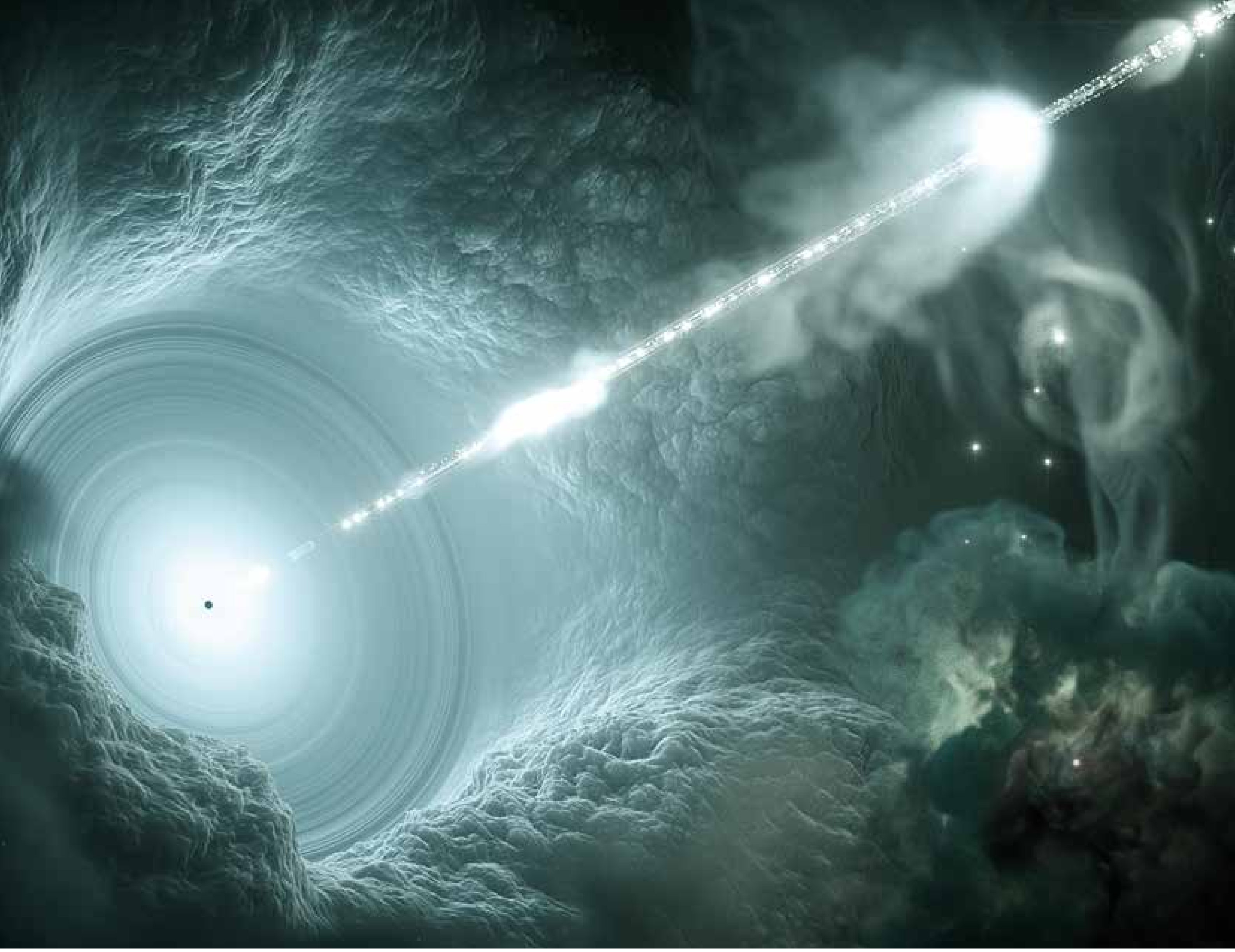


PARTICLE PHYSICS 2018.

Highlights and Annual Report

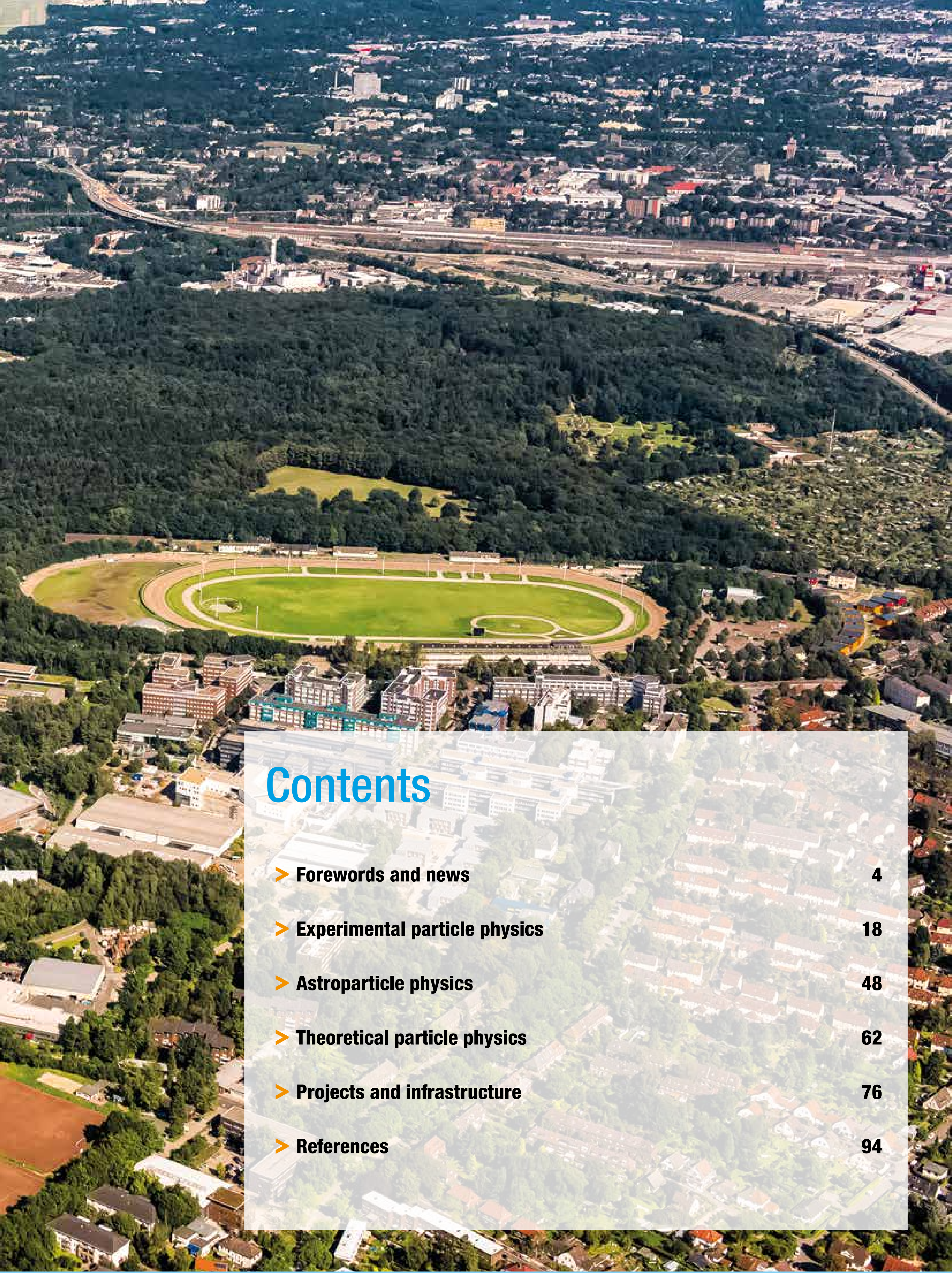
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

Cover

Artistic 3D visualisation of an active galactic nucleus

PARTICLE PHYSICS 2018.

Highlights and Annual Report



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Chairman's foreword

Dear Colleagues and Friends of DESY,

An eventful and very successful year at DESY is drawing to a close.

After the comprehensive DESY 2030 strategy process and the very successful evaluation of the scientific clout of the research centre by a high-ranking international commission of experts, DESY is well prepared for the coming Helmholtz funding period 2021–2027. The outstanding results achieved in the German Excellence Initiative give the research campus an additional boost: In both physics-related clusters of excellence of Universität Hamburg that were approved for funding – one in photon science and nanoscience ("Advanced Imaging of Matter") and one in particle and astroparticle physics ("Quantum Universe") – DESY is a key partner of the university.

All in all, the message is clear: The DESY research campus in Hamburg-Bahrenfeld is an international leader in the investigation of matter. There is no laboratory in the world with a comparable scientific thrust that can match the Hamburg-Bahrenfeld campus in terms of its future-oriented interdisciplinary research orientation, its ultramodern research infrastructures and its high number of top-class scientists.

The DESY campus in Zeuthen and our activities in astroparticle physics are also undergoing significant transformations. From 2019 on, astroparticle physics will form a separate division at DESY, increasing the visibility of our efforts in the field. At the same time, a master plan for the development of the Zeuthen research campus is taking shape. One important building block – besides a new canteen – will be the Science Data Management Centre of the Cherenkov Telescope Array (CTA), the next-generation gamma-ray observatory, for which final contracts for the southern-hemisphere location in Chile were signed and a first large prototype was installed on La Palma in 2018.

On the DESY campus in Hamburg, the preparations for the upgrades of the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN are gaining strong momentum. The R&D activities for the new silicon trackers for ATLAS and CMS are in full swing, taking advantage of the existing technical infrastructure in laboratories and at the DESY II Test Beam Facility. The setup and commissioning of the dedicated Detector Assembly Facility (DAF) is nearly completed, and the new cleanrooms with the respective technical infrastructure will be ready in mid-2019. This is well in time for production and assembly of the two silicon trackers, which will be built at DESY in cooperation with German universities and other institutes in the coming years.

Almost routine, but still a triumph, was the operation of the European XFEL X-ray laser. In the second half of the year, the superconducting linear accelerator was brought up to its nominal performance. The DESY operating team, led by Winfried Decking, masters every physical and technical detail of the complex facility, to the benefit of the experiments on the European XFEL campus in Schenefeld. Only one year after the start of operation for users, the first successful results were published in *Nature Communications*.

DESY continues to drive innovation forward. The Innovation Village, which will provide spin-offs with the necessary office space and infrastructure, is currently being built on the DESY site in Hamburg. After a suitable provider has been found, the construction of the Innovation Centre, which was unfortunately delayed, can now finally begin. I very much welcome that our ambitious plans to expand the Hamburg-Bahrenfeld research campus into a modern science ecosystem in which research, education and innovation intelligently stimulate each other are strongly supported by the German Bundestag, the German Federal Ministry of Education and Research (BMBF) and the Hamburg Authority for Science, Research and Equality (BWFG).

DESY is currently planning new interdisciplinary research buildings, which will re-bundle existing expertise and focus

on future new research potentials, among them the Centre for Data and Computing Science (CDCS) and the Wolfgang Pauli Centre.

The CDCS is currently being designed in close cooperation with all Hamburg universities. It is one of several projects that the BWFG is considering as part of the HamburgX project. Fortunately, DESY has been able to raise substantial Helmholtz funding for the "Data Science in Hamburg – Helmholtz Graduate School for the Structure of Matter" (DASHH). DASHH is supported by all the CDCS partners.

Theoretical physics in Hamburg is an international lighthouse. Its beginnings go back to quantum physics pioneer Wolfgang Pauli, who stayed in Hamburg from 1923 to 1928 and published his famous work on the exclusion principle here. Today, more than 80 theoretical physicists conduct research in Hamburg. They deal with a range of very different problems, from string theory to superconductivity. In the Wolfgang Pauli Centre, a new research building on the DESY campus exclusively designed for theoretical physics, an interdisciplinary hub for the advancement of theoretical physics is to be created, which will open up new spaces for scientific exchange for Hamburg's theorists and attract young talented scientists from all over the world.

In 2018, our focus was on a key appointment, the successor to our director of the Accelerator Division, Reinhard Brinkmann, who passed on the baton at the end of the year. We are proud and pleased that the world's leading accelerator physicist in the field of plasma acceleration, Wim Leemans, could be persuaded to leave the Lawrence Berkeley National Laboratory in the USA and come to DESY. This is a great success, which will decisively strengthen the research centre and in particular the accelerator development in Hamburg. I would like to express my gratitude to the BMBF, in particular to the chairman of our Foundation Council, Dr. Volkmar Dietz, for the great cooperation, which helped to make this challenging appointment a reality.

I thank the DESY staff and all our partners, national and international, who have contributed to the success of our research centre.

Helmut Dosch
Chairman of the DESY Board of Directors

Particle and astroparticle physics at DESY

Introduction

Dear Colleagues and Friends of DESY,

Belle II, ATLAS and CMS, ALPS, the DAF, the DESY II Test Beam Facility – all the ingredients of DESY's experimental programme in particle physics flourished productively in 2018, and with the DESY-2030 strategy process behind us, we are also well equipped for the future.

The Belle II experiment at the SuperKEKB collider at KEK in Japan passed the last major milestone before data taking with the full detector in November, when the vertex detector (VXD) was installed into the experiment (Fig. 1). The VXD consists of a silicon strip detector and of the pixel vertex detector (PXD), which was built by a German consortium and assembled and tested at DESY. We are now eagerly looking forward to the start of data taking in March 2019. In summer 2020, we hope to fully complete the PDX, which for production reasons had to be installed with only parts of its second layer in place.

Figure 1

Installation of the vertex detector into the Belle II experiment at the SuperKEKB collider in Japan in November 2018

In contrast to SuperKEKB, where Belle II is awaiting collisions, the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, has gone into two years of hibernation: Run 2 ended in December, after successful delivery of altogether more than 160 fb^{-1} of valuable proton–proton data at 13 TeV centre-of-mass energy to the ATLAS and CMS experiments. The collider – again – exceeded expectations, and this raises high hopes for Run 3 in the years 2021–2023, when the LHC is expected to run for the first time at the design energy of 14 TeV. Preparations are under way in the currently ongoing Long Shutdown 2, in which the LHC injector complex is being upgraded and first (Phase 1) upgrade steps on the experiments are being carried out.

However, the LHC story will not end in 2023: Already now, DESY is deeply involved in the Phase 2 upgrades for the High-Luminosity LHC (HL-LHC), which will take over after Long Shutdown 3 (2023–2026). Together with German university consortia, we are building tracker end-caps for both ATLAS and CMS, and while the R&D work for these immense components is slowly coming to an end, (pre-)production is starting. We are very happy that the infrastructure needed for this endeavour, the dedicated Detector Assembly Facility (DAF) that we set up at DESY over the past two years, has become operational in 2018. The two end-caps need to be ready for shipping to CERN and for installation and commissioning around the end of 2025, and this goal will keep many of us busy during the next few years.

The same is true for the ALPS experiment at DESY, which aims to probe for hypothetical very weakly interacting ultralight particles (WISPs): In 2018, the necessary conditions for the installation of the ALPS II experiment were created in the HERA hall North. In addition, most of the required dipoles from DESY's former HERA collider were successfully straightened (Fig. 2), and good progress was also made on the experiment optics and detector systems. We are confident that the ALPS II data taking can start as planned in 2020.

Figure 2
Straightened HERA dipole for the ALPS II experiment during measurements and testing at DESY

In astroparticle physics, progress was made in particular in the preparation of the Cherenkov Telescope Array (CTA), the next-generation gamma-ray observatory: In 2018, Chile, the European Southern Observatory (ESO) and the company CTAO gGmbH signed the final contracts for the CTA site on the southern hemisphere. With this achievement, the way is paved for the construction of CTA on the ESO Paranal premises in Chile, which will probably start in 2020. As a specific highlight, the first large-sized telescope of CTA was inaugurated in October 2018 at the northern CTA site on the island of La Palma, Spain. DESY is responsible for the development and construction of the workhorses of CTA, the mid-sized telescopes, and will also host the observatory's Science Data Management Centre in Zeuthen.

The IceCube neutrino observatory, the other large experiment in astroparticle physics in which DESY is strongly involved, marked a breakthrough in neutrino astronomy: For the first time, it became possible to identify the source of a high-energy neutrino detected with IceCube. In a concerted action, numerous other telescopes around the globe observed the corresponding cosmic object in their respective wavelength range. The source turned out to be TXS 0506+056, a flaring high-energy quasar with a relativistic jet pointing directly towards Earth. This event is a prime example of true multi-messenger astronomy and as such of decisive importance for astroparticle physics in general.

But our planning and expectations go beyond those concrete experiments – in fact, ideas for future projects ripened a great deal in 2018. This development is not least supported by the great success of DESY and Universität Hamburg in the German Excellence Initiative: With the "Quantum Universe" cluster of excellence approved, great opportunities are arising for new initiatives on site. These are further generously supported by the Helmholtz Initiative and Networking Fund, which is providing funds for a new cryogenic platform to be installed in the HERA hall North of the former H1 experiment. This facility will be able to serve various experiments and test setups. One example of our experiment ideas is MADMAX, a hunt for dark-matter axions through their conversion to microwave radiation in a magnetic field. Data taking for MADMAX is envisaged for around 2026; however, until then a number of challenges still has to be mastered.

The International Axion Observatory (IAXO) is another axion search experiment with strong DESY ties. IAXO is an axion haloscope, the principle of which has been tested with the CAST experiment at CERN. DESY considers hosting the precursor experiment babyIAXO, and a detailed review of this proposal by the DESY Physics Research Committee (PRC) will take place in 2019. If successful, IAXO too might, in the mid-term future, find a home at DESY.

Finally, and maybe most importantly to our mission and our hearts, we take the task we set ourselves in the DESY 2030 strategy very seriously, namely to prepare leading contributions to future global collider projects with significant German involvement. For many years, we have been driving the efforts towards future linear colliders, and in view of the ongoing update of the European Strategy for Particle Physics, we will certainly do all we can to make sure that particle physics has a project beyond the LHC – a project that will help us to further pursue our mission to identify the fundamental building blocks of nature and their interactions.

In light of a successful year 2018, I congratulate all the staff members of DESY on their successes, and I thank them very much for their continued efforts for the research centre!

Joachim Mnich
Director in charge of Particle Physics
and Astroparticle Physics

News and Events

A busy year 2018

January

European astroparticle physics strategy presented in Brussels

Astroparticle physicists from across Europe gathered in Brussels on 9 January, alongside their colleagues from all over the world and important guests from the European Commission, for the official announcement of the new strategy of the Astroparticle Physics European Consortium (APPEC), which will guide the community's research priorities over the next ten years.

Astroparticle physics is a rapidly growing field that has already achieved important results, such as the first detection of gravitational waves in 2015, which earned the field the 2017 Nobel Prize in Physics. Gravitational waves, neutrinos, dark matter and gamma rays are high on the list of research priorities recommended with the launch of the latest European astroparticle physics strategy.

YerPhI Medal of Honour for Manfred Fleischer

Manfred Fleischer, deputy director of research at DESY, received the Medal of Honour of the Yerevan Physics Institute (YerPhI) for his long-time coordination of the cooperation between the two institutions. DESY and YerPhI have been working together since the late 1960s, with Manfred Fleischer coordinating the efforts since 1999. Joint activities in the past 20 years ranged from the development of power supplies to collaboration in particle physics experiments, such as H1, HERMES, OLYMPUS, Belle and CMS, through infrastructure actions up to preparations for the upcoming Cherenkov Telescope Array (CTA) in astroparticle physics and common educational activities in the training of students and pupils.

Manfred Fleischer

February

In-depth scientific evaluation of DESY

At the beginning of February, DESY underwent a scientific evaluation on behalf of the Helmholtz Association. The evaluation was part of the programme-oriented funding (POF), which provides funding to the 18 Helmholtz centres within the framework of cross-centre research programmes. The current third funding period started in 2015 and runs until the end of 2020. The Helmholtz Association will use the completed evaluation to prepare the upcoming fourth funding period (POF IV).

During a five-day on-site visit, DESY's research and user facilities were evaluated by an external panel of 26 international experts, chaired by Hugh E. Montgomery, former director of the Jefferson Lab accelerator centre in the USA. In 70 talks, 126 posters and numerous personal encounters, about 400 DESY employees presented the scientific achievements and gave an outlook on DESY's strategy for the upcoming funding period. The staff members and in particular the high proportion of young researchers especially convinced the evaluators. "You are part of a remarkable lab," said Montgomery in the final presentation.

Otmar Wiestler, President of the Helmholtz Association, during his concluding remarks

March

DESY 2030 strategy unveiled

On 20 March, the DESY Directorate gave the starting signal for the implementation of the DESY 2030 strategy

After a comprehensive strategy-finding process, the future strategy DESY 2030 was officially presented at a one-day kick-off event in Hamburg, attended by about 1000 DESY employees and guests. With its strategy, DESY is setting priorities in science and innovation as well as in the future development of its large-scale research facilities in order to address the upcoming challenges and demands of science and society. In panel discussions, at information booths and in many personal discussions, representatives of the more than 400 DESY staff members who had contributed to the strategy process presented its key points.

In the field of particle physics, DESY will continue to expand its leading position as a key partner in international projects, such as ATLAS, CMS, Belle II and future major projects. DESY will set up an attractive R&D programme with the aim of hosting particle physics experiments such as the already running axion-like particle haloscope ALPS II on campus. DESY will continue to expand its national and international networks and develop its Hamburg and Zeuthen sites into attractive places for the interdisciplinary exchange of ideas, science and innovation. DESY’s Zeuthen site is being expanded to become an international centre for astroparticle physics, focusing on gamma-ray and neutrino astronomy.

On the DESY campus in Hamburg, several interdisciplinary research buildings will be established: the Centre for Data and Computing Science (CDCS), which will help to meet the increasing demands made by data-intensive applications in research, the Wolfgang Pauli Centre (WPC) for theoretical physics and the Centre for Molecular Water Science (CMWS), which will be established in collaboration with national and European partners.

DESY will also further develop and test new concepts for building future compact particle accelerators as well as for realising new generations of high-resolution detector systems that will enable unparalleled insights into the structure of matter.

April

Galactic science with 15 years of H.E.S.S. data

The H.E.S.S. telescopes in Namibia have surveyed the Milky Way in gamma-ray light for the last 15 years. To celebrate this anniversary, the H.E.S.S. collaboration published its largest set of science results to date in a series of papers in a special issue of the journal *Astronomy & Astrophysics*.

More than a dozen scientific articles describe the H.E.S.S. Galactic Plane Survey, studies of the populations of pulsar wind nebulae and supernova remnants as well as the search for new object classes unseen before in very high-energy gamma rays, such as microquasars or shocks around fast-moving stars. These studies are complemented by precision measurements of shell-type supernova remnants such as RX J1713-3946 and diffuse emission at the centre of our galaxy. This legacy data set will serve as a benchmark for the community for the coming years and until the next-generation Cherenkov Telescope Array (CTA) gamma-ray observatory comes online in the 2020s.

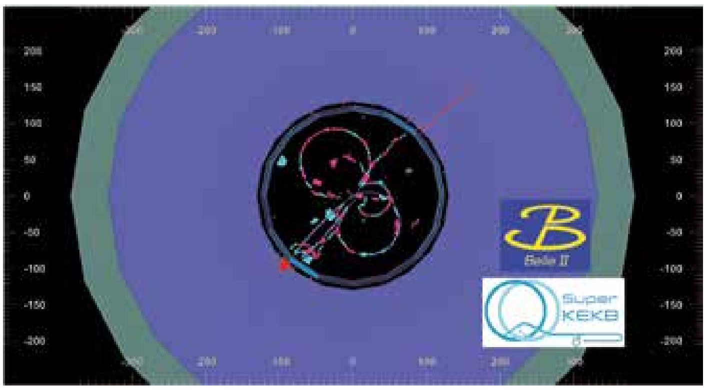
Montage of galactic gamma-ray sources in the Milky Way above the H.E.S.S. telescopes in Namibia

First collisions in the upgraded SuperKEKB accelerator

After eight years of refurbishing, electrons and positrons collided for the first time in the SuperKEKB accelerator at KEK in Japan on 26 April. The Belle II particle detector was also completely redesigned, a process in which DESY and other German research groups were integrally involved.

Belle II is specifically designed to look for physical phenomena extending beyond the previously explored realms of physics. It specialises in measuring rare particle decays, for example that of *b* quarks, *c* quarks or tau leptons. The over 750 scientists involved in the project hope that this will help them to unravel the mysteries of dark matter, track down new phenomena or explain the imbalance between matter and antimatter in the universe.

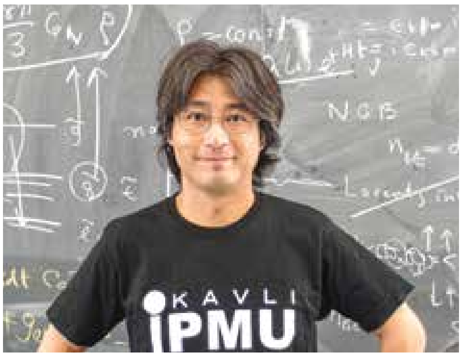
The first collisions were a key milestone on the way to launching the research programme at Belle II. For about a month, particles had been circling again inside the accelerator, which had been fitted with a new system of focusing magnets and a new damping ring. Together, these ensure that the particle beams are extremely narrow, leading to a high collision rate, or luminosity. An important prerequisite was achieved in January with the installation of the sophisticated remote vacuum connection, which links the focusing magnets and the detector and which was designed and built at DESY.



Event display from a collision in the Belle II detector

Humboldt Award for Hitoshi Murayama

Hitoshi Murayama, Japanese professor of theoretical particle and astroparticle physics and cosmology, received the prestigious Humboldt Research Award by the Alexander von Humboldt Foundation. Murayama will spend up to a year at DESY, working with colleagues from DESY and all over Europe to advance the search for dark matter with the help of new theoretical models.



Hitoshi Murayama

Murayama was born in Japan in 1964 and spent a few years of his childhood in Germany. After gaining his PhD in theoretical physics from the University of Tokyo, he moved to the Lawrence Berkeley National Laboratory in the USA, becoming a professor at the University of California, Berkeley, later. He is also director of the Kavli Institute for the Physics and Mathematics of the Universe and deputy director of the Linear Collider Collaboration, the international group planning a future electron–positron collider.

May

Detector Assembly Facility (DAF) goes into operation

The future of the Large Hadron Collider (LHC) at CERN is also being prepared at DESY. A former photon science research building on the Hamburg campus was converted into a cleanroom with a lab. In May, DESY scientists started preparing and producing key components for the upgrades of the LHC experiments ATLAS and CMS in this dedicated Detector Assembly Facility (DAF).

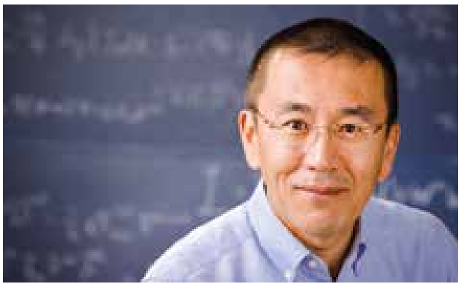
The high-luminosity phase of the LHC (HL-LHC), which will begin in 2026, requires new, more efficient detectors for ATLAS and CMS. For each of the two experiments, DESY is building an end-cap for the new silicon tracking detectors in collaboration with national and international partners. To this end, DESY is producing and testing several thousand silicon detector modules and will afterwards install them in the mechanical structure of the end-caps before delivering these to CERN, where they will be connected with the remaining detectors and put into operation.

Cleanroom of the new Detector Assembly Facility (DAF) at DESY

Hirosi Ooguri awarded Hamburg Prize for Theoretical Physics

The 2018 Hamburg Prize for Theoretical Physics was awarded to the Japanese physicist Hirosi Ooguri, a professor at the California Institute of Technology (Caltech) in Pasadena, USA. Born in 1962, Ooguri is one of the world's leading experts on topological string theory, which addresses mathematical aspects of superstring theory – an important path towards an all-encompassing theory on the nature of our universe. In his work, Ooguri has overcome many of the major mathematical difficulties of string theory, thus making many physical phenomena computable with the help of string theory. His research on the quantum mechanics of black holes continues the work of physicist Stephen Hawking, who died earlier in 2018.

The Hamburg Prize for Theoretical Physics is awarded by the Joachim Herz Foundation in partnership with the Wolfgang Pauli Centre (WPC) of Universität Hamburg, DESY and the Hamburg Centre for Ultrafast Imaging (CUI) at Universität Hamburg.



Hirosi Ooguri

Federal Minister of Education and Research visits DESY

German Federal Minister of Education and Research Anja Karliczek visited DESY on 31 May as part of her inaugural visit to Hamburg. Minister Karliczek, who was accompanied by Hamburg's Deputy Mayor Katharina Fegebank, learned about current projects at DESY, activities in knowledge and technology transfer and plans to expand the centre into the International Science Park Hamburg, which DESY is pursuing together with its research partners. Among other things, Karliczek visited experimental stations at the high-brilliance synchrotron radiation source PETRA III and the DESY school lab.

“The insights gained at DESY benefit society in wide-ranging ways. Scientists from all sorts of different fields, from medicine and biology, through physics and materials science, to the history of art, work side by side at DESY,” said Anja Karliczek during her visit. “All around DESY, the science location has developed very favourably.”

Research Minister Anja Karliczek in the DESY school lab

June

Weighty insights from heavy quarks

The two collaborations of the H1 and ZEUS experiments at DESY's former electron–proton collider HERA combined their measurements on the production of heavy quarks. A team led by DESY physicists produced the final results for the paper on "Combination and QCD analysis of charm and beauty production cross-section measurements in deep inelastic ep scattering at HERA", which was published by the *European Physics Journal* – a culmination of over 20 years of work. Like the previously published results from HERA, it will appear in textbooks of the future and be used in research at the LHC at CERN, to which DESY groups are also making key contributions.

The HERA accelerator tunnel

Joachim Mnich, DESY director in charge of particle and astroparticle physics, noted: "The HERA experiments have collected a very valuable set of lepton–proton collisions and continue to produce high-level publications even ten years after the end of data taking. The publication is also a substantial proof that our efforts to preserve the HERA data for later analysis pay off."

YerPhI Medal of Honour for Johannes Knapp

DESY physicist Johannes Knapp received the Medal of Honour of the Yerevan Physics Institute (YerPhI) for his many years of contributions to the local education and training of young Armenian scientists in astroparticle physics. The medal was presented in June by YerPhI Director Ashot Chilingarian. The participants raised a glass of the best Armenian cognac to the 26-year-old personal connections, the even longer partnership between YerPhI and DESY and the further good cooperation.

FLASHForward makes waves

The plasma wakefield accelerator project FLASHForward at DESY reached an important milestone in June, when the team generated a wakefield with a field strength of more than 12 GV/m in a plasma using an electron beam from DESY's FLASH accelerator. The experimental demonstration confirmed that it is possible to use the FLASH beams to produce very strong accelerating field strengths in a plasma with field strengths exceeding those in conventional metallic accelerator cavities by more than two orders of magnitude. The next goal of the team is to accelerate particles in the wakefield generated by the beam.

View into the three-centimetre plasma cell of FLASHForward

July

DESY summer student programme 2018

The DESY summer student programme started on 20 July with a record number of 117 participants from 35 countries, selected among over 860 applicants from all around the world. About 70 students took part in the particle physics part of the programme. At the big closing session on 6 September, a number of students presented their work done during the almost eight weeks of the programme.

The students attending the 2018 summer student programme at DESY in Hamburg

 Johannes Knapp

Working on a small project in a specific DESY research team made up the essential part of the stay. In addition, the students attended a series of lectures on DESY activities, consisting of a first common part followed by specific lectures for the high-energy physics and photon science students, respectively. A couple of social events completed the programme. The students again appreciated the open-minded international atmosphere at DESY, which made the stay an unforgettable experience.

German–Canadian network for quantum computing and data analytics

The Helmholtz centres DESY and Forschungszentrum Jülich, the Canadian particle accelerator centre TRIUMF and the companies D-Wave Systems Inc. and 1QBit signed a memorandum of understanding for establishing a network to pool their strengths in the research and use of quantum computers, data analytics and in particular machine learning. The idea for the cooperation came from a Helmholtz delegation visit to Canada led by Helmholtz President Otmar Wiestler.

The networks are intended to facilitate national and international cooperation in the use of quantum computers and machine-learning tools for supporting research and are open to other partners during their development. The networks comprise four joint working groups focusing on four pillars of data science: quantum computing, large-scale computing, machine learning and big data analytics. The network partners will contribute resources and expertise to the collaboration to advance their initiatives of common interest. Another important goal is the training of young scientists.

Joachim Mnich and Jonathan Bagger at the signing of the MOU

August

"Bring the world together"

About 70 young scientists attended the RACIRI Summer School on the Rügen island in August. In 2018, the RACIRI Summer School took place in Germany for the second time. A highlight of the event was the keynote lecture of Rolf-Dieter Heuer. Heuer is chairman of the Group of Chief Scientific Advisors of the European Commission, former research director of DESY and CERN director general, president of the SESAME Council and vice-president of the German Physical Society (DPG). In his lecture, Heuer described the roles of CERN and the SESAME synchrotron radiation source in Jordan as "innovate, discover, publish, share and bring the world together".


Rolf-Dieter Heuer

Science meets art: Astroparticle Immersive Synthesizer³ – AIS³ [aiskju:b]

The science-inspired light and sound installation [aiskju:b] celebrated its premiere in Berlin. The "Astroparticle Immersive Synthesizer³ – AIS³ [aiskju:b]" by concept artist Tim Otto Roth captures the structure and function of the IceCube neutrino telescope, which spies for high-energy cosmic neutrinos in the perpetual ice of Antarctica. DESY, the largest European partner involved in IceCube, supported Tim Otto Roth in the realisation of his ambitious project right from the start. To accompany the opening of [aiskju:b] in Berlin, DESY organised a comprehensive supporting programme, including an exhibition on the IceCube research at the South Pole, evening lectures, guided tours for schools and a further training course for teachers.


Tim Otto Roth's sound and light installation [aiskju:b] at the cultural church St. Elisabeth in Berlin

September

Kerstin Borras elected APS fellow

Kerstin Borras, leading scientist at DESY and Helmholtz professor at RWTH Aachen University, was appointed a fellow of the American Physical Society (APS). She was honoured for her "outstanding contributions to particle physics including providing exemplary leadership at DESY, Fermilab and CERN." Kerstin Borras is an expert for calorimeters and for data analysis in the search for dark matter. She has also been involved in the management of the CMS experiment at the LHC for a long time, most recently as deputy head of the collaboration, which consists of more than 5300 people from over 50 countries.

Kerstin Borras

Graduate school in data science approved

A new graduate school for data science will be established in Hamburg. The "Data Science in Hamburg – Helmholtz Graduate School for the Structure of Matter", or DASHH for short, will offer young scientists an interdisciplinary and application-oriented education in the processing and analysis of large volumes of data generated when studying the structure of matter. The Helmholtz Association decided to fund the initiative with almost six million euros over the next six years.

DESY's research facilities generate huge amounts of data. Their intelligent and efficient use is the subject of the new DASHH graduate school.

Multidisciplinary collaboration is essential to fully exploit the research potential of the large-scale facilities at DESY, generate new ideas and refine existing methods. DASHH is meant to provide a long-term link between the excellent research on the Hamburg-Bahrenfeld campus and state-of-the-art computer science research at the Hamburg universities. Alongside DESY, Universität Hamburg, the Hamburg University of Technology, European XFEL, the Helmholtz Centre for Infection Research, the Helmholtz Centre Geesthacht, the Max Planck Institute for the Structure and Dynamics of Matter and the Helmut Schmidt University are also involved in DASHH.

Theory Workshop 2018

The annual DESY theory workshop, organised jointly with the elementary particle physics community in Germany, was held on 25–28 September, attracting around 200 participants from all around the world. The 2018 edition focused on the current and future challenges in particle physics, including recent developments in particle physics phenomenology and new ideas in particle theory. In accordance with the on-going preparation of the European Strategy for Particle Physics, special attention was devoted to the physics at current and future colliders and to the physics beyond colliders. George Sterman, one of the founders of the theory of quantum chromodynamics, which describes the quarks and gluons, gave the distinguished DESY Heinrich Hertz Lecture on Physics.

Clusters of excellence for Universität Hamburg with DESY participation

The Excellence Initiative of the German federal government and the federal states is intended to strategically promote excellent science and cutting-edge research at German universities. On 27 September, the German Research Foundation (DFG) and the German Research Council announced the results of the selection by a committee supported by international top-level scientists. Universität Hamburg was very successful with four accepted proposals, two of them – "Advanced Imaging of Matter" and "Quantum Universe" – involving a collaboration with DESY. Both clusters will be funded over a period of seven years. The Quantum Universe cluster aims at combining all the disciplines and topics of particle physics into an overall picture to unlock the universe's remaining mysteries.

October

First CTA telescope inaugurated

The first gamma-ray telescope on a site of the future Cherenkov Telescope Array (CTA) observatory was inaugurated on the Canary Island of La Palma in October. The telescope, tagged LST-1, is the first of four large-sized telescopes (LSTs) on the northern site of the CTA observatory, which is located on the premises of the Instituto de Astrofisica de Canarias' Observatorio del Roque de los Muchachos at La Palma. The plan for the site also includes 15 mid-sized telescopes (MSTs).

LST-1, the prototype for the large-sized telescopes of CTA

The LST has a 23 m diameter parabolic reflective surface, which is supported by a tubular structure made of reinforced carbon fibre and steel tubes. A reflective surface of 400 m^2 collects and focuses the Cherenkov light into the camera, where photomultiplier tubes convert it into electrical signals that can be processed by dedicated electronics. Although the LST-1 stands 45 m tall and weighs around 100 t, it is extremely manoeuverable and can be repositioned within 20 s to capture brief, low-energy gamma-ray signals. The prototype is the first telescope on a CTA site to be operated by the CTA observatory.

Alexander Grohsjean

Alexander Grohsjean wins CMS Research Prize

DESY scientist Alexander Grohsjean was awarded a scholarship from the CMS collaboration. In its Distinguished Researcher programme, the LHC Physics Center (LPC) at Fermilab in the USA honours international scientists who are to decisively strengthen and advance the physics programme of the CMS experiment at the LHC in cooperation with the LPC. To this end, the prize winners will be able to use research resources at Fermilab and develop new approaches together with their colleagues. The scholarship runs for one year and starts in March 2019.

Georg Forster Fellowship for Sara Taheri Monfared

The Alexander von Humboldt Foundation awarded Sara Taheri Monfared from the Institute for Studies in Theoretical Physics and Mathematics (IPM) in Tehran, Iran, a Georg Forster Fellowship. With these research fellowships for experienced researchers, the foundation enables highly qualified scientists from abroad to spend extended research stays in Germany. Taheri Monfared's work in the CMS group at DESY focuses on strong interactions in particle physics. She will analyse measurements obtained at DESY's former HERA electron–proton collider HERA and at the LHC.

Sara Taheri Monfared

Dark Matter Day

31 October was the International Dark Matter Day – and as DESY scientists too are searching for dark matter, DESY and the Hamburg planetarium showed the film "The Phantom of the Universe" twice on the occasion. The film follows scien-tists hunting for the mysterious dark matter – from the big bang to its hoped-for discovery, for example at the LHC at CERN. At the event, DESY scientists answered questions about dark matter and particle physics. At the same time, the first conference bringing together experts from various dark-matter research fields was held at DESY in Hamburg from 29 to 31 October.

November

Federal government funds campus for high-tech start-ups at DESY

In early November, the budget committee of the German Bundestag agreed to set up a start-up incubator in the immediate vicinity of the DESY campus in Hamburg. The planned technology and start-up centre will be established as a federal institution with a volume of 95 million euros. DESY initiated the idea and will be in charge of building the integrated incubator, which is aimed at start-ups and innovation issues in the high-tech fields of biotechnology, nanotechnology and new, intelligent materials.

Johannes Kahrs and Swen Schulz (left), delegates to the German Bundestag, during a visit to DESY in August

The planned technology centre is meant to open up the economic and innovative potential offered by new technologies, possibilities and developments in the fields of life sciences and materials science for the benefit of Germany. Start-ups will find an environment with an excellent infrastructure, including state-of-the-art laboratories and offices, and will be uniquely integrated into the science ecosystem of the research campus in the Hamburg-Bahrenfeld district.

Kerstin Tackmann new leading scientist at DESY

DESY scientist Kerstin Tackmann strengthens the particle physics department at DESY, becoming a W3 professor at Universität Hamburg and at the same time a leading scientist at DESY, where she has already headed a Helmholtz Young Investigator Group and a working group funded by a European Research Council (ERC) Starting Grant.

Kerstin Tackmann

She will continue to study the Higgs boson in detail at the ATLAS experiment, working on differential cross section measurements and leading the Higgs working group within the ATLAS collaboration. In addition, as part of her professorship, she will be involved in the Belle II experiment at KEK, measuring CKM matrix elements in inclusive *B*-meson decays.

PhD Thesis Prizes 2018

Alexander Knetsch and Stefan Zeller were awarded the 2018 PhD Thesis Prize 2018 of the Association of the Friends and Supporters of DESY (VFFD). The prize was presented as part of the DESY Science Day in recognition of their excellent doctoral theses.

From left: DESY Director Helmut Dosch, PhD Thesis Prize awardees Alexander Knetsch and Stefan Zeller and former VFFD Chairman Friedrich-Wilhelm Büßer

Alexander Knetsch completed his doctoral thesis on “Acceleration of laser-injected electron beams in an electron-beam driven plasma wakefield accelerator” in the field of accelerator physics at DESY and Universität Hamburg. In his doctoral thesis about “The Helium Dimer”, Stefan Zeller used DESY’s FLASH free-electron laser to measure the distribution of atoms along the weakest naturally existing bond between two helium atoms. Using the extreme brightness of FLASH to remove electrons from the helium molecule in a carefully controlled way, he measured its shape with extreme precision.

Qualification with distinction

Two DESY apprentices, Carsten Patzke and Lucas van Tuyl, were honoured by the Hamburg Chamber of Commerce for their outstanding vocational training qualification. Van Tuyl completed a vocational training in electronics for devices and systems, Patzke became an IT specialist. Both received their awards at a ceremony presenting Hamburg’s best trainees. The Chamber of Commerce congratulated them on their out-standing performance and emphasised that such results are only possible "if capable young people are instructed and motivated in committed training companies." The Chamber of Commerce honoured DESY as "Excellent Training Company 2018".

Carsten Patzke and Lucas van Tuyl

Annual meeting of the Terascale Helmholtz-Alliance

HELMHOLTZ ASSOCIATION

The 12th annual Helmholtz Alliance workshop on "Physics at the Terascale" took place at DESY at the end of November. About 300 physicists from Germany and abroad came to Hamburg for three days of intense scientific discussions on current and future issues in particle physics. A central part was played by the presentation of recent results from the latest run at the LHC. The continuing high level of interest for this community meeting demonstrates the central role the Alliance continues to play in the German particle physics community.

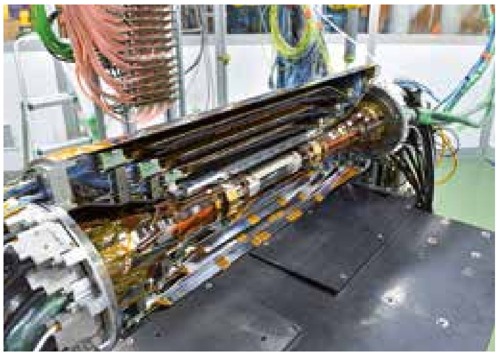
Armenian President visits DESY in Zeuthen

On 30 November, the president of the Republic of Armenia, Armen Sarkissian, and a delegation of Armenian and local officials visited DESY in Zeuthen. President Sarkissian was welcomed on the research campus by Brandenburg's State Secretary for International Relations Thomas Kralinski, DESY Director Helmut Dosch and Christian Stegmann, representative of the DESY Directorate in Zeuthen. After touring the workshops, experimental halls and the PITZ accelerator, the guests discussed the cooperation between Armenia, Brandenburg and DESY with their hosts. A chat with scientists was also on the agenda – after all, the Armenian president is also a professor of theoretical physics. DESY has been cooperating with Armenia in the fields of accelerators, particle physics and astroparticle physics since the 1960s, also supported by cooperations with the German federal state of Brandenburg. In recent years, several DESY staff members attended events in Armenia. "DESY has had very friendly and lively research cooperations with Armenian science for over 50 years. We are therefore very pleased that Mr. Sarkissian is visiting our research centre during his several-day stay in Germany," said DESY Director Helmut Dosch on the occasion.

December

Belle II experiment completed

At the Japanese research centre KEK, the last component was inserted into the Belle II particle detector, which had been completely upgraded over the last few years and which is scheduled to start up in spring 2019. The final piece, the vertex detector, consists of two independent parts that complete the overall detector. The inner part of the vertex detector is a novel pixel detector developed and built by 12 institutes in Germany. This highly sensitive detector consists of two half-shells and is only about the size of a soda can. It had been extensively tested at DESY over the previous few months. Having safely arrived at KEK, the pixel detector was mounted on the beam pipe through which the particles in the SuperKEKB collider will travel and combined with the rest of the vertex detector, which was assembled in Japan.



The vertex detector of the Belle II experiment

Wim Leemans new director of DESY's Accelerator Division

As of 1 February 2019, Wim Leemans is to become the new director of DESY's Accelerator Division. Leemans, who was born in Belgium, was previously in charge of the Accelerator Technology and Applied Physics Division at the Lawrence Berkeley National Laboratory in the USA and and the head of the Berkeley Lab Laser Accelerator (BELLA) Center.

Leemans succeeds Reinhard Brinkmann, who has been director of DESY's Accelerator Division since July 2007 and is returning at his own request to DESY accelerator research as a leading scientist.

Wim Leemans, plasma accelerator pioneer from Berkeley Lab in California, joins DESY.

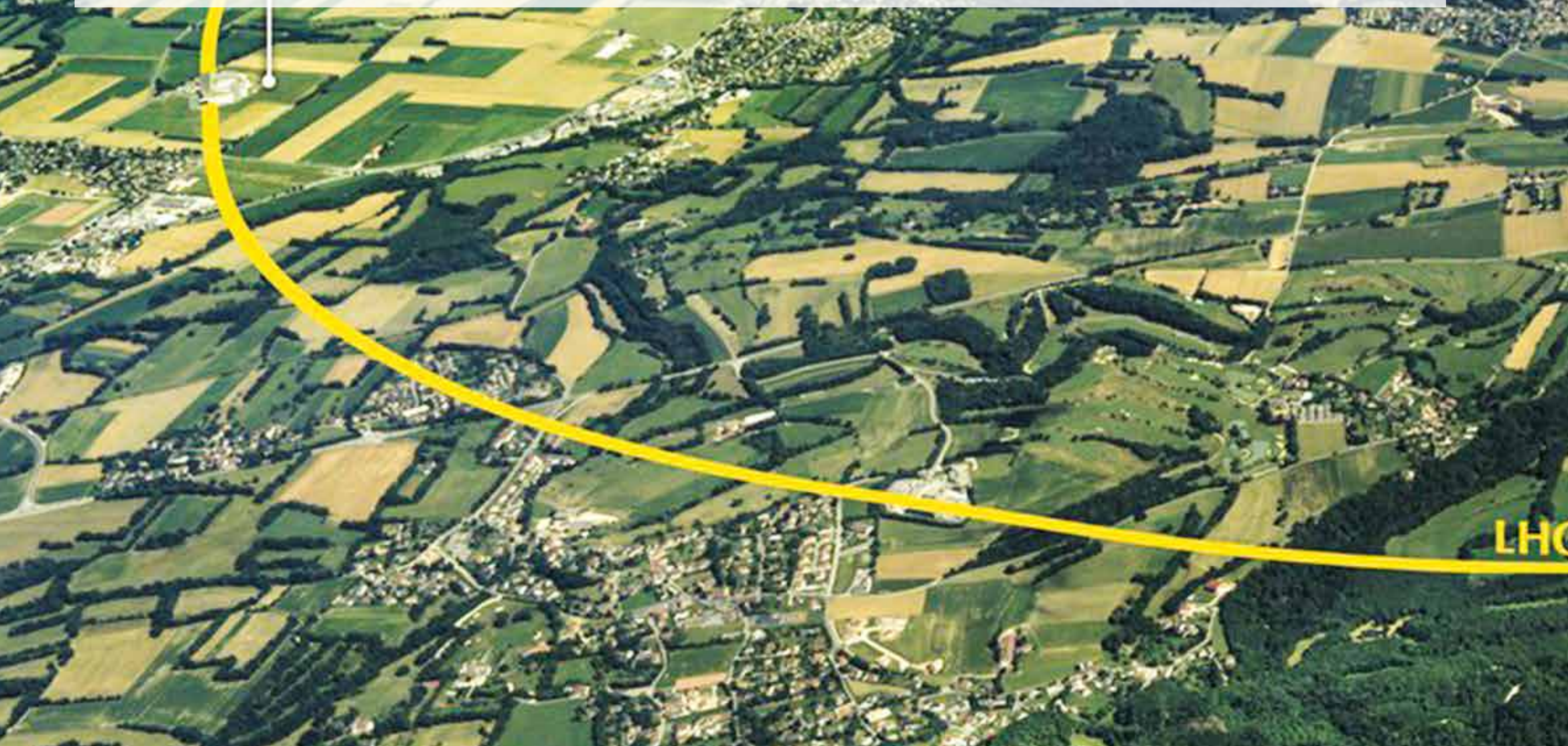
Experimental particle physics

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.

One activity paving the way to the discovery of new phenomena is the re-establishment of Standard Model measurements at the LHC. These include precision measurements of the scattering of same-sign *W* bosons by ATLAS and CMS (p. 20) as well as other Standard Model tests involving the top quark (p. 22). Another focus of the DESY LHC groups is the properties of the Higgs boson. Enhanced accuracy allowed the DESY ATLAS group to observe the decay of Higgs bosons into bottom quarks for the first time (p. 26), the decay into pairs of top quarks (p. 24), and to improve the precision of previous coupling-constant measurements (p. 27). Moreover, studies with discovery potential are continuously being performed, including searches for dark matter (p. 28) or vector-like quarks (p. 21). 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 2. This includes phenomenological studies of the expected observations at the HL-LHC (p. 30) as well as the development of new detectors (p. 32).

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 future linear colliders, particularly the International Linear Collider (ILC), and on the upgraded SuperKEKB accelerator with the Belle II experiment at the Japanese national particle physics laboratory KEK. The first Belle II data were taken in 2019 (p. 42), paving the way for new experimental discoveries in the future. The main focus at Belle II is to scrutinise the flavour sector of the Standard Model (p. 45), but the experiment also has the potential to discover dark matter (p. 44). The strong ties of DESY to Japan through the Belle II activities are supported by two EU projects that foster interactions between the EU and Japan, namely E-JADE (p. 40) and JENNIFER (p. 41). Regarding a future electron–positron linear collider, the two main activities at DESY are detector development (p. 34 and p. 36) and material tests for positron sources (p. 38).

Last but not least, DESY has broadened its activities in the field of axion-like particles (p. 46). The construction of the ALPS II experiment is proceeding as foreseen, while preparations started for two new experiments, IAXO and MADMAX.




LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
27 km

Probing the Standard Model with *W* bosons

New insights into the electroweak and strong interactions

The Standard Model (SM) of particle physics represents our current understanding of the fundamental building blocks of matter and their interactions. Measurements of the production of *W* bosons in proton–proton collisions at the LHC enable important tests of different aspects of the model. Observing the production of two *W* bosons with the same electric charge is an essential milestone in understanding the electroweak interaction, and measuring the associated production of *W* bosons with charm quarks gives insights into the strong interaction, directly probing the strange-quark sea of the proton. DESY scientists are leading the relevant experimental efforts of the ATLAS and CMS collaborations at the LHC.

Probing the strange-quark sea of the proton

The precise description of the proton structure is of key importance for interpreting the observations in proton–proton collisions at the LHC. The proton structure is expressed through universal parton distribution functions (PDFs), which depend on the fraction x of the proton momentum carried by a parton and on the energy scale μ of the process. The determination of PDFs requires measurements of various physics processes.

The production of *W* bosons in association with charm quarks at the LHC provides the only direct probe of the strange-quark distribution in the proton at a hadron collider. The results of the CMS experiment on the fraction of strange quarks in the proton using *W* + charm production at a centre-of-mass energy of 13 TeV [1] are shown in Fig. 1. The CMS result agrees well with the global PDF fits by different phenomenology groups, who use data from neutrino scattering experiments, and provides important input for understanding the strange-quark content of the proton.

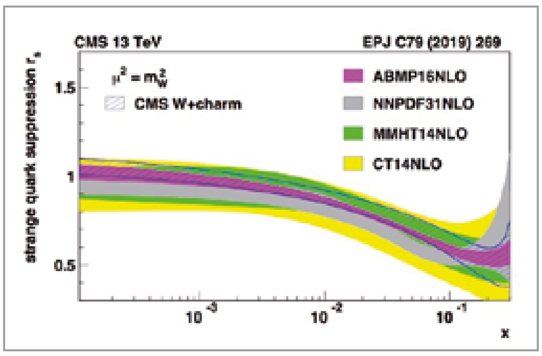


Figure 1
Suppression of strange quarks with respect to up and down quarks in the proton sea

Observing the scattering of same-charge *W* bosons

The electroweak production of a pair of *W* bosons with the same electric charge in association with jets (denoted in the figures as $W^{\pm}W^{\pm}jj$ EW), through a process known as vector boson scattering, is an important process to study because it is strongly affected by the presence of the Higgs boson (discovered in 2012 at the LHC). Without the latter, the predicted production rate would be much larger than what is seen in the LHC data.

DESY scientists contributed to the observation of this process using proton–proton collisions at a centre-of-mass-energy of 13 TeV collected with the ATLAS detector [2] in 2015 and 2016, confirming another prediction of the SM. The observed event yields as a function of a property of the two jets (the dijet invariant mass m_{jj}), shown in Fig. 2, are in good agreement with the SM. This result and upcoming, more precise measurements of this process provide an essential probe of the role of the Higgs boson in the SM and help to constrain new physics models extending it.

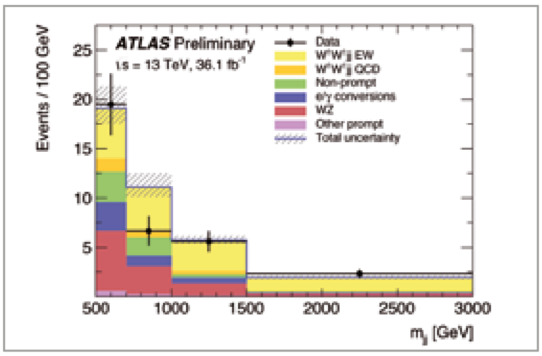


Figure 2
Predicted (coloured bars) and observed (data) event yields in bins of m_{jj}

Contact:
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References:
[1] CMS Collaboration, Eur. Phys. J. C79, 269 (2019)
[2] ATLAS Collaboration, ATLAS-CONF-2018-030

Searching for vector-like quarks

Stronger together: a combination of ATLAS searches

With strong involvement of several German institutes, including the DESY ATLAS group, the ATLAS collaboration is searching for new particles called vector-like quarks, which are predicted in several theories extending the Standard Model. Seven searches were designed to target all experimental signatures sensitive to the existence of such vector-like quarks. After major contributions to two of the most sensitive analyses, DESY led the first combined interpretation of those searches, yielding the most stringent constraints to date on such signals.

The discovery of the Higgs boson at the LHC in 2012 confirmed key Standard Model predictions, but many questions remain to be answered. For instance, interactions at the quantum level between the Higgs boson (*H*) and the top quark (*t*) ought to lead to a huge Higgs-boson mass, possibly as large as the Planck mass (>10^{18} GeV). So why is it only 125 GeV? Is there a mechanism at play to cancel these large quantum corrections caused by the top quark? Finding a way to explain the lightness of the Higgs boson is one of the most pressing questions in particle physics.

Several solutions have been proposed, which often predict the existence of vector-like quarks – in particular, a vector-like top quark (VLT), denoted *T*. Like other quarks, they would be spin-½ particles that interact through the strong force. While all spin-½ particles have left- and right-handed components, the weak force only interacts with the left-handed components of Standard Model particles. But vector-like quarks would have “ambidextrous” interactions with the weak force, giving them a bit more freedom in how they decay. While the Standard Model top quark always decays to a bottom quark (*b*) by emitting a *W* boson ($t \rightarrow Wb$), a VLT can decay in three different ways: $T \rightarrow Wb$, $T \rightarrow Zt$ or $T \rightarrow Ht$, and those decays vary from one model to another.

ATLAS has built a program to search for VLT pairs in LHC data. It uses data from seven dedicated analyses, each of them sensitive to various experimental signatures (involving leptons, boosted objects and/or large missing transverse momentum), allowing ATLAS to look for all possible decays and increasing the chance of discovery. The DESY ATLAS group played a major role in two of the most sensitive analyses of this program [1, 2].

ATLAS has gone one step further by performing a combination of all the individual searches [3], led by the DESY ATLAS group. The combined results provide sensitivity to all possible sets of decays and have allowed ATLAS to probe the existence of 0.6–1.5 TeV VLTs. But they are so far nowhere to be found. With this analysis, ATLAS set the most stringent lower mass limits on vector-like partners of the top and bottom quarks for arbitrary sets of branching ratios to the three decay modes. In particular, for specific decays, VLT masses below 1.4 TeV are excluded (Fig. 1).

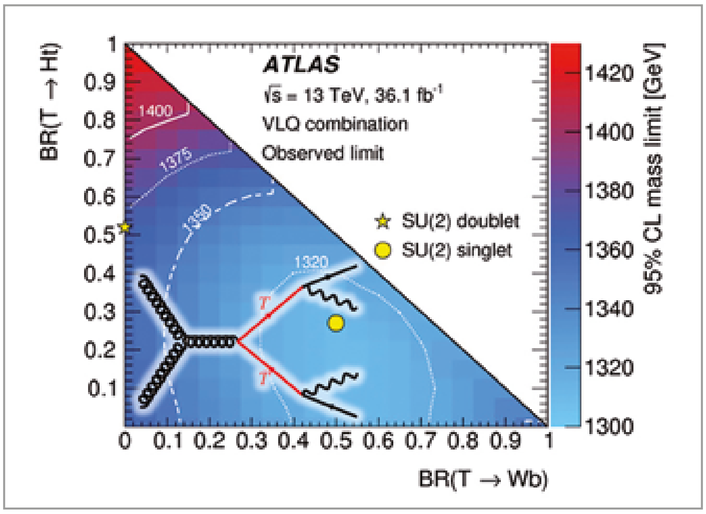

Figure 1

Lower 95% confidence level (CL) lower limit on the vector-like top mass for various combinations of decay branching ratios

Contact:

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References:

[1] ATLAS Collaboration, JHEP 12, 039 (2018)

[2] ATLAS Collaboration, JHEP 07, 089 (2018)

[3] ATLAS Collaboration, Phys. Rev. Lett. 121, 211801 (2018)

Radiography of the top quark at CMS

Exploring the heaviest elementary particle known today

One of the most fascinating particles studied at the LHC is the top quark. As the heaviest elementary particle to date, the top quark lives less than a trillionth of a trillionth of a second and decays before it can form hadrons. This provides the unique opportunity to study a bare quark without the dilution effects of the strong interaction and allows its exciting properties to be explored. The DESY CMS group has analysed LHC data where top quark–antiquark pairs are produced. Particularly important are measurements of differential cross sections, asymmetries in the production of top quarks and antiquarks, the top-quark polarisation and the spin correlation between top quark and antiquark.

The top quark is as heavy as a gold nucleus, which is a striking property for a particle we think is pointlike and elementary. Because of its large mass, it has long been suspected of potentially carrying key information for solving some of the paramount open questions in particle physics. Very precise knowledge of the top-quark properties is crucial for testing the Standard Model (SM) of particle physics. Moreover, many models of novel physics phenomena beyond the SM (BSM) expect the top quark to couple to yet unknown particles whose existence could hereby be revealed.

At the LHC, top quarks are mostly produced in pairs ($t\bar{t}$) via the strong interaction. The dominant mechanism is gluon fusion, corresponding to ~90% of the generation process at a centre-of-mass energy of 13 TeV, while quark annihilation amounts to ~10%. Top quarks decay almost exclusively into a bottom quark and a W boson, which subsequently decays into leptons or quarks. The DESY CMS group studied more than one million $t\bar{t}$ pairs in dilepton final states recorded in 2016 [1, 2]. Precision measurements of $t\bar{t}$ production as a function of numerous kinematic properties of the top quark were performed and confronted with state-of-the-art SM theoretical calculations and Monte Carlo (MC) simulations after correcting for experimental effects [1]. In general, good agreement was found with the SM, although not all the MC predictions were able to describe the measured observables accurately.

Top-quark charge asymmetries

The $t\bar{t}$ production via gluon fusion and quark annihilation is predicted to be symmetric under charge conjugation at leading order (LO) in quantum chromodynamics (QCD). Due to the interference between initial- and final-state gluon

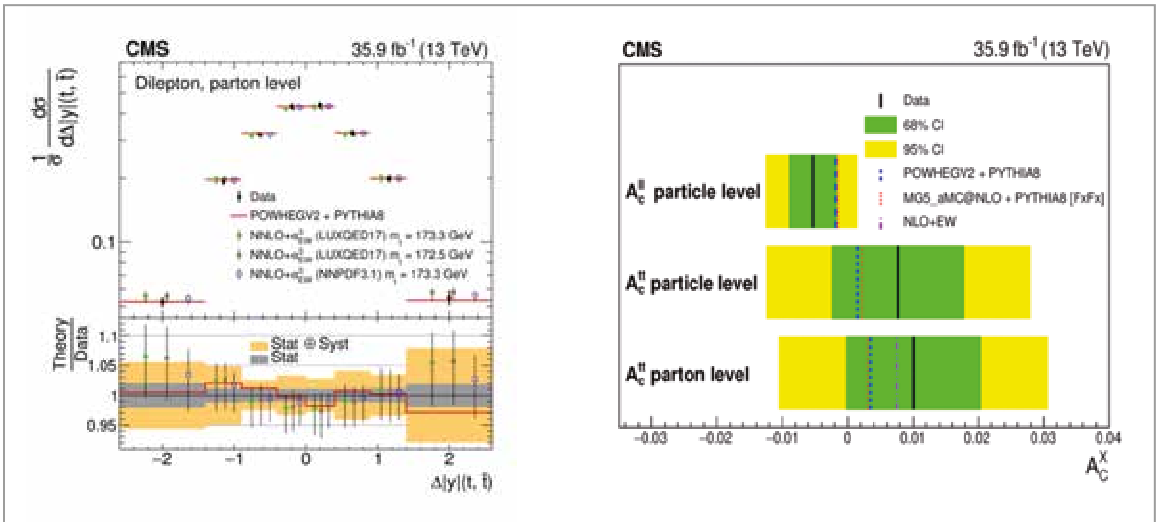

Figure 1

Distribution of the difference in absolute rapidity between the top quark and antiquark (left panel) used to extract the top-quark charge asymmetry $A_c^{t\bar{t}}$ (right panel). Good agreement with the SM predictions can be observed.

radiation and the interference between Born and box diagrams, a net asymmetry arises at next-to-LO (NLO) for $t\bar{t}$ production. The proton–proton collisions at the LHC provide a symmetric initial state, and a small charge asymmetry (A_c) is induced by the momentum difference of the valence and sea quarks: Valence quarks carry on average a larger fraction of the proton momentum than sea antiquarks, hence top quarks are produced slightly more forward and top antiquarks are produced slightly more centrally.

Signals of BSM physics could appear in $t\bar{t}$ production as top-quark or leptonic charge asymmetries different from those predicted by the SM. Hence, the DESY CMS group extracted these quantities from differential $t\bar{t}$ cross section measurements as a function of the difference in absolute rapidity between the top quark and antiquark (Fig. 1, left) and of the difference in absolute pseudorapidity between the charged leptons in the final state [1]. Good agreement with the SM predictions was found (Fig. 1, right).

Top quark–antiquark spin correlation and polarisation

The spin of the top quark can be inferred from the particles it decays to. The SM makes precise predictions for the frequency that the spin of the top quark is aligned versus opposed to the spin of the top antiquark. The measurement of the correlation of the top quark and antiquark spins is therefore a highly sensitive test of the SM. If, for example, an exotic heavy Higgs boson would exist, it could decay into a pair of top quark and antiquark and change their spin correlation significantly. The high-precision measurement of the spin correlation opens a window for exploring physics beyond our current knowledge.

The DESY CMS group studied all spin and polarisation effects accessible in $t\bar{t}$ production by measuring different observables sensitive to spin correlation and to the top-quark polarisation and comparing them to high-precision theory predictions [2]. Figure 2 (top) shows the azimuthal opening angle between two leptons. As can be seen, one of the MC simulations (POWHEGv2 + PYTHIA8) exhibits a moderate discrepancy to the data. This is also in accordance with an observation made by the ATLAS collaboration [3]. The NLO SM calculation, however, shows better agreement. In all other observables studied in this analysis, good agreement

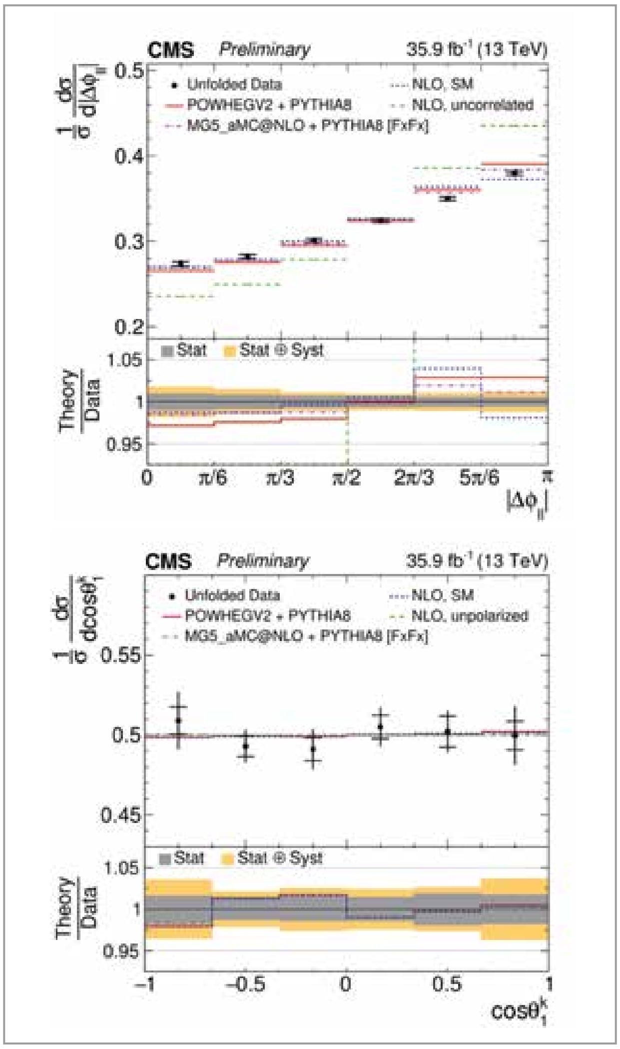

Figure 2

Distribution of the azimuthal opening angle between two leptons (top panel) and lepton angle with respect to the top-quark momentum (bottom panel). Good agreement with the NLO predictions indicated by the blue dashed line can be observed.

between data and theory predictions was found. As an example, a measurement sensitive to the top-quark polarisation is presented in Fig. 2 (bottom), showing no angular dependence, as expected for unpolarised top quarks.

In summary, a general good agreement with the SM prediction is observed in the CMS data. The full LHC Run 2 data set already recorded by CMS contains four million $t\bar{t}$ pairs. This will allow even more precise measurements, increasing the chances for a first glimpse of new physics.

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References:

[1] CMS Collaboration, JHEP 02, 149 (2019)
[2] CMS Collaboration, CMS-PAS-TOP-18-006 (2018)
[3] ATLAS Collaboration, arXiv:1903.07570

Higgs boson makes top quark heavy

Rare Higgs boson process shines light on the origin of particle mass

The DESY ATLAS and CMS groups have independently observed the rare production mode of a Higgs boson associated with a top quark–antiquark pair at the LHC. This observation provides a direct probe of the top–Higgs coupling, the mechanism through which the top quark acquires its mass, according to the Standard Model of particle physics.

Introduction

Since the discovery of the Higgs boson at the LHC in 2012, studying its properties has been of major importance for particle physicists. The Standard Model (SM) of particle physics predicts that fundamental particles acquire their mass through interactions with the Higgs field and that this mass is proportional to the interaction probability, or coupling, of any particle with the Higgs boson. The top quark is the heaviest particle in the SM. Therefore, its coupling to the Higgs boson is expected to be the strongest, and measuring the value of this coupling is hence of utmost importance for studying the Higgs mechanism.

While the top-quark coupling to the Higgs boson influences many Higgs-related measurements, such as the Higgs-boson decay into a pair of photons, a direct measurement of the top–Higgs coupling can only be obtained by studying the associated production of the Higgs boson with top quarks, and in particular with a top quark–antiquark pair ($t\bar{t}H$ production).

The measurement of the $t\bar{t}H$ production rate is crucial to verify the SM and the nature of its associated Higgs field. A deviation of the expected coupling could reveal the first signs of new phenomena beyond the SM. The $t\bar{t}H$ process represents a very rare Higgs production mode at the LHC (only 1% of all Higgs boson events), and the challenge is to identify such events against a background that can be orders of magnitude larger. In 2018, the ATLAS [1] and CMS [2] experiments have observed evidence for this process in the analysis of proton–proton collisions delivered at the LHC. The DESY groups played a leading role in this measurement.

Divide and conquer

Multiple decay modes of the Higgs boson are targeted in dedicated search channels, covering a variety of final states. The DESY groups contributed to the channels in which the Higgs boson decays to a pair of b quarks, photons, W or Z bosons and τ leptons. The best sensitivity is ultimately obtained by combining all these different channels by means of advanced statistical methods.

Finding the needle in the haystack

The most probable (58%) decay of the Higgs boson is to a pair of b quarks. This channel provides a high-statistics sample of $t\bar{t}H$ events, but suffers from a large background. Since the top quark almost always decays into a W boson and a b quark, the decay of $t\bar{t}H$ leads to complex final states with four b-quark jets, as illustrated in Fig. 1. The large background from top-quark pairs, particularly with additional radiation of b-quark jets, are almost indistinguishable from the signal (Fig. 1).

SM backgrounds were significantly reduced by selecting events with three or more b-quark jets, although even in the most sensitive analysis category (one lepton plus at least six jets, with at least four b-quark jets), the $t\bar{t}H$ signal was 20 times smaller than the background. In order to further disentangle the signal from background events, state-of-the-art machine-learning techniques and advanced statistical tools were used in the analyses. Figure 2 shows the distribution of a deep neural network (DNN), optimised for the $t\bar{t}H$ ($H \rightarrow b\bar{b}$) signal, in CMS [3]. The observed contribution from $t\bar{t}H$ events (blue) can be seen at high values of the DNN output, as opposed to the background (red), which is

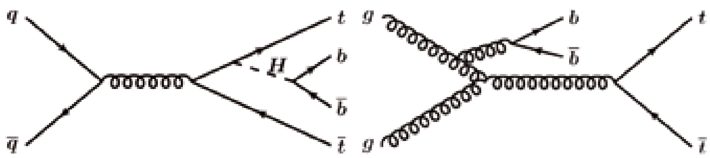

Figure 1

Example of Feynman diagrams for $t\bar{t}H$ production with $H \rightarrow b\bar{b}$ decay (left) and for $t\bar{t} + b\bar{b}$ production (right). In both cases, four b-quark jets are present in the final state, two of which arise from the decay of top quarks.

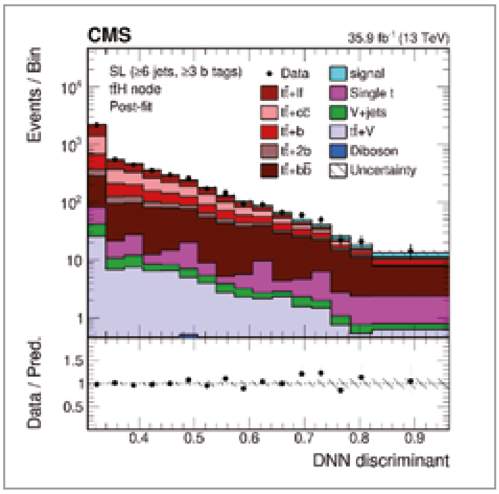

Figure 2

Distribution of the deep neural network score, optimised to separate the $t\bar{t}H$ signal (blue) from other SM processes, in single-lepton events. The distribution is shown after the fit to the data [3].

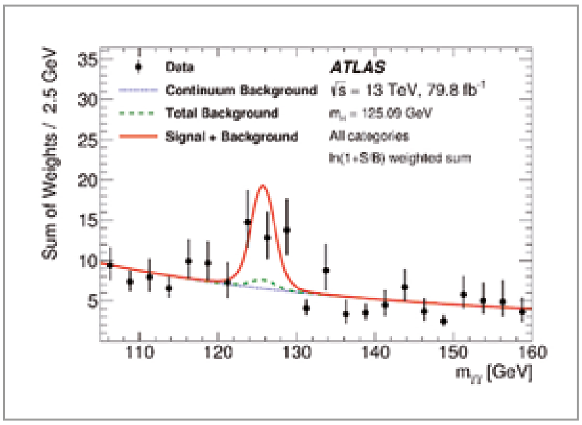

Figure 3

Diphoton invariant mass in the $t\bar{t}H$ signal region. The signal + background hypothesis (red) and the background-only hypothesis (blue) are compared to the data points. The contribution from other Higgs production modes is indicated by the green line [2].

concentrated in the low-score region. A simultaneous fit to the DNN outputs in multiple signal regions was performed to extract the $t\bar{t}H$ signal, exploting the difference expected for background-like and signal-like events in the shape of these distributions. This analysis was limited by the large systematic uncertainties on the modelling of the dominant $t\bar{t}b\bar{b}$ background, for which independent measure-ments were performed to aid the $t\bar{t}H$ analysis [4].

The $t\bar{t}H$ channels in which the Higgs decays to a pair of massive gauge bosons (W or Z), or a pair of τ leptons, were studied in events with two same-sign or three charged leptons. These channels contribute significantly to the final sensitivity for $t\bar{t}H$ production; the main challenge in this analysis is the determination of backgrounds from misidentified charged leptons.

Bump hunting

The Higgs boson only decays to a pair of photons less than 1% of the time, but it produces a clear experimental signature with a well-understood background. In this case, the presence of the $t\bar{t}H$ process can be established by looking for a bump in the otherwise smoothly falling background of the diphoton invariant-mass spectrum.

Figure 3 shows the $m_{\gamma\gamma}$ peak from $t\bar{t}H$ events. The sensitivity in this channel is still limited by statistics and will thus improve significantly as more data is collected.

Observation

The ATLAS and CMS experiments independently observe a significant excess in the data over background, which is compatible with the SM prediction of the $t\bar{t}H$ signal. Through the combined analysis of multiple channels, each experiment disfavours the background-only hypothesis by at least five standard deviations, thereby claiming observation of the $t\bar{t}H$ production mode of the Higgs boson at the LHC [1, 2]. These measurements use data collected in both LHC Run 1 (2011–2012) and Run 2, from June 2015 up to the 2017 data-taking period. Table 1 shows the measured $t\bar{t}H$ production rate, normalised to the SM expectation, for the individual channels and their combination. For both experiments, these measurements are found to be in good agreement with the SM expectation (μ = 1.0), within their current uncertainties.

These analyses firmly establish the coupling of the Higgs boson to the top quark and shed more light on the mechanism giving mass to fundamental particles. The analysis of more data will allow ATLAS and CMS to improve the precision of this measurement and perform an even stricter validation of the SM, where any deviation would hint at new phenomena.

$t\bar{t}H$ Observed Signal Strength ($\mu = \sigma/\sigma_{SM}$)		
Channel	ATLAS	CMS
$H \to \tau^+\tau^-$	$1.36^{+1.19}_{-1.02}$	$0.28^{+1.09}_{-0.96}$
$H \to b\bar{b}$	$0.83^{+0.61}_{-0.61}$	$0.82^{+0.44}_{-0.42}$
$H \to VV^*$	$1.50^{+0.63}_{-0.59}$	$1.97^{+0.71}_{-0.64}$
$H \to \gamma\gamma$	$1.41^{+0.48}_{-0.42}$	$2.27^{+0.86}_{-0.74}$
Combination	$1.32^{+0.28}_{-0.26}$	$1.26^{+0.31}_{-0.26}$

Table 1

Observed signal strengths of the $t\bar{t}H$ production mechanism [1, 2], for individual analysis channels and their combination. VV^* denotes the decay to either a pair of W or Z bosons; the CMS result corresponds to WW^* only, while the ZZ^* final state is included in the combined measurement.

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Observing the $H \to b\bar{b}$ decay

Shedding light on Higgs-boson couplings to down-type quarks with the CMS experiment

The Standard Model (SM) of particle physics predicts that the Higgs boson, discovered by the ATLAS and CMS collaborations at the LHC in 2012, decays into a pair of *b* quarks nearly 60% of the time. However, this prime decay mode had evaded detection for many years. In collaboration with colleagues from research groups around the world, scientists from the DESY CMS group were now able to observe the decay of the Higgs boson into a pair of *b* quarks by analysing data collected during LHC Run 1 and Run 2.

A major challenge

Despite the large Higgs-boson branching ratio into a pair of *b* quarks, observing this decay was not simple. The two *b* quarks appear as jets of particles in the detectors, a signature that is easily obscured by huge multijet backgrounds. Therefore, the key idea is to search for Higgs bosons (*H*) produced in association with other striking particle signatures. The best sensitivity is achieved by looking for a Higgs boson that is produced in association with a leptonically decaying vector boson (*VH*).

In addition to the presence of backgrounds, the dijet mass resolution is limited. This means that the Higgs-boson signal does not present itself as a clean peak over the background in the dijet mass spectrum. To improve the separation between signal and backgrounds, state-of-the-art machine learning techniques are employed.

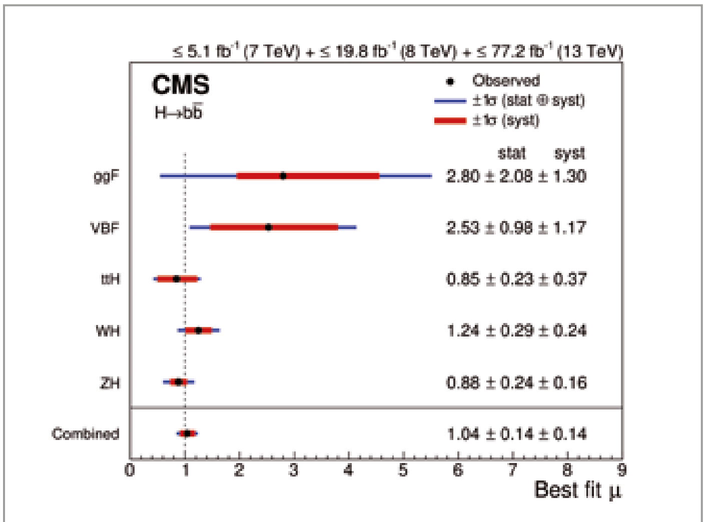

Figure 1

Signal strengths for the $H \to b\bar{b}$ decay per production mode and for all production modes combined. The *VH* and $t\bar{t}H$ processes contribute most to the total sensitivity [1].

The DESY CMS group participated in the search for *VH* production with the Higgs boson decaying into a pair of *b* quarks using data collected during Run 2, and in the combination with earlier searches for this process. In this analysis, the production cross section of the *VH* process, multiplied by the Higgs-boson branching ratio into a pair of *b* quarks, both relative to their SM expectation, was measured. This signal strength was found to be 1.01 ± 0.22, corresponding to a statistical significance of 4.8 standard deviations (σ) with respect to the background, where 4.9 σ were expected.

Putting it all together

The $H \to b\bar{b}$ decay was not only targeted in the *VH* production mode, but also in other Higgs-boson production processes. The DESY CMS group worked on combining all searches for the Higgs boson decaying into a pair of *b* quarks. The signal strengths for the decay per Higgs-boson production mode are shown in Fig. 1 with their corresponding uncertainties. The smallest uncertainties and therefore largest sensitivities are for the *Z*- and *W*-associated Higgs-boson production processes, followed by the $t\bar{t}H$ process.

The combined measured signal strength is 1.04 ± 0.20, corresponding to an observed significance of 5.6 σ with respect to the background, where 5.5 σ were expected. This observation of $H \to b\bar{b}$ is crucial for precisely identifying the nature of the Higgs boson.

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Approaching the precision Higgs physics era

Measuring the properties of the Higgs boson with the ATLAS detector

The higher centre-of-mass energy and larger data set of LHC Run 2 offer the possibility of greatly increasing our understanding of the Higgs boson. Measurements of its properties also provide important tests of Standard Model (SM) predictions. The DESY ATLAS group was strongly involved in measurements performed with data taken in the period 2015–2017 in both the diphoton and four-lepton decay channels.

Measuring Higgs-boson cross sections

We can probe the Higgs boson's properties by measuring its cross section in various phase space regions. Measurements of differential cross sections as functions of kinematic variables or event properties are highly model-independent, in particular in a fiducial region that mimics the detector coverage. This allows tests of all aspects of the theoretical modelling of Higgs-boson production. We can also probe the Higgs boson's couplings to other particles by measuring cross sections in the simplified template cross section (STXS) framework. This method defines measurement fiducial regions based on the SM prediction of the kinematics and topology of each Higgs-boson production process. Observed deviations from the predictions could be evidence for physics beyond the SM. The decay channels with the best signal-to-background ratios are used for the measurements. These are the diphoton channel and the four-lepton channel, in which the Higgs boson decays via Z bosons to electrons or muons. The four-lepton channel has less background, but a lower rate: With 79.8 fb^{-1} of 13 TeV proton–proton collision data collected in 2015–2017, the channels have a similar level of precision.

Figure 1 shows the differential fiducial cross section of the transverse momentum of the leading jet p_{Tj1}, as measured in the diphoton decay channel [1]. The first bin contains events with no jets passing the p_T threshold of 30 GeV. The measurement is corrected for detector effects; results are shown at particle level. The data are compared to several theoretical predictions for SM gluon–gluon fusion (including SCETlib [3], developed by DESY theorists). Good agreement is observed. Figure 2 shows the observed and SM expected values of the cross section times branching fraction (normalised by the SM values) in several STXS production bins, as measured in the four-lepton decay channel [2]. The different colours indicate different Higgs-boson production modes; the $t\bar{t}H$ parameter is constrained to be positive. Good agreement with SM predictions is observed.

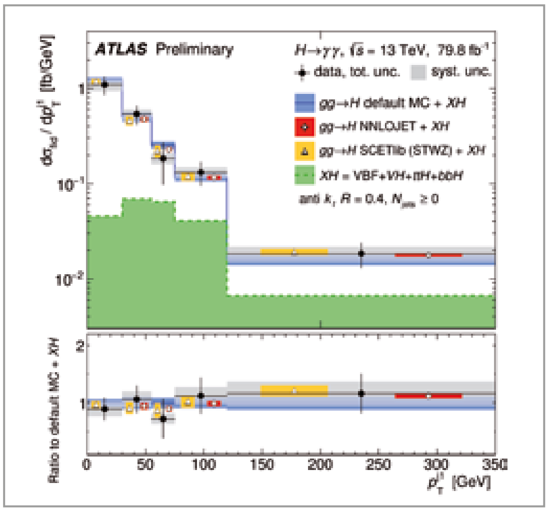

Figure 1
Differential fiducial cross section of the leading-jet transverse momentum measured in the diphoton decay channel

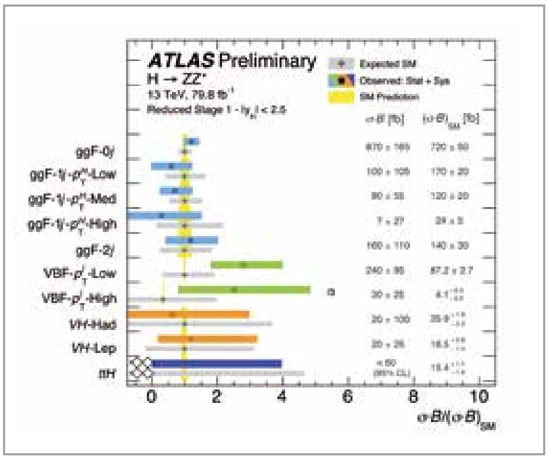

Figure 2
STXS cross sections measured in the four-lepton decay channel

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Probing the dark universe

Dark-matter and dark-energy searches with the ATLAS experiment

Only around 5% of our universe is known. The elementary particles and their interactions making up this "visible" universe are described in the Standard Model of particle physics. Another 27% of the universe is made up of dark matter, the existence of which is strongly supported by numerous astrophysical observations. The remaining 68% is known as dark energy, which is linked to the accelerated expansion of the universe. Unravelling the nature of the dark universe is one of the key goals of particle physics in the 21st century. The DESY ATLAS group plays a leading role in searches for dark matter and dark energy in the data collected with the ATLAS experiment at the LHC.

A key strength of collider experiments lies in their ability to probe a large range of possible dark-matter (DM) and dark-energy signatures in a multitude of different final states. In particular, they could directly probe the interaction between dark matter and ordinary matter by searching for "mediator" particles that would decay either invisibly into dark matter or visibly into quarks or leptons. The Higgs field may also interact with dark matter. This motivates searches for rare or non-standard Higgs-boson decays.

Search for invisible Higgs decays

A possible coupling of the hypothetical DM to the Higgs boson, as predicted by theories known as Higgs portal models, would lead to an increased probability for the decay of the Higgs boson into invisible particles, assuming a small enough DM mass. This process is very rare (~ 0.1%) in the Standard Model (SM), and its observation at a larger value would be a clear indication for physics beyond the SM. The sensitivity to this process is best if the Higgs is produced in a vector boson fusion (VBF) process (Fig. 1).

In VBF processes, the two quark jets are emitted in the forward direction in opposite hemispheres and provide additional power to suppress the SM background. Selected events are required to have missing transverse energy, no isolated electrons or muons, no third jet and a large invariant dijet mass to capture the VBF topology. The dominant expected background for such a selection is from *W*+jets events with the *W* boson decaying into an unidentified lepton and a neutrino, or from *Z*+jets processes with the *Z* boson decaying invisibly into two neutrinos. Those two backgrounds are estimated from *W*/*Z*-enriched control regions requiring either one or two isolated leptons. A further small but difficult to estimate background contribution originates from quantum chromodynamics (QCD) multijet events, either because the jets are strongly mismeasured and/or because overlaying pile-up events fake the VBF-like topology. A data-driven technique for the estimation of the multijet background was developed at DESY and used in this analysis.

The events that passed the selection were divided in three bins of dijet masses above 1 TeV. In each bin, a good agreement between observed and expected numbers of events was observed for 36 fb^{-1} of data collected in 2015 and 2016 at a centre-of-mass energy of 13 TeV. This allowed us to put an upper limit of 37% (95% CL) on the Higgs branching ratio to invisible particles, while an upper limit of 28% was expected from simulated events only [1].

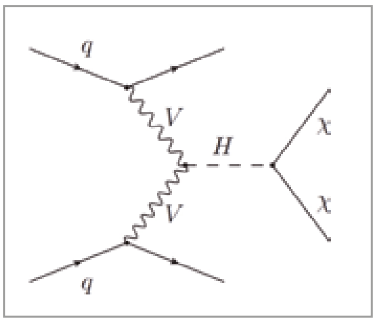

Figure 1

Feynman diagram for vector boson fusion production of a Higgs boson. In case of an invisible Higgs-boson decay, only the two quark jets can be reconstructed.

Dark matter produced in association with hadronically decaying vector bosons

A further typical DM signature that can be detected by the LHC experiments is a large overall missing transverse momentum from a pair of DM particles recoiling against one or more SM particles. We performed a search for DM particles produced in association with a hadronically decaying *W* or *Z* boson (mono-*W*/*Z* search) for specific DM models, including DM production via invisible Higgs-boson decays. In addition to the mono-*W*/*Z* search, the as-yet unexplored hypothesis of a new vector boson *Z′* produced in association with DM was considered (mono-*Z′* search).

The analysis used LHC proton–proton collision data at a centre-of-mass energy of 13 TeV collected by the ATLAS experiment in 2015 and 2016. Events were characterised by large missing transverse momentum and a hadronically decaying vector boson reconstructed as either a pair of small-radius jets or as a single large-radius jet with substructure.

No significant excess over the SM prediction was observed. The results of the mono-*W*/*Z* search were interpreted in terms of limits on invisible Higgs-boson decays into DM particles, constraints on the parameter space of a simplified vector mediator model and generic upper limits on the visible cross sections for *W*/*Z*+DM production [2].

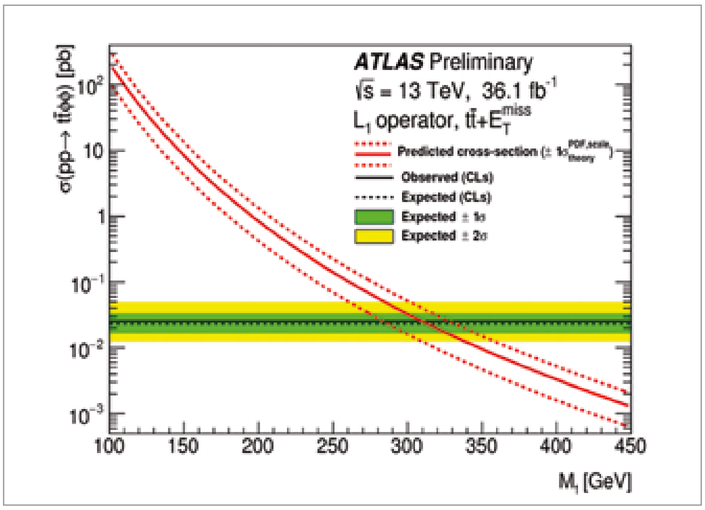

Figure 3

Exclusion limits on the cross section for dark-energy pair production in association with a top–antitop quark pair as a function of the effective mass scale of the dark-energy EFT model (see text) [5]

Multisignature searches for dark matter

The ATLAS collaboration published a comprehensive paper that compares, combines and extends the results of 17 recent searches for DM in the context of selected, mediator-based benchmark models [3]. This effort was led by members of the DESY ATLAS group. The publication not only provides a reference for the DM community, but can also be used as a roadmap for upcoming, improved searches on the full LHC Run 2 data set.

The publication features the first summary of constraints from searches in different final states in the context of a new model, which was developed partly by the DESY theory group and adopted as a new benchmark model by the LHC experiments [4]. It builds on the well-motivated assumption of the existence of a second Higgs field, leading to heavy scalar and pseudoscalar Higgs bosons (*A*, *H*) in addition to a postulated pseudoscalar mediator (*a*). The searches for invisible Higgs decays and mono-*W*/*Z* signatures constrain the parameter space of this “2HDM+a” model, as shown in Fig. 2.

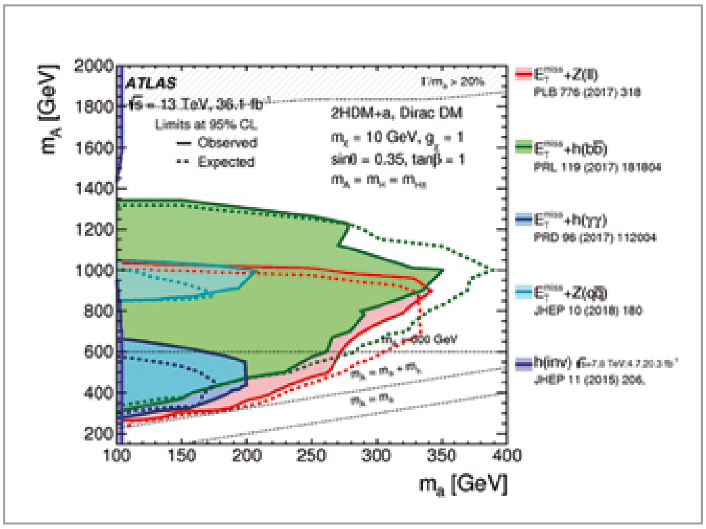

Figure 2

Constraints from different ATLAS DM searches on 36.1 fb^{-1} interpreted in the context of the “2HDM+a” benchmark as a function of two model parameters, the mass of the heavy pseudoscalar *A* and of the pseudoscalar mediator *a* [3]

Search for scalar dark energy

For the first time, the LHC data was used to search for possible signatures of the hypothetical dark energy [3, 5]. Under the assumption that dark energy is a scalar field, an existing search for DM produced in association with a top–antitop quark pair was reinterpreted in the context of an effective field theory (EFT) model of dark energy based on a Horndeski theory (Fig. 3). The DESY ATLAS group played a significant role in this DM search and its dark-energy reinterpretation. The current result is based on 36.1 fb^{-1} of ATLAS data.

The DESY ATLAS group is currently working on searches for DM with significantly improved sensitivity that will rely on the full LHC Run 2 data set.

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Physics at the HL-LHC

Refining high expectations

The High-Luminosity LHC (HL-LHC) is scheduled to start operation in 2026. By the end of the 2030s, it is expected to deliver a factor 20 more data than collected so far to the upgraded LHC experiments. To further refine the expectations of the physics potential of the HL-LHC, the "Workshop on the Physics of the HL-LHC and Perspectives for the HE-LHC" took place from October 2017 to December 2018. The ATLAS and CMS groups at DESY contributed to the organisation of the workshop and performed analyses and projections in several areas, ranging from precision measurements to searches for new physics.

Introduction

Since the start-up of the LHC in 2009, accelerator and experiments have outperformed expectations: in many areas, results with higher precision were achieved earlier than anticipated. In parallel, theoretical advances have led to significantly improved tools and predictions.

In light of these improvements, the "Workshop on the Physics of the High-Luminosity LHC and Perspectives for the HE-LHC" was organised to update and refine expectations for the HL-LHC and its possible upgrade to higher energy (HE-LHC). The whole LHC community – theorists and experimentalists – collaborated closely and produced detailed studies of HL-LHC measurements towards ultimate precision and of searches for new phenomena.

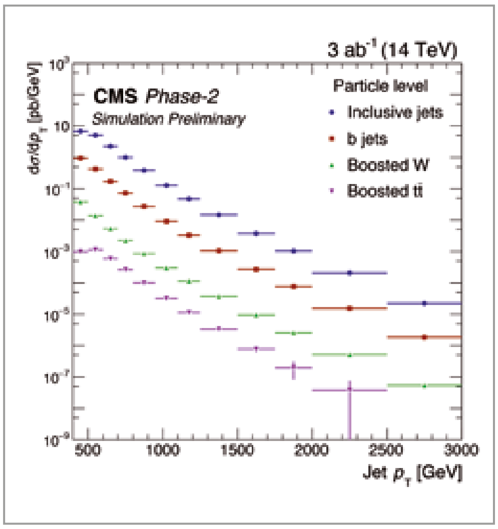

Figure 1

Differential jet cross sections as a function of transverse momentum for different jet flavours. Inclusive jets and bottom-quark, top-quark and *W*-boson jets are displayed in blue, red, green and purple, respectively. From [1].

The results were presented in a report comprising five chapters with a total of more than 1300 pages [1–7]. This up-to-date documentation of the HL-LHC physics potential also provides important input for the update of the European Strategy for Particle Physics, which is due to be completed in 2020.

Standard Model measurements

Precision measurements provide an important tool to probe phenomena at mass scales beyond the direct reach of the LHC. With the HL-LHC, precise jet cross sections can be measured up to several TeV. Figure 1 shows the transverse-momentum (p_T) distributions for jets of different origin. The high-p_T region is of particular interest for studying the strong interactions described by quantum chromodynamics (QCD). At large p_T, the top-quark mass is small with respect to the momentum, and the interplay between their respective scales can be studied.

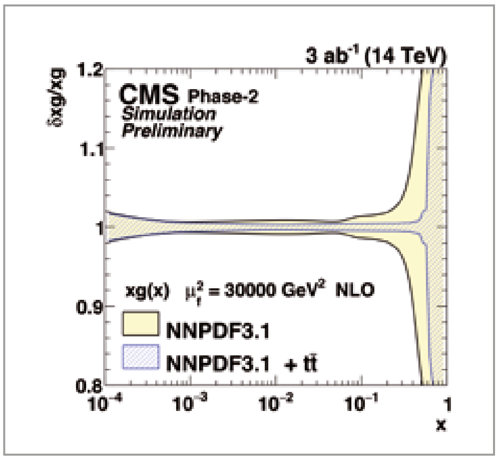

Figure 2

Relative uncertainty for the distribution of the gluon density in the proton as a function of the gluon momentum fraction *x*. Yellow and hatched areas indicate the uncertainty excluding and including the top-quark data. From [1].

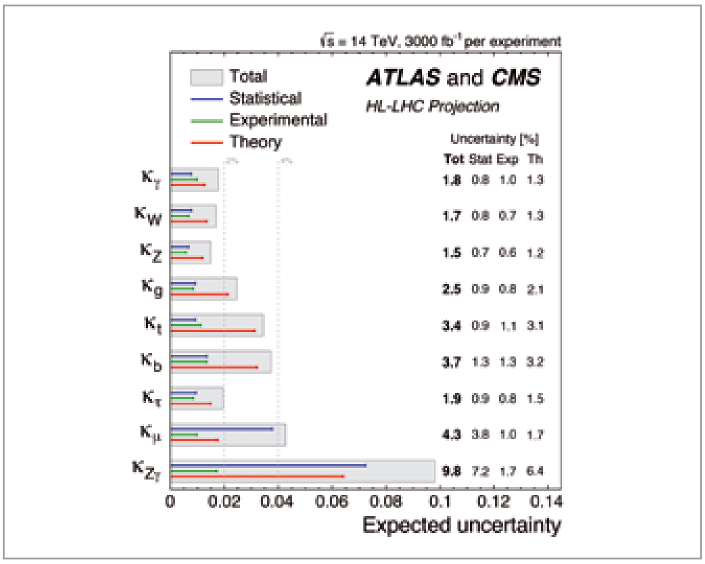

Figure 3

Projected uncertainties of the Higgs coupling modifiers κ, defined as $\kappa^2 = \sigma(\text{measured})/\sigma(\text{expected})$, where σ are the production and decay rates. The total, statistical, experimental and theoretical uncertainties are shown as grey box and blue, green and red bars, respectively. From [2].

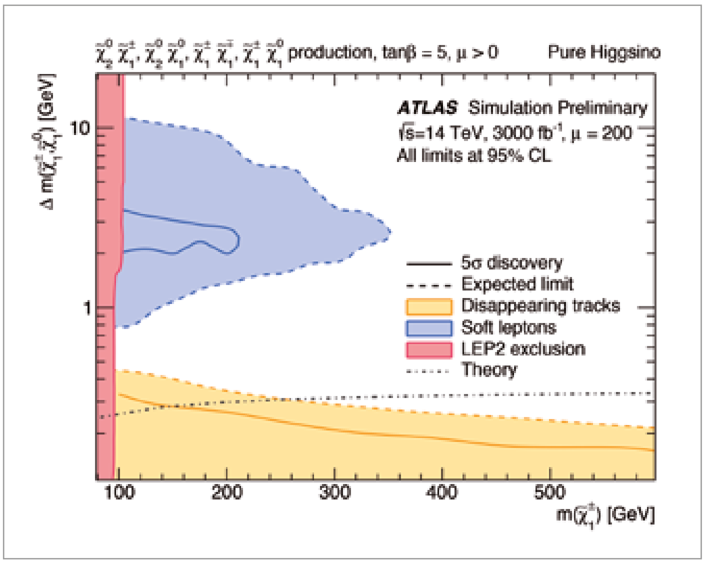

Figure 4

Expected 95% CL exclusion/discovery reach from the disappearing-track (yellow) and low-momentum lepton pair (blue) searches in the higgsino-like electroweakino models. From [3].

Multidifferential measurements of jet cross sections also provide crucial input for the determination of the proton structure at ultimate precision. The results presented in Fig. 2 demonstrate that differential top-quark cross section measurements have a significant impact on the determination of the parton density distributions of the proton.

Properties of the Higgs boson

The determination of the Higgs-boson properties is one of the primary targets of the HL-LHC physics programme. So far, the data seem to align with Standard Model predictions. However, significant deviations cannot yet be excluded.

Inclusive and differential measurements of cross sections as well as direct and indirect width measurements can be exploited to further improve the understanding of the Higgs sector: The main Higgs-boson couplings will be measured at the HL-LHC with a precision at the percent level. Possible deviations from the pure Standard Model expectation can be expressed in terms of coupling modifiers κ_i, assuming no additional interactions. Figure 3 shows the projected uncertainties for the measurement of these coupling modifiers.

The production of Higgs-boson pairs, which is key to determining the Higgs-boson self-coupling, is expected to be measured at the HL-LHC with a significance of at least 4 standard deviations.

Searches for new phenomena

Direct searches for new phenomena will continue to be a priority at the HL-LHC. A much larger data set together with upgraded ATLAS and CMS detectors will provide significantly improved sensitivity.

The signatures that are most involved from an experimental point of view, such as those of long-lived particles, will benefit the most from the detector upgrades. Long-lived particles could arise when interactions are feeble, or when the phase space is small. Supersymmetric spectra with nearly degenerate masses are theoretically well motivated but are among the most challenging scenarios experimentally.

Figure 4 shows the physics potential of searches for pairs of higgsino-like electroweakinos, exploiting either very low-momentum lepton pairs or disappearing inner-detector tracks.

Conclusions

The upgrades of the ATLAS and CMS experiments and the LHC accelerator for high luminosity will open up a new realm of precision and physics reach. The DESY groups have made significant contributions to refining the high expectations placed in these upgrades.

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New detectors for the HL-LHC

Upgraded ATLAS and CMS silicon trackers

The ATLAS and CMS collaborations are preparing for the high-luminosity phase of the LHC (HL-LHC). The current ATLAS and CMS trackers will be replaced by new, all-silicon trackers during the three-year shutdown starting in 2024. Given the magnitude of the project, the preproduction phases for portions of the trackers need to start as early as 2020. The DESY ATLAS and CMS groups, along with other ATLAS and CMS institutions from Germany and abroad, will deliver an end-cap detector for each experiment. DESY has put in place the necessary infrastructure for this effort in 2017 and 2018, and the ATLAS and CMS groups are in the final stages of the R&D work, providing significant contributions in module building, support structure manufacturing, end-cap assembly as well as quality control and quality assurance techniques.

CMS Phase 2 tracker end-cap assembly

The future tracking detector of the CMS experiment will have a conventional barrel end-cap design with six barrel layers and one end-cap at each end. The end-caps are made up of five double-disks, with each disk consisting of two half-disks (Dees). DESY has committed to build on the order of 1000 detector modules, supervise the industrial production of almost 50% of the Dees needed for two end-caps, integrate modules onto Dees and assemble one of the two end-caps. Module production and all integration and assembly steps will be carried out in the cleanrooms of the Detector Assembly Facility (DAF) at DESY in Hamburg.

The Dees are 2.3 m diameter, highly complex objects with integrated positioning and cooling inserts as well as cooling pipes that will act as the main support for the detector modules and their infrastructure. Designing and prototyping of the Dees focus on a prototype with two full-sized cooling sectors that will be built at DESY by mid-2019. In parallel, the development and commissioning of the required equipment for reception tests of components from industry and tests needed during the integration phase have picked up pace. These setups include a metrology system, setups for infrared and ultrasonic inspection as well as test systems for operating the modules and integrated Dees at the target operation temperature of -33°C.

A novelty in the design of the future CMS tracker end-caps is the fact that they are not supported by a mechanical skeleton. The Dees themselves are an integral component of the mechanical structure, which will be established only in a late assembly step by connecting the double-disk with longitudinal bars. This approach reduces the overall material budget but comes with the trade-off of a challenging assembly procedure that requires dedicated tooling for high precision. Within the CMS end-cap consortium, DESY is in charge of the development of this tooling, which requires close collaboration with the groups designing the support bars (IPNL Lyon) and the services (UC Louvain). In 2018, DESY CMS physicists and engineers developed an assembly concept and designed the corresponding tooling.

The central element of this concept is the so-called arc-frame, which acts as a handling frame for the Dees from the

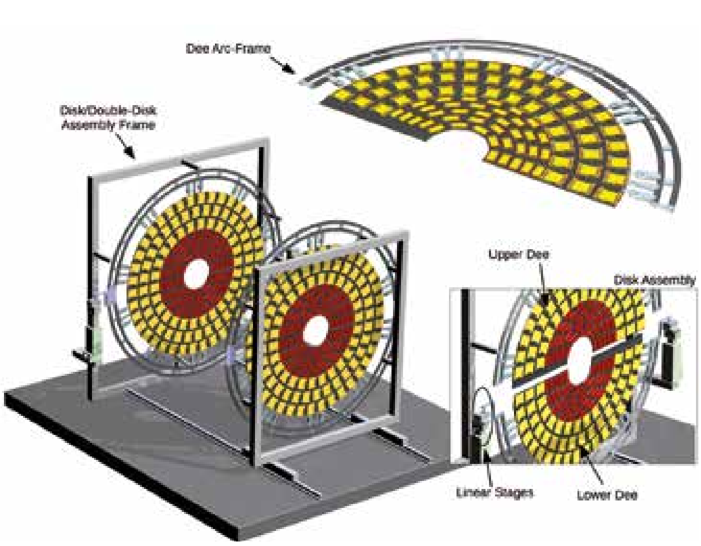

Figure 1

CAD models of the tooling required for disk and double-disk assembly for the CMS end-cap reception tests up to the final end-cap assembly. All Dees have to be equipped with modules and undergo the aforementioned testing. During disk assembly, the upper Dee is held in a static frame, whereas the lower Dee is supported by linear stages that allow a precise relative positioning of both Dees. Two disks are then assembled to a double-disk on the same setup, following the same concept. Figure 1 shows the CAD model of a Dee in its arc-frame, the disk and double-disk integration setup and a detailed view of one step in the disk assembly procedure. After all five double-disks are available, they are aligned with respect to each other and the support bars are mounted to the outer radius to form the final end-cap. All parts for a prototype arc-frame are now available, allowing for first tests and further refinement of the assembly concept.

ATLAS Phase 2 upgrade activities at DESY

The instrumentation activities of the DESY ATLAS group focus mainly on the Phase 2 upgrade of the inner tracker (ITk). In particular, DESY will assemble one of the two end-caps of the strip tracker. In the strip end-caps, the silicon microstrip modules are arranged on low-mass, carbon-based, wedged-shaped local support structures called petals. Each of the end-caps consists of six disks hosting a total of 192 petals, each of them comprising 18 silicon modules (six module types in total). The DESY ATLAS group is involved in a wide variety of activities, ranging from single module building to end-cap assembly.

The DESY ATLAS group reached a significant milestone with the construction and testing of the first electrical modules at both DESY locations, in Zeuthen and in Hamburg. New building techniques are being developed at DESY and adopted by the ITk collaboration, such as the use of UV-curable glues, the realisation of sensor back-side high-voltage (HV) connections using HV tabs and the automation of glue dispensing using gluing robots. Both DESY locations are gearing up for the construction of numerous module types and moving towards qualification as module building sites within the ITk collaboration.

DESY is the leading institution working on the design and test of the petal data concentrator boards, called end of substructure (EoS) boards. Eight variants are required for the whole ITk strip tracker. Three prototype versions have already been designed and tested at DESY. These prototypes are crucial to make progress in the multimodule structure prototyping effort across the whole ITk collaboration.

DESY is also responsible for the design of the local support structures of the end-caps, the petals. The design was optimised over numerous iterations across the ATLAS collaboration and is ready for design review. In addition, six petal support structures were manufactured so far in the DESY workshops using custom-designed assembly tools. Quality control and quality assurance test setups are in place

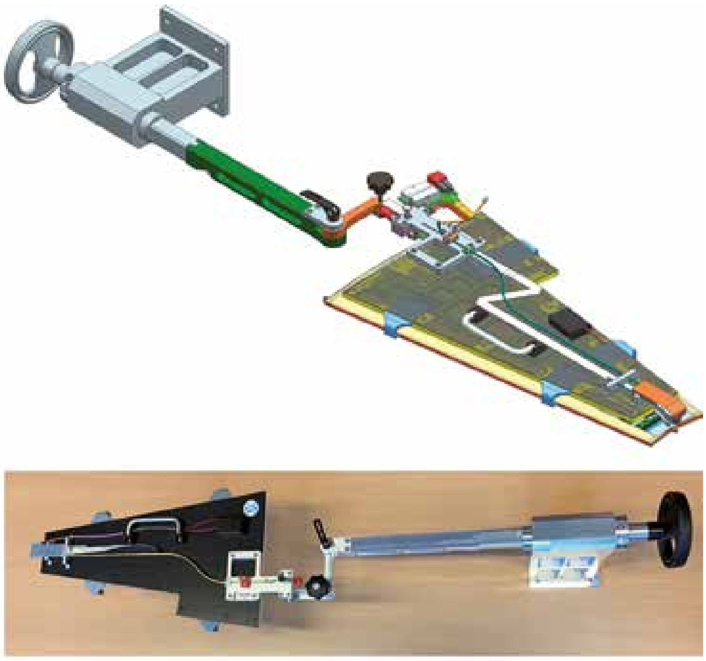

Figure 2

Prototype insertion tool for the placement of petals into the ATLAS end-cap. Top: CAD design of the insertion tool arm. Bottom: Arm of the prototype insertion tool (version 2 as built).

at DESY and were extensively used to test the support structures.

Highly specialised equipment including a robotic gantry system was assembled at the DESY laboratories for the automated, precise loading of the modules onto the structures. DESY will fit approximately 100 petals with silicon modules and the associated electronics (approximately 50% of an end-cap) using this equipment.

The DESY ATLAS group also invented the mechanical tool that will insert the fully loaded petals into the end-cap structures with the required precision. Numerous prototypes of this tool have already been manufactured and successfully tested at various end-cap mock-ups, both in-house and at partner institutions. One of these tools is shown in Fig. 2.

The ATLAS ITk strip detector is approaching the preproduction phase. A significant number of internal CERN reviews, which are mandatory for launching the preproduction phase, were successfully held in 2018. The DESY ATLAS group has a significant representation in the ATLAS ITk management team, with four of its scientists holding ITk activity coordinator positions.

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Versatile SiPM-on-tile technology

Calorimeter concept for electron–positron and hadron colliders

What started 15 years ago with a small proof-of-principle prototype has turned into a success story with applications ranging from a hadron calorimeter concept for a future linear electron–positron collider to the upgrade of the calorimeter end-cap of the CMS detector for the High-Luminosity LHC (HL-LHC). The respective concept for a highly granular calorimeter is based on small scintillator tiles of a few cm^2 that are individually read out by silicon photomultipliers (SiPMs). The year 2018 has seen progress in both areas: a successful test beam campaign with a large prototype close to the geometry planned for the ILD detector at the ILC electron–positron collider as well as big steps towards the engineering design for the CMS end-cap.

Introduction

In 2003, the Minical [1] – a small proof-of-principle prototype of the SiPM-on-tile technology for a highly granular calorimeter – was built and tested as a result of the fruitful CALICE collaboration between DESY and international partners, especially from Russia. Encouraged by the positive experience with the SiPMs, which were a brand-new type of device at that time, the collaboration went on to build a first large prototype based on the SiPM-on-tile technology [2], then called Analogue Hadron Calorimeter (AHCAL). This prototype demonstrated the performance that could be reached with the technology, but it was not scalable to a collider detector because of the huge amounts of electronics surrounding the calorimeter itself. In order to change this, a second-generation technological prototype of the AHCAL was built, with integrated readout electronics. With its about 22 000 readout channels, it corresponds only to roughly half a percent of the calorimeter barrel of the future ILD detector, but is a big step from the Minical, which consisted of about 100 tiles.

The successful development of the SiPM-on-tile technology for calorimeters at a linear electron–positron collider was also noticed elsewhere, and the CMS collaboration adopted the concept for the hadronic part of its calorimeter end-cap upgrade. The environment at the HL-LHC poses completely new challenges in terms of radiation hardness, data rates and cooling, which are being addressed by DESY with contributions to the R&D towards an engineering design.

Second-generation AHCAL prototype

Building the prototype of a hadronic calorimeter is no small endeavour: In order to capture the full hadronic shower, you need a volume of nearly a cubic metre, filled with absorber layers (stainless steel for the AHCAL) interleaved with layers containing the active detection elements. For the construction of the active layers for the AHCAL technological prototype, mass production techniques scalable to a full collider detector were employed.

The construction was a distributed effort shared between German and international partners: The scintillator tiles were moulded in Russia and then sent to Universität Hamburg, where they were individually wrapped in reflective foil in a specially designed machine. In parallel, the boards with the integrated readout electronics were assembled at DESY, with dedicated application-specific integrated circuits (ASICs) that were developed and produced in France and tested at the University of Wuppertal. The SiPMs from a Japanese manufacturer were soldered to these boards, after sample checks had been performed at the University of Heidelberg,

Figure 1

AHCAL prototype installed in the SPS test beam area at CERN. Insert: Detailed view of the SiPM-on-tile design.

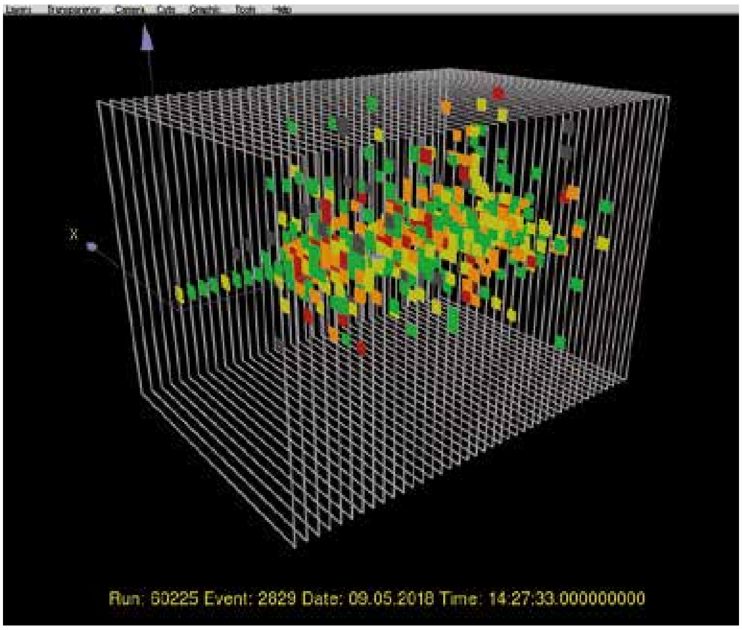

Figure 2

Event display of a shower produced by a hadron in the AHCAL prototype

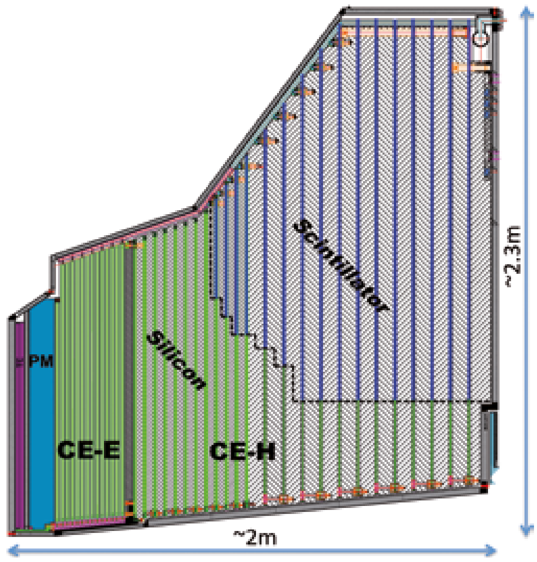

Figure 3

Drawing of the upgrade of the CMS calorimeter end-cap, with the silicon part (green) facing the collision point, and the scintillator part (blue) in the rear

demonstrating the excellent uniformity and low noise features of the latest-generation sensors. The boards and the wrapped tiles were joined in an automated assembly procedure at the University of Mainz. Checks performed after all the construction steps ensured the quality of the final detector. After an intensive production phase spanning from October 2017 to February 2018, the readout boards equipped with tiles arrived back at DESY to be assembled into full layers, commissioned in the DESY test beam and integrated in the absorber stack. The DESY team took care of the coordination of the project and of system aspects such as mechanics, cooling, data acquisition, overall integration and software.

In two 20-feet containers, the AHCAL technological prototype travelled to CERN in April 2018, where it was exposed to muon, electron and hadron beams at the SPS test beam facility (Fig. 1). After a very smooth start-up phase, nearly 100 million events were recorded in two periods of two weeks each (Fig. 2). The prototype worked reliably, using two features especially important for a detector at a linear electron–positron collider: power pulsing, which reduces the power consumption of the readout electronics, and automatic temperature compensation, which adjusts the supply voltage of the SiPMs according to the temperature such that the SiPM signal stays constant. The collected data set is a rich source for testing models of the development of hadronic showers, providing for the first time detailed information on the amplitude and time of the calorimeter hits.

CMS calorimeter end-cap upgrade

The end-cap calorimeter of the CMS detector at the LHC will need to be upgraded for the high-luminosity phase of the LHC, which is due to start in 2027. The expected radiation levels, which make the upgrade necessary, pose stringent requirements on the detector materials. In order to be able to disentangle particles produced in different proton–proton collisions in the same bunch crossing (“pile-up”), the CMS collaboration has chosen the Highly Granular Calorimeter (HGCAL) concept [3]), with silicon pad sensors in the front part and SiPM-on-tile technology in the rear, where radiation levels allow this (Fig. 3). This environment is still challenging, however, not only because of the radiation, but also due to the high data rates and the operation temperature of -30°C.

Based on its experience with the AHCAL prototype, DESY is contributing to the R&D work for the SiPM-on-tile part of the HGCAL by developing an engineering design and board-level electronics. DESY will also set up a demonstrator production chain for SiPM-on-tile boards, adapting the procedures developed for the AHCAL. These efforts profit greatly from the existing cooperation with French and Russian partners. A first step was combined beam tests of the prototype of the silicon part of the HGCAL together with the AHCAL technological prototype, which took place at the CERN SPS. The combined operation was facilitated by the use of EUDAQ [4] by both detectors, a generic data acquisition framework supported by AIDA-2020 [5], a EU project advancing detector technologies beyond their current limits.

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AIDA's 12

New beam telescope at DESY

The DESY II Test Beam Facility hosts a superconducting solenoid for scrutinising large devices under test (DUT) with a radius of up to 75 cm in a magnetic field of up to 1 T. For highly precise reference measurements of particle trajectories within this magnet, DESY is currently developing – in close collaboration with SLAC – a beam telescope with three layers of silicon strip sensors before and three behind the DUT. These have to fit into the limited space between the magnet and the DUT and to provide a resolution of better than 10 µm in the bending direction of the trajectory. A beam test with two of the final 12 sensors was very successful, and the telescope is nearing completion.

Area T24/1 at the DESY II Test Beam Facility [1] hosts a special setup to test large detector prototypes in a strong magnetic field. Its centre piece is a superconducting 1 T solenoid magnet with an inner bore of about 85 cm diameter, in which detector prototypes with a diameter of up to 75 cm can be inserted. The whole setup is mounted on a movable stage and includes a beam and a cosmic trigger, a gas system and a two-phase CO_2 cooling plant. Many groups, e.g. from the Belle II experiment, the ATLAS upgrade efforts, T2K and the LCTPC collaboration, have already made use of this unique infrastructure.

For precision tests of the detector prototypes, the particle trajectories inside the magnet have to be known accurately.

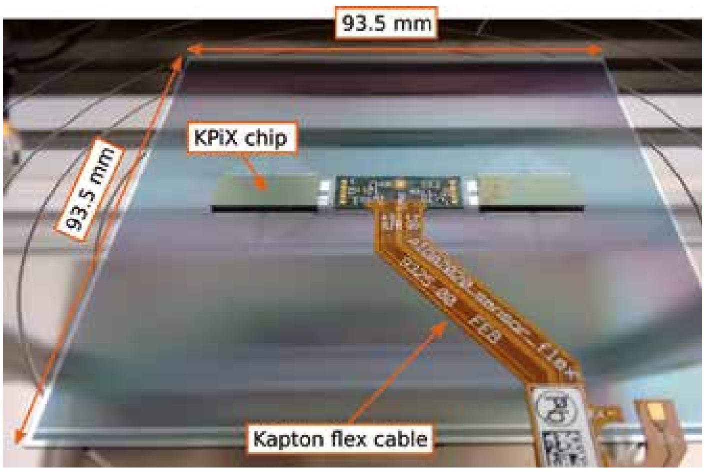

Figure 1

Silicon strip sensor with two bump-bonded KPiX readout chips and attached Kapton flex readout cable

To this end, DESY plans to install a beam telescope as an external precision reference. Due to scattering processes in the wall and coil of the magnet, the beam telescope has to be installed inside the magnet in the narrow gap around the DUT. In addition, it needs to contribute little material itself and provide a point resolution of better than 10 µm in the bending direction of the trajectory in the magnetic field. The design should also enable the use of the telescope outside the magnet, for example to provide large-area tracking coverage in calorimeter tests.

Based on these requirements, a silicon strip telescope is being developed with three layers before and three behind the DUT. Following the tradition of naming beam telescopes at DESY after poisonous flowers, it is called LYCORIS. The telescope is based on hybrid-less silicon strip sensors (Fig. 1), which were originally developed at SLAC for the SiD detector concept. They feature a 25 µm strip pitch with every second strip being read out, resulting in a hit resolution of about 7 µm. The active area measures 9.35 x 9.35 cm^2, and each sensor is read out by two KPiX [2] chips, developed at SLAC as well.

A pitch adapter, which connects all the strips to the application-specific integrated circuits (ASICs), is integrated into the sensor, so that the KPiX is bump-bonded directly to the sensor. The bump-bonding was performed at IZM in Berlin. For the reliable and precise installation of the Kapton flex readout cable, a gluing station was developed similar to one used by the CMS collaboration. The wire bonding of the KPiX to this cable is being done by the DESY service centre electronics in Hamburg.

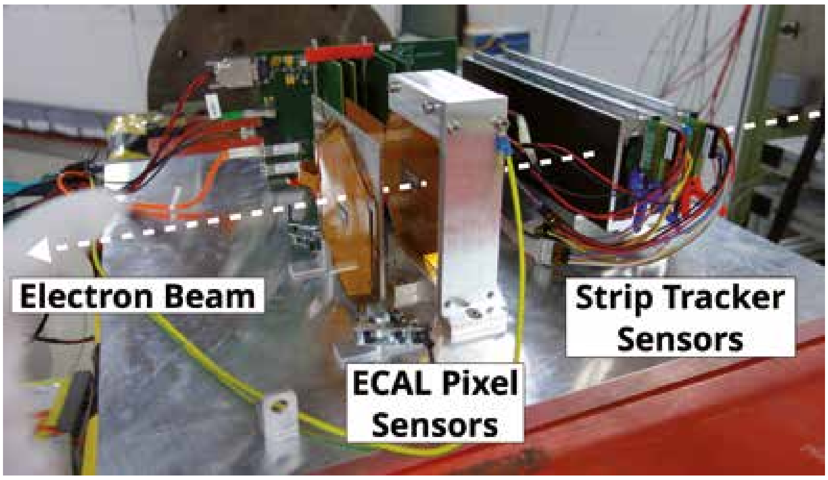

Figure 2

Measurement setup at the DESY II Test Beam Facility, including two silicon strip tracking sensors and two large pixelated calorimeter sensors

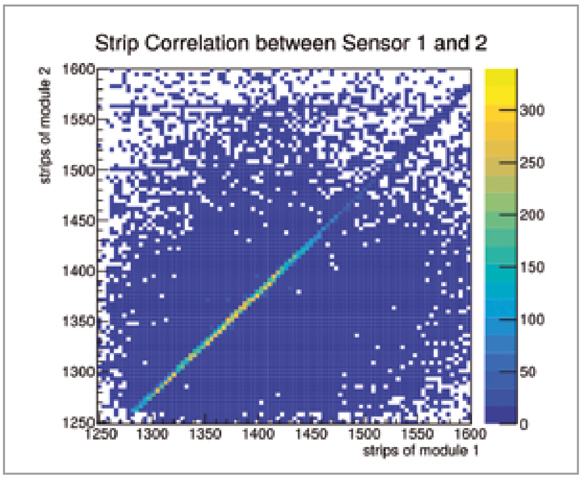

Figure 3

Correlation of measured beam position in sensor 1 and sensor 2 during the beam test

The sensors are housed in two cassettes, which are designed such that each can host three sensitive layers with two sensors per layer, resulting in 12 sensors overall. They are only 3.3 cm thick in order to fit into the narrow space between the DUT and the magnet. The material budget of a fully equipped cassette adds up to only about 1% of the radiation length X_0. The mounting structure for the cassettes is designed such that the cassettes can be moved along the magnetic field axis as well as radially around the DUT. All the mechanical parts are available, and assembly tests have been performed.

In 2018, all the components of the readout system also arrived at DESY to be tested, including a board developed at SLAC, which provides an interface with plugs from the sensors to the outside of the cassette. In addition, a newly developed data acquisition (DAQ) board offering optimised interfaces is being thoroughly tested in comparison to a previous version. Finally, the AIDA trigger logic unit (TLU) is available, which is needed to synchronise the readout of the telescope and the DUT and which provides a common clock for all the devices. Software-wise, the system has been successfully integrated into the EUDAQ2 central data acquisition, developed within the AIDA-2020 project.

The system has undergone several tests in the lab as well as at the DESY II Test Beam Facility. The most recent beam test used two tracking strip sensors in parallel, together with two pixelated calorimeter sensors developed for the electromagnetic calorimeter of SiD, which are also read out with the KPiX chip. The setup is shown in Fig. 2. A total of 600 000 events were recorded in different running modes and settings.

Based on the collected data, the reconstruction software is being developed and improved. In Fig. 3, the measured beam position on one sensor is plotted against the position on the other sensor, indicating a clear correlation. The small offset of about 20 strips (~1 mm) is due to slightly different positions of the sensors with respect to the electron beam.

The preparation of all 12 sensors for the final telescope is ongoing. In April 2019, a beam test is planned with all six equipped layers inside the 1 T solenoid, together with a EUDET-type pixel telescope as reference. In parallel, the DAQ and reconstruction software are being improved, and the user documentation is being prepared. All signs point towards a successful launch of the LYCORIS telescope as a user infrastructure in 2019.

This project is pursued in close collaboration by the DESY ATLAS and FLC groups and SLAC. It is strongly supported by DESY's FE and ZE groups as well as by the European Horizon 2020 project AIDA-2020, GA no. 654168.

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Material tests for positron sources

Target tests for a high-luminosity positron source for future high-energy colliders

The positron source is a challenging part for all future high-energy linear collider designs, for the International Linear Collider (ILC) as well as for the Compact Linear Collider (CLIC). The demands for high luminosity cause a high load on the target materials. Target material tests are therefore mandatory. In collaboration with the universities of Hamburg and Mainz and the Helmholtz-Zentrum Geesthacht (HZG), the DESY FL group in Zeuthen performed such tests at the Mainz Microtron MAMI. The target materials were analysed with both laser scanning methods and high-energy X-ray diffraction using the world-class infrastructure available at DESY in Hamburg.

The production of positrons for a high-energy linear electron–positron collider is a challenge. At the nominal luminosity of the ILC, about 1.3 x 10^{14} positrons per second are required at the collision point in order to fulfil the physics demands. This number of generated positrons per pulse is three orders of magnitude higher than that of the former SLAC Linear Collider (SLC). All concepts of positron production are based on the secondary production of positrons in a target interacting with a high-intensity electron or photon beam.

The key challenge is to achieve a manageable thermal and radiation load on the target and the other source systems. In particular, the load on the target requires a careful selection of material and design as well as extensive studies to demonstrate the feasibility and reliability of the chosen setup.

The most mature positron source concept for future linear electron–positron colliders to date is based on undulator radiation [1, 2]: A high-energy electron beam travels through a ~200 m long helical undulator, generating circularly polarised photons of about 10 MeV, which then interact in a thin target of about 0.4 radiation length. The resulting positrons are then extracted from the beam behind the target, refocused and accelerated. An advantage of the undulator-based source is that because of the photon polarisation, the generated positrons are longitudinally polarised. The concept of this positron source was first proposed by Alexander A. Mikhailichenko (Fig. 1), a brilliant and well-known accelerator physicist, who died suddenly in 2018. He was a long-standing collaborator of DESY with numerous common publications, e.g. [3]. The fundamental concept of the undulator-based positron source was demonstrated successfully in the E166 experiment at SLAC [4]. The undulator source was chosen as the baseline source for the ILC and as an option for CLIC.

If the positron target is manufactured as a rotation wheel, it is exposed to about 3 x 10^6 bursts during a normal year of operation. The high cyclic load at elevated temperatures and radiation levels fatigues the target material and might lead to failure of the target.

Figure 1

Alexander A. Mikhailichenko at the prototype experiment for the production of polarised positrons through inductor radiation at E166 at SLAC

Figure 2

Magnetic system for focusing the beam at the MAMI accelerator in Mainz

To study this complex material response, the DESY FLC group performed experimental tests to understand the behaviour of the proposed target materials and study their limitations. Tests were carried out with the electron beam at the MAMI accelerator at the University of Mainz, where it is possible to generate a similar target load on the titanium alloy target as expected for the ILC positron source (Fig. 2). Several such tests at different electron beam energies and with different material thicknesses and beam pulse parameters were performed, accompanied by comprehensive FLUKA and GEANT4 simulations studies (Fig. 3).

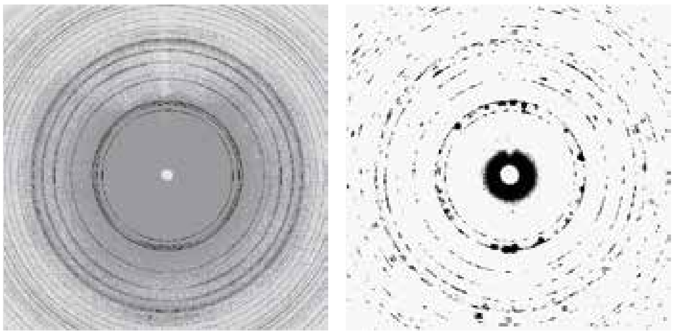

Figure 4

Left: XRD detector picture of non-irradiated area (x = 0 mm).

Right: XRD detector picture of irradiated area (x = 6 mm).

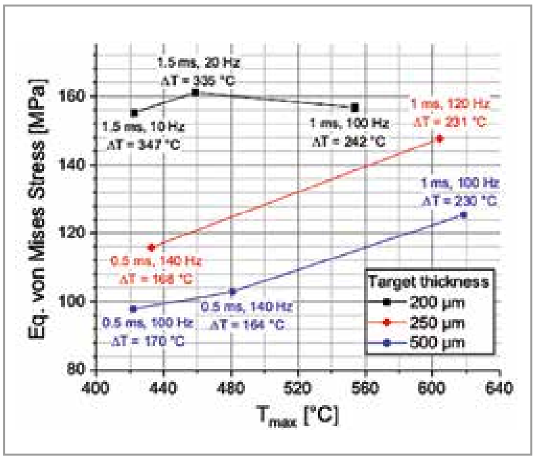

Figure 3

Simulated von Mises stress versus peak temperature at the end of the pulse for different target thicknesses

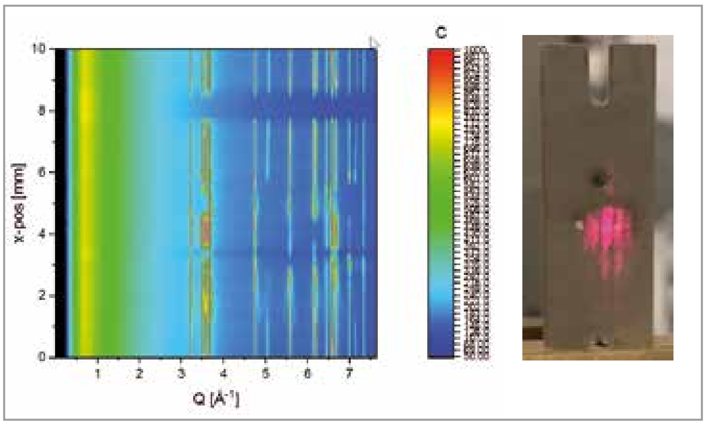

Figure 5

Left: Azimuthal integrated intensity of the observed Bragg reflections for the line scan across the irradiated area. Right: Irradiated TiAlV sample (200 µm thick) with laser alignment.

To simulate a load corresponding to that expected at the ILC positron target or exit windows to the photon beam dump, the MAMI electron injector was used at two energies of 14 MeV and 3.5 MeV. The beam was focused onto the target with a spot size of $\sigma \sim$ 0.2 mm and below; various load amplitudes were created using different pulse lengths. With a repetition rate of 100 Hz, a number of cycles corresponding to about two years of ILC running time was reached.

These irradiated material samples were analysed at DESY in collaboration with Universität Hamburg with a scanning electron microscope and a laser scanning microscope [5, 6]. Only for very high thermal load exceeding that at ILC did we observe changes in the surface (Fig. 4 and 5). From the observed temperature change, a phase transition from α- to β-Ti alloy is most likely happening. The target material was investigated using high-energy X-ray diffraction (HE-XRD) performed at the PETRA III beamline HEMS in collaboration with HZG. Clear indications were found that the target material also changed in the bulk. We observed not only a shift in the ratio of the α and β phases of the TiAl alloy, but also a coarsening of the grain sizes in the strongly irradiated areas.

Although the quantitative evaluation of the structural changes in the target samples is still ongoing, the effect of the electron beam on the material structure and properties was clearly demonstrated. At least, the MAMI tests have proven that no shock waves are to be expected and that the positron target will survive under ILC conditions.

The results are promising, and the tests will be continued and intensified in order to optimise the chosen materials for the ILC conditions. Common supervision of Hamburg students by the research centre and university staff has already started. Such a successful endeavour exemplifies the privileged position of Hamburg research students, who are offered access to sophisticated materials analysis facilities such as PETRA III in connection with state-of-the-art high-energy particle physics experiments.

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E-JADE

Strengthening historic ties with Japan

Close to 300 trips to Japan, 31 deliverable reports and many other publications as well as lots of samplings of Japanese cuisine – those were the results of the Europe–Japan Accelerator Development Exchange Programme (E-JADE) [1], a Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) action that was funded by the EU under the Framework Programme Horizon 2020 from 2015 to 2018 with about 1.3 million euros.

E-JADE – aptly named to bring back memories of the Japanese–German–English JADE experiment running at DESY's PETRA electron–positron collider in the late 1970s and early 1980s – focused on the urgent need for exchange of ideas on R&D and implementation of future accelerators for particle physics. With 17 beneficiaries from eight European countries – including DESY as a driving force – as well as five Japanese institutions as receiving partners, E-JADE supported travels of researchers for a whole slew of activities in three scientific work packages: i) LHC consolidation, upgrades and R&D for future hadron facilities; ii) nanometre-scale beam handling at the Accelerator Test Facility (ATF) at KEK; iii) linear-collider-targeted R&D. In particular, E-JADE gave young researchers a unique opportunity to spend time in Japan and experience intense collaboration with Japanese scientists (Fig. 1).

As one of the leading ILC institutions worldwide, DESY was predominantly active in the linear collider work package. Our efforts were directed for example towards physics and detector optimisation studies, the design of the interaction region and background studies. The main focus, however, was on site-specific studies for the realisation of the ILC in the Kitakami mountain region. Questions of logistics and transportation, infrastructure, integration, shielding and assembly were raised among E-JADE partners from many institutions in a now firmly established series of mini-workshops on "ILC Infrastructure and Civil facilities and Services for Physics and Detectors" [2].

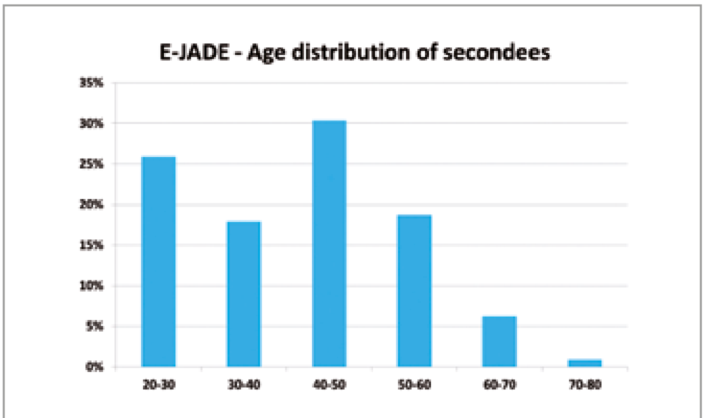

Figure 1

Age distribution of E-JADE secondees

In connection with these workshops, European researchers had ample opportunity of making new valuable contacts: to scientists from Japanese partners, to local industries and to local administrators, politicians and chamber of commerce representatives. The experience included visits to large underground installations such as water power plants, test facilities for the disposal of nuclear waste or power stations – all large installations providing valuable experience in earthquake-endangered Japan.

All in all, E-JADE was a tremendous success: socially, politically and scientifically. Many new contacts were made, new collaborations were initiated, and the mutual understanding between young and old researchers from East and West was increased. Most importantly, the basis for large international projects – be it the HL-LHC or the ILC – was significantly strengthened.

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JENNIFER

Successful EU project goes into second round

The Japan and Europe Network for Neutrino and Intensity Frontier Experimental Research (JENNIFER) is a Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) project funded by the EU. The aim of the project partners is to jointly investigate the quark and lepton flavour structure of the Standard Model of particle physics through participation in the Belle II and the T2K experiments, both located in Japan. During the initial four-year funding period, the German Belle II members of the consortium received funding for a total sojourn time in Japan of 100 person months. In summer 2018, the EU recognised the big success of the project by approving JENNIFER2, a follow-up project of the somewhat enlarged consortium.
The seamless transition between the two projects will take place in April 2019.

Scope and organisation of the project

The JENNIFER consortium comprises 13 academic and one industrial (CAEN) European organisations as well as two Japanese institutions, the KEK laboratory and the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo (Fig. 1). The members of the consortium are involved in the upgraded Belle II experiment at KEK in Tsukuba and in the Tokai to Kamioka (T2K) neutrino oscillation experiment, which is working towards the upgraded HyperK experiment in the second half of the next decade [1]. For the participating German Belle II institutions (Univ. Bonn, DESY, Univ. Gießen, Univ. Heidelberg, MPP Munich), DESY acts as the single German beneficiary.

Figure 1

Member institutions of the JENNIFER consortium, which is coordinated by INFN

The goal of the two experiments is to significantly enhance our understanding of the flavour and CP structure of the universe by exploring unchartered territory both in the lepton sector (neutrino oscillations and tau decays) and the quark sector (bottom and charm). Besides its scientific objectives, JENNIFER aims in particular at fostering synergies between the different communities: flavour and neutrino physicists, scientists from Europe and Japan as well as academic and industrial partners. To this end, several general consortium meetings – sometimes combined with dedicated academia–industry and outreach events – were held both in Europe and in Japan. Another important element was a very well received common Belle II and T2K summer school for young students organised by the University of Gießen in 2016.

Scientific contributions

The German groups used the JENNIFER funds to contribute to two out of a total of five work packages. The objectives of the first work package are to develop, implement and optimise the software tools and algorithms needed for performing physics analysis at Belle II. Secondments were for example used to contribute to the Belle II theory interface platform (B2TiP), which recently led to the publication of the *Belle II Physics Book* [2].

The second work package is concerned with several new detector systems employed in Belle II. The German groups were predominantly involved in the installation and commissioning of the novel two-layer pixel vertex detector as part of the new Belle II vertex detector. A very important Belle II milestone was achieved in November 2018 with the successful installation of this complex device in Belle II.

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First results from Belle II

The Standard Model puzzle and the Belle II experiment

Belle II is a new experiment at the SuperKEKB collider at KEK in Tsukuba, Japan, aiming to search for physics beyond the Standard Model (SM) through direct observation of non-SM particles or indirectly by studying *B*-meson and τ-lepton decays. From April to July of 2018, Belle II completed the commissioning Phase II, in which approximately 500 pb^{-1} of electron–positron collision data were recorded. This data set allowed the Belle II collaboration to rediscover many known SM processes and pursue searches for new physics. The DESY Belle II group led the rediscovery of the $e^+e^- \to \tau^+\tau^-$ process and the mass measurement of the τ lepton and played a key role in searches for dark-matter candidates, including processes that violate lepton flavour conservation.

The Belle II experiment

Belle II is a major upgrade of the prior Belle detector at the SuperKEKB accelerator, an energy-asymmetric electron–positron collider (7 and 4 GeV, respectively) designed to reach a 50 nm beam width. This will allow it to achieve an unprecedented instantaneous luminosity of 8.0 x 10^{35} $cm^{-2}s^{-1}$. Over its lifetime, the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than the Belle experiment.

The Belle II detector was rolled into SuperKEKB in April 2017. Until June 2018, during the commissioning phase called Phase II, it recorded approximately 500 pb^{-1} of electron–positron collision data using all detector subsystems excluding the full vertex detector (VXD). Producing measurements from these data requires a thorough understanding and control of the hardware and software performances. The DESY Belle II group was strongly involved – partly in a leading role – in such studies, enabling it to deliver the first results in the fields of dark-sector and τ physics.

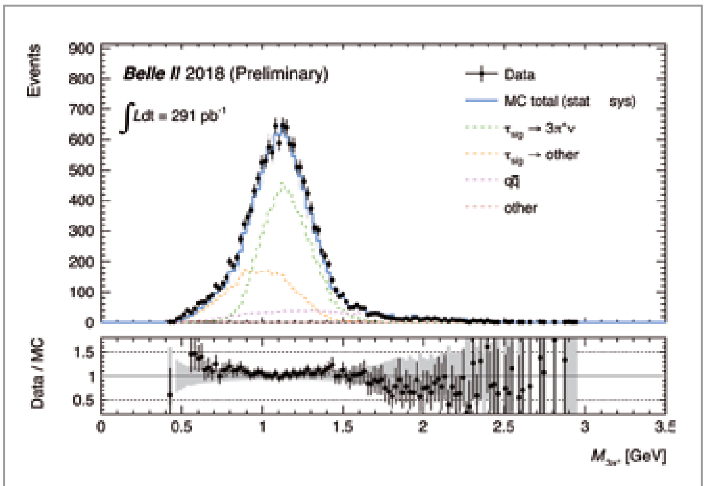

Figure 1

Invariant-mass distribution $M_{3\pi}$ of the three pions coming from $\tau \to 3\pi\nu$ candidates reconstructed in Phase II data

Rediscovery of τ leptons

The Belle II experiment records electron–positron collisions at energies of the $\Upsilon(nS)$ resonance, which decay into *B*-meson pairs. For this reason, the experiment is referred to as a *B*-factory. However, as the cross section for $e^+e^- \to \tau^+\tau^-$ at those energies is of the same order, the experiment is also a τ-factory, providing a unique environment to study τ physics with high precision.

In the $e^+e^- \to \tau^+\tau^-$ centre-of-mass system, both τ leptons are boosted in opposite directions, and their decay products populate two distinct hemispheres of space. In the τ rediscovery study, one hemisphere was expected to contain the products of the three-prong decay, $\tau \to 3\pi\nu$, the other the product of the one-prong decay, i.e. either $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$ or $\tau \to \pi\nu$. Selections were applied to suppress the background originating from extraneous processes, mostly composed of $e^+e^- \to q\bar{q}$ (with $q = u, d, s, c$) events.

The DESY Belle II group demonstrated a clear evidence for the $e^+e^- \to \tau^+\tau^-$ process in the Phase II data (Fig. 1). After the trigger selections, there was a good agreement between the data and the Monte Carlo simulation for the $\tau \to 3\pi\nu$ invariant-mass ($M_{3\pi}$) distribution.

τ-lepton mass measurement

The τ mass cannot be measured directly, since the τ flight direction is unknown. However, a "pseudomass" can be derived by approximating the flight direction of the 3π system to be the τ one. The pseudomass distribution is expected to exhibit a sharp threshold behaviour in the region close to the nominal value of the τ mass. Using this technique, first developed within the ARGUS collaboration at DESY [1], the DESY Belle II group contributed to the τ-lepton mass measurement. Figure 2 shows the pseudomass distribution fitted with an empirical edge probability density function. The result m_τ = 1776.4 ± 4.8 (stat) MeV is in good agreement with previous measurements.

We foresee that Belle II will provide the best τ pseudomass measurement once a larger data set with fully operational VXD will be available during the Phase III data taking. The DESY group aims to exploit the gradually increasing luminosity of Belle II to perform τ precision measurements and lead the searches for lepton flavour violating (LFV) τ decays.

Towards new physics searches

One of the exciting riddles of modern high-energy physics is the existence of dark matter (DM), which was proven through cosmology observations. However, DM is neither described by the SM nor has it been discovered experimentally. Some minimal DM theories ($L_\mu - L_\tau$ theories [2]) suggest the presence of a heavy mediator Z' that couples with SM and DM particles.

At Belle II, this particle can be directly produced in $e^+e^- \to \mu\mu Z'$. Since Z' is mostly decaying to invisible final states, it can be found by analysing kinematic distributions of dimuon events. The sensitivity of Belle II to the coupling g' of the Z' with the SM particles reached with the current data set is shown in Fig. 3.

In addition to testing $L_\mu - L_\tau$ theories, the DESY Belle II group initiated searches for LFV DM. Analogously to $L_\mu - L_\tau$ theory, the LFV mediator X is expected to be produced in $e^+e^- \to e^-\mu^+X$ and to decay invisibly. This search will allow us to exclude regions of LFV phenomenological phase space complementary to existing constraints from e.g. $\mu \to 3e$ and $\mu \to e\gamma$ (Fig. 4).

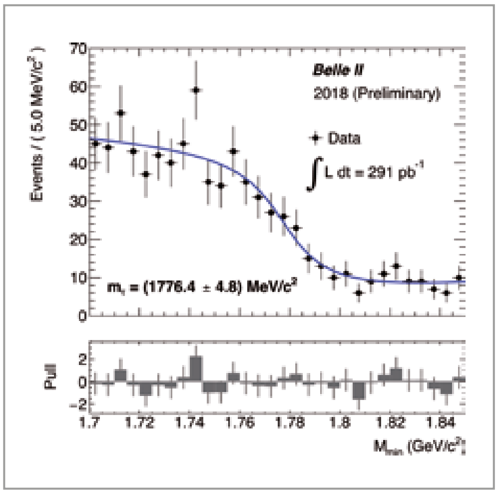

Figure 2

Distribution of the pseudomass M_{min} of $\tau \to 3\pi\nu$ candidates reconstructed in Phase II data. The blue line is the result of a fit with an edge function where one of the parameters is the estimator of the τ-lepton mass.

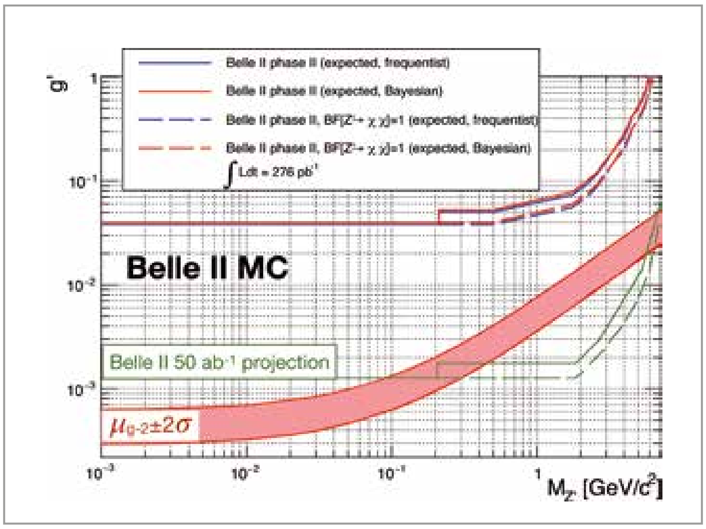

Figure 3

Expected frequentist-based (blue line) and Bayesian-based (red line) 90% CL upper limits to γ'. The solid line assumes the $L_\mu - L_\tau$ predicted rates for $Z' \to$ invisible, while the dashed line assumes the branching fraction BF[$Z' \to$ invisible] = 1. The red band shows the region that could explain the anomalous muon magnetic moment $(g_\mu - 2) \pm 2\sigma$.

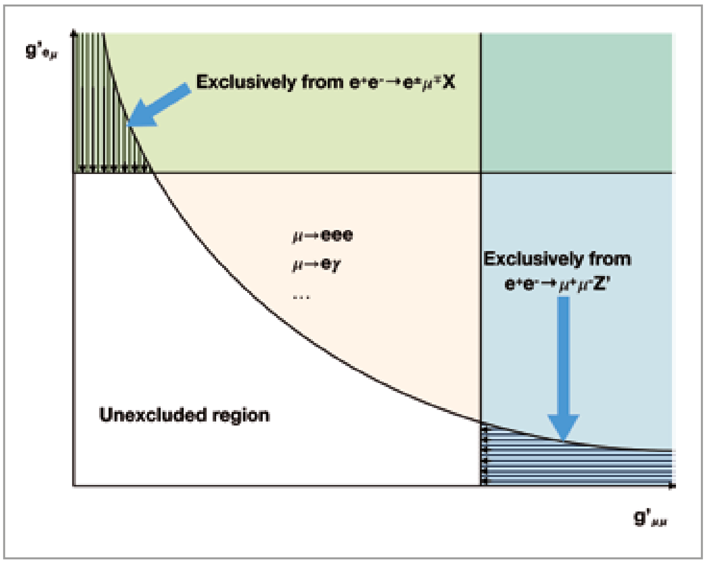

Figure 4

Sketch of the LFV DM phase space with potential exclusion regions from various processes

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Dark matter at the intensity frontier

Searches for dark matter and axion-like particles at Belle II

The laws of gravity are well-tested fundamental laws of physics. In the last decades, however, increasing evidence for deviations from these laws has arisen in various astrophysical observables at the largest scales. A new type of matter, called dark matter, could likely explain these discrepancies. A Helmholtz Young Investigator Group (YIG) at DESY is using data from the intensity frontier experiment Belle II in Japan to search for light dark matter and axion-like particles in previously unreachable regions.

The Belle II experiment is a second-generation *B*-factory currently preparing for first physics runs at the high-intensity electron–positron collider SuperKEKB at KEK in Japan. SuperKEKB will operate at a centre-of-mass energy of about 10.58 GeV with an extremely high instantaneous luminosity. Until 2027, Belle II will ultimately accumulate a data set that is more than 50 times larger than that of the predecessor experiment Belle.

Light dark matter may be produced in pairs through decays of dark photons produced in electron–positron collisions. The visible final state consists of a single highly energetic photon only. The precise knowledge of the initial state at electron–positron colliders and the hermetic Belle II particle detector will allow us to search for very small dark matter couplings through missing-momentum signatures. The YIG focuses on light dark matter particles that are out of reach of both LHC and direct detection experiments searching for elastic dark matter–nucleon scattering.

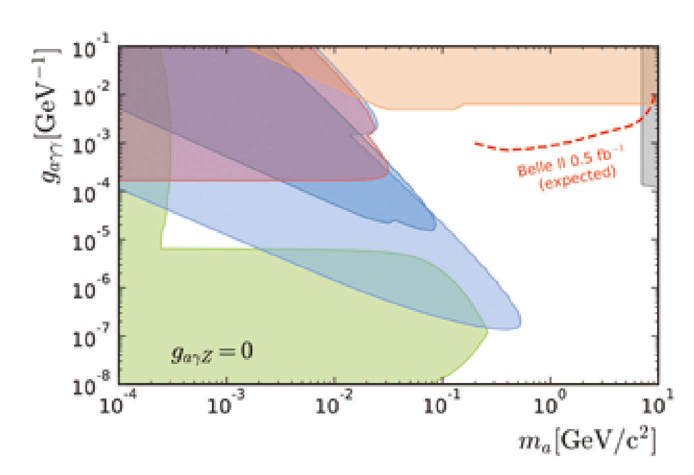

Figure 1

Expected Belle II sensitivity (90% CL) for the 2018 data set in the three-photon final state compared to existing constraints for ALPs with photon coupling

Another set of particles that could mediate interactions between dark matter and ordinary matter are axion-like particles (ALPs), a generalisation of hypothetical particles originally postulated to solve the strong CP problem in quantum chromodynamics (QCD). The YIG is searching for ALPs in two different final states with either one or three photons. These searches will be sensitive to ALP masses up to 10 GeV and to small couplings to photons in a previously unexplored region of ALP parameter space. The YIG will exploit very loose trigger conditions for the calibration data set acquired by Belle II in 2018 (Fig. 1) to perform first searches.

The YIG is also leading the development of calorimeter reconstruction software with a strong focus on machine learning to improve calibration, particle identification and cluster reconstruction.

Helmholtz Young Investigator Group

"Searches for Dark Matter and Axion-Like Particles at Belle II"

HELMHOLTZ ASSOCIATION

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Exploring flavour at LHC and SuperKEKB

Bringing together the Higgs boson and the *B* meson

Six different types of quarks are known to exist, distinguished by what is called their flavour. The quarks differ in their masses, which introduces the possibility for a quark to transition into a quark of a different generation. The Standard Model of particle physics offers no explanation for the large range of masses between the different quarks, nor for the amount of their mixing. Often referred to as the question of flavour, this is one of the interesting puzzles in particle physics. A new group established in the context of the W2/W3 professorship programme at Universität Hamburg and DESY will use data from the ATLAS and Belle II experiments to study the masses of the quarks and their mixing.

The Higgs boson is intimately related to the question of flavour: The mass hierarchy between the different quarks and leptons in the Standard Model has its origin in the hierarchy of their couplings to the Higgs boson. The Standard Model predicts that the Higgs coupling to each quark is proportional to the mass of that quark.

The shape of the transverse-momentum distribution of Higgs bosons produced at the LHC carries information about the couplings between the Higgs boson and the quarks, including the *b* and *c* quarks. This distribution, among others, has been measured in Higgs boson decays to two photons and to four leptons (see page 27).

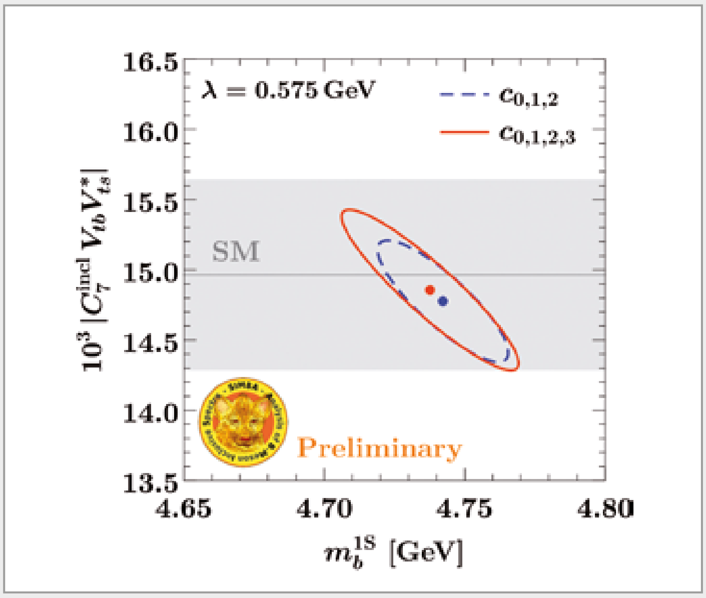

Figure 1

The *b*-quark mass and a parameter determining the total $B \to X_s\gamma$ branching ratio, which is sensitive to physics beyond the Standard Model, determined from a combined fit to measurements of the BABAR and Belle experiments. Only experimental uncertainties are included.

The *b*-quark mass m_b and the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$, which determine the probability for the transition of a *b* quark into a lighter *u* quark or *c* quark, can be determined from inclusive *B*-meson decays at the Belle II experiment at the SuperKEKB collider in Japan. By combining differential distributions measured in inclusive $B \to X_u l\nu$ and $B \to X_s\gamma$ decays in a global fit, it is possible to determine $|V_{ub}|$, m_b and the total branching fraction of $B \to X_s\gamma$ decays, while at the same time allowing non-perturbative effects and theoretical uncertainties to be treated more robustly than previously. As a first step, such a fit has been developed for $B \to X_s\gamma$ decays [1]. Figure 1 shows the result of a fit to photon energy spectra in inclusive $B \to X_s\gamma$ decays measured by the BABAR and Belle experiments, which were operated at the PEP-II and KEKB colliders at SLAC and KEK, respectively.

The much larger data sets that will be collected by the ATLAS and Belle II experiments over the coming years and a close collaboration with the DESY theory group will enable us to improve the precision and robustness of the measured Yukawa couplings, m_b and $|V_{ub}|$, allowing for stringent tests of the Standard Model in the flavour sector.

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Any light dark matter searches

ALPS II, IAXO and MADMAX move ahead

At DESY in Hamburg, a strategic approach to search for the axion, for axion-like particles (ALPs) and for other weakly interacting slim particles (WISPs) is taking shape. In 2018, major progress was made in the construction of the ALPS II experiment and in preparations for the planned IAXO and MADMAX experiments. First ALPS II data might be available in early 2021, which could mark the start of a decade-long programme to search for fundamental particles beyond the Standard Model of particle physics. This strategy is supported by preparations for the update process of the European Strategy for Particle Physics.

Three experimental approaches

The existence of axions and other WISPs is strongly motivated by theory and cosmology to explain both open questions in the Standard Model and the evolution and structure of the universe. If detected, such particles would give insight into particle physics at energies at least four orders of magnitude beyond the reach of the LHC. Unfortunately, the interaction of these WISPs is much too weak to be spotted at accelerator-based experiments. Dedicated experiments at DESY in Hamburg will provide unique detection opportunities.

WISPs can be searched for in pure laboratory experiments, where one strives to generate and detect such particles independently of any astrophysical or cosmological assumptions, in so-called haloscopes, which are sensitive to the dark matter explaining the kinematics of our Milky Way, and in helioscopes, which are looking for particles emitted by the sun.

The ALPS II experiment at DESY is an experimental approach of the first kind. ALPs and other WISPs might be generated by shining light into a strong magnetic field. The reverse process – WISP conversion into light in a magnetic field behind a light-tight barrier – would provide a clear signature for the discovery of a new elementary particle. ALPS II is driven by an international collaboration uniting expertise in accelerator dipole magnets, long baseline optical resonators similar to the technologies used in gravitational-wave interferometers and extremely low light flux detection.

Figure 1

Left: Dismantling of the HERA accelerator in the ALPS II area. Right: The empty tunnel segment in autumn 2018.

Details of ALPS II have been presented in previous editions of this annual report. A particular highlight of 2018 was the beginning of work for the ALPS II setup in a straight section of the tunnel that formerly hosted DESY's HERA collider. Figure 1 shows the start of dismantling of the HERA electron and proton accelerators in this area and the cleared tunnel in autumn 2018. The other activities proceeded as planned as well, resulting for example in 15 straightened dipole magnets of the HERA proton accelerator ready for installation. Major optics milestones were reached, and detector studies resumed with a new He^3/He^4 dilution refrigerator. ALPS II in the HERA tunnel could be ready for first light in autumn 2020.

The work for ALPS II is complemented by a dedicated project for renewing the cryogenic 4 K helium supply and the infrastructure in the HERA hall North. This is also related to projects proposed in the context of the "Quantum Universe" cluster of excellence of Universität Hamburg and the planned dark-matter searches with MADMAX.

The international Magnetized Disc and Mirror Axion (MADMAX) collaboration is led by the Max Planck Institute for Physics (MPP) in Munich. The experiment will be located in the iron yoke of the former HERA experiment H1 in the HERA hall North. It will be based on a new technological approach in order to search for axionic dark matter in a previously not

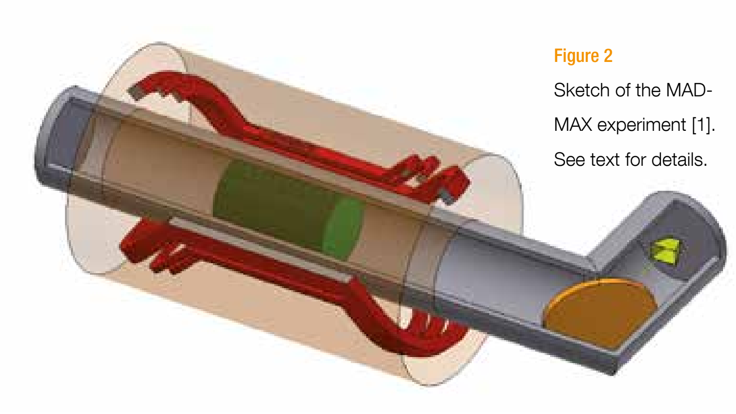

Figure 2
Sketch of the MADMAX experiment [1]. See text for details.

accessible parameter region [1]. A corresponding sketch is shown in Fig. 2. A tuneable resonating structure of up to 80 dielectric discs will be embedded in a newly developed dipole magnet that provides field strengths close to 10 T with an aperture of 1 m^2 on a length of 2 m. Dark-matter axions entering the magnetic volume might convert to microwave photons with a probability enhanced by about four orders of magnitude by the dielectric disc “booster”. A 45° mirror will guide and focus such photons onto a detector system capable of measuring powers of 10^{-22} W.

The first phase of the MADMAX R&D programme concluded in 2018 with conceptual designs for the large dipole magnet. A dedicated review by an experts committee took place in November 2018. The committee attested the principle feasibility and encouraged the elaboration of a more detailed conceptual design report. Significant progress was also achieved in the understanding of the booster and detection methods. The present schedule foresees the development of a prototype booster and detector system by 2022. The final magnet could be installed in the HERA hall North by 2026.

The International Axion Observatory (IAXO) is a helioscope that will search for WISPs emitted by the sun and, at a later stage, also provide a large-volume magnet for dark-matter searches complementary to MADMAX. The physics case for IAXO also comprises a search for eV-mass axions not accessible with other techniques. Axions emitted by the sun would enter the toroidal magnet and convert to X-ray photons, which will be focused onto dedicated detectors by optics similar to the ones used in X-ray satellites. IAXO builds on the experience with the CAST experiment at CERN. A concept for IAXO was worked out already some time ago [2].

However, the large costs of the experiment require it to be embedded in the future European Strategy for Particle Physics before the start of funding discussions (see below). Meanwhile, the collaboration is going for a prototype called BabyIAXO [3] (Fig. 3). It will combine the development of magnet coils for the large IAXO toroid and tests of the X-ray focusing optics with advanced low-flux detectors for IAXO. The concept was presented to the DESY Physics Research Committee (PRC) in autumn 2018, and a dedicated review will take place in spring 2019. A crucial component will be the magnet design as being worked out by CERN. BabyIAXO will use the support developed for the mid-sized telescopes of the Cherenkov Telescope Array (CTA) and be located at DESY in the HERA hall South or East. It could be ready for data taking in 2024.

Axion strategy

In preparation for inputs to the update process of the European Strategy for Particle Physics, axions and WISPs have become very visible at the national and European level. The IAXO collaboration has submitted a summary on the scientific case, status and plans for IAXO and BabyIAXO [3]. An international editorial team has worked out “A European Strategy Towards Finding Axions and Other WISPs” [4], which is supported by more than 140 physicists. Figure 4 shows the parameter space that could potentially be probed by future experiments up to about 2035.

Figure 3
BabyIAXO concept as described in the text

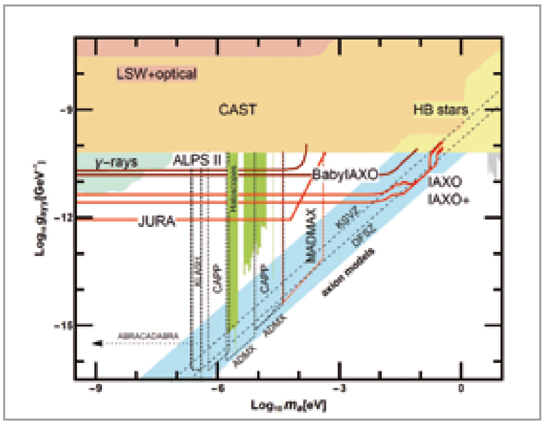

Figure 4
Landscape of axion and ALP searches [4]. Shaded regions show present-day exclusions and the QCD axion band (blue). The red lines show parameter regions to be probed by possible future larger-scale experiments located in Europe. JURA denotes a possible successor of ALPS II based on CERN accelerator dipole magnets.

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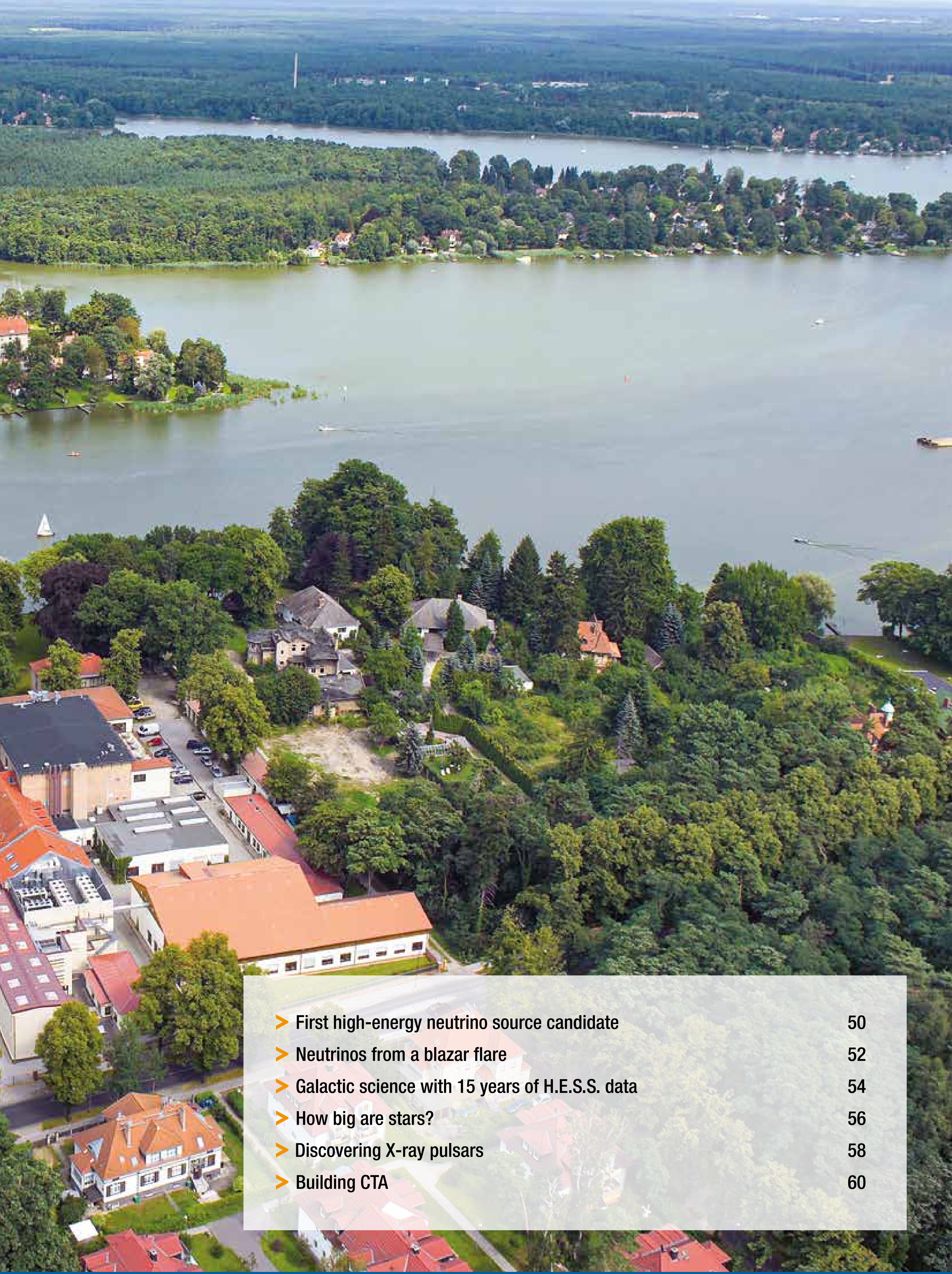
Astroparticle physics

Astroparticle physics at DESY spans a broad range of topics, from theoretical studies to a plethora of experimental activities. Of these, the Cherenkov Telescope Array (CTA), the next-generation gamma-ray observatory, is currently the largest endeavour. The DESY CTA group is instrumental in numerous crucial aspects of the experiment, from software to telescope development and analysis of the physics case (p. 60).

DESY has extensive experience in gamma-ray astronomy. The research centre is an important contributor to the H.E.S.S. telescope system in Namibia, the first of the second generation of experiments in this field. In 2018, to celebrate its 15-year anniversary, the H.E.S.S. collaboration published its largest set of science results yet (p. 54). DESY is also involved in the VERITAS gamma-ray telescope in Arizona, USA, which presented a novel method for determining the size of stars (p. 56). Moreover, DESY scientists led a search for X-ray pulsars (p. 58) using data from the Chandra space observatory.

The second major field of experimental activities in astroparticle physics is neutrino physics. DESY is strongly involved in the IceCube neutrino telescope at the South Pole, which continues to deliver high-quality data and observed the first extragalactic high-energy neutrino source candidate (p. 50). This experimental activity is supported by theoretical work to model the activity of blazars, which can accelerate neutrinos (p. 52).



First high-energy neutrino source candidate

Gamma-ray blazar TXS 0506+056

After the discovery of a diffuse high-energy neutrino flux in 2013 by the IceCube neutrino observatory in Antarctica, the most pressing question in the young field of neutrino astronomy is where those neutrinos are being produced. In 2017, IceCube detected a 290 TeV neutrino that points back to the direction of the blazar TXS 0506+056, which was found in a flaring state in all wavelengths ranging from radio waves to TeV gamma rays. The multimessenger groups at DESY found that the chance coincidence of such a correlation is only 10^{-3}. Motivated by this finding, an archival search for TeV neutrino emission from TXS 0506+056 revealed an additional excess of neutrinos in 2014/15 lasting for 160 days with a statistical significance of 3.5 σ. These findings indicate that blazars are capable of accelerating cosmic rays to energies larger than PeV.

The IceCube real-time programme

The IceCube neutrino observatory is located at the geographic South Pole. 5160 digital optical modules (DOMs) instrument a cubic kilometre of clear glacial ice to detect the Cherenkov light of secondary charged particles produced in neutrino interactions in the ice close to or in the detector. In 2013, IceCube detected for the first time a diffuse flux of high-energy neutrinos [1]. The arrival directions of the neutrinos were compatible with an isotropic distribution pointing to an extragalactic origin. The next important step was to identify the sources of those neutrinos. Since such neutrinos are exclusively produced in interactions of protons or nuclei with matter or radiation fields, they can reveal the sources of high-energy cosmic rays.

To identify the sources of high-energy neutrinos, the IceCube collaboration implemented a programme that detects the most interesting neutrino events in real time and forwards their direction within ~30 s to a network of telescopes around the Earth [2]. The telescopes then observe the corresponding direction in the sky, aiming for the detection of an electro-magnetic counterpart. The DESY IceCube group laid the foundation for this programme, which has been in operation since April 2016.

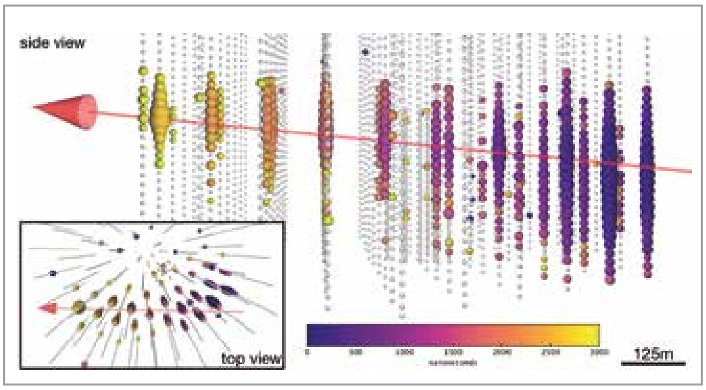


Figure 1

Event display of IceCube-170922A. The time at which a DOM observed a Cherenkov light signal is reflected in the colour of the hit (dark blues for earliest hits, yellow for latest). The size of the spheres is proportional to the logarithm of the amount of light observed at the DOM.

IceCube-170922A

On 17 September 2019, the IceCube real-time programme detected the neutrino event IceCube-170922A with a most probable energy of 290 TeV (Fig. 1) [3]. This indicated the existence of > PeV protons in the source. Its sky position was reconstructed as RA = 77.43, Dec = 5.72, with an error circle of 0.97 deg^2 (Fig. 4). This information was released to the astronomy community through the Gamma-ray Coordinates Network (GCN) only 43 s later.

Follow-up of IceCube-170922A

The neutrino alert initiated a large multiwavelength follow-up campaign (Fig. 2). The X-ray telescope on board the Swift

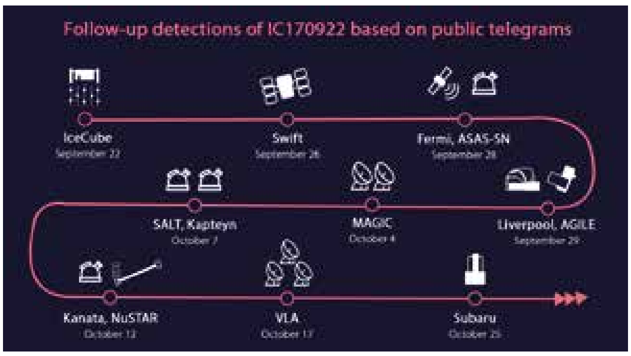


Figure 2

Time line of the multiwavelength follow-up of IceCube-170922A

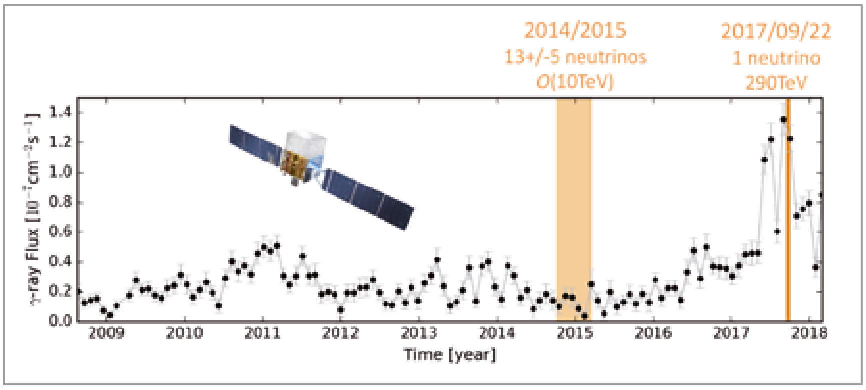


Figure 3

Fermi-LAT light curve of TXS 0506+056. The arrival time of IceCube-170922A is indicated as an orange line and the duration of the archival neutrino flare as an orange band. Figure from [3].

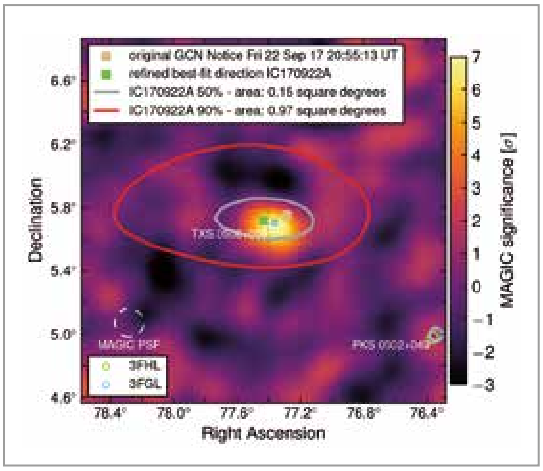


Figure 4

MAGIC significance map. Neutrino 90% and 50% errors are shown in red and blue and the best-fit neutrino position in green. Known gamma-ray sources from the Fermi catalogues are shown as blue and green circles. Figure from [3].

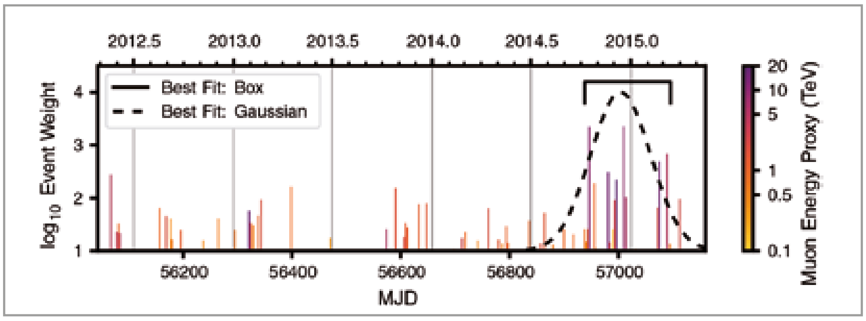


Figure 5

Each vertical line represents an observed neutrino event. The height indicates the event weight determined by the distance to the source position weighted with the neutrino angular uncertainty and the neutrino energy. The colour for each event indicates the approximated reconstructed muon energy. The dashed curve and the solid bracket indicate the neutrino flare length for a Gaussian and box-shaped time window, respectively. Figure from [4].

satellite was the first to release results on nine potential X-ray sources within the neutrino error circle. The Large Area Telescope (LAT) on board the Fermi satellite identified one of those sources as an already known GeV gamma-ray blazar and found the source in an increased state of gamma-ray activity at the neutrino arrival time (Fig. 3). For the first time, the two MAGIC Cherenkov telescopes on La Palma detected >100 GeV gamma-ray emission from this blazar (Fig. 4). The DESY gamma-ray group analysed the Fermi-LAT and MAGIC data and calculated the chance probability of such a coincidence to be 10^{-3}, which corresponds to a 3 σ significance.

Archival neutrino flare

The detection of this IceCube event from the direction of TXS 0506+056 during an active state motivated the search for more 1–10 TeV neutrinos in archival IceCube data from the direction of that blazar. The DESY IceCube group searched for time-dependent neutrino emission and found an excess during 2014/15. 13 ± 5 neutrinos events were found above the atmospheric background in a time window of 160 days (Fig. 5). The spatial proximity of the events to the position of TXS 0506+056 and their higher average energy yield an excess of 3.5 σ significance.

Modelling of the multimessenger data

The multiwavelength data can be combined with a spectral energy distribution (SED), which shows two humps typical for non-thermal emission. The origin of the hump at higher energies is still under debate. Leptonic models assume that it is produced by inverse Compton scattering of relativistic electrons on various photon fields. Hadronic models predict the origin of the second hump from proton synchrotron emission or the decay of neutral pions produced in proton interactions. Only the latter hadronic scenario can explain the neutrino emission.

Scientists at DESY were involved in the successful modelling of the SED during the 2017 flare [5, 6]. The 2014/15 neutrino flare, however, with its lack of coincident gamma-ray emission, challenges current models and leaves open questions [7]. More data and more coincident observations in the future will allow us to get a more complete picture of neutrino – and cosmic-ray – production in blazars.

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Neutrinos from a blazar flare

Modelling the first cosmic neutrino source beyond stars

The sources of the high-energy neutrinos observed by the IceCube detector in Antarctica remained a complete mystery until a coincident observation was made in September 2017 of a neutrino event and a flare of a blazar, at various wavelengths, from the same direction in the sky. This was a smoking-gun signature of proton interactions, as neutrinos reveal hadronic particle interactions, probably inside the jets launched from the supermassive black hole at the centre of the corresponding active galaxy.

Blazars are celestial objects in which relativistic jets are launched from the supermassive black holes located at the centre of active galaxies, with the jets pointing towards Earth. Blazars dominate the gamma-ray sky beyond our Milky Way. The potentially hadronic origin of those gamma-rays turns blazars into prime candidate sources of ultrahigh-energy cosmic rays, discovered more than 100 years ago. However, cosmic rays cannot be used to verify this hypothesis, as they are deflected during their propagation by magnetic fields. Meanwhile, leptonic mechanisms can explain most blazar emissions equally well.

A major breakthrough occurred in September 2017, when the IceCube neutrino observatory recorded a neutrino event of about 290 TeV that coincided with a major electromagnetic flare from the blazar TXS 0506+056, located around four billion light years away (see page 48 and [1]). As the decay products of mesons generated in interactions of high-energy protons, neutrinos are smoking-gun signatures of hadronic interactions in astrophysics. Because they interact extremely

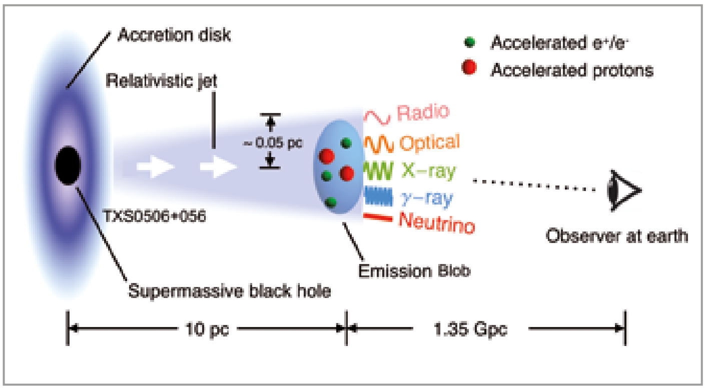

Figure 1

Geometry of the model for the neutrino-emitting blazar TXS 0506+056. The sizes and distances are not to scale.

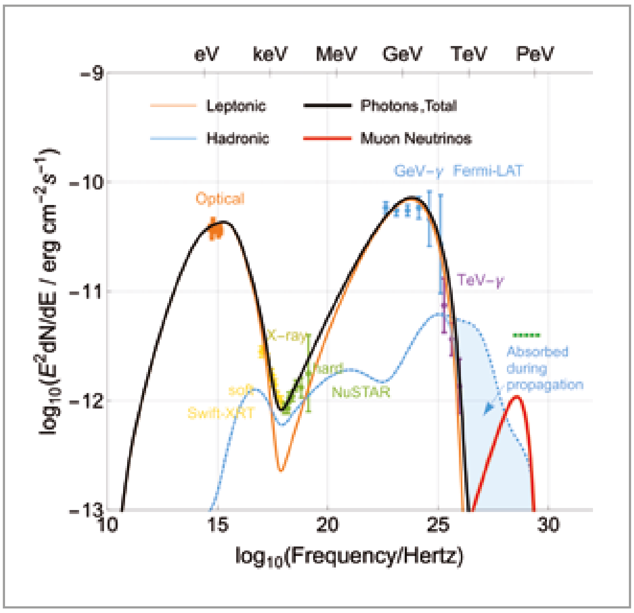

Figure 2

Energy flux from TXS 0506+056 across the electromagnetic spectrum and for neutrinos. The spectrum is the best-fit result selected from the lepto-hadronic model. The hadronic photons are shown as a blue curve with the corresponding muon neutrino spectrum in red. The predicted neutrino flux is below the horizontal green line, while the expectation number of IceCube neutrinos is exactly one during the flare.

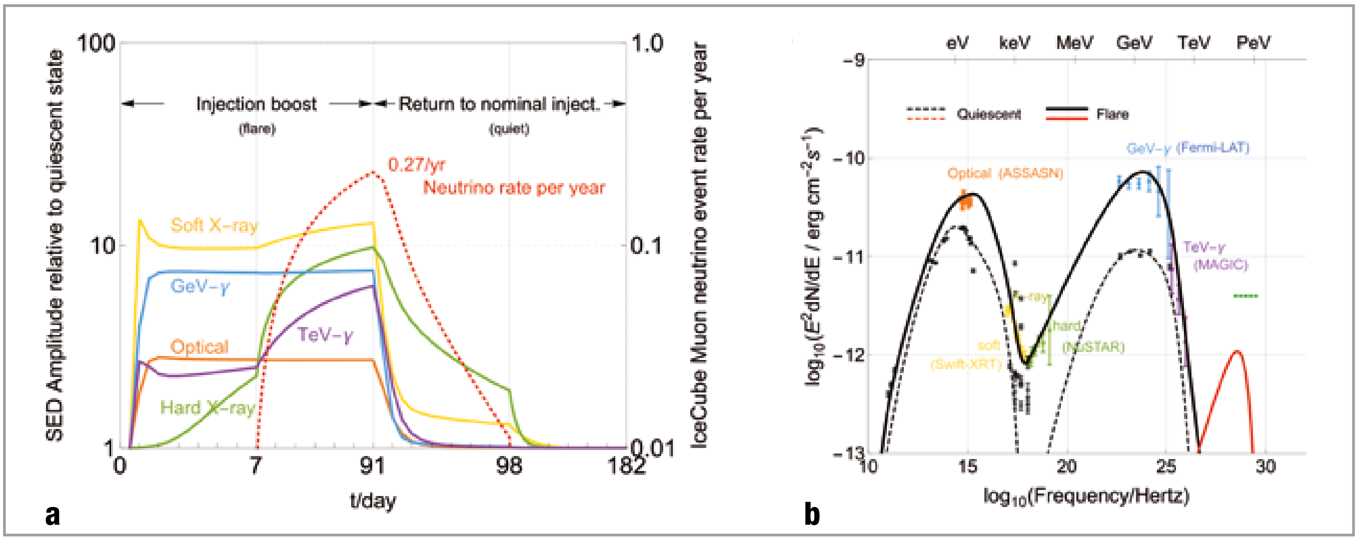

Figure 3

Time-dependent simulation of the light curve in various frequency bands (panel a) and spectrum (quiet state and flare state of TXS 0506+056, panel b). Note that in panel a), the scale of the *x* axis (in time) is not uniform; the initial rise and decay phases (days 0–7 and 91–98) are zoomed in to show the details.

weakly with matter, neutrinos travel essentially unimpeded over cosmological distances. Therefore, this observation alone points strongly towards hadronic particle interactions in the jet of TXS 0506+056.

The DESY astroparticle physics group systematically tested this hypothesis quantitatively against observations, for a number of observation-motivated models [2]. We started from a simple geometry: a spherical emission blob with injection of electrons and cosmic-ray protons following a power law, which is a typical prediction of Fermi acceleration in astrophysics. Fermi acceleration is the most natural mechanism giving energy to charged particles up to the highest energies. In the blob, particles interact with each other and emit various types of particles (Fig. 1). Our AM3 code efficiently simulates all relevant processes and computes particle distributions by solving a time-dependent system of kinetic differential equations [3].

Thanks to the large computing cluster at DESY, millions of simulations can be performed every day, covering a large parameter space. From simulations, we first found that not all gamma rays from TXS 0506+056 can be of hadronic origin. Coproduced electron–positron pairs in proton–photon interactions (Bethe–Heitler process) would emit more X-rays than observed by the Swift and NuSTAR space telescopes. To comply with X-ray observations, we propose a “mixed” lepto-hadronic scenario where the two humps of the spectrum are produced leptonically and the saddle region between the two humps is filled with the hadronic cascades (Fig. 2).

In this scenario, we also investigated time-dependent features. As shown in Fig. 3a, the light curves of the optical, soft X-ray and MeV–GeV flux are indeed correlated due to their common leptonic origin, whereas the hard X-rays, the TeV photons and the neutrino behave as if produced hadronically. Figure 3 also shows the ~30x boost of the neutrino flux during the flare phase relative to the quiet phase.

While the model offers a satisfactory explanation overall, there is still a number of concerns: the sparsity and uncertainty of the multiwavelength data, the imperfect match between the predicted neutrino flux and the observed one, the large proton budget needed and the degeneracy of the parameters, which implies the coexistence of many solutions.

Our results demonstrate the importance of multiwavelength and multimessenger observations. Current and future telescopes, such as KM3NeT and the Cherenkov Telescope Array (CTA), will contribute essentially to deciphering the interplay between leptonic and hadronic interactions in jets of blazars and other astrophysical particle accelerators.

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Galactic science with 15 years of H.E.S.S. data

Special issue compiles scientific achievements

The H.E.S.S. telescopes in Namibia have surveyed the Milky Way in gamma-ray light for the last 15 years. To celebrate this anniversary, the H.E.S.S. collaboration published its largest set of science results to date in a series of papers in a special issue of the journal *Astronomy & Astrophysics*. More than a dozen scientific articles describe the H.E.S.S. Galactic Plane Survey, studies of the populations of pulsar wind nebulae and supernova remnants as well as the search for new object classes unseen before in very high-energy gamma rays, such as microquasars or shocks around fast-moving stars. These studies are complemented by precision measurements of shell-type supernova remnants such as RX J1713.7-3946 and of diffuse emission at the centre of our galaxy. This legacy data set will serve as a benchmark for the community for the coming years until the next-generation Cherenkov Telescope Array (CTA) comes online in the 2020s.

In spring 2003, when the High Energy Stereoscopic System (H.E.S.S.) was still being commissioned, its first two telescopes were pointed at the centre of our galaxy and the remnant of an exploded massive star. Both of these targets revealed gamma-ray emission – a discovery that marked the opening of a new window for the study of galactic sources of very high-energy (VHE) gamma rays. In the following 15 years, the H.E.S.S. telescopes [1] have continuously surveyed the galaxy and targeted specific sources, making discoveries of ever new sources and object classes and thus pushing the field of ground-based gamma-ray astronomy ever further. This programme has now culminated in the publication of a series of 14 papers in a special issue of Astronomy & Astrophysics entitled “H.E.S.S. phase-I observations of the plane of the Milky Way” [2, 3], the publication of which was coordinated at DESY.

The special issue is a milestone of gamma-ray astronomy and presents the vast breadth and depth of the galactic science programme of H.E.S.S. over 15 years. Two of the 14 papers cover the first two objects observed and studied in 2003, the galactic centre and the exploded star RX J1713.7-3946, rounding up an exciting time of discovery and precision measurements of the Milky Way in gamma rays. We could only dream of detecting almost 80 VHE gamma-ray emitters in the Milky Way when the H.E.S.S. Galactic Plane Survey (HGPS) was started more than a decade ago.

The updated HGPS offers not just a much deeper view of the inner part of our galaxy at extreme energies, it is also a very thorough systematic study and marks the first time that major data products from this waveband are released to the entire astrophysics community [3]. This will open the results to a much wider community of astronomers interested in cosmic particle accelerators. A public release will allow the community to compare the H.E.S.S. data with other multiwavelength data sets and will also break ground for the upcoming CTA observatory, which plans to release all data to the public. The HGPS also provides the basis for the characterisation of populations of gamma-ray emitters, such as the abundant classes of pulsar wind nebulae and supernova remnants, three of which are newly identified in the HGPS.

In a second class of publications in the special issue, H.E.S.S. members perform precision measurements of individual particle accelerators, such as RX J1713.7-3946, or entire regions, such as the galactic centre. These studies reveal the detailed properties of the underlying particle

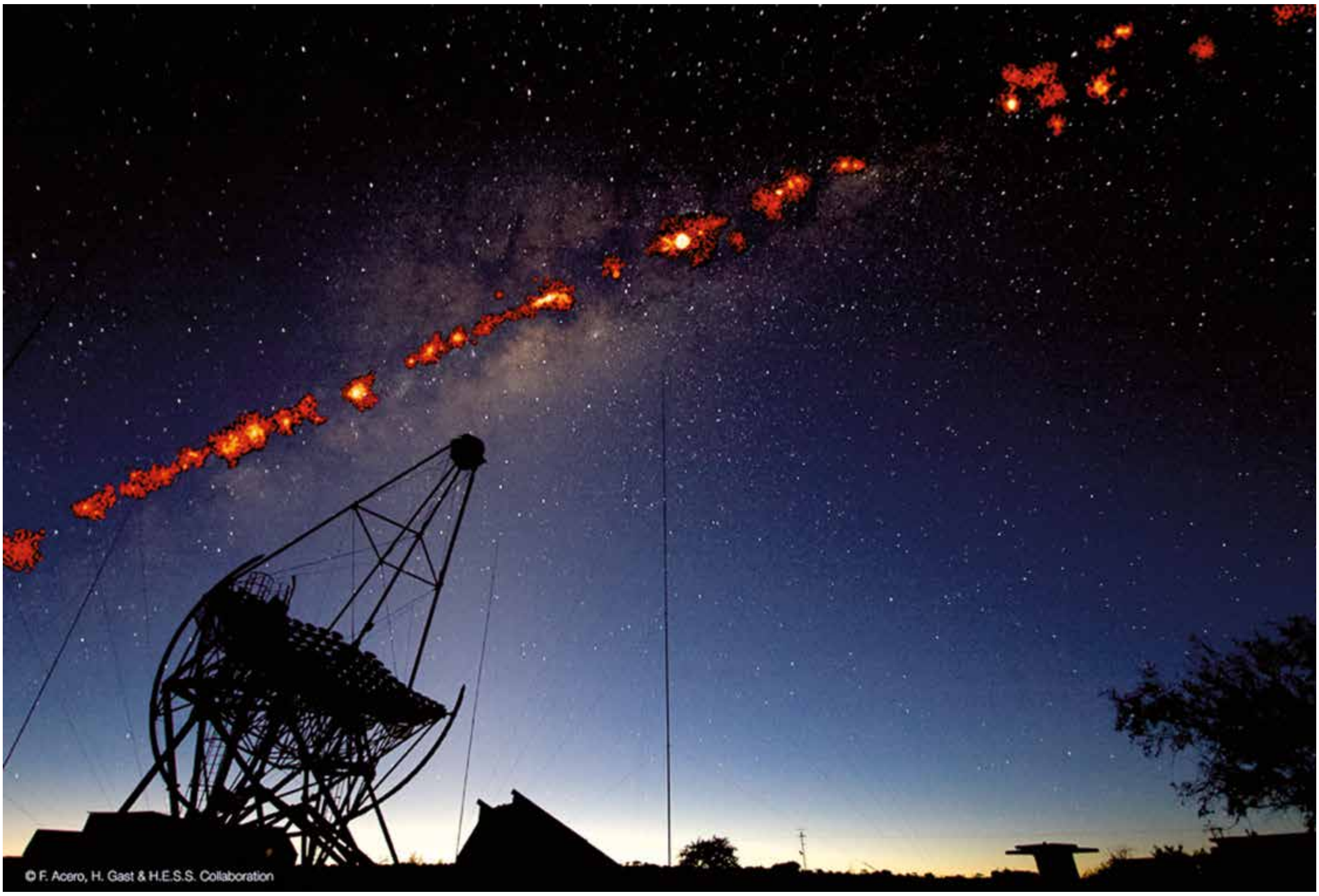

Figure 1

Gamma-ray emission from the galactic plane as seen with the H.E.S.S. observatory, overlaid onto a night sky image in the optical range with one of the H.E.S.S. telescopes in the foreground

accelerators and shed new light on how cosmic rays move through the interstellar medium and shape their environment. Finally, the H.E.S.S. collaboration has searched its data for emission from hypothesised new object classes, such as run-away stars or stellar-mass black holes orbiting massive stars. The spectrum of topics covered in the special issue demonstrates that VHE gamma-ray astronomy has developed into a mature field. Our knowledge of high-energy astrophysics in our galaxy has significantly deepened.

The global community of gamma-ray astronomers is currently preparing the much more sensitive next-generation instrument CTA, which is a global project to be built at two sites in the northern and southern hemisphere. Scheduled to come into regular operation in the 2020s, it will provide a more detailed and sensitive image of our Milky Way in gamma rays. Until then, the H.E.S.S. data set published in the special issue will remain the state-of-the-art of the field.

The H.E.S.S. telescopes are located in Namibia in south-west Africa. The telescope system, which comprises four 13 m diameter telescopes and the huge 28 m H.E.S.S. II telescope built in 2012, is one of the most sensitive detectors of VHE gamma rays. These are absorbed in the atmosphere, where they create a short-lived shower of particles. The H.E.S.S. telescopes detect the faint, short flashes of bluish Cherenkov light (lasting a few billionths of a second) that these particles emit, collecting the light with big mirrors that reflect it onto extremely sensitive cameras. Each image gives the position in the sky of a single gamma-ray photon, and the amount of light collected yields the energy of the initial gamma ray. By building up the images photon by photon, H.E.S.S. creates maps of the gamma-ray sky.

The H.E.S.S. telescopes have been in operation since late 2002. At the end of 2016, in 13 700 h of observations, the telescopes had collected data from about 20 billion particle showers. The majority of the about 200 known cosmic objects emitting VHE gamma rays have been discovered by H.E.S.S..

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How big are stars?

Measuring the size of stars through asteroid occultations with VERITAS

The size of a star is a key information for determining its basic properties, but at interstellar distances stars are generally too small to be resolved by any individual telescope. This limitation can be overcome by studying the diffraction pattern in the shadow cast when an asteroid accidentally passes by in front of a star. Atmospheric Cherenkov telescopes are generally used for particle astrophysics, but their large mirror area makes them well suited for precision photometry measurements at high time resolution. By detecting two asteroid occultations with the VERITAS gamma-ray telescope in Arizona, USA, we were able to constrain the respective star's angular diameter at the ≤ 0.1 milliarcsecond level – a resolution never achieved before with optical measurements.

Measuring the size of stars through asteroid occultations

When a solar-system object, such as an asteroid or the Moon, passes in front of a star as viewed on the celestial sphere, it provides a powerful tool for studying both the occulting object and the occulted star [1]. As viewed from the ground, the rapid drop in the observed intensity of light is modified by diffraction fringes preceding and following the edges of the central shadow region of the obscuring object. Above a minimum angular size, the extended disc of a star will modify and reduce the intensity of the diffraction fringes, diverging noticeably from the pattern of a point-like source. A fit to observable diffraction fringes thereby enables a direct measurement of the angular size of the star, even though this may be far below the imaging angular resolution limit of the telescope. Observations of stellar occultations by asteroids are frequently used to determine the properties of an asteroid, such as its size and shape [2]. However, to date, there has been little success in measuring asteroid occultation diffraction fringes to make such angular size measurements.

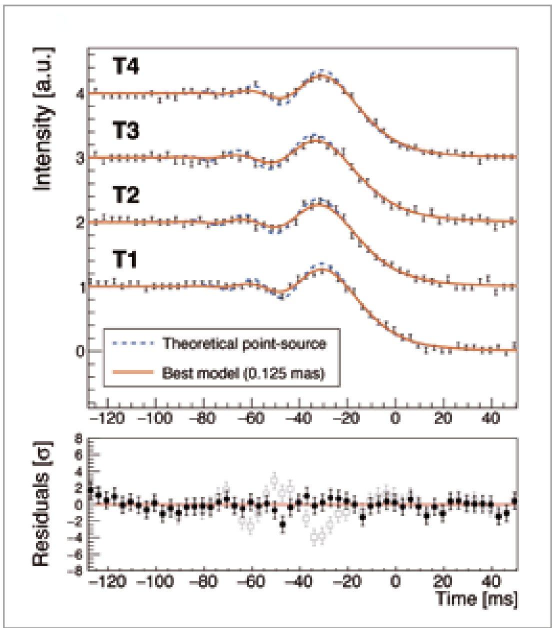

Figure 1

Light curve of the asteroid (1165) Imprinetta occulting the star TYC 5517-227-1. The black data points show the measurements. The best-fit diffraction pattern (red line) and the theoretical point source model (dashed blue line) are presented too. The bottom panel shows the combined (averaged) residual with respect to the point source (grey empty squares) and the best-fit (black filled circles) models.

On 22 February 2018, the ~59 km diameter carbonaceous (C-class) asteroid (1165) Imprinetta occulted the 10.2 V-magnitude star TYC 5517-227-1, with the shadow path predicted to have a 50% chance of detection from the Fred Lawrence Whipple Observatory (FLWO), where the Very Energetic Radiation Imaging Telescope Array System (VERITAS) is located. The four 12 m diameter imaging atmospheric Cherenkov telescopes (IACTs) of VERITAS act as effective "light buckets" collecting the fast, faint emission of Cherenkov light generated by particle showers initiated in the upper atmosphere by very high-energy cosmic radiation.

Its large mirror surface, with a recent upgrade of the camera's central pixel monitoring instrumentation, also makes VERITAS a very sensitive detector for optical photometry with high time resolution. Distinct diffraction fringes were detected during ingress and egress, as shown in Fig. 1. This marks the first time an occultation has been measured using an IACT and successfully demonstrates that these instruments are indeed capable photometers for fast optical astronomy.

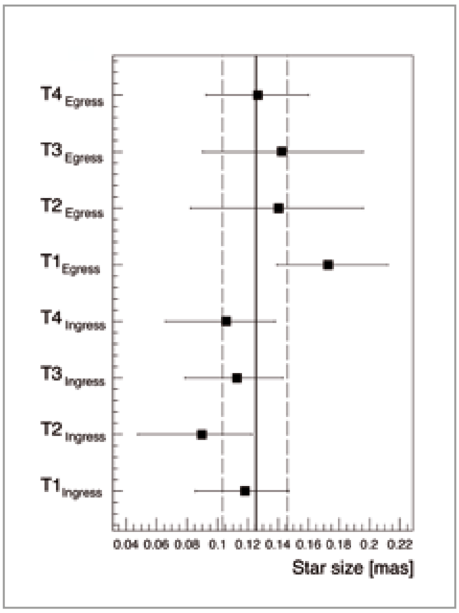

Figure 2

Individual and combined stellar size measurements of TYC 5517-227-1 from each ingress and egress light curve assuming a uniform disc profile

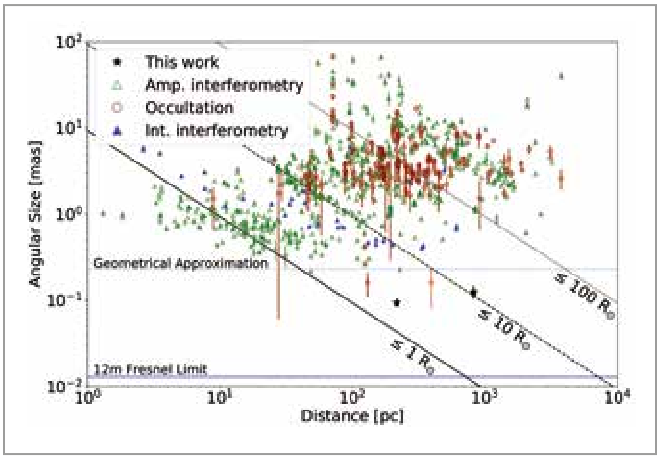

Figure 3

Comparison with the available directly measured stellar angular size measurements

Following the success of the Imprinetta observation, on 22 May 2018, VERITAS observed an occultation of a 9.9 V-magnitude star, TYC 278-748-1, by the 88 km diameter asteroid (201) Penelope. Again, the diffraction pattern was clearly detected, allowing for a direct measurement of the star's diameter.

Sub-milliarcsecond resolution measurements with VERITAS

The diffraction pattern measured by VERITAS constrains the angular sizes of both stars. In the case of TYC 5517-227-1, the star occulted by Imprinetta, the diameter was measured to be $0.125^{+0.021}_{-0.022}$ milliarcsecond (mas), as shown in Fig. 2. Once the measured parallax distance [3] of 820 ± 40 parsecs (pc) is taken into account, the angular size measurement determines the radius to be $11.0^{+1.9}_{-2.0}\ R_{\odot}$, unambiguously establishing TYC 5517-227-1 to be a giant star. In the case of TYC 278-748-1, the star occulted by Penelope, the star's angular size was again directly measured to be $0.094^{+0.009}_{-0.010}$ mas, consistent with the estimates from the Tycho and JSDC catalogues [4, 5]. With the measured parallax distance [3] of 215 ± 2 pc, we established the star to have a radius of $2.17^{+0.22}_{-0.23}\ R_{\odot}$, classifying it as a sub-giant (IV). As shown in Fig. 3, this is a resolution never achieved before with optical measurements and represents an order of magnitude improvement over the equivalent lunar occultation method.

The only available estimates of these star radii are from empirical fits to measurements of the effective temperature and luminosity in the Kepler K2 Ecliptic Plane Input Catalog (EPIC) [6] and the Gaia DR2 Final Luminosity, Age and Mass Estimator (FLAME) catalogue [3]. By comparing our measurements with these catalogues, we confirmed that empirically derived estimates from brightness can be biased for stars with ambiguous stellar classifications.

Asteroid occultation shadows regularly pass over the Earth's surface, with the potential number of occulted stars per year exponentially increasing as fainter and fainter stars are considered. The shadow paths are predicted by combining star catalogues with the orbital trajectories of known asteroids with a precision usually comparable to the asteroid size.

The problem with exploiting these occultations is that only 7% of them have a ≥ 20% chance of actually being observed from any fixed location, making them difficult to catch with the large, non-portable telescopes that are necessary to resolve the diffraction fringe. However, a telescope capable of detecting an occultation of a 10th magnitude star can view, on average, five viable occultations per year. This increases to almost one per week for occultations of 13th magnitude stars. Using this technique, we are not any more limited to nearby, bright objects and can thus greatly increase the volume of space and variety of stars that can be studied. A corresponding publication has been submitted [7].

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Discovering X-ray pulsars

A new way to understand pulsar emission from X-rays to gamma rays

Based on a new theoretical model prediction, DESY scientists led a search of the rich data archives of ESA's XMM-Newton and NASA's Chandra space observatories to find pulsating X-ray emission from three known gamma-ray pulsars. The discovery verifies a novel method for investigating and better understanding the mysterious mechanisms of pulsar emission and possibly using them for space navigation in the future.

Dubbed the lighthouses of the universe, pulsars are fast-rotating neutron stars that emit beams of radiation (Fig. 1). As pulsars rotate and the beams alternately point towards and away from Earth, the source oscillates between brighter and dimmer states, resulting in a signal that appears to "pulse" every few milliseconds to seconds, with a regularity rivalling even that of atomic clocks.

Pulsars are the incredibly dense, extremely magnetic relics of massive stars and among the most extreme objects in the universe.

Understanding how particles behave in such a strong magnetic field is fundamental to understanding how matter and magnetic fields interact more generally.

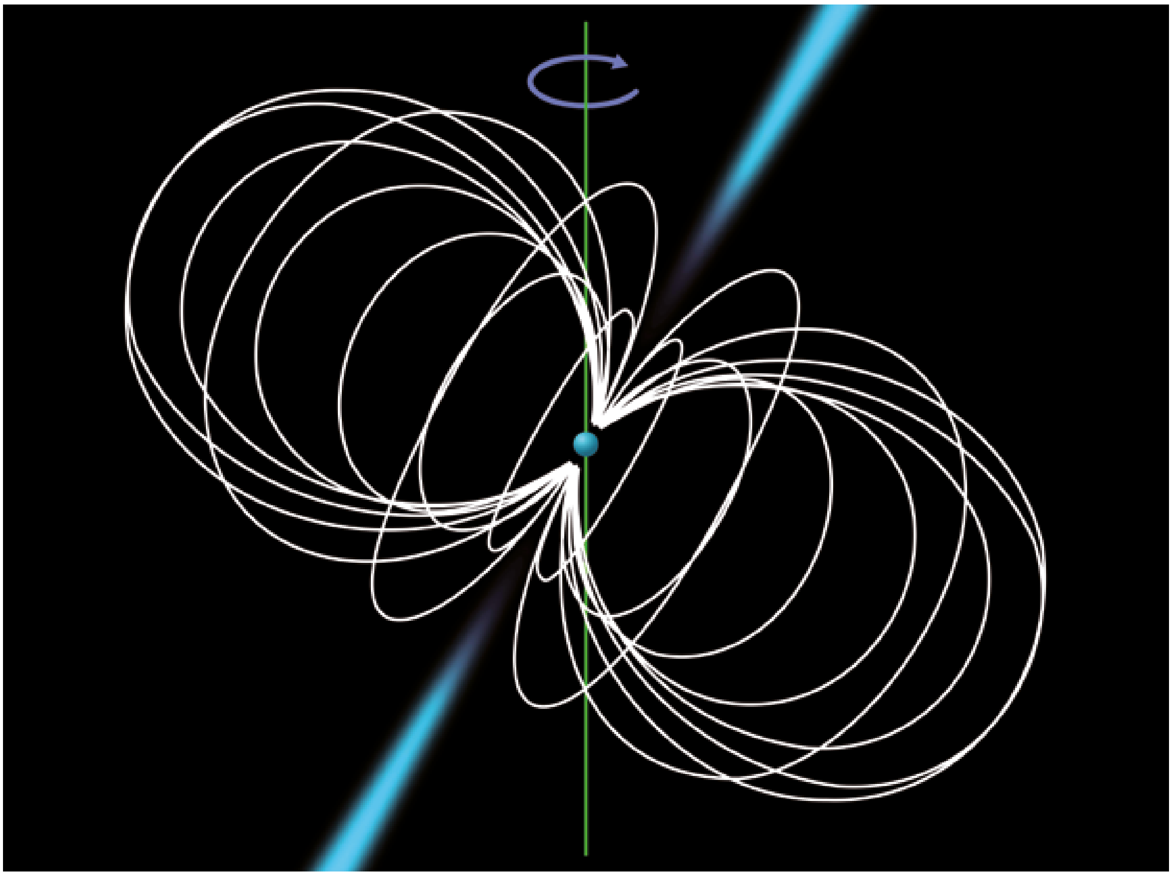

Figure 1

Schematic view of a pulsar. The sphere in the middle represents the neutron star, the curves indicate the magnetic field lines, and the protruding cones represent the emission beams.

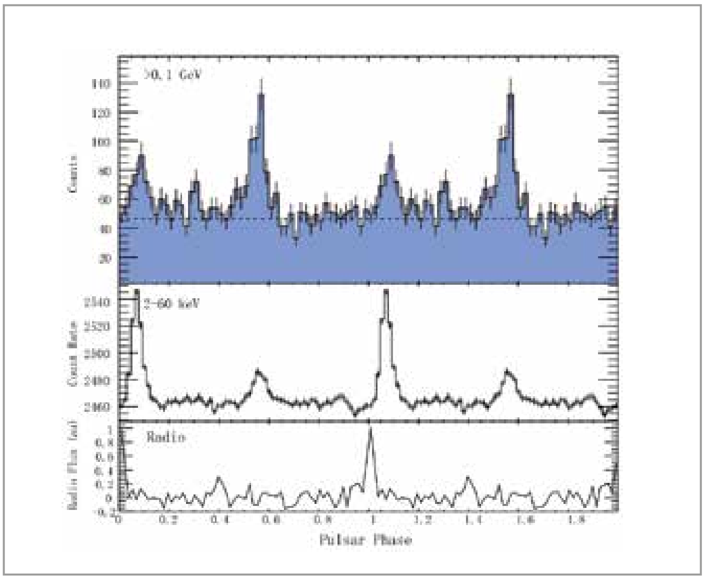

Figure 2

Pulse profile of the 65.7 ms pulsar PSR J0205+6449 in the gamma-ray (top), X-ray (middle) and radio (bottom) band (from Abdo et al. 2010)

Pulsars show pulsations in several wavelength bands, including radio waves, X-rays and gamma rays (Fig. 2). It is relatively easy to find pulsars that emit gamma rays. NASA's Fermi Gamma-ray Space Telescope has detected more than 200 of them over the past decade, thanks to its ability to scan the whole sky. But only around 20 have been found to pulse also in non-thermal X-rays. Unlike full-sky survey instruments for gamma rays such as Fermi, X-ray telescopes must be told exactly where to point in order to detect X-ray pulsars.

DESY scientists, together with colleagues from other institutes, selected three known gamma-ray-emitting pulsars detected by Fermi, which, based on a recent pulsar model [1], were expected to also shine brightly in X-rays. They dug into the data archives of ESA's XMM-Newton and NASA's Chandra X-ray space observatories to search for evidence of non-thermal X-ray emission from each of them. X-ray pulsations were clearly detected from all three (Fig. 3). The XMM data showed clear X-ray emission from PSR J1826-1256, a radio-quiet gamma-ray pulsar with a period of 110.2 ms. The spectrum of light received from this pulsar was very close to that predicted by the model. X-ray emission from the other two pulsars, PSR J1747-2958 and PSR J2021+3651, which both rotate slightly more quickly, was found in the Chandra data [2].

The discovery already represents a significant increase in the total number of pulsars known to emit non-thermal X-rays. The DESY team expects that many more can be discovered over the next few years. Finding more X-ray pulsars is important for revealing their global properties and population characteristics. A better understanding of pulsars is also essential for potentially using their accurately timed signals for future space navigation.

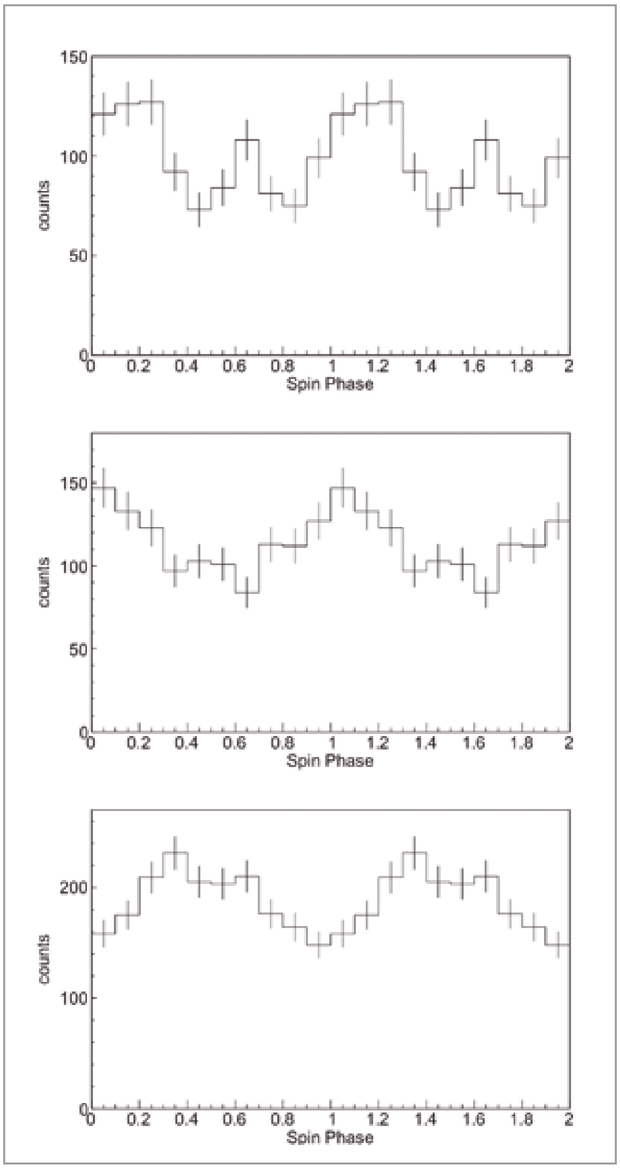

Figure 3

From top to bottom: Pulse profiles for PSR J1747-2958, PSR J2021+3651 and PSR J1826-1256. Clear periodicities are seen in all three pulsars.

The result is an important step towards understanding the relationships between the emissions of pulsars in different parts of the electromagnetic spectrum, enabling a robust way to predict the brightness of a pulsar at any given wavelength. The comparison of the model with the data also improves the understanding of the interaction between particles and the magnetic fields of pulsars.

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Building CTA

Major steps towards the construction of the Cherenkov Telescope Array

The Cherenkov Telescope Array (CTA) will be the world's largest and most sensitive observatory for gamma rays in the energy range from 50 GeV to 300 GeV. CTA will consist of two large arrays of telescopes for complete sky coverage: the northern array on La Palma (Spain) and the southern array to be built near Paranal (Chile). DESY personnel are working hard on preparing the CTA technology, from software to camera and telescope development. Among other contributions, DESY is responsible for the development and construction of the mid-sized telescopes, the "work horses" of CTA. Furthermore, DESY will host the CTA Science Data Management Centre on its Zeuthen campus. The planning of the new CTA building is well under way. After a review in 2018, CTA became a Landmark project of the European Strategy Forum on Research Infrastructures (ESFRI).

Green light for construction

In December 2018, the CTA Observatory, the European Southern Observatory (ESO) and Chile signed the final agreements needed for CTA's southern hemisphere array to be hosted near ESO's Paranal observatory in Chile [1]. With these agreements in place, the way is now paved for the start of construction of the southern hemisphere array in the Atacama desert (Fig. 1). CTA's southern site lies only 11 km south-east of the Very Large Telescope and just 16 km from the construction site of the upcoming Extremely Large Telescope. This is one of the driest and most isolated regions on Earth, making it an astronomical paradise. In addition, the installation of CTA on ESO ground brings the advantages of ESO's expertise and infrastructure. In the north, the hosting agreement between CTA and the Instituto de Astrofísica de Canarias is already in place. CTA's northern array is to be built at the Observatorio del Roque de los Muchachos on La Palma, Spain. Construction of both arrays is expected to begin in 2020.

In 2018, CTA became an ESFRI Landmark, i.e. a project that is in an advanced implementation phase and represents major elements of competitiveness for the European Research Area.

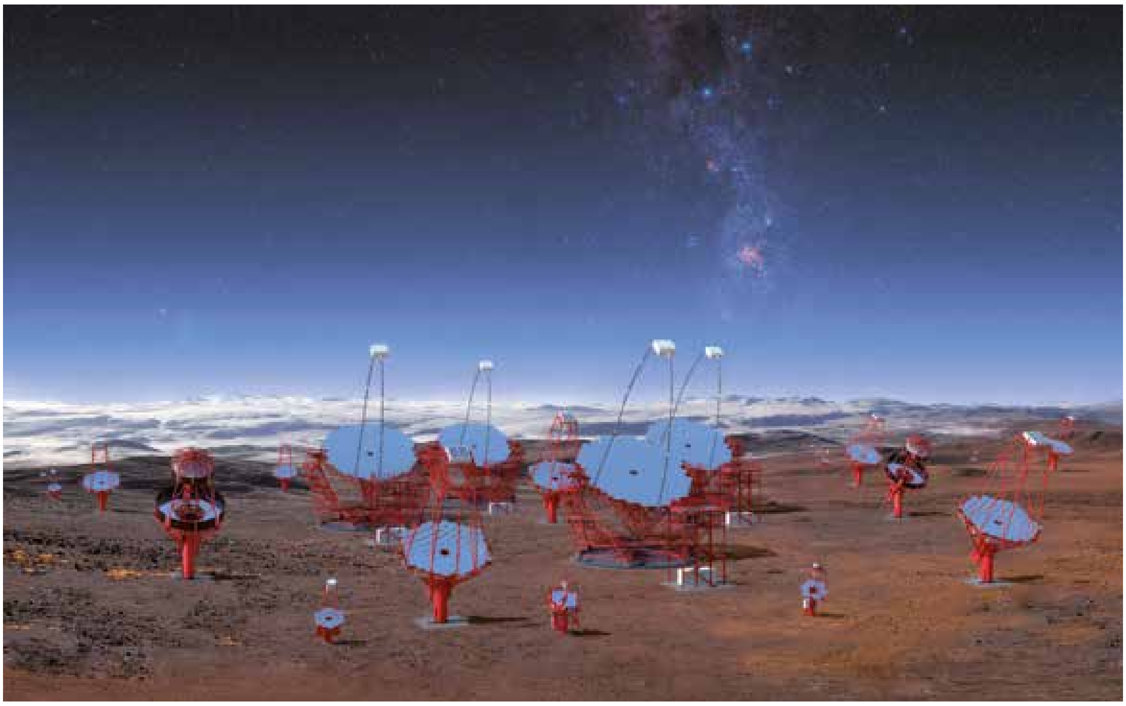

Figure 1

Illustration of the three sizes of telescopes planned for the southern array of CTA

Figure 2
Locations of the four CTA sites: CTA headquarters (Bologna), Science Data Management Centre (Zeuthen) and northern and southern telescope arrays on La Palma and in Chile

Preparing the production of the first MSTs

The mid-sized telescopes (MSTs) of CTA will be the core components of the observatory, covering the energy range from about 150 GeV to 5 TeV. The prototype telescope structure operated in Berlin is equipped with mirror segments provided from France, Italy and Poland. DESY leads the evaluation of the different mirror types, testing them in-house on their temperature dependence and long-term environmental impacts. In early 2018, new mirrors were mounted on the telescope prototype. After several design iterations, the new mirrors are now all fulfilling the specifications.

In November 2018, the final camera support structure was tested at the prototype. The new design was optimised to reduce its weight and shadowing by using thinner structures and replacing some poles by pre-tensioned steel ropes. Staff from CTA institutes in Germany, France, Brazil and Spain are working closely together towards the first fully equipped and functional MST with a NectarCAM camera (MST-N) for the preproduction phase of CTA. DESY is the lead institute of this subproject. In 2018, all necessary documentation for cost, construction and maintenance was prepared. Deployment, commissioning and validation of the performance of the first prototype MST on the northern site are planned for early 2021. Deployment of the first MSTs on the southern site in Chile is planned to begin in parallel.

CTA Science Data Management Centre

The Science Data Management Centre (SDMC) of CTA, which will be in charge of science planning and operations and make CTA's science results available to the worldwide community, will be located in a new building complex on the DESY campus in Zeuthen (Fig. 2). While first SDMC employees have commenced work in Zeuthen in temporary offices, planning is under way for a new SDMC building as part of a campus master plan, which also includes a new canteen and an education centre. After a successful architectural competition, detailed construction planning began in early 2019. The SDMC team supports the development of the CTA software products and prepares the science planning, science operations, data processing, simulations and science user support.

Simplification and harmonisation

CTA will be a large science infrastructure with a large number of subsystems and a high degree of complexity. It is imperative to design and implement the simplest and most harmonised system possible in order to achieve reliable operation and keep maintenance and operation cost as low as possible. Harmonisation is needed for example for the three proposed designs for the small-sized telescopes (SSTs), of which 70 units are supposed to be built. The SST harmonisation process is under way to converge on a single design for the SST (structure, mirrors, camera). The compact high-energy camera (CHEC) is a very promising candidate camera to be installed at all SSTs. An updated prototype with silicon photo-multipliers has been assembled and is ready for testing at DESY. DESY is coordinating the development activities of the camera back-end electronics, which make use of embedded systems for triggering, accurate timing and data acquisition.

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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.

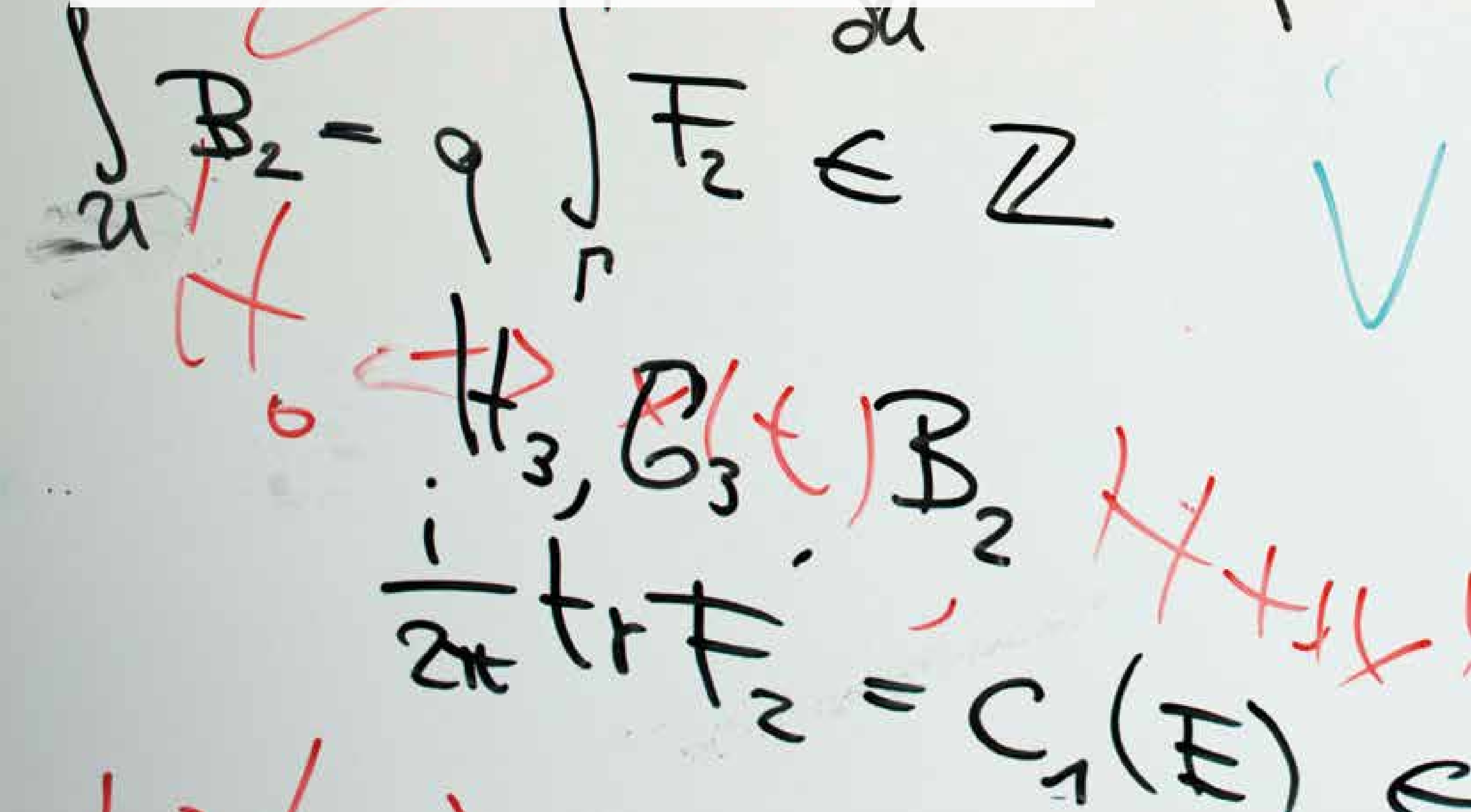
In particle phenomenology, results from the Large Hadron Collider (LHC) at CERN are at the centre of current activities. These include for example general techniques for precision calculations of initial-state radiation (p. 64) and double parton scattering (p. 66).

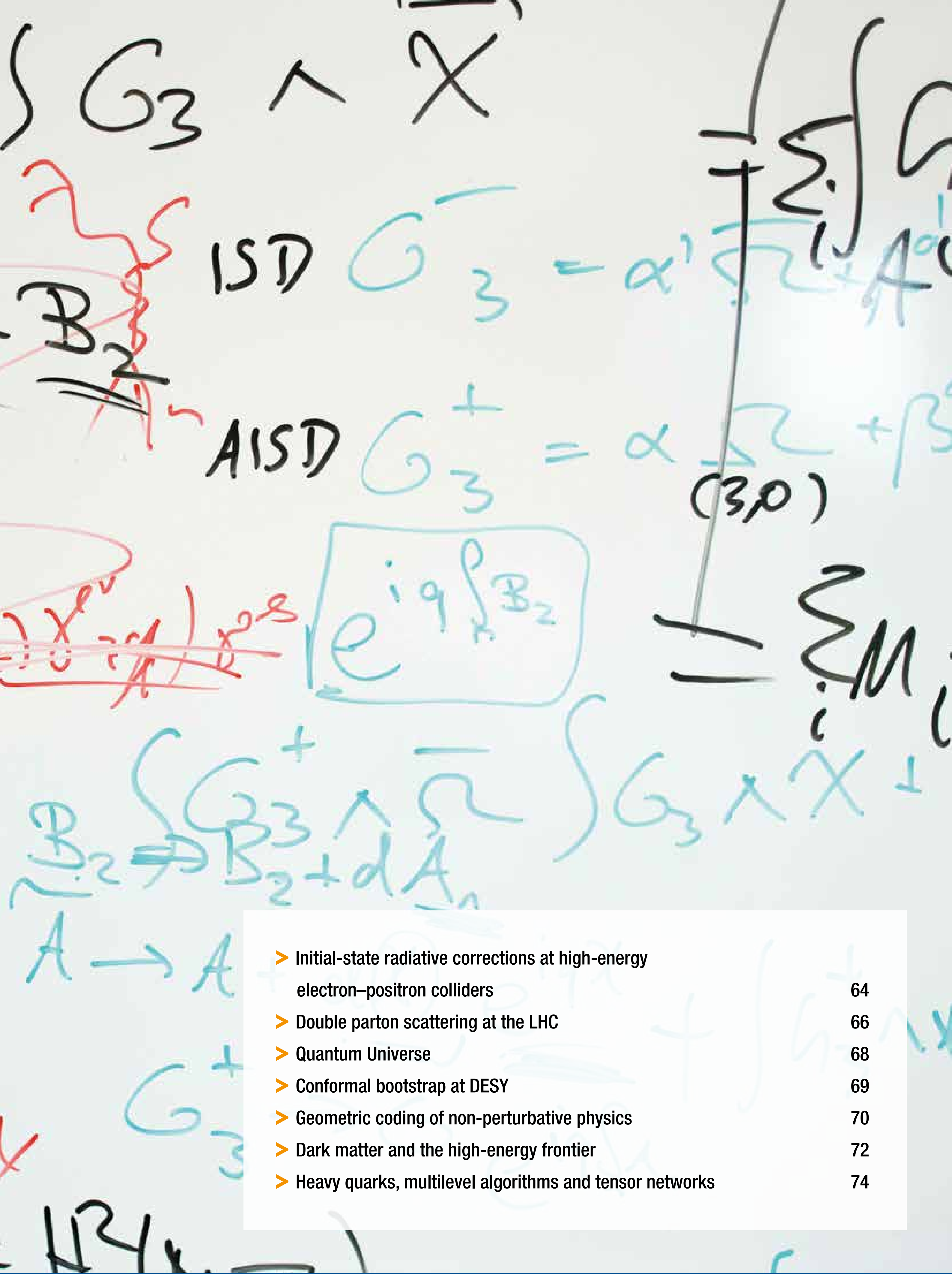
Particle phenomenology activities at DESY are strongly connected to efforts in both lattice gauge theory and cosmology. In 2018, these efforts led to an improved understanding of heavy-quark dynamics in lattice simulations (p. 74).

Moreover, theoretical efforts in cosmology yielded much progress in our understanding of dark matter. In particular, this concerned dark-matter candidates that are significantly heavier than the electroweak scale and lead to interesting observables in cosmic rays (p. 72).

The last 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. Two promising avenues are to search for analogies with supersymmetry (p. 70) or to exploit the conformal bootstrap method (p. 69).

Finally, the DESY theory group is very active in the new cluster of excellence “Quantum Universe”, which was awarded to Universität Hamburg by the German Research Foundation (DFG) (p. 68).





Initial-state radiative corrections at high-energy electron–positron colliders

Direct analytic computation at $O(\alpha^2)$ without any approximations

Perturbative calculations in quantum field theory are still one of the main building blocks for any analysis at collider experiments. This is especially true at lepton colliders. We calculate the non-singlet contribution, the pure singlet contribution and their interference term at $O(\alpha^2)$ due to electron pair initial-state radiation for the e^+e^- annihilation process into a neutral vector boson in a direct analytic computation without any approximation. The correction is represented in terms of iterated incomplete elliptic integrals. Performing the limit $s >> m_e^2$ we find discrepancies with the earlier results of Ref. [1] and confirm results obtained in Ref. [2], where we use the effective method of massive operator matrix elements, which works for all but the power corrections in m^2/s. In this way, we also confirm the validity of the factorisation of massive partons in the Drell–Yan process. In Ref. [3], we add non-logarithmic terms at $O(\alpha^2)$ that were not considered in Ref. [1]. The corrections are of central importance for precision analyses of e^+e^- annihilation into γ^*/Z^* at high luminosity.

Initial-state radiation (ISR) QED corrections to e^+e^- annihilation are of crucial importance for experimental analyses at the former LEP collider and for planned projects such as the ILC and CLIC, the FCC_{ee}, muon colliders and notably e^+e^- Higgs factories, using the processes $e^+e^- \to ZH^0$ and $e^+e^- \to t\bar{t}$. The ISR corrections were carried out before analytically to $O(\alpha \ln(s/m^2)^5)$ in the leading logarithmic series using the structure function method; a small z resummation was performed as well. In Ref. [1], the $O(\alpha^2)$ corrections were calculated neglecting terms of $O(m^2/s \ln(m^2/s))$. Here, s is the centre-of-mass energy squared and m is the mass of the electron. These corrections are used in analysis codes such as TOPAZ0 and ZFITTER. The ISR corrections can be written in terms of the following function

$$H\left(z,\alpha,\frac{s}{m^2}\right) = \delta(1-z) + \sum_{k=1}^{\infty}\left(\frac{\alpha}{4\pi}\right)^k C_k\left(z,\frac{s}{m^2}\right),$$

$$C_k\left(z,\frac{s}{m^2}\right) = \sum_{l=0}^{k}\ln^{k-l}\left(\frac{s}{m^2}\right)c_{k,l}(z),$$

which yield the respective differential cross sections through

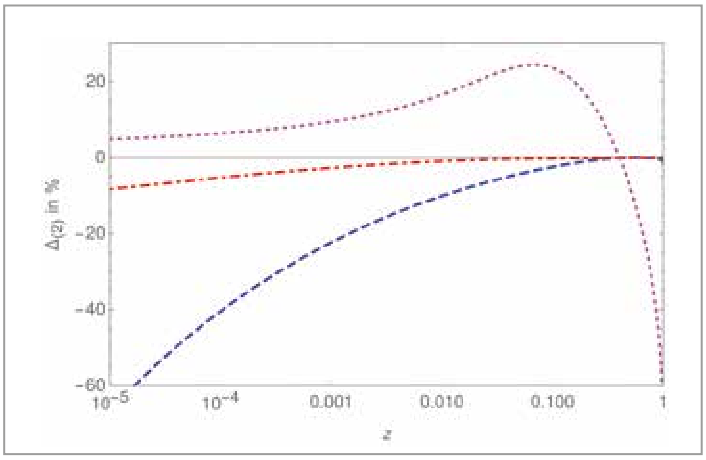
$$\frac{d\sigma_{e^+e^-}}{ds'} = \frac{1}{s}\sigma_{e^+e^-}(s')H\left(z,\alpha,\frac{s}{m^2}\right),$$

with $\sigma_{e+e-}(s')$ the scattering cross section without the ISR corrections, $\alpha \equiv \alpha(s)$ the fine structure constant and $z = s'/s$, where s' is the invariant mass of the produced (off-shell) γ^*/Z^* boson.

In Ref. [2], we applied the method of massive operator matrix elements (OMEs) to calculate the $O(\alpha^2)$ corrections, factorising the process into universal massive contributions and the massless Wilson coefficients of the Drell–Yan process [4]. This method has been known to work in the case of external massless fields, including the non-logarithmic contributions. However, the results of Refs. [1] and [2] were found to disagree in the constant terms, which are relevant for precision predictions.

One way to find out the correct answer is to perform the direct analytic calculation of the corresponding contributions without doing any approximation. We calculate this in Ref. [3] for three of the subprocesses of the $O(\alpha^2)$ corrections related to fermion pair production, i.e. for the processes II–IV of Ref. [1] and one more process not contained in Ref. [1].

The complete results have an iterative integral representation, partly in terms of Kummer-elliptic integrals. We compare the exact result numerically with the one obtained in the limit $\rho = m^2/s \to 0$. Both results agree better than a relative deviation of 10^{-7}, which is the expected accuracy. As an example, we present the difference term for process III, see Ref. [3],



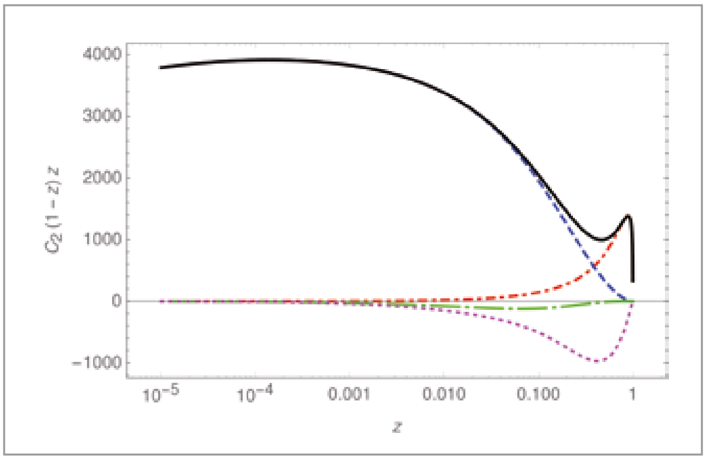


Figure 1

Relative deviations of the results of Ref. [1] from the exact result in percent for the $O(\alpha^2)$ corrections. Non-singlet contribution (process II): dash-dotted line; pure singlet contribution (process III): dashed; interference term between both contributions (process IV): dots; for $s = M_Z^2$, M_Z = 91.1879 GeV.

Figure 2

Initial-state $O(\alpha^2)$ corrections to γ^*/Z^* production due to e^+e^- pair production multiplied by $z\,(1-z)$. Non-singlet contribution (process II): red line; pure singlet contribution (process III): blue; interference term between both contributions (process IV x 10): violet; vector contributions implied by process B, Ref. [4], and interferences x100: green.

$$
\begin{aligned}
\delta_{\rm III} \;=\; & \frac{160}{3} - \frac{32}{z} + \frac{128}{3(1+z)^2} - \frac{64}{1+z} + 96(1+z)\zeta_3 \\
& - \left[52(1-z) + \frac{64}{3z}(1-z^3)\right]\ln^2(z) - \frac{56}{3}(1+z) \\
& \times \ln^3(z) + \Big[24(1-z) + 16(1+z)\ln(z)\Big]\zeta_2 + \ln(z) \\
& \times \Bigg[\frac{104}{3} - \frac{32}{z} + \frac{128}{3(1+z)^3} - \frac{256}{3(1+z)^2} - \frac{64}{1+z} \\
& + 64\left(1 - z + \frac{1-z^3}{3z}\right)\ln(1+z)\Bigg] - \Bigg[40(1-z) \\
& + \frac{64}{3z}(1-z^3) + 48(1+z)\ln(z)\Bigg]\mathrm{Li}_2(1-z) \\
& + 64\left[1 - z + \frac{1}{3z}(1-z^3) - (1+z)\ln(z)\right]\mathrm{Li}_2(-z) \\
& + 128(1+z)\mathrm{Li}_3(-z) - 96(1+z)S_{1,2}(1-z) \\
& + 2\delta_{\rm interf}^{\rm PS}
\end{aligned}
$$

where Li_n denotes the polylogarithm and $S_{p,n}$ the Nielsen integrals.

In Fig. 1, we depict the relative deviations in percent of the results given in Refs. [1] and [3] at $s = M_Z^2$ for the whole $O(\alpha^2)$ corrections including the logarithmic contributions. They turn out to be significant in the high-energy region at small z and for process IV also at large z. The reason for this deviation is that in Ref. [1], terms $O(m^2/s)$ that contribute to the constant term of the cross section were neglected too early. Figure 2 shows the results at $O(\alpha^2)$ for the processes II–IV and one more process (see also Ref. [4]).

In future precision analyses of e^+e^- annihilation into vector bosons at high luminosity, these corrected scattering cross sections will be essential for high accuracy.

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For a detailed list of references, see Ref. [3].

Double parton scattering at the LHC

Beyond the simplest picture of proton–proton collisions

Heavy particles at the LHC are produced through the interactions of the partons – quarks, antiquarks, or gluons – inside the colliding protons. Several of these parton–parton interactions may take place in a single proton–proton collision. The case of double parton scattering, which is studied intensively in the DESY theory group, offers some surprising insights into the structure of hadrons and their interactions at the quark–gluon level.

In its high-luminosity phase, the LHC will produce a wealth of data. To interpret these and find possible deviations from the predictions of the Standard Model, it will be essential in many cases to understand the strong-interaction dynamics of proton–proton collisions as well as possible. The textbook mechanism for producing heavy particles, for instance Higgs or *W* bosons, is that a parton from one proton collides with a parton from the other proton. This parton-level collision happens at space–time distances well below a femtometre and can be computed in perturbation theory, provided of course the interactions of the heavy particles are known. To compute the overall process, one must also know the density of partons of a specified type and with a specified momentum fraction *x* inside the proton.

If two heavy particles are produced, they can originate from a single parton–parton interaction, but also from two separate parton-level collisions in one and the same proton–proton collision, as sketched in Fig. 1(a) and 1(b), respectively. The second mechanism, called double parton scattering, is often suppressed compared to single parton scattering, but it can compete or even dominate in specific kinematic configurations of the final-state particles, and its importance generically grows with the collision energy.

Its computation requires knowledge of double-parton distributions, which give the joint distribution of two partons

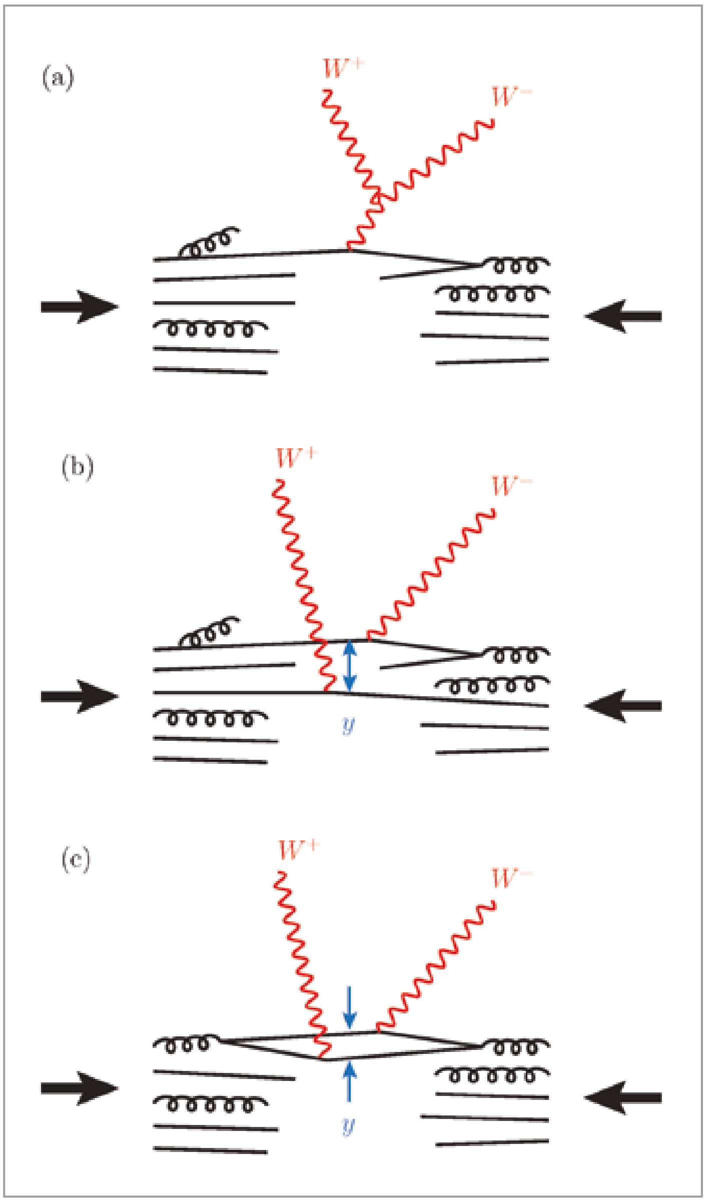
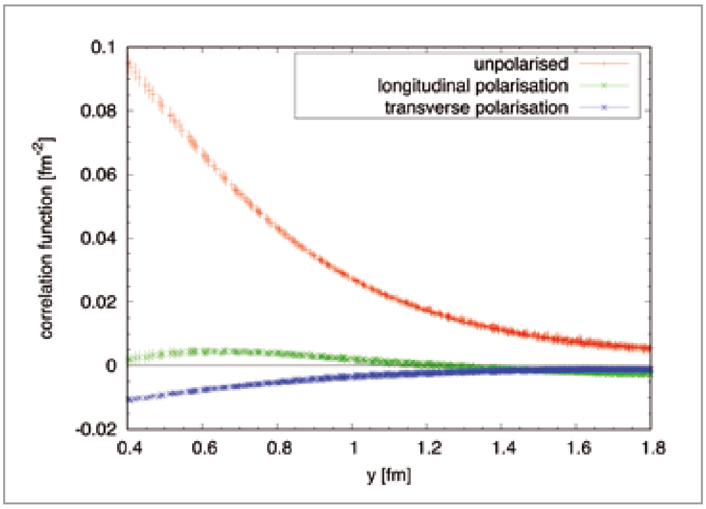


Figure 1

Graphs for the production of a *W* pair in the collision of two protons (represented by large arrows). The standard single parton scattering mechanism (a) is of particular interest because of its sensitivity to the coupling between three electroweak gauge bosons. In double parton scattering (b), the two *W* bosons are produced in two short-distance processes separated by a distance *y*. Depending on the distance *y*, graph (c) is interpreted as single or double parton scattering.

Figure 2

Lattice QCD results for a correlation function closely related to the joint distribution of a *u* quark and a *d* antiquark in a π^+. Shown are the functions for unpolarised partons and for spin correlations as explained in the main text. Details of the lattice computation are given in Ref. [5].



with momentum fractions x_1 and x_2 inside a proton. These distributions also depend on the distance *y* between the two partons in the plane transverse to the proton momentum. Although these distributions are poorly known compared with their single-parton counterparts, our theoretical understanding of double parton scattering has much improved in recent years. On the experimental side, there is an increasing number of LHC measurements of double parton scattering, some of them with strong participation of the DESY CMS group [1].

Somewhat surprisingly, there is actually no sharp distinction between single and double parton scattering in general. At small distances *y*, the two partons specified in a double-parton distribution can arise from the splitting of a single parton. Thus, the graph in Fig. 1(c) contributes to double parton scattering. If, however, *y* becomes comparable to the inverse *W*-boson mass (which sets the characteristic scale of the short-distance process), then the appropriate description is as a single gluon–gluon collision producing the *W* pair. In the cross section, the distance *y* is integrated over, and it is non-trivial to combine the two descriptions in a consistent and manageable way. This is achieved in the formalism of Ref. [2], which in particular provides a field-theoretic definition of double-parton distributions, so that these can be investigated systematically in both the short- and long-distance regime. A first calculation for small *y* at next-to-leading order in perturbation theory has just been completed [3].

Double-parton distributions reveal interesting aspects of proton structure, as they quantify how the properties of two partons inside a hadron are correlated with each other. A recent study [4] has shown that spin correlations between two partons can have observable consequences in double parton scattering processes. At short inter-parton distances *y*, one easily finds that the splitting mechanism in Fig. 1(c) gives rise to strong parton spin correlations. The situation at large distances requires methods beyond perturbation theory and remains largely unknown.

An exploratory study of double parton distributions in lattice QCD has been performed by members of the DESY theory group and the lattice group at the University of Regensburg. For technical reasons, this study was performed for a pion. Figure 2 shows the results for a correlation function that is related to the joint quark–antiquark distribution in a pion. In the curves for polarised partons, quark–antiquark pairs with aligned spins are counted with a positive sign and pairs with anti-aligned spins with a negative sign. Here, “longitudinal” and “transverse” polarisation is with respect to the direction of movement of the pion.

One finds that both spin correlations are very small. This is a surprising result, because the simplest picture of a pion as a bound quark–antiquark pair with anti-aligned spins would yield spin correlations equal in size and opposite in sign to the unpolarised curve. It will be very interesting to investigate what the situation is for the corresponding distributions in a proton, the calculation of which is now under way.

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Quantum Universe

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

The new cluster of excellence "Quantum Universe", which Universität Hamburg won in the German Excellence Strategy competition coordinated by the German Research Foundation (DFG), officially started in January 2019. The research of the cluster centres on a comprehensive investigation of the intriguing relations between quantum physics, which describes the smallest objects in nature, and the structure and evolution of the universe. Roughly 300 researchers work in the cluster. The research team includes leading scientists from mathematics, particle physics, astrophysics and cosmology at Universität Hamburg and DESY. The cluster will approach the fundamental puzzle of mass and gravity from four different directions: Higgs physics, dark matter, gravitational waves and quantum theories of matter and gravity.

Progress on Higgs physics, dark matter, axions and gravitational waves, together with their relations to phase transitions and inflation in cosmology, has to be based on the development of new mathematical structures connecting quantum theory and gravity, as illustrated in Fig. 1. With its comprehensive coverage of the relevant scientific spectrum, the cluster is well positioned to carry out this ambitious endeavour. We foresee concrete scientific and structural achievements that will prepare the stage for activities in Hamburg to extend beyond the timescale of the cluster. In order to foster the synergies between the different projects and to strengthen interdisciplinary knowledge transfer, four cross-disciplinary platforms are being implemented on theoretical and mathematical physics, data science, detector science and future facilities.

In Higgs physics, we will develop new tools for high-precision measurements and searches for new phenomena in order to exploit the expected large increase in ATLAS and CMS data. Together with corresponding high-precision calculations, this will enable us to derive implications for new phenomena connecting Higgs physics with dark matter and early universe cosmology. This includes phenomenological studies as well as sophisticated statistical analyses of data and their interpretation. These results will be used in the platform for future facilities to assess the physics case for the next generation of particle colliders.

On the dark-matter front, astrophysical data from gamma-ray telescopes and new extragalactic surveys will be analysed and combined to investigate thermally produced dark matter over a very large parameter range. We will participate in the development of new detection schemes for light dark matter searches and plan to make Hamburg a hub for axion searches by complementing ALPS II activities through the development of several novel experiments on site (MADMAX, BRASS, IAXO).

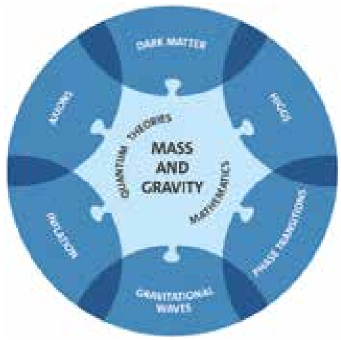

Figure 1
Sketch of the science of the Quantum Universe cluster

Gravitational-wave (GW) research will be a new core element of the cluster. For the next generation of GW detectors, such as the envisioned Einstein Telescope, we will launch a new R&D programme on cryogenic test mass mirrors. The long-term goal is to reach the sensitivity required for the detection of GW signals of cosmological origin, which are motivated by fundamental particle physics questions.

As a rather novel path to answering questions about astrophysical phenomena, we will also work on laboratory astrophysics experiments to examine the properties of hot magnetised plasmas.

The challenges addressed in this cluster necessitate the development of qualitatively new theoretical tools. In a coordinated effort of mathematicians and physicists fostered by the platform for theoretical and mathematical physics, which will ensure a constant influx of the most recent ideas, we aim to improve our understanding of quantum field theories and string theories.

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Conformal bootstrap at DESY

Physics of the extremes

Conformal field theories (CFTs) are of fundamental importance in theoretical physics. They describe condensed-matter systems at criticality and, more generically, the extreme high- and low-energy behaviour of quantum field theories (QFTs). At DESY, a dedicated Emmy Noether research group is studying CFTs using an elegant approach known as the bootstrap.

Our modern understanding of quantum field theory is as a renormalisation group flow between an ultraviolet (UV) and an infrared (IR) description. Different systems in the UV flow to a handful of possible critical behaviours in the IR. We call this "universality", and it implies that quite dissimilar systems, such as the boiling point of water and ferromagnets at the critical temperature, are described by the same theory. The theories in the extremes of the flow (Fig. 1) are invariant under a symmetry known as conformal symmetry, which is why they are called conformal field theories.

CFTs are severely constrained by symmetry, and a successful approach to study them goes by the name of the bootstrap. The bootstrap approach attempts to describe the physics of a theory using consistency requirements with minimal external input. At DESY, there is a dedicated group on the conformal bootstrap funded by the German Research Foundation (DFG) through its Emmy Noether Programme [1].

One of the lines of research explored by the group is the dynamics of extended objects in CFT. QFT observables are not always point-like – examples include Wilson lines in gauge theories as well as boundaries and interfaces in condensed matter. Extended objects are usually called defects, and they break the conformal symmetry down to a subgroup. The subgroup is nevertheless powerful enough that bootstrap techniques are applicable.

The Emmy Noether group also focuses on supersymmetric theories. The addition of supersymmetry enhances the already powerful conformal symmetry to an even more powerful superconformal symmetry. The tight structures associated with superconformal invariance allow for many exact results. This second line of research has a more formal motivation, but fits nicely within the profile of the DESY theory group, in which formal aspects of quantum field theory play a prominent role.

In the coming years, the group intends to deepen the understanding of these systems, but also to expand the applicability of the bootstrap. An ambitious long-term goal relevant for particle physics would be to study quantum chromodynamics (QCD) in its conformal phase, which should be amenable to bootstrap techniques.

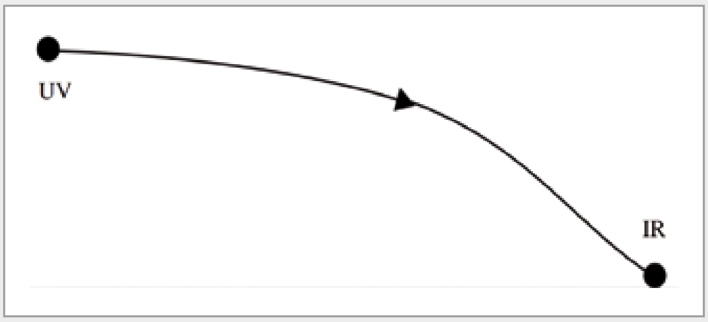

Figure 1

Quantum field theories interpolate between a UV and an IR description

Emmy Noether group

"The Conformal Bootstrap Program"

Emmy Noether-Programm DFG

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Geometric coding of non-perturbative physics

A road to strong coupling

The physics of gauge theories at low energies remains an enormous challenge. Progress has been made in simplified models. The famous work of Nathan Seiberg and Edward Witten published in 1994 led to a proposal for how to compute the low-energy effective actions for large classes of quantum field theories with $N = 2$ supersymmetry. Nikita Nekrasov was able to verify this proposal by computing all instanton corrections to the low-energy effective action. Recent work of a group at DESY led to a significant generalisation of these results. It provides a mathematical description of the result of the sum over all quantum corrections, giving access to the physics at strong coupling.

The challenge of low-energy physics

Gauge theories are an indispensable ingredient in our current understanding of high-energy physics. For many applications of gauge theories to the physics of the strong interactions, it is crucial that the strength of the interactions gets small at high energies, a phenomenon known as asymptotic freedom. This allows us to use the Feynman diagram technique to calculate physical quantities such as scattering cross sections with good accuracy. The physics of the strong interactions at low energies is much less well understood. It is expected to be very different, exhibiting phenomena such as quark confinement. A lot of effort has been invested into the development of methods that give control over this regime. However, it seems fair to say that many basic questions remain unanswered, and there are various regimes that are far from being understood.

In this situation, it may help to adopt a broader point of view. We need to understand what happens when the coupling constants of quantum field theories are no longer small. In order to develop more powerful methods and gain insights, it may help to look at simpler quantum field theories first. A particularly encouraging phenomenon discovered in such quantum field theories is called duality. This means that it may happen that a Feynman diagram description can be regained at sufficiently strong coupling, although this description may be very different from the one used to describe the theory at low coupling. Such dualities have been found in a large family of quantum field theory models. In some examples in lower-dimensional space–times, there exist even mathematical proofs of such dualities, such as the duality between the sine-Gordon and massive Thirring models predicted by Sidney Coleman. In other cases, such duality conjectures have been checked with great precision.

Figure 1

Riemann surface

(Source: Wikipedia, public domain)

A large class of examples where the low-energy physics has been understood in great detail is provided by supersymmetric quantum field theories. The work of Seiberg and Witten [1] has led to a beautiful description of the low-energy physics of various $N = 2$ supersymmetric quantum field theories. These results have in particular led to an understanding of the confinement phenomenon in some models for quantum field theories with $N = 1$ supersymmetry.

Seiberg–Witten theory

The description Seiberg and Witten proposed in [1] is based on a classical chapter of mathematics, the theory of Riemann surfaces (Fig. 1). The theory of Seiberg and Witten roughly works as follows: The goal is to compute the low-energy effective action that encodes a lot of the information one may want to have about the physics at low energies. This effective action is a function of the fields describing massless excitations. The constraints from supersymmetry imply that the low-energy effective action can be written down once one knows a single function of the scalar fields that survive at low energies. This function is called prepotential. The goal is therefore to compute this function.

Here is how Seiberg and Witten computed the prepotential for a large family of cases: Everything is encoded in geometric objects called Riemann surfaces, which are two-dimensional surfaces of a special kind. Many of them can be described as the set of solutions of an equation in two variables, such as

$$R(x,y)=0\,,\quad R(x,y)=y^2-q(x)\,,\quad (1)$$

with $q(x)$ a known function in which the coupling constants, masses and vacuum parameters of the theory are encoded. The variables x and y are complex numbers. The set of solutions of Eq. (1) therefore defines a two-dimensional surface.

One may then consider the collection of integrals of the form

$$a_\gamma = \int_\gamma \sqrt{q(x)}dx$$

where the contours of integration are closed curves around the handles. Among all such contours, let us consider the subsets containing the curves coloured green and blue in Fig. 2, respectively. A classical result of Riemann surface theory (Riemann's bilinear identity) implies that there exists a function F of the integrals along the green curves such that the integral along the blue curve is simply the derivative of F with respect to the integral along the green curve intersecting it. The prepotential is exactly this function F if one identifies the integrals along the free curves with the scalar fields one finds at low energies.

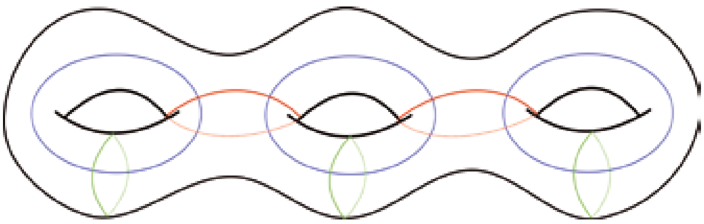

Figure 2

Curves on a Riemann surface (Source: Wikipedia, CC BY-SA 3.0)

The geometric description of the low-energy physics given by the theories of Seiberg–Witten is very powerful. One can use it to investigate – quantitatively – what happens when the coupling constants get large.

"Quantising" Seiberg–Witten theory

Even more information about a quantum field theory can be extracted from expectation values of observables. Nekrasov identified a particular observable $O(P)$ in 2002, which turns out to be both particularly interesting and explicitly calculable at the same time. It depends on a parameter P in such a way that the observable disappears (becomes equal to the identity) when P vanishes. By further developing a mathe-matical technique known as localisation, Nekrasov was able to compute the expectation value of $O(P)$ exactly. The resulting function is often called Z-function. The Z-function can be written as a sum of powers of P. Nekrasov showed that the coefficient of the term with the lowest power of P is exactly equal to the prepotential conjectured by Seiberg and Witten. The coefficients of higher powers of P contain additional information on the quantum field theory under consideration.

It is natural to ask if there is a geometric description of the Z-functions similar to the one Seiberg and Witten gave for the prepotential. The main result of our recent work [3] at DESY is such a description. Remarkably, it is based on a "quantised" version of the Riemann surface considered above, which is described by the differential equation

$$R\left(x, \frac{\hbar}{i}\frac{d}{dx}\right)\psi(x)=0\,,\quad (2)$$

which resembles the stationary Schrödinger equation from quantum mechanics. To extract the Z-functions from the solutions to Eq. (2), we had to develop a certain mathematical machinery. It involves a combination of some classical results from the mathematics of Riemann surfaces and the theory of the Painlevé equations with very recent advances on the relations between the theory of integrable models and conformal field theory.

The power of the method developed in [3] lies in its huge potential for generalisations, which goes significantly beyond the cases covered by Nekrasov's theory. Furthermore, the description is not based on a particular series expansion. It offers an elegant mathematical description of the result of the summation over all perturbative and non-perturbative quantum corrections for the Z-function. This makes it possible to investigate the strong-coupling behaviour of this class of gauge theories in geometric terms, leading to highly non-trivial checks of some duality conjectures.

Our results nicely illustrate the significant contribution of mathematics to our ongoing efforts to understand how quantum field theory works.

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Dark matter and the high-energy frontier

New goal for cosmic-ray experiments

Dark matter constitutes one of the most pressing open issues in our understanding of nature. Experimental searches for it have mostly focused on new particles lighter than a TeV or so, but have so far turned out empty-handed. Heavier dark-matter candidates therefore constitute a motivated alternative, especially in light of the new wealth of high-energy cosmic-ray data from operating (e.g. H.E.S.S. II, IceCube) and planned (e.g. CTA) telescopes. The DESY theory group is exploring models of heavy dark matter and has demonstrated that these models could indeed give rise to detectable signals in such telescopes, opening a new observational window on this long-standing mystery.

Why dark matter?

Take all the matter that we are able to see in galaxies and galaxy clusters, from stars to gas clouds. Then try to predict the motion of galaxies based on these observations and on the theory of gravity: You will obtain speeds that are orders of magnitude slower than the ones measured by astronomers. Now go to even larger scales and marry the two most successful scientific theories to date – the Standard Model of particle physics and the theory of General Relativity – into the standard cosmological model. Again, you will be disappointed to find that some predicted properties of the universe, from the distribution of galaxies to the precise features of the cosmic microwave background (the fossil radiation from the moment the universe became transparent), are completely different from what is observed.

Remarkably, these outstanding and apparently disconnected failures of our fundamental understanding of nature can be solved all at once with the assumption that a new kind of matter permeates our universe. This new matter should interact little with atoms, nuclei and in particular with light – otherwise we would have seen it already – hence the name "dark matter" (DM). To quantitatively explain all the observations above, our universe should contain approximately five times more DM than the matter we understand and which forms everything we see, from stars to living beings. It is then no surprise that the quest for the nature of DM constitutes a major goal of modern physics. This goal lies at the intersection of cosmology, particle physics and astronomy, and the DESY theory group is striving to push back all these frontiers.

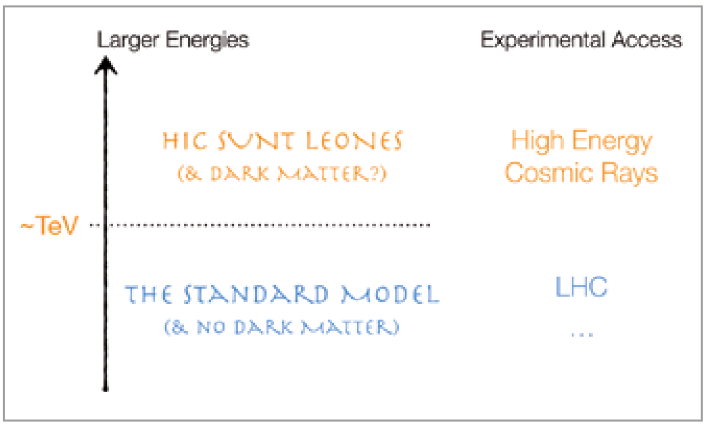

Figure 1

Sketch of the theoretical and experimental dark-matter landscape

A way forward from data

Many theoretically appealing extensions of the Standard Model, proposed to solve some other of its failures, predict as a bonus the existence of particles that have all the good properties to constitute the observed DM. The most notable example is given by frameworks such as supersymmetry and extra dimensions, which can accommodate DM in the form of weakly interacting massive particles (WIMPs), with a mass between a few GeV and a few TeV. Despite huge and lasting experimental efforts, no evidence for WIMPs or for the frameworks mentioned above has so far been found in the data. While it is too early to declare the WIMP paradigm defeated, this situation has led many physicists to explore other directions.

Intriguingly, the lack of evidence for the models that motivate WIMPs is indicating an alternative road to make progress. Indeed, one lesson from the current LHC data is that the needed new physics may lie (well) above the TeV scale. In the

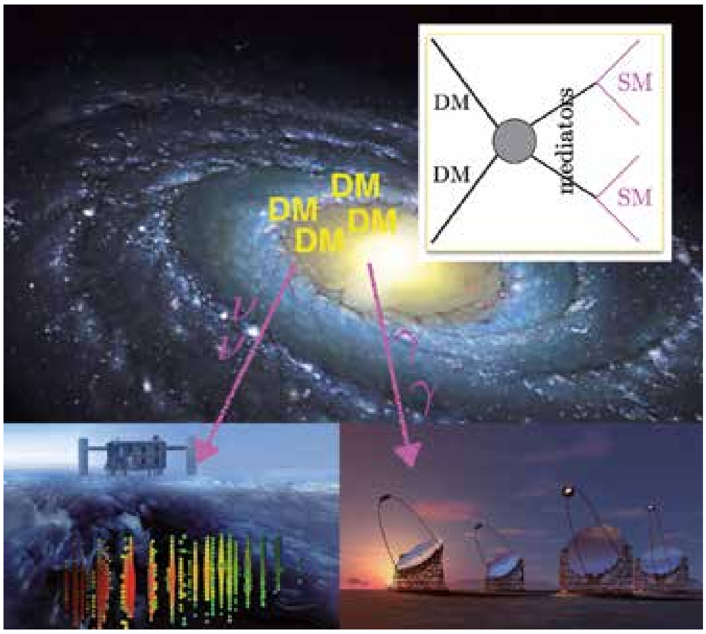

Figure 2

Neutrinos and gamma rays are two messengers relevant for dark-matter searches.

decades that separate us from the much needed higher-energy colliders, how to investigate nature at such scales? Cosmic rays with energies above a TeV currently constitute our unique direct access to that realm. The new physics models at these energy scales naturally predict DM candidates in a similar mass range ("heavy DM"), see e.g. [2]. The situation described so far is represented in Fig. 1.

Studies of heavy dark matter by the DESY theory group

Contrarily to WIMPs and other DM candidates such as sub-GeV particles or primordial black holes, the community has so far invested relatively little effort in exploring the experimental detectability of heavy DM. This effort is now gaining motivation by the general situation described above and, importantly, by the recent and foreseen wealth of data from telescopes observing high-energy neutrinos (e.g. ANTARES, IceCube), gamma rays (e.g. H.E.S.S. II, TAIGA, CTA), electrons (e.g. CALET), etc. Could these data be used to look for the product of DM annihilations (Fig. 2), and could they teach us some-thing about the existence and the properties of heavy DM?

The DESY theory group recently led a project that resulted in a positive answer to these questions [3]. A theoretical challenge was the so-called unitarity bound: The simple requirement that the DM annihilation probability be smaller than 1 translates into an upper bound on the DM mass of *O*(100) TeV, otherwise there would be more DM in the universe than what is observed. This challenge is solved in models where the DM abundance is set by its early annihilation into "mediators", which in turn decay into Standard Model particles (top right corner of Fig. 2). If the mediators are sufficiently long-lived, when decaying they increase the universe's entropy and so dilute the abundance of DM, thus opening the possibility of larger DM masses. The same class of models automatically addresses another technical challenge to testing heavy DM in cosmic rays, related to the computation of their energy spectra.

Encouraged by these promising properties, we computed the DM signals in cosmic rays as predicted by these models. We found that these signals are within the reach of several telescopes, offering a multimessenger line of attack to test heavy DM. This study also led us to realise that some telescopes – especially neutrino and gamma-ray telescopes – have an unexplored potential to test annihilating DM with a mass of *O*(100) TeV. This motivates an experimental effort in this direction, which has already been initiated in cooperation with the ANTARES collaboration.

These results enrich the physics case of high-energy telescopes and open a new observational window on heavy new physics sectors. Future directions include the interplay of such cosmic-ray signals with other experimental avenues (collider, gravitational waves) and, on a more theoretical side, the exploration of connections of heavy DM models with solutions to other problems of the Standard Model.

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Heavy quarks, multilevel algorithms and tensor networks

Developing methods for non-perturbative aspects of quantum field theories

The particle physics group at the John von Neumann Institute for Computing (NIC) at DESY in Zeuthen focuses on quantum field theories, in particular their non-perturbative aspects. Major efforts of the group aim at developing new methods and concepts to understand non-perturbative phenomena in quantum field theories and calculate physical observables with high precision.

Tensor network methods

Nowadays, the path integral is clearly the method of choice for evaluating lattice quantum field theories (LQFT). Still, in the early days of LQFT, it was the Hamiltonian formalism that was most frequently used. In practice, this approach was abandoned, though, due to the untractably large size of the Hilbert space. In the last years, however, theorists have realised that only a small set of all possible states is relevant to obtain ground state properties. This small corner of the Hilbert space is built by states that obey the so-called area law.

These states can in general be constructed through tensor network states, which become matrix product states (MPS) in one dimension. In this approach, the very high-dimensional coefficient tensor needed in the Hamiltonian formalism is replaced by a product of complex matrices. By systematically increasing the size of these matrices and computing their entries through a variational method, minimising the energy as a cost function, ground state properties can be computed very precisely. In fact, mathematical theorems state that this procedure converges exponentially fast to the ground state of the considered Hamiltonian. In practice, the size of the used matrices is of order 100, which makes such computations completely feasible, and tensor networks have been used for condensed-matter systems very successfully.

As one of the first, the NIC group adapted this approach of the Hamiltonian formalism using MPS for models in high-energy physics [1]. Since the Hamilton formalism is free of the sign problem, it offers the exciting possibility to study, in principle, questions where conventional Monte Carlo methods fail and which include non-zero baryon density that is relevant for understanding the early universe, topological terms for the matter–antimatter asymmetry and real-time evolutions of physical systems.

By computing the low-lying particle spectrum of the one-dimensional Schwinger model as a benchmark, we were able to provide a proof of principle that MPS can be used also for gauge theories. Followed by a calculation in this model at non-zero temperature, the Schwinger model for two flavours of fermions was studied with a non-zero (isospin) chemical potential. Addressing this question by conventional Monte Carlo methods is impossible due to a severe sign problem. It was therefore very important to test whether MPS can overcome this difficulty, or whether the sign problem reappears in a different way. However, we were able to show that the MPS technique performs very well also in the situation with a non-zero chemical potential.

Working first with a zero fermion mass, MPS results were confronted with an analytically known expression, and a complete agreement was found, demonstrating that MPS solves the problem of a non-zero chemical potential. Switching on a fermion mass, we established the phase diagram in the plane of chemical potential and fermion mass [2] (Fig. 1). Here, no analytical result is available, and only the use of MPS made it possible to obtain this phase diagram, making MPS or tensor networks a most promising tool to address important and so far intractable problems in high-energy physics.

Still, a warning is in order, since the computational cost of calculations for dimensions higher than one is presently too large to study systems of realistic size. However, a substantial amount of research is ongoing to find better techniques for high dimensions, as discussed in a recent workshop co-organised by the NIC group. There, several new ideas were presented, which have the potential to make tensor networks practical also in higher dimensions.

Towards multilevel Monte Carlo methods for QCD

A major obstacle to progress in lattice field theory computations is the deterioration of the signal of *n*-point correlation functions with increasing distance of these points. Large distances are needed to effectively study the ground state properties of the theory. Since lattice computations employ Monte Carlo sampling, uncertainties decrease with the inverse square root of the number of measurements – an expensive technique in the face of a noisy signal. By using the locality of the underlying theory and designing algorithms where this fundamental property is manifest even in the presence of fermions, sampling strategies can be devised that have an improved convergence: Depending on the number of regions, a convergence with the inverse number of measurements, or even a higher power become possible.

Such methods have been available for some time for pure gauge theory, where the formulation is manifestly local and observables are also typically easily decomposed into products of local contributions. Each of these local components can then be averaged over independently, leading to an exponential speed-up in the size of the observable.

Fermions are fundamentally different from bosons. They are integrated out analytically before formulating the Monte Carlo and thus lead to non-local contributions. Using domain decomposition techniques, we managed to propose a strategy how these multilevel methods become amenable to theories with fermions [3]. In order to achieve this, the hadronic two-point functions and the contributions from the fermion sea to the path integral had to be factorised, such that the independent averages of each of the factors can be taken. First tests are very encouraging, and more detailed investigations are under way.

Effects of heavy fermions on low-energy physics and high-energy strong coupling

The discretisation of space–time on a regular lattice leads to a Brilloin zone just like in crystals. Thus, the high-momentum high-energy behaviour is distorted. In addition, particles with large masses cannot be simulated properly. For this reason, lattice simulations include up, down and strange quarks, while the bottom and top quarks with masses above 4 GeV are excluded, since they would contribute more distortion effects than physical effects. The charm quark with a mass of around m_{charm} = 1.3 GeV is in between the typical scale of hadronic physics E_{had} ~ 0.5 GeV and the achievable cut-off (the edge of the Brilloin zone) of E_{cut} ~ 4 GeV. A good question is thus whether it is better to include the charm quark (often called 2+1+1 simulations) or not (2+1), and what are the uncertainties introduced by leaving it out.

In general, the answer to this question will depend on many details, from how one discretised QCD to which process one wants to predict from the simulations. Fortunately, some rather universal statements can also be made.

At low energies and momenta, say at E_{had} and below, there is a systematic expansion in terms of $y = E/m_{\text{charm}}$, given in terms of an effective field theory, which excludes the charm quark, but has a few additional terms in its Lagrangian with coefficients proportional to $1/m^2_{\text{charm}}$. We have investigated these corrections in a special limit of QCD and found that

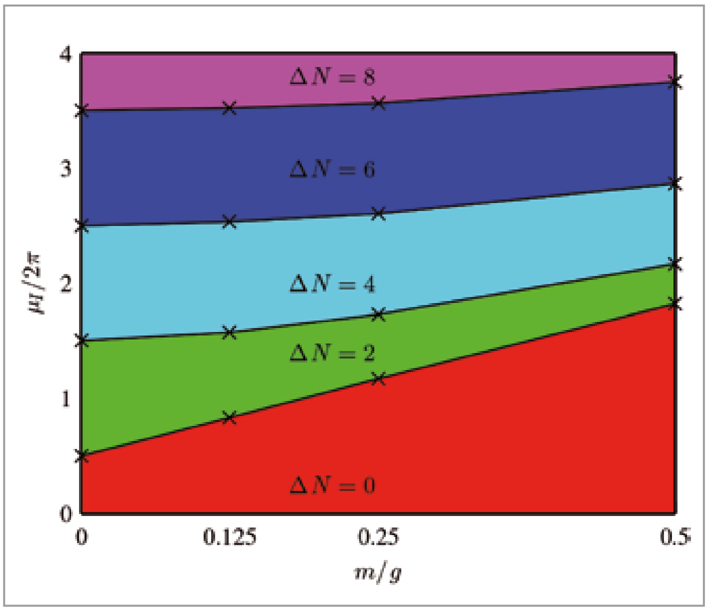

Figure 1

Phase diagram of the two-flavour Schwinger model in the mass–chemical potential plane. The different phases are characterised by different particle densities. There is no analytical prediction for this phase diagram, and its determination became only possible by applying tensor network methods.

they are at the (few) permille level, much smaller than one may naively have expected. It is justified to conclude that for low-energy physics, also in QCD as realised in nature, one may safely leave out the charm quark and work with the 2+1 theory [4].

At truly high energy, one can also make simple statements on how to include the charm quark. The reason is that there, the QCD coupling $\alpha(E)$ is small and one can expand in it. Still, it is a most relevant task to predict the coupling in terms of the low-energy physics, described by the 2+1 theory. We have recently demonstrated – again in a model computation – that for the step of connecting the coupling of the 2+1 theory to the one of QCD with the charm quark, the perturbative expansion in $\alpha(m_{\text{charm}})$ is very accurate [5].

As a second outcome of that study, one can conclude that the heavy-quark contribution to the coupling of scalar dark matter to hadrons is accurately given by perturbation theory and therefore known more accurately than previously thought.

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Workshop: https://indico.desy.de/indico/event/21941/overview

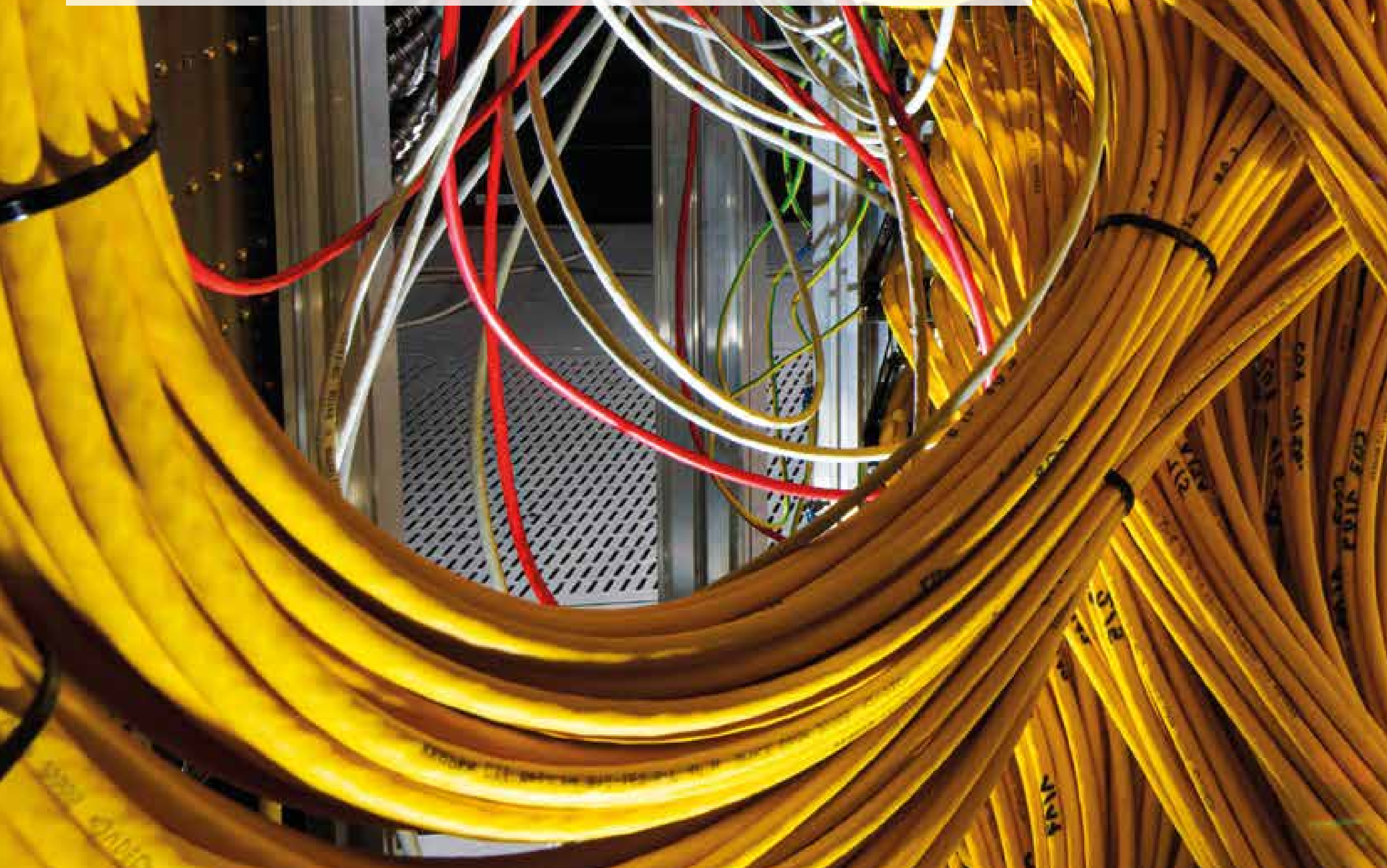
Projects and infrastructure

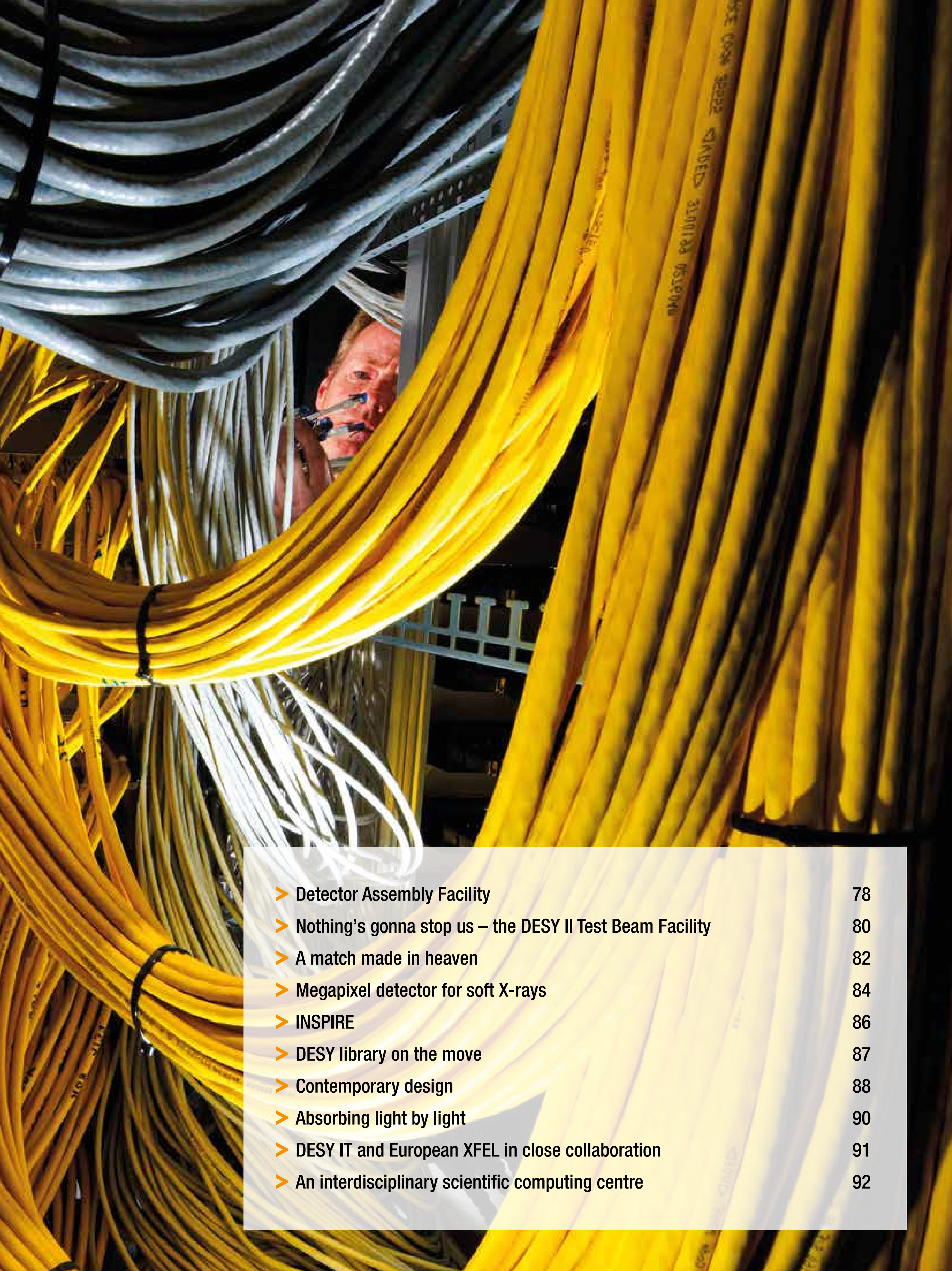
The experimental and theoretical research activities at DESY would not be possible without the contributions and support from numerous groups and people. One important service offered by DESY is its Test Beam Facility at the DESY II synchrotron. Scientists from all over the world are using the facility to subject newly developed detector components, e.g. for the International Linear Collider (ILC) or the LHC upgrades, to tests with electron or positron beams (p. 80). Another important facility in this context is the Detector Assembly Facility (DAF), which was commissioned in 2018 (p. 78).

Just as essential are the DESY electronics groups, which design and manufacture important components for particle physics detectors (p. 84). Other activities in this realm are the development of new spectrometers that are then tested at DESY's FLASH facility (p. 82) or studies of the feasibility of new experiments, as in the LUXE project (p. 90).

Computing too is a crucial ingredient. The DESY IT group is constantly striving to improve its services for all users and needs, for example for the European XFEL X-ray laser (p. 91). These efforts led to the plan to unify access for all users and unite the provided services in an interdisciplinary scientific computing centre (p. 92).

As the DESY campus is rapidly evolving and growing, computer-aided design systems are increasing in importance (p. 88). Meanwhile, the DESY library group is supporting the important publication database INSPIRE-HEP (p. 86) and improving the usability of the traditional library (p. 87).





Detector Assembly Facility

Infrastructure for developing and building large-scale high-precision detectors

For the High-Luminosity LHC (HL-LHC) tracking detector upgrades of ATLAS and CMS, the DESY groups will build one end-cap each for both experiments together with the collaborating German institutes. These high-precision large-scale detectors made of silicon sensor modules have to be built in a clean environment to reach the required quality. Large cleanrooms are therefore needed to enable the production of the modules and the assembly of the end-caps. This infrastructure was realised by re-using two existing buildings on the DESY campus in Hamburg. After three years of planning and construction, the Detector Assembly Facility (DAF) was completed and commissioned in 2018.

Cleanroom for silicon sensor module production

The tracker end-caps of the upgraded ATLAS and CMS experiments are based on silicon sensor modules with an active area of about 10 x 10 cm^2. Each end-cap is composed of roughly 3000 modules and will have an area of 30 m^2 (ATLAS) and 46 m^2 (CMS) covered with silicon sensors. The sensors and readout hybrids are very delicate objects that have to undergo several assembly steps in order to build a module. These production steps require a clean, temperature- and humidity-controlled environment, which is now available in a cleanroom on the ground floor of Building 25c on the DESY campus in Hamburg. The cleanroom was planned for quality classification 6 according to ISO 14644-1 (ISO-6), which corresponds to a maximum of 8320 particles larger than 1 µm per cubic metre of air.

Figure 1

ATLAS area in the DAF cleanroom

The cleanroom has a total area of 250 m^2, which is divided into an entrance area of 20 m^2 and two separate lab spaces of about 115 m^2 each for ATLAS and CMS. In order to reach the required cleanliness of the air, the ceiling is equipped with 72 fan filter units (FFUs), which cover about 25% of the area and blow filtered air into the cleanroom. The walls of the cleanroom are made of double-walled aluminium sandwich plates that act as air ducts for the consumed air. Consumed air from the cleanroom flows through these air ducts into a circulation volume – the plenum – on top of the cleanroom and is again filtered by the FFUs before being blown back into the cleanroom. With this configuration, the longevity of the FFU prefilters is significantly increased, as the air conditioning system has to provide only a limited amount of unfiltered air.

At various locations throughout the cleanroom, outlets for dry and clean pressurised air, nitrogen and vacuum are provided to the users. In the entrance area, a wet bench with a purified water outlet and drains for liquid chemicals is available for small-scale cleaning applications. The cleanroom is entered through a personnel air lock. In addition, a material air lock is available that can be accessed with a forklift in order to bring larger pieces of equipment into the cleanroom.

The commissioning of the cleanroom started in mid-2018 and was finished by fall. Since then, the temperature and humidity have been constantly monitored, and the environmental conditions lie well within the specifications of 21 ± 0.5°C in temperature and 45 ± 5% in relative humidity. In addition, particle counts are being measured on a regular basis at various locations in the cleanroom. Although planned for ISO-6, the measurements suggest an even better air quality close to the ISO-5 standard.

The cleanroom on the ground floor is complemented by two grey rooms and a solder lab on the first floor of Building 25c. With the cleanroom and labs fully commissioned, the DESY ATLAS and CMS groups started to install the equipment required for the production tasks. In the meantime, both groups have built first prototypes in order to learn how to handle the delicate components and to define the final production procedures. Figure 1 shows the ATLAS area with (from left to right) the probe station, automatic wire bonder, wire bond pull tester and optical inspection equipment.

DAF assembly and integration labs

The produced silicon detector modules will be mounted onto mechanical structures, and finally both end-caps will be assembled. To this end, a second cleanroom system with a total area of 750 m^2 was set up in Building 26 on the DESY campus in Hamburg. This cleanroom with less stringent requirements in terms of particle contamination and hence only ISO-7 classification (less than 83 200 particles larger than 1 μm per cubic metre) is divided into two parts connected by a clean transit area with an air lock to decouple the two areas. The system can be accessed through a personnel air lock, and for larger equipment a material air lock is available.

One part of the cleanroom with 290 m^2 will be used for the integration of the modules onto their mechanical support structure and the subsequent testing at the final operation temperature of -35°C. The second part of the cleanroom with 332 m^2 and a ceiling height of 5 m will be used for the final assembly of the end-caps.

Although the requirements in terms of particle contamination are less stringent than for the cleanroom used for module production, the environmental conditions in this cleanroom are stabilised to 21 ± 0.5°C in temperature and 45 ± 5% in relative humidity. At several locations in both areas, cooling water outlets are available that allow for an efficient operation of the CO_2 and other cooling plants required for the cold tests. In addition, outlets for nitrogen and dry pressurised air are provided throughout the cleanroom.

The commissioning of the cleanroom was finished at the end of 2018. The groups started to install and commission equipment and devices and moved parts of their R&D activities into the new laboratory. Figure 2 shows the area of the integration hall where the CMS end-cap will be assembled.

Figure 2

CMS integration area in Building 26

The portal crane visible at the back of the room will be used to handle the end-cap disks with a diameter of almost 2.5 m during assembly. A high-precision mounting platform of 3.6 m x 4.4 m will be installed on the floor in front of the crane to allow assembly of the CMS end-cap disks with the required accuracy.

For ATLAS, an insertion tool for installation of the wedge-shaped parts into the ATLAS end-cap is presently being constructed.

Current planning foresees that the two end-caps for ATLAS and CMS will be built and tested in this infrastructure until the end of 2024 before being delivered to CERN for final installation into the full detector system.

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Nothing's gonna stop us

DESY II Test Beam Facility continues to deliver beam to its global user community

DESY operates the DESY II Test Beam Facility for R&D projects of the global detector community. After the Christmas shutdown 2017, the facility started running again in February 2018 and – excluding a short summer shutdown – reliably delivered electron and positron beam to its users until Christmas 2018. User groups ranging from the upcoming LHC upgrades to small groups pursuing generic R&D for both detectors and accelerators made extensive use of the facility, appreciating the world-class infrastructures at DESY, such as the EUDET-type pixel beam telescopes or the large-bore magnets. During the shutdown 2018/19, the facility will be further upgraded for the 2019 run, which will start at the beginning of February.

The DESY II Test Beam Facility

The DESY II Test Beam Facility uses the DESY II synchrotron for beam generation by means of micrometre-thin carbon fibre targets placed in the primary electron beam. It offers three beamlines located in Hall 2 on the DESY campus in Hamburg. 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. The ease of use and excellent infrastructure make it a very popular facility within the global user community. The test beam team constantly adds improvements to the beamlines and strives to keep it a world-class facility for detector R&D.

The EU-funded AIDA-2020 project continues to support activities at the DESY II Test Beam Facility in many ways. Under its Transnational Access programme, it helps users from outside Germany to come to DESY and perform their tests at the facility. AIDA-2020 supported the development of a large-area silicon strip telescope and the design and test of the EUDAQ2 framework, which allows different detectors to be run using a common data acquisition framework. It also continues to support exisiting infrastructures, such as the EUDET-type pixel beam telescopes.

Highlights from 2018

During the Christmas shutdown 2017/18, the test beam team was busy as usual with general maintenance and preparations to get the facility ready again for the 2018 run. The entire network infrastructure was replaced, and "gigabit Ethernet everywhere" is now the standard at the DESY II Test Beam Facility, with an easy upgrade path to 10 Gb Ethernet.

In 2018, the facility was operated for 37 weeks in total. Over all beamlines, this resulted in 111 user weeks, 70% of which were used. The beam telescopes were again in high demand, with 72% of the groups requesting their use, leaving only 20% of telescope slots unused. Among the user communities, the LHC groups dominated with 43% of requests. As usual, groups from many different fields, ranging from Belle II to ILC detector R&D, made use of the facility. There was also a significant increase in generic R&D for detectors and accelerators, a category to which about a quarter of the groups belonged.

Mu3e

The search for charged lepton flavour violation with the Mu3e experiment at PSI in Switzerland is based on a novel, thin and fast pixel tracker technology (HV-MAPS). During three test beam campaigns at DESY in 2018, the Mu3e pixel team was able to demonstrate the excellent performance of its first large sensor prototype. Using the facility's beam telescopes, the team studied the homogeneity of the sensor response. Eight sensor layers in a custom tracking telescope (Fig. 1) and two scintillating tiles were operated successfully together in the beam, marking a milestone towards the final pixel tracker design. Based on the results of the beam test at DESY, last minor improvements were planned for the final sensor production in 2019.

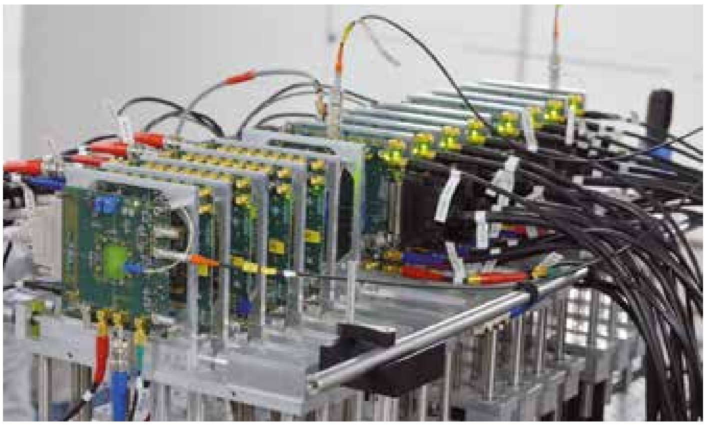

Figure 1

Eight Mu3e sensor layers together with two scintillating tiles in a custom tracking telescope

OSCaR

In the OSCaR experiment, a group from INFN (sections of Ferrara, Legnaro Laboratories and Milano Bicocca) and the Insubria University in Italy studied the enhancement of bremsstrahlung radiation and pair production processes in oriented high-*Z* crystals due to channelling and related effects. By using materials commonly employed to build calorimeters or converters for nuclear, particle and medical physics, this could lead to new detector concepts [1] and intense positron sources [2]. The crystal was placed after two of three tracking planes before a big dipole magnet, which deflects charged particles away. A photon calorimeter was set up behind the magnet. In the first data, an energy loss depending on the crystal orientation was observed (Fig. 2). The research will continue in 2019 in the ELIOT experiment.

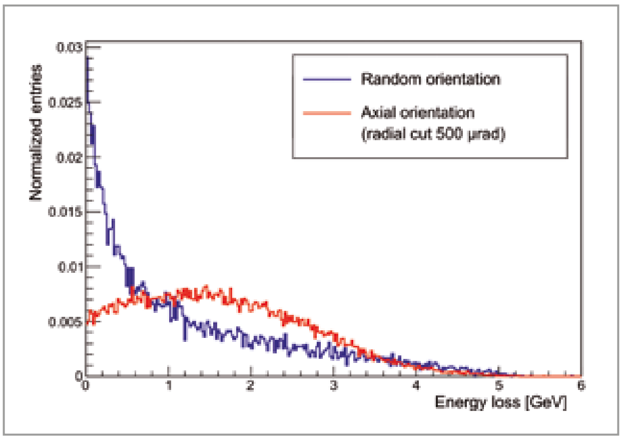

Figure 2

Preliminary results of the OSCaR experiment: Radiated energy loss distribution by 5.6 GeV electrons in a 2.25 mm thick tungsten crystal in case of random/amorphous (blue) and axial (red) orientation

CMS

Throughout 2018, a team from the CMS group at Universität Hamburg conducted tests on CMS inner tracker pixel assemblies for the Phase 2 upgrade for the High-Luminosity LHC (HL-LHC), taking advantage of the beam telescopes. Initially, small prototype sensors produced by Hamamatsu photonics and bump bonded to the ROC4Sens R&D readout chip developed at PSI were tested before and after proton and neutron irradiation. When the novel RD53A chip became available in the summer of 2018, RD53A assemblies were tested before and after proton irradiation. The RD53A chip was developed by the CERN RD53 collaboration as a half-size prototype for the HL-LHC upgrades using a 65 nm CMOS process. The group successfully demonstrated that planar silicon pixel sensors can be operated up to the HL-LHC lifetime fluence of the second layer of the CMS inner tracker.

The educational use of the beamlines of the DESY II Test Beam Facility is by now a well-established part of the programme. In 2018, summer students conducted experiments at the test beam, as did the participants of the course “Particle Physics for Teachers” run by the DESY further education group.

Following up on user requests received during the test beam user workshop in 2017 [3], tests were conducted to operate the DESY II synchrotron with multiple bunches. They showed the potential of increasing the rates available to users by a factor of three with no impact on DESY II operation. The final highlight of the year was the publication of the DESY II Test Beam Facility reference paper, which summarises the technical details and performance of the facility and its infrastructure [4].

Outlook for 2019 and beyond

The Christmas shutdown 2018/19 will again be a busy time for the facility, with the entire interlock and safety system being replaced and upgraded to a state-of-the-art system. During the shutdown, the final electronics for multibunch operation will be installed, and commissioning will follow in spring 2019.

With the shutdown of the test beams at CERN in 2019 and 2020, DESY will operate the only multi-GeV test beam facility in Europe, and the test beam time for 2019 – a total of 120 weeks – is already almost fully booked. As expected, the LHC groups are again the leading user community with 50% of the slots. But we are happy to also welcome a few first-time users from different experiments, such as TOTEM, LHCb and SHIP.

As a novelty in 2019 in consequence of the CERN shutdown, DESY and CERN will co-host the international Beamline for Schools competition [5] for the first time at DESY. In this competition, students can propose their own particle physics experiment to be conducted at a beamline. With around 200 groups of high-school students participating worldwide, this is a truly international enterprise, and we are very much looking forward to welcoming the winning teams and supporting them in conducting their experiments at one of the DESY test beamlines.

In memoriam

To our deepest grief, we had to mourn the loss of Ulrich Kötz in January 2018, who was a member of the test beam team for many years. We sorely miss him, his profound expertise in numerous fields and – more importantly – his contagious enthusiasm and genuine kind personality.

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A match made in heaven

Benchmarking femtosecond diagnostics

For the operation of free-electron lasers (FELs), electron bunches have to be compressed down to micrometre lengths, carrying currents of several thousand amperes over very short times in the femtosecond regime. Very few methods allow the current profiles of these bunches to be measured and monitored with appropriate resolution. At DESY, we have developed an ultra-broadband spectrometer for measuring the coherent radiation of the compressed bunches with high accuracy. Using an elaborate phase reconstruction algorithm, we are able to reconstruct the current profile with a resolution of a few femtoseconds. In 2018, we demonstrated with specially prepared bunch profiles at DESY's FLASH FEL facility that this indirect method is in very good agreement with costly high-power, high-frequency devices.

Challenge and methods

The operation of FELs requires bunches of highly relativistic electrons with very high charge density [1]. In the linear accelerators of FLASH and the European XFEL X-ray laser, electrons are not only accelerated to GeV energies, the electron bunches are also compressed from initially a few millimetres to below 10 μm length. These ultrashort electron bunches enable the process of induced emission of coherent X-rays during their passage through a sinusoidal transverse magnetic field, thereby generating unmatched, intense and short radiation pulses that allow users to observe molecular processes with femtosecond resolution.

The intensity and quality of the X-ray flashes critically depend on the charge distribution of the electron bunches. Two complementary methods were established at DESY to gauge this critical parameter. The more direct method works in the time domain, like in an ultrafast streak camera [2]. The longitudinal charge distribution is projected onto a view screen and observed using a conventional CCD camera. The transverse streaking is achieved by means of a high-power (20 MW) radio frequency pulse travelling in a special microwave resonator called a transverse deflecting structure (TDS).

The second method is more indirect: If the short electron bunches pass through (or even near) a metallic foil, a broadband pulse of electromagnetic radiation is emitted. The frequency spectrum of this radiation reveals information about the spatial distribution of the electrons. The shorter the wavelength of the radiation is compared to the length of the electron bunch, the lower the intensity of the radiation. Mathematically, the power spectrum of the radiation is determined by a frequency-dependent form factor $F(\omega)$ of the bunch, that is, the Fourier transform of the normalised longitudinal charge distribution $\rho(t)$

$$F(\omega) = |F(\omega)|e^{\phi(\omega)} = \int_{-\infty}^{\infty} \rho(t)e^{-i\omega t}\,dt$$

The experimental challenge is to measure the spectral intensity of the radiation simultaneously over an exceedingly large range of wavelengths from a few micrometres up to several hundred micrometres, corresponding to frequencies between 400 GHz and 50 THz. (For comparison: The complete visible spectrum from blue to red light covers less than a factor two in frequency.) At DESY, we have developed a

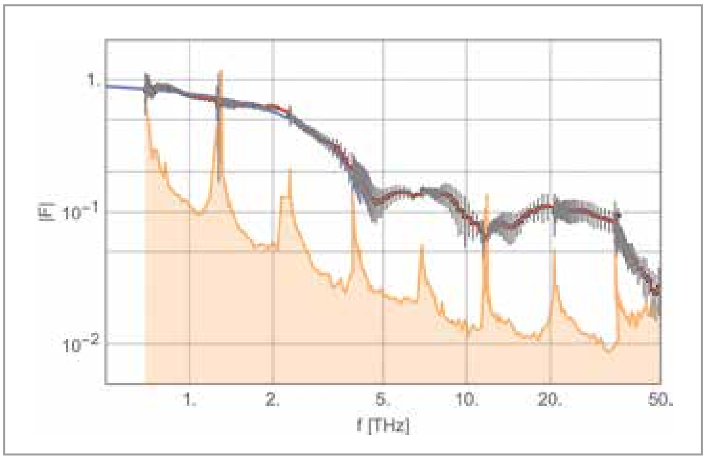

Figure 1

Experimentally determined form factor modulus as a function of frequency for electron bunches at FLASH. The grey vertical lines indicate the shot-to-shot fluctuations. The orange-shaded area marks the sensitivity limit of the instrument.

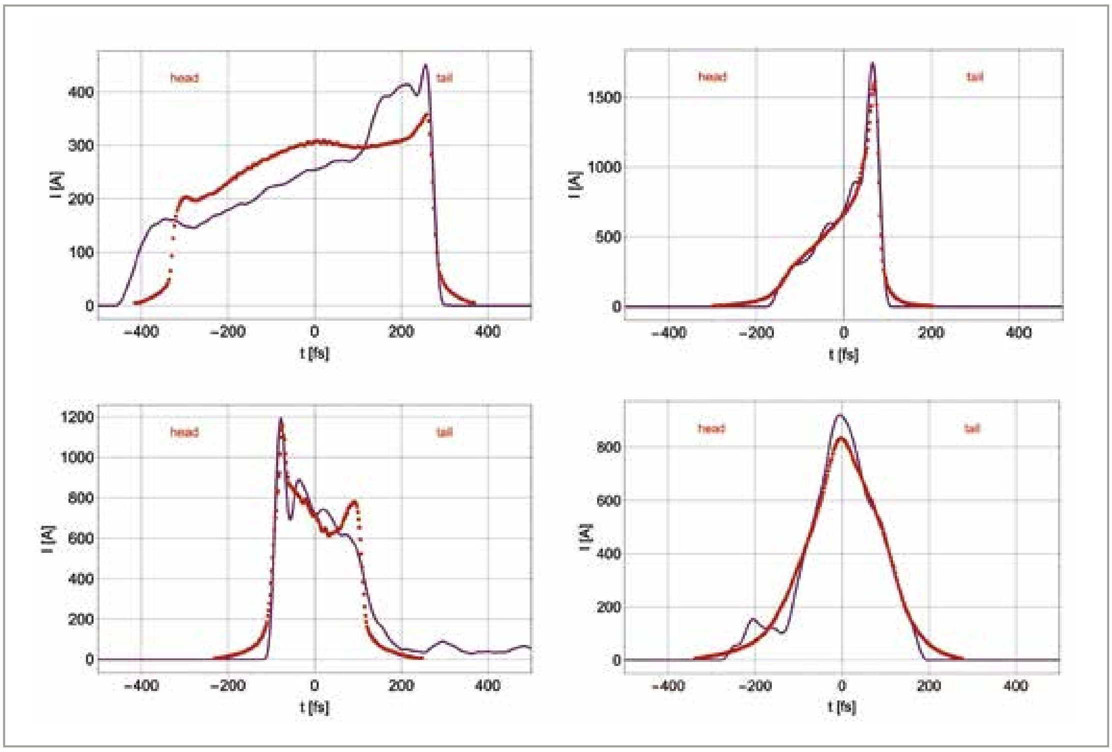

Figure 2

Four examples of electron bunch profiles (current versus time) produced at FLASH and measured with the time domain method (TDS, red dots) and reconstructed from spectroscopic data (solid lines)

unique device called CRISP, for Coherent Radiation Intensity Spectrometer [3], which is installed and operated at FLASH and the European XFEL. An example of a measured form factor is shown in Fig. 1. Both the frequency range and the form factor cover almost two orders of magnitude.

Results

Reconstructing the time profile from the measured form factor as a function of frequency is a non-trivial task, since the inverse Fourier transform additionally requires the relative phase $\phi(\omega)$ of the different frequencies. This relative phase has no influence on the measured intensity, however, and is therefore unknown. But using an elaborate iterative procedure and some fundamental constraints (the electron bunch is a compact object of purely negative charge), at least the most likely charge distribution can be reconstructed. Despite the fact that the method was proposed and used almost 25 years ago [4], only now, using our unique spectrometer, could we demonstrate that the method can be complementary to and equally powerful as direct time domain methods.

In 2018, we made substantial efforts to improve the phase reconstruction procedure and finally compare the results with measurements using a TDS device at FLASH. In contrast to [4], we used an iterative approach to determine the most likely phase based on the fundamental work described in [5]. A detailed comparison of the different approaches can be found in [6].

To make the comparison meaningful, we had to prepare a dedicated setting of the FLASH magnet optics to optimise the resolution of the TDS down to 10 fs. Using this setting, a variety of electron bunch profiles with different lengths and shapes was produced and simultaneously measured with both devices, CRISP and TDS. A selection of these profiles is shown in Fig. 2. They demonstrate impressively that the reconstruction method from the spectroscopic data works and gives comparable results to the time domain method.

More to come

The CRISP spectrometer at the European XFEL is set up in such a way that spectra from all bunches of the bunch train can be recorded simultaneously. This will give us the unique possibility to study dependencies and variations of all the individual bunches, while the TDS method is restricted to one single bunch per train. The CRISP device will be fully operational in 2019.

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Megapixel detector for soft X-rays

Fast low-noise imager for the European XFEL

The DSSC consortium completed the development and production of a first low-noise megapixel camera based on miniaturised silicon drift detector (mini-SDD) cells for the detection of single photons in the soft X-ray regime at megahertz frame rates. A unique feature is the digitisation and digital storage of up to 800 frames at pixel level. The front-end electronics are operated in power-pulsing mode to minimise power consumption. In the future, the camera electronics can be upgraded with depleted field effect transistor (DEPFET) sensors. All components were successfully integrated and operated in a vacuum chamber. The camera was delivered to European XFEL and is ready for commissioning and calibration. It is currently the fastest camera for low photon energies worldwide.

In 2009, a collaboration of Politecnico di Milano, Università di Bergamo, the University of Heidelberg, DESY and European XFEL as the leading institute was founded to design and realise a DEPFET sensor with signal compression (DSSC) X-ray imager for experiments at the European XFEL X-ray laser. The Spectroscopy and Coherent Scattering (SCS) and Small Quantum Systems (SQS) instruments, both situated at the SASE3 undulator beamline of the European XFEL, will each be equipped with a DSSC megapixel camera. Figure 1 shows the first megapixel camera based on mini-SDD sensors developed by the semiconductor laboratory of the Max Planck Society in Munich. This camera will be installed at SCS. Each quadrant comprises four modules with eight monolithic 256 x 128 pixel sensors in the focal plane.

Figure 2 is a view of the rear side of the chamber. Each copper cooling block (see Fig. 1) has its own inlet and outlet pipe for the cooling medium. The electrical connectors serve as cable interface to the power crates. Each housing also contains subassemblies for slow control and data transmission via optical 10 Gb Ethernet links.

For single-photon resolution, the detector provides at least a one-to-one relation between the photon number and the analogue-to-digital converter count, where the dynamic range is limited to 256 counts with a linear transfer characteristic for the mini-SDD camera. The pixel error rate is minimised by precise trimming of gain and offset at pixel level. A noise level below hundred electrons was achieved. In the future, the consortium intends to deliver a DEPFET-based imager with higher dynamic range and improved noise performance for future experiments at the European XFEL.

Figure 3 shows the smallest unit of the megapixel X-ray imager containing two monolithic 256 x 128 pixel sensors mating 2 x 4 readout application-specific integrated circuits

Figure 1

Entrance window side of the DSSC X-ray imager based on mini-SDDs

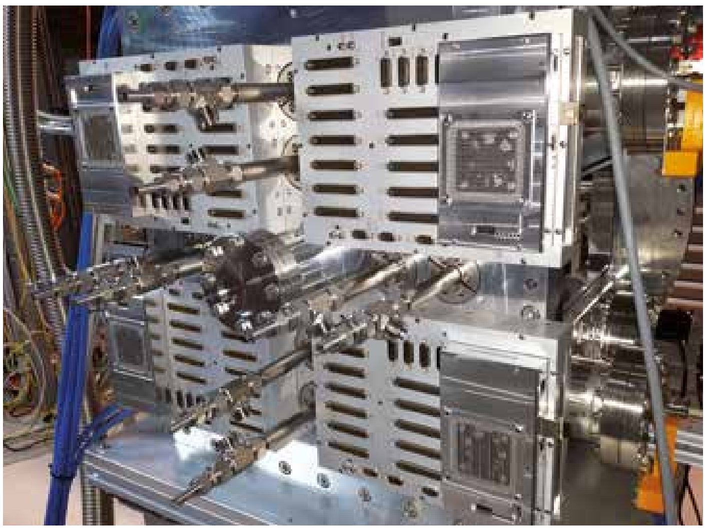

Figure 2

Rear side of the megapixel camera

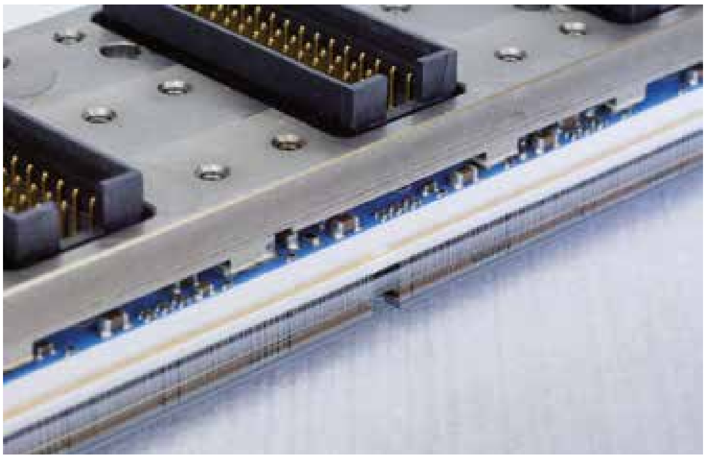

Figure 3

Focal-plane module with (from top to bottom) metal frame, low-temperature co-fired ceramics (LTCC) main board, silicon heat spreader and two bare modules with readout ASICs and sensors

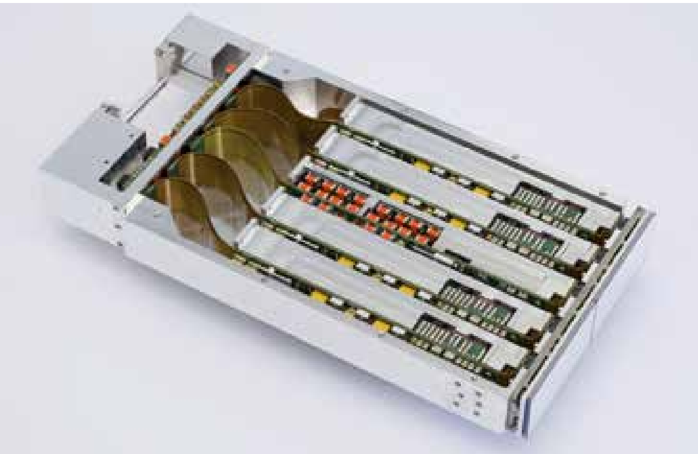

Figure 4

Ladder electronics with two bare 128 x 256 pixel modules

(ASICs) each. Wire bonds connect these bare modules to a ceramic board assembled with active and passive components as well as connectors. A metal frame on top acts as thermal and mechanical interface to the cooling blocks (see Fig. 1).

Five printed-circuit boards (PCBs) are perpendicularly oriented to the focal plane and connect the focal-plane module (Fig. 4). Four regulator boards provide the supply voltages for the readout ASICs. The central board collects the data of the focal-plane module. The flex leads of the PCBs are connected to an interconnection board. Signals and power are distributed via a single connector on the top side from and to the outer world.

Before mounting the focal-plane modules and ladder electronics to the cooling blocks, they were extensively tested in a vacuum chamber at room temperature. The measurements were performed using the full readout electronics in power-pulsing mode with 200 µs long switched-on states at a repetition rate of 10 Hz corresponding to the European XFEL timing structure.

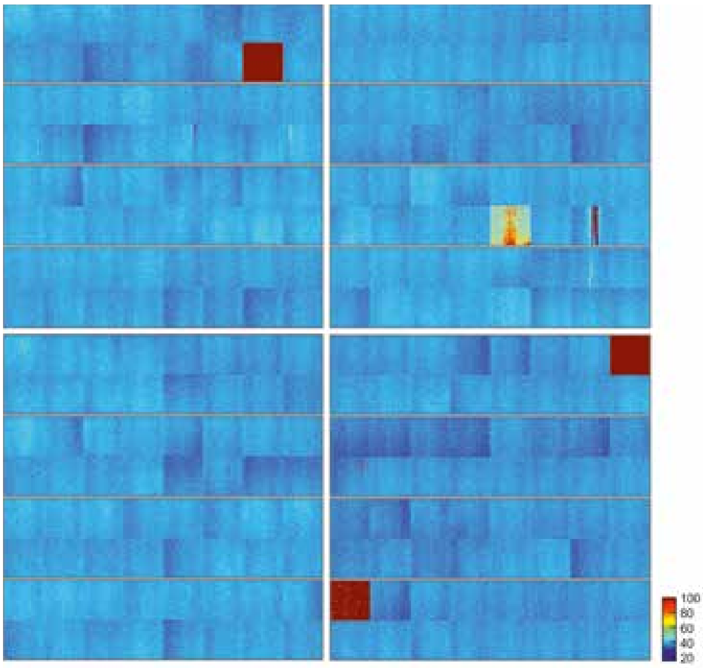

Figure 5

Dark-image maps of the megapixel camera

The performance test included a pixel-wise trimming of the gain to obtain a resolution of 1 keV per bin. The offset trimming ensures that any entry falls into the centre of the bin. Finally, a sensitivity test of the full signal chain with LED-spot-illuminated sensors was performed. Taking the performance test results and misalignments of bare and focal-plane modules into account, the best sixteen ladders were finally integrated into the chamber.

Figure 5 shows the dark-image maps taken for default gain and offset settings from all 16 modules of the mini-SDD camera. Only five of 256 ASICs showed failures. The optimisation of the detector performance was part of the following commissioning and calibration campaign.

Scientists from Politecnico di Milano, Università di Bergamo, the University of Heidelberg and DESY's electronics development group designed the readout ASIC. DESY contributed the analogue-to-digital converter with adjustable gain and offset, circuit blocks to distribute clocks and data as well as a global bandgap circuit and network to distribute reference currents. At the module level, DESY designed all boards (except the data acquisition PCBs) as well as the cabling and power system. Colleagues from the University of Heidelberg designed two data acquisition PCBs as well as the firmware and software. DESY's photon science detector systems group designed the vessel with motion units as well as the cooling block and pipes. The integration of the quadrants, flanges and peripheral electronics outside the chamber was a joint activity of the European XFEL detector group and DESY.

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INSPIRE

Curated at DESY

INSPIRE-HEP, the primary database for publications in high-energy physics, now includes more than 1.3 million records. In 2018, cataloguers at DESY did most of the manual editing: The DESY library and documentation group carried out 95% (70%) of the curation for journal (arXiv) records. In addition, almost all manual selection of articles is taken care of at DESY.

A total of 51 120 records were added to INSPIRE in 2018, increasing the volume of the database to 1.3 million records. As shown in Fig. 1, the number of articles coming from arXiv was relatively stable at around 2000 records per month, with about 75% of them published in a journal within a year. The journal publication usually comes with a delay, and the corresponding information is added later by merging journal and preprint. This is why recent articles do not have the journal information yet.

In addition, we added 1000 to 2000 articles per month from journals that were not on arXiv. Big conferences such as IPAC2018 or ICRC2017, which were added in August 2018, led to spikes in the distribution. So-called grey literature (e.g. theses, other report series and conference proceedings) made up the rest. 2551 old reports from the DELPHI collaboration were added in March. Roughly half of all the records were about high-energy physics topics and were curated manually.

Since the start of the SPIRES database, which was established by DESY and SLAC in the 1970s, articles harvested from arXiv had been curated by cataloguers at SLAC. At the beginning of 2018, this service was taken over by DESY due to lack of (wo-)manpower at SLAC, which just continues to participate in the development and maintenance of the database. The last cataloguer at SLAC left in September 2018. This unfortunate lack of funding by the United States Department of Energy (DOE) marked the end of an era. Thanks to the newly integrated back-end staff at the other institutes (CERN, DESY, Fermilab and IHEP), it was possible to continue most of the tasks, but some services had to be reduced or dropped.

For example, references of arXiv articles are not curated any more. Most will be replaced by better-quality references of the published journal article later on. In addition, processes are automatised wherever possible, at the cost of a larger number of errors. Assignment of standardised affiliations will continue, since this is an essential ingredient for author disambiguation. Widespread use of the ORCID contributor identification scheme will facilitate this task. Merging the journal and arXiv records takes up a large portion of the curation. An automatic merger is being developed at CERN to reduce this workload.

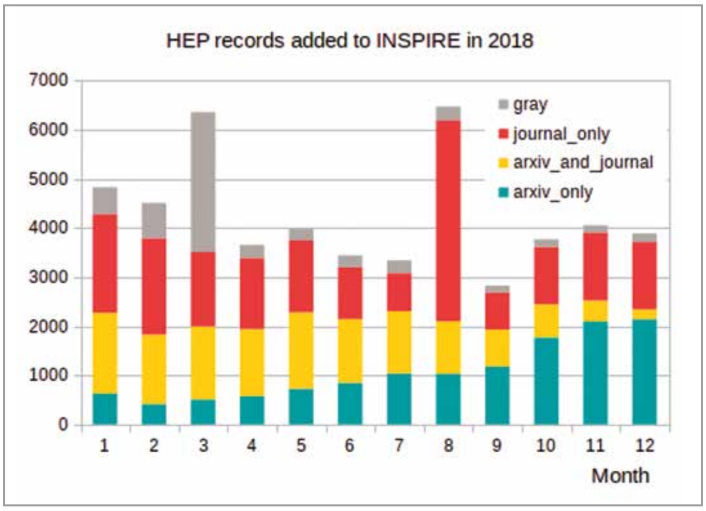

Figure 1

Number of records added to INSPIRE-HEP in 2018 per month. Journal information as of 16 January 2019.

In 2018, DESY merged 14 151 records manually and curated 7810 (11 453) journal (arXiv) records. While most of the content is selected automatically by source (some arXiv categories and 15 journals), we routinely examine 346 journals to select articles about or relevant for high-energy physics, thus scanning 238 000 articles. For about half of these journals, we receive feeds from the publisher, the other half is harvested by web-scraping. The necessary scripts are maintained at DESY.

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DESY library on the move

Further increasing usability and services

For more than 50 years, the printed collection of the DESY library was presented using a homemade shelf classification, with rather broad subject groups driven by the needs of primarily high-energy physicists. With the diversification of research fields on the campus and the availability of new technologies due to the introduction of the new library system in 2017, the time had come for a change.

Books on the move

To appropriately reflect the diversity of research activities at DESY, the need arose to come up with a new, clearly structured shelving that reflects all areas of science. To this end, we selected the well-established, internationally used Dewey Decimal Classification (DDC) scheme to rearrange the collection (Fig. 1 and 2). The main objective of the change is to enhance the usability of the printed collection, enabling thematic browsing of the shelves and serendipitous discoveries. In addition, the application of DDC at the DESY library will support our collection development and allow us to use readily available data for subject indexing.

Of course, this required us to rearrange the collection, so a few books (we already tackled more than 4000 titles) are still on the move, and some rarely used items even went to the stacks. Don't hesitate to ask if you can't find the item you are looking for, and feel free to request items from our catalogue to pick them up later at the library desk.

Enhanced library services

In addition to our well-known services such as information desk, 24/7 circulation, e-books, databases and patron-driven acquisition, we noticed an increasing relevance of our additional services, such as

- Personal advice on copyright and licensing issues
- Handling of article-processing charges (e.g. for gold open access)
- Acquisition of standards
- Acquisition of usage rights for images and fonts
- Document delivery
- Interlibrary loan

Supplied by our users, the newly installed book-sharing shelf (Fig. 3) even provides books for leisure reading for our guests and staff members. Browse the topics, pick an item or bring one you want to share with your colleagues. We roughly sort the items thematically, so you should be able to find something of interest easily – free of charge, of course.

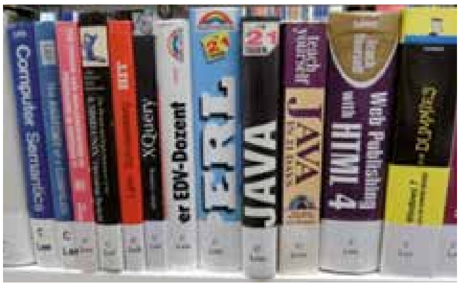

Figure 1

Before: The DESY computer books were shelved in subject group C sorted by authors. For thematic access, the reader had to refer to the online catalogue.

Figure 2

After: DESY computer books shelved according to DDC: Similar topics, such as programming languages, are naturally sorted together. This allows for topical browsing and enables serendipitous discoveries.

Figure 3

New book-sharing shelf

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Contemporary design

Next-generation computer-aided design for next-generation projects

Computer-aided design systems are indispensable tools in the design and engineering of large-scale scientific infrastructures, such as particle accelerators and detectors. DESY has evaluated the experience and lessons learned from the recent construction of the European XFEL X-ray laser to update and further optimise its design engineering tools and processes for the next generation of projects.

Motivation

Computer-aided design (CAD) implies using computers to create 3D models and technical drawings for the design and development of products. Products in scientific projects range from simple devices to complex machines, large installations and even entire facilities. CAD systems create renderings and drawings that are used for conceptual design, technical specification, layouts, dynamic performance analysis, installation planning and more. Figure 1 illustrates the role of CAD models for the construction of complex scientific facilities.

In distributed projects, where multiple interdisciplinary engineering teams are jointly working on the same facility design, CAD systems have to be connected with engineering data management platforms. Called product lifecycle management (PLM) systems, they ensure that all engineers are accessing the same version of data and that design changes are properly reviewed and carefully propagated to all participating engineering teams. Furthermore, PLM systems ensure the availability of design data throughout the entire lifecycle of the facility, which often lasts for several decades. CAD data usually have to be made available to several generations of engineers, who continue to maintain the facility, repair components, refurbish subsystems and add extended services. Figure 2 illustrates the interplay of CAD and PLM systems in the facility lifecycle. PLM systems are particularly important for project teams that are distributed across several locations.

DESY's current CAD tools had reached their technological end of life, and they were also at their limits in terms of size and complexity of the engineering models that are needed to describe DESY's facilities. DESY thus conducted a CAD technology update, incorporating experience and lessons learned from the recent construction of the European XFEL, to prepare its CAD and PLM tools and processes for the next generation of projects.

Brave new world: Challenges and opportunities

"Conducting a CAD technology update" is a harmless designation for an enormous effort; it involves (1) upgrading the current CAD software to a state-of-the-art, integrated high-end CAD/PLM solution for engineering collaboration in extremely large projects, (2) converting 20 years of history of CAD data for continued use with the new systems, (3) retraining about 500 CAD engineers for the use of the new software and (4) developing and establishing methods for improving the design engineering processes and engineering collaboration for next-generation projects.

Opportunities of the new CAD/PLM solution lie in added support for the specific needs of large scientific projects and, most importantly, in the provision of specific functionality for developing extremely large assemblies, scaling up to representing entire facilities.

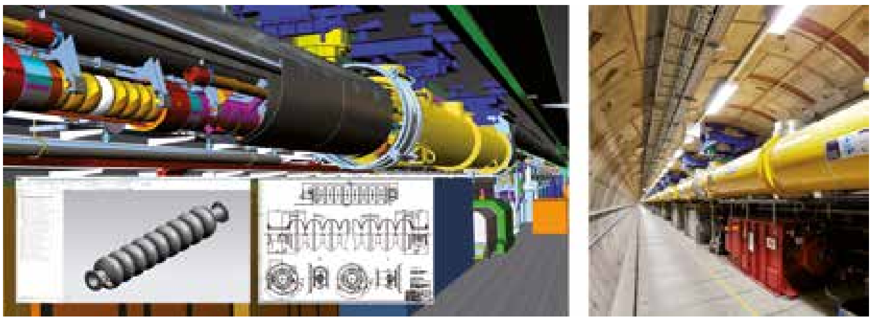
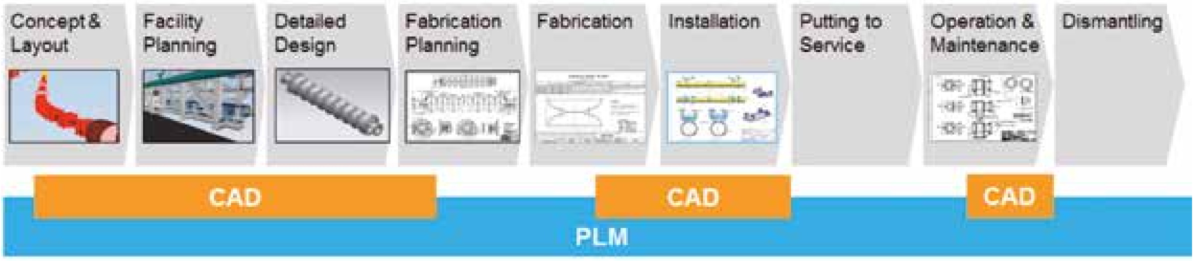


Figure 1

Example for the manifold role of CAD models in the development of scientific facilities: component design, construction drawing and rendering of the integrated facility (left), compared with the final accelerator (right).

Figure 2

Various types of CAD data, linked through a PLM system, in the lifecycle of a scientific facility, which often lasts over several decades.



(R)Evolution: A CAD technology update project

The CAD technology update was performed over a period of two years by a project team of at peak times up to ten CAD specialists, design engineers, software developers and CAD coaches, who systematically developed solutions for all the major challenges. As a foundation, a reliable and well-performing installation of latest integrated CAD and PLM systems was developed and made available for the distributed environment at DESY and its partners. Figures 3 and 4 show impressions of the CAD and PLM systems.

A CAD data conversion process was developed based on a commercial CAD data converter, which uses the history of the existing CAD data to reconstruct the models in the new CAD system. The process is managed by a dedicated project database, which analyses the incoming and outgoing CAD data for correctness, observes reused CAD parts across multiple models and propagates revisions of the original parts. In the first year of running, more than 120 000 CAD parts were converted, of an expected total of about 500 000 parts. While most of the conversion is automatic, some features cannot be properly translated between systems, thus all the models are checked and post-processed manually before they are released to the new CAD/PLM solution.

Almost 400 design and project engineers were retrained in specifically developed week-long CAD update trainings, which covered the essential CAD functionality adapted to how it would be used at DESY. Additional advanced training classes addressed specific topics, such as handling large assemblies, modelling the frequently occurring welding assemblies, or performing essential engineering review and release workflows. A novel, model-based engineering approach for designing large-scale scientific facilities was developed, which promotes evolutionary modelling and parameterises models with values from design specifications and simulation results. The method, which scales to extremely large assemblies of up to hundreds of thousands of parts, was successfully demonstrated in a first application in the development of the SINBAD/ARES accelerator.

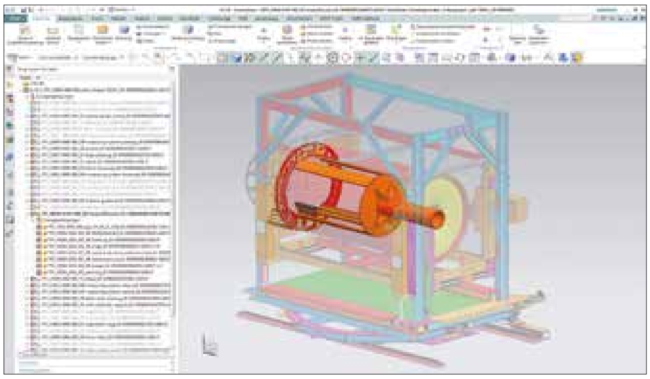


Figure 3

Visual model of an assembly in the CAD system

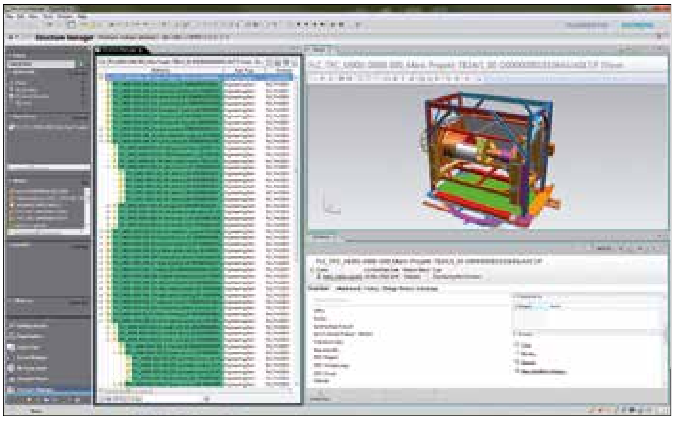


Figure 4

The same assembly in the PLM system, showing part list and properties

Perspective

The CAD technology update was performed after the completion of the European XFEL, with the ambition of it being available in time for the upcoming construction of the PETRA IV facility. The project is now ready as expected, the new CAD/PLM solution has been delivered to all engineers' desks, the systems are in full production, and user experience is rapidly growing.

The new CAD/PLM solution will also further strengthen DESY's outstanding lifecycle competencies. DESY as a lab has the capabilities and experience to manage and contribute to scientific projects at any stage of their lifecycle. The new CAD/PLM solution provides a first-class technological foundation for a fully integrated product lifecycle management.

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Absorbing light by light

Design of the LUXE experiment at the European XFEL

During the early phase of the development of quantum electrodynamics, Werner Heisenberg, Leonhard Euler, Julian Schwinger and others considered a regime that has yet to be tested experimentally. In this regime, the electro-magnetic interaction becomes so strong that matter particles can be produced from the absorption of light by light. Such strong fields occur in several astrophysical phenomena, such as neutron stars, black holes and the early phase of the universe. At DESY, a study examines whether it is feasible to design an experiment called LUXE using high-energy photons created from the electron beam of the European XFEL X-ray laser and low-energy photons from a high-power laser. It is expected that electron–positron pairs will be created, which could be measured using dedicated detectors designed for this purpose.

The linear accelerator of the European XFEL, which is operated by DESY, produces electron beams that are among the highest-energy electron beams currently available anywhere in the world. While it was designed for the purpose of photon science, it is also ideally suited to study quantum physics in the strong-field regime. This is the goal of the LUXE experiment, which is currently being designed by DESY accelerator, particle and laser physicists together with collaborators from German, Israeli and UK institutes.

The LUXE experiment foresees to direct one of the 2700 bunches per train of the electron beam onto a tungsten target, where a high-energy photon is created through the bremsstrahlung process. This high-energy photon then collides with low-energy photons from a laser, and pairs of electrons and positrons are expected to be created in what is known as the Schwinger process. A sketch of the experimental setup is shown in Fig. 1.

The intensity of the laser will be varied between 5 x 10^{18} W/cm^2 and 10^{20} W/cm^2, and the rate of electron–positron pair production will be measured as a function of this intensity. It is expected that the rate will increase fast with the laser intensity, but asymptotically reach a value directly related to the Schwinger critical field $E_S = \frac{m_e^2 c^3}{e\hbar} \approx 1.3 \times 10^{18}$ V/m. The measurement of the rate of pair production is directly related to this field through $R \propto E^2 \exp(-E_S/E)$, where E is the electric field provided by the laser. A similar experiment was conducted at SLAC in the 1990s. The production of electron–positron pairs was observed, but the critical field was not reached [1].

The LUXE experiment is designed to proceed in two stages, where the initial stage uses a relatively low-power laser with moderate focusing while the second stage employs a strongly focused high-power laser so that an intensity of up to 10^{20} W/cm^2 is reached. Figure 2 shows the expected number of positrons per laser shot, which should increase steeply and then asymptotically reach a value of about 20.

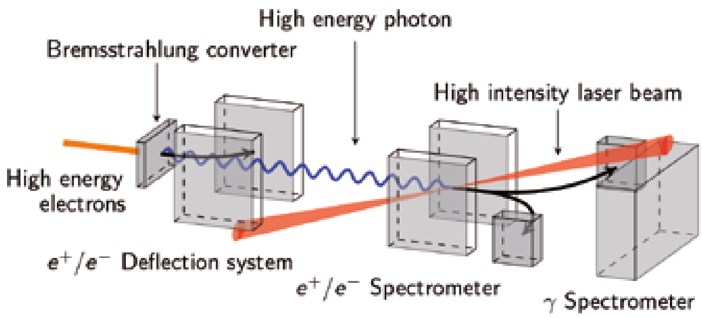

Figure 1

Experimental setup for the LUXE experiment. The 17.5 GeV electron beam hits a converter, producing a high-energy photon that interacts with an intense laser field. In that interaction, an electron–positron pair is created. Detectors for measuring the electrons, positrons and photons are foreseen. (Fig. from [2])

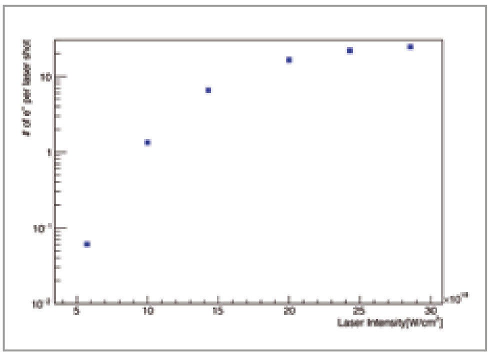

Figure 2

Number of positrons produced per laser shot as a function of the laser intensity (Fig. by M. Hoffmann, A. Hartin)

The LUXE collaboration aims to use this rate to determine the value of the Schwinger field. In addition to the Schwinger process, other phenomena in the strong-field limit will also be explored, e.g. the $e^- \rightarrow e^- \gamma$ and $e^- \rightarrow e^- e^+ e^-$ processes.

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DESY IT and European XFEL in close collaboration

From infrastructure support to data analysis

Experimental data from the scientific instruments of the European XFEL X-ray laser are stored in a multi-tiered storage system. It consists of an on-premises online system (one per beamline), tuned for fast ingest of the detector data, and an offline system used for data analysis, which stores not only the raw data but also the processed (calibrated) data and results. The last system is the dCache storage, in which data are kept for a longer time than in the more expensive offline system and which also serves as a buffer for copying data to long-term archival on tapes. The DESY IT group manages all of these systems, which – apart from the online systems – are housed in the DESY data centre.

Machine learning

The scientific computing team at DESY is developing and evaluating modern deep-learning methods, for example deep convolutional neural networks, to support ongoing research in photon science. Deep convolutional neural networks are supervised machine-learning algorithms primarily used for 2D and 3D image analysis and pattern recognition.

The DESY IT group is currently pushing developments for automated pattern recognition for nanocrystallographic experiments at the European XFEL and for semantic segmentation of 3D volumes as measured with X-ray tomography at the beamlines of DESY's PETRA III synchrotron radiation source.

dCache development

DESY has received 400 000 euros through its membership in the eXtreme DataCloud (XDC) project. This money has helped to fund dCache developments that bring improvements for European XFEL data management as well as for the more general photon science community and dCache users throughout the world.

One major improvement is the introduction of storage events. These allow services to learn of changes within dCache, for example that new data has just been uploaded or that data has been staged back from tape. This support in dCache allows DESY to build innovative solutions, for example enabling users to provide functions that process new data automatically when uploaded. Storage events are provided through two interfaces: One (Kafka) is intended for integrating services within DESY, while the other (SSE) allows dCache users to innovate by receiving events directly.

EOSC pilot

In the pilot project for the European Open Science Cloud (EOSC), DESY IT collaborated with European XFEL, the European Spallation Source (ESS) and other European partners in the Photon and Neutron Science Demonstrator project (PaN SD). We built and extended an OpenStack Cloud in the DESY data centre to provide access to large-scale compute and storage resources (Infrastructure-as-a-Service, IaaS).

On top of this cloud, we evaluated latest deployment strategies for distributed applications (Platform-as-a-Service, PaaS), which automatically scale up with demand. Comprehending concurrent integrated container computing, we demonstrated full-stack support for autoscaling microservices (Function-as-a-Service, FaaS), also often referred to as serverless computing. Scientists can publish microservices and let them consume dCache storage events in order to execute codes in a fully automated manner in response to incoming data from the European XFEL and other experiments.

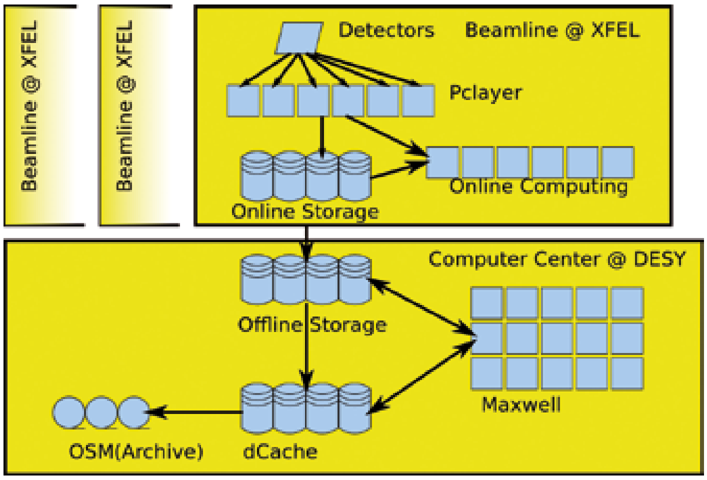

Figure 1

Data flow from the European XFEL beamlines to the DESY data centre

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An interdisciplinary scientific computing centre

Providing services for all branches of science at DESY

DESY carries out research in many different branches and at different locations, both at the two DESY sites and at remote sites, such as CERN, various astroparticle physics experiments or remote light sources. It is the mission of the DESY computing groups in Hamburg and Zeuthen to best serve all DESY communities and increasingly also external groups and guests. As a general concept, the DESY computing groups aim for large, multipurpose infrastructures to efficiently serve different communities, while creating specialised infrastructures when necessary. While we presented the infrastructure of the interdisciplinary Scientific Computing Centre at DESY in the previous annual report, we will now focus more on additional services and new developments.

Grid and NAF at DESY in Hamburg

The DESY Grid infrastructure provides a large portfolio of Grid services. The actual workhorses are a large common batch system based on HTCondor, with about 20 000 cores, and high-capacity dCache storage elements. These resources serve different projects, most of them with a high-energy particle physics background, as multipurpose infrastructures.

In addition, the National Analysis Facility (NAF) has been in operation at DESY since 2007. It complements the DESY and German Grid resources and serves similar projects. As the NAF supports direct interactive access, it allows for fast-response workflows necessary for development, debugging, testing and small-scale private productions – important complements to the Grid infrastructure, which provides computing resources for a continuous massive production albeit has higher latencies.

The dCache storage elements provide long-term storage for experimental and user data with several petabytes in curation for each group. Deployment and management of the storage elements have been automated and can be easily scaled thanks to the distributed setup, thus allowing for highly parallel input and output. NAF and Grid users have identical access to these central data stores. Additionally, NAF users have access to fast scratch space for more direct and interactive work.

Since 2016, DESY has been operating the collaborative services for the Belle II experiment in Japan, including a collaboration membership management system. In May 2018, DESY hosted the yearly one-week Belle II software workshop with 48 participants.

Infrastructures at DESY in Zeuthen

HPC

High-performance parallel computing (HPC) has a long history at DESY in Zeuthen, starting with special-purpose architectures for lattice quantum chromodynamics (LQCD) simulations developed by INFN and DESY up to a server cluster installation containing about 1800 CPU cores. Though LQCD projects (under the umbrella of the John von Neumann Institute for Computing, NIC) are still dominating the cluster utilisation, theoretical astroparticle physics applications are catching up. The computing components of the cluster are connected via a low-latency Fourteen Data Rate (FDR) InfiniBand network. To ensure fast data transfer, all nodes are connected to a distributed parallel Lustre storage system.

Grid and compute farms

The DESY Zeuthen computer centre operates the European Tier-1 centre for the IceCube neutrino experiment, supports the Cherenkov Telescope Array (CTA) and runs 50% of DESY's Worldwide LHC Computing Grid (WLCG) ATLAS Tier-2 (4500 cores) as well as a local compute farm (3000 cores). In addition to CPU resources, about 100 general-purpose graphics processing units (GPUs) are used mainly by IceCube. The Grid and compute farms are connected to a large dCache storage system (5 PB) as well as to a Lustre-based parallel file system (2 PB).

Project support

In 2018, the support of already existing projects was extended and new projects, especially in the field of astroparticle physics, were started. Members of the DESY Zeuthen computing group are responsible for the design and definition of the CTA On-site Data Centers at the two CTA sites –

Figure 5

Roque de Los Muchachos, La Palma, Spain: CTA On-Site Data Center North, supported by the DESY CTA group, in front of the Large-Sized Telescope (LST1) prototype

CTA North on La Palma, Spain, and CTA South at Paranal, Chile (Fig. 1). Software for the CTA central control system is being designed and developed within the embedded systems subgroup. Computing group members are also strongly involved in the upgrade of a computing test cluster and the on-site data acquisition system of another imaging atmospheric Cherenkov telescope, the H.E.S.S. observatory in Namibia. Another new project is the Zwicky Transient Facility (ZTF), an instrument for an all-sky survey in California, for which the DESY Zeuthen computing group created an initial computing environment for data retrieval and analysis. In addition, in the framework of the Tier-1 centre, the computing group was strongly involved in developing the IceCube computing strategy.

For the PITZ photoinjector test facility at DESY in Zeuthen, the support covers system administration activities (data acquisition and storage) and a significant part of the embedded software development.

Maxwell HPC cluster at DESY in Hamburg

Launched in 2011, the Maxwell HPC cluster has quickly grown into a massive HPC platform. The Maxwell cluster is a truly collaborative and cross-disciplinary compute infrastructure also open for different tenants and different applications. These range from data analysis (PETRA III, European XFEL, etc.) over machine/deep learning (high-energy physics) to massively parallel computational tasks (simulations for laser wakefield accelerators and PETRA IV design studies, molecular dynamics and photon–matter interactions, etc.). A small collection of publications supported by the Maxwell cluster is listed on https://confluence.desy.de/display/IS/Publications.

Data storage is offered for PETRA III, FLASH, the European XFEL and others using the GPFS cluster file system and BeeGFS. Access to dCache data is also possible from the Maxwell cluster.

New services and developments

In 2018, the DESY IT group set up a regular seminar on high-performance computing, which enjoys large participation from all users. The seminar is intended both for novice users seeking a general introduction to the field and to the use of the Maxwell cluster and for expert users with in-depth special topics. A round table on GPU computing and machine-learning activities was held in late 2018 for users on and around the DESY Hamburg campus, which brought together high-energy physics, photon science and accelerator experts from DESY, Universität Hamburg and European XFEL. As a regular follow-up to this kick-off meeting, DESY IT is organising a monthly meeting on machine learning to further foster the exchange between disciplines and institutes in this emerging field.

In parallel to these machine-learning efforts, DESY IT increased the number of GPU systems available in the Maxwell cluster and introduced the first GPU systems into the NAF.

DESY IT also carried out work to ease access and usage of the infrastructure. Most notably, support for Jupyter notebooks was set up on the infrastructure side in the Maxwell cluster and the NAF. Work is ongoing to finally integrate experiment software setups into the Jupyter infrastructure. In order to facilitate the porting of applications to different environments, users can provide Docker containers to the batch system, in which their application is built with all necessary dependencies. The Singularity container technology is also partially used to decouple user workflows and operating system setups.

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