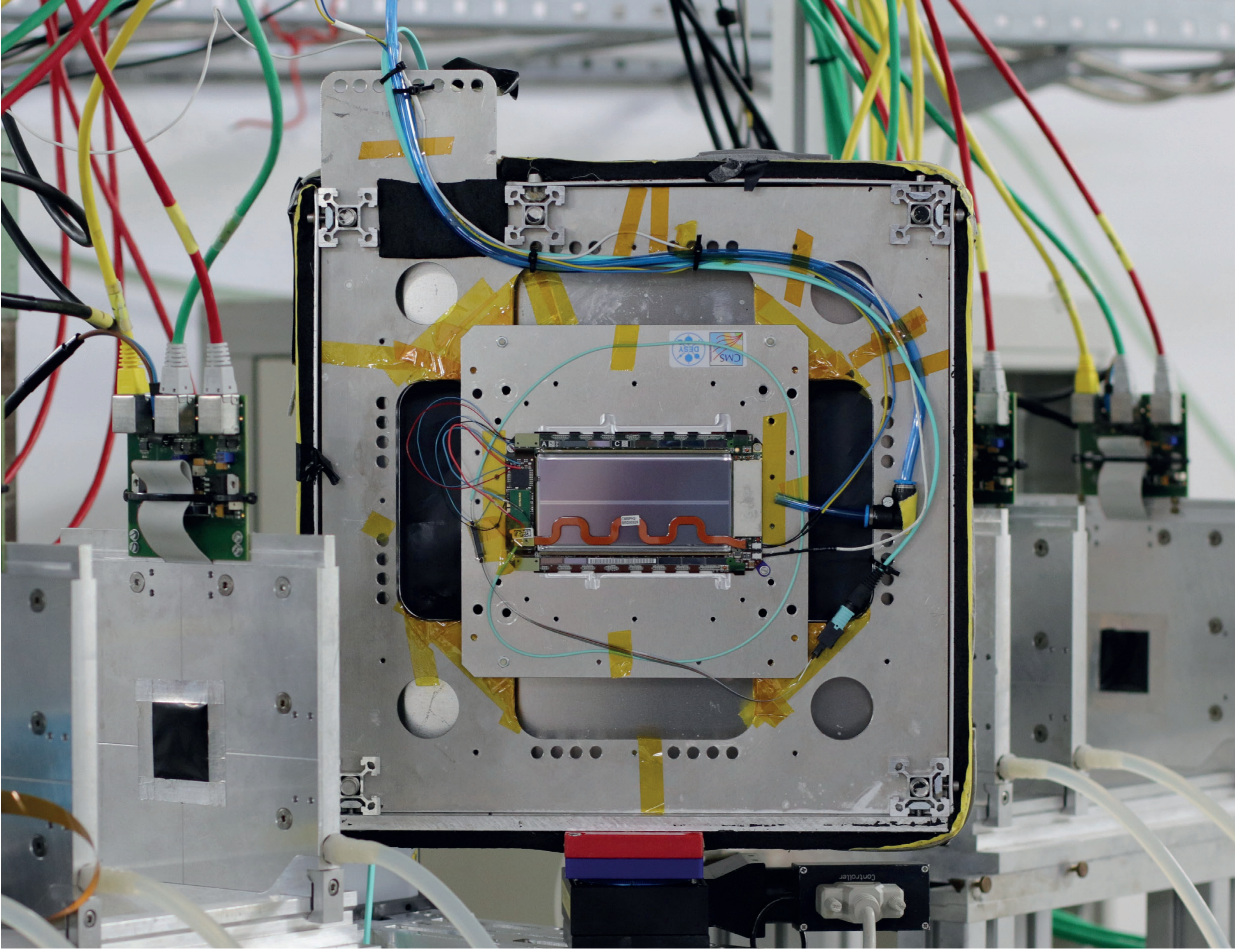

PARTICLE PHYSICS 2022.

Highlights and Annual Report

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

PARTICLE PHYSICS 2022.

Highlights and Annual Report

Cover
First strip sensor (PS) module for the CMS experiment
in the DESY II Test Beam Facility

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Chairman's foreword

Dear Colleagues and
Friends of DESY,

The DESY management has been working in crisis mode ever since the outbreak of the COVID-19 pandemic in March 2020. After the strains of the pandemic, the Russian war on Ukraine is now calling into question much of what we have hitherto taken for granted and posing enormous challenges. Our main concern remains the suffering people in Ukraine and the families who have fled the war with its dire human consequences.

This war now also affects research at DESY. Our current problems include the general uncontrolled price development on the energy market and in the construction sector, the enormous inflation trend and the shaky supply chains worldwide. All of these pose unprecedented challenges for the research centre that we have not known before on this scale in Europe and beyond.

In our current deliberations, we assume that we will have another three very difficult years ahead of us and will therefore have to implement massive cost-saving measures. These will include cuts in the operation of our major research infrastructures, if we do not receive financial relief, and painful personnel decisions. The DESY Directorate sees a particularly sensitive area here in the next generation of scientists and engineers, whom we must not abandon under any circumstances. However, we do not give up hope that the German government will also focus more strongly on saving the nation's future innovation potential. The current signals from politics to set up a rescue package also for science make us cautiously optimistic.

In a high-tech nation like Germany, research and innovation are the decisive – if not the only – levers to lead us out of the crisis and secure our long-term sovereignty in key technologies. Against the background of the most acute problems in energy supply, we must not forget that the main threat to our survival on this planet is man-made climate change, which we have to counter with new energy concepts. Nor must we lose sight of the constant threat of viral or bacterial pandemics. At DESY, we are all working at full speed to play our part in solving these complex challenges. This is also reflected in our strategy loop, which we are currently working on intensively – in addition to daily crisis management.

We have identified three pillars for the future development of DESY:

- The cross-divisional DESY Transformation Project (DTP), which is to prepare the future strategy of our "solution ecosystem" and which requires profound conceptual changes in how we organise research and innovation in the future
- The National Analytics Centre (NAC) with the facilities PETRA IV, FLASH2020+ and the Plasma Accelerator as well as an integrated data management structure as the core research infrastructures of DESY
- Increased focus in particle physics on medium-sized dark-matter projects on the DESY campus and exploration of new opportunities in astroparticle physics offered by the Science Data Management Centre (SDMC) of the Cherenkov Telescope Array (CTA) observatory and by the German Center for Astrophysics (DZA)

Sustainable concepts play a central role in all our planning. The Directorate has a clear vision for DESY's path to energy-saving and climate-friendly operation. In 2022, we published our first sustainability report, which will appear at regular intervals in the future.

In September 2022, we presented the PETRA IV project – the upgrade of our synchrotron radiation source PETRA III to a 3D X-ray microscope – to a broader public at a major event with representatives from science, politics and industry. I was very pleased that the project was also supported by Stefan Hell from the Max Planck Institutes in Göttingen and Heidelberg, a Nobel Laureate and one of the world's most renowned representatives of new microscopy concepts. On the evening of the event, he gave an impressive lecture in Hamburg's City Hall, demonstrating the innovative power that new types of high-performance microscopes can unleash.

Figure 1

The Hamburg Senate invited DESY to present the PETRA IV project at the Hamburg City Hall. From left: Nobel Laureate Stefan Hell, Hamburg Science Senator Katharina Fegebank and DESY Director Helmut Dosch.

Under the leadership of Harald Reichert and Riccardo Bartolini, the preparation of the PETRA IV project continues to make great progress. The technical design is essentially complete, and the team is currently working on the application for inclusion of the project in the German national roadmap for research infrastructures. PETRA IV will be a key building block in the transformation process of DESY that we have been designing over the past few months. The major impact of the facility will not only be due to its technical design as an interdisciplinary "discovery and solution engine" that includes AI-assisted operations, a new access model and comprehensive involvement of the broad user community. Although these will increase the construction and operational costs of the facility, the expected socio-economic impact will outweigh this investment many times over. In view of the competing Chinese High Energy Photon Source (HEPS) project in Beijing, for instance, which is already at an advanced stage, we must not lose any valuable time now in implementing the PETRA IV project.

We have noted with great pleasure the positive decision of the German Federal Ministry of Education and Research (BMBF) to realise the German Center for Astrophysics (DZA), which was prominently promoted by the European Space Agency (ESA) and DESY. On the DESY side, Christian Stegmann, Director in charge of Astroparticle Physics, and Arik Willner, Delegate of the Directorate for Innovation, were instrumental in the application. This development is a new piece of the puzzle in our 2022/2023 strategy loop, which fits perfectly into DESY's aspiration to build an international beacon in astroparticle physics at its Zeuthen site.

It is gratifying to see that our on-site axion search experiment ALPS II is developing very well. We are currently working on implementing the campus projects BabyIAXO and LUXE also for axion research. Under the given circumstances, this is a major challenge that we hope to master.

We live in difficult times and so does our research centre. My special thanks therefore go to the DESY staff and all our national and international users and partners for their reliable support at all times. I hope this annual report will show you that, despite the current challenges that occupy us on a daily basis, we are keeping DESY on course for a bright future development!

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Particle physics at DESY

Introduction

Dear Colleagues and Friends of DESY,

We all note with relief that the detrimental effects of the COVID-19 pandemic are slowly fading and that we are returning to our pre-pandemic way of life, though in a modified fashion: We are returning to the offices – but a certain amount of home office will stay with us; we are travelling to CERN and KEK to contribute to the operation of our experiments – but remote operation will become increasingly important; we are again organising and attending meetings, workshops and conferences – but, not least for sustainability reasons, we are more carefully considering the necessity of trips.

Since travelling has become possible again, we have seen many visitors at DESY, e.g. at several events we organised in 2022: We celebrated the 80th birthday of former DESY Director Albrecht Wagner at the "Wagner Fest" and the 25th anniversary of the DESY school lab "physik.begreifen" (which has had more than 100 000 participants since its foundation!).

In the Particle Physics division specifically, we hosted the DESY Theory Workshop on "Higgs, Flavour and Beyond" in September and the first workshop of the European Committee for Future Accelerators (ECFA) on physics and experiments at electron–positron colliders with more than 300 participants in October, the latter event also including the Heinrich Hertz Lecture by renowned theorist Hitoshi Murayama from the University of California, Berkeley, USA. We organised for the first time a retreat of the DESY Particle Physics division in August, an occasion on which many of us came together to discuss future directions and avenues for our division – an event to be repeated!

However, 2022 also had its downsides. It was a year of challenges, unforeseen crises and scaring global developments, most notably the Russian war on Ukraine, which is entering its second year while I am writing these words. The open aggression against Ukraine has many dire consequences, first and foremost for the country and its people. I am grateful to see the great commitment of many colleagues in assisting those in need professionally or privately, and I also appreciate the efforts made by DESY and the Helmholtz Association: At DESY, we are trying to help by accommodating around 40 Ukrainian refugees in our guest houses and providing them with basic services. And within the Helmholtz "Researchers at Risk" initiative, six researchers have found at least temporary refuge and scientific perspective in our Particle Physics division: Four scientists from Ukraine and one each from Belarus and Russia have the opportunity to continue their research work or PhD theses for a duration of six months on DESY contracts. Quite a few members of the DESY Particle Physics division are also involved in a winter school organised for students from Ukraine.

Figure 1
The 25th anniversary of the DESY school lab "physik.begreifen" was celebrated in October 2022. From left: Science communicator Michael Büker, DESY Directors Christian Harringa, Beate Heinemann and Helmut Dosch, Senator Ties Rabe, physik.begreifen coordinator Karen Ong and Helmut Krech, founder of physik.begreifen during his tenure as DESY Administrative Director.

Figure 2
Former DESY and CERN Director Herwig Schopper and Beate Heinemann in discussion during the "Wagner Fest"

Beyond the terrible human consequences, this war in Europe has a serious impact on numerous aspects of our scientific lives: Energy costs have increased massively, threatening the operation of our accelerators; important working connections to Russian institutions are cut, and projects for which Russian contributions were foreseen are suffering and experiencing delays; scientific collaboration on our experiments and joint publications have become difficult.

Despite these adverse circumstances, we have produced remarkable scientific output in 2022, which you will learn more about in this highlights brochure. On our Hamburg campus, the ALPS II axion search experiment is ready for data taking. Its complex optics system was installed, the magnet string cooled down at full current, and the entire setup commissioned in 2022. ALPS II even established a world record for storing light in a cavity for several microseconds. Other on-site experiments are also progressing well: The laser-and-XFEL experiment LUXE gained the important CD 1 status, which puts the experiment on the DESY roadmap and is a key milestone for attracting further collaborators and funding. The collaborations of the BabyIAXO and MADMAX axion search experiments are working on their technical designs.

Our external collaborations with CERN in Switzerland and KEK in Japan are flourishing as well, despite the difficulties mentioned above. One outstanding result with DESY contribution is certainly the publication of today's best knowledge about the Higgs boson in two articles in *Nature*, using the full LHC Run 2 data sets of the ATLAS and CMS experiments, on the occasion of the 10th anniversary of the discovery of the Higgs boson in July 2022.

These exciting scientific results would not be possible without the immense technological efforts in computing and detector R&D and construction that we are involved in together with our partners. Consequently, we are glad and proud that our large construction projects are progressing well: The tracker endcaps for both ATLAS and CMS are now ready to enter the production phase, as is the CMS high-granularity calorimeter (HGCAL). Both half-shells for the Belle II pixel vertex detector (PXD2) are currently being commissioned at DESY before being transported to KEK later in 2023. The performance of our IT efforts is documented not least by the record set in 2022 for daily stored data volumes of more than 1 PB for dedicated experiments at the European XFEL X-ray free-electron laser.

A lot of exciting activities are going on in the theory area, for example related to axions, gravitational waves and phase transitions in the early universe, which have been very prominent in the context of the Cluster of Excellence of Universität Hamburg and DESY, aptly named "Quantum Universe".

We are now preparing for a challenging year 2023. Important events and activities will include the finalising of the DESY strategy loop and the update of the DESY 2030 strategy, the beginning of preparations for the next round of the programme-oriented funding cycle of the Helmholtz Association, and others. I am very much looking forward to taking these and others steps together with you at DESY and in our partner institutions around the world!

Kind regards,

Beate Heinemann
Director in charge of Particle Physics

News and events

A busy year 2022

January

Ask a Prof – "Wir wollen's wissen"

For the third time, the "Wir wollen's wissen!" ("We want to know it!") week took place at Hamburg schools. Scientists from Universität Hamburg and DESY swapped lecture halls for classrooms, presenting their research and answering questions from upper-school students. The aim of "Wir wollen's wissen!" is to bring pupils into contact with science and research at an early age to initiate them to the fascination of physics.

Thank you, Ties!

Ties Behnke's time as Interim Director of the DESY Particle Physics division came to an end. He was in office for 13 months and enabled a smooth transition from Joachim Mnich to Beate Heinemann. He has resumed research activities in the meantime, concentrating on detector development and on-site experiments in particle physics as well as on management within the Helmholtz programme "Matter and Technologies".

Ties Behnke

February

Beate Heinemann is new DESY Director in charge of Particle Physics

Beate Heinemann, a lead scientist at DESY and professor at the University of Freiburg, took over as DESY Director in charge of Particle Physics on 1 February.

Heinemann succeeds Joachim Mnich, who moved to CERN as Director for Research and Computing at the beginning of 2021, and Ties Behnke, who led the division as Interim Director. Alongside the particle physicists, engineers and technicians involved in the international experiments, the DESY Particle Physics division also includes the Theory group, the DESY IT department, the Library group and many service groups, such as Electronics Development.

Beate Heinemann, the first woman on the DESY Board of Directors

Belle II Achievement Award for Michel Hernández Villanueva

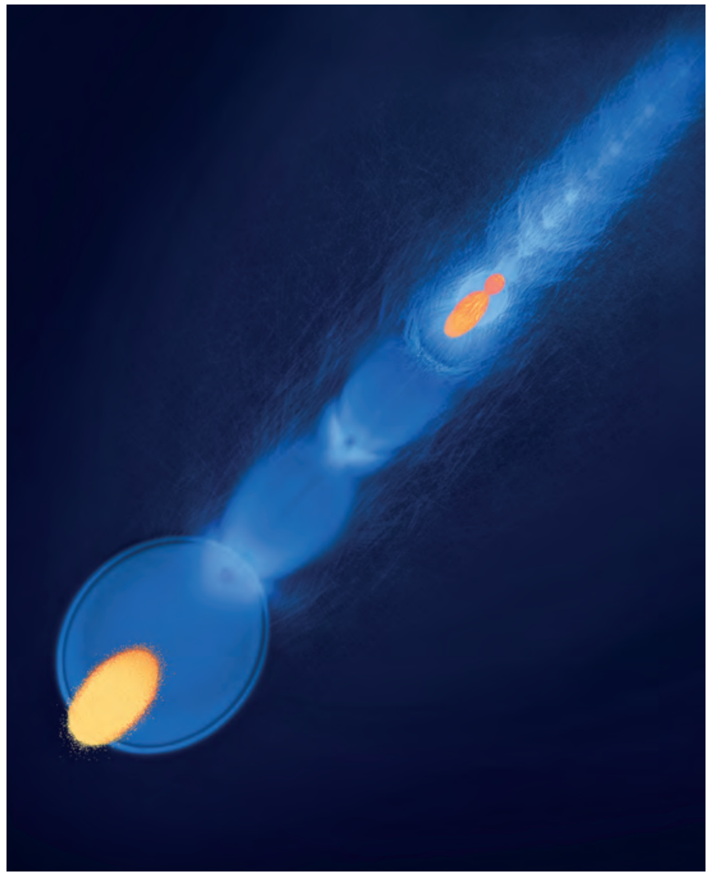
Michel Hernández Villanueva, who joined the DESY Belle II group as a post-doctoral fellow in 2021, has made significant contributions to several areas in Belle II computing. In recognition of these outstanding achievements, which he accomplished in addition to his work as one of the two convenors of the Belle II tau physics working group, he was presented with the Belle II Achievement Award at the experiment's collaboration meeting.

Michel Hernández Villanueva

March

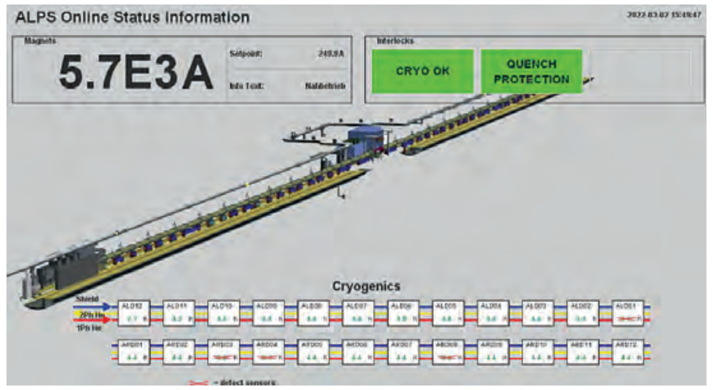
Plasma accelerators recover in a FLASH

At DESY's FLASHForward experiment, an international team led by DESY demonstrated for the first time that it is possible in principle to operate plasma accelerators at the repetition rates required for experiments in particle physics and photon science. This opens up the possibility to use such high-gradient accelerators as booster stages in existing high-repetition-rate facilities, such as the large-scale X-ray free-electron lasers FLASH and European XFEL, in order to significantly increase the energy of long particle trains over short distances. The team presented their results in the journal *Nature*.



ALPS II magnets all powered up

If you want to learn more about dark matter with a new experiment, you need to pass many individual milestones. The team of the ALPS II experiment, which is located in the tunnel of DESY's former HERA accelerator, reached an important milestone at the beginning of March. The superconducting magnets, in which particles of light are ultimately supposed to transform into dark-matter particles, were operated at the full amperage of 5700 A for the first time.



ALPS II superconducting magnets operated at full current in early March 2022

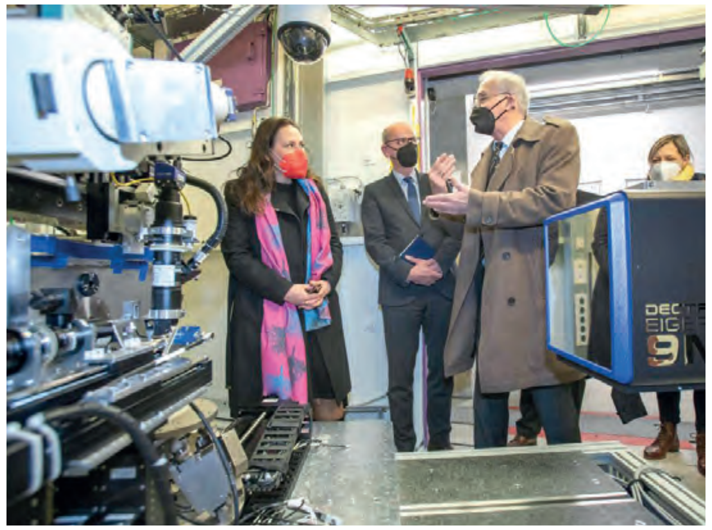
Slava Ukraini!

Ever since the Russian invasion of Ukraine, DESY staff members have been very willing to help Ukrainian refugees. DESY employees got involved in many ways, e.g. by helping with administrative matters, doing shopping for the International Office, organising trips to nearby clothing or cell phone shops, providing laptops for school classes, doing translation work or simply providing space and time for talking. DESY employees also helped financially by contributing money to the GoFundMe pot, from which many needed things and activities are being financed.

April

Brandenburg's Research Minister Manja Schüle visits Hamburg campus

The good relationship between the Ministry of Science, Research and Culture of the German federal state of Brandenburg and DESY became even closer in April. After visiting DESY in Zeuthen in Brandenburg, Research Minister Manja Schüle came to Hamburg to learn more about research at DESY. On 8 April, she met with the DESY Board of Directors for an exchange on scientific topics and was given an exclusive a tour of the research facilities and pioneering projects.



Brandenburg's Research Minister Manja Schüle on her tour of the DESY campus in Hamburg

Funding for two new quantum technology projects

Quantum research at DESY got an additional boost: The German federal government and the European Union (EU) approved funding for two new quantum technology projects in which DESY is significantly involved. The NiQ project, supported by the German Federal Ministry of Education and Research (BMBF), investigates the role of noise in quantum computers, while the T-NiSQ project, funded by the EU in the QuantERA framework programme, develops, among other things, diagnostic tools for the validation of quantum components.

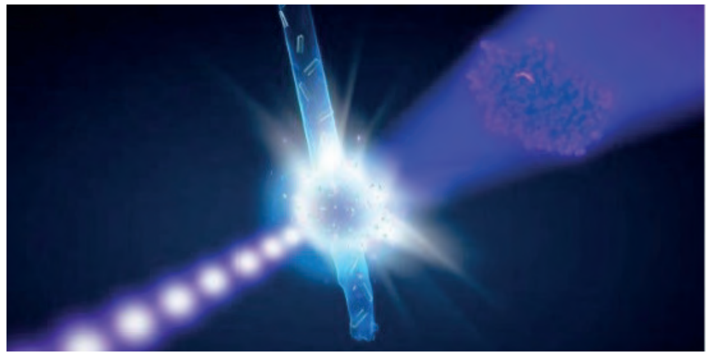
Multiple awards for accelerator physicist Sarah Schröder

For her excellent PhD thesis in plasma accelerator physics, DESY scientist Sarah Schröder was awarded the Doctoral Prize of the German Physical Society (DPG) in the section "Matter and Cosmos" as well as the Helmholtz Doctoral Prize for mission-oriented research in the Helmholtz research field "Matter". The Helmholtz Association awards the prize to young scientists who combine the search for knowledge and possible applications in their research.

Helmholtz President Otmar Wiestler handing over the award to Sarah Schröder

Boost for data science in the natural sciences

The natural sciences have made great progress in recent decades with the help of computers. In 2020, the Center for Data and Computing in Natural Sciences (CDCS) was established in Hamburg as a "Hamburg-X" project to develop new informatics concepts for processing and analysing the gigantic amounts of data from research. In interdisciplinary teams, physicists, chemists and biologists are cooperating with computer scientists on the development of innovative methods using data science and machine learning. The CDCS kick-off symposium was held on the DESY campus from 26 to 28 April.



May

Detector expert Ingrid Gregor is new lead scientist

Ingrid Gregor, a DESY particle physicist and professor at the University of Bonn, was appointed lead scientist at DESY. Gregor, an expert for silicon detectors, works on the ATLAS experiment, one of the big international detectors at the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland. She is in charge of the construction of silicon tracker components for the upgrade of the ATLAS detector, which are assembled at DESY. She also heads the ATLAS group at DESY.

Ingrid Gregor

First Diversity Day at DESY

After signing the Diversity Charter in 2021, DESY celebrated its first Diversity Day on 31 May 2022 – a nationwide day of action launched by the "Charta der Vielfalt" association. For DESY, diversity in the work context means an appreciative and conscious approach to difference and individuality with regard to factors such as gender, origin, age, sexual orientation as well as physical and mental abilities.

June

Albrecht Wagner Fest

Happy birthday, Albrecht Wagner! On 16 June, DESY celebrated the 80th birthday of its long-time director with a scientific colloquium held in his honour. In his many years at DESY, Wagner contributed significantly to the scientific successes and the national and international reputation of the research centre. In 1991, he was appointed Director of Research at DESY. From 1999 until 2009, he served as Chairman of the DESY Board of Directors.

Wagner played an important role as leader of several international consortia, e.g. as Chairman of the TESLA Technology Collaboration Board and of the International Committee for Future Accelerators (ICFA). The landmark decisions on the TESLA superconducting accelerator technology and the European XFEL X-ray free-electron laser were made under his leadership.

Albrecht Wagner at the colloquium held in his honour

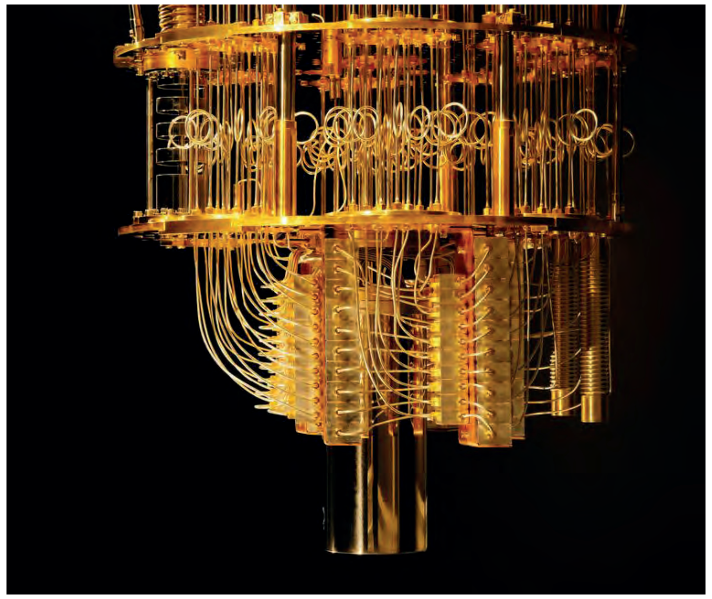
Science on tap – return to the pubs!

How loud was the big bang? Man flu – fairy tale or truth? Or: What does the dosage of drugs have to do with beer foam? At the “Science on tap” event, researchers from Universität Hamburg and DESY give answers to exciting questions from their research. After a pandemic-related break, the entertaining lectures finally took place live again in more than 20 Hamburg pubs. Cheers!

July

DESY joins IBM Quantum Network

DESY and IBM entered an agreement on quantum computing that welcomed DESY as a member of the IBM Quantum Network. As a future hub in the network, DESY seeks to exploit the opportunities of the new technology to solve scientific problems much more efficiently on quantum computers in the future and even potentially tackle challenges that are not accessible to classical computers. IBM hopes that DESY will identify new and important fields of application for this emerging technology.



Cryostat of an IBM quantum computer

DESY wins Hamburg 2040 award

DESY received the first Hamburg 2040 award at the premiere of the Hamburg Business Summer Festival. With this award, the Hamburg Chamber of Commerce honours companies, institutions or individuals who are actively shaping the future of the city of Hamburg, demonstrating innovative strength and advancing the region in line with the Hamburg 2040 location strategy developed by the Chamber of Commerce.

The DESY Board of Directors at the Hamburg 2040 Award ceremony, together with Norbert Aust, President of the Hamburg Chamber of Commerce (left), and Andreas Dressel, Finance Senator of the City of Hamburg (right)

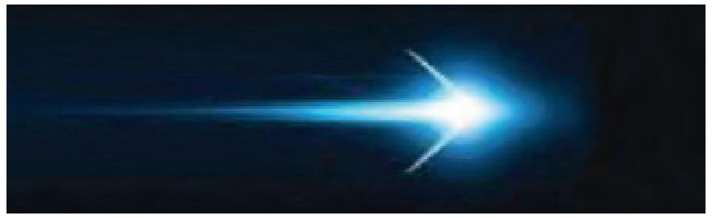
DESY co-hosts International Physics Olympiad

Following the cancellation of the International Physics Olympiad (IPhO) in the Belarusian capital Minsk, DESY stepped in as co-host: From 10 to 17 July, school teams from five countries competed against each other on the Hamburg campus and virtually against 70 other teams from all over the world. At the IPhO, the young participants solve challenging experimental and theoretical physics problems that go far beyond the school curriculum.

Participants of the International Physics Olympiad 2022 at DESY

Strategy update: DESY gets fit for the future

With a first meeting on 4 July, DESY started a comprehensive update of its DESY 2030 strategy, setting the course for a successful future at the forefront of research. The goals fixed in the DESY 2030 strategy in 2018 needed to be sharpened to incorporate current challenges – such as advancing climate change, the new threat to society from pandemics and the digital transformation – even more strongly and visibly into future planning. The strategy update is to be completed in spring 2023, and the results will be presented in summer 2023. For DESY, these will form the basis for the scientific planning and application for the fifth round of the Helmholtz Association’s programme-oriented funding (PoF V).



August

Summer student season

Ever wanted to characterise digital cameras for beam diagnostics? Try your hand at real data from the Belle II experiment? Get functional cellulose lignin coating on porous materials underway or work on machine learning techniques for laser plasma acceleration? These were just a few examples of the many different hands-on research experiences that were possible in the 2022 DESY summer student programme. After cancellation in 2020 due to the pandemic and one year of very restricted hybrid summer student programme in 2021, a total of 84 students from around the world took part in the 2022 DESY summer student course either in person or remotely.

Summer students at DESY in Hamburg

15 years of DESY Science Café

In the past 15 years, the Science Café has become an institution at DESY. Once a month, interested young people meet scientists in a relaxed atmosphere to hear a vivid presentation of some exciting research topic. This is followed by a discussion round, the heart of the event. On the occasion of its 15th birthday, the Science Café welcomed a special guest: Rolf-Dieter Heuer, speaker at the first Science Café back in 2007, former DESY Director in charge of Particle Physics and then CERN Director General, talked about "CERN – the world of smallest particles. Building bridges across national and cultural borders".

Rolf-Dieter Heuer talking at the DESY Science Café

Retreat of the DESY Particle Physics division

DESY particle physicists at the division's retreat in August

On 29 and 30 August, the scientists of the DESY Particle Physics division had two days of intense discussions. The retreat took place outside DESY in the Mozart Säle in Hamburg to gain the right distance from the busy DESY workplace. The task force teams (on flavour opportunities, scientific computing, feebly interacting particles, the seminar programme, sustainability, third-party funding, detector development and on-site gravitational-wave experiments) presented the status of their deliberations. Focal points of the discussions were internal communication to enable transparency as well as strategic issues for the upcoming preparations for PoF V, the fifth round of the Helmholtz Association's programme-oriented funding.

September

Beamline for Schools winning team from France comes to DESY

"We are very happy to be here and very excited to see how our experiment will go," said Matthieu Ducret from the École du Sacré-Coeur in Reims, France. The 17-year-old was one of seven students who spent two weeks at DESY working like real researchers – including safety briefings, shift work and data analysis. The team "Supercooling" was one of three winning teams of the 2022 high-school competition Beamline for Schools. The other two teams from Spain and Egypt conducted their experiments at CERN. They were supported by scientists from the two research centres.

Team "Supercooling" from Reims, France

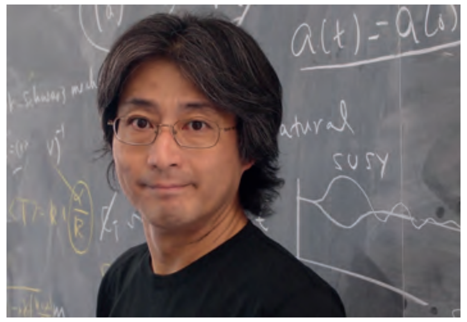
BMBF State Secretary Judith Pirscher visits DESY

Judith Pirscher, State Secretary at the German Federal Ministry of Education and Research (BMBF), accompanied by Hamburg's State Councillor for Science Eva Gümbel, visited DESY in Hamburg to learn about the research centre's current projects and plans for the future. Her conclusion after the visit: "Basic research on large-scale facilities, such as that carried out at DESY, is an innovation driver and a source of impetus, for example in climate protection or the development of new therapeutic agents. In view of today's pandemic, geopolitical and economic challenges, we need it more than ever."

BMBF State Secretary Judith Pirscher (left) and Hamburg State Councillor for Science Eva Gümbel (right) at DESY's synchrotron radiation source PETRA III

Theory Workshop with lecture by Hitoshi Murayama

The 2022 DESY Heinrich Hertz Lecture on Physics for public outreach was held by renowned theoretical particle physicist Hitoshi Murayama from the University of California, Berkeley, USA, and the Kavli Institute for the Physics and Mathematics of the Universe at the University of Tokyo, Japan. His lecture focused on the millennia-old question of humanity: "Where do we come from? Perspectives from Physics". The talk was part of the annual DESY Theory Workshop, which was attended by over 170 scientists.



Hitoshi Murayama

October

Volker Soergel (1931–2022)

DESY mourns the death of Volker Soergel, long-time Chairman of the DESY Board of Directors and pioneer of the united DESY with its locations in Hamburg and Zeuthen. Soergel passed away on 5 October at the age of 91. He was one of the great visionaries of the research centre and key in shaping DESY as it is known today. Under his 12-year leadership, the electron–proton collider HERA progressed from a proposal to a funded project and was completed on time and within budget. At the time, HERA was the largest basic-science project in Germany. Soergel and his successor Bjørn H. Wiik launched the "HERA model" of international cooperation – a major breakthrough in the financing and organisation of large-scale research projects that became a model for the implementation of many other international facilities.

Volker Soergel

A universe of music

Composer and soprano Gloria Bruni in the church of San Fantin, Venice

What happens when particle physics inspires art could be heard on 24 October in the church of San Fantin in Venice, Italy. It was the venue for the world premiere of the concert "Fragments of Creation", a work in which composer and soprano Gloria Bruni translated the creation of the universe into notes and music. DESY was the patron of this world premiere: A visit to DESY and intensive discussions with particle physicist Isabell Melzer-Pellmann, head of the DESY CMS group, rekindled Bruni's interest in the origin and history of the universe and also inspired her art project CREATION.

Science up close: The great questions of humanity

Where do we come from, where are we going? Or: Does the universe have a beginning and an end? From 26 October 2022 to 10 April 2023, the multimedia special exhibition "How it all began: Of galaxies, quarks and collisions" at the Hamburg Museum der Arbeit (Museum of Labour) took visitors to the big bang and the infinity of the universe. The exhibition was a unique cooperation between Universität Hamburg, its Cluster of Excellence Quantum Universe, DESY and Museum der Arbeit. It made Hamburg's top-level research tangible for its citizens and also offered an extensive accompanying programme for children and young people.

ALPS II achieves world record

Even before starting up, DESY's on-site dark-matter experiment ALPS II already broke a world record. The experiment is located in the tunnel of the former HERA accelerator and uses upcycled HERA magnets to (hopefully) send light through a wall in search of axions and axion-like particles. The team managed to store laser light for 6.75 ms – a world record for the longest amount of time laser light spent circulating between two mirrors. This record is a milestone on the way towards starting up the experiment in early 2023. The previous world record of 5.4 ms was held by the PVLAS experiment for quantum electrodynamics in Italy.

November

Three prizes awarded on DESY Science Day

The PhD Thesis Prize of the Association of the Friends and Sponsors of DESY (VFFD) was presented on the DESY Science Day on 23 November. It was awarded in equal parts to Sarah Schröder for her thesis "External injection of electron beams into plasma-wakefield accelerators" and to Andrea Cardini for his thesis "Measurement of the CP properties of the Higgs boson in its decays to τ leptons with the CMS experiment". Both Schröder and Cardini remain as postdocs in the Particle Physics division.

Andrea Cardini, Sarah Schröder and DESY Director Helmut Dosch

The DESY Exceptional Achievements Award was presented to ATLAS engineer Frauke Poblotzki for her work on a CO_2 cooling method for silicon detectors – an eco-friendlier alternative to conventional techniques.

Frauke Poblotzki and DESY Director Helmut Dosch

Nicola Spaldin

Hamburg Prize for Theoretical Physics 2022

The Hamburg Prize for Theoretical Physics 2022 was awarded to Nicola Spaldin, professor of materials theory at ETH Zurich in Switzerland. Spaldin is known for her theoretical prediction of multiferroics, a new class of materials, and the subsequent development of these materials in the laboratory. She is the first woman to receive this award – one of the most highly endowed prizes for physics in Germany.

No violence!

It is appalling that this is still an issue – violence against women. On the International Day for the Elimination of Violence against Women on 25 November, DESY set a sign by making the campaign colour orange the colour of the campus.

FLASH experimental hall illuminated in orange on the International Day for the Elimination of Violence against Women

December

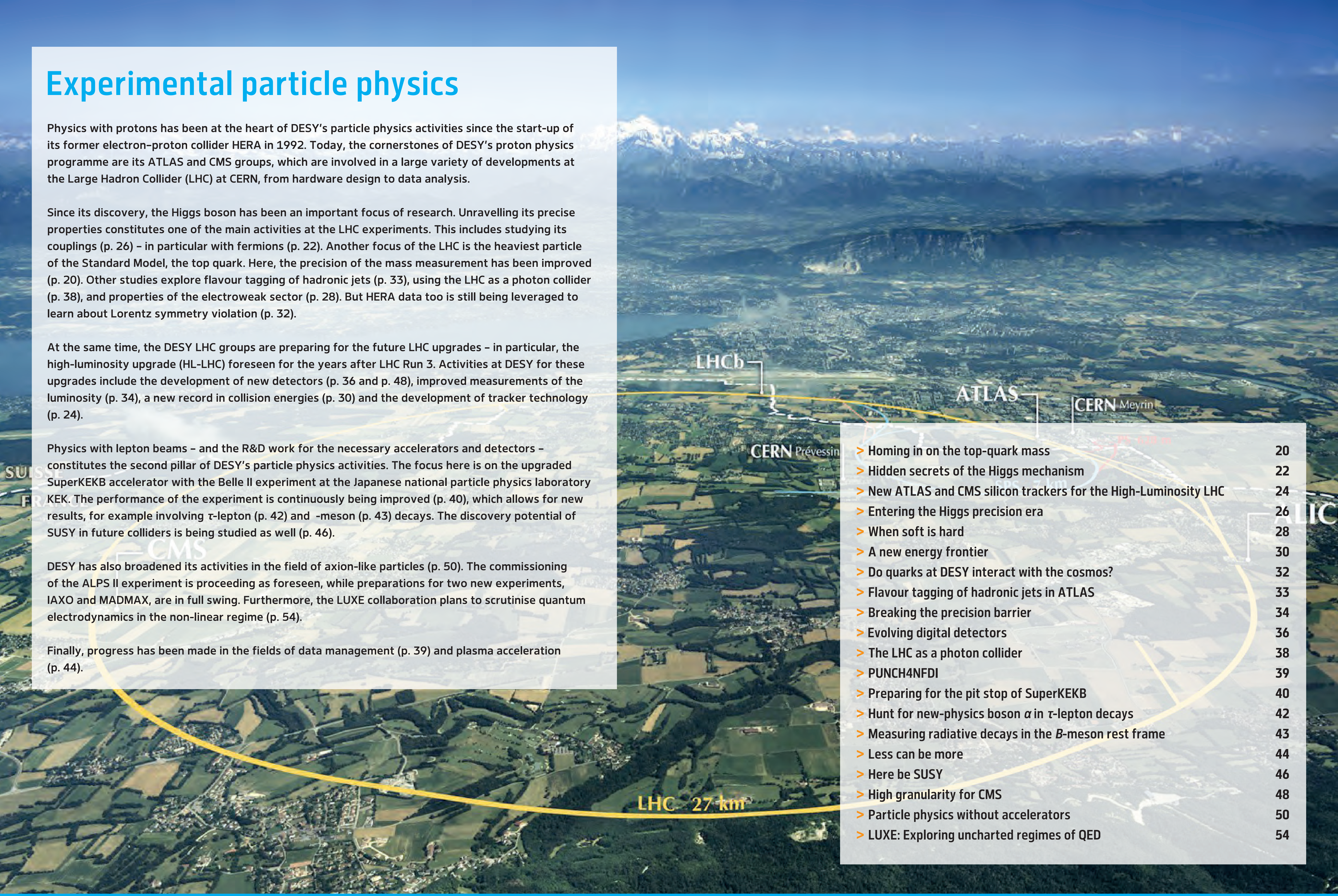
DESY publishes its first sustainability report

DESY's first sustainability report entitled "Providing impulses. Doing sustainable research." for the period 2019–2021 was published in December. In addition to presenting reliable figures, concrete activities, interim goals and interesting ideas, the 36-page document features inspiring stories about the people on the campus who are behind the main projects and sustainable strategies. The clear message is: DESY is on the right track.

Providing impulses.
Doing sustainable research.

DESY Sustainability Report
2019–2021

SUSTAINABLE
DESY.



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 its couplings (p. 26) – in particular with fermions (p. 22). Another focus of the LHC is the heaviest particle of the Standard Model, the top quark. Here, the precision of the mass measurement has been improved (p. 20). Other studies explore flavour tagging of hadronic jets (p. 33), using the LHC as a photon collider (p. 38), and properties of the electroweak sector (p. 28). But HERA data too is still being leveraged to learn about Lorentz symmetry violation (p. 32).

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 new detectors (p. 36 and p. 48), improved measurements of the luminosity (p. 34), a new record in collision energies (p. 30) and the development of tracker technology (p. 24).

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. 40), which allows for new results, for example involving τ-lepton (p. 42) and -meson (p. 43) decays. The discovery potential of SUSY in future colliders is being studied as well (p. 46).

DESY has also broadened its activities in the field of axion-like particles (p. 50). The commissioning of the ALPS II experiment is proceeding as foreseen, while preparations for two new experiments, IAXO and MADMAX, are in full swing. Furthermore, the LUXE collaboration plans to scrutinise quantum electrodynamics in the non-linear regime (p. 54).

Finally, progress has been made in the fields of data management (p. 39) and plasma acceleration (p. 44).

Homing in on the top-quark mass

New concepts enable measurements of this fundamental parameter at CMS

The top quark is by far the most massive elementary particle we have discovered so far. Due to its large mass, it is of particular relevance to the Standard Model (SM), our theoretical description of nature at the smallest distances we can experimentally probe. Since the discovery of the top quark, considerable theoretical and experimental effort has been put into the measurement of its mass, which is a key parameter in assessing the internal consistency of the SM and which is needed for precise predictions in the SM and beyond. The DESY CMS group has conducted two measurements of the top-quark mass using new concepts, which help to bridge the gap between theory and experiment.

New ways to measure the top-quark mass

The SM of particle physics has 19 free parameters, which cannot be predicted from first principles, but have to be measured experimentally. The top-quark mass m_t is one of these free parameters, and it is paramount for testing the SM and obtaining precise predictions at the LHC. With a mass of about 173 GeV, it is the most massive elementary particle we know of. Latest direct measurements achieve an uncertainty of less than 0.4 GeV, but it is difficult to interpret these measurements. There are effects connected to the nature of the strong force at energies below 1 GeV, where bound states of quarks are formed, that possibly dilute these direct measurements. It is presently unknown precisely how large this dilution is, with a number of theoretical studies ongoing.

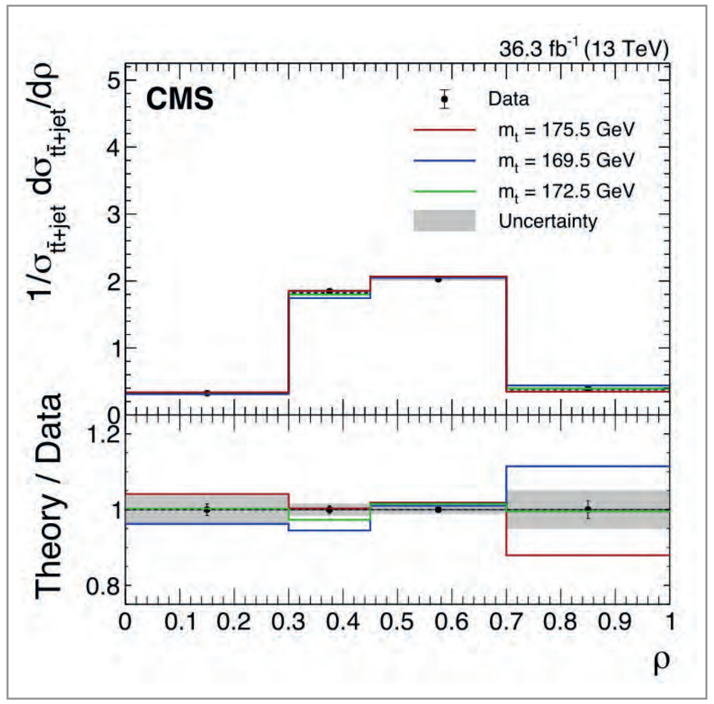


Figure 1

Measured distribution for top-quark pair production in association with a jet (black markers), compared to predictions using different top-quark masses [1]

The large amount of data recorded by the CMS experiment allows us to develop new approaches to measure m_t. Direct measurements need to account for non-perturbative effects such as multiple-parton interactions and the formation of hadrons. Members of the DESY CMS group have devised methods to determine m_t indirectly from the production cross section of top-quark pair ($t\bar{t}$) production, measured as a function of a variable sensitive to m_t. In these studies, we can determine the value of m_t in a theoretically well-defined scheme and measure it in a regime where the modelling of non-perturbative effects plays a minor role.

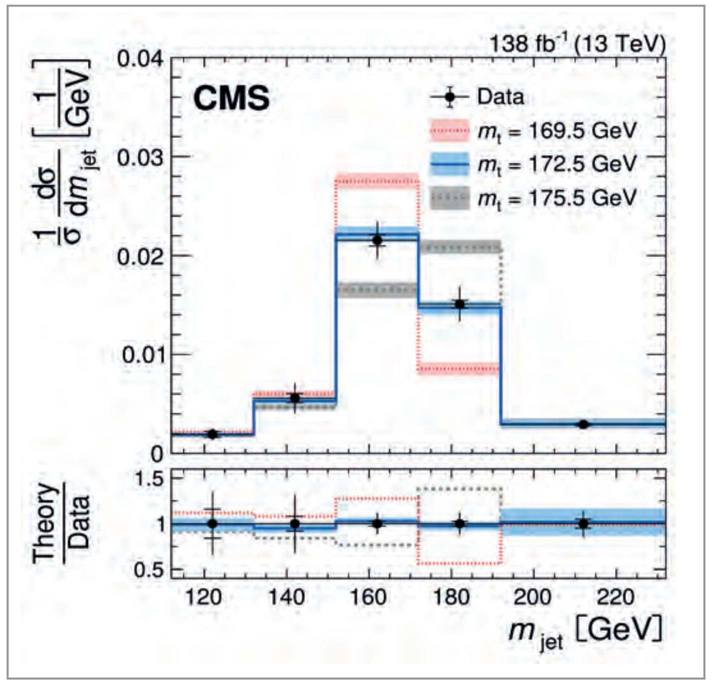
Top quarks and additional jets

In about one third of the $t\bar{t}$ events at the LHC, the $t\bar{t}$ system is produced in association with an additional energetic jet ($t\bar{t}$+jet). As the strength of the radiation depends on m_t, a measurement of $t\bar{t}$+jet production has higher sensitivity to m_t than a measurement of $t\bar{t}$ production agnostic of additional radiation.

We devised a measurement of $t\bar{t}$+jet production as a function of a variable related to the mass of the $t\bar{t}$+jet system, called ρ. We selected $t\bar{t}$+jet events with two charged leptons, neutrinos and jets, because of the clean signature of this decay channel. In these events, the reconstruction of the $t\bar{t}$+jet system is a challenge because of the two undetected neutrinos. We tackled this using a machine learning technique, which improved the experimental resolution significantly compared to previous approaches. This allowed us to reconstruct ρ close to the production threshold of the $t\bar{t}$+jet system, corresponding to $\rho \approx 1$, where the largest sensitivity to m_t is observed.

Figure 3

Measured probability distribution for producing a top-quark jet with a given mass in top-quark pair production. The measurement (black markers) is compared to the distributions predicted for different top-quark masses [2].



The cross section measurement was corrected for detector effects using state-of-the-art analysis techniques. It is shown in Fig. 1. From a fit of the theoretical predictions, calculated by theorists from Universität Hamburg, a value of m_t = 172.93 ± 1.36 GeV was extracted [1].

Top quarks with large Lorentz boosts

When the top quark is produced at rest, the decay into three quarks results in three separate jets. These can be used to fully reconstruct the top-quark decay and measure m_t, with the most precise direct measurements being based on this signature. Because of its large mass, it is rare for the top quark to receive a high Lorentz boost such that all three quarks from its decay end up in the same jet. Even though these events are rare, we found more than 40 000 of them in the large amount of CMS data. We applied a novel method of reconstructing these events to capture the full top-quark decay inside one jet, which enabled us to reconstruct a large jet with three sub-jets inside. An example for such an event [3] is shown in Fig. 2.

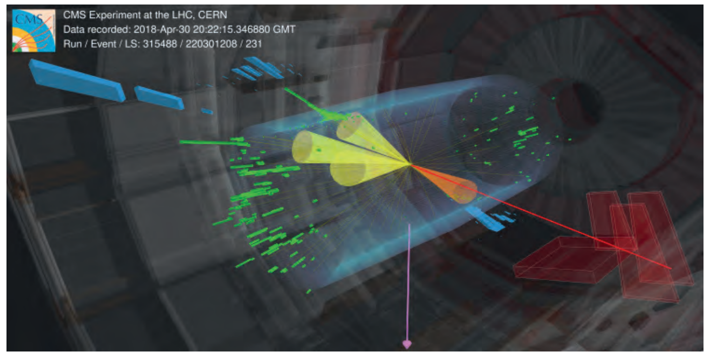


Figure 2

Event recorded with the CMS detector, consistent with the signature of a highly energetic top-quark pair. One top quark decays into three quarks and the other into one *b* quark, one muon (the red line) and one neutrino, which is not detected. The reconstructed jets are shown as yellow and orange cones, with the three jets on the left corresponding to the top-quark decay into three quarks [3].

We measured the $t\bar{t}$ cross section as a function of the jet mass, which is very sensitive to the value of m_t. The many events in the data allow for a precise calibration of our large jets as well as a detailed study of the influence of additional radiation in our simulation, which can affect the jet mass. The measured distribution of the jet mass, corrected for detector effects, is shown in Fig. 3. Comparing the data to the predictions from simulated $t\bar{t}$ production shows how much this distribution would change if the top-quark mass were different. We used this comparison to perform a statistical test, resulting in a precise top-quark mass of 172.76 ± 0.81 GeV [2].

The measurement at high Lorentz boosts is affected by very different effects than the measurement at threshold production in $t\bar{t}$+jet production. We found remarkable agreement between the two results, with complementary sources of systematic uncertainties. The two approaches deepen our understanding of the top-quark mass as a fundamental SM parameter. In the future, a simultaneous determination of m_t using these two measurements will become possible.

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References:

[1] CMS Collaboration, arXiv:2207.02270 [hep-ex]
[2] CMS Collaboration, arXiv:2211.01456 [hep-ex]
[3] CMS Collaboration, https://cms.cern/news/jet-cones-top-flavour

Hidden secrets of the Higgs mechanism

Fermions probe the Higgs sector

In the Standard Model and in many of its extensions, the Brout–Englert–Higgs mechanism is responsible for generating the masses of the weak bosons and fermions. A large data set of proton–proton collisions recorded at the LHC is used to gain deeper insights into the Higgs mechanism and uncover those of its secrets that are still hidden from us. Final states with fermion pairs are a powerful probe for these studies, in which the DESY CMS group is strongly involved.

Ten years have passed since the discovery of a scalar boson with a mass near 125 GeV by the ATLAS and CMS collaborations at the LHC. Over the past decade, the properties of this particle have been studied in great detail, exploiting a multitude of experimental signatures. The measurements performed so far confirm the hypothesis that the discovered particle is the Higgs boson that arises in the Standard Model (SM) as a result of the Brout–Englert–Higgs mechanism of electroweak symmetry breaking. Nevertheless, more comprehensive studies involving yet unexplored channels and using a larger data set are needed to deepen our understanding of the electroweak symmetry breaking mechanism.

The SM Higgs boson with a mass near 125 GeV decays most frequently into a bottom-quark pair with a branching ratio of about 58%. This decay mode is used to study the vector boson fusion (VBF) production of the Higgs boson (Fig. 1). This process, which is very clean as no particle of colour charge is directly involved, has the second largest cross section at the LHC and, due to large momentum transfers, it is particularly sensitive to momentum-dependent anomalous couplings of the Higgs boson to *W* and *Z* bosons.

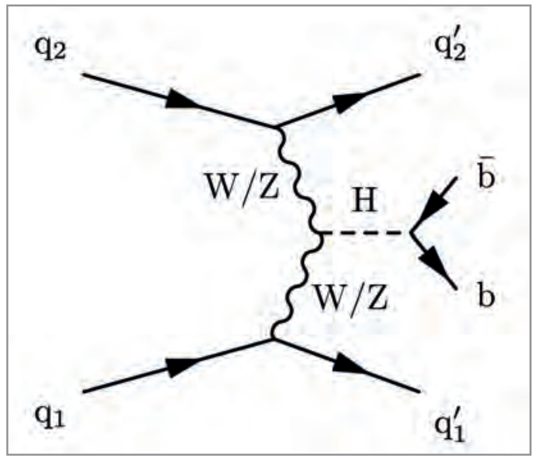

Figure 1
Feynman diagram for VBF Higgs-boson production followed by $H \rightarrow b\bar{b}$ decay

The CMS collaboration carried out a dedicated analysis with participation of researchers from DESY to study VBF production followed by $H \rightarrow b\bar{b}$ decay with 91 fb^{-1} of data collected at a centre-of-mass energy of 13 TeV [1]. The analysis targeted distinct signatures of the signal process – the resonant production of a central bottom-quark pair from the Higgs-boson decay and two additional jets mainly produced in the forward and backward directions relative to the beamline, which consequently have a large rapidity gap between them as well as high invariant mass. The detection of a signal in this channel is challenged by a large background from quantum chromodynamics multijet production, which has a nearly eight orders of magnitude higher cross section than the VBF signal. To distinguish the signal from the background, state-of-the-art machine learning techniques were applied. Events compatible with the signal signatures were classified into multiple event categories with varying signal-to-background ratio using boosted decision trees.

The signal was extracted from the distributions of the reconstructed invariant mass of a bottom-quark pair, $m_{b\bar{b}}$, in all categories. Figure 2 presents the $m_{b\bar{b}}$ distribution combining all categories. The contribution of each category to the combined distribution is weighted with the respective signal-to-background ratio. The $m_{b\bar{b}}$ spectrum exhibits a clearly visible contribution from the $H \rightarrow b\bar{b}$ signal at 125 GeV. The signal strength, defined as the probed rate of the signal process relative to the rate predicted in the SM, is measured to be $\mu = 0.97 \pm 0.49$, perfectly consistent with the SM prediction. The VBF signal is observed with a significance of 2.4 standard deviations relative to the background prediction. Very convincingly, at slightly lower mass, a peak originating from $Z \rightarrow b\bar{b}$ decays is also visible, just as expected, which serves as a standard candle. The larger data set expected in LHC Run 3 will facilitate differential measurements in this channel, such as measurements of the distribution of the Higgs-boson transverse momentum, which is particularly sensitive to potential effects induced by new physics beyond the Standard Model (BSM).

Fermionic decay modes are also excellent signatures in direct searches for additional Higgs bosons predicted by BSM theories. An example is two Higgs doublet models, which predict two neutral CP-even, one neutral CP-odd and two charged Higgs bosons. DESY scientists have made crucial contributions to the search for additional neutral Higgs bosons decaying to a pair of tau leptons [2]. The study was performed on 138 fb^{-1} of Run 2 data collected with the CMS experiment, covering a wide mass range from 60 GeV up to 3.2 TeV. The analysis targeted two production mechanisms of additional Higgs bosons – by fusion of two gluons and by production in association with *b* quarks. Four decay modes of tau-lepton pairs – $\tau_e\tau_\mu$, $\tau_\mu\tau_h$, $\tau_e\tau_h$ and $\tau_h\tau_h$ – were analysed. Here, τ_μ (τ_e) denotes the leptonic decay of a tau lepton into an electron (muon), τ_h stands for its hadronic decay.

The analysis profited greatly from a novel algorithm employed to identify hadronic decays of a tau lepton. The algorithm combined low-level detector information with a set of high-level observables characterising τ_h by means of a convolutional neural network. The approach increased the identification efficiency of genuine hadronic decays of tau leptons by about 20%, while reducing the corresponding rate of misidentification by 25% compared to the previously used algorithm.

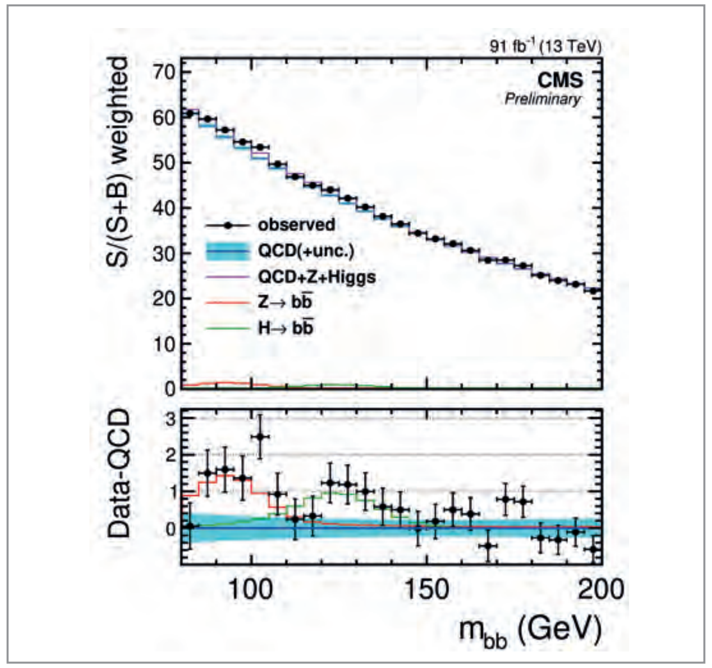

Figure 2
m_{bb} distribution from the CMS analysis targeting VBF production followed by $H \rightarrow b\bar{b}$ decay

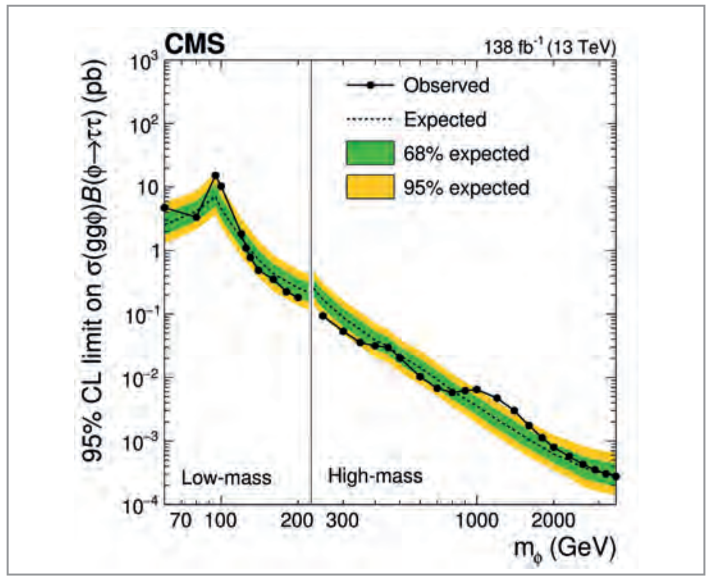

Figure 3
Upper 95% CL limit on the cross section of Higgs-boson production via gluon–gluon fusion times the $H \rightarrow \tau\bar{\tau}$ branching ratio as a function of the probed Higgs-boson mass

The analysis classified the selected events into two event categories based on the number of identified hadronic jets produced by the hadronisation of *b* quarks accompanying a pair of tau leptons. Events with at least one *b*-tagged jet target the *b*-quark-associated production of neutral Higgs bosons, while events with no identified *b*-jets target production by gluon–gluon fusion. The distribution of the reconstructed invariant mass of tau leptons was inspected for any traces of additional neutral Higgs bosons.

The data revealed two excesses for the gluon–gluon fusion production at probed masses of 0.1 and 1.2 TeV, each of them with local *p*-values equivalent to about 3 standard deviations. The results of the search were interpreted in terms of upper 95% confidence level (CL) limits on the production cross sections times the branching ratio of the $HH \rightarrow \tau\bar{\tau}$ decays and in terms of constraints on the parameters of the BSM theories. As an example, Fig. 3 presents an upper 95% CL limit on the gluon–gluon fusion cross section times the $HH \rightarrow \tau\bar{\tau}$ branching ratio as a function of the probed Higgs-boson mass, m_φ. For both production modes, limits range between 0.2–0.5 fb at $m_\varphi > 3$ TeV and 2–15 pb at $m_\varphi < 100$ GeV. More data, as they are currently being collected in LHC Run 3, should help us to clarify whether these excesses are merely statistical fluctuations or indeed the first hints of new physics.

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References:

[1] CMS Collaboration, CMS-PAS HIG-22-009
[2] CMS Collaboration, arXiv:2208.02717 [hep-ex]

New ATLAS and CMS silicon trackers for the High-Luminosity LHC

The big task of building the next generation of tracking detectors

The ATLAS and CMS collaborations are preparing for the required detector upgrades to fully benefit from the era of the High-Luminosity LHC (HL-LHC) at CERN, which is to start after the LHC shutdown till 2027. Both detector groups at DESY are heavily involved in the design and construction of the new silicon tracking detectors, concentrating on the respective end-cap detector segments. In 2022, the two projects made big steps towards the production of the detector components and the development of integration tooling and related procedures in the large cleanroom facilities of the Detector Assembly Facility (DAF) at DESY.

New trackers for ATLAS and CMS

With the high-luminosity upgrade of the LHC on the horizon at CERN, new tracking detectors are required for the two main experiments, ATLAS and CMS, placing high demands on the detector performance and radiation tolerance of the components used. The ATLAS and CMS groups at DESY have committed to assembling one of the end-cap segments of the respective trackers each.

The ATLAS Inner Tracker (ITk) will replace the currently operating inner detector to cope with the higher requirements of the HL-LHC conditions. The DESY ATLAS group is one of the leading forces in the worldwide collaborative effort of the ITk project and delivers key contributions to the design, production and construction of the strip end-cap detector. The main building blocks of the end-cap are so-called petals – core structures with six different types of silicon strip modules glued on both sides and a data concentrator board, called the end-of-substructure, at the end. In total, 192 petals will be arranged in six disks covering a volume of 2 m in diameter and 1.5 m in length, located in the forward directions of the detector.

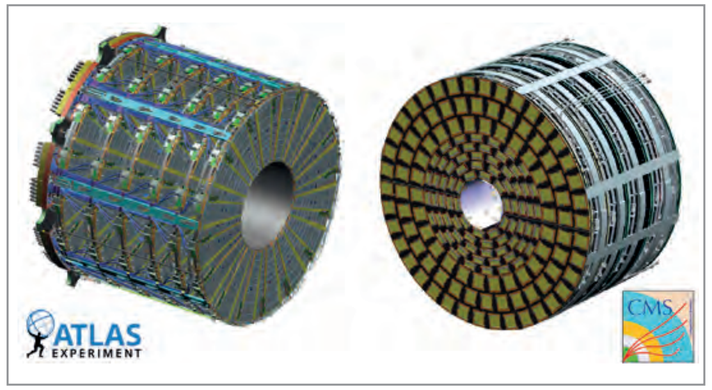

Figure 1

Comparison of the design concepts for the two tracking-detector end-caps of the ATLAS Inner Tracker (left) and the CMS Outer Tracker (right)

The CMS Phase-2 Outer Tracker is the foreseen upgrade of the tracking detector in the CMS experiment. The DESY CMS group is highly engaged in the design, production and construction of the tracker end-cap detector (TEDD). It consists of five double disks (DD), with each DD having four surfaces with modules arranged to cover the full area with sensitive detector components, resulting in at least one hit from a traversing particle. The smallest mechanical substructure is a half disk (Dee), with each DD consisting of four Dees. Figure 1 compares the design concepts of the ATLAS and CMS end-cap structures being assembled at DESY.

Due to the global shortage of components, long lead times caused by interrupted supply chains and rising material prices, the Phase-2 upgrade projects for the HL-LHC have faced and continue to face several challenges. But these are being tackled by the motivated and well-trained teams of technicians, engineers and physicists of the DESY ATLAS and CMS groups.

Integration tooling for the ATLAS ITk end-cap

In addition to producing the silicon sensor modules, manufacturing the mechanical core structure and combining these into fully loaded petals, the ITk team at DESY is also in charge of developing procedures and tooling for installing the petals in the end-cap global structure.

For the insertion operation, the engineering team designed a combination of two tools, called the insertion hand and the insertion tower. The insertion hand mechanically grabs and protects the petal with its thin and sensitive silicon sensors connected to the electrical readout boards by tiny wire bonds. In the next step, the hand can be attached to the insertion tower, which allows manual movements defined by the operator to insert the petal into the openings of the vertically oriented global support structure. Finally, the petal can be lowered and secured in its dedicated position in the end-cap. This insertion procedure was thoroughly tested and improved in the DAF assembly hall (Fig. 2). After successful demonstration, production of the final tool sets is progressing at DESY.

Moreover, tools for the transport and integration of the end-caps into the other parts of the ITk detector at CERN need to be designed, constructed and tested. To this end, the team designed a so-called superframe (Fig. 3), which allows both stable mounting of the global end-cap structure in the vertical orientation during petal insertion and rotation of the full end-cap into the horizontal position for transport and integration into the full detector at CERN.

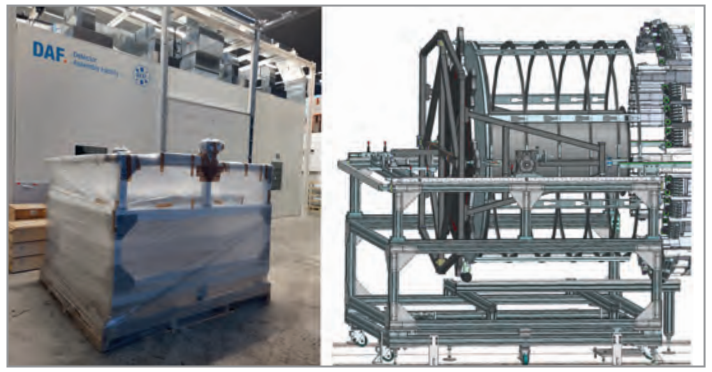

Figure 3

Delivery and testing of the superframe tool for handling the global end-cap structure for insertion and transport to CERN

CMS double-disk assembly

To allow the handling of the large and fragile Dees for the CMS outer tracker end-caps, they are supported by a so-called Arc frame. The Arc frame itself forms the interface to the various tools of the TEDD integration procedure.

During design, special care was taken to ensure negligible mechanical stress on the Dees throughout the process, especially when combining the Arcs to rings and to double rings in the DD assembly. The tooling to assemble DDs was fully constructed and verified (Fig. 4). Two major milestones were achieved: a disk assembly from the two available Dee prototypes and a DD assembly using mechanical dummies.

Figure 4

Final DD assembly tooling. The left part for disk assembly comprises a fixed Dee portal and precision stages to align the second Dee. The rail frame on the right serves as pick-up for the disk and the final disk-to-disk alignment.

The assembly of a disk from the two available Dee prototypes yielded an object with excellent flatness. A laser scan of the final disk is shown in Fig. 5 (left). The goal of maintaining a flatness that is no worse than the flatness of the individual Dees was achieved.

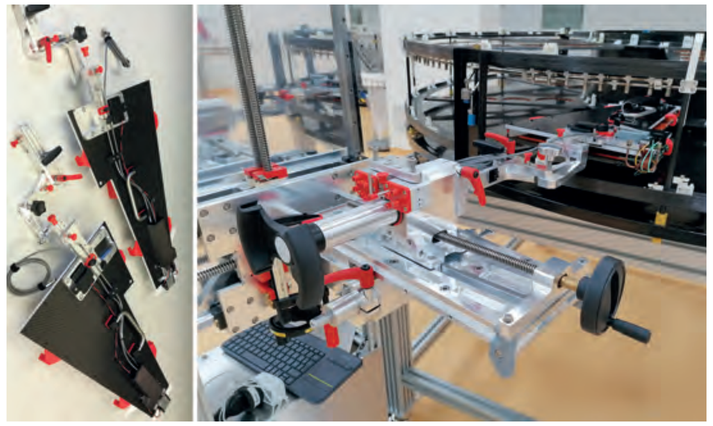

Figure 2

Insertion of petals into the end-cap structure by the insertion hands (left) attached to the insertion tower, as tested in trials with a dummy end-cap structure (right)

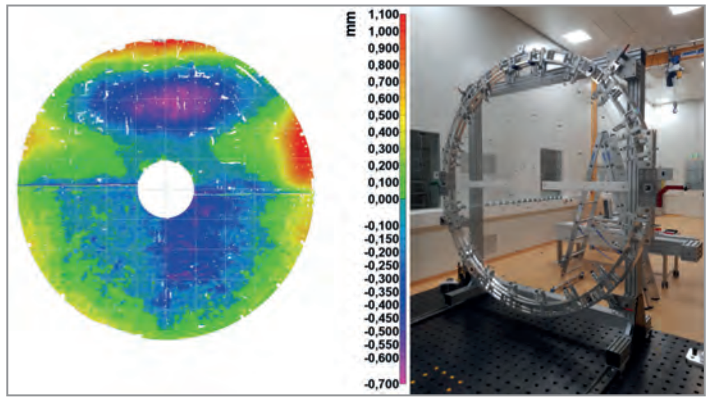

Figure 5

Left: Laser scan of the first disk assembled using Dee prototypes. Right: First DD assembly using acrylic dummy Dees.

The assembly of a DD using dummy acrylic Dees was completed to verify the entire procedure. The final object is shown in Fig. 5 (right). Although flatness testing of the dummy object was not possible, the Arc frame flatness was measured to be below 0.7 mm, showing that the DD is not affected by the tooling in this process. The next milestone will be the assembly of a DD using the four preproduction Dees, manufacturing of which has started.

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Entering the Higgs precision era

Anniversary celebrated with most precise measurements to date

Monday, 4 July 2022, marked the tenth birthday of the Higgs boson. Its discovery proved the existence of the Higgs field, which interacts with elementary particles, thereby giving them mass. However, open questions remain, such as on the exact nature of the Higgs field or whether further Higgs bosons exist. We may find answers to these questions by measuring very precisely how the Higgs boson interacts with other particles and even itself. To that end, the DESY ATLAS and CMS groups helped to push precision levels to unprecedented heights with their contributions to Higgs-boson measurements in different decay channels and their statistical combination.

Since its discovery, the number of Higgs-boson events recorded by ATLAS and CMS has grown by a factor 36, increasing the precision of measurements across all channels and allowing us to also explore the rarer channels. To determine the strength of the interaction between the Higgs boson and other particles, the so-called couplings, measurements from many channels need to be combined, as individually they can only measure the product of production and decay rate. The results of such combinations performed by ATLAS and CMS were published in *Nature* to celebrate the anniversary of the Higgs-boson discovery [1, 2].

The Higgs boson and its friends

Both ATLAS and CMS combined measurements of single-Higgs-boson event rates in different channels to study the interactions between the Higgs and other particles. The latest results from the discovery channels, where the Higgs boson decays into a pair of vector bosons or photons, were included in these combinations, together with measurements of Higgs-boson decays to pairs of the heavier fermions, such as *b* quarks and τ leptons. As the coupling between the Higgs and another particle is proportional to the mass of the particle, decays involving lighter particles such as muons are rarer. But thanks to the large data set collected during LHC Run 2, this channel was also explored by both collaborations, and ATLAS additionally included results from the decay to *c* quarks. Moreover, both collaborations included the very rare decay to a $Z\gamma$ pair. Searches for Higgs decays to *invisible* final states, i.e. to particles arising from beyond the Standard Model (BSM) theories that do not interact with ordinary matter and are therefore invisible to the detector, were also considered.

With this wealth of data, Higgs-boson production cross sections, branching fractions and couplings were measured with unprecedented precision. Across both experiments and in all aspects, the observations agreed remarkably well with the predictions from theory.

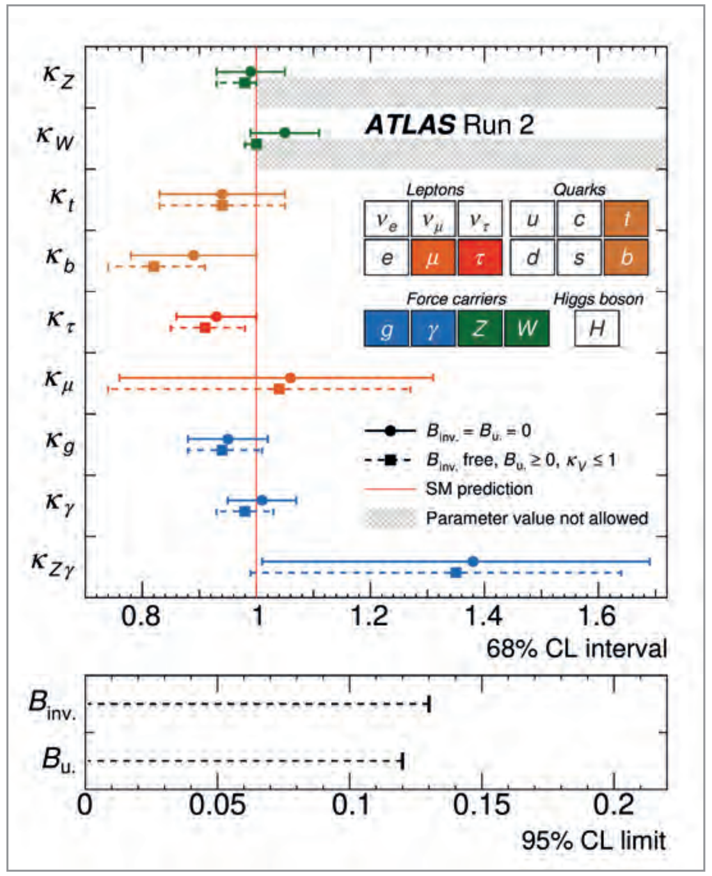

Figure 1

Measurements of the coupling modifiers parametrising the Higgs-boson interactions with other SM particles, with (dashed lines) or without (solid lines) allowing invisible and undetected Higgs-boson decays. The bottom panel shows upper limits on the branching fractions of such decays.

Coupling measurements were performed in the so-called κ framework, where the κ factors are modifiers of each individual coupling and are equal to 1 in case of perfect agreement with the Standard Model (SM). Figure 1 shows an example from the ATLAS results, where in one scenario decays of the Higgs boson into invisible or undetected final states are explicitly allowed. This means that particle loops in its production or decay are parametrised with effective coupling modifiers, allowing for BSM particles to appear in these loops. The total Higgs decay width can then be exploited to derive upper limits on the branching fractions of those unmeasured decays.

The Higgs boson all by itself

While we can learn much from continuing the journey on improving the precision of single-Higgs measurements discussed above, searches for double-Higgs (*HH*) production are critical to understand the nature of the Higgs boson. Observing *HH* production will allow us to measure the strength of Higgs-boson self-interactions, which is responsible for the shape of the Higgs potential. Experimentally, *HH* production presents a great challenge, as it is expected to be very rare at the LHC. Nevertheless, both the ATLAS and CMS collaborations performed searches for *HH* production already with Run 2 data.

The CMS collaboration included the most recent combination of such searches in the anniversary publication, reporting a sensitivity beyond all expectations, boosted by rapidly evolving analysis techniques and machine learning methods. The combined measurements were interpreted in the κ framework, similar to the single-Higgs coupling measurements. Here, the Higgs self-coupling is modified by κ_λ. Figure 2 shows upper limits set on κ_λ as derived from single-Higgs and double-Higgs measurements, demonstrating superior sensitivity in the direct *HH* production measurements. However, with the current data set, even this result is only able to set a limit of roughly seven times the SM expectation.

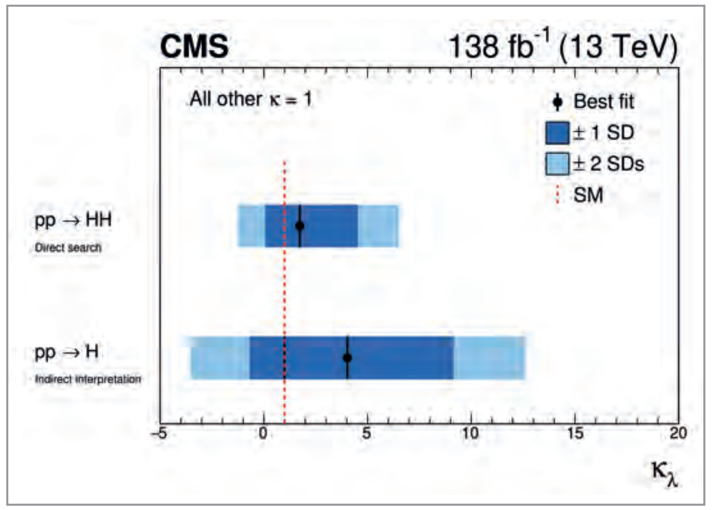

Figure 2

Upper limits on the Higgs self-coupling modifier extracted from single- and double-Higgs production processes

A bright future ahead

In the coming years, we expect even better precision from the Run 3 data set, followed by the HL-LHC era. Figure 3 demonstrates how the sensitivity evolved from the time of the Higgs discovery in 2012 to the end of Run 2. In addition, it provides a prediction for the improvements at the end of the HL-LHC era. As can be seen, we expect to be able to measure most of the Higgs couplings with a precision of a few percent, which will greatly enhance our understanding of the SM. Furthermore, with growing statistics and improvements in analysis techniques, we expect that rare processes such as double-Higgs production will become accessible.

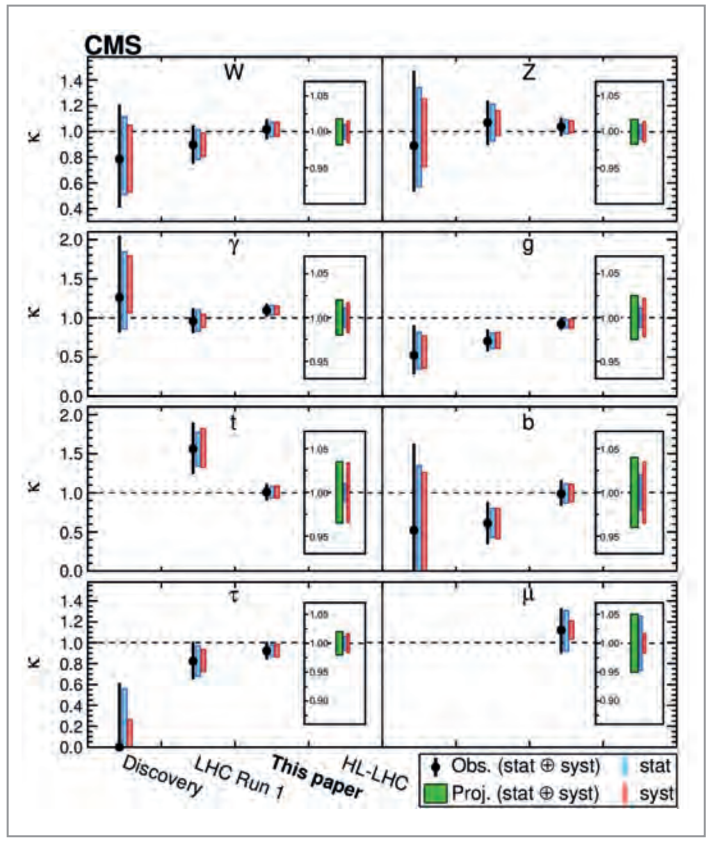

Figure 3

Measurements of the coupling modifiers parametrising the Higgs-boson interactions with other SM particles and projections to the HL-LHC era

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[1] ATLAS Collaboration, Nature 607, 52–59 (2022)
[2] CMS Collaboration, Nature 607, 60–68 (2022)

When soft is hard

Studying quantum chromodynamics in events with one or two bosons

In high-energy proton–proton collisions at the LHC, the production of electroweak bosons, such as *Z* bosons, is regarded as a standard measurement tool, an excellent probe of both the Standard Model of particle physics itself and the accuracy of calculations and simulations based on it. Two DESY teams, one from CMS and one from ATLAS, performed measurements of hadronic jets in events with a *Z* boson and with a *Z* boson and a photon, respectively. These measurements can provide fundamental tests of quantum chromodynamics (QCD).

Hard and soft

QCD predictions need to describe very different processes: The "hard" reaction, such as quark–antiquark annihilation to a *Z* boson and the subsequent decay to leptons, can be calculated through perturbation theory up to a certain precision in the order of the strong coupling constant.

Other contributions include the parton structure inside the proton as well as cascades, i.e. showers, of soft and collinear radiation. The latter part is often dealt with in cross section calculations by resummation of so-called Sudakov logarithms. Monte Carlo event generators, on the other hand, usually approximate it through the generation of parton showers.

Angles to disentangle

The CMS collaboration recently published a measurement of angular correlations in *Z*+jets production [1]. The production of partons accompanying the *Z* boson results in a non-zero value of the *Z*-boson transverse momentum. Depending on this momentum, different observables were used to probe various aspects of QCD, such as multiple parton interactions or soft-gluon radiation.

The *Z*+jets production cross section was measured as a function of the jet multiplicity and of the azimuthal correlation between the *Z* boson and the most energetic jet for various regions of the transverse momentum of the *Z* boson. The measurements were compared with several predictions that systematically merge hard-scatter matrix elements at leading and next-to-leading orders in QCD. Predictions based on transverse-momentum-dependent parton distributions (TMD) and corresponding parton showers [2, 3] were of particular interest.

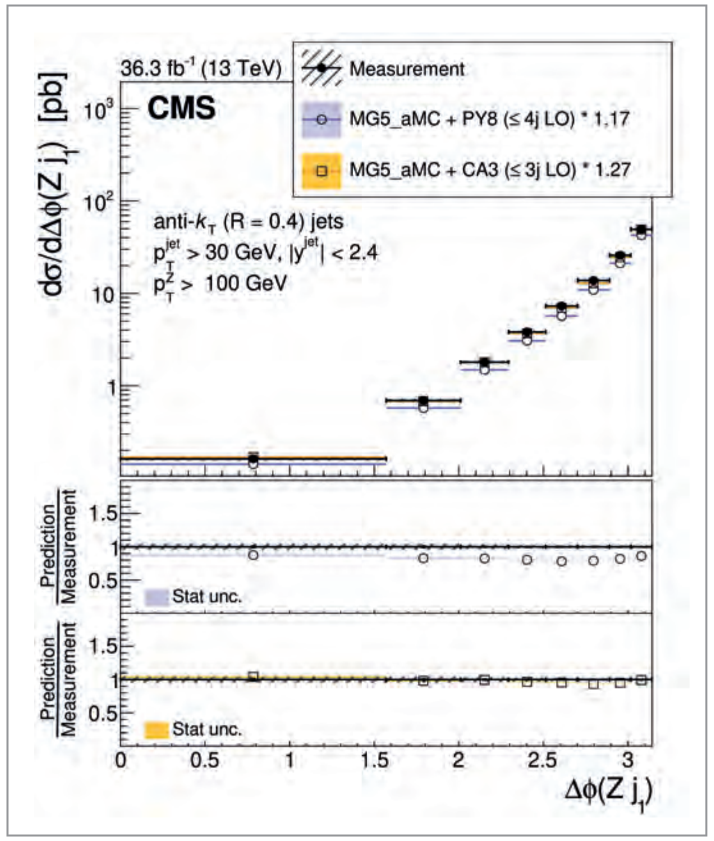

Figure 1

Measurement of the azimuthal separation between the *Z* boson and the most energetic jet compared to predictions from Madgraph+Pythia8 (blue) and Madgraph+Cascade3 (TMD showers) (yellow)

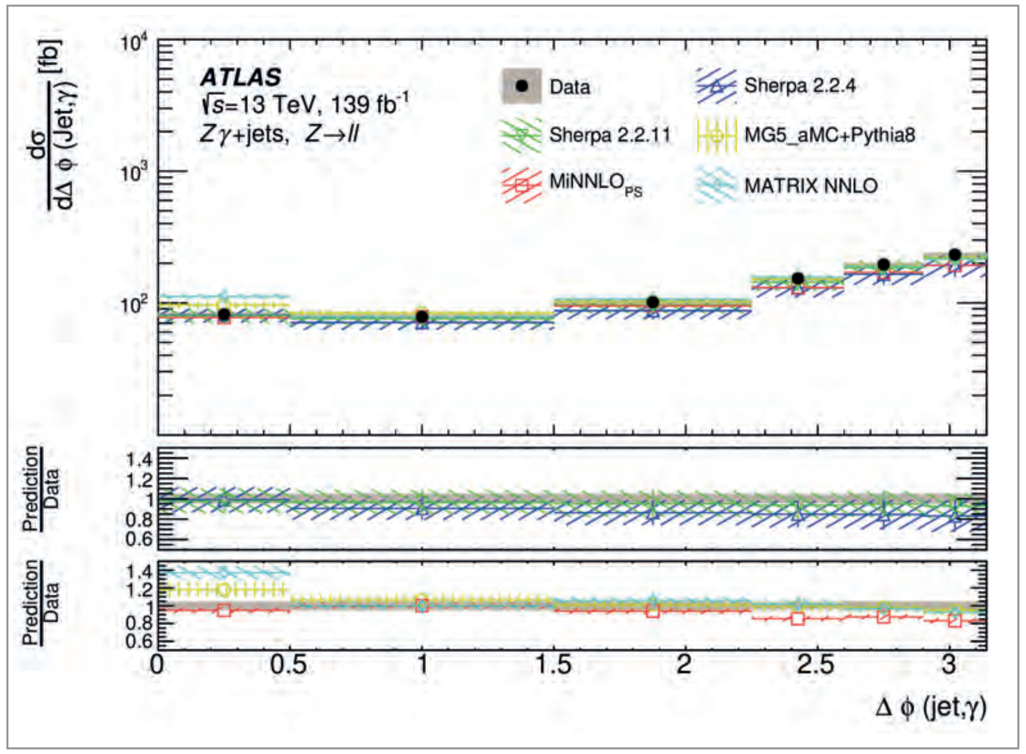

Figure 2

Measured differential cross sections as a function of the azimuthal angle between the photon and the leading jet. The bottom panels show the ratio of different Standard Model predictions to the measured cross section.

The measurement of the azimuthal separation between the *Z* boson and the most energetic jet is depicted in Fig. 1 for high transverse momenta of the *Z* boson. The Madgraph+Cascade3 prediction, which includes TMD showers, provides a good description of the region around *π*, where the simple back-to-back topology can be modified by multiple soft partonic emissions. In this region, multiple parton interactions and higher jet multiplicities are not important.

Illuminating QCD

The ATLAS collaboration recently published a measurement of jets produced together with a *Z* boson and a photon [4]. The measurement was performed in a fiducial phase space enhanced in photons from initial-state radiation.

Differential cross sections were measured as functions of the kinematics of jets, leptons and photons. Both one-dimensional and two-dimensional distributions were chosen to probe soft collinear radiation in different regimes of the energy of the hard-scatter process. Observables sensitive to the polarisation of the *Z* boson were measured as well. All measurements were compared with predictions from Monte Carlo generators involving different precision levels of multileg-merging at leading and next-to-leading order in QCD, as well as recent predictions at next-to-next-to-leading order and fixed-order calculations.

As an example, the measured azimuthal angle between the photon and the leading jet is shown in Fig. 2. As can be seen, the Monte Carlo generators (Sherpa, MG5_aMC+Pythia8 and MiNNLOPS), which include parton shower estimates, describe the data reasonably well, whereas MATRIX, a fixed-order calculation without parton shower or resummation correction, is more challenged at low angular separation.

What's next

Cross section measurements of boson production in association with hadronic jets can be used to test the Standard Model and to validate and improve theoretical predictions. The measured distributions and their selection algorithms are or will be made public to allow for further study by anyone interested and to ultimately improve QCD predictions.

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A new energy frontier

DESY groups analyse record-breaking collisions

In July 2022, the LHC resumed proton–proton collisions after three years of scheduled maintenance and upgrades. Through numerous improvements and hardware upgrades, the accelerator reached a new record in collision energy, marking the start of an extended data-taking period known as Run 3. Almost immediately, particle physicists worldwide were busy analysing the fresh data, working on early measurements that are crucial to scrutinise the performance of the different LHC experiments. DESY scientists working on the LHC experiments were among the first to rigorously analyse this data, with the DESY CMS and ATLAS groups helping to produce the first two measurements of LHC Run 3 in record time.

A tale of two top quarks

The start of the LHC data taking in 2022 was an exciting time for the DESY ATLAS and CMS groups, who were among the first to study the physics of collisions at the new energies of Run 3. Both groups turned their sights towards the top quark, the heaviest known fundamental particle and a key piece to the Standard Model of particle physics. Using different techniques, the two experiments independently explored the rate at which pairs of top quarks are produced in proton–proton collisions at the new LHC beam energy. In particle physics, this rate is determined by a quantity called the cross section, which is predicted to rise by 10% at the new LHC operating energy. This rise provided scientists with a first target to test their models, probing the behaviour of particles at energies never before created in a lab environment.

The top quark, as the particle with the largest mass, has a special place in the Standard Model. Its mass arises as a consequence of its strong interaction with the Higgs boson, first observed at the LHC in 2012 in a landmark co-discovery by the CMS and ATLAS experiments. Measurements of the top quark can thus also provide insight into the remaining mysteries of the Higgs sector of the Standard Model.

At the same time, its large mass causes the top quark to be very unstable and decay much faster than other quarks, producing a unique ensemble of different objects, such as electrons, muons and collimated clusters of particles referred to as jets (Fig. 1). In order to measure this assortment of particles, many different components of the CMS and ATLAS experiments must be properly calibrated and functioning in harmony. This makes measurements of top-quark production useful as tests of detector performance, which are extremely valuable when recording data under new operating conditions.

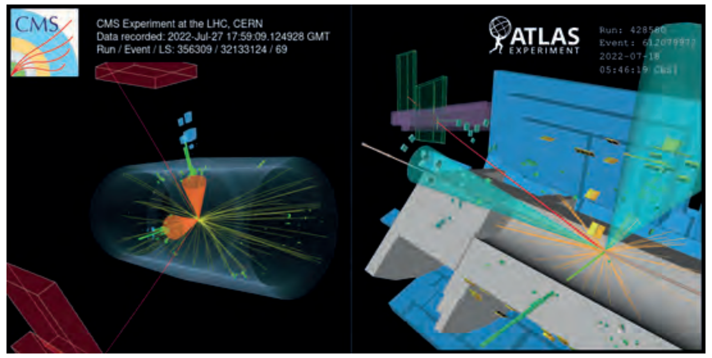

Figure 1

Visualisations for top-quark pair production candidate events at CMS and ATLAS

CMS breaks ground on Run 3

The DESY CMS group used a new technique to measure the top-quark pair production cross section with impressive speed and precision, using the data from roughly one week of collisions beginning in late July 2022. This marked the first public physics result of LHC Run 3 in September 2022, a mere two months after the start of data taking [1].

A small team within the DESY CMS group prepared for the new data in advance in the lead-up to Run 3, devising a measurement strategy that could be executed immediately once the data arrived. A key idea was to consider not only collision events where both top quarks decay leptonically (each producing an electron or muon), but also events in which one of the two top quarks decays hadronically (producing three or more jets). The inclusion of both decay channels greatly increased the number of events available to study, while comparison between the channels allowed analysers to design new calibration procedures specific to their measurement. At the same time, members of the team contributed to cutting-edge simulations at the new energies and also managed hardware that measures the total number of collisions produced while the detector is recording, called the luminosity. This quantity is critical in estimating the production rate of particles at the LHC, and the DESY CMS group played a major role in promptly obtaining a reliable luminosity estimate.

As collision data started to become available, all of the pieces were in place just in time to produce a remarkably fast measurement. This result gives the first look at physics seen in proton–proton collisions at a record centre-of-mass energy of 13.6 TeV (Fig. 2), while also providing a valuable check of CMS data that will aid future high-precision measurements from the collaboration.

ATLAS adds bosons to the mix

Meanwhile, working with their own fresh batch of data, members of the DESY ATLAS group studied the production of top-quark pairs in combination with the production of another heavy particle, in this case the *Z* boson. The *Z* boson is one of the mediators of the weak interaction and the third-heaviest known elementary particle. Similarly to the top quark, the large mass makes the *Z* boson very unstable and causes it to decay through various processes, resulting for example in a pair of an electron and a positron or a muon and an antimuon. These decay channels were exploited in the ATLAS measurement, using the very clean signature that they leave in the detector. This allowed the scientists to detect the *Z*-boson decay with very high precision and very low background contamination, similar to top-quark pair production. In the case of top-quark pair production, ATLAS used the decay channel in which each of the top quarks decays leptonically.

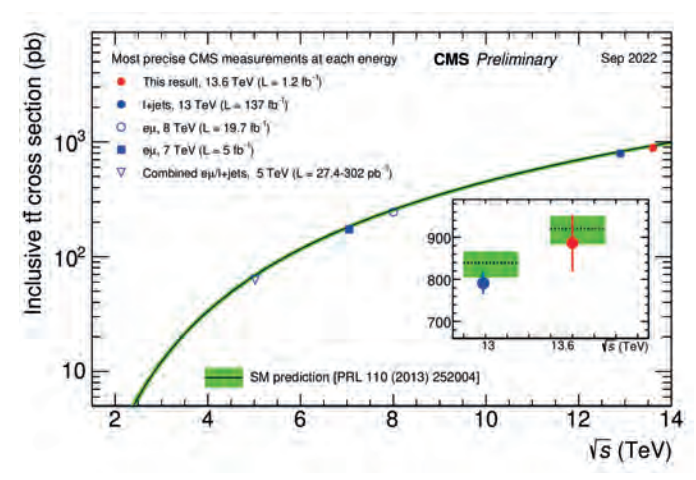

Figure 2

CMS measurements are compared to the theoretical dependence of the top-quark pair production cross section on the proton–proton centre-of-mass energy, √s.

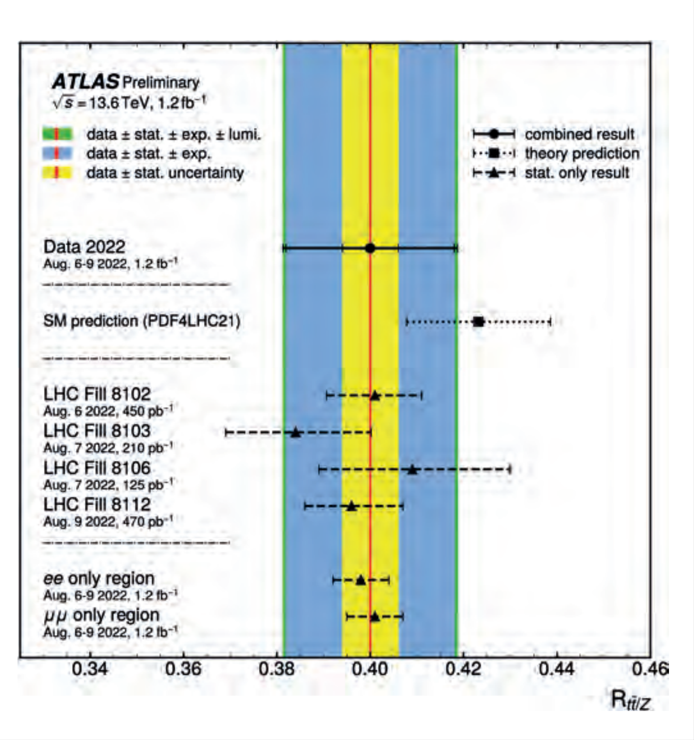

Figure 3

ATLAS presents the ratio of top-quark pair production to *Z*-boson production, breaking their result down by electron/muon channel and by LHC fill.

The ATLAS measurement focused on the ratio of the top-quark pair production cross section to that of the *Z* boson, which can be measured more precisely than individual cross sections and is sensitive to the inner structure of the colliding protons. In order to maximise precision, both processes were measured simultaneously in a careful combination of the decay channels (Fig. 3), which included a dedicated procedure to reduce the impact of uncertainties on reconstruction and identification of the two jets from the top-quark pair decay.

While working on the measurement, the DESY ATLAS group contributed to the scrutiny of the early Run 3 electron and muon identification, while also playing a crucial role in the early ATLAS luminosity calibration. Their result was announced in November 2022, marking the second physics result of LHC Run 3 and further cementing the presence of DESY scientists at the new energy frontier [2].

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Do quarks at DESY interact with the cosmos?

Search for violation of Lorentz invariance in electron–proton collisions at HERA

Rotation and Lorentz invariance are assumed to be fundamental symmetries of nature. Therefore, the results of experiments should not depend on the orientation or speed of the experimental apparatus in space. To check this invariance, data from deep-inelastic scattering events in electron–proton collisions taken by the ZEUS detector at DESY's former HERA accelerator between 2003 and 2007 were reanalysed by an international team at DESY, in this case driven by external theorists. No significant time dependence was found. From this, bounds on different kinds of interactions of the quarks in the protons circulating in the HERA ring with potential cosmic background fields could be derived, many of them for the first time.

Any experiment on Earth or at DESY has, at any given time, a well-defined orientation and velocity with respect to the centre of the solar system, the centre of our galaxy and the rest frame of the universe. An apparent effective violation of rotation and Lorentz invariance might thus arise from interactions with some so far unknown cosmic or galactic background field through which Earth might be "plowing". If such interactions took place with the quarks inside a proton, then the ZEUS data might show a characteristic time dependence, as the collisions occurring in the detector "see" the cosmos or e.g. a fixed star in different directions at different times.

Figure 1 indicates how the orientation of an object on Earth's surface changes with time as Earth (grey) rotates around itself and around the sun (orange). Under this combined motion, the orientation of a cosmic background field (red) with respect to the ZEUS detector varies as a function of so-called sidereal time, about 4 minutes short of a day (blue). While a small time dependence with an exact 24 hour cycle may be expected e.g. from the operation cycle of the HERA accelerator, such systematic variations average out for sidereal time when data taken over several years are combined.

Upon suggestion by and under the active lead of two external theorists joining the ZEUS experimentalists, data from electron–proton collisions taken between 2003 and 2007 were reanalysed in a way never done before. However, no significant sidereal time dependence was found (Fig. 2). This yields new world-leading bounds on different kinds of effective interactions of quarks in the proton with potential cosmic background fields. The result also illustrates the value of the DESY effort to keep the HERA data alive and in active use, exploiting new ideas, for decades after the end of data taking.

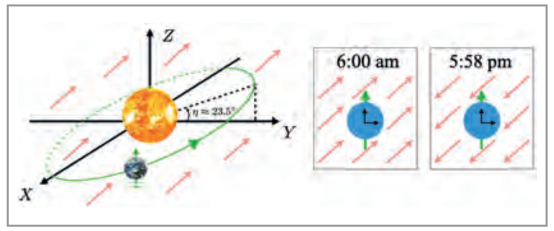

Figure 1

Changes of the orientation of an object on Earth's surface with time

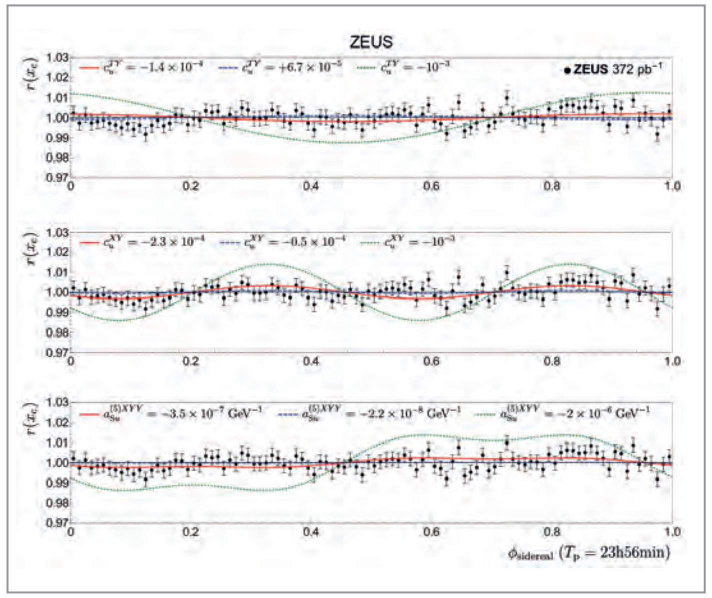

Figure 2

Ratio *r* of high/low-momentum quark–electron collisions vs. sidereal time. Potential modulations from different variants of effective cosmic background field interactions are also shown.

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Reference:

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Flavour tagging of hadronic jets in ATLAS

Identifying jets initiated by bottom and charm quarks with machine learning

Jets of hadrons initiated by a bottom or charm quark provide a powerful signature for rare processes at the LHC. The large mass of these quarks and the long lifetime of the hadrons containing them enable algorithms to discriminate between jets initiated by quarks with different flavour. The DESY ATLAS group is strongly involved in the design and calibration of the flavour-tagging algorithms used in the data analysis of the ATLAS experiment.

Improving flavour-tagging algorithms for Run 3

The ATLAS flavour-tagging algorithms exploit the long lifetime, high mass and large decay multiplicity of hadrons containing bottom (*b*) and charm (*c*) quarks. In a two-stage approach, first specialised and physics-informed algorithms process charged particle trajectories (tracks) associated with a jet. These algorithms reconstruct the secondary vertices from the displaced decay of *b*-hadrons and identify distinct track properties. Second, a neural network uses the algorithms' output to classify the jet as a *b*-jet, *c*-jet or light-flavoured jet (*l*-jet). The analysis of the LHC Run 3 data strongly benefits from an overhaul of the currently employed DL1r algorithm [1]: a Deep Sets neural network [2] infers the presence of *b*-hadrons using the displacement of tracks from the primary interaction point. The new DL1d algorithm has better precision in discriminating *b*-jets from *c*-jet and *l*-jet backgrounds, as shown in Fig. 1.

The DESY ATLAS group also develops algorithms for the identification of *b*-hadrons decaying semi-leptonically or with very low momentum. The latter are predicted in several theories extending the Standard Model of particle physics. Their low momentum precludes their reconstruction as jets, necessitating specialised algorithms and their calibration.

Calibration of *b*-jet identification efficiency

An accurate calibration of the algorithms is essential for high-quality physics results. The DESY ATLAS group is strongly involved in the *b*-tagging efficiency calibration [4]. Di-leptonic $t\bar{t}$ events are selected from the ATLAS data to obtain an enriched *b*-jet sample thanks to the $t \rightarrow bW$ branching ratio (~99%). A signal region and three control regions are defined to reduce the contribution of *l*-jets and correct the purity of non-*b*-jets in the signal region. A fit is then performed to determine the *b*-tagging efficiency in data. Calibration results are expressed as scale factors, which correct the ATLAS simulation *b*-jet efficiency to the observed efficiency for different bins of the *b*-jet discriminant and transverse momentum. The DESY ATLAS group is also dedicated to validating the new algorithms in the Run 3 data and automating the calibration code.

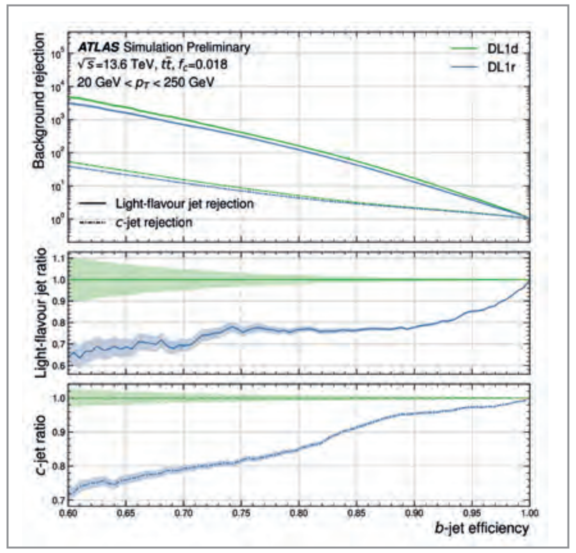

Figure 1

l-jet and *c*-jet background rejection as functions of *b*-jet efficiency, comparing the DL1r algorithm with the more recent DL1d algorithm [2]. The two lower panels indicate significant improvements for the DL1d algorithm for all *b*-jet efficiencies.

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Breaking the precision barrier

ATLAS delivers most precise luminosity measurement at the LHC

Accurate knowledge of the number of proton–proton interactions in a collected data set is of crucial importance for almost every measurement or search for new phenomena at the LHC. However, measuring the integrated luminosity, which is the quantity of interest, is challenging at hadron colliders. Members of the DESY ATLAS group played a key role in the latest measurement of the full LHC Run 2 data set collected by the ATLAS experiment from 2015 to 2018. The researchers achieved a record sub-percent uncertainty of 0.83%, setting a new benchmark for LHC experiments.

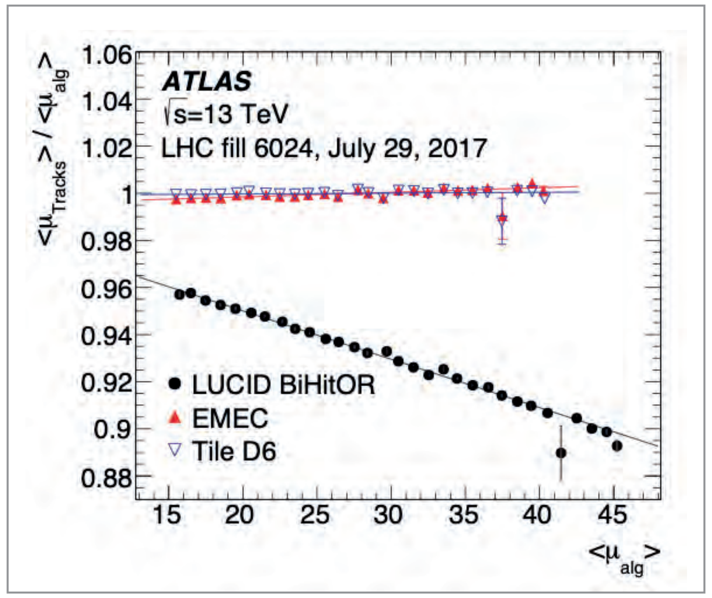

Figure 2

Ratios of the mean number of interactions per bunch crossing ⟨μ⟩ (equivalent to ratios of instantaneous luminosity) [1], measured by track counting, to that measured by LUCID and by the two calorimeter systems (EMEC and TileCal D6) as a function of ⟨μ⟩ measured by the latter algorithms in a long LHC physics fill in 2017

Precision frontier

Reaching sub-percent-level precision in measuring luminosity is a significant milestone for hadron colliders. ATLAS has now pushed beyond this limit and achieved an impressive precision of 0.83% [1], analysing the complete data set collected from 2015 to 2018. In comparison, the CMS collaboration achieved a remarkable result earlier in 2021 with a precision of 1.2% [2] for their LHC data set collected between 2015 and 2016.

To achieve this high level of precision, many effects and sources of experimental uncertainties with similar impact on the final measurement need to be considered and understood. To this end, the collaboration carried out detailed studies of various effects. The ATLAS group at DESY played a leading role in this complex endeavour.

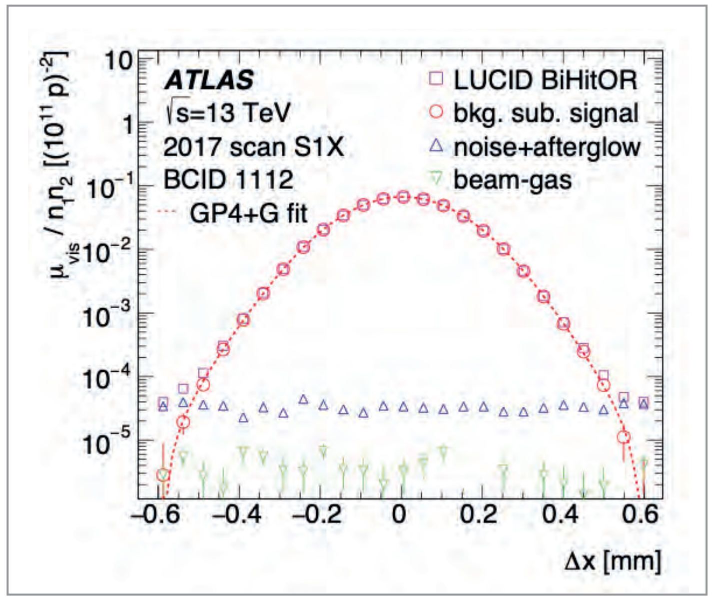

Figure 1

The vdM scan curve [1], obtained with the LUCID-2 subdetector in 2017, shows the number of visible interactions normalised by the number of protons in the bunches as a function of the horizontal beam separation for a specific colliding bunch pair. To extract the width of the beams, the backgrounds are subtracted and the remaining signal curve is fitted.

Luminosity detectors

One of the main luminosity-sensitive detectors in ATLAS is LUCID-2, which was designed specifically for the measurement of luminosity. LUCID-2 consists of two sets of photomultiplier tubes (PMTs) that surround the LHC beam pipe, 17 m on either side of the interaction point. The PMTs detect Cherenkov light emitted by charged particles coming from proton–proton collisions when traversing the PMTs' fused silica windows. Additionally, two other detector systems provide information about the luminosity in a complementary way when particles traverse the ATLAS detector: the inner detector, which counts the number of reconstructed tracks, and the calorimeters, which monitor the energies deposited by charged and neutral particles. The various detector systems provide a relative measurement proportional to the delivered luminosity.

Measurement strategy

The overall measurement strategy comprises three main pillars: the determination of the absolute-luminosity calibration in special runs, the extrapolation to nominal physics conditions and the monitoring of both aspects during each data-taking year.

To obtain an accurate measurement of the absolute luminosity, a special LHC beam configuration, with an average of approximately 0.5 proton interactions per bunch crossing and long gaps between the bunches, is needed to calibrate the detector signals. This calibration is done once per year by displacing the LHC proton beams from their nominal position in the horizontal and vertical planes to perform so-called van der Meer (vdM) beam separation scans, a technique developed in the 1960s for application at CERN's Intersecting Storage Rings (ISR) [3]. One such scan curve is shown in Fig. 1. The accuracy of this calibration is influenced by various effects, typically ranging in magnitude from 0.1% to 0.5%. To ensure the reliability of the results, a careful evaluation of the size and impact of all systematic effects was conducted. One such effect is related to the electromagnetic interaction of the two colliding proton beams, which affects their separation and characteristics in vdM scans. A more accurate mathematical model was employed to correct for the effects of beam–beam interactions in the scan data.

While vdM scans require these specific beam settings, the typical operational conditions at the LHC involve bunches that are closer together in a train structure, with about 20 to 50 interactions per bunch crossing. To account for these differences, the calibration from the vdM scans is extrapolated to the LHC's normal running conditions. Since the LUCID-2 detector is sensitive to such differences, an independent algorithm is needed that shows a well-understood behaviour between the vdM and physics conditions. For this purpose, the track-counting measurement is used, which is cross-checked with the measurement from the calorimeter system to assign uncertainties on the extrapolation. Figure 2 shows an example of the size of the correction to the LUCID-2 estimate as a function of the average interaction rate per bunch crossing ⟨μ⟩.

Lastly, the absolute-luminosity calibration and its extrapolation need to be monitored throughout the data-taking year, since data-taking conditions can vary and affect the measurement.

Results

Putting everything together, the ATLAS collaboration determined the luminosity of the full Run 2 data set to be 140.1 ± 1.2 fb^{-1}. This result is the most precise luminosity measurement achieved at a hadron collider to date, with an uncertainty of only 0.83%. This new measurement represents a significant improvement by a factor of 2 over previous ATLAS measurements and is comparable to results achieved by some of the second-generation total-cross-section experiments at the CERN ISR, with an uncertainty of 0.9%.

Looking forward

The techniques developed for this measurement are crucial for the ongoing Run 3, and they will enable researchers to achieve sub-percent-level precision in the future. These precise luminosity measurements are necessary to accurately determine the rates of various physics processes and to search for rare phenomena.

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Evolving digital detectors

Monolithic active pixel sensors and digital silicon photomultipliers

Future particle physics experiments will require detector systems with so far unmatched requirements. Silicon sensors manufactured in commercial CMOS processes were identified as candidates for the next generation of particle detectors, and members from many DESY particle physics groups have formed teams to investigate these new technologies. A digital silicon photomultiplier has been designed and is being characterised at DESY to investigate its advantages over the analogue devices currently used in many applications. As part of the Helmholtz Innovation Pool project TANGERINE, DESY is developing a monolithic active pixel sensor as an upgrade of the beam telescopes at the DESY II Test Beam Facility to demonstrate the readiness of the technology.

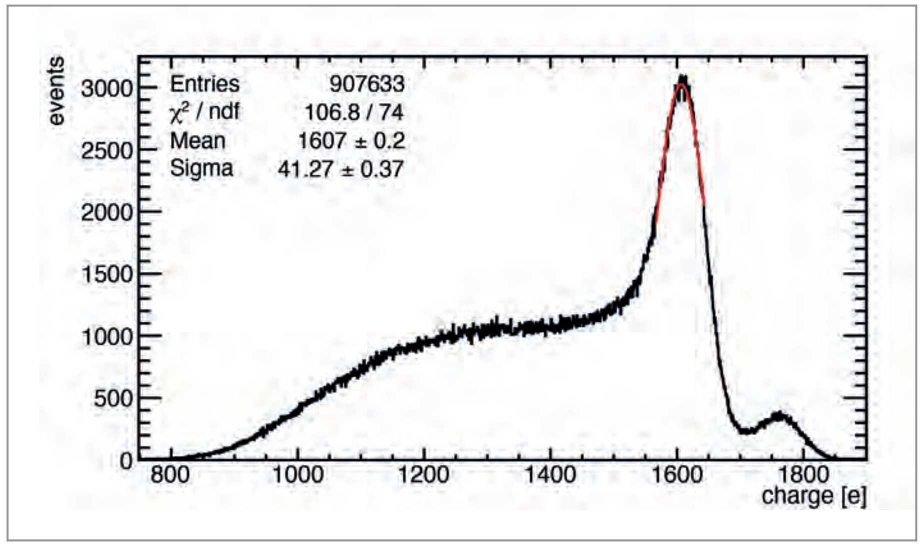

Figure 2

Spectrum of a ^{55}Fe X-ray source measured with a detector prototype produced in a 65 nm CMOS imaging sensor process. The position of the Kα line, expected at 1606 e, was used to calibrate the detector response.

Keeping pace, stepping ahead

Future particle physics experiments require higher and higher granularity in their detector systems, for example to cope with high track densities at the LHC experiments or to allow the structure of particle showers in calorimeters to be reconstructed.

This requires cost-efficient detector elements with high levels of integration to handle the large amount of recorded data. Monolithic active detectors combine the sensing element and the readout circuitry in a single device. They are produced in modern CMOS processes, allowing cost-efficient production and complex circuitry for signal processing, with the perspective of even higher circuit densities in the future. Another key advantage of this technology is the possibility to achieve smaller sensitive volumes for particle detection and lower power consumption, consequently relaxing requirements on cooling. This will make it possible to reduce the amount of active and passive material in tracking detectors.

Several projects at DESY explore the possibilities of these developments, overcoming the challenges to build the next generation of detectors that will meet the requirements of future experiments: The DESY dSiPM project investigates digital silicon photomultipliers (dSiPMs) produced in a 150 nm CMOS process. The TANGERINE project studies monolithic active pixel sensors (MAPS) manufactured in a novel 65 nm CMOS imaging sensor process.

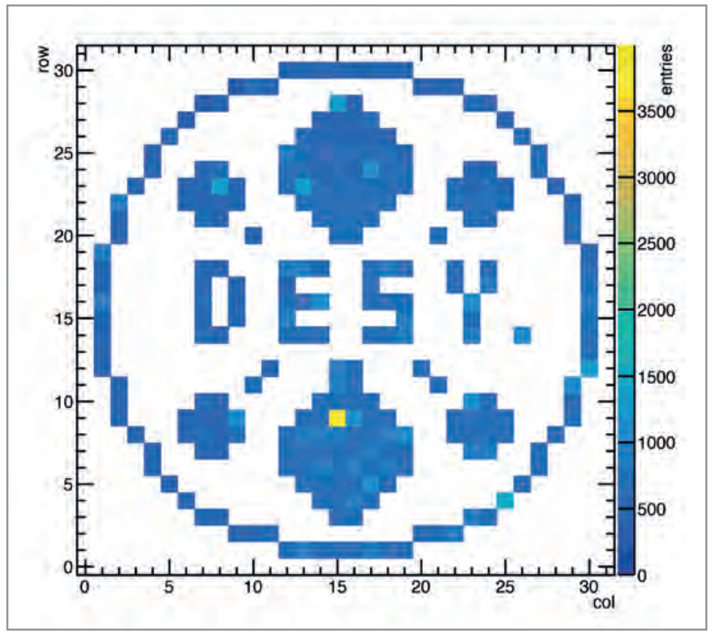

Figure 1

Hit map recorded with the DESY dSiPM indicating the number of dark counts in 10 000 readout frames at room temperature. An arbitrary selection of pixels was masked for demonstration purpose.

Digital silicon photomultipliers

Conventional silicon photomultipliers comprise an array of single-photon avalanche diodes (SPADs), which are operated in Geiger mode and sensitive to single photons. The individual SPADs are connected in parallel and the analogue output signal is processed in a separate device.

In dSiPMs, each SPAD signal is processed on a pixel level, which can have various advantages and applications: the availability of position information, for example, which would be interesting for the readout of scintillating fibres [1], or on-chip digitisation of signals, which would potentially ease the integration in highly granular detector systems.

DESY has developed a dSiPM produced in a 150 nm CMOS process with 32 x 32 pixels of about 70 µm width. Each pixel contains four SPADs with shared readout electronics. Measurements with electrons at the DESY II Test Beam Facility have shown that hit positions can be resolved on a pixel level. The DESY dSiPM features a masking mechanism that makes it possible to disable any pattern of pixels, as demonstrated in Fig. 1, which helps to reduce the impact of noisy pixels. Finally, the dSiPM provides time measurements, associated to the first pixel firing per quadrant and readout frame of 333 ns. The corresponding time resolution is expected to be better than 100 ps, rendering the dSiPM a possible candidate for 4D tracking applications.

Monolithic active pixel sensors

A DESY team is investigating a 65 nm CMOS imaging sensor process, aiming to develop a MAPS optimised for future lepton colliders, for instance, but also suited for a beam telescope at the DESY II Test Beam Facility. The goal is to reach a spatial resolution below 3 µm, a temporal resolution below 10 ns and a total thickness below 50 µm. The team is part of the Helmholtz Innovation Pool project TANGERINE and combines the expertise of several DESY particle physics groups: ATLAS, CMS, Electronics Development (FE) and Research and Technologies for Future Particle Physics Experiments (FTX).

Three main lines of research are followed: detector performance simulations, circuit design and prototype characterisation. The developed simulation procedure applies the finite element method to derive the electric field in the detectors and the Monte Carlo method to model the stochastic effects of particle–matter interaction and charge transport [3]. Characterisation of detector prototypes designed at DESY and CERN is ongoing to prove that the technology is ready to validate the simulation procedure [3, 4]. Measurements with an ^{55}Fe X-ray source are used to calibrate the charge response of the prototypes for analysis of beam tests. The spectrum of the X-ray source is shown in Fig. 2.

New detector prototypes, featuring 64 x 16 pixels, are in production, and characterisation studies at DESY will begin in summer 2023.

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The LHC as a photon collider

Casting light on new phenomena

As the highest-energy hadron collider in the world, the LHC has enabled important insights into the nature of elementary particles. These hadron collisions are studied in almost all LHC research. In contrast, the focus of a new Helmholtz Young Investigator Group (YIG) at DESY is on using the LHC in a novel way: as the world's highest-energy photon collider. Photon collisions occur when each proton radiates a photon in the electromagnetic field of the opposing proton. This opens a new kinematic regime for laboratory photon collisions, providing a promising route to discovering new phenomena that could solve some of the most fundamental questions in particle physics, for example the nature of dark matter.

The YIG will search for dark-matter particles produced in LHC photon collisions and pioneer the use of novel forward proton detectors. An important experimental feature of photon collisions is that the protons do not collide themselves. This means that they can remain intact and are deflected at a small angle by the LHC magnet system. These intact, deflected protons can be measured using the ATLAS Forward Proton (AFP) detectors. Measuring intact protons helps us to identify photon collisions and provides unique information about them. By combining information from the AFP detectors and the central ATLAS detector, we can determine the total missing momentum, which is a powerful observable for dark-matter searches. We plan to use this new information to gain sensitivity to scalar leptons and dark matter in key areas of phase space favoured by cosmological observations and muon anomalous magnetic moment ("g-2") discrepancies.

In contrast to the electron and muon anomalous magnetic moments, which are known to better than one part in a million, the anomalous magnetic moment of the tau lepton is exceptionally unconstrained. The poor experimental constraint could hide new phenomena, making it imperative to improve this measurement. The short tau lifetime prevents direct observation of its behaviour in a magnetic field, as employed for the electron and the muon. Alternative techniques are therefore needed.

The YIG will perform measurements of tau-lepton pairs produced in LHC photon collisions. We will use both high-energy proton collision data and exceptionally clean lead ion collision data (Fig. 1). These measurements are sensitive to the tau-lepton anomalous magnetic moment ("g-2"), and the use of this technique shows promise to achieve world-leading precision. In this way, we could test if photons interact with each lepton generation in the same way (lepton universality), which is a cornerstone of the Standard Model.

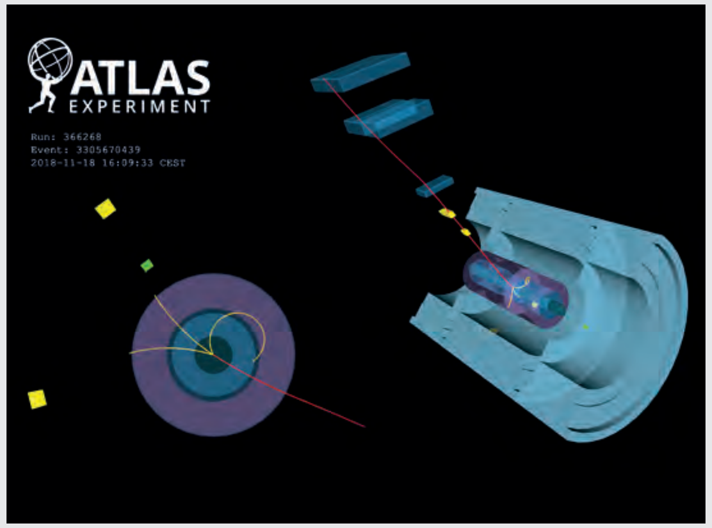

Figure 1

Di-tau candidate produced by a photon–photon collision [1]. The event contains a muon (red) and three charged particle tracks (orange).

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PUNCH4NFDI

Data management full steam ahead

The German National Research Data Infrastructure (NFDI) is picking up speed. DESY is home to the DAPHNE4NFDI and PUNCH4NFDI consortia, which together integrate over 60 institutions in Germany. Additional players, such as the Base4NFDI initiative or the Helmholtz Federated IT Services (HIFIS), further raise awareness of data management issues in general and also come with significant funding for related projects.

The NFDI [1] project started almost 2.5 years ago, providing significant funding for up to 30 consortia for initially five years. The goal is to facilitate sustainable use of research data, establish FAIR (findable, accessible, interoperable and reusable) data management [2] and ensure coherent integration with efforts at the European and international level. PUNCH4NFDI [3], the consortium of particle, astroparticle, hadron and nuclear physics as well as astronomy, aims to bring data management in these disciplines to a new level, not least with the future vision of a science data platform (SDP) and the notion of digital research products that encapsulate data, publications, software and workflows in an easy-to-maintain and interoperable manner.

Steps towards these goals are being implemented: access mechanisms to federated compute and storage resources across disciplines, a unified authentication and authorisation infrastructure (AAI) environment for services and resources, workflow mechanisms and others. In particular, a rich set of use cases is being implemented, and real-life scientific workflows are being integrated. They will act simultaneously as nuclei for attracting further workflow examples and for broadening the basis of available data and knowledge for the future SDP and as test cases for the elements that are already in place, e.g. the usage of Compute4PUNCH and Storage4PUNCH federated resources in Bonn, Münster, Karlsruhe and at DESY.

At the same time, conceptual discussions on relevant metadata schemes, persistent identifiers and similar topics are being conducted with other consortia such as DAPHNE4NFDI (for photon and neutron science) [4], within the NFDI or the ErUM-Data community [5] and also in the framework of the new Base4NFDI initiative [6]. A particular focus is on the definition of interfaces for digital research products and their metadata content. The work is also supported and complemented by smaller third-party-funded projects in data management, such as PATOF [7].

The PUNCH4NFDI work will be accompanied by a rich programme of workshops, technical trainings, colloquia and seminars that is organised by the consortium itself and in collaboration with numerous other players. Most notably, the PUNCHLunch seminar series invites everybody interested in data management and related questions [8].

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Preparing for the pit stop of SuperKEKB

After four years of beam operation, SuperKEKB and Belle II face a major overhaul

Figure 2

The current Belle II computing model considers interaction with data stored on the Grid via batch-like access, with processing taking days. NAF@DESY has been working as a complement for data analysis, with quick and frequent iteration via a JupyterHub interface and the local farm.

The first years of operation of the SuperKEKB electron–positron collider at KEK in Japan allowed the accumulation of a data set comparable to the first-generation *B* factory experiment BaBar in the USA. However, they also revealed some issues that need to be addressed in the current first long shutdown of SuperKEKB, which began in June 2022. The pause in operation will be used to install the new pixel vertex detector, which was thoroughly commissioned at DESY. A well-functioning data production system based on distributed computing resources and efficient use of the National Analysis Facility (NAF) at DESY are important elements for timely and successful physics analysis of the large amount of data already collected.

SuperKEKB operation

In summer 2022, SuperKEKB achieved a new world record luminosity of 4.7 x 10^{34} $cm^{-2}s^{-1}$, which represents a significant accomplishment and more than doubles the previous KEKB record. Figure 1 shows the time evolution of the luminosity recorded by Belle II, totalling 428 fb^{-1}, which is about the entire BaBar data size or half that of the predecessor experiment Belle.

The various issues encountered during beam operation included the interplay between single-bunch instabilities and the feedback system, which was successfully solved by feedback tuning, still unexplained sudden beam losses, which were tentatively attributed to so-called "fireballs" [1], large vertical equilibrium emittances in both rings, emittance growth in the beam transport system and poor or unstable injection conditions. The latter in particular led to visible performance degradation in several Belle II subdetectors, such as the central drift chamber (CDC) and the electromagnetic calorimeter (ECL).

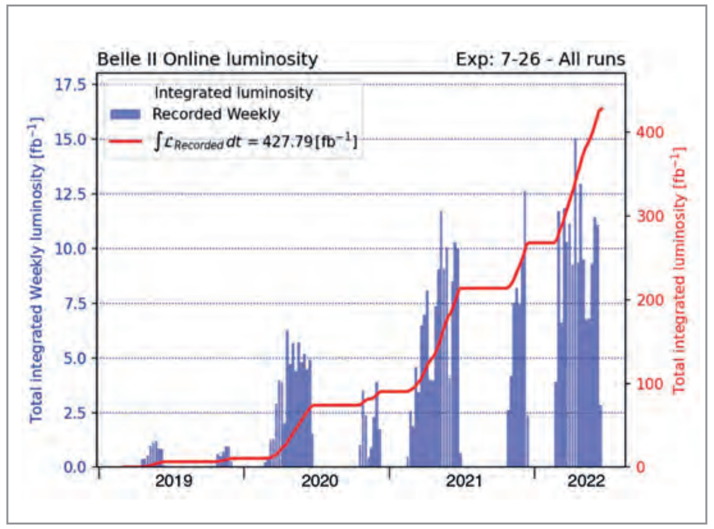

Figure 1

Evolution of weekly and total integrated luminosity recorded by the Belle II collaboration in the years 2019–2022

Members of the DESY Belle II group were strongly involved in characterising the problem and developing mitigation strategies both in the reconstruction software and in optimising the operating parameters of the CDC. In the current long shutdown (LS1), many accelerator upgrade activities are being carried out to implement improvements to the machine aimed at increasing its stability and resistance to the issues mentioned above. Beam operation is expected to resume in winter 2023/2024.

PXD2 production

The commissioning of the new pixel vertex detector (PXD2) was somewhat delayed due to unforeseen thermomechanical difficulties in the operation of the detector in the commissioning setup at DESY. The second half of 2022 was used to conduct very detailed investigations into these issues and to develop mitigation strategies that will enable safe long-term operation of this very sensitive device under the challenging operating conditions at SuperKEKB. After completion of slight modifications to the PXD2 mechanics, the two detector half-shells will be ready for transport to KEK in spring 2023.

Belle II computing activities

In 2022, the DESY Belle II group played a major role in data production and distributed computing operations. The positions of the current deputy computing coordinator and the former Monte Carlo (MC) production coordinator were both held by DESY research fellows. Their main tasks were to coordinate activities between the data reprocessing and simulation campaigns and the objectives of the physics groups as well as to support end users in analyses performed on the Grid, with an average number of 1.3 million jobs executed per week.

The procedure to simulate run-dependent MC events was established, and a full campaign to simulate events with run-dependent conditions was successfully completed, providing the collaboration with a MC data set equivalent to four times the integrated luminosity collected by Belle II. Additionally, data set collections for analyses were established. A collection in Belle II is defined as a single logical path that represents a list of files defined by the data production managers, minimising mistakes when selecting input data sets for analysis. With the data set collections, the reproducibility of results is ensured.

The Belle II computing model considers two copies of the raw data, one stored at KEK as the host laboratory and the second replicated in raw-data centres around the world. DESY serves as one of the six raw-data centres for Belle II, sharing 15% of all the data collected by the detector. In addition, in 2022, DESY acted as a calibration centre for the collaboration, sharing 100% of the data sets intented for calibration and providing computing resources requested by Belle II for calibration.

In parallel, the National Analysis Facility (NAF) at DESY provides complementary computing resources, including a JupyterHub, to Belle II collaborators, downloading fractions of the data set on demand and providing interfaces for both interactive access and batch processing. In 2022, 170 TB of data and MC were downloaded to the NAF out of 1 PB available on the Grid. A total of 338 Belle II collaborators registered for the NAF, with roughly a third coming from institutions outside Europe. Around 50 Belle II users regularly run batch jobs or use JupyterHub. They can be considered power users.

The DESY Belle II group has established a setup for multicore processing on the Grid. Currently, the maximum size of the skimmed raw-data files is 2 GB, which is too small for efficient staging operations on the tape systems and limited by the wall-clock time required for processing. With multicore processing, the target size of the skimmed raw data can be increased significantly, reducing the time of execution inversely proportionally to the number of parallel processes and allowing the production of files large enough for sustainable staging operations. Six raw-data centres have been configured, three of them validated with small prototype MC and raw-data reprocessing activities and ready for large-scale tests.

DESY has also been hosting the Belle II collaborative services and tools since 2016, mainly using the IT infrastructure of the research centre. This includes the user registry, which assigns each Belle II member a unique account to securely log in. In 2022, DESY (like other institutions of the Helmholtz Association) decided to abandon the ATLASSIAN tool suite for cost reasons. The Belle II collaboration therefore started to prepare the migration of the repository tool Stash and the issue tracker JIRA to a GitLab instance at DESY. The software building system BAMBOO will be integrated as well. A solution for the wiki implementation CONFLUENCE is still under discussion.

In addition, the DESY Belle II group was involved in efforts to secure the long-term sustainability of the high-energy physics (HEP) research software ecosystem, contributing to the training activities of the HEP Software Foundation (HSF) [2]. In 2022, a research fellow of the group participated as convener of the software training programme, coordinating the activities of three major training events during the year for newcomers in HEP. These events covered basics in Bash, Python and Git and reached more than 200 students from several experiments. In addition, a new training event on analysis preservation in HEP was established, which included the writing of a new training module about Singularity/Apptainer and the update of material previously prepared for Docker and GitLab CI/CD pipes.

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Hunt for new-physics boson α in τ-lepton decays

First Belle II τ-physics paper sets competitive limit

Researchers from DESY, in collaboration with other institutions working on the Belle II experiment at the SuperKEKB collider at KEK in Japan, have published the first Belle II paper on τ physics. They studied the decays of τ leptons produced in pairs in electron–positron collisions and searched for lepton-flavour-violating $\tau^- \to e^-\alpha$ and $\tau^- \to \mu^-\alpha$ decays, where α is an invisible, beyond-the-Standard-Model (BSM) boson. This direct search for the α boson can probe BSM theories with high sensitivity.

The Belle II experiment and τ decays

Nowadays, with the immense amount of electron–positron annihilation data and the large cross section of pairwise τ-lepton production, progress in τ physics mostly occurs at B factories. However, quite remarkably, searches for τ-lepton decays into final states involving a lepton ($\boldsymbol{\ell} = e$ or μ) and a BSM boson α were not conducted at the first-generation B factory experiments, Belle and BaBar. The existence of that light, undetected and thus invisible boson is predicted in models with e.g. axion-like particles (ALPs) [2], and the coupling of τ to ALPs can only be studied in collider experiments. The last search for this boson in τ decays dates back to the ARGUS collaboration in 1995 [1]. Consequently, $\tau - e$ and $\tau - \mu$ couplings to ALPs are quite unexplored [2].

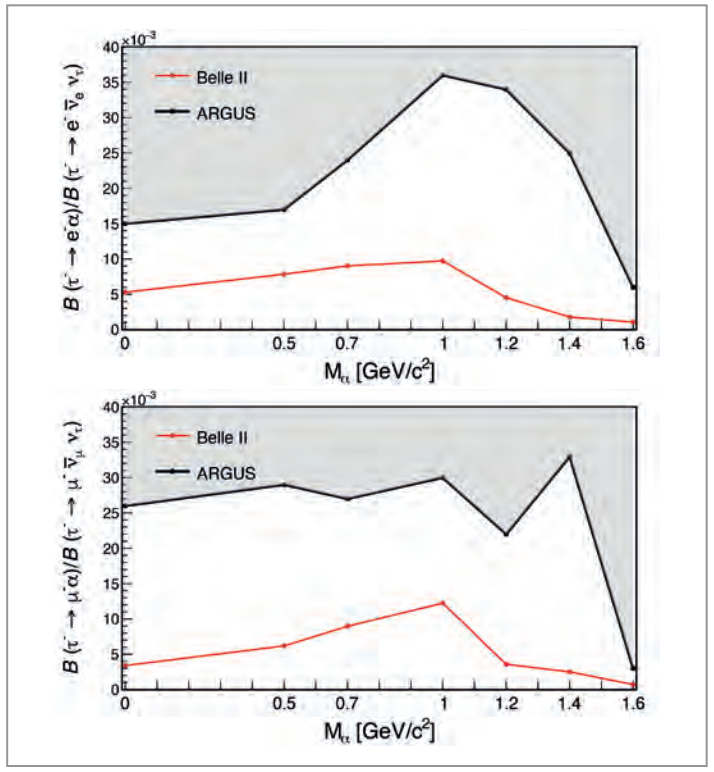

Figure 1

Upper limits at 95% CL on the branching-fraction ratios $B(\tau^- \to e^-\alpha)/B(\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau)$ (top) and $B(\tau^- \to e^-\alpha)/B(\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau)$ (bottom) as a function of the α mass, determined by the ARGUS and Belle II collaborations

DESY researchers led the search for $\tau^- \to \boldsymbol{\ell}^- \alpha$ decays using 63 fb^{-1} of Belle II data. These τ decays have visible topologies identical to that of the SM decay $\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau$. Thus, the latter forms an irreducible background. However, in $\tau^- \to \boldsymbol{\ell}^- \alpha$, the magnitude of the lepton momentum depends only on the α mass. The two-body decay provides a distinctive signature for the signal above the spectrum of $\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau$, where the lepton momentum has a broad distribution. The group searched for $\tau^- \to \boldsymbol{\ell}^- \alpha$ by looking for an excess of events above the spectrum of $\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau$. They observed no significant signal and determined upper limits on the ratio of the branching fractions $B(\tau^- \to \boldsymbol{\ell}^- \alpha)/B(\tau^- \to \boldsymbol{\ell}^- \bar{\nu}_\ell \nu_\tau)$.

Figure 1 shows the 95% confidence level upper limits for the electron and muon channels for various values of the α mass, compared to the previous upper limits measured by the ARGUS collaboration. The Belle II results constitute the most stringent limits on the new-physics boson α produced in τ-lepton decays, allowing SM extensions to be directly constrained in ways not otherwise possible outside of collider experiments.

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Measuring radiative decays in the B-meson rest frame

A unique method for studying inclusive B-meson decays at Belle II

Belle II is a B factory experiment, recording B mesons produced in pairs in electron–positron collisions provided by the SuperKEKB collider. Analysing the Belle II data, researchers from DESY successfully measured the photon energy spectrum of the rare transition of a B meson into a photon and a hadronic system (denoted X_s) from the underlying quark-level decay $b \to s\gamma$. The work by the DESY Belle II group used the second B meson and the precisely known initial state of the electron–positron collision to measure the X_s and γ parameters directly in the rest frame of the decaying B meson.

In 2022, the Belle II group at DESY analysed the photon energy spectrum of the $B \to X_s\,\gamma$ decay in the B-meson rest frame with 189 fb^{-1} of data [1]. The resolution of the decay in the B-meson rest frame was enabled by an advanced machine-learning-based hierarchical reconstruction technique called full event interpretation [2]. It reconstructs the second B meson produced in the electron–positron collision in thousands of its hadronic subdecay chains. Using the precise knowledge of the collision energy that produced the two B mesons, the charge, flavour and four-momentum of the $B \to X_s\,\gamma$ decay could be inferred without any requirements on the X_s system, enabling an inclusive measurement of all states evolving from an s quark. This is known as the hadronic recoil method.

The analysis measured all decays contributing photons with energies as low as 1.8 GeV. This threshold was achieved by relying on high-precision detector modelling and performance studies, such as the Belle II photon detection efficiency analysis, which was also performed by the DESY Belle II group. Machine learning algorithms were employed to differentiate the γ from the background photons. This was the second time that the hadronic recoil method was performed for a $B \to X_s\,\gamma$ measurement, achieving a higher statistical precision and a lower energy threshold than the former BaBar analysis [3].

Particles outside of the framework of the Standard Model may affect the rate of the $B \to X_s\,\gamma$ process. Moreover, a precise knowledge of the $B \to X_s\,\gamma$ photon energy spectrum is important for understanding the Fermi motion of the b quark within the B meson. This reduces the model dependency in the determination of the $|V_{ub}|$ parameter in the Standard Model. For this reason, $B \to X_s\,\gamma$ decays are being studied by many theory groups, including the SIMBA collaboration, which involves researchers from DESY. The SIMBA collaboration analysis combined all available experimental information to improve the theoretical understanding of the $B \to X_s\,\gamma$ decays and simultaneously constrain contributions from beyond the Standard Model [4].

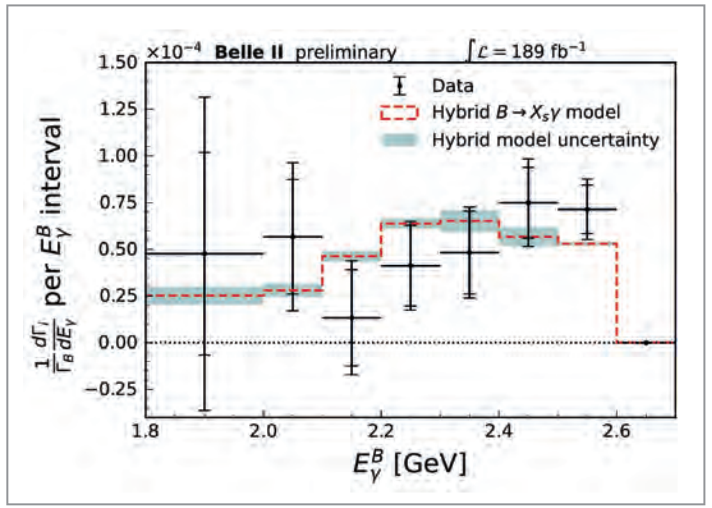

Figure 1

Measured photon energy spectrum of $B \to X_s\,\gamma$ decays using the hadronic recoil method. The expected results based on a chosen model are overlaid with the Belle II results with inner (outer) error bars showing the statistical (total) uncertainty.

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Less can be more

FLASHForward demonstrates drive beam energy depletion in a plasma accelerator

Plasma wakefield accelerators promise a drastic reduction of particle accelerator facilities in size and cost thanks to their gigavolt-per-metre-level accelerating gradients. DESY's beam-driven plasma wakefield accelerator experiment FLASHForward has demonstrated great strides in the field in recent years, but the jury is still out on how energy-efficient plasma accelerators can be. This is crucial for facilities that deliver high average beam power, such as free-electron lasers and particle colliders. To maximise efficiency, it is necessary to maximise the transfer of energy from the beam driving the wake to the plasma and then from the plasma to the accelerated beam. A world-best result for the latter was shown at FLASHForward in 2021, but the former was still missing. Until now.

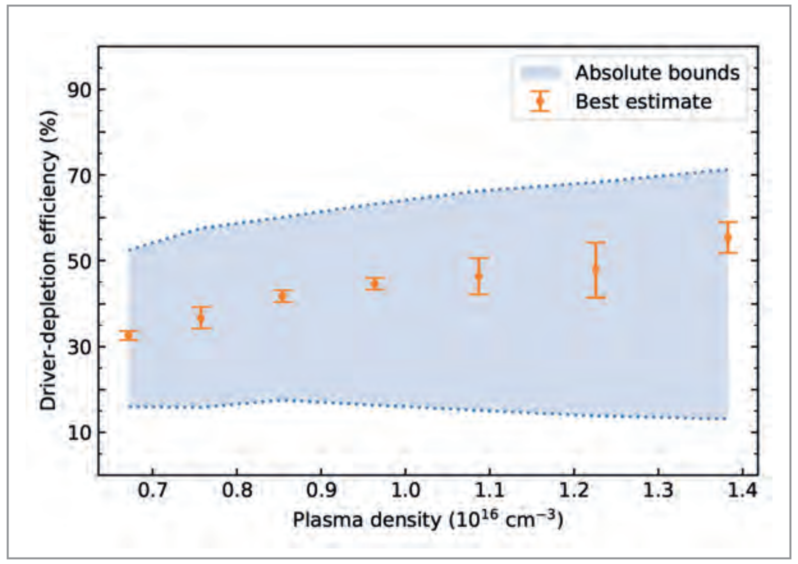

Figure 2

Driver depletion efficiency for a scan of plasma density, showing both the absolute bounds from measurements (blue area) and an estimate when modelling the charge loss due to the high divergence of the low-energy electrons (orange error bars, representing the improved bounds).

Energy efficiency in science

Energy transfer efficiency is a key metric in particle accelerators, as it partly defines their electricity bill and environmental footprint. Such particle accelerators include particle physics colliders and accelerators delivering hard X-rays. As the average power of the facilities increases, either through peak energy or repetition rate, efficiency becomes more important. Thus, any technology striving to replace or augment current accelerators must be at least as energy-efficient as conventional accelerator technology.

The potential of plasma accelerators

A high-intensity charged-particle bunch passing through plasma can generate large electromagnetic fields in its wake. If appropriately placed, a second bunch trailing in these wakefields will be accelerated, gaining the energy deposited by the first bunch. The strength of the wakefields can be orders of magnitude greater than those of conventional accelerators. This could drastically shorten accelerators by up to a factor of 100 and reduce their construction costs. For high overall energy transfer efficiency, the energy deposited by the drive bunch in the wake – i.e. drive bunch energy depletion – must be maximised. Similarly, the accelerated bunch must retrieve as much energy as possible from the plasma. While FLASHForward [1] had previously shown that an energy transfer efficiency of 42% from the plasma to the trailing bunch is possible [2], significant driver depletion had not yet been achieved.

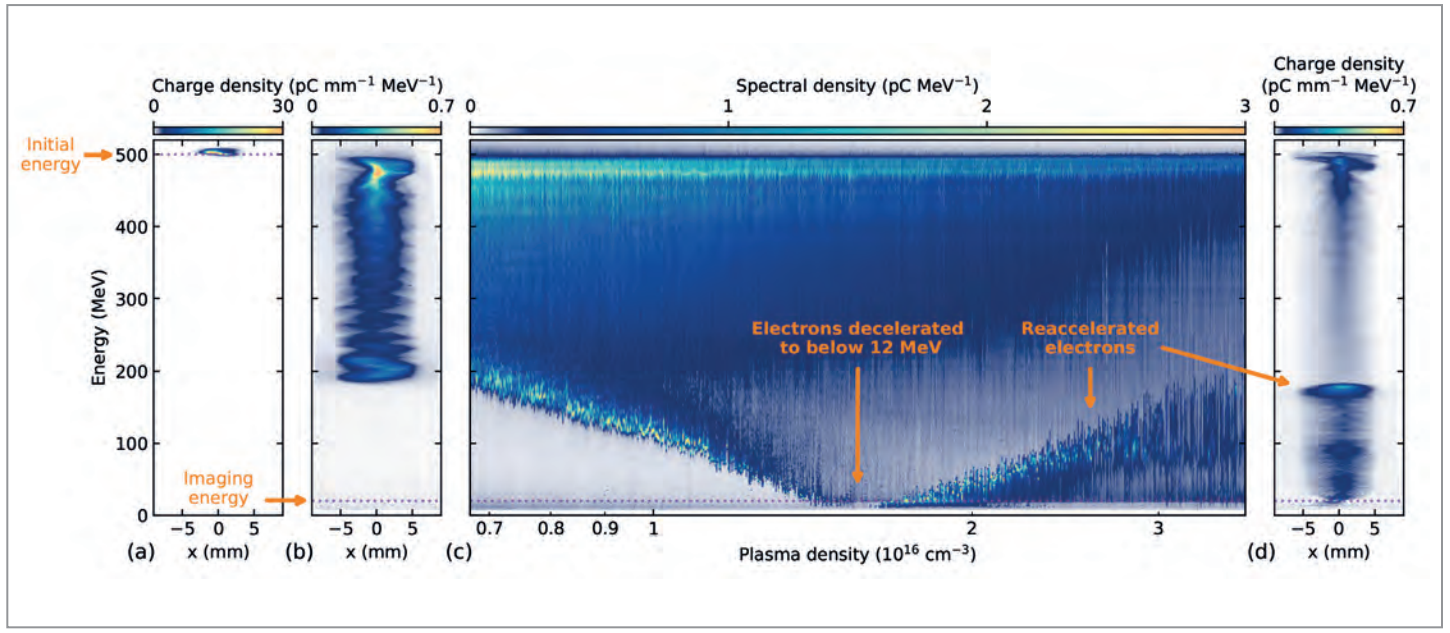

Figure 1

Charge distribution of the drive bunch where no plasma was present (a) and at minimum and maximum plasma densities (b, d).
Measured energy spectra (projections onto the energy axis) as a function of changing plasma density (c).

Extracting driver energy up to the limit

Figure 1 shows a 500 MeV bunch interacting with a plasma. At a density of ~1.5 x 10^{16} cm^{-3}, some electrons lose up to 98% of their energy to the wake! At such low energies, the electrons are no longer relativistic and slow down. As such, they lag behind until they are re-accelerated by the accelerating fields at the back of the wakefield cavity. This additional charge in the accelerating fields may hinder key properties of the plasma wake that are required for beam quality preservation of the accelerated bunch. To delay the onset of this limiting process, the drive bunch must be shaped such that all electrons are decelerated at the same rate. The onset of this re-acceleration can be seen in Fig. 1(d) at densities larger than 1.5 x 10^{16} cm^{-3}. The interplay between the longitudinal shape of the driver and the plasma density ultimately determines the maximum possible depletion before the wakefield is deleteriously affected.

Demonstration of large energy depletion

Comparing the total energy of the bunch with and without plasma interaction at each density tells us by how much the driver was depleted in energy (Fig. 2). Most common accelerator beamlines are designed to handle beams with energy spreads below 1%. The depleted drive bunch, with a much larger energy spread of 98%, therefore requires special treatment. For example, the lower-energy electrons have a large divergence, which means that the focusing magnets after the plasma stage are incapable of capturing and transporting them. This leads to charge loss between the plasma stage and the diagnostics, increasing the uncertainty when estimating the total bunch energy, shown by the blue bands in Fig. 2. By carefully modelling and correcting for this charge loss, a driver depletion of up to (55 ± 4)% can be estimated, approximately an order of magnitude higher than other published results.

Why is this important?

Large driver depletion, as demonstrated here, is the first step in maximising the energy transfer efficiency of a plasma accelerator. The second step is to show large energy extraction from the plasma to the accelerated beam, where FLASHForward also demonstrated a world-best value [2]. The next step will be to simultaneously combine these two efficiencies in experiment. Such a result would finally demonstrate that plasma accelerators can compete with and possibly even exceed the energy efficiencies of planned particle colliders based on radio frequency technology.

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Here be SUSY

We have not yet found SUSY – maybe we are looking in the wrong place?

Among models for physics beyond the Standard Model (SM), supersymmetry (SUSY) stands out, for several reasons. It provides, within a single model, remedies to several of the fundamental problems of the SM. The tight connection between the SM and SUSY implies that many features are fixed by the corresponding SM process. Some say: "SUSY is dead" because the LHC has not discovered it yet. But is this really true? It turns out that the story is more subtle. SUSY can be "just around the corner", even if no signs of it have been found and a closer look is needed to quantify the impact of LHC limits and their implications for future colliders. The Science with Lepton Beams (FTX-SLB) group at DESY contributed to several studies in this direction.

Introduction

SUSY is a well-motivated theory that promises solutions to several shortcomings of the SM, such as the hierarchy problem, naturalness, dark matter and the muon g-2 enigma. It predicts that, for every SM particle, there is a "superpartner" with identical properties, except for spin: Fermions have scalar partners – sfermions – and bosons have fermionic partners – bosinos.

To avoid conflicts with data, the concept of conserved "R-parity" is introduced, which implies that sparticles can only be produced in pairs and that the lightest of them, the LSP, is stable.

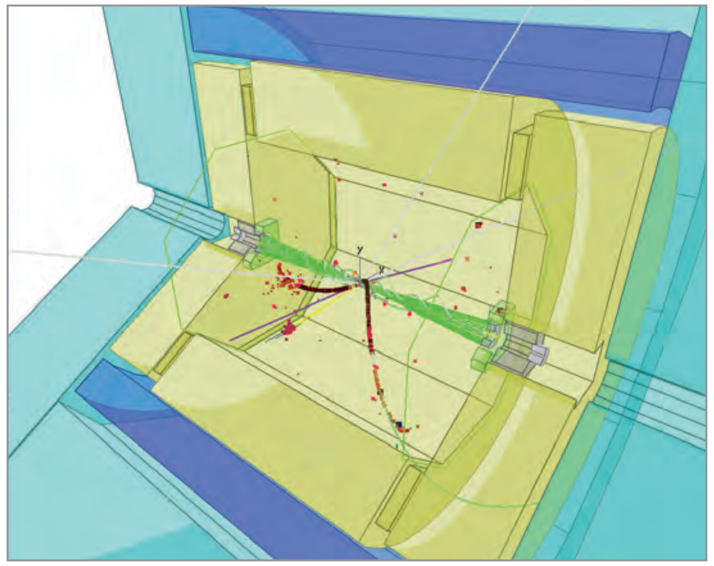

Figure 1

Simulated $\tilde{\tau}$ event in the International Large Detector (ILD) at the ILC. All machine-induced backgrounds are included. The solid purple lines indicate where the invisible LSPs are and the faint grey lines where the neutrinos from the τ decays are.

Still, many free parameters – and hence different signatures – prevail. A key player is the next-to-lightest SUSY particle, the NLSP, as it is the one for which R-parity only allows one decay mode. The NLSP is either the next-to-lightest bosino or the lightest slepton.

LHC: Looking under the lamppost

The LHC has not seen any squarks or gluinos, which would be produced abundantly in strong interactions. Neither of these particles would be the NLSP, however, so any search for these particles *will* be model-dependent.

To evaluate the model-independent SUSY reach of hadron colliders, the most challenging scenario should be studied: the one in which, as expected, the lightest sparticles are the electroweak bosinos – or possibly the lightest slepton – but with other sparticles out of reach. A wide scan over SUSY models with a bosino NLSP lighter than a few TeV was confronted with projections of sensitivity at future hadron colliders [1]. The conclusion is that, although these colliders have a large discovery reach, i.e. potential to discover *some* SUSY model, hardly any models with low-to-medium LSP–NLSP mass differences can be excluded with certainty.

The problem here is that the signature in the detector is close to identical to that of SM processes with neutrinos and that these have a much higher probability to occur than the SUSY processes. The models expected to be detected are either those with mass differences larger than those allowed by a quite wide class of models or those in a tiny region where the mass difference is so small that the NLSP decays in the detectors.

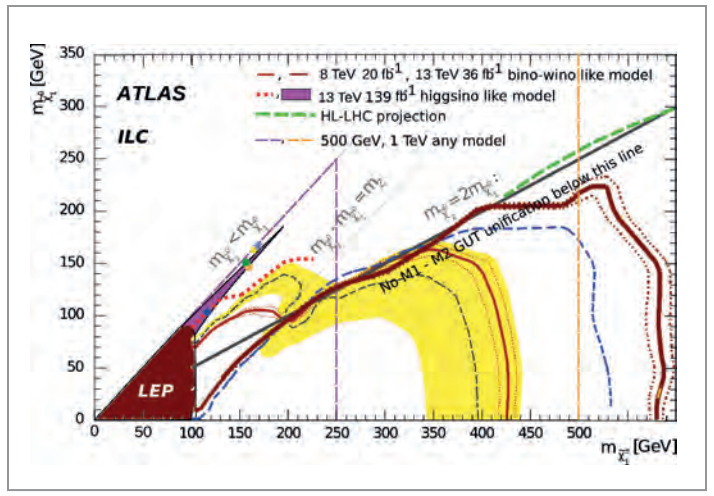

Figure 2

Current or projected exclusion limits for a chargino NLSP for different colliders, as indicated in the figure. The ILC lines are both exclusion and discovery limits – the difference between the two is within the widths of the lines. All others are exclusion limits, dashed for expected limits, solid for observed. From [1].

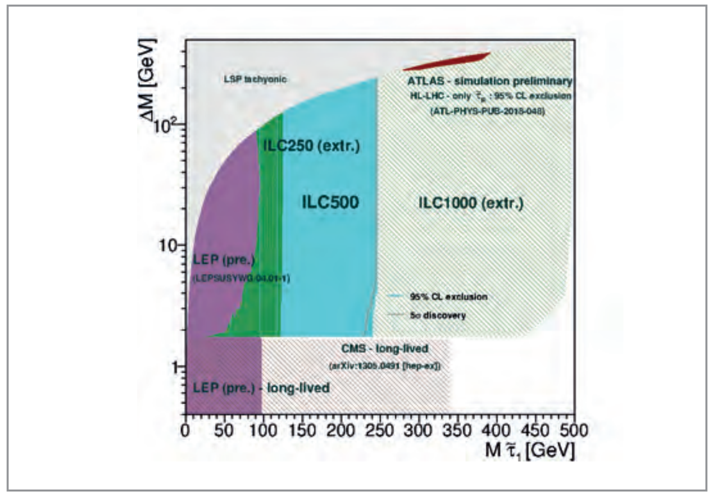

Figure 3

Current or projected exclusion limits for a $\tilde{\tau}$ NLSP. LEP and CMS limits are observed ones, others are expected. The expected HL-LHC limit is exclusion only, and only for $\tilde{\tau}_R$ (not the lowest cross section one) – discovery is not possible. For ILC500, both exclusion and discovery limits are shown for the lowest possible cross section – the ILC250 and ILC1000 limits are extrapolations of the full analysis at 500 GeV. From [2].

ILC: Moving the lamppost

Looking at the capabilities of future electron–positron colliders such as the International Linear Collider (ILC), the picture is different. Electrons are, unlike protons, truly elementary particles. This means that the full energy of the beams is carried by the particles colliding, so the total properties of the final products are also known. As the background from SM processes is much smaller, the final states are not only well known, but will also be quite free of backgrounds. In fact, the event rates are so small that everything can be recorded (so-called trigger-less operation). A typical SUSY event ($\tilde{\tau}$ pair production) with all the background included is shown in Fig. 1.

The shortcoming of electron–positron colliders is a different one: Even if the full beam energy is available for interactions, it is much harder to accelerate electrons to high energies than protons. The average collision energy at hadron colliders is significantly less than the beam-energy, but due to higher beam energies, the maximal available energy is still higher at hadron machines.
The DESY FTX-SLB group has taken on the challenge to show conclusively that, at electron–positron colliders, any SUSY model that predicts an NLSP with a mass up to slightly below half the centre-of-mass energy will be discovered.

A first study simply involved a very conservative extrapolation of the limits set on bosino production by the former LEP II collider at CERN. Already with this naive approach, we found that any bosino NLSP will be discovered if its mass is just a few GeV below half the centre-of-mass energy of the collider. A comparison of this extrapolation with existing or projected limits from LEP II or the LHC is shown in Fig. 2.

A second study, this time with detailed simulation of the signal, of all the SM background and of all expected machine-related backgrounds, was done for the reach for direct pair production of a $\tilde{\tau}$ NLSP. The $\tilde{\tau}$ is likely to be the lightest of the sleptons, and the signature of $\tilde{\tau}$ pair production is the experimentally most difficult one. Due to mixing, the production cross section might be quite low. The τ lepton itself decays fast and partially to unobservable neutrinos. Also due to mixing, the visible decay products are a moving target, and one must assure that the theory point studied is as pessimistic as possible from the experimental perspective. With all these possible loopholes taken into account, we could still asses that this case would also be discovered up to NLSP masses just below the maximal reach of the collider (Fig. 3).

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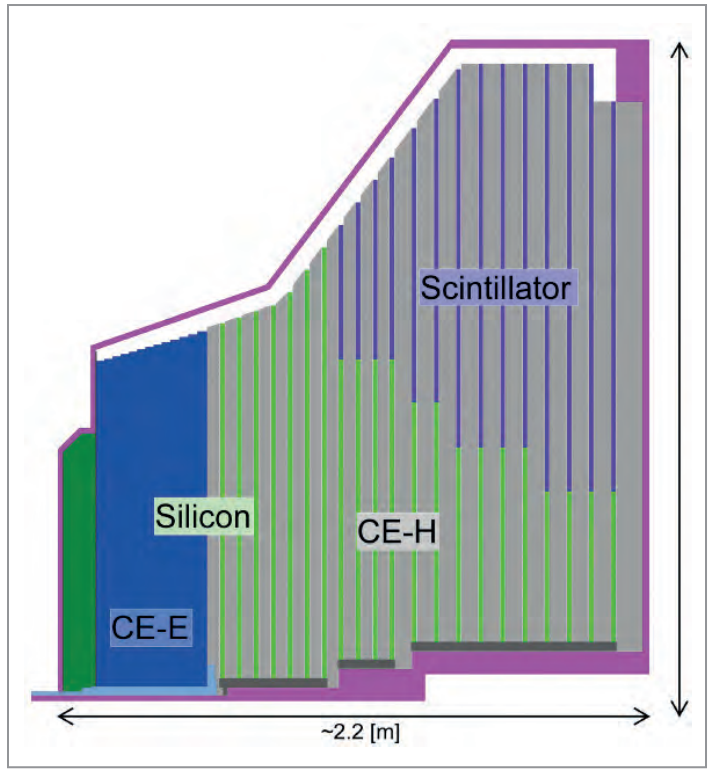
High granularity for CMS

Getting ready to build a highly granular calorimeter end-cap for the CMS experiment

The LHC detectors need upgrades for the high-luminosity phase of the facility (HL-LHC), which is planned to start in 2029. One of these will be a high-granularity calorimeter end-cap for the CMS experiment. After several years of design and prototyping, preparations for the production and construction of the final calorimeter components are picking up speed also at DESY.

While the LHC has just started its third run, physicists at DESY and around the world are already preparing for the future high-luminosity phase of the LHC. The increased luminosity will lead to unprecedented rates of particles produced in proton–proton collisions, which require upgrades to the current detectors of the LHC experiments. One of these upgrades involves the calorimeter end-cap for CMS [1], which will be replaced by a highly granular calorimeter (HGCAL, Fig. 1). This will make it possible to disentangle particles produced in different proton–proton collisions in the same bunch crossing ("pile-up").



The front part of the HGCAL and the areas closest to the beam pipe, which are most strongly affected by radiation, will be based on silicon pad sensors, while the rear part will consist of small scintillator tiles that are directly read out by silicon photomultipliers (SiPMs). This SiPM-on-tile technology has been developed over many years by DESY and its international partners within the CALICE collaboration. Originally conceived for an electron–positron collider, the technology will now find its first application in a collider detector in the CMS end-cap.

While 2029 might seem far in the future, it is very soon if you need to build and install a new calorimeter! DESY and its partners are therefore getting ready to build detector elements for the HGCAL SiPM-on-tile part. DESY contributes in several areas:

- The design and test of the tileboards – the electronic boards holding the SiPMs and tiles on one side and the readout application-specific integrated circuits (ASIC) on the other side
- The wrapping of the scintillator tiles in reflective foil, including the design and construction of a machine to do the wrapping
- The assembly of the electronics on the tileboards and the gluing of the tiles on them
- The development of the test methods that will be used during the production of the HGCAL SiPM-on-tile modules as well as their application

Figure 1

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

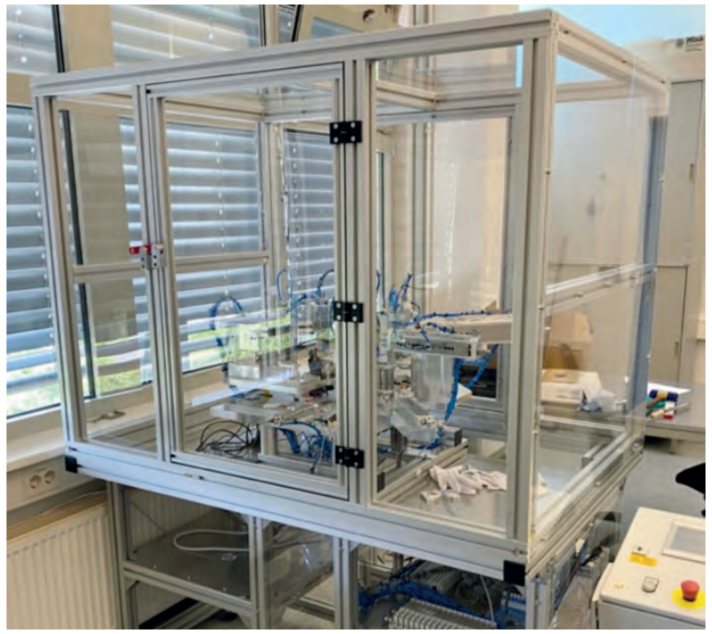


Figure 2

Tile wrapping machine inside its protective housing

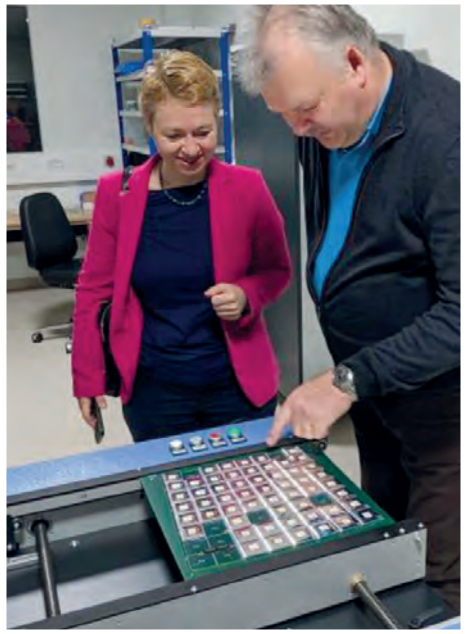


Figure 3

Beate Heinemann, Director of the DESY Particle Physics division, and Reinhard Schappeit from the DESY ZE group inspect a tileboard after gluing of the tiles with the pick-and-place machine.

An important step towards building SiPM-on-tile modules to be installed in the CMS detector is the construction of pre-series modules, with close to final components, which is foreseen for 2023. Before this, the individual steps of the production procedures are being tested with prototypes.

The DESY FTX group developed a dedicated machine to wrap the scintillator tiles in reflective enhanced specular reflector (ESR) foil (Fig. 2). By exchanging a few parts, the machine can be adapted to the 21 tile sizes foreseen in HGCAL, with side lengths ranging from ~2.5 cm to ~5.5 cm. The required precision for the size of the wrapped tiles of at most 100 µm deviation from the nominal size is very challenging. So far, the wrapping machine has been used to successfully wrap several hundreds of tiles in five formats.

The wrapped tiles are fixed to the tileboards with a radiation-hard two-component glue. The assembly is performed with a commercial pick-and-place machine (Fig. 3). The DESY ZE group optimised and tested the process carefully. After several test runs with mechanical "dummy tileboards" (boards without electronic functionality), the first working tileboards were equipped with tiles and exposed to particles in the DESY II Test Beam Facility.

To make sure that all modules work, DESY and its partners are developing test stands and procedures to test both the components that go into building a module and the module itself. These include dedicated setups for measuring the size of a tile before and after wrapping, for determining the light output of wrapped tiles and for testing the SiPMs. The performance of the tileboards at -30°C, the operating temperature of HGCAL, will be measured in a climate chamber (Fig. 4). More setups are in preparation to test the modules with cosmic muons.

Figure 4

A tileboard in the climate chamber

After construction of the pre-series modules, a smooth transition to the production phase for the final detector modules is foreseen. The pre-series modules will be used not only to practice the production process, but also to build a small prototype calorimeter. Exposing this prototype to particles in beam tests will provide important information about the achievable physics performance as well as input for tuning the simulation of HGCAL in CMS, which will be done in the DESY CMS group.

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Particle physics without accelerators

Axions and gravitational waves

Very lightweight axions and similar particles offer solutions to long-standing problems of particle physics and cosmology, but they interact much too weakly to be found at accelerators. Now, the first of three dedicated axion search experiments at DESY, ALPS II, is very close to its initial science run. Significant progress has also been achieved on the other two experiments, BabyIAXO and MADMAX. In addition, the particle physics potential of searches for high-frequency gravitational waves is being investigated.

Figure 2
ALPS II optics team members with the vacuum chamber housing the central optical bench

Axions or other feebly interacting particles (FIPs) might offer solutions to open questions beyond the Standard Models of particle physics and cosmology. At DESY in Hamburg, three non-accelerator-based experiments will search for FIPs as dark-matter candidates (ALPS II, BabyIAXO) or for FIPs constituting the dark matter in our home galaxy (MADMAX). Such experiments have to strive for sensitivities many orders beyond the reach of collider and beam-dump experiments.

The year 2022 also saw first thoughts on dedicated experiments to search for high-frequency gravitational waves. Such signals are not expected from known astrophysical phenomena, but would clearly point to new physics in the very early universe or at constituents in our Milky Way (such as lightweight black holes) originating from physics beyond the Standard Model.

ALPS II

Any Light Particle Search II (ALPS II) is a light-shining-through-a-wall experiment (LSW, see previous *DESY Particle Physics* reports) that improves the sensitivity on the axion–photon coupling by a factor of 1000 compared to its predecessors. This jump in sensitivity will be achieved by using a long string of superconducting dipole magnets and two mode-matched optical cavities before and after the light-tight wall. For the first time, ALPS II will enable axions to be probed for in a model-independent manner beyond present-day limits from astrophysics.

Figure 1
The ALPS II experiment in the 300 m long straight tunnel section around the HERA North Hall

The installation of ALPS II began in 2019. In March 2022, the magnet string was successfully tested, and in September 2022, the optics installation was completed for the initial science run. The experiment is now close to starting operation (Fig. 1). Both, the challenge posed by the optical system and the corresponding competences built up in the last years, are clearly demonstrated by an intermediate milestone in the optics commissioning: In October 2022, a DESY news was issued on a world-record light storage time between two mirrors, achieved by the ALPS II optics team [1]. Figure 2 shows members of the team in the ALPS II central cleanroom.

The initial science run (based on a heterodyne sensing method) in spring 2023 will not include the production cavity in front of the wall so as to optimise the run for the study of stray light. Nevertheless, it will outperform earlier LSW experiments by a factor of 100 in the axion–photon coupling.

The full optical system will be installed in the second half of 2023, and a science run with upgraded optics is planned for 2024. The future programme might include axion searches with a transition edge sensor (TES) detector system, vacuum magnetic birefringence measurements, improved axion searches and a dedicated hunt for high-frequency gravitational waves.

In 2022, also the ALPS II data acquisition and control system was brought into full operation. It is based on the DOOCS distributed object-oriented control system framework (originally developed at DESY for accelerator controls), data conversion to the HDF5 format, data storage in the dCache system and analysis on DESY's National Analysis Facility (NAF) cluster. This ALPS II system serves as a blueprint for other on-site particle physics experiments, such as LUXE, BabyIAXO and MADMAX.

(Baby)IAXO

Another method of searching for axions is to look for axions generated in the sun, which would be converted into photons inside a magnetic field. These photons, with energies ranging from 1 to 10 keV, are then focused by X-ray optics and detected at the focal point by a dedicated detector. The whole setup has to be mounted on a rotating support structure to track the sun. The International Axion Observatory (IAXO) will significantly increase the axion sensitivity beyond that of the CAST experiment at CERN. The collaboration is now pushing for a prototype, called BabyIAXO, in the HERA South Hall.

The main components of BabyIAXO are a 10 m long superconducting dipole magnet, X-ray optics, vacuum systems and detectors, all mounted on a large rotating support frame. As the requirements and specifications are similar to those of the medium-sized telescopes (MSTs) for the Cherenkov Telescope Array (CTA) gamma-ray observatory, we will use the so-called MST positioner prototype for BabyIAXO. The MST prototype was in operation in Berlin-Adlershof for many years, disassembled in February 2020, shipped to DESY in Hamburg and moved to the HERA South Hall. The design of the structure and drive system is nearing completion. We are currently investigating the manufacturing of the large 21 m long support frame.

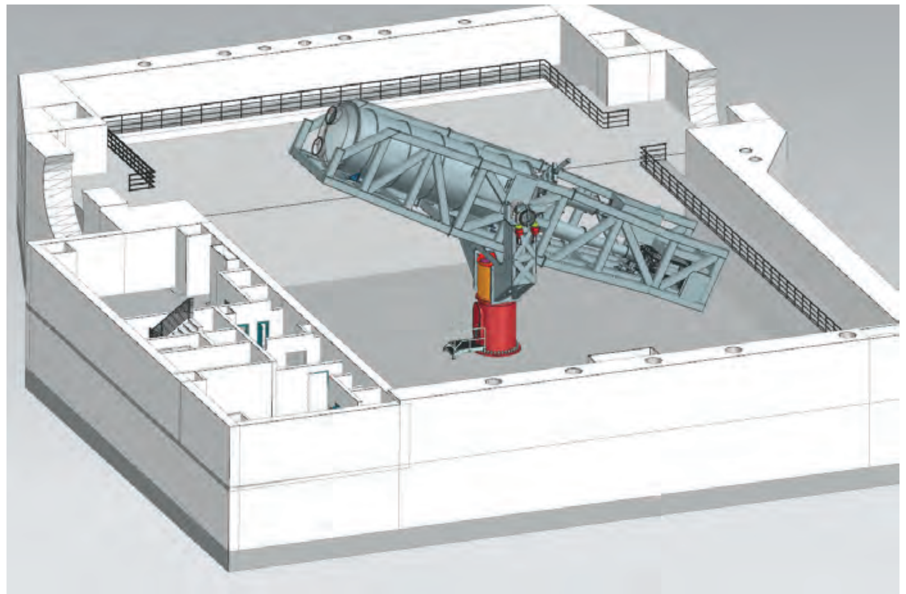

Figure 3

Drawing of BabyIAXO in the HERA South Hall

BabyIAXO will have two “beamlines”. For one, we will use a spare optics of the XMM Newton satellite of the European Space Agency (ESA). The other optics will be built by the IAXO institutes that specialise in X-ray optics for satellites. Several detector options are being developed. The baseline is a small time projection chamber using pixelated Micromegas readout. The main challenge is to achieve extremely low background rates, aiming at less than 10^{-7} counts/keV/cm^2/s. This can be reached by the use of an external cosmic-ray muon veto system, dedicated lead shielding and careful selection of the materials. A drawing of the experiment is displayed in Fig. 3.

Despite the very good design progress, there is a serious problem with the large superconducting dipole magnet. The aluminium stabilised cable was developed and going to be produced in Russia. It is obviously not available anymore. In addition, this type of cable is currently not commercially available. Several other cable options have been considered and were reviewed in a dedicated workshop on superconducting detector magnets organised by CERN and KEK in September 2022. Switching to a different type of cable, which has never been used for a large detector magnet, poses high risks, would require extensive research and development, would be expensive and would take several years. We therefore plan to continue using the standard cable. Setting up a co-extrusion process at CERN to manufacture aluminium stabilised cables is now being considered.

MADMAX

MADMAX will search for axions around us. An assembly of movable, well-aligned dielectric disks is able to boost a weak electromagnetic wave, expected by dark-matter axion conversion into photons in the presence of a high magnetic field (see previous *DESY Particle Physics* reports). In the past years, the MADMAX collaboration developed some smaller booster systems to improve our understanding of microwave detection. One of these, a setup with three non-movable 100 mm disks and a reflecting mirror on the back side, was tested in CERN’s MORPURGO dipole magnet in 2022. Room temperature reflectivity and noise temperature measurements were performed to calibrate the system. Analysis of the data taken in a magnetic field of 1.6 T is still ongoing. Further tests at CERN are planned in 2023. The mechanical functionality of the motor drives to position the booster disks were demonstrated in a 5 K helium gas environment and 5.3 T field in an ALPS II spare dipole magnet.

The design of the MADMAX prototype cryostat, which will allow operation with up to 20 disks of 300 mm diameter, was finished, the delivery is expected at the end of 2023.

Developments of the final magnet are ongoing, albeit on the back burner for financial reasons. The collaboration plans a prototype magnet to check the stick-and-slip behaviour of the coil and confirm the challenging operation with 90% of the maximal current density (depending on the peak field and temperature) on the cable load line. A potential use of this magnet for physics is being investigated. The infrastructure for the final magnet is also making good progress. The procurement process for the distribution box, a key DESY contribution to the cryoplatform, was finished in 2022, and its delivery is expected in late 2023.

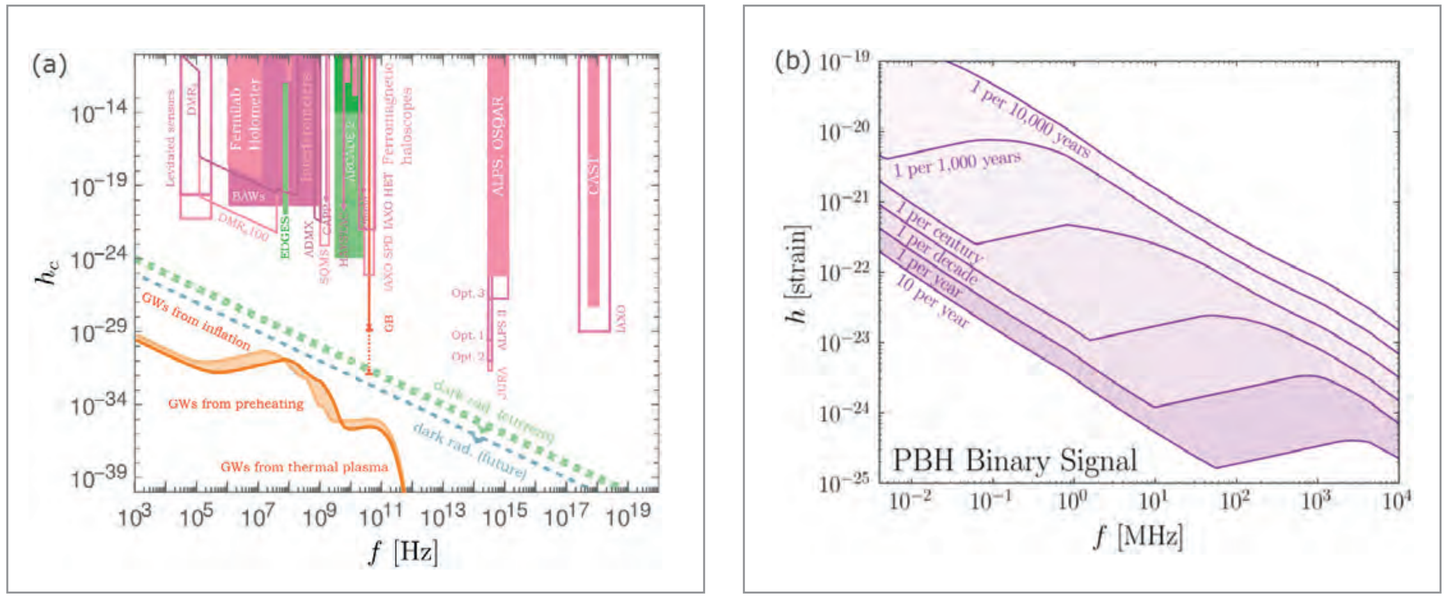

Figure 4

Predicted signals and sensitivities of planned and existing detectors for high-frequency gravitational waves. (a) Characteristic strain of primordial gravitational waves in the SMASH model (orange) compared to present (shaded areas) and projected limits (coloured solid lines). Indirect dark radiation constraints are shown with dashed lines. Abbreviations: BAWs: bulk acoustic wave devices, SPD: single-photon detection, HET: heterodyne detection, Res.: resonant, GB: Gaussian beam, and rad.: radiation. Adapted from [4], where additional details are provided. (b) Required strain sensitivity for observing gravitational waves from merging or inspiralling primordial black hole (PBH) binary systems at different rates. From [5], where additional details are provided.

High-frequency gravitational waves

Efforts towards dedicated searches for high-frequency gravitational waves (HFGWs) beyond the reach of experiments such as LIGO and Virgo are currently gaining momentum [2]. Figure 4(a) shows stochastic GW signals, which might have originated in the first second of the universe [3]. Also shown are sensitivities of realised (filled areas) and planned (open areas) detectors, over a frequency range from 10^4 to 10^{20} Hz.

Figure 4(b) shows required sensitivities for detecting HFGWs from primordial black holes (PBHs), which might have resulted from density fluctuations during the first second of the universe. These signals are considered to be coherent and appear to be within reach of some of the planned detectors. Another possible source is axion superradiance, which offers prospects for detection with levitated sensors [6]. DESY has been actively involved in investigating possible HFGW sources and detectors with improved sensitivities, e.g. as part of the Ultra-High-Frequency Gravitational Wave Initiative [7].

The current activities at DESY towards the three on-site axion experiments provide a unique opportunity to exploit synergies with regard to the development of HFGW detectors. A gravitational wave might convert to an electromagnetic wave of the same frequency inside a magnetised volume (inverse Gertsenshtein effect). Therefore, the aforementioned axion experiments also enable searches of HFGWs. Corresponding limits have been derived, e.g. from ALPS I data (Fig. 4(a)) [8]. For ALPS II, three possible configurations with enhanced sensitivity for HFGWs, compared to the “axion configuration”, are currently being studied: a single 250 m long cavity with a TES; two 125 m long cavities and cross-correlating both TES signals; and a broadband search without cavities.

Prospects for dedicated HFGW detectors are also being investigated at DESY: One option is levitated sensors [6], which correspond to dielectric nanoparticles or membranes (partially) levitated by the light field inside an optical cavity, similar to the ones used in ALPS II. Another option is provided by superconducting radio frequency cavities, similar to the ones used for accelerating particles, e.g. in the European XFEL or FLASH. Operation at liquid-helium temperatures could be realised with the cryoplatform in the HERA North Hall.

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LUXE: Exploring uncharted regimes of QED

High-rate detector development and quantum computing at DESY

The LUXE experiment [1] intends to study quantum electrodynamics (QED), the interactions between photons and matter, in an uncharted regime of extreme electromagnetic fields. To achieve such high fields, LUXE will probe collisions between an ultrahigh-intensity optical laser pulse (~100 TW) and a high-energy (16.5 GeV) electron beam from the linear accelerator of the European XFEL X-ray laser. In November 2022, LUXE was recognised as an official on-site experiment at DESY. The experiment, supported by a collaboration of 19 institutes worldwide, is a synergy between laser, particle and accelerator physics. The installation of LUXE is anticipated to start in 2025, with first collisions expected in 2026.

Introduction

QED is one of the most precisely tested theories in nature. Most QED predictions and experimental tests rely on perturbative theory calculations. However, there is a regime of strong-field backgrounds where the default perturbative calculations break down. LUXE's main physics goal is to explore, for the first time, the transition of QED between the well-studied perturbative regime and the non-perturbative regime.

There are several characteristic processes for the non-perturbative regime: Firstly, in the non-linear Compton scattering process, the incoming probe electron absorbs multiple laser photons and emits a high-energy photon.

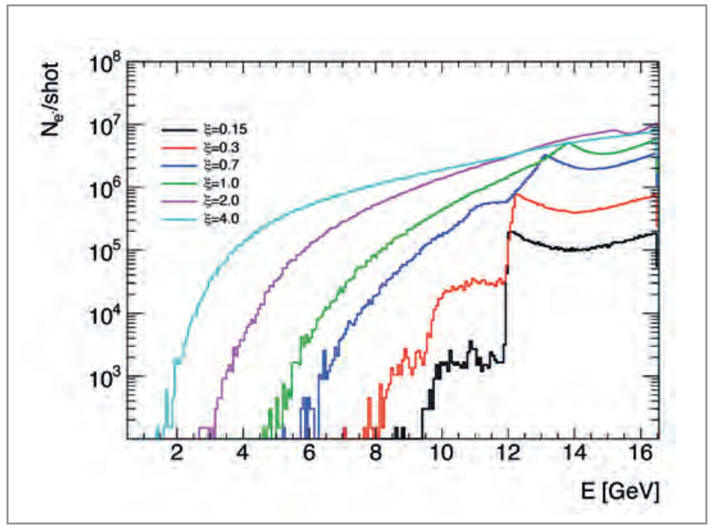

Figure 1

Electron energy spectrum in non-linear Compton scattering expected at LUXE. Different values of the ξ parameters are shown to illustrate how the spectrum is modified by strong-field QED.

The non-linear Compton electron energy spectrum (Fig. 1) shows the kinematic edge shifting to higher energies as a function of the dimensionless laser intensity parameter, ξ, as well as contributions of higher-order scattering processes appearing as additional edges at lower energies. Secondly, the non-perturbativity is present in the rate of non-linear Breit–Wheeler electron–positron pair production through the scattering of a high-energy photon with multiple laser photons. The positron rate is expected to follow a power law in the perturbative regime, but departs from the power law in the non-perturbative regime.

LUXE Cherenkov detector development

The LUXE Cherenkov detector is a system dedicated to measuring the Compton electron energy spectrum. It is part of a magnetic spectrometer, placed downstream of a dipole magnet. The trajectory of the electrons in the magnetic field depends on their energy, therefore the spatial distribution of the electron flux in the horizontal direction is used to reconstruct the electron energies.

Fine spatial segmentation of the Cherenkov detector is achieved by using a grid of air-filled metal straw tubes. The detection principle (Fig. 2) relies on the production of Cherenkov radiation (optical to ultraviolet wavelengths) inside the straw, which is reflected by the inner straw surface and guided towards a silicon photomultiplier at the end of the straw. By reading out the electronic signal from the end of each tube, the electron flux can be measured as a function of the deflection after the dipole field, yielding the energy spectrum.

The use of a gas-filled Cherenkov detector is motivated by the extremely high flux of electrons (10^3–10^8 per detector channel), because such a detector provides a robust flux measurement and, thanks to the Cherenkov energy threshold of air at 20 MeV, helps to reject low-energy and photon background.

A working prototype of the Cherenkov detector with four straw channels was constructed at DESY with the aim of studying the detector performance using a pulsed LED and test beam facilities. This way, the final design choices of the detector will be fixed and the relation between injected charge and observed signal will be determined.

Quantum computing

The rate of Breit–Wheeler pair production is computed from the positron flux, which is measured using a silicon pixel tracking detector with four layers. The positrons leave energy deposits in each layer of the tracker that they traverse. Their trajectories can be reconstructed by identifying the correct combinations of detector hits. The positron rate varies considerably in the experiment, from about 0.001 to as many as two million particles per interaction. The tracking algorithm needs to reject significant background when the signal is rare, while being efficient at a high signal rate. Reconstructing these many tracks is no mean feat, due to the large combinatorics, which are challenging for classical computers to solve. To put this into perspective, the number of tracks at the highest laser intensity is more than a hundred times higher than the maximum expected by the ATLAS and CMS experiments in the HL-LHC phase.

The LUXE team is using a novel approach [2] of representing the track pattern recognition problem as a quadratic unconstrained binary optimisation (QUBO), allowing the problem to be mapped onto a quantum computer and solved using variational quantum eigensolver (VQE). The QUBO problem defines an energy landscape of biases and couplings applied to quantum bits, and the minimum energy value in the landscape represents the correct track reconstruction.

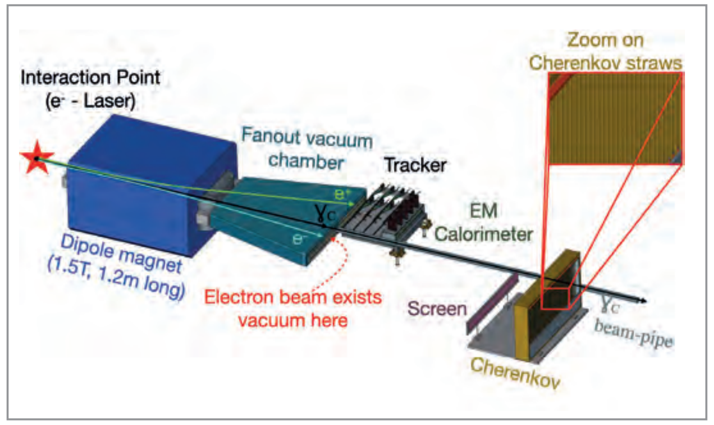

Figure 2

Sketch of the detectors after the interaction point magnet

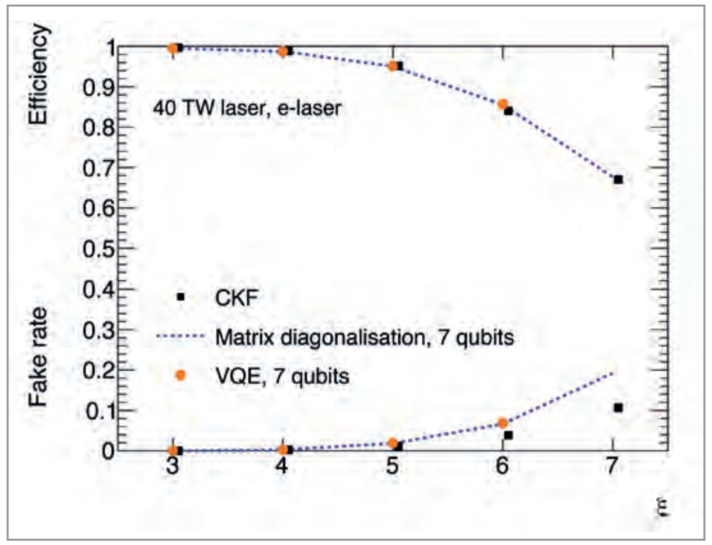

Figure 3

Track reconstruction efficiency and fake rate as a function of the field intensity parameter ξ

Due to the limited number of quantum bits, the QUBO is partitioned into smaller sizes and solved sequentially. The performance of this tracking method is being evaluated on simulated data samples and benchmarked against the classical approach using a combinatorial Kalman filter (CKF) technique. VQE results are obtained using simulated quantum computers without noise and are benchmarked against the exact solutions provided by matrix diagonalisation. Preliminary results of the performance metrics (track reconstruction efficiency and track fake rate), shown in Fig. 3, demonstrate that the VQE solutions match the exact solutions and that the quantum-computing-based approach is comparable to the classical method.

Summary and outlook

The LUXE experiment poses challenges in terms of particle detection due to its high-multiplicity environment. Significant progress has been made in the development of both dedicated detectors and advanced reconstruction methods to cope with this challenging environment and optimally exploit the physics reach of the experiment. More globally, the process for the full approval of the LUXE experiment at DESY and European XFEL is being followed up, aiming for first electron–laser collisions in LUXE in 2026.

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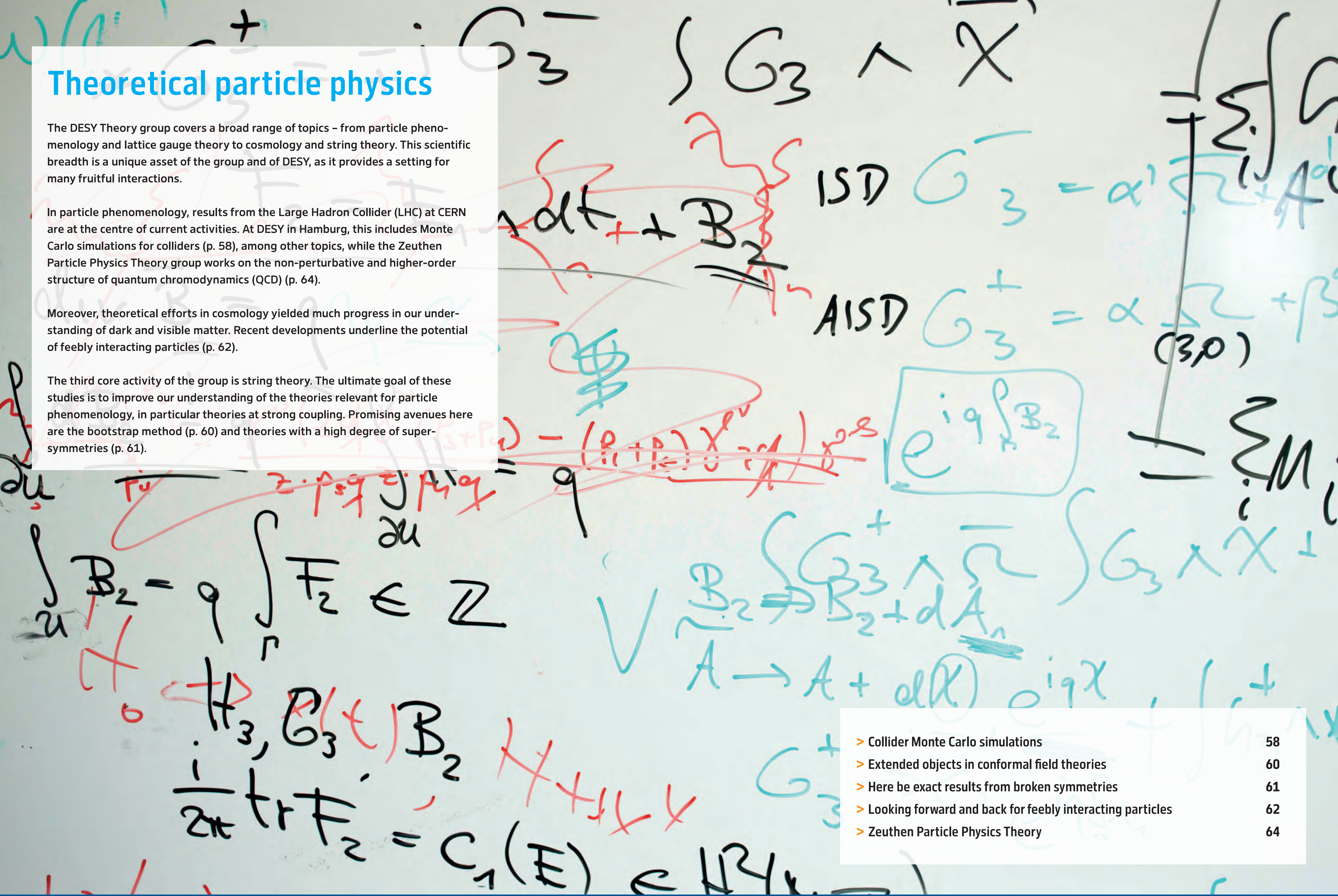


Theoretical particle physics

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 Monte Carlo simulations for colliders (p. 58), 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 dark and visible matter. Recent developments underline the potential of feebly interacting particles (p. 62).

The third core activity of the group is string theory. The ultimate goal of these studies is to improve our understanding of the theories relevant for particle phenomenology, in particular theories at strong coupling. Promising avenues here are the bootstrap method (p. 60) and theories with a high degree of supersymmetries (p. 61).

Collider Monte Carlo simulations

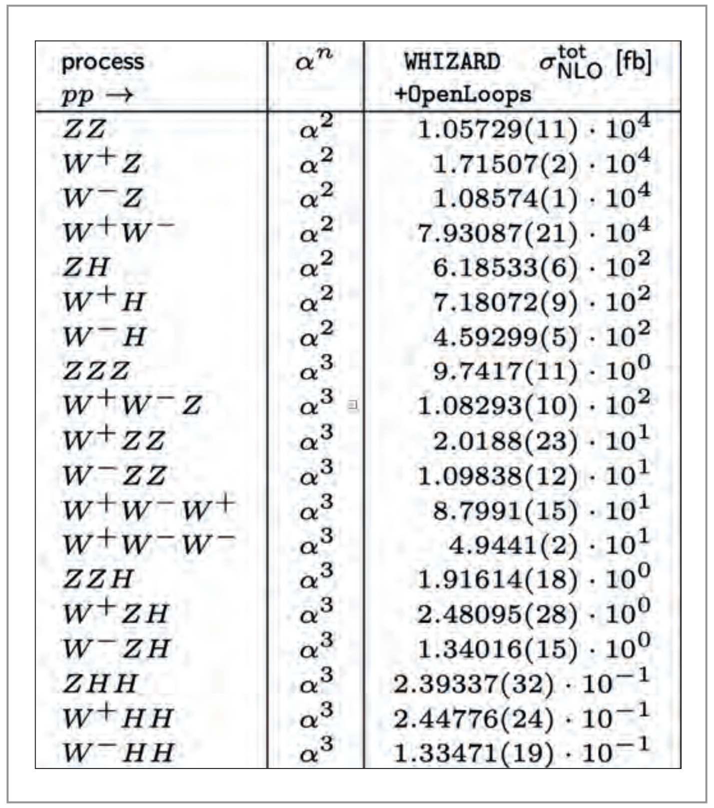
Automated, efficient and precise black boxes

High-energy colliders are the main drivers of research in particle physics. DESY scientists are involved in running experiments at colliders such as the LHC at CERN and SuperKEKB at KEK in Japan, and they play a major role in the design and planning of future colliders such as CEPC, CLIC, FCC and ILC. Both for data analyses at existing colliders and for assessing the physics potential of future colliders, simulations of known and hypothesised particles and interactions are indispensable. The tools used for this purpose are so-called multi-purpose Monte Carlo (MC) event generators, and DESY is a major hub for their development. This article discusses current developments in MC event generators, their complexity and the quest to increase their efficiency.

The need for MC event generators

MC event generators are an indispensable tool for the simulation chain at particle colliders [1]. They are very complex because they encode all of the known particles, interactions and experimental data. Their core component is the hard scattering process, which is the main focus of scientific interest. The state of the art today is the automatic generation of these hard processes at next-to-leading order (NLO) in the Standard Model couplings. At DESY, this endeavour was undertaken by five doctoral students, Christian Weiss, Bijan Chokoufé, Vincent Rothe, Pascal Stienemeier and Pia Bredt, with the help of the postdocs Fabian Bach and Simon Braß, for quantum chromodynamics (QCD), electroweak and mixed corrections, for lepton and hadron colliders, within the framework of the event generator WHIZARD [2].

Work has started on the automation for next-to-next-to-leading order quantum electrodynamics (QED) corrections for future lepton colliders. These new implementations have also been applied at DESY, in addition to processes for hadron colliders such as the LHC or lepton colliders such as the ILC, CLIC or FCC-ee, to provide the first precision predictions for future muon colliders [3, 4]. As examples for the validation, Fig. 1 shows corrections for NLO electroweak cross sections at the LHC at 13 TeV and Fig. 2 the energy distributions of the hardest jet for five-jet production at the ILC at 1 TeV.



process $pp \to$	α^n	WHIZARD +OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]
ZZ	α^2	$1.05729(11) \cdot 10^4$
W^+Z	α^2	$1.71507(2) \cdot 10^4$
W^-Z	α^2	$1.08574(1) \cdot 10^4$
W^+W^-	α^2	$7.93087(21) \cdot 10^4$
ZH	α^2	$6.18533(6) \cdot 10^2$
W^+H	α^2	$7.18072(9) \cdot 10^2$
W^-H	α^2	$4.59299(5) \cdot 10^2$
ZZZ	α^3	$9.7417(11) \cdot 10^0$
W^+W^-Z	α^3	$1.08293(10) \cdot 10^2$
W^+ZZ	α^3	$2.0188(23) \cdot 10^1$
W^-ZZ	α^3	$1.09838(12) \cdot 10^1$
$W^+W^-W^+$	α^3	$8.7991(15) \cdot 10^1$
$W^+W^-W^-$	α^3	$4.9441(2) \cdot 10^1$
ZZH	α^3	$1.91614(18) \cdot 10^0$
W^+ZH	α^3	$2.48095(28) \cdot 10^0$
W^-ZH	α^3	$1.34016(15) \cdot 10^0$
ZHH	α^3	$2.39337(32) \cdot 10^{-1}$
W^+HH	α^3	$2.44776(24) \cdot 10^{-1}$
W^-HH	α^3	$1.33471(19) \cdot 10^{-1}$

Figure 1

List of NLO electroweak corrections to total cross sections (in femtobarn) for several processes at the LHC for 13 TeV, calculated with WHIZARD+OpenLoops. The middle column shows the electroweak coupling order of the Born process.

Challenges of being exclusive

The automation of perturbative higher-order corrections in the full Standard Model necessitates a deep understanding of quantum field theory for radiation phenomena in the soft and collinear limits. For fixed-order NLO calculations, this happens via so-called subtraction schemes; they give very precise predictions for total cross sections and differential distributions of more inclusive (hard) observables, but they describe only the first one or two (QCD or QED) emissions.

For comparisons with experimental data, they need to be "matched" to parton showers, quasi-classical logarithmic approximations to QCD radiation. In the framework of the generator WHIZARD, this matching has been automated for arbitrary processes at hadron and lepton colliders using the POWHEG algorithm. For lepton colliders, the precise resummation of QED radiation has to be combined with exclusive photon emissions: Several different algorithms based on collinear or soft resummation are being studied at DESY. A special complication for high-energy lepton colliders is the simulation of the classical electromagnetic radiation from the highly collimated nano-sized bunches. In WHIZARD, this is simulated as a two-dimensional binned histogram, smoothened with Gaussian filter, separately for the continuum and the boundary to avoid an artificial beam energy spread. This is a unique feature of the WHIZARD event generator.

Efficient and sustainable simulation software

The design of scientific software has to be sustainable in a double sense: More efficient software contributes to reducing CO$_2$ pollution, while it must also be sustainable in terms of compatibility – future versions have to reproduce scientific results from simulation with past versions. The second task is achieved with a clean modular design, test-driven development and good code documentation. These tasks are very important but hardly ever acknowledged in scientific measures.

Bottlenecks of MC generators are costly matrix element evaluations, the multi-dimensional phase space sampling and the initial-state parton distribution function simulation. Highly parallelised phase space algorithms make it possible to reduce the time needed for integrations of processes with complicated final states from weeks to hours, which is already relevant at leading order [6]. Note that this is different to event generation, which can be trivially parallelised.

Recently, two further projects started to explore the possibilities of using i) GPU graphic cards to parallelise the WHIZARD MC integration and ii) machine learning techniques such as invertible neural networks (INNs) instead of adaptive multi-channel VEGAS-like phase space integrators and samplers.

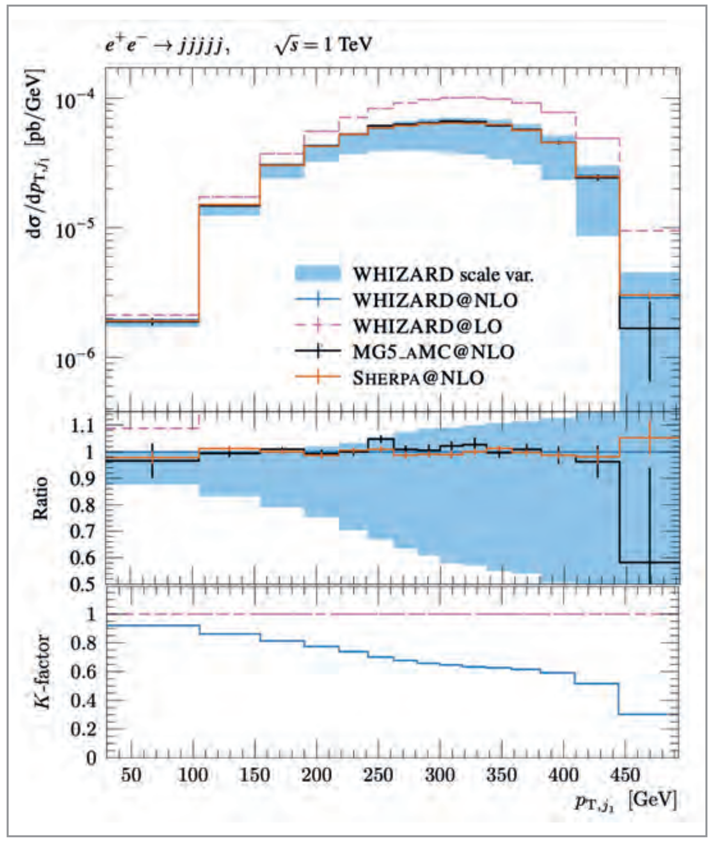


Figure 2

Transverse momentum distribution of the leading jet for five-jet production at NLO QCD at a 1 TeV electron–positron collider such as the ILC, compared between WHIZARD, MG5_aMC@NLO and Sherpa. The dashed line is the leading-order prediction from WHIZARD, the blue band is the scale variation.

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Extended objects in conformal field theories

Breaking free from point-like observables

Quantum field theories can be understood as a renormalisation group flow that connects a high-energy (ultraviolet, UV) model with a low-energy (infrared, IR) model. The theories at the extremes of this flow have enhanced symmetry and are known as conformal field theories (CFTs). Conformal field theories are not only relevant for understanding the extreme energy regime of generic quantum field theories, the models themselves also find direct applications in condensed-matter physics, modern mathematical physics and even string theory. Our Emmy Noether group "The Conformal Bootstrap Program" within the DESY Theory group is using modern bootstrap techniques to study extended objects in CFT, which generalise the more common point-like observables.

Our Emmy Noether group at DESY studies conformal field theories using an approach known as the conformal bootstrap. The idea of the bootstrap is to put symmetry at the forefront and try to solve for the dynamics of a theory using a mathematical set of consistency conditions known as crossing symmetry. Our specific area of expertise is the study of extended objects in CFT (also known as defects). In the past decade and a half, there has been huge progress in the understanding of local (point-like) objects in CFT, but less effort has been made on extended operators, which are fundamental observables in quantum field theory. Well-known examples include Wilson loops in gauge theories as well as boundaries and interfaces in condensed matter (Fig. 1).

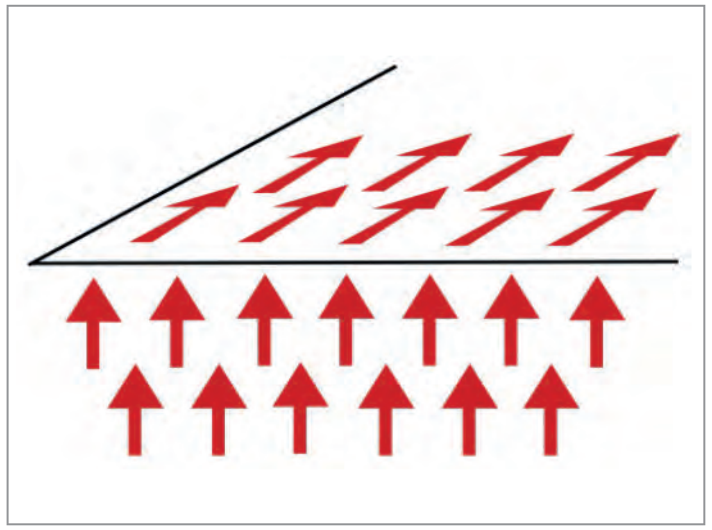

Figure 1

Schematic representation of a system in the presence of a boundary

The highlights of our research in the past few years include the study of local operators in the presence of a Wilson line in *N*=4 supersymmetric Yang–Mills (SYM) theory, which can be thought of as a supersymmetric cousin of standard quantum chromodynamics. Our techniques have also been applied to CFTs in the presence of a boundary. The addition of a boundary makes the system more realistic, as samples in a laboratory have a finite size. We have obtained several analytical results, which are fully consistent with other standard techniques, such as the epsilon expansion. Finally, we are using powerful numerical methods to study magnetic line defects. These defects can be thought of as the word lines formed by magnetic impurities in a condensed-matter system, which means our results might be relevant for experiments.

Despite the progress, we have the feeling that we are just scratching the surface of the dynamics of extended objects in CFT. It is a very active research field where much remains to be done, and new ideas are always welcome!

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Here be exact results from broken symmetries

From maximum symmetry to the real world

Symmetries serve as our main guide in studying physical phenomena. The more symmetric a system is, the more constrained are its degrees of freedom and the better prospects we have to understand and solve it. Significant progress has been achieved in the study of theories with high amounts of symmetry in the last decades. These breakthroughs are, unfortunately, applicable only to theories with unrealistic amounts of symmetry, supersymmetry and conformal invariance. Our group at DESY aims to break this impasse by applying and generalising the ideas to more realistic theories, in which some of the supersymmetry and/or conformal invariance is broken.

The physical world as we understand it today consists of particles that interact due to four different types of interactions. Three of these interactions are successfully described by quantum field theory (QFT) as gauge theories: electromagnetism, weak interactions and strong nuclear interactions. The fourth interaction, gravity, does not quite fit in this picture. While gauge theories are compatible with quantum mechanics, gravity is not. The quantum theory of strong interactions, quantum chromodynamics (QCD), asserts that nuclear matter is composed of particles known as quarks and interaction carriers called gluons. However, the experimental fact that quarks can never be isolated, but are always confined inside the nuclei remains a mystery. Confinement, as this property is called, is one of the biggest open problems in theoretical physics, for which the Clay Research Institute has announced a million-dollar prize. It is part of the general problem of not knowing how to handle gauge theories that interact strongly (at strong coupling).

My work is precisely devoted to overcome this deadlock, by developing tools with which we can understand gauge theories beyond the weak coupling, tailored to apply to the strong coupling regime. To this end, I am using supersymmetry and conformal invariance as tools. Based on the symmetry enhancement that stems from them, powerful techniques have been developed, which allow for exact computations. With these exact results, we can address long-standing physics questions and explain non-perturbative phenomena. Supersymmetric gauge theories not only serve as toy models that we can solve and understand in detail, they also share many properties with theories in the real world, such as QCD. Thus, we can draw otherwise inaccessible lessons for non-supersymmetric theories.

Sharpening our tools will allow us to gradually break supersymmetry and conformal invariance and study non-perturbative phenomena also for gradually more realistic theories. Finally, the more we understand supersymmetric gauge theories, the closer we come to answering a plethora of questions in mathematics that are intimately connected with questions in gauge theory.

In recent years, we were able not only to learn about the strong coupling regime of gauge theories using holography, but also to calculate processes exactly that previously seemed unreachable. These breakthroughs are, unfortunately, applicable only to theories with unrealistic amounts of supersymmetry and conformal invariance. We aim to break this impasse by applying the aforementioned ideas and tools to more realistic theories, in which some of the supersymmetry and/or conformal invariance is broken.

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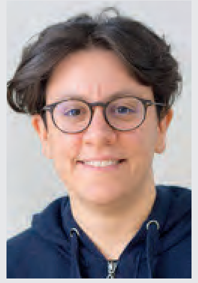

Looking forward and back for feebly interacting particles

From the LHC to gravitational waves

The study of feebly interacting particles has become an important area of research, as they appear prominently in numerous models addressing fundamental questions in particle physics and cosmology. Members of the DESY Theory group are playing an active role in such research efforts, developing new ideas and simulation tools for new physics programmes related to feebly interacting particles on multiple fronts, from searches in the forward direction at the LHC to novel gravitational-wave signals from dark phase transitions in the early universe.

Feebly interacting particles

Although the Standard Model (SM) of particle physics is in excellent agreement with numerous measurements, there remain several phenomena that it cannot account for, such as dark matter, baryon asymmetry and neutrino masses. In response to these questions, theorists have suggested various SM extensions, while experimentalists have been searching extensively for deviations from its predictions. Many of these models contain particles that interact feebly – that is, with interaction strengths several orders of magnitude smaller than the electroweak interactions of the SM. In recent years, feebly interacting particles (FIPs) have become an important area of research. Some well-known examples of FIPs and their connection to different needs for beyond-the-SM physics in our field are shown in Fig. 1.

The feeble interactions characterising FIPs can give rise to diverse signatures. FIPs could be abundantly produced at particle accelerator experiments of all energies and, if metastable, would be observable through their decay at a distance from the production point (e.g. dark photons or heavy neutral leptons). Millicharged FIPs can deposit detectable amounts of energy when passing through material. FIPs might also be so light that they exhibit a wave-like behaviour (e.g. axions). In cosmology, metastable FIPs can act as dark radiation or dark matter.

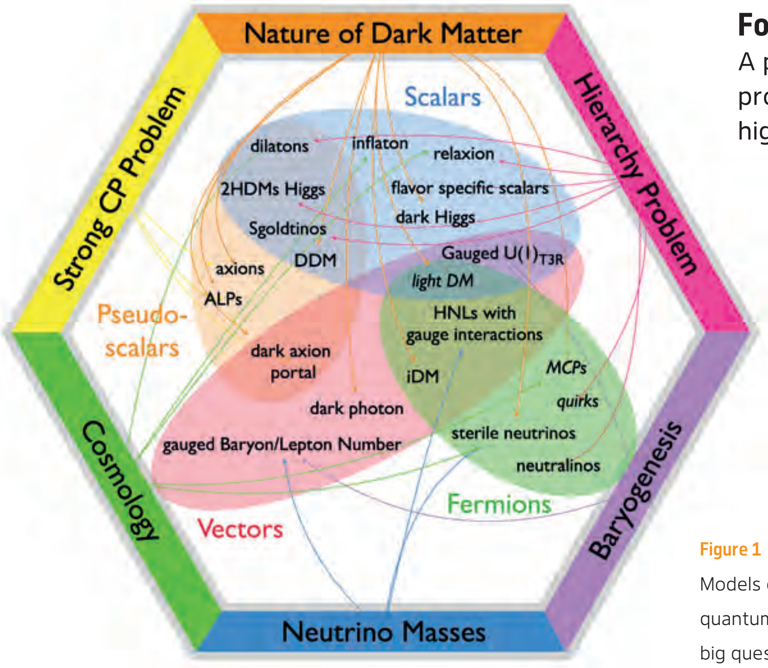

Figure 1

Models of feebly interacting particles (grouped by their quantum numbers) and how they are connected to the big questions in particle physics

Forward FIP searches at the LHC

A promising place to look for FIPs is the LHC, where proton–proton collisions produce an enormous number of highly energetic hadronic particles along the beam axis, some of which may subsequently decay into FIPs. Such FIPs form a strongly collimated beam pointing in the forward direction, which can be detected by placing an experiment into the beam a few hundred metres downstream of the interaction point [1]. This idea has led to the FASER experiment, which is currently operating. A continuation of this programme with upgraded detectors for both FIP searches and high-energy neutrino measurements has been proposed in the context of the Forward Physics Facility (FPF) initiative [2], which is co-led by a member of the DESY Theory group.

The forward FIPs search programme requires dedicated simulation tools. A Monte Carlo package, FORESEE, has been developed for this purpose and is being maintained by the DESY Theory group [3]. It can be used for sensitivity estimates in phenomenological studies and for signal generation by experiments, making it an ideal interface between theory and experiment.

Figure 2 shows the reach in the forward direction for a specific type of FIP: dark photons, i.e. massive particles similar to SM photons that couple to charged particles but with a coupling suppressed by a factor ε. The sensitivities of the existing FASER experiment and the proposed FPF, as estimated using FORESEE, are shown as red curves. In particular, these searches will probe interesting scenarios in which the dark photon acts as a portal to dark matter and explain its observed abundance in the universe.

Gravitational-wave signals of FIPs in cosmology

FIPs in the early universe can also produce striking observable signals. Gravitational waves (GW) are a new and exciting probe of the very early universe, and one of the primary targets of GW experiments is a first-order phase transition, which proceeds through the nucleation, expansion and collision of bubbles of true (stable) vacuum in a background of false (metastable) vacuum.

GWs are generally produced through scalar field evolution after bubble collisions or from the evolution of the thermal plasma surrounding the bubble walls. A team of DESY theorists recently pointed out [4] that FIPs at first-order phase transitions can constitute a novel source of GWs, with spectra qualitatively different from those produced by traditionally studied sources. This phenomenon occurs if the energy released in the phase transition is primarily transferred to FIPs, which form extended particle shells that trace the expanding bubbles of true vacuum. The overlap of such expanding particle shells (illustrated schematically in Fig. 3), which pass through each other without interacting due to the feeble nature of FIPs, gives rise to novel forms of GWs, which can potentially be detected with upcoming GW detectors such as LISA and the Einstein Telescope.

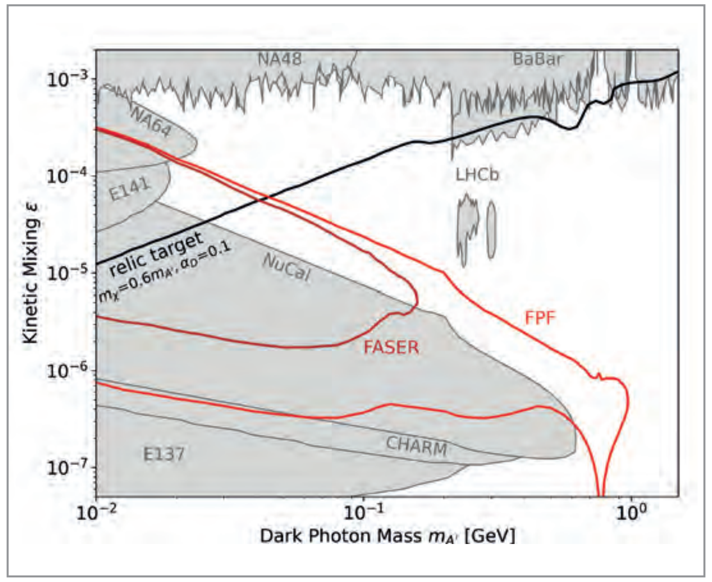

Figure 2

Parameter space of the dark photon in terms of its coupling strength and its mass, including the existing constraints (in grey), the estimated sensitivity of forward LHC searches (red curves) and dark-matter relic target (black line)

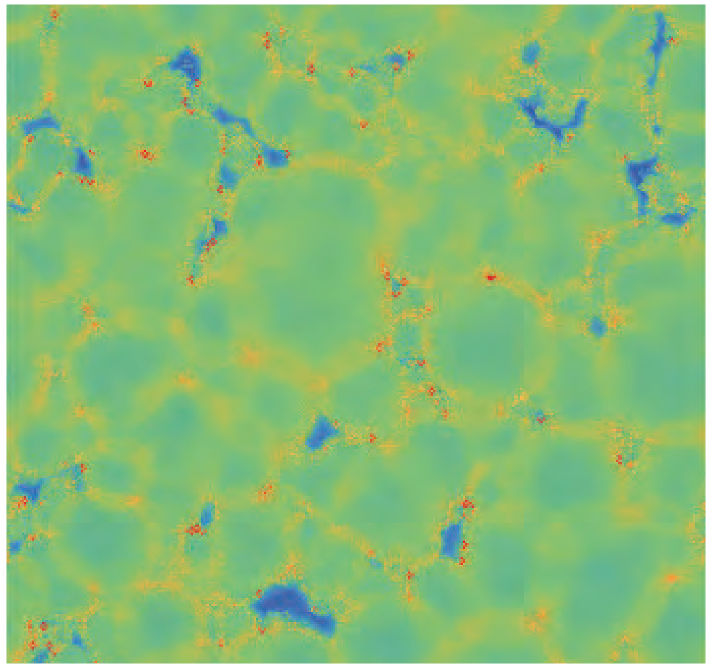

Figure 3

Overlapping, expanding shells of feebly interacting particles at a first-order phase transition in the early universe can produce novel forms of detectable gravitational waves.

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Zeuthen Particle Physics Theory

Theoretical perturbative and non-perturbative particle physics at DESY in Zeuthen

At DESY in Zeuthen, the Zeuthen Particle Physics Theory (ZPPT) group studies theoretical particle physics with the aim of achieving high-precision results for input into and the interpretation of ongoing and planned high-energy and nuclear-physics experiments worldwide. This work is done using both high-loop perturbation theory and non-perturbative lattice quantum chromodynamics (QCD), with the lattice researchers also forming a group at the John von Neumann Institute for Computing (NIC). This article presents a lattice QCD study of interactions between baryons as well as ongoing efforts in the management of large scientific data.

From QCD to nuclear physics

Quantum chromodynamics (QCD) is the established elementary theory of quarks and gluons, the fundamental constituents of hadrons. These include nucleons (protons and neutrons), which are bound states of three quarks and serve as the basic ingredients of atomic nuclei. In principle, the main features of nuclear physics should be derivable from QCD, with small corrections coming from electromagnetism and the weak interaction.

The primary research area of the NIC group is numerical lattice QCD. By discretising Euclidean space-time using a four-dimensional lattice of spacing *a* and periodic finite box size *L*, it becomes feasible to perform non-perturbative QCD calculations using Monte Carlo simulations carried out on supercomputers.

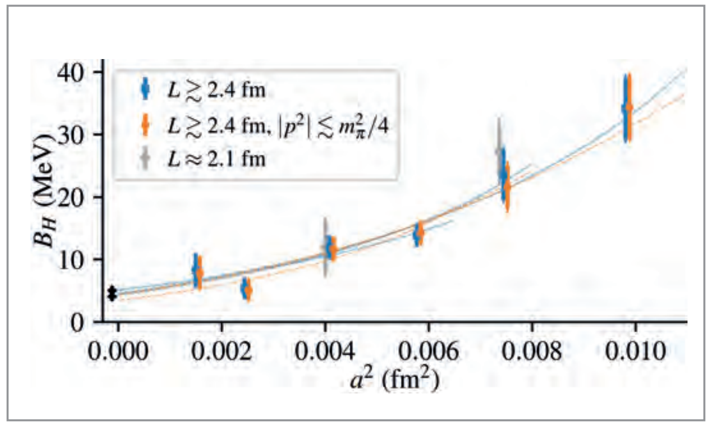

Figure 1

Continuum extrapolation of the binding energy of the *H* dibaryon at unphysical quark masses. The points show results from each of the six lattice spacings, and the curves indicate results from global fits. The black point marks the final result including statistical and systematic uncertainty.

A first step towards deriving nuclear physics from lattice QCD is to understand the interaction between two nucleons, which is already a very challenging problem due to its exponentially bad signal-to-noise ratio. As a warm-up, we studied interactions of hyperons, i.e. baryons containing at least one strange quark. Decades ago, it was conjectured that there could exist an exotic bound state called the *H* dibaryon, a hexaquark with quark content *uuddss*. We found that, for the unphysical situation where the up, down and strange quarks all have the same mass, a weakly bound state exists [1]. Its small binding energy of about 5 MeV means that, for physical quark masses, it is probably unbound.

This calculation, which was performed on machines at the Jülich Supercomputing Centre, is the first study of a two-baryon system that includes a continuum limit, i.e. an extrapolation to zero lattice spacing. It had previously been assumed that lattice artifacts would mostly cancel when computing an energy difference to determine a binding energy. To our surprise, we found that, at non-zero lattice spacing, the binding energy was inflated severalfold (Fig. 1). This demonstration that lattice artifacts cannot be neglected makes the study of baryon–baryon interactions even more challenging than expected.

In a follow-up, we investigated nucleon–nucleon interactions at the same set of unphysical quark masses [2]. We found that the deuteron, which is the only nuclide with atomic number 2 in nature, is unbound. In the future, we want to determine how close quark masses have to be to their physical values to obtain a bound deuteron. Using finite-volume quantisation conditions, we determined the *NN* scattering phase shifts from the shifts of finite-volume energy levels away from their non-interacting values (Fig. 2). This is akin to how the spectrum of a particle in a box will be shifted in the presence of a non-trivial potential.

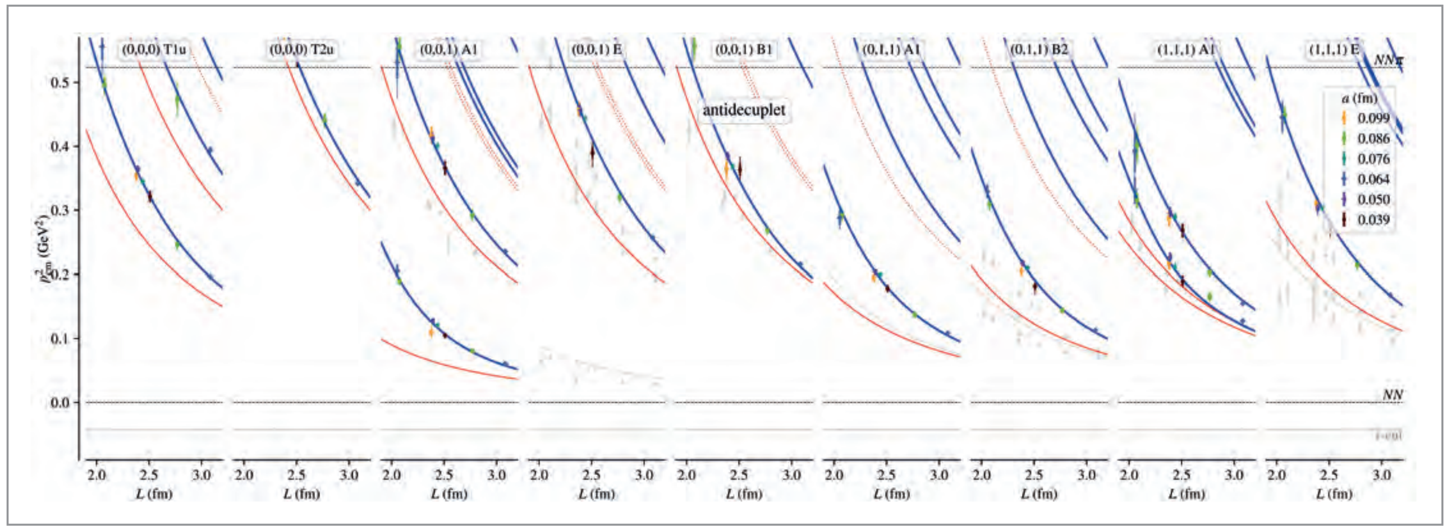

Figure 2

Finite-volume *NN* spectrum relevant for spin-zero P and F waves: centre-of-mass scattering momentum squared versus *L*. The different panels correspond to different total momenta and irreducible representation of the little group, which plays the role of total angular momentum on the lattice. The shifts of the lattice data (points) and the fit (blue curves) away from their values assuming no interaction (red curves) provide constraints on the scattering phase shifts. For these non-trivial partial waves, the effect of changing the lattice spacing (indicated by the colours of the points) is relatively small.

This calculation employed a small subset of the ensembles of lattice gauge field configurations generated over the last decade by the Coordinated Lattice Simulations (CLS) effort, which coordinates the generation and sharing of these ensembles among a group of researchers across Europe. The lattice group at DESY plays a central role in the organisation and data management of CLS.

From lattice data grids towards the cloud

Gauge configurations are the primary data for lattice QCD. In the case of CLS, they amount to about a hundred thousand in number and a petabyte in total storage. Their production requires large-scale high-performance computing resources, and the community-wide data volume (at the permille level compared to LHC data) is sizable.

Due to the need and wish to share these precious data, within and between collaborations, the lattice community started about 20 years ago to set up the International Lattice Data Grid (ILDG): a federation of regional grid infrastructures and services, together with the definition of a community-wide metadata schema and data format. This allows the data to be registered in searchable catalogues and makes them accessible through standard protocols and client tools.

The usability of ILDG has been degrading during the last years due to the lack of person power and the use of outdated grid middleware. Therefore, an effort was started to modernise and extend ILDG [3] to lay a foundation for FAIR (findable, accessible, interoperable and reusable) data [4] and to enable the use of modern (cloud) technologies.

In the framework of the German National Research Data Infrastructure (NFDI) initiative, the NIC and IT groups at DESY are making major contributions to the redesign and organisation of ILDG, e.g. through the development of metadata and file catalogue services, which are an essential component of the ILDG regional grids and in other use cases of scientific data management. With these ongoing improvements, ILDG is taking a further step to enable and simplify the sharing of gauge configurations across the lattice community and to realise the FAIR principles of scientific data management and stewardship.

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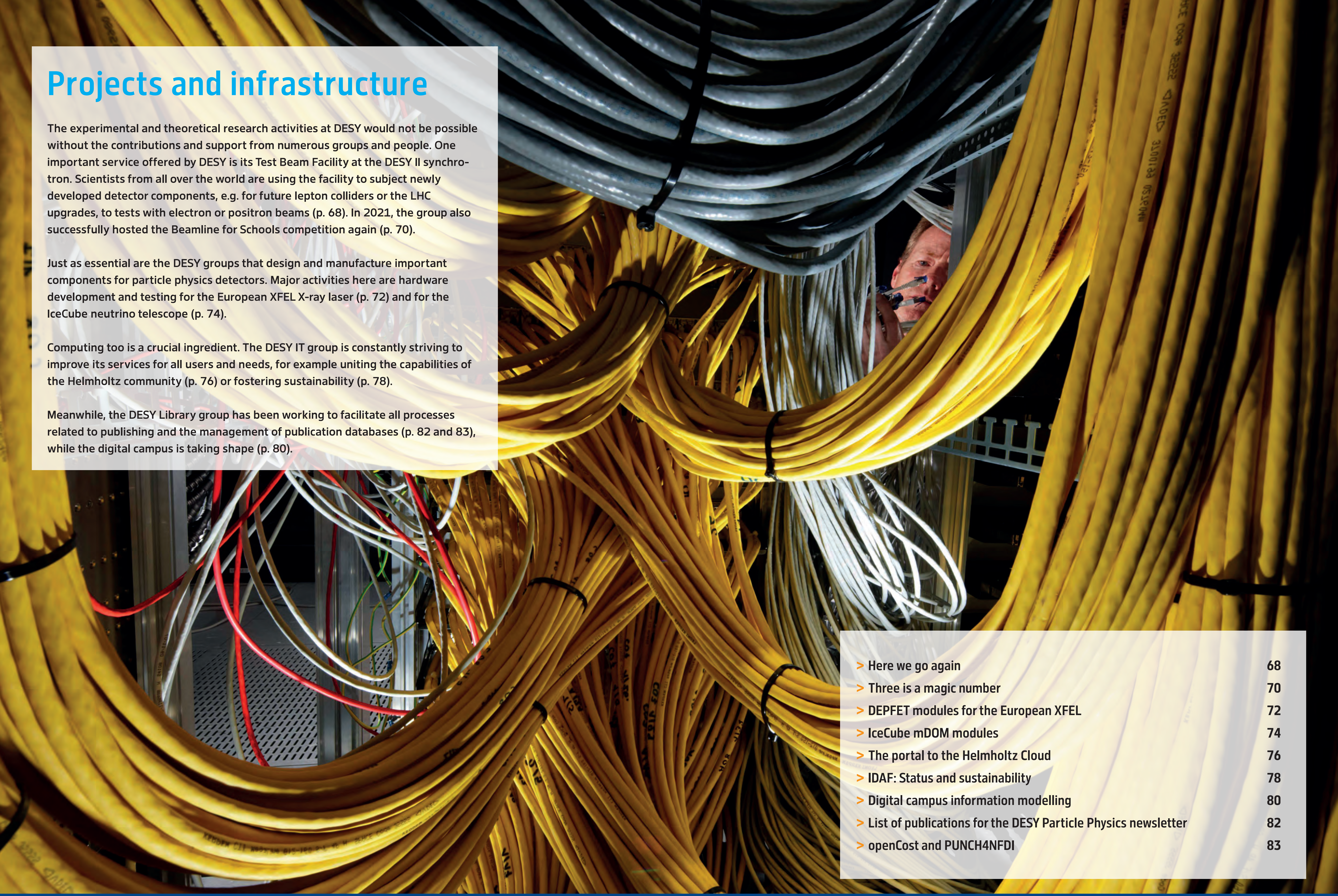
Projects and infrastructure

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 2021, 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 testing for the European XFEL X-ray laser (p. 72) and for the IceCube neutrino telescope (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 capabilities of the Helmholtz community (p. 76) or fostering sustainability (p. 78).

Meanwhile, the DESY Library group has been working to facilitate all processes related to publishing and the management of publication databases (p. 82 and 83), while the digital campus is taking shape (p. 80).



Here we go again

DESY II test beam comes back to normal operations

DESY operates the DESY II Test Beam Facility for R&D projects from the global particle detector community and beyond. In 2022, after two years with COVID-19-related lockdowns, the facility was able to run again without extraordinary shutdowns. Though a few travel restrictions and a size limit for user teams were still in place, over 400 users came to DESY this year. The world-class infrastructures at DESY, such as the EUDET-type pixel beam telescopes, continued to be in strong demand. The facility also hosted the Beamline for Schools competition again, in close collaboration – and this year in parallel – with CERN.

The DESY II Test Beam Facility

The DESY II Test Beam Facility in Hall 2 on the DESY campus in Hamburg is fed by the DESY II synchrotron and offers three beamlines for detector prototype tests. The beamlines can be individually controlled by the user groups and provide electron or positron beams in the energy range from 1 to 6 GeV and with rates up to several 10 kHz. The infrastructure is constantly being improved and extended to keep the facility a world-class venue for detector R&D.

2022 – Operations back to normal

During the winter shutdown 2021/22, the test beam team was busy getting the facility ready for the 2022 user run, which started on 7 February and continued after a four-week summer shutdown in July and August until 22 December.

Although several COVID-19-related restrictions were still in place, 2022 was again a rather normal year at the test beam after 2020 and 2021. A total of 92 of the 111 available beamtime slots were booked, which corresponds to a usage of 83%. Figure 1 shows the development of beamtime booking over the last 10 years. Over the years, one can see a rise in the need for beamtime as well as the highly increased demand during the shutdowns of the CERN test beamlines.

Overall, 405 users from 21 countries came to the DESY test beam in 2022, and the share of first-time users of the facility increased again to over 30%. That nearly 70% of the users are young postdocs or students underlines the role of the test beam facility as a central part in the training of the next generation of detector experts.

In total, 40% of the beamtime was used for LHC-related beam tests. The generic detector R&D projects, exploring new sensors and ideas for the next generation of experiments, kept going strong, using 33% of available beamtime.

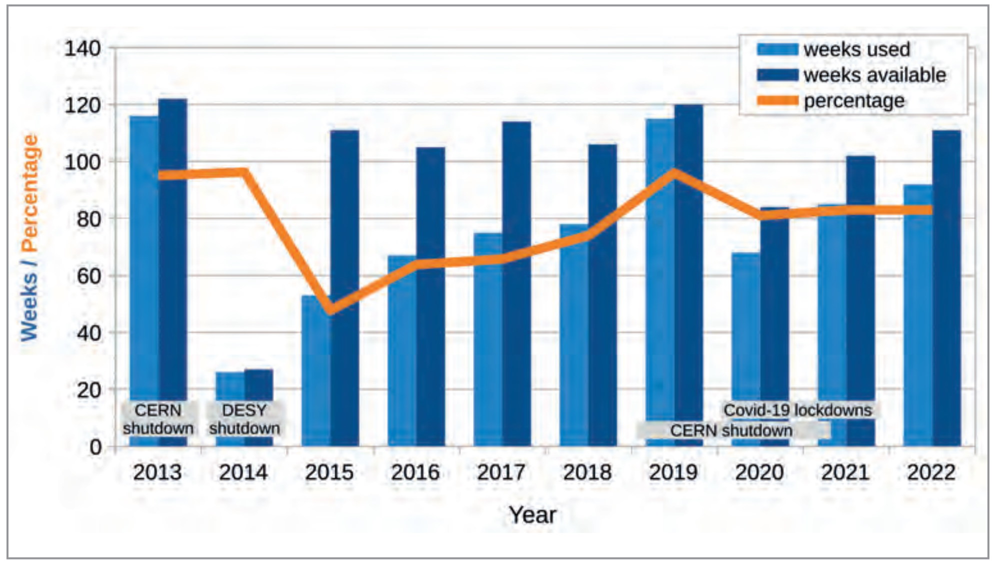


Figure 1

Usage statistics for the DESY II test beam from 2013 to 2022

Figure 2

New Adenium telescope prototype in Beamline 24, with six ALPIDE sensors (in the green frames) and a mechanical holder for the network switch in front

Beam telescopes

Beam telescopes are essential instruments used in detector prototype tests that measure the trajectories of passing beam particles to extrapolate the exact position where the particles traversed the prototype under test. As in previous years, the telescopes were the most requested infrastructure, with 82% of the groups using them.

For about 15 years, so-called EUDET-type telescopes have been used at DESY and many other beamlines worldwide. They are based on the MIMOSA26 sensor with an active area of 2 cm x 1 cm and a pixel size of 18.4 µm x 18.4 µm, resulting in a tracking resolution down to 2 µm. But these systems are reaching their end of life and have a limited rate capability due to ambiguities in their 230 µs long readout frames.

Adenium telescope prototype

Since 2022, DESY Hamburg has had the end-user license for the ALPIDE pixel sensors, which were originally developed for the ALICE experiment at the LHC. These sensors are well characterised and highly available. They have a sensitive area of 1.5 cm x 3.0 cm and a pixel pitch of 29.24 µm x 26.88 µm. They can reach a tracking resolution down to about 3 µm, comparable to the one of MIMOSA26, and their readout frames are about 10 times shorter than those of MIMOSA26.

Supported by the AIDAinnova project, an ALPIDE-based telescope prototype called Adenium was installed in summer 2022 in Beamline 24 (Fig. 2). From the users' perspective, in terms of operation, the prototype looks like a EUDET-type telescope. In this way, it can be seamlessly integrated in existing setups and has been running successfully throughout the second half of 2022. The concept is presently being developed into a final system to replace the current telescopes in the future.

TelePix

One focus of current silicon sensor R&D is on the timing resolution. To study these novel sensors at the test beam, the telescope infrastructure also needs to deliver excellent timing capabilities using additional, specialised timing layers. The TelePix project, funded by the Cluster of Excellence Quantum Universe, is developing a sensor with nanosecond hit timing and a very flexible region-of-interest trigger to be used in such a timing layer. In 2022, a small-scale demonstrator (4.75 mm x 3 mm) with a pixel size of 160 µm x 25 µm was successfully tested and reached a time resolution of around 2.4 ns. A full-scale chip is in production and will be commissioned in early 2023.

Outlook for 2022 and beyond

The winter shutdown 2022/23 will again be a time for cleaning up, maintenance and upgrades. Since no extremely time-critical bookings were among the beamtime requests for the beginning of 2023, user operation will start one month later than usual, on 6 March, to contribute to the overall energy-saving efforts. Also with this goal in mind, the schedule for 2023 is designed to avoid operating a single beamline as much as possible and instead run the experiments in parallel whenever feasible.

A major focus is still on the future of the test beam facility in light of the major overhaul of the accelerator complex for the PETRA IV upgrade. The plans for a future test beam facility are taking shape, and several options are being explored in detail.

Summary

In retrospect, 2022 was a step back to normality after the challenges in user operation in 2020 and 2021, and we are looking forward to a successful year 2023. The success of the DESY II Test Beam 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.

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Three is a magic number

CERN's Beamline for Schools competition for the first time with three winning teams

In autumn 2022, CERN's Beamline for Schools competition entered its ninth round. For the first time, it was held in parallel at a beamline of the Proton Synchrotron (PS) at CERN and at a beamline of the DESY II Test Beam Facility. This made it possible to expand the competition so that three winning teams of high-school students could be invited to perform their experiments at a beamline. DESY welcomed the team "Supercooling" from Reims in France at Beamline 21 to test an innovative particle detection technique that relies on the phase transition between liquid and solid water.

Global science competition for high-school students

Beamline for Schools (BL4S) is a global science competition in which teams of high-school students submit their own research questions and design fixed-target experiments to investigate them. The first prize for the winning teams is a two-week visit to CERN or DESY to conduct their experiment at a real beamline.

Over the past nine years, there have been contributions by more than 15 000 students from more than 92 countries. In 2022 alone, 304 experiment proposals were submitted from 84 different countries.

The BL4S competition was launched by CERN in 2014, as a highlight of CERN's 60th anniversary activities. Until 2018, the experiments were performed at the PS test beam at CERN. Due to a long shutdown of the CERN accelerator complex, the competition had to evolve: DESY premiered – in close collaboration with CERN – as host in 2019, coincidently the year of the 60th anniversary of DESY. DESY received the winning teams again in 2020 and 2021. At the end of the shutdown at CERN in 2022, CERN and DESY agreed to run the experiments in parallel, allowing for tree winning teams, two visiting CERN and one coming to the DESY test beam.

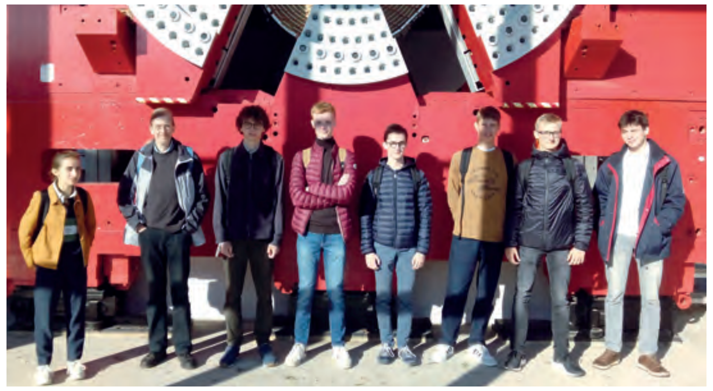

Figure 1

The winning team "Supercooling" from Reims, France, in front of the ARGUS detector at DESY

Winning teams 2022

In 2022, 25 of the 304 teams made it onto the shortlist, from which the three winning teams were selected. The winners came from Spain, Egypt and France.

The team "Club de Física Enrico Fermi" from Vigo, Spain, studied the charge induced by the passage of ultra-relativistic charged particles in multigap resistive plate chambers (MRPCs). The students investigated the relationship between the charge produced in the detector, the particles' mass and the incident angle of the particle beam.

The team "STA" from the Elsewedy Technical Academy in Cairo, Egypt, worked with MRPCs as well, but focused on studying the use of more environmentally friendly gases than the commonly used mixtures and the effect of these gases on the detection efficiency. These two teams conducted their experiments at the PS test beam at CERN.

The team "Supercooling" from the École du Sacré-Coeur in Reims, France, visited the test beam at DESY to perform their innovative detector experiment trying to detect particles based on the phase transition between liquid and solid water. In a process analogous to the one used in fog and bubble chambers, the team investigated the detection of passing particles using water in a supercooled state. Supercooled means that the water temperature is below its freezing point, but without a seed crystal or nucleus the freezing process hasn't started. The idea is that the interaction of the traversing high-energy particle with the supercooled water disturbs this fragile state and causes a phase transition from liquid to solid along its path.

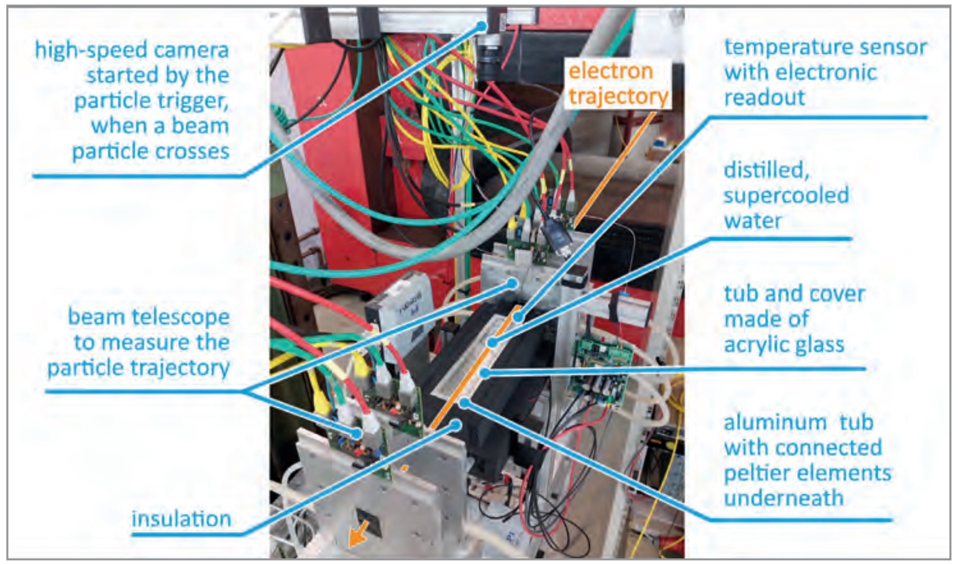

Figure 2

Experimental setup of the team "Supercooling" installed at Beamline 21

Cool experiment at Beamline 21

The experimental setup installed at DESY II Beamline 21 consisted of a high-speed camera to film the freezing process in detail and a tub of acrylic glass containing supercooled water (Fig. 2). To cool the water below 0°C, this tub was fitted into a surrounding aluminium case with connected Peltier devices for thermoelectric cooling. To speed up the cooldown, the water was precooled to close to 0°C in a conventional fridge. The experimental conditions were constantly monitored by a connected temperature sensor. The complete setup was mounted inside a beam telescope, an instrument to determine the exact position where the particle crossed the experiment.

The challenges were that any small disturbance could trigger the phase transition and that the team had to find the correct experimental conditions. This was a comparably lengthy process, as the tub had to be emptied, refilled and cooled again between each measurement.

Shortly before the final presentations, a candidate event for a particle-induced phase transition could finally be filmed, leading to a successful end of this beam test.

Being a physicist for two weeks

The students' visit started with a tour of the city of Hamburg and an introduction to DESY. These were followed by safety courses and lectures on the beamlines at CERN and DESY as well as an introduction to data acquisition and analysis.

Many points of the two-week programme took place in video conferences to ensure communication between the student teams at both locations. In the daily routine at DESY, the students took turns in measurement shifts, while the rest of the team learned how to perform particle tracking and data analyses.

The VIP and sponsor day took place on the last Friday of the two weeks, with official representatives of the home countries and the sponsors as well as delegates from the CERN Council. It was held in parallel at CERN and DESY and transmitted via video conference. After the welcome words by the CERN Director for Research and Computing, Joachim Mnich, and the DESY Director in charge of Particle Physics, Beate Heinemann, the students presented their experiments at the beamlines. This year too, the excellent presentations led to lively discussions with the invited guests.

Acknowledgements

Beamline for Schools is an education and outreach project funded by the CERN & Society Foundation. The 2022 edition was supported by the Arconic Foundation and the Wilhelm and Else Heraeus Foundation, with additional contributions from Amgen, Switzerland.

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.

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Reference:

https://beamlineforschools.cern/

Summary video of the team "Supercooling":
https://www.youtube.com/watch?v=B2RMeDF2a7c

DEPFET modules for the European XFEL

Active sensors reach ultimate performance

The DSSC consortium (short for Depleted P-Channel Field Effect Transistor Sensor with Signal Compression) is developing a second megapixel camera for the soft X-ray regime based on active pixel sensors with depleted field effect transistors (DEPFETs) instead of passive arrays of miniaturised silicon drift detectors (mini-SDDs). The active pixel sensors improve the performance in terms of single-photon resolution and dynamic range. In 2022, the first DEPFET fabrication run was completed and the first batch of modules assembled and fully characterised at DESY. The module results confirm the prototype performance and the achievability of unique noise levels at MHz frame rates and room temperature.

In 2019, the DSSC consortium delivered the first megapixel camera for the European XFEL X-ray laser based on passive mini-SDDs (see *DESY Particle Physics 2018*). Since that time, the camera has successfully been operated in more than 20 user experiments at the Spectroscopy and Coherent Scattering (SCS) and the Small Quantum Systems (SQS) soft X-ray instruments. At the same time, the production of a second camera based on monolithic active pixels was started to further improve the noise and dynamic range capabilities. The active pixels consist of DEPFET devices. Thanks to the extremely low input capacitance of the signal charge-collecting internal gate of the DEPFETs, the sensor pixels provide excellent noise performance down to about 10 electrons of equivalent noise charge (ENC) at highest gain settings of the analogue front-end. Moreover, by shaping the doping profile of the internal gate, a signal compression is obtained that expands the dynamic range to about five thousand electrons at highest gain and 1.3 million electrons at a gain that still maintains single-photon resolution.

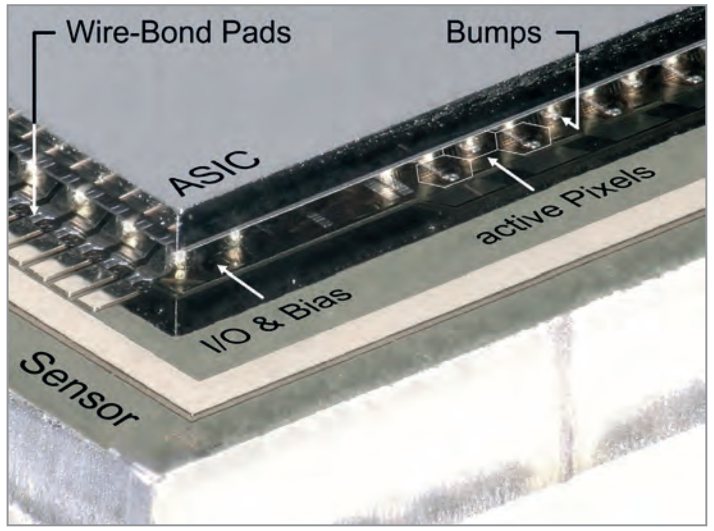

Figure 1

Bird's eye view of an ASIC (top) bump-bonded to a DEPFET sensor (bottom)

On the readout application-specific integrated circuit (ASIC), the front-end amplifiers for both the mini-SDD and the DEPFET sensor pixels (hexagons with 136 µm side length) are implemented in the pixel area. The adequate circuitry can be selected later by two variations of a single metal mask. The downstream analogue signal shaping, digitisation and digital storage are shared between the variants. At ASIC level, the analogue-to-digital converter matrix with adjustable gain and offset, the clock- and data distribution as well as the global voltage/current references with distribution network were designed by the DESY Microelectronics Development (FEC) group. Figure 1 shows a corner section of an ASIC bump-bonded to a DEPFET sensor. The ASIC is thinned down to about 250 µm, whereas the sensor chip thickness amounts to 725 µm, ensuring a sufficiently high radiation tolerance in the operating energy range up to 6 keV.

The camera-head and back-end electronics, which reside inside and outside vacuum, respectively, are also shared between the two camera variants. For the mini-SDD version, however, specific DEPFET components were not assembled. The FEC group designed all subassemblies except two data acquisition printed-circuit boards, which were developed by partners from Heidelberg University.

The smallest independent unit of the megapixel camera is called a ladder. It consists of a focal-plane module assembled to its camera-head electronics. The focal-plane module is built from two monolithic pixel sensors, each bump-bonded to eight readout ASICs, forming a bare module. Both bare modules are glued on and wire-bonded to a heat spreader mainboard frame sandwich, forming an array of 512 x 128 pixels. Figure 2 shows a photograph of its entrance window (top) and a corresponding ENC map obtained in high-gain configuration (bottom).

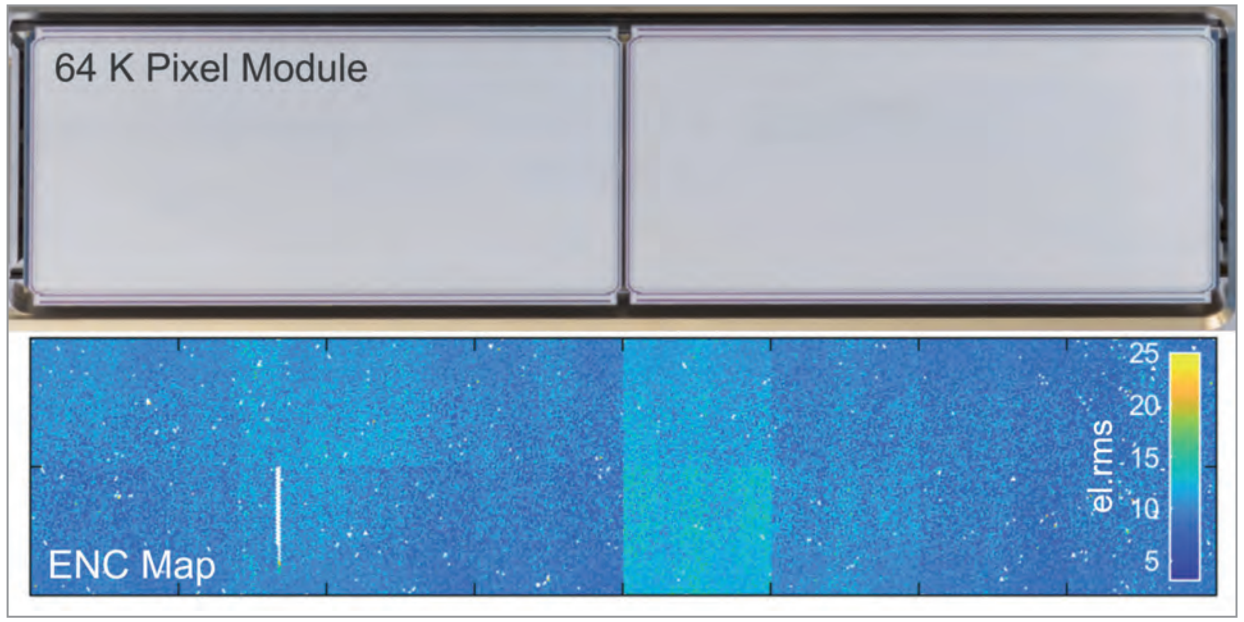

Figure 2

Front view of a ladder composed of two sensors of 256 x 128 pixels (top) and an ENC map obtained in high-gain mode (bottom)

The first prototype ladders equipped with DEPFET sensors were extensively tested at 18°C in our laboratory to verify the full functionality of all the components together. The measurements were performed at different operating frequencies and front-end gains. The main properties of the system were characterised, and the DEPFET bias current and the leakage current of the sensor pixel were determined. The system gain was calibrated by means of an ^{55}Fe radioactive source, and the non-linear response was characterised using a pulsed high-power laser diode array. In this way, a mean charge per pulse of about 230 electrons was achieved.

As summarised in Fig. 3, the DEPFET system shows an excellent noise performance down to 9.8 electrons RMS when operated at 1.1 MHz frame rate and 300 ns integration time. At a maximal frame rate of 4.5 MHz, an ENC of about 25 electrons is achievable. The operation of cooled mini-SDDs almost doubles the ENC and does not offer signal compression. The performance values were also verified during a dedicated calibration campaign at the SQS instrument in late 2022, confirming the outstanding performance and the reliability of our in-house measurements.

The first production run of the DEPFET-based focal planes was completed, and each module was mounted to its electronics. The ladders were extensively characterised to assess the functionality and performance level and to select the best modules for the camera assembly. First, the gain and offset trimming capabilities were verified, and the set of operating voltages was optimised. Then, the DEPFET bias current was equalised (100 µA) and the system calibrated. Finally, the leakage current was measured (~1 pA/pixel) and the non-linear response characterised. The yield of the first production is sufficiently high to populate two out of four quadrants of the final DEPFET camera. The second sensor fabrication is running and should allow the camera assembly to be completed.

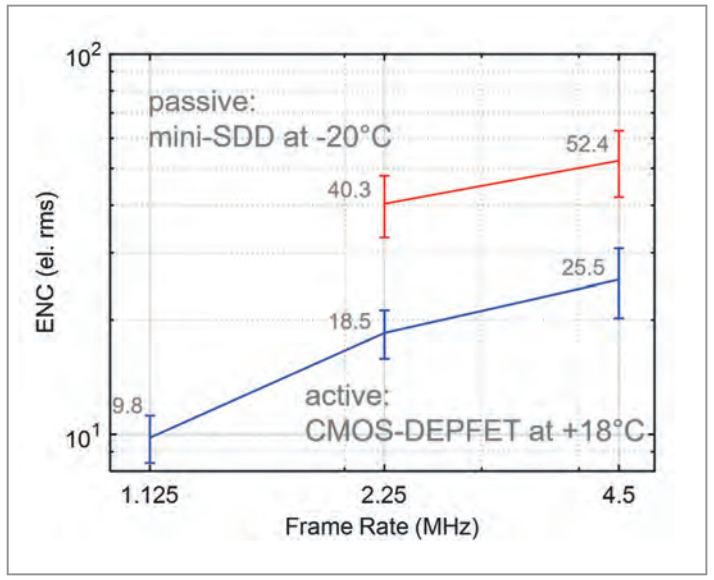

Figure 3

DEPFET (blue) and mini-SDD (red) noise performance versus frame rate

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IceCube mDOM modules

From hot ovens to icy landscapes

New instruments will be added to the existing IceCube neutrino detector at the South Pole, upgrading it to IceCube-Gen2. They will be frozen underground in the eternal ice of Antarctica, more than 1 km deep underground. The new detector will increase the rate of cosmic neutrino observations. But the upgrade is not only about scientific superlatives: There are also some superlatives in the production and testing of the highly sensitive electronic parts. The DESY Service Centre Electronics (ZE) group was chosen for the production of the multi-PMT digital optical modules (mDOMs) – the electronics are manufactured in the ZE workshop and tested in the ZE test lab. In this article, we describe what the electronic components for such an instrument look like and how are they manufactured and tested.

Challenges in production

An important part of the IceCube-Gen2 detector are the new mDOMs. Compared to the boards usually manufactured by ZE, two major challenges have to be overcome here: a huge number of components and a special geometry.

On every module, footprints for 3919 single components are provided, and 3543 of these components are assembled. Only 110 of them have to placed and soldered by hand, all others are surface-mounted devices (SMDs). The board is populated with the SMDs by an automatic pick-and-place machine, which can process up to 400 components per minute. A camera installed in the machine can "see" which component is just being picked and processed. The machine can also rotate the components. Usually, they are rotated by 90° or 180°, but here, the geometry is a little more special. The board has an unusual round shape, and the 24 signal channels are distributed over a bit less than 270°. The machine therefore required some specific programming.

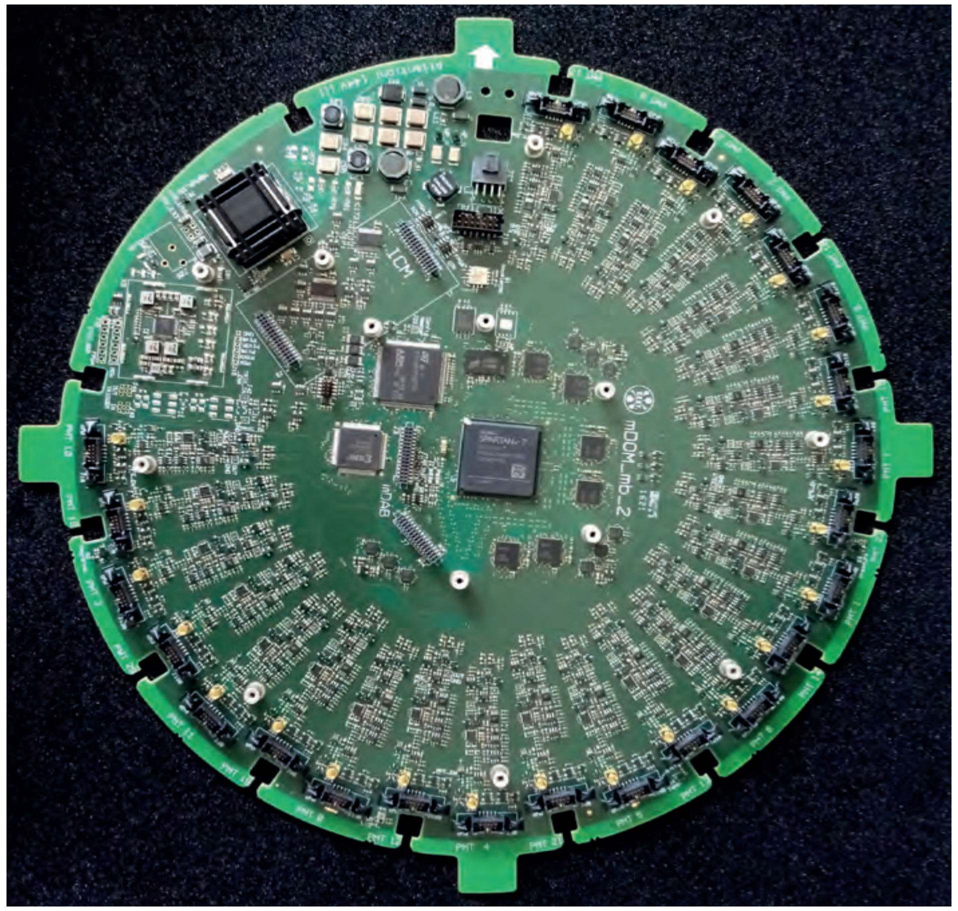

Figure 1

Populated mDOM board

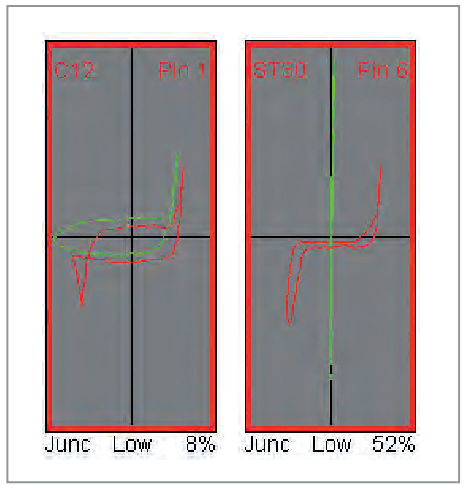

Figure 2

Component signature created by the flying probe tester. A failure is easy to recognise if you know what the signature means.

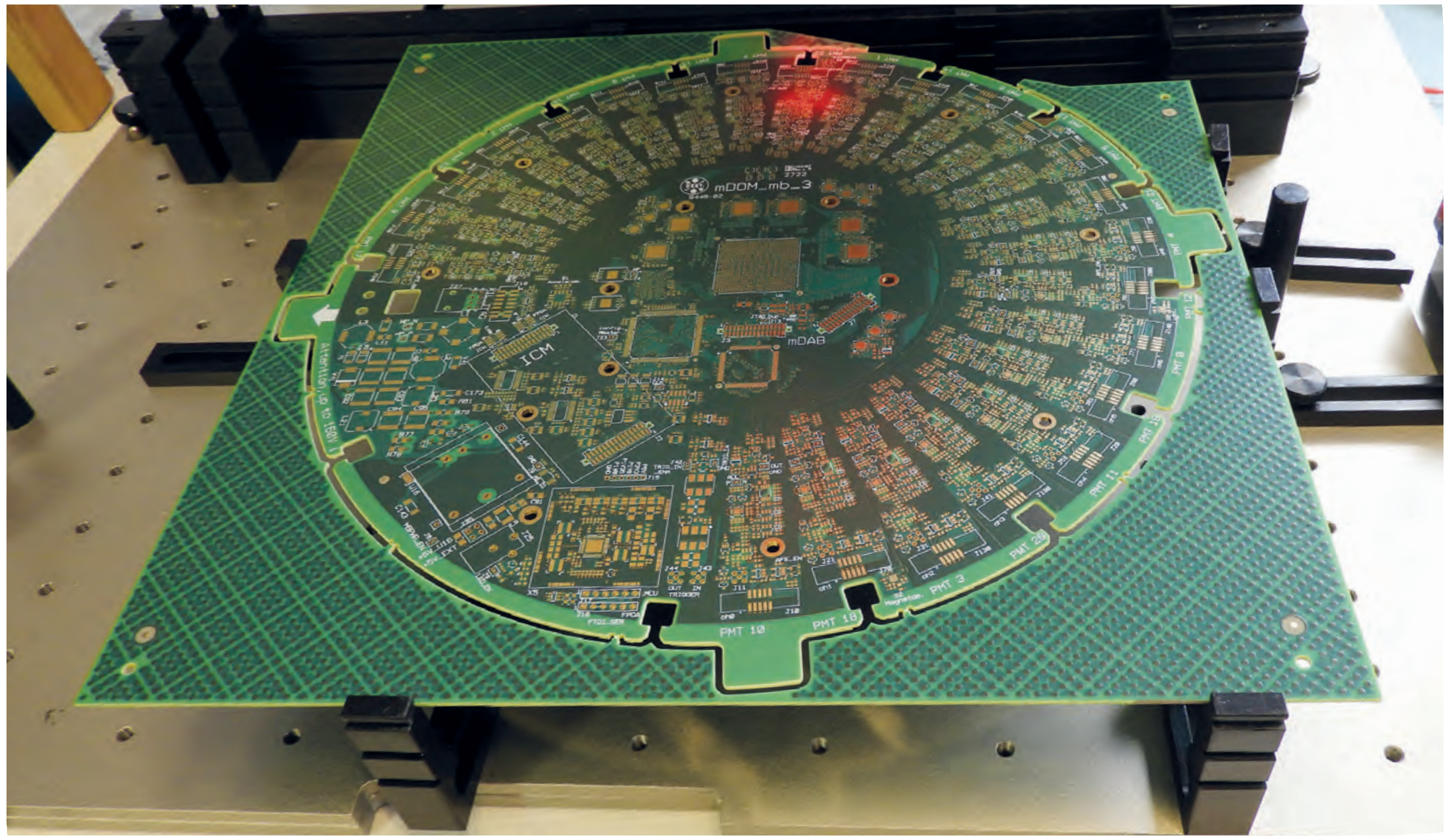

Figure 3

An mDOM board clamped in the Polar GRS500 flying probe tester

Populating one mDOM board from both sides takes about 22 min. After populating, the boards are soldered in a reflow oven, passing through a temperature profile for about 8 min. Including the setup of the machine, it took a total of about one week to manufacture a series of 40 boards (Fig. 1).

Challenges in testing

The same challenges had to be overcome in testing too. Additionally, a complete electrical or functional test of all components is not feasible in the ZE test lab. It is possible to test all connections with a flying probe tester, however. For this, the circuit is divided into different electrical networks. Each network is connected to a ground potential. A signal is then fed into every network by a needle, and the signature of every component is measured and displayed. When the signature exceeds a certain tolerance, the flying probe tester marks a failure. At this point, the crux is to define a suitable tolerance level for acceptance. The only available reference is a golden sample of the board that was successfully tested by the developers before, so a tolerance level is not given but has to be worked out. Every signature is displayed graphically (Fig. 2), so it is easy to see what is wrong, as each type of component has its own characteristic signature (e.g. diode, capacitor, resistor). The space on the tester is limited – Fig. 3 shows a first clamping of an unpopulated board to make sure that it fits on the tester and to see if the needle can reach every pad.

Next steps

A preproduction batch of eight pieces, followed by another 40 ones, has successfully been produced and tested. 400 more are expected to be produced in 2023. The final test, programming and assembly will take place at DESY in Zeuthen.

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The portal to the Helmholtz Cloud

A window to Helmholtz-wide resources and services

The Helmholtz Cloud, set up and maintained by Helmholtz Federated IT Services (HIFIS), offers a large collection of useful and professional services, contributed by now nine Helmholtz centres for all members of the Helmholtz Association – including DESY users. To guarantee scientists an optimal user experience and optimise the assignment of expensive IT resources across the Helmholtz Association, DESY, as a major HIFIS member, provides a portal for these shared IT services, allowing users to select the best services for their scientific work. Both the portal and the available services will be continuously improved in 2023 and beyond.

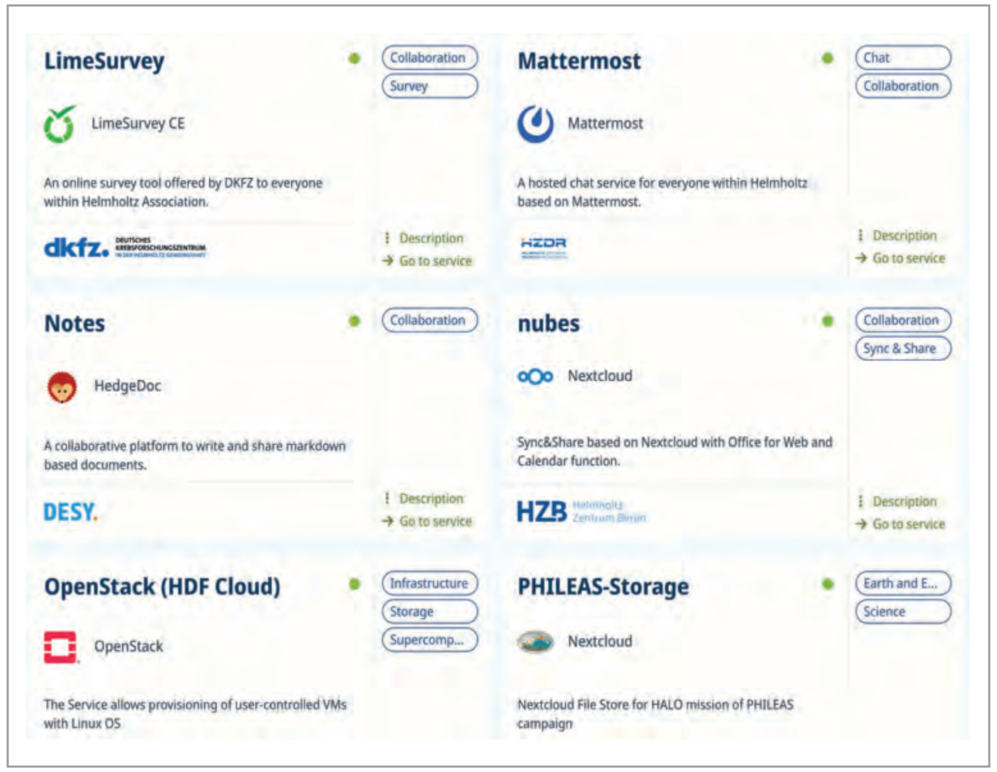
Figure 2
HIFIS supports scientific projects with Helmholtz-based digital resources, services, consulting and expertise. Particular focus is placed on sustainable research software development.

Helmholtz Cloud services for all Helmholtz members

The HIFIS platform [1] was created to better exploit the synergies between the distributed Helmholtz infrastructures and their research areas. HIFIS catalyses the pooling of efforts and resources in the IT area and thus optimises knowledge exchange and resource use for all Helmholtz members and their communities, regardless of their affiliation.

Building such a distributed infrastructure involves a wide range of legal, administrative and technical activities. One of these is the provision of a central portal to promote shared services, making them seamlessly available and align with users' workflows.

To this end, the DESY IT Research and Innovation in Computing (RIC) group launched the Helmholtz Cloud Portal (Fig. 1) [2]. It offers a wide range of information and search criteria to find just the right service for each scientist and use case. These include the type of service, its provider, service description, access details, support contact and, in some cases, links to training materials. To be listed on this portal, services must undergo a rigorous onboarding process, guarantee high quality and availability and demonstrate that they are useful to the Helmholtz "family".



LimeSurvey
Collaboration
Survey
LimeSurvey CE
An online survey tool offered by DKFZ to everyone within Helmholtz Association.
dkfz. DEUTSCHES KREBSFORSCHUNGSZENTRUM
⋮ Description
→ Go to service

Mattermost
Chat
Collaboration
Mattermost
A hosted chat service for everyone within Helmholtz based on Mattermost.
HZDR
⋮ Description
→ Go to service

Notes
Collaboration
HedgeDoc
A collaborative platform to write and share markdown based documents.
DESY.
⋮ Description
→ Go to service

nubes
Collaboration
Sync & Share
Nextcloud
Sync&Share based on Nextcloud with Office for Web and Calendar function.
HZB Helmholtz Zentrum Berlin
⋮ Description
→ Go to service

OpenStack (HDF Cloud)
Infrastructure
Storage
Supercomp...
OpenStack
The Service allows provisioning of user-controlled VMs with Linux OS

PHILEAS-Storage
Earth and E...
Science
Nextcloud
Nextcloud File Store for HALO mission of PHILEAS campaign

Figure 1
Excerpt from the Helmholtz Cloud Portal Service Catalogue: Helmholtz members can choose from a variety of services provided by other Helmholtz centres.

What's in it for me?

In effect, this reduces the need to set up similar services at all Helmholtz centres – instead, the centres can specialise in their own specific high-quality services and roll them out to all Helmholtz members, while themselves making use of services provided by other centres. On top, all services are per definition specialised in cross-institutional collaboration, which makes resource sharing with your partners from within and outside the Helmholtz Association a no-brainer.

As examples, DESY currently provides an event management platform (based on Indico) for all Helmholtz members, while other centres offer services such as LimeSurvey or CollabTeX, which can be used by DESY members directly and thus do not need to be set up at DESY itself. The same applies for a multitude of other services – check it out!

One Helmholtz – one login

To enable seamless access to distributed cloud resources, especially avoiding the need to constantly create local accounts, HIFIS maintains and continuously expands a technical and procedural infrastructure for a common login procedure, the Helmholtz Authentication and Authorisation Infrastructure (AAI) [3]. This technology follows worldwide standards and also allows for cross-centre group management, single sign-on and the set-up of secure interconnected service pipelines between different centres.

Feedback? Questions? Contact us.

The HIFIS universe is new and developing very rapidly. We are always happy to receive suggestions and answer your questions. To this end, you may refer to our FAQ [4] or query our single-point-of-contact support desk [5].

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References:

[1] https://hifis.net
[2] https://helmholtz.cloud
[3] https://hifis.net/aai
[4] https://hifis.net/faq
[5] support@hifis.net

IDAF: Status and sustainability

Challenges for sustainable computing

The Interdisciplinary Data and Analysis Facility (IDAF) at DESY provides storage and computing resources for large national and international research infrastructures. In 2022, the infrastructure was expanded to take into account the high data rates from various experiments. Moreover, the tape library integration was migrated to new software. The year also saw a focus on sustainability, with investigations into power-saving measures in compute clusters and measurements of power consumption at different workloads. For optimal energy use, it is best to either run systems at full capacity or not run them at all. In setups with varying load, schedulers should be tuned to switch off whole worker nodes when they are empty. Users are being made aware of sustainability efforts through weekly usage reports.

Status of the IDAF

The IDAF is a compute and storage infrastructure at DESY that provides access to data storage and processing capacity, in particular for the large national research infrastructures operated within the Helmholtz research field “Matter”, PETRA III and FLASH, and for the international infrastructures European XFEL, CERN and KEK.

As an example workflow, data generated at the European XFEL is transferred and processed from its origin at the European XFEL facility in Schenefeld to the DESY data centre on the main campus through a dedicated 4 km InfiniBand fabric that allows an effective rate of more than 1 Tbit. Shortly after the final storing in the DESY data centre, full processing starts at the IDAF, producing an additional 60% of data compared to the raw detector data volume. In 2022, experiments at the European XFEL regularly generated raw data volumes of more than 1 PB per day.

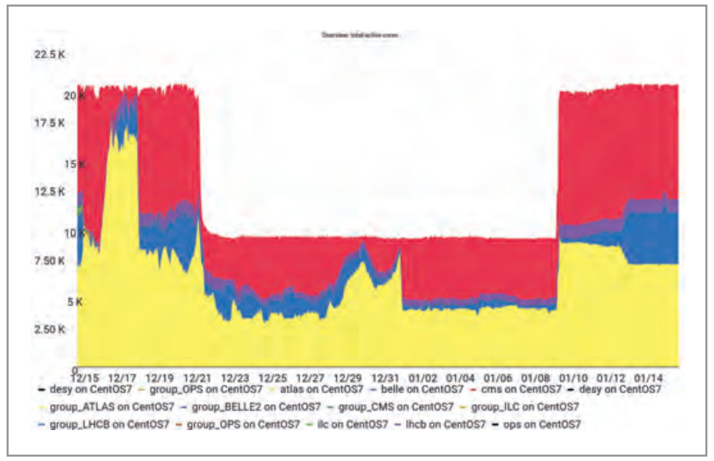

Figure 1

Grid cluster: load shedding of inefficient nodes over Christmas

Throughout 2022, the infrastructure was further expanded to be able to continue to store these consistently high data rates from the European XFEL, PETRA III and FLASH and make them available for analysis. In addition, large parts of the storage infrastructure for the high-energy physics (HEP) experiments had to be renewed due to age. Unfortunately, the worldwide difficulties in procuring hardware, especially in the networking and high-performance computing (HPC) environment, continued in 2022. The capacity of the systems at the end of 2022 was about 60 000 physical compute cores, about 1500 compute nodes including 340 GPU nodes, and access to about 200 PB of data.

In addition, the migration of tape libraries was largely completed. The new tape software, CERN Tape Archive, will replace the existing software in spring 2023 and is transparently connected to the dCache mass storage environment used at DESY.

Political developments outside science led to new challenges, especially for the LHC experiments ATLAS and CMS. The future of the Russian Tier-1 resources is questionable. In coordination with the experiments, the IDAF will provide tape resources for both experiments starting in spring 2023.

Some international projects, which started to create portals that facilitate the development of portable and transparent software to allow access to data compatible with the FAIR data principles (findability, accessibility, interoperability and reusability), were finalised. Parts of this infrastructure will be hosted at the IDAF. These portals will allow scientists outside the Helmholtz research field “Matter” to access the data through federated authentication and authorisation infrastructures.

Despite the pandemic situation, interaction with existing and new user groups and communities increased to further leverage the IDAF: Together with groups from the DESY Accelerator division, concepts for access permissions, availability of the IDAF compute systems as well as archiving of publication data and their access in the context of partnerships with external groups have been developed. Numerous discussions were also held with the ALPS II collaboration, an on-site experiment at DESY, on many aspects of converting the raw data to a format compatible with modern data analysis methods, also in the context of the PATOF project of the Helmholtz Metadata Collaboration. At the same time, archiving and analysis are planned in a coordinated way. Last but not least, a successful satellite workshop on “Computing for Photon Science” was prepared and held in early 2023 during the DESY Photon Science Users’ Meeting.

Sustainability and the IDAF

2022 has made sustainability one of the first priorities, in the short, medium and long term. The power saving aspect is particularly important for a computer centre, as it directly reduces electricity costs and indirectly reduces both investments in power infrastructure and cooling costs.

Besides the usual IT energy efficiency measures, in 2022, we investigated how to save electricity in our large-scale instruments. The large batch farms of the IDAF (NAF, Maxwell, Grid) have different usage profiles and scheduling strategies:

- The National Analysis Facility (NAF) is used mostly by users for their daily work. While the NAF is operated on a 24/7 scheme, we see a day/night occupancy change as well as dips in occupancy over weekends. Users provide the scheduler with a maximum runtime, ranging from 3 hours to 7 days. Different user jobs can run concurrently on the same worker node. The HTCondor scheduler is used.
- The Maxwell HPC system has a similar operation and usage scheme as the NAF, with the difference of a whole-node scheduling strategy. SLURM is used as a scheduler.
- The Grid is used mostly by large production frameworks, operating on a 24/7 scheme. No actual jobs are submitted but rather pilot jobs, which load the payload from remote facilities during a maximum time of 48 hours. HTCondor takes care of scheduling.

We carried out measurements of the power consumption at different workloads and processor speeds. The whole system, including external storage and network, has optimal power efficiency when running at full load. Obviously, newer systems are more power-efficient than older ones. The span in our setup reaches a factor of 4. Thus, in order to save energy, it is best to either run systems at full capacity, or not run them at all. In setups with constant load, the offered pledges should be revisited with sustainability in mind.

As a proof of concept, we switched off older Grid cluster servers over the Christmas period (Fig. 1), using only 40% of the total cluster power consumption while keeping about 65% of the compute power. In total, about 35 MWh were saved, equivalent to ~15 t of CO_2 based on the average German electricity mix.

While the Grid cluster is used nearly all the time and saving options are only static, in setups with varying loads like the user utilisation of the NAF, the schedulers are tuned such that whole worker nodes are empty at about the same time and can be switched off, allowing for dynamic power savings. Together with the HTCondor developers, we have been working on new scheduling strategies. Projected savings of the NAF cluster power usage range up to 100 kW depending on the utilisation.

We upgraded the SLURM scheduler such that it is able to steer the run status of empty nodes via the server out-of-band controller. Around Christmas, we piloted a first switch-off, and we will work on dynamic switch-off/switch-on during 2023. All this should happen unnoticed by users: No job should be lost, and no additional waiting times should be experienced.

Additionally, as part of the Cooperation for Application and Innovation (KAI) with Hochschule für Angewandte Wissenschaften Hamburg, work on self-adaptive dCache systems will start to enable efficient and optimised usage of the provided storage and thus contribute to Green IT at DESY.

A complementary effort is being made to raise users’ awareness of sustainability. A weekly summary report is sent to the NAF users on their usage of the batch system. The time used is converted to kWh and CO_2 produced. Users thus have a metric for their computational work and a handle to improve their CO_2 footprint. A similar information system is in preparation for Maxwell HPC. Further refinement of the metrics is planned and needs to be investigated in more detail by the providers.

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Digital campus information modelling

Helping to coordinate campus development, campus users and their activities

DESY's research campuses in Hamburg and Zeuthen are the dynamic centres of the laboratory's ambitious science programme. A digital campus information model helps to coordinate the many campus users and supports their activities. It makes campus operation and development more efficient and sustainable. The planned PETRA IV project is a driver for technology and process innovation and helps to advance digital campus information to the next level of maturity. This article illustrates selected campus information model applications and their perspective as a foundation for an increasingly digital campus.

The DESY campuses

DESY's campuses in Hamburg and Zeuthen host the large-scale research infrastructures and provide the environment for conducting scientific experiments. They also accommodate institutes from a number of partner institutions, such as Universität Hamburg, EMBL and the Max Planck Society. They stimulate and foster the bustling and vibrant science life, offering work space and collaboration environment for researchers and serving as venues for science events such as conferences and lectures as well as for student, educational and visitor programmes. In parallel, planning and construction of next-generation science projects such as PETRA IV are already under way.

Digital campus information model

The campus information model is a digital representation of the DESY campuses. It helps to coordinate the many campus users and supports their activities. It visualises the campuses, the many campus installations and their planned evolution, and it provides technical and user information for campus activities.

Digital campus information models support a wide and complementary range of applications, such as designing and building new infrastructures, optimising the layout of routes and facilities and the usage of available space, establishing safe working environments and guiding visitors on trips. Campus information models make campus operation and development more efficient and sustainable.

What's in it?

DESY digital campus information covers the campuses, buildings, accelerators and science experiments. The campus model represents campus topology, map and (underground) utility networks. Building models, including temporary and planned buildings, represent the building architecture and technical infrastructure. Accelerators, beamlines and scientific experiments are described by integrated engineering models of the various technical systems and components. Figure 1 shows an overview of various elements of the digital DESY campus information model.

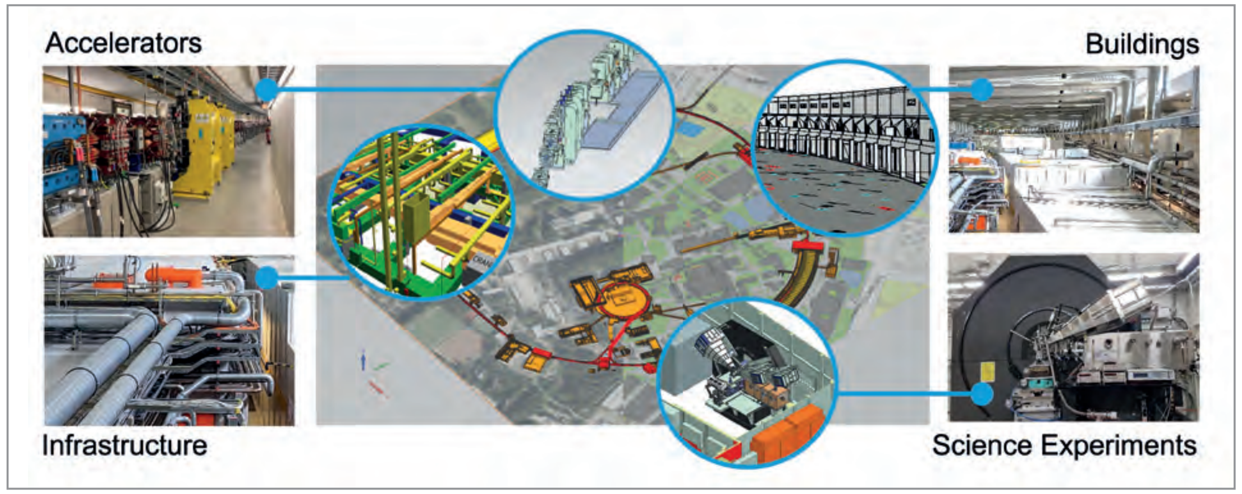


Figure 1
Overview of integrated DESY campus information models

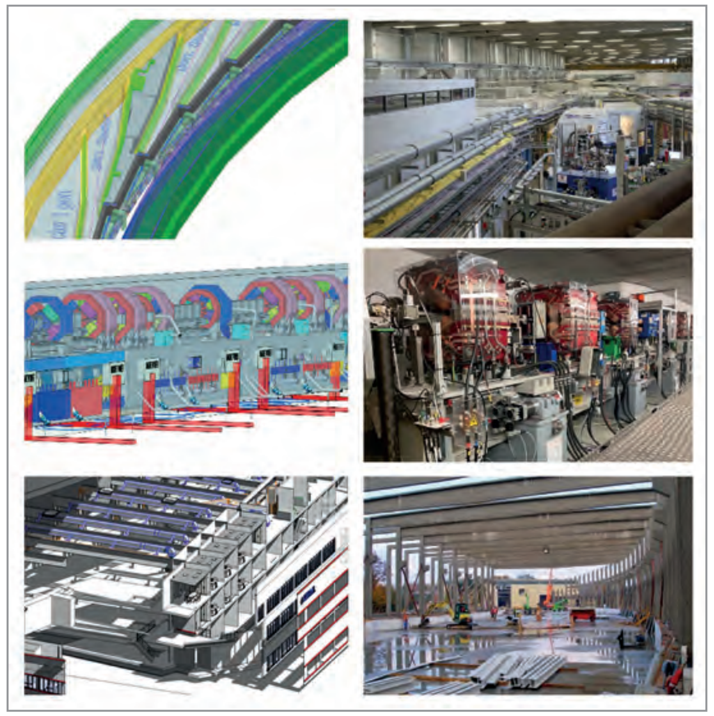


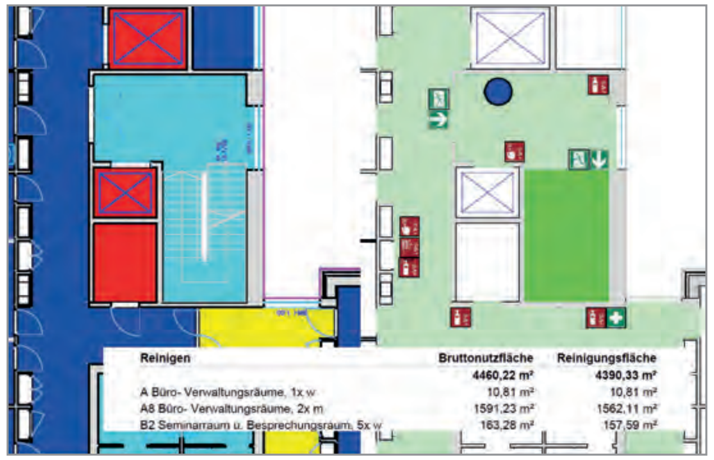
Figure 2
PETRA IV project model and sample applications: Managing occupied space (top), interfaces of accelerator components and infrastructure (center), civil construction (bottom)

Serving different user groups

Campus modelling is primarily driven by science and civil construction projects. The same campus information is provided in different formats targeted to specific user groups and their particular needs.

The PETRA IV project team is developing integrated engineering models of buildings and topology and of accelerators and science experiments. The models help to allocate space to the facilities and arrange their layout, define their interfaces, plan and organise system production and installation and govern all the logistics. Selecting model elements leads to further technical documentation (Fig. 2).

Campus Management is responsible for operating and maintaining the campus. Building information models connect 3D building geometry, floor plans, assets and room books. While the 3D geometry is used to validate the building design against planned installations, floor plans and asset databases support facility management and safety processes, such as providing contact persons, specifying cleaning contracts, managing keys, planning escape and rescue and maintaining cadastres for regular inspections of technical devices and safety equipment (Fig. 3).



Reinigen	Bruttonutzfläche	Reinigungsfläche
	4460,22 m²	4390,33 m²
A Büro- Verwaltungsräume, 1x w	10,81 m²	10,81 m²
A8 Büro- Verwaltungsräume, 2x m	1591,23 m²	1562,11 m²
B2 Seminarraum u. Besprechungsraum, 5x w	163,28 m²	157,59 m²

Figure 3
Floor plan with color codes for room type and summary of areas for cleaning contracts, and the same plan rendered for escape and rescue planning

Campus Planning coordinates the many civil construction activities. The campus map shows current campus facilities and areas of ongoing and planned maintenance and construction works, helping to guide campus evolution. For suppliers and service providers, the map shows utilities and routes of the supply networks, a foundation for any campus development. For campus users, the map contains points of interest, such as service points, visitor information or temporary event locations (Fig. 4), providing orientation and navigation.

What's next?

Current campus information models are to a large extent a static description of the campus. They are an essential foundation for campus information processing and a starting point for more ambitious digital transformation. Future extensions could add actual sensor data and offer remote control of e.g. room temperature and heating, thus getting on the way from digital building models to digital building twins. And further down the road, offering service workflow within the digital campus model would enable remote users to benefit from campus services as if they were on-site.

Figure 4
Campus map in different renderings with construction areas, supply networks, and points of interest (left to right)

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List of publications for the DESY Particle Physics newsletter

Synergies between INSPIRE and PubDB

At the beginning of 2022, a bi-weekly newsletter of the DESY Particle Physics division was launched. Every issue contains a list of all arXiv papers and dissertations published since the last issue. The DESY Library and Documentation group uses synergies between INSPIRE and the DESY repository PubDB to compile this list.

The DESY Particle Physics newsletter comprises a list of all arXiv publications and dissertations published within the last two weeks. Unfortunately, it is not feasible to automatically retrieve this kind of list from third-party databases, because division-level information is not available on preprints or in their respective metadata. Moreover, there is no central database for dissertations, but most of the particle physics dissertations are listed in INSPIRE. On the other hand, all DESY publications – including preprints and dissertations – have to be entered into the DESY publication database (PubDB) for approval prior to publication. However, regular cross-checking with INSPIRE still leads to the discovery of records that were previously missing in PubDB and need to be amended.

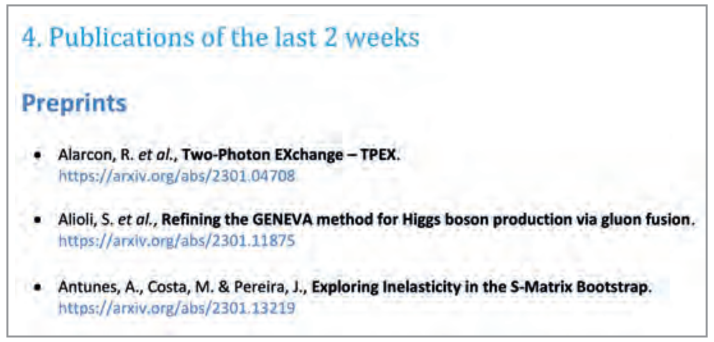
Figure 1 shows the raw data from the INSPIRE matching. Here, the arXiv category and an additional manual search are used to verify particle physics publications. In the majority of cases, affiliations derived from INSPIRE are useful to solely ascertain that publications are related to DESY.

```
@article{Bishara:2023epi,
_comment = "Theorie",
    author = "Bishara, Fady and Paul, Ayan and Dy, Jennifer",
    title = "{High-precision regressors for particle physics}",
    eprint = "2302.00753",
    archivePrefix = "arXiv",
    primaryClass = "physics.comp-ph",
    reportNumber = "DESY 22-174",
    month = "2",
    year = "2023",
    url = "https://arxiv.org/abs/2302.00753",
_inspire_PubDB = "https://bib-pubdb1.desy.de/record/484827 Genehmigt,
                  https://bib-pubdb1.desy.de/record/570293 Freigegeben",
    note = "( ✓ , ✓ , - ) ( ✓ , - , ✓ ) ",
}

@article{Bonnefoy:2023bzx,
_comment = "",
    author = "Bonnefoy, Quentin and Gendy, Emanuele and Grojean, Christophe and Ruderman, Joshua T.",
    title = "{Opportunistic CP Violation}",
    eprint = "2302.07288",
    archivePrefix = "arXiv",
    primaryClass = "hep-ph",
    reportNumber = "DESY 23-018, HU-EP-22/39, TUM-HEP-1453/23",
    month = "2",
    year = "2023",
    url = "https://arxiv.org/abs/2302.07288",
_inspire_PubDB = "https://bib-pubdb1.desy.de/record/570353 Genehmigt",
    note = "( ✓ , ✓ , - ) ",
}
```

Figure 1

Raw data of INSPIRE search for DESY publications and match with PubDB



4. Publications of the last 2 weeks

Preprints

- Alarcon, R. *et al.*, **Two-Photon EXchange – TPEX.** https://arxiv.org/abs/2301.04708
- Alioli, S. *et al.*, **Refining the GENEVA method for Higgs boson production via gluon fusion.** https://arxiv.org/abs/2301.11875
- Antunes, A., Costa, M. & Pereira, J., **Exploring Inelasticity in the S-Matrix Bootstrap.** https://arxiv.org/abs/2301.13219

Figure 2

List of publications in the DESY Particle Physics newsletter

In contrast, PubDB matching draws on the proper records in our database to obtain more information, such as Helmholtz programme-oriented funding, hereby excluding entries from other DESY divisions. BibTex is used to create the publication list, which has the advantage that it can be automatically compiled to MS Word via the document converter Pandoc. The metadata of all matched INSPIRE entries are carefully checked manually for correct affiliation, proper group and institution assignment as well as availability in PubDB. Missing entries are added to PubDB and forwarded to the corresponding groups for further processing.

Figure 2 shows the final publication list after curation by the Library group and the newsletter editorial staff. The example of this service demonstrates the synergies of two groups within Library&Documentation: the international database INSPIRE and the DESY repository PubDB and that manual handling is still required for the exact verification

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openCost and PUNCH4NFDI

Library project news

In 2022, the DESY Library and Documentation group started the groundwork for the German Research Foundation (DFG) project openCost: Still solidly within the framework of the JOIN^2 collaboration and with our other major DFG project "Open Access Publication Funding" in mind, we cross-checked our internal handling and monitoring of publication costs and confirmed that we are (easily) able to meet the reporting requirements set by the DFG. With 2022, we furthermore reflect on the first full year of DESY participation in the PUNCH4NFDI project – with the DESY Library group investigating issues for the particle, universe, nuclei and hadron physics (PUNCH) communities within the German National Research Data Infrastructure (NFDI).

openCost

As an intermediate step, we enabled the DESY publication database (PubDB) to produce the spreadsheets required for publication cost reporting for the DFG programme Open Access Publication Funding from our stored records, confirming that we do not miss any crucial values. Alongside the implementation of several new transformative agreements with publishers, this led to improvements of our work flows and finally to the implementation of a simple XML-based format to transport publication costs based on article IDs (e.g. doi).

After thorough tests by our project partners at the OpenAPC initiative based at Bielefeld University, this finally enabled DESY to successfully deliver data and join the internationally important OpenAPC project. The main advantage of our approach is full automation: PubDB is exposing data for OpenAPC partners to harvest at their leisure. Right now, OpenAPC only handles open-access article processing charges (APCs) and not yet any additional fees we handle, but this can still be seen as a proof of concept for the whole openCost project.

Another major event in 2022 was the international openCost expert workshop, entitled "The Road to Publication Cost Transparency", held at DESY in Hamburg. Several contributions from AT2OA in Austria, the California Digital Library, JISC, the National Library of Finland, OA Switchboard, the Open Access Monitor and Unpaywall as well as countless intense discussions highlighted the topic from different angles. In his keynote address, Bernhard Mittermaier from Forschungszentrum Jülich gave insight into the transformation of library budgets towards an information budget. The workshop's results will be published by the DESY publishing house in a proceedings volume, also forming a solid foundation for the upcoming openCost data formats. The first format will handle article-based payments and will be published for commentary on github (https://github.com/opencost-de).

PUNCH4NFDI

The DFG-funded PUNCH4NFDI project aims to create a FAIR data portal that provides the infrastructure essential to access and use data and computing resources produced by the communities involved according to the FAIR data principles (findability, accessibility, interoperability and reusability). The DESY Library group takes responsibility in this process and participates in the development of compatible metadata concepts. Physicists and information scientists work closely together and benefit from different expertise. Indeed, the knowledge about metadata and publication processes is an important interface to the topic of research data and currently a thematic path that the DESY Library group is pursuing. The intermediate result is a strategy for an experiment-dependent and individually extensible metadata composition based on the requirements of the latest DataCite metadata schema.

For the first time, a joint meeting of the entire consortium took place in person in Göttingen, bringing together colleagues from all participating research institutions in Germany.

Since FAIRness doesn't end with data, we are also part of the subcommittee Women4PUNCH, which emphasises the importance of gender equality and strengthens awareness of diversity.

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Publications

ALPS

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