high energy and high precision

Light, feebly interacting particles, such as well-motivated dark matter candidates, can escape detection at high-energy colliders. Thanks to their unparalleled precision, quantum sensors provide a complementary search window for light dark matter and gravitational waves. A new joint professorship in the DESY Theory group with Leibniz University Hannover will explore novel detection possibilities through tiny changes in the rates of atomic and nuclear clocks, with atom interferometers and in cavities. The research will also include the complementarity of tests at low and high energy, e.g. to determine viable explanations for the matter–antimatter asymmetry of the universe.

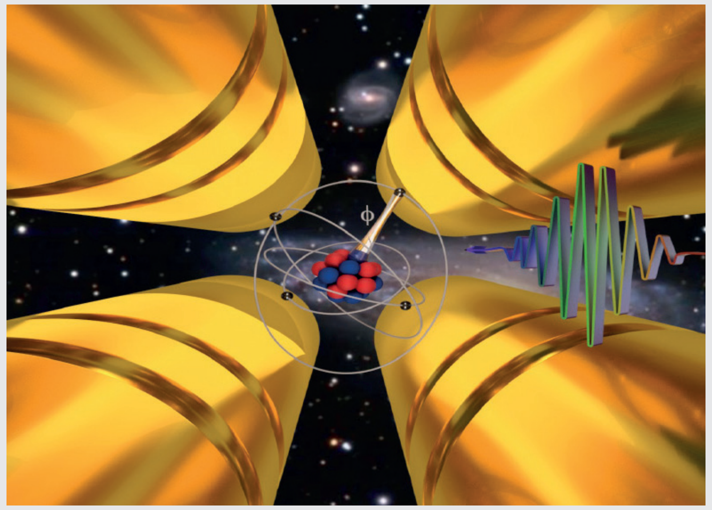

Figure 1
Probing new physics (here a new boson as a mediator between visible and dark matter) via optical atomic clock transitions. From a collaboration with Aarhus University.

Understanding the properties of dark matter (DM) and the origin of the observed baryon asymmetry of the universe are among the main motivations to search for new particles and interactions. New particles interacting with electrons and the nucleus can shift the energy levels in atoms, ions and nuclei and therefore change the corresponding transition frequencies. To make use of the remarkable relative precision of 1 in 10^{18} achieved in measured transition frequencies between electronic levels in optical atomic clocks, while theory predictions are far less precise, the new group will develop data-driven approaches to reduce uncertainties that compete with a possible signal. Beyond the method of frequency comparisons in different isotopes [1], the group will also investigate the implications of time-resolved frequency measurements of optical atomic clocks and the prospects of the thorium nuclear clock, which has an up to 10^4 times increased sensitivity and allows for direct tests of DM couplings to quarks and gluons [2]. In collaboration with experimentalists at DESY and in Hannover, new searches for DM and gravitational waves with cavities and atom interferometers will furthermore be developed.

The aim of maximising detection prospects and the interpretation of the precise data by employing quantum techniques, such as squeezing, entanglement and quantum information, contributes to the Helmholtz Quantum initiative [3].

The new Helmholtz-funded team will complement its results at low energy with high-energy tests at the LHC and at future colliders with a focus on the Higgs boson as a window to the baryon asymmetry and dark matter.

Contact:
Elina Fuchs, elina.fuchs@desy.de

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Towards QCD at five loops

Can we do genuine five-loop calculations?

Much progress has been made in the field of multiloop calculations in quantum chromodynamics (QCD). This article gives a glimpse of what is needed to perform the next steps and overcome arising challenges.

A cursory inspection of publications over the last two decades suggests that the first five-loop QCD calculation was completed as early as 2005, with more five-loop QCD results coming out over the following years. However, a second look reveals that almost all of these works use techniques such as asymptotic expansion or the R* operation to reduce the number of loops to at most four. The only exception is a series of works that introduces an unphysical auxiliary mass, which means that the theory is arguably no longer QCD. It can therefore be argued that there are no genuine five-loop QCD results to date.

What could we hope to learn from a five-loop QCD calculation? The works mentioned above give us a first idea about the type of quantities that should be within reach soon. Order α_s^5 corrections to the Adler function and to total hadronic decay widths, e.g. of the τ or of the Z boson, are in principle desirable for determinations of the strong coupling. However, in general better data will be needed for a significant increase in precision. Next, the energy dependence of the strong coupling and the quark masses could be determined to formally six-loop order. This would include decoupling of heavy flavours at five loops. Another example is the calculation of five-loop moments of the total cross section for heavy hadroproduction at lepton colliders, which would greatly benefit charm- and bottom-quark mass determinations.

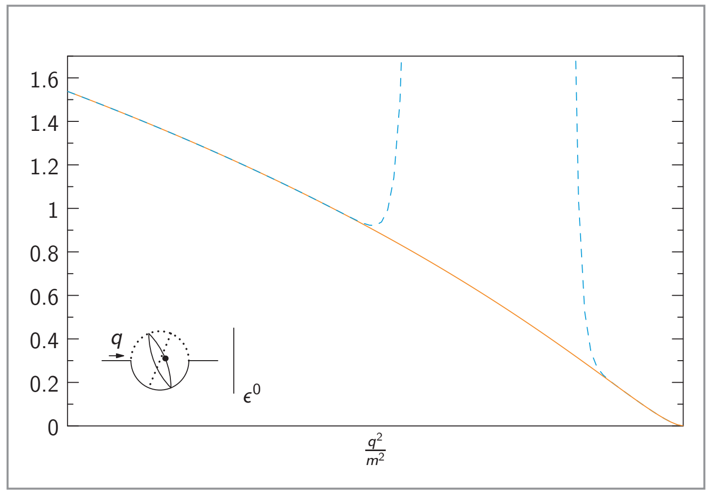


Figure 1
Low- and high-energy expansion together with the interpolating Pade approximation for the order ε^0 term

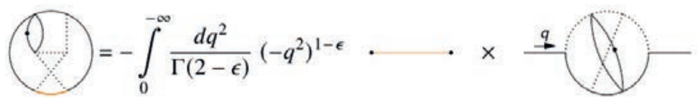
Aside from general interest in the precise knowledge of fundamental parameters, the masses of the charm and bottom quark have to be known with high precision for applications in flavour physics and for future Higgs coupling measurements. Projections for the HL-LHC suggest that the strength of the Yukawa coupling to the bottom quark will be measured with statistical and systematic experimental uncertainties of about one percent. At a high-energy lepton collider, the overall uncertainty could be improved by at least a factor of 2, and percent-level precision is within reach for the charm Yukawa coupling. In order to draw conclusions about the Higgs sector, this precision has to be matched by the Standard Model prediction. This means that the bottom-quark mass has to be known to within half a percent and the charm quark mass to within one percent.

Whether this level of precision has already been reached with present quark mass determinations depends on the way errors are assessed and propagated when evolving the quark masses from the scale at which they are determined up to the Higgs-boson mass. Following the original four-loop determination, the perturbative uncertainty amounts to 3 MeV for the bottom quark and 2 MeV for the charm quark and is therefore negligible. However, this viewpoint has been challenged in subsequent publications, where the theory uncertainties are estimated at 10 MeV for the bottom quark and 21 MeV for the charm quark. A five-loop quark mass determination would resolve this disagreement and ensure that future Higgs coupling measurements are not limited by theory.

The most promising candidates for the first genuine five-loop QCD calculations are quantities depending on a single scale, which can be factored out from all Feynman integrals. If this scale is an external momentum, one arrives at massless propagator-type Feynman diagrams. For this class of diagrams, a range of dedicated methods have been developed. Thanks to the glue-and-cut method, all 281 master integrals are known. Still, the fact that there are 64 diagram families with 15 propagators and 20 possible scalar products poses a considerable combinatorial challenge.

An alternative is to consider problems with a single nonzero internal quark mass and vanishing external momenta. If all external particles are massless, there are 34 families of massive five-loop vacuum diagrams, with 12 propagators and 15 possible scalar products. While there are only 156 master integrals, most of them remain unknown. In the following, we will focus on the calculation of these master integrals.

For the quark condensate, which is the simplest five-loop problem that can be investigated, 3451 diagrams contribute. After inserting the Feynman rules, we obtain approximately 400 000 scalar vacuum integrals, which we have successfully mapped to 156 master integrals. After inspection of the numerical cancellations between the contributions from different masters, we concluded that we lose two significant digits per order in the dimensional regulator ε, which in turn means we need to achieve double precision accuracy for the numerical results for the master integrals. For the calculation of the master integrals, we cut one of the propagators and integrate over the resulting two-point function, as depicted here:



The two-point function itself can be calculated by interpolating between the low- and high-energy expansion using a Pade approximation.

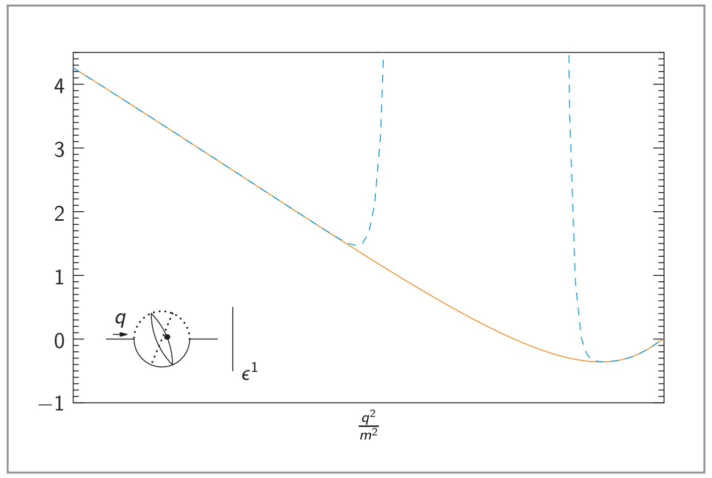


Figure 2
Low- and high-energy expansion together with the interpolating Pade approximation for the order ε^1 term

In Fig. 1 and 2, we show results for the first two orders in ε for the two-point function from the example. We can see that the Pade approximation nicely interpolates between the low- and high-energy region. Numerical integration of the results for the two-point function obtained with 20 expansion terms in the low- and high-energy region according to the preceding formula results in: $5.8125309358416596949 - 31.572349480122869826\varepsilon$. As an error estimate, we can change the integration contour to lie along the imaginary axis and obtain agreement of more than $10^{-19} + 2 \times 10^{-18}\varepsilon$. The result can also be verified by using more expansion points. Performing a brute force nine-dimensional numerical Monte Carlo integration yields $5.81409 - 31.58070(87)\varepsilon$, nicely in agreement but with much lower precision.

What remains is to implement this procedure for all required five-loop master integrals. This in turn requires the calculation of the corresponding four-loop two-point functions, which poses additional challenges that need to be overcome.

Contact:
Peter Marquard, peter.marquard@desy.de

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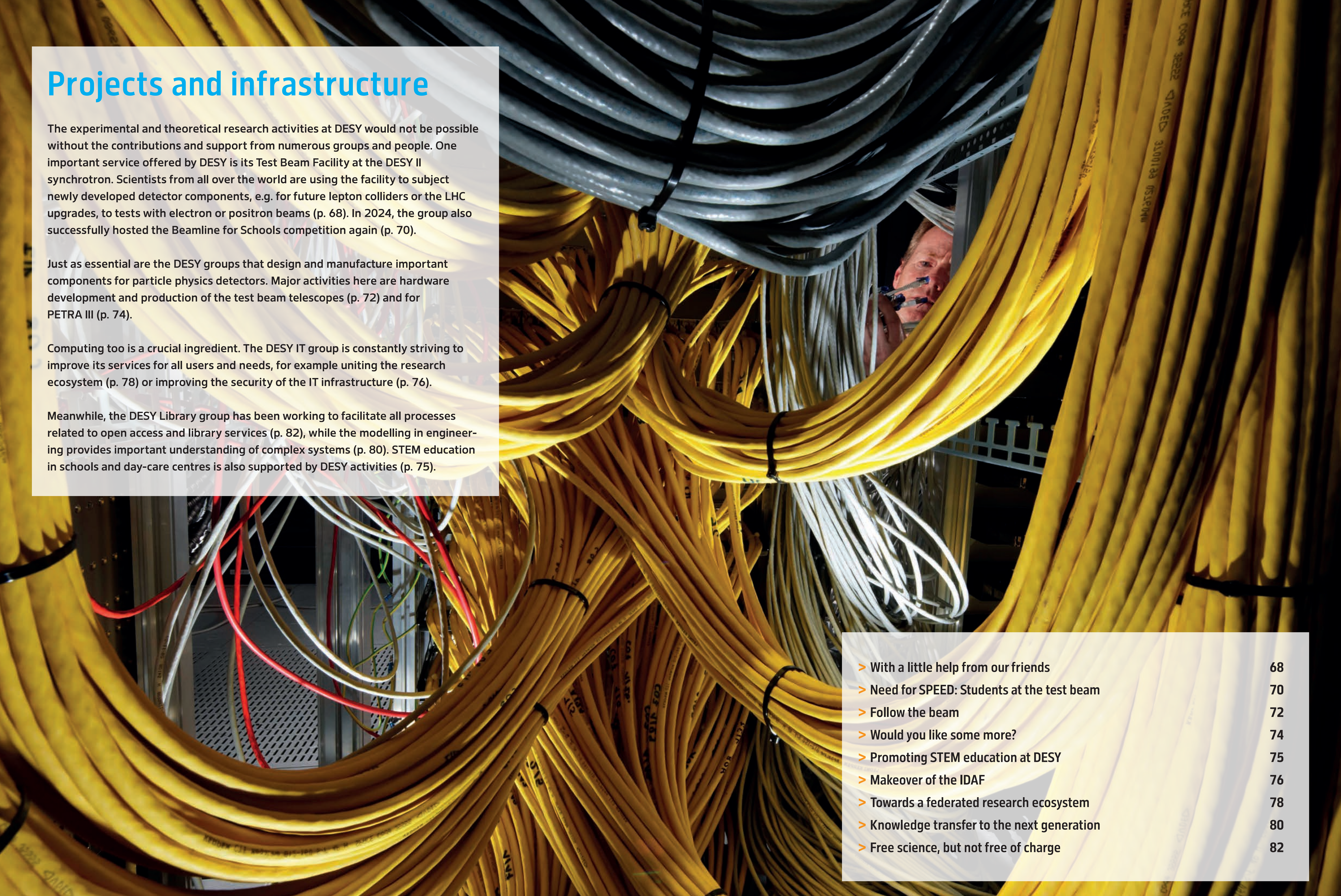

Projects and infrastructure

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 2024, 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 the test beam telescopes (p. 72) and for PETRA III (p. 74).

Computing too is a crucial ingredient. The DESY IT group is constantly striving to improve its services for all users and needs, for example uniting the research ecosystem (p. 78) or improving the security of the IT infrastructure (p. 76).

Meanwhile, the DESY Library group has been working to facilitate all processes related to open access and library services (p. 82), while the modelling in engineering provides important understanding of complex systems (p. 80). STEM education in schools and day-care centres is also supported by DESY activities (p. 75).

With a little help from our friends

The DESY II test beam had a successful year despite facing an exceptional incident

In 2024, the DESY II Test Beam Facility continued to deliver highly reliable electron and positron beams with gigaelectronvolt energy. This year, the otherwise successful run was interrupted for three weeks due to fire damage in the central electronics room of the DESY II synchrotron. Nevertheless, the facility welcomed over 500 users from the particle detector community worldwide, and its world-class infrastructures, such as the highly precise pixel beam telescopes, continued to be in strong demand.

The DESY II Test Beam Facility

The DESY II Test Beam Facility is located in the historic Hall 2, one of the first two experimental halls on the DESY campus in Hamburg. Three beamlines deliver electron or positron beams with an energy of 1 to 6 GeV for detector prototype testing. These beams are extracted parasitically from the DESY II synchrotron. Each beamline can be individually controlled by the user groups and provides single-particle rates up to several 10 kHz. The international user groups of the facility are supported by the local test beam crew, which also constantly works on improving the beamlines and infrastructure to keep the facility a world-class venue for detector characterisation.

Operations in 2024

After the test beam crew prepared the beamlines and infrastructure during the winter shutdown 2023/24, the user run started on 5 February 2024. After a three-week summer shutdown in August, user operation continued until 22 December. Overall, 66 beamtimes were booked, using 89 of the available 105 weeks, which corresponds to 85% booking of the facility. With 514 registered users, the facility had its second highest user count, only topped by 2019, when the CERN test beamlines were shut down (Fig. 1). The users came from institutes across 18 countries.

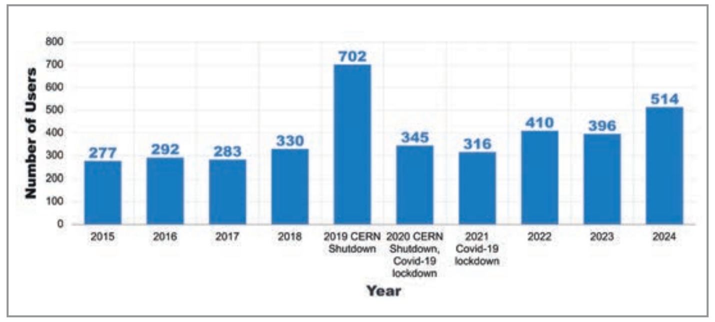

Figure 1

Number of test beam users in the past 10 years

As usual, the majority (58%) were sent by German institutes, and 33% of the users were first-time users of the facility. As in 2023, the largest fraction of user groups (44%) were preparing for upgrades of the LHC detectors at CERN, which underlines the key role of the test beam facility in this endeavour. At 35%, general R&D for the next generation of detector technologies was again the second most common purpose for beamtimes.

Down by the schoolyard

Besides being an essential infrastructure for detector R&D, the test beam also serves as a training ground for the next generation of detector experts. This was again evident in 2024, as 46% of the users were undergraduate or postgraduate students and 47% were under 30 years old.

In addition to on-the-job training, the test beam facility also hosted several distinct education events. Together with the test beam team, the HighRR Research Training group from the University of Heidelberg offered a full-week hands-on course in April. The event included hands-on training for 32 students on particle tracking with silicon devices, timing detectors and calorimetry, with introductory lectures on instrumentation.

Also in April, a group of 23 highly talented 17- and 18-year-old students from the Israeli Schwartz/Reisman Science Education Centers, a unique platform for physics enthusiasts, visited DESY. As one part of the programme during their week-long stay at DESY, the students had the opportunity to assemble a mini calorimeter and perform tests with it at the test beam facility.

Every September since 2019, the Beamline for Schools competition has been taking place at Beamline TB21. In this global science competition, the three winning teams of high-school students are invited to realise their experiments at the beamlines at CERN and DESY.

Figure 2

From left to right: The tent hosting the electronics cleaning street in Hall 2, experts cleaning electronic components inside the tent and final testing in a neighbouring test beam area

Let's work together

Shortly before midnight on Monday, 28 October, a power supply in the central electronics room of the DESY II synchrotron, called the SER, caught fire. Fortunately, nobody was hurt and, thanks to the rapid intervention of the Technical Emergency Service at DESY and the Hamburg Fire Department, the fire was quickly extinguished.

This interrupted DESY II operation and, for the first time ever in the test beam schedule history, the category "Unscheduled Downtime" appeared. Three test beam user groups, two of which had only started less than 24 h before, lost their booked beamtime.

After the first examinations, it became clear that most installations in the SER were severely affected by smoke and powder from the fire extinguishers. The test beam team and the machine group therefore quickly established a cleaning and testing "street" for the movable electronic infrastructure (Fig. 2). Meanwhile, the SER, including its fixed installations, and the connected tunnel were cleaned by a specialised company.

Thanks to the efforts of the machine group with strong support of the Particle Physics Division and the Administration, DESY II operation was able to resume on the morning of 20 November, only three weeks after the fire. Just an hour later, stable beam was achieved in the PETRA III synchrotron. The success of putting the DESY synchrotron back into operation in such a short time to provide valuable beamtime to the users of the test beam and PETRA III is a prime example of the DESY spirit of collaboration across departments and divisions.

The show must go on

The winter shutdown 2024/25 will be used for maintenance and upgrades before the start of the user run on 17 February 2025. The call for beamtime for the first half of 2025 received a high response: 87% of the available beamtime has been booked, with 100% bookings in February and March. The first available slots in 2025 were assigned to the three groups that lost beamtime due to the fire incident, so they can catch up on their scientific programme as quickly as possible. As usual, requests for the remaining slots that arrive after the official call are scheduled on a first-come, first-served basis.

A major ongoing task at the test beam facility is preparing to provide beams during the operation of the future PETRA IV X-ray radiation source in order to continue to meet the global needs of future experiments in high-energy and nuclear physics. In 2024, these efforts continued strongly in close collaboration with experts from the PETRA IV project, resulting in first cost estimates and feasibility studies of different possible solutions to keep the test beam facility running in the future.

Summary

2024 was another year in which the DESY II Test Beam Facility provided much-needed beam to the international detector development community, and we are looking forward to a successful year 2025. The success of the facility would not have been possible without the support from many individuals and groups from the DESY Particle Physics and Accelerator Divisions. We would like to take this opportunity to thank everybody involved.

Contact:
Ralf Diener, Norbert Meyners, Marcel Stanitzki
testbeam-coor@desy.de

Reference:
DESY II Test Beam Facility
https://testbeam.desy.de

Need for SPEED: Students at the test beam

10 years of Beamline for Schools

In 2024, the Beamline for Schools competition celebrated its 10th anniversary. The competition, hosted by CERN and DESY, welcomed high-school students from Japan, Estonia and the USA. At its beamlines, DESY received the SPEEDers team from Andover, Massachusetts, who designed an experiment to detect Smith–Purcell radiation.

Worldwide particle physics competition for high-school students

Have you ever heard of Smith–Purcell radiation? Maybe, if you are an expert in beam diagnostics. Otherwise, like us, probably not. Eight high-school students had investigated it so well that they were able to design a winning experiment for the Beamline for Schools (BL4S) competition in 2024.

The competition, established in 2014 at CERN, used to offer two teams of high-school students from around the world the opportunity to design and run an experiment at a world-class research accelerator facility. Since 2022, the event is co-hosted by both CERN and DESY, increasing the number of winning teams from two to three: Two teams perform their experiments at the CERN PS test beam and another team at the DESY II Test Beam Facility.

The winning teams in 2024

BL4S has seen an ever-growing number of proposals each year, reaching 461 submissions from more than 3000 students representing 78 countries in 2024. The two winning teams hosted by CERN were the Mavericks from Estonia, who calibrated their home-made cosmic-ray detector originally designed for stratospheric balloon flights, and the Sakura Particles from multiple schools in Japan, who characterised their detector designed for muography.

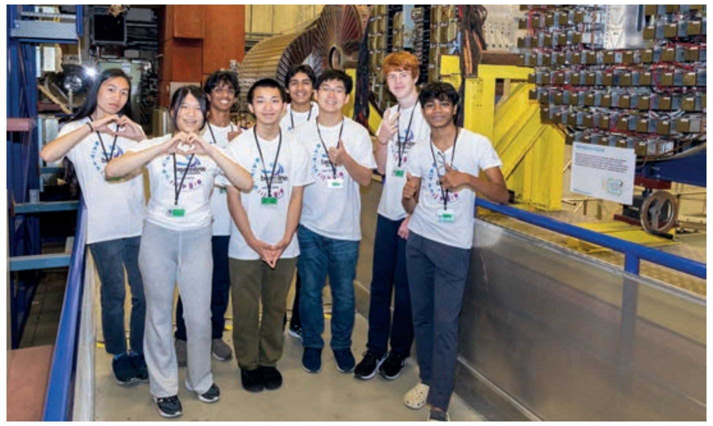

Figure 1

The eight SPEEDers team members from the Andover High School (Massachusetts, USA) surrounded by the old detectors in the HERA-B hall at DESY

The Smith–Purcell Effect Emission Determination (SPEEDers) team was hosted at DESY, comprising eight students from the Andover High School, Massachusetts, and their two teachers (Fig. 1). BL4S proposals are required to be creative, so the team proposed an experiment to measure the polarisation of Smith–Purcell radiation. This had never been studied at BL4S and is still an open field of research in the scientific community.

An experiment with challenges

The Smith–Purcell effect occurs when an electron beam travels extremely close and parallel over a conductive surface engraved with a periodic structure, for example an optical diffraction grating. As the beam passes over the grating, a faint light is emitted, which can then be measured by photodetectors. The frequency of the emitted radiation depends on the position of the photodetector compared to the beam direction. This dispersion relation can be used to characterise the radiation.

The devil is always in the details: The emitted light is so faint that only a few dozens of photons, hundreds at best, are expected to be seen. To maximise the light intensity, the beam needs to be as close as possible to the grating. However, if the beam hits the grating instead of passing over it, transition radiation is produced instead, which pollutes the measurement. Given these two competing restrictions, the position and tilt of the grating need to be controlled with high precision.

Figure 2

The SPEEDers looking at their first beam data at Beamline 21

Figure 3

The SPEEDers presenting their experiment during the BL4S VIP event

First time at the test beam

While the BL4S scientific team at DESY had prepared all the necessary devices, it was left to the SPEEDers to assemble and carry out the experiment. The enthusiastic team needed only a few hours to set it up, and the first data quickly appeared on the monitoring screen (Fig. 2).

However, a test beam provides higher hurdles and tougher challenges than those usually faced in the classroom, which the SPEEDers tackled with grit and persistence. The team experienced the scientific method first-hand, removing, checking and reinstalling the components of their experiment one by one to understand the effect of each on their measurements.

Without a trained eye, the data might look cryptic at first glance. With the help of volunteer DESY PhD candidates and postdocs, the team started building their analysis, selecting the most promising events and extracting their properties. They also contacted Smith–Purcell radiation experts at DESY to refine their understanding.

A live video link between the DESY and CERN control rooms enabled effortless communication between the teams. Together, the teams discussed and solved similar issues they faced in their setups and shared their joy about achieving experimental or analytical milestones.

The final task, as required after all scientific experiments, was to make a report of the findings. The team prepared an impressive conference-style presentation that was given in front of all other teams and support scientists. Did they see Smith–Purcell radiation? Two weeks of experiments were unfortunately too short to tell for certain, and more data was needed. The experience was nevertheless a success for all the teams, who lived as real scientists for two weeks and learned how to run their own unique experiments for the first time.

Double BL4S anniversary

In 2024, BL4S celebrated its 10th anniversary and the 5th anniversary of the successful CERN–DESY collaboration. A VIP event held at CERN, DESY and online was attended by official delegations from Estonia, Japan and the USA as well as former BL4S participants. The event featured short talks from representatives of the CERN and DESY Directorates, Mike Lamont and Beate Heinemann, from the three 2024 winning teams (Fig. 3) as well as a recollection of the past BL4S editions by CERN physicist Christoph Rembser, the originator of the competition.

The traditional barbecue, organised by the DESY test beam group, provided an opportunity to share experiences between the generations of BL4S teams and for the SPEEDers to show on-site attendees their setup.

Acknowledgments

BL4S is an education and outreach project funded by the CERN & Society Foundation. The 2024 edition was supported by Rolex and the Wilhelm and Else Heraeus Foundation. The BL4S competition is only possible thanks to the contributions and support of a large number of groups and individuals at CERN and DESY. We would like to take this opportunity to thank the volunteers, colleagues and groups who have contributed their time and expertise for their invaluable support.

Contact:

Antoine Laudrain, antoine.laudrain@desy.de
Marcel Stanitzki, marcel.stanitzki@desy.de
bl4s.team@cern.ch

Reference:

https://beamlineforschools.cern

Follow the beam

Next-generation test beam telescope

Most measurements performed at test beams require the information of exactly where and when a particle traversed the device under test. The instruments typically used to determine this information are called beam telescopes. The DESY II Test Beam Facility provides them to user groups at all beamlines. After one and a half decades in operation, the model that is used not only at DESY but at test beam facilities around the globe is now due for an upgrade. DESY's test beam team in the FTX group and the digital design team in the FE group have therefore collaborated to develop and produce the next generation of beam telescopes based on state-of-the-art monolithic active pixel sensors and data acquisition concepts. The first beam test of the new prototype took place in December 2024 and was a great success.

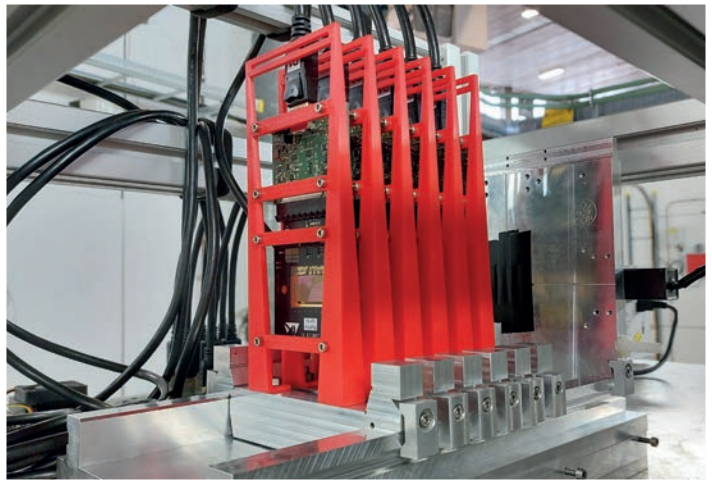

Figure 2

Six planes of the telescope prototype during beam tests

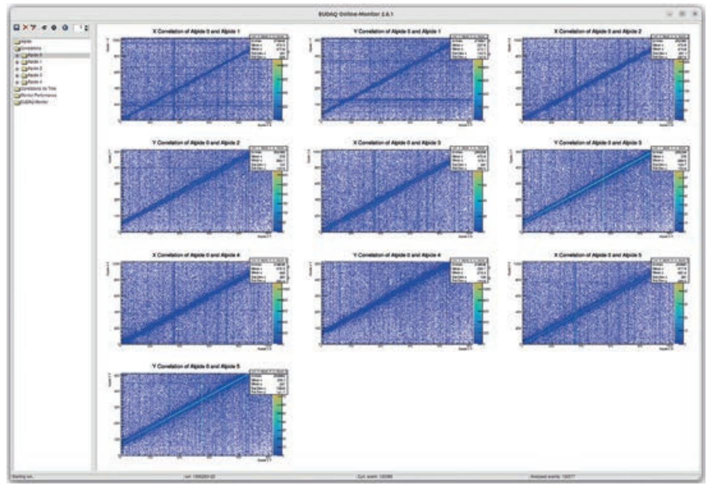

Figure 3

Screenshot from an online monitoring tool showing hit correlations between the first and all other planes of the telescope in real time

Test beams and beam telescopes

Building a particle physics experiment typically starts with developing dedicated particle detectors. This process involves extensive testing, for which the conditions that come closest to a real experiment are found at test beams. These are beams of particles whose type, rate and energy vary across the facilities that provide them. Such facilities are quite rare, which makes the DESY II Test Beam Facility [1] indispensable for the global particle physics community (see article on p. 68).

The name "beam telescopes" is historical – "hodoscopes" would be more accurate. They are small-scale tracking detectors consisting of pixel sensors arranged one behind the other in a beam. A device under test (DUT) is usually placed between the two innermost telescope layers (Fig. 1). The hit positions measured in all layers are used to reconstruct the trajectories of the beam particles, which are then interpolated onto the DUT. Checking for matching hits registered by the DUT allows its detection efficiency to be determined; comparing the reconstructed hit positions to the measured ones yields the spatial resolution, etc.

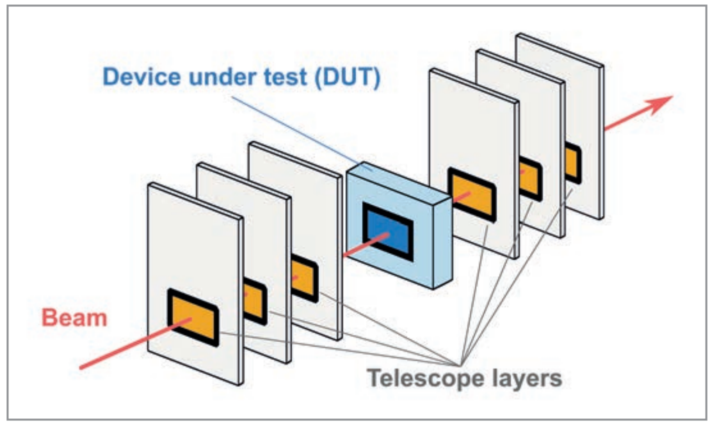

Figure 1

Sketch of a beam telescope

Common test beam infrastructure

Test beam time is limited and expensive and should be used efficiently. One step to achieving this is for the facilities to provide tools that are common among them. DESY has been strongly involved in such efforts, out of which came the so-called EUDET-type beam telescopes [2] one and a half decades ago. To this day, they are operated at CERN, DESY, ELSA in Bonn, Germany, and SLAC in the USA, and they have become indispensable for a large global user base.

Due to ever increasing performance requirements, the lifespan of an instrument like the one described here is limited. To make the common beam telescopes fit for at least the next decade, the DESY test beam team in the FTX group collaborated with the digital design team in the FE group to develop an upgraded version. The pixel sensor for this upgrade had already been selected in the scope of the European AIDAinnova project, which provided a large part of the funding. The choice fell on ALPIDE [3], a silicon sensor developed for and currently being operated in the ALICE experiment at the LHC at CERN. ALPIDE is well suited for this application as it is a very low-material detector (50 µm thin) with small pixels (~ 29 µm x 27 µm), which enables excellent track resolution. At the same time, it has a one order of magnitude faster readout than the previously used MIMOSA26, so it can cope with much higher particle rates.

Designing the new telescope

ALPIDE sensors have integrated circuits that read out the pixel matrix and convert particle hit information into a digital data stream. The sensors are delivered on carrier boards with an edge connector. The FE group designed an interface board that is directly connected to the carrier board and contains the necessary power supplies and interface circuits. The interface and carrier board together with a mechanical frame form one telescope plane. Six such planes are connected to a central unit that provides them with power and control signals and acquires data from the sensors.

The central unit, also developed by FE, is based on an AMD Zynq UltraScale+ system-on-chip (SoC), which is basically a combination of a multicore Advanced RISC Machine (ARM) processing system and a programmable logic (field-programmable gate array, FPGA) on one chip. The processing system runs an embedded Linux distribution and a software called Peary. It provides a unified interface to the hardware from a command line or through an application interface. Peary is a part of Caribou [4], a data acquisition (DAQ) framework widely used by the test beam community for operating sensor prototypes as DUTs.

However, to be able to control a telescope, Peary had to be extended with several new features and functions. The FPGA part of the SoC runs a logic design (a.k.a. firmware) that implements counterparts to custom interfaces of the ALPIDE sensor, handles time-critical tasks and keeps the system synchronised to the rest of the test beam setup by monitoring timing reference signals from a trigger logic unit (TLU). The corresponding timestamps and trigger numbers from the TLU are added to data streams from the sensors so that the telescope events can later be matched with the events from a DUT. Acquired data is handed to Peary, which sends it out to a superior DAQ system (e.g. EUDAQ) or stores it on a network-attached storage.

A prototype of the new telescope was successfully tested in the beam during the last week of DESY II accelerator operation in 2024 (Fig. 2). The tests proved that the architecture chosen for the telescope control and DAQ system will be able to provide the requested services. There are, however, still some things to improve and add before the telescope will be released to test beam users.

Figure 3 shows a screenshot of a software tool that monitors data coming from the telescope online. Each diagram shows one dimension of the 2D hit position in the first plane plotted against that in one of the other five planes. True correlations result in a diagonal line, since the tracks are approximately straight and perpendicular to the sensors. For each plane, there are two plots for the two dimensions. The diagrams are an overlay of about 1.3 million events, each of which may have multiple tracks. Multiple tracks in one event are also the reason for some hits being shown outside the diagonal line.

The first users should be able to use the new telescope in the course of 2025, initially in the DESY II test beam areas and later also in other test beam facilities around the world. About 10 telescopes are to be produced.

Contact:

Adrian Herkert, adrian.herkert@desy.de

Tomas Vanat, tomas.vanat@desy.de

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Would you like some more?

Reproduction of devices in large series

DESY's future project PETRA IV is still some years in the making, and the existing synchrotron radiation facility PETRA III thus has to run for some more years. This means that all the devices at PETRA III have to do their work for an extended period of time. But some devices are now old, and it is not always easy to keep them alive: Components have been discontinued years ago, some can only partially be replaced, and others are only available in residual quantities on the global market, meaning they tend to be of bad quality. The DESY Electronics Service Centre (ZE) is helping to redesign and reproduce them.

DESY's PETRA III X-ray source went into operation in 2009, which means that the installed devices are at least 15 years old. But the problem goes beyond PETRA III: Other accelerators around the world are equipped with the same devices, and their operators would like to keep them running for some more years too.

Some – sometimes crucial – parts, such as field-programmable gate arrays (FPGAs) or special semiconductors, are not available anymore, so redesigns have to be done or replacements for obsolete parts have to be found. Special high voltage transformers even had to be redeveloped because the external company that had been delivering the transformers since the early 1980s eventually decided to scrap the production equipment.

Some discontinued parts are still available on the global market but often in bad quality. Remaining quantities can be purchased at unrealistic prices out of all proportion to their value – distributors know that there are people who need exactly those parts.

A lot of the devices at PETRA III are very old, and it is not clear how long they can be kept working. This has led to DESY ZE receiving several reorders for complete devices, especially different types of power supplies. As any manufacturing beyond a prototype is considered serial production at DESY ZE, these orders are very large compared to the quantities DESY ZE usually produces. A total of 360 power supplies for magnet current regulation, 220 high-voltage power supplies and 70 chopper power supplies have been the most extensive orders, which still cause space problems here and there. In contrast, storing 2 x 2500 small boards for the CTAO telescopes is much easier (Fig. 1), but the production was a small adventure as well.

Figure 1

2500 advanced mezzanine card boards for the CTAO telescopes, four layers in each box

Figure 2

5 kV power supplies, ready for repair

In addition to the orders of "new old" equipment, DESY ZE is doing a lot of repair and maintenance work, and the number of devices that have to be repaired is increasing with their age (Fig. 2).

The same procedure as last year? We'll do our very best!

Contact:
Julia Müller, julia.mueller@desy.de

Promoting STEM education at DESY

How to get children and pupils interested in natural science

For more than 27 years, DESY has been running the school lab "physik.begreifen" with the support of the school authorities in Hamburg to get schoolchildren interested in physics. In one-day practical courses, participants learn that physics can also be fun. Existing prejudices are broken down. With the support of the "Neugier ahoi!" network (formerly "Kleine Forscher Hamburg"), a cooperation with the "Kinder forschen" Foundation, DESY is expanding the target group to include children in day-care centres. Further training for educational staff will encourage children to carry out their own research in the day-care centres.

DESY school lab "physik.begreifen"

In 2024, more than 6000 pupils visited the school lab "physik.begreifen" ("Grasping physics"). Pupils from Hamburg and the surrounding area as well as groups from the Netherlands, Sweden and Israel experimented on the topics of vacuum, magnetism, radioactivity, quantum physics and particles in fields.

The ELB Academy is a programme offered by the school lab for particularly interested sixth-grade pupils. After school, more than 60 engaged participants learned about physics, talked to scientists and visited the research facilities on the DESY campus.

Competitions are also motivating offers. The school lab team organised a "Jugend forscht" competition at regional level with 80 participants. The national selection competition for the International Physics Olympiad was also held at DESY in a motivating and authentic environment.

Figure 1

Pupils experimenting with a chocolate marshmallow in the DESY school lab

Figure 2

Fifth birthday of the "Kleine Forscher Hamburg" network, now called "Neugier ahoi!"

"Neugier ahoi!"

The "Neugier ahoi!" network ("Curiosity ahoi!", formerly "Kleine Forscher Hamburg") has been part of DESY since 2019. Its fifth birthday was celebrated together with the Hamburg Social Welfare Authority, the "Kinder forschen" Foundation, supporters and friends.

In many interesting training courses, early childhood and primary school teachers had wonderful creative moments. The workshops and publication on early mathematics of the network are mentioned in the new official educational guidelines for day-care facilities in Hamburg.

Contact:
Karen Ong, karen.ong@desy.de

Makeover of the IDAF

Lots of activities (not always) under the hood

A pivotal element in science today is a first-class computational platform to accompany first-class experimental facilities. DESY operates both kinds of facilities. This article summarises some of the work performed in 2024 on the Interdisciplinary Data and Analysis Facility (IDAF): the migration from the CentOS 7 operating system to RHEL 9 in Maxwell HPC, Grid, NAF and dCache; the unification of the NAF and Maxwell project spaces under GPFS-based DUST; the upgrade of the PETRA III beamline file system, which gained 400 TB of SSD-only space with ~100 GB/s throughput; and eBPF-based monitoring to enhance data insights.

Migration from CentOS 7 to RHEL 9

The operating system for most servers in IDAF, CentOS 7, reached its end of support on 30 June 2024. Consequently, a new operating system was required, and DESY selected Red Hat Enterprise Linux (RHEL) 9. Significant work was carried out to ensure a smooth transition. This included setting up test systems with all the necessary software (e.g. scheduling software, management tools) and providing test environments for users to port their code and workflows. Special attention was paid to migrating the extensive suite of scientific software offered to users of the Maxwell High-Performance Computing (HPC) cluster, resulting in the recompilation of over 100 packages for RHEL 9.

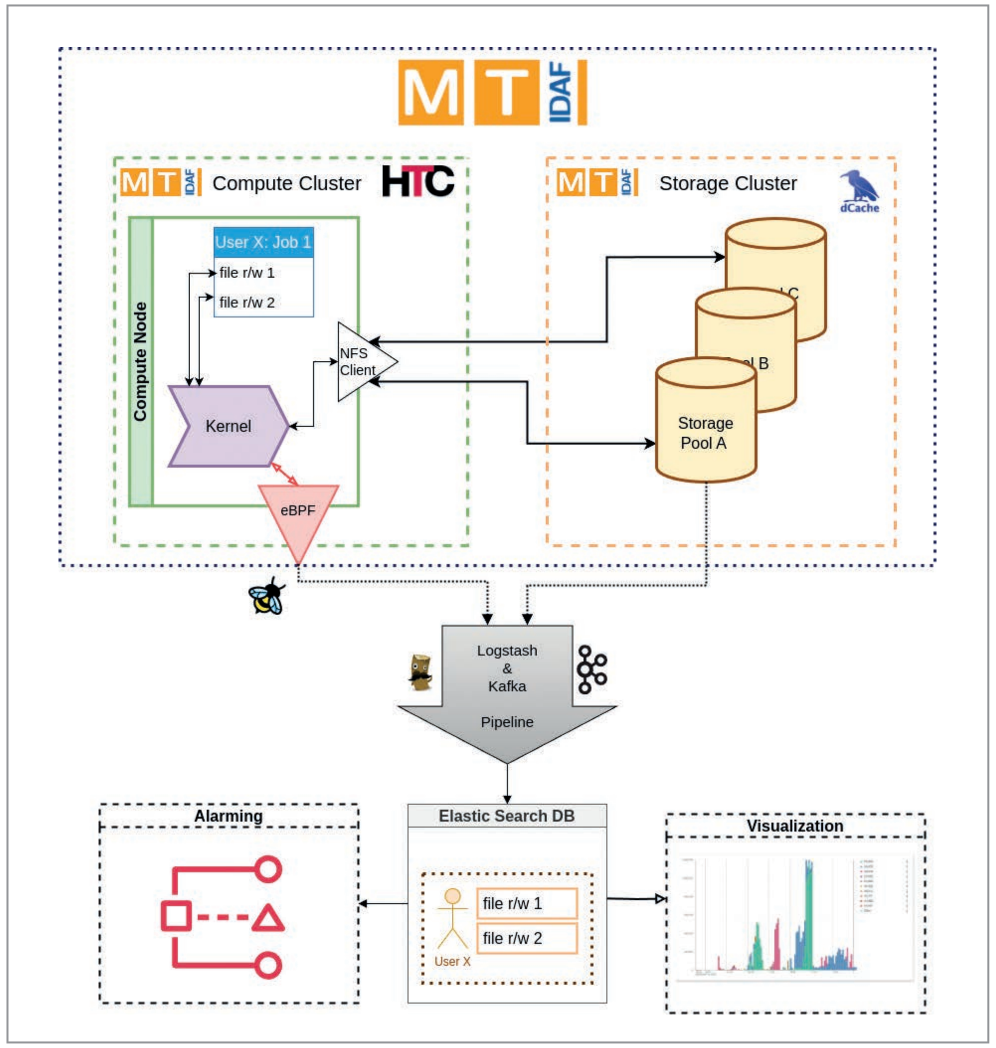

Figure 1
Workflow of the ePBF-based monitoring

The migration proceeded differently for each cluster:

- Grid cluster: Preparation was completed in April, followed by a rolling migration that gradually shifted all grid nodes to RHEL 9.
- National Analysis Facility (NAF) cluster: Mostly migrated in June and July. Unforeseen bugs in third-party software caused a period of instability, but these were resolved in collaboration with the developers.
- Maxwell HPC cluster: The core migration took place in July and August, alongside upgrades to JupyterHub and FastX.
- dCache storage: Most dCache storage systems were upgraded to RHEL 9. The largest European XFEL instance – holding over 100 PB of data on about 400 disk servers – was completely reinstalled within two days, without any data loss.
- Grid services: Certain products are no longer supported under RHEL 9. The DESY virtual organization management system (VOMS) was decommissioned, with VOs now using IAM hosted elsewhere. The APEL accounting tool also ceased functioning, necessitating a migration to the AUDITOR system, which was still ongoing at the end of 2024.

Unification of NAF and Maxwell HPC project space

NAF and Maxwell HPC each had separate project spaces: the NAF "DUST" based on the General Parallel File System (GPFS) and Maxwell HPC on the BeeGFS file system. A major focus in 2024 was on merging these spaces to streamline both user access and system administration. First, the two systems were consolidated into an expanded GPFS-based DUST platform. Second, mount points as well as user and group directory hierarchies were standardised for consistent management and unified access across all NAF and Maxwell HPC nodes. During this process, over 1200 user and group directories – representing more than 3 PB of data and 1.3 billion files – were migrated. In the meantime, the BeeGFS system with around 1.6 PB of data used by 400 users was also transferred to DUST and decommissioned after completion. The migration began in 2024 and will end in March 2025.

Upgrade of PETRA III beamline file system

In collaboration with the PETRA III beamline operations team, a new file system was introduced, offering 400 TB of SSD-only space. Real-world tests demonstrated effective write throughput of approximately 100 GB/s, significantly enhancing data ingestion and analysis for beamline experiments. These improvements accommodate high-throughput operations at PETRA III, alleviating potential bottlenecks when data generation peaks.

Although users primarily interact through compute nodes, IDAF is fundamentally a data-centric facility. Providing a reliable, high-performance user experience requires seamless integration of storage, compute and network resources. As part of a bachelor's thesis, eBPF-based access monitoring was developed to improve system-wide visibility (Fig. 1). Previously, dCache could identify access only by path and client IP address, making it challenging to correlate user-level activity on worker nodes with storage operations. By using eBPF, user- and application-specific file access information can be gathered on the worker nodes and aggregated in an Ellastic Search database. In the Kibana data visualisation interface, these data can now be cross-referenced with dCache logs for a deeper insight into usage patterns, enabling more targeted trouble-shooting and resource management.

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. 85 publications citing Maxwell HPC.
Grid cluster: 20 000 CPU cores, integrated into federated WLCG experiment production frameworks, mostly serving ATLAS, CMS and Belle II.
NAF – National Analysis Facility: ~10 000 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 50 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.

Contact:
Christoph Beyer, christoph.beyer@desy.de
Stefan Dietrich, stefan.dietrich@desy.de
Martin Flemming, martin.flemming@desy.de
Sandro Grizzo, sandro.grizzo@desy.de
Thomas Hartmann, thomas.hartmann@desy.de
Yves Kemp, yves.kemp@desy.de
Frank Schlünzen, frank.schluenzen@desy.de
Sven Sternberger, sven.sternberger@desy.de
Christian Voß, christian.voss@desy.de

Reference:
https://idaf.desy.de/

Towards a federated research ecosystem

DESY, NFDI and EOSC

In 2024, DESY made a significant contribution to a European Commission lighthouse project by helping to establish a platform for knowledge sharing among scientists across different domains, countries and research infrastructures. Through the German National Research Data Infrastructure (NFDI) and its scientifically diverse consortia, DESY will provide data and services to the European Open Science Cloud (EOSC). The European Commission supports this initiative by guiding the process of establishing EOSC as a legal entity, setting up core computing and storage resources and providing project grants to help countries and research infrastructures develop interoperable interfaces for data and related scientific services.

Creating a European scientific platform

In 2024, the European Commission reached a significant milestone in its mission to establish a pan-European platform that enables seamless collaboration among scientists across countries and scientific domains. As part of the EOSC initiative and in close collaboration with the EOSC Association [1] and EU Member States, the Commission introduced the concept of the EOSC Federation (Fig. 1). This innovative framework consists of abstract entities known as thematic and national EOSC Nodes (Fig. 2). These nodes serve as accessible collections of digital services that integrate core offerings, either provided by scientific domains at the European level or by national entities such as BMBF, Helmholtz Association or NFDI [2].

To provide a concrete, functional and practical example of an EOSC Node, the European Commission established a fully funded core node – the EU Node – as a model for future implementations. The EU Node offers essential functionalities, such as data sharing, Jupyter notebooks, virtual machines and a broad range of additional services.

Figure 1

First set of candidate EOSC Nodes building the EOSC Federation

These resources are made available to the scientific community through a credit-based system, demonstrating the tangible benefits and operational approach envisioned for the broader EOSC Federation.

As the next step, the European Commission, the EU Member States and the EOSC Association invited member states and scientific collaborations to volunteer as candidates for the initial implementation of scientific nodes. Among the first accepted nodes was a proposal submitted by the NFDI, funded by the German Research Foundation (DFG) and comprising 27 consortia.

NFDI and EOSC Node candidates

The NFDI e.V., established as a non-profit association in Karlsruhe in October 2020, plays a pivotal role in coordinating Germany's research data infrastructure initiatives. More than 270 institutions are now members of the NFDI, including science organisations, universities, higher-education institutions, non-university research institutions, scientific societies and associations. This strong network is jointly shaping the future of research data management in Germany.

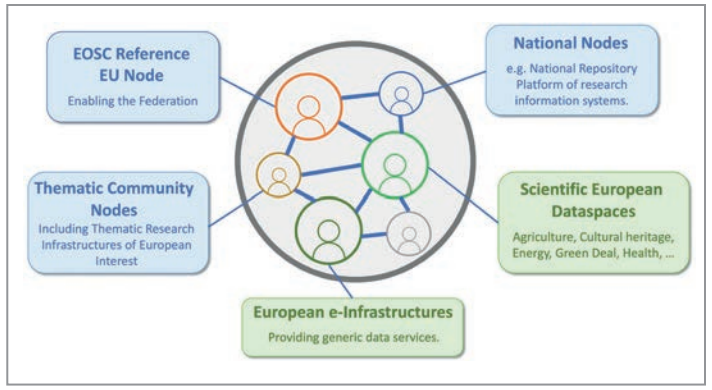

Figure 2

Thematic and national EOSC Nodes building the EOSC Federation

In the context of the EOSC Federation, the NFDI offers a robust portfolio of services from nearly all its consortia, which will be fully integrated into the final implementation of its proposed German NFDI Node.

DESY is the lead partner in two of these consortia: PUNCH4NFDI [3], representing the German high-energy and astro community, and DAPHNE4NFDI [4], focused on the German photon and neutron community.

One of the flagship services to be offered through the inaugural implementation of the EOSC NFDI Node will be the Open Data Portal, operated by the DESY IT department. This portal has been developed in close collaboration with the DESY Photon Science Division, the DAPHNE4NFDI project and the international SciCat [5] collaboration.

A second candidate node in which the DESY IT department plays an active role is the PaNOSC Node (Fig. 3), a thematic node led by the European Synchrotron Radiation Facility (ESRF) and composed of European and national photon and neutron facilities. Within this node, the DESY Research and Innovation in Computing (RIC) team provides data management services, supporting seamless access and interoperability. DESY's involvement in the PaNOSC [6] Node is rooted in its long-standing commitment to open science, particularly through collaborations with other LEAPS [7] facilities. More recently, this engagement has been strengthened by DESY's participation in OSCARS, a Horizon Europe project related to EOSC (Fig. 4), where DESY IT/RIC represents the photon and neutron community alongside ESRF and which funded nearly 60 open science initiatives across Europe.

Details on the legal structure of the EOSC Federation, the relationship to the central EU Node, the interfaces between the nodes and the conditions for using those nodes are still under discussion. These discussions are guided by the EOSC Association and documented in the EOSC Federation Handbook, available on the Association's web pages [1].

EOSC Node pilots

To prepare for building a node on a technical level, DESY IT/RIC joined the Horizon 2020 grant EOSC Beyond [8], led by the European Grid Initiative (EGI [9]), in 2022. This project involves three German partners in developing a prototype German national node, with Forschungszentrum Jülich contributing to the TEXT+ consortium [10], the Karlsruhe Institute of Technology (KIT) supporting NFDI4Ing [11] and DESY advancing NFDI4DAPHNE. Within EOSC Beyond, numerous European partners are collaborating to integrate their prototypes into the broader federation.

Figure 3

The European LEAPS community in PaNOSC

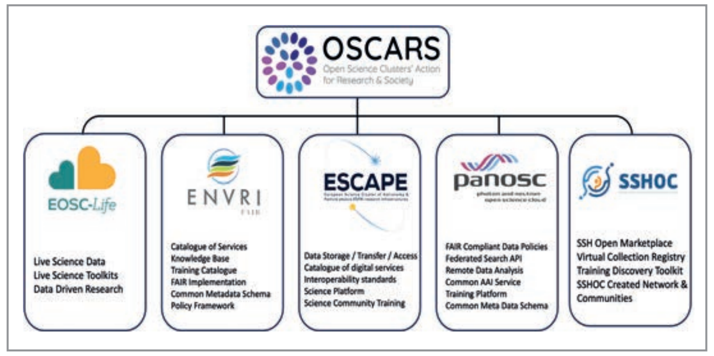

Figure 4

The OSCARS project and the European Science Clusters

Through these coordinated efforts, DESY continues to play a critical role in shaping the future of open science and research data management both within Germany and across Europe. Its commitment to collaboration, innovation and technical excellence ensures that DESY remains at the forefront of the evolving EOSC landscape.

Contact:
Patrick Fuhrmann, patrick.fuhrmann@desy.de
Paul Millar, paul.millar@desy.de
Sophie Servan, sophie.servan@desy.de
Tim Wetzel, tim.wetzel@desy.de

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Knowledge transfer to the next generation

Product Lifecycle Management shares experience among large-scale projects

Large-scale scientific projects are challenging and unique in numerous aspects. Product Lifecycle Management provides a digital platform for managing complexity and organising multidisciplinary engineering collaboration. Its template solutions transfer experience and lessons learned to the next generation of projects.

Scientific projects face various unique challenges: They develop unique cutting-edge instruments, they solve outstanding technological problems, and they organise special forms of collaboration. But they also share commonalities: They are long-lasting efforts, often covering a decade of development and two decades of operation and upgrade. They are used to changing staff and organisation as generations and demands evolve over time. They share a similar culture of collaboration as well as a prototype-based approach to development and an openness to life-long continuous optimisation.

Managing complexity with PLM

Product Lifecycle Management (PLM) is a systematic approach to digitising process and information throughout the lifecycle of complex products. A PLM system is an information system for storing technical product information and for implementing engineering workflows. PLM systems foster efficient engineering and communication by helping to manage complexity and multidisciplinary engineering collaboration.

PLM is implemented phase-by-phase along the product lifecycle. As projects often need decade(s) to traverse a full lifecycle, DESY converts project-specific PLM solutions into reusable templates. These templates are passed on and adapted to new projects, which benefit from the best practices, experience and lessons learned they receive in this way.

Figure 1 shows a typical lifecycle of a large-scale scientific infrastructure. It illustrates PLM-based cross-pollination of three projects at different stages: the successfully completed construction of the European XFEL X-ray laser, the production of the first Medium-Sized Telescopes (MST) of the Cherenkov Telescope Array Observatory (CTAO) and the planning of the X-ray light source PETRA IV.

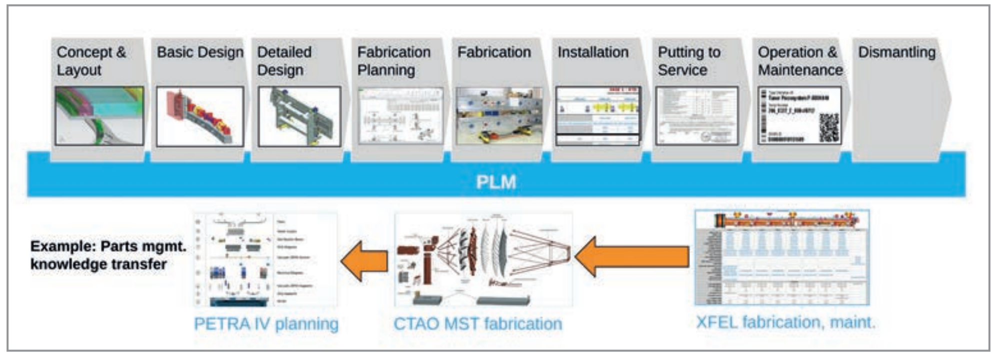

Figure 1
PLM fosters cross-pollination of different projects at different stages

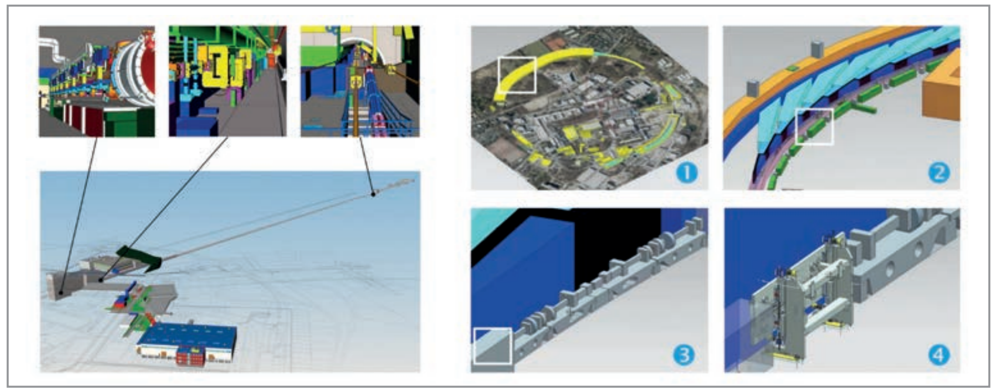

Figure 2
Design integration for the construction of the European XFEL (left) and the planning of PETRA IV (right)

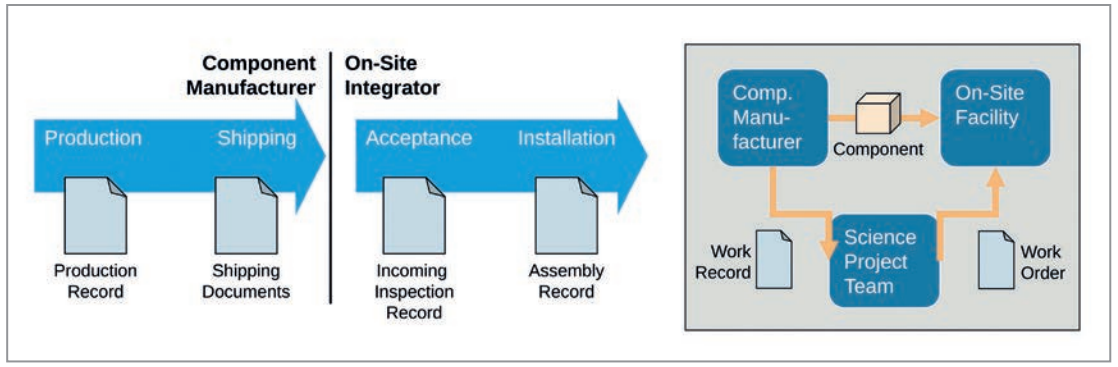

Figure 3
Documents digitise fabrication process control by providing instructions and recording work results.

Example: PLM for designing complex facilities

A typical characteristic of large-scale science facilities is the close interweaving of the scientific instruments and their technical infrastructures. The designs from the multiple engineering disciplines must therefore be very tightly coordinated: Instruments, experiments, beamlines, supplies and buildings need to be compatible and optimised, both for each individual system and as a whole, while continuing technological development of the scientific instruments keeps adding constraints to the design of the technical infrastructure.

In this scenario, PLM is the facilitator of the multidisciplinary engineering collaboration. It organises the procedures and offers a platform for contributing, integrating and sharing designs. It provides a common workspace for the many project teams, external partners and suppliers, and it ensures that component designs are updated only by their owners. All designs can be viewed and checked in the overall context at any time, and they are also integrated with requirements and further technical documentation. The result is a thorough, common design, and, just as important, a shared common vision and understanding of the emerging facility right from the start.

Figure 2 shows the evolution of design integration from the European XFEL (left), which had a detailed model of the entire facility, to the planning of PETRA IV (right), with added capability to switch the model's level of detail between different representations for e.g. overview layout and installation.

Example: PLM for producing equipment

Many scientific facilities are unique, and during their development, their components go through the entire lifecycle from the first laboratory prototype through industrialisation to high-paced series production on the critical path of the project. The production process is frequently, often rapidly changed as it evolves, and manufacturers, assembly sites and decision makers are often widely distributed.

PLM is again the facilitator of the engineering collaboration. It supports fabrication planning and progress monitoring, as well as the tracking of physical parts and material during fabrication. The parts tracking concept is based on documents (Fig. 3, left): Documents serve as template work instructions and checklists, as well as work records once filled and signed off. They define procedures and drive decisions. A work record document present in PLM indicates that the corresponding part was at that time in that location at that task. The result is a predictable production process, a growing and up-to-date technical documentation and insight into the actual production status and quality.

As document flow and material flow can follow separate paths, off-site persons can be included in digital review (Fig. 3, right). The approach is universally applicable and has been used for projects as diverse as an accelerator facility and a telescope observatory: different projects, different parts, different tasks, different documents, using the same digital process and tool. Accelerator components went from various European suppliers to an integrator and then for installation to DESY, while telescope parts will be shipped from DESY for installation at the observatory sites. In both cases, scientists at DESY need to be able to review and approve production steps.

PLM as a digital companion

Lifecycles of large-scale scientific projects encompass decades of building up knowledge and experience. PLM proves to be a very well-suited set of concepts, methods and tools for capturing and maintaining this knowledge and experience and passing it on to the next generations of researchers and projects.

Contact:
Lars Hagge, lars.hagge@desy.de
Benno List, benno.list@desy.de

Free science, but not free of charge

DESY Library starring on the stage of open access

The move from closed-access journals to open-access publishing is a big change for everyone involved. It is not just a shift in how scientific results are published, but also in how the money involved is managed. With open-access publishing, we move from contract-based accounting to publication-based accounting. To make sure scientists are not bogged down by administrative work, centralised structures are required to handle publication costs, an area that the DESY Library and Documentation group has already been pioneering for a decade.

Figure 2
Even before the conclusion of the project, openCost was shortlisted for the Enter Award, the first national prize for Open Access sponsored by the German Federal Ministry of Education and Research (BMBF)

Setting the stage

To promote the necessary structural adjustments, the German Research Foundation (DFG) initiated the programme "Open Access Publication Funding" (OAPK) [1]. It enables libraries to apply for a fixed grant to co-finance open-access publications.

As early as 2021, the DESY Library successfully applied for this funding programme and was granted 220 000 € for 2022–2024. This allowed it to co-finance each eligible publication with up to 700 €. The programme is almost transparent to the researchers on campus, although it does require detailed, externally audited cost monitoring, which is handled by the Library. It relieves pressure on budgets without requiring additional work from the researchers, as it is closely linked to the general publication process set up by the DESY Directorate. Submitting a forthcoming publication to the DESY publication database PubDB to initiate the mandatory internal review ("approval for scientific publication") fulfils the reporting requirements in a timely manner and is already sufficient for the Library to handle the subsequent "paperwork" on publication costs, including possible co-funding through the OAPK.

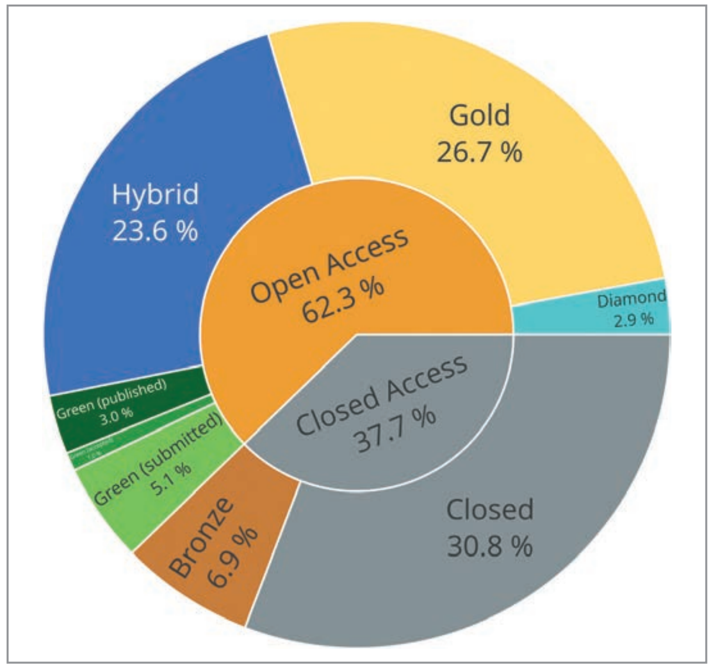

Figure 1
Open/closed-access ratio of journal articles in Germany in 2021–2025 [2]

Improving the process

According to the DFG, the OAPK "should [...] lead to [...] adequate structures at the institutions [...] to enable them [...] to determine the costs of publications in an automated and standardised manner". Together with its partners from the Universities of Bielefeld and Regensburg, the DESY Library addresses this issue in its groundbreaking openCost project [3].

Setting standards

openCost sets standards for the automatic provision of cost data. In fact, the required reporting for OAPK has gradually shifted to using the openCost entities and vocabularies, and the OAPK monitoring project now delivers data in openCost format to OpenAPC [4, 5], hosted at the University of Bielefeld.

It goes without saying that PubDB can fill in the reports required for the OAPK monitoring as well as the proof of use required by the DFG using its internal openCost structures. Both independent reports are generated automatically and mainly serve to cross-check the data.

openCost is very well received in the library community, not only in Germany, as numerous contributions to (inter-)national conferences show [6]. One highlight was the nomination of the project as finalist for the Enter Award [7], the first national prize for Open Access.

For researchers and librarians, openCost also improved the internationally renowned Electronic Journal Library (EZB) [8] in order to reuse cost data and add information on the cost handling practices of individual institutions.

Into the future

Thanks to its solid groundwork, the DESY Library was able to successfully apply for the second phase of the OAPK. For 2025–2027, the Library received more than half a million euros. While only publications resulting at least partly from DFG scientific projects will be funded in this second phase, the established processes won't entail any extra work for the scientists at DESY: The processes already provide information on third-party funding (such as DFG or EU) in PubDB because of other monitoring requirements. Again, co-funding will be almost transparent to the researchers. This time, eligible publications will relieve the budget by up to 1400 €.

The openCost project also finalised its first stage in 2024 with a large international conference hosted by the University Library Regensburg [9], appropriately entitled "openCost – The Next Stage". The conference summarised the results of the first funding period and gave an outlook on open issues in the ever-changing publications landscape. The DESY Library is happy that its application for a second phase of openCost together with its partners in Bielefeld and Regensburg was successful and that it will be able to tackle these open issues in the coming years.

Figure 3
Managing the openCost project (front left to back right): Bianca Schweighofer[1], Lisa-Marie Stein[2], Julia Bartlewski[3], Silke Weisheit[1], Alexander Wagner[2], Colin Sippl[1], Cornelia Lang[1], Gernot Deinzer[1]
([1]University Library Regensburg, [2]DESY, [3]University Library Bielefeld)

Contact:
Lisa-Marie Stein, lisa-marie.stein@desy.de

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L. Berg
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Publishing and contact
Deutsches Elektronen-Synchrotron DESY
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Hamburg location:
Notkestr. 85, 22607 Hamburg, Germany
Tel.: +49 40 8998-0, Fax: +49 40 8998-3282
desyinfo@desy.de

Zeuthen location:
Platanenallee 6, 15738 Zeuthen, Germany
Tel.: +49 33762 7-70, Fax: +49 33762 7-7413
desyinfo.zeuthen@desy.de

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