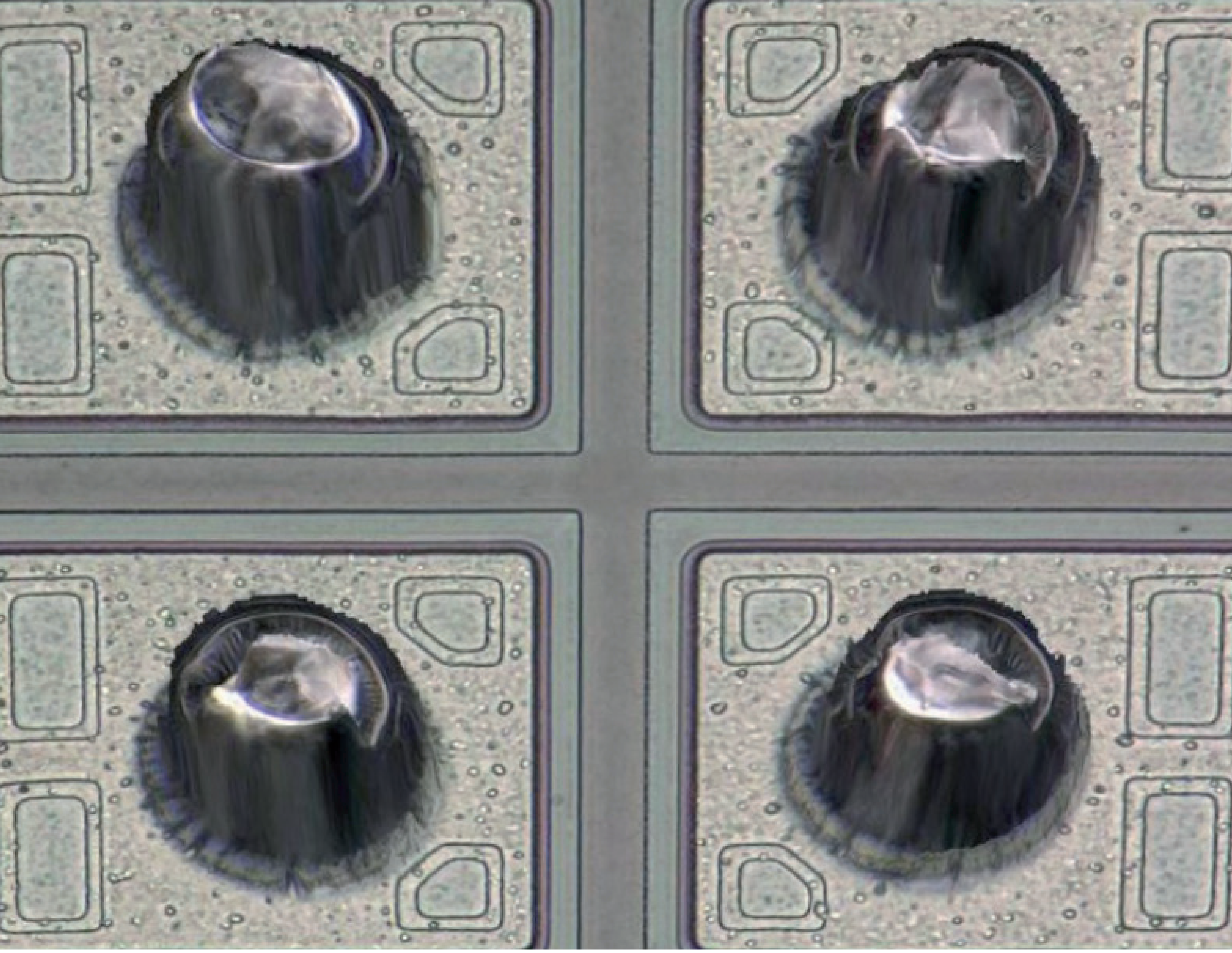

PARTICLE PHYSICS 2015.

Highlights and Annual Report

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

PARTICLE PHYSICS 2015.

Highlights and Annual Report

Cover
A detail from the new CMS silicon pixel vertex detector: Four pixels with solder balls placed on top.
The height of the balls is 40 µm.

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The year 2015 at DESY.

Chairman's foreword

2015 – the UNESCO "International Year of Light" – was a highly dynamic year for DESY, and many areas of the research centre were buzzing with activity. Ongoing projects, extensive construction work for new facilities and significant planning work towards new projects kept us busy. At the same time, DESY engaged in new national and international research collaborations and developed a location of excellence concept for both the Hamburg and the Zeuthen campus.

In the field of photon science, the construction of the European XFEL X-ray free-electron laser – currently DESY's largest project – is in full swing. More than two thirds of the required 100 superconducting accelerator modules have already been manufactured and installed in the tunnel (Fig. 1). Our plan is to inject the first electron beam into the linear accelerator before the end of 2016. Two other major DESY projects, the expansion of the PETRA III synchrotron radiation source and the FLASH soft X-ray free-electron laser, are progressing similarly well. In 2015, the outer facades of the two PETRA III extension halls were completed, and the technical equipment is now being put into place.
The FLASH2 experimental hall was also completed (Fig. 2), and commissioning of the experimental setups started.

In particle and astroparticle physics, DESY scientists were not idle either, as this brochure attests to, and the second Nobel Prize awarded to this field in three years (in 2013 for the Higgs mechanism and in 2015 for the discovery of neutrino oscillations) clearly provided a significant boost in motivation and morale.

The astroparticle physics community was particularly involved in the preparations for the next large facility, the Cherenkov Telescope Array (CTA) gamma-ray observatory. In 2015, negotiations about the two intended sites on the northern and southern hemisphere started, and the DESY site in Zeuthen will soon apply to host the CTA headquarters, the location of which will be decided in 2016.

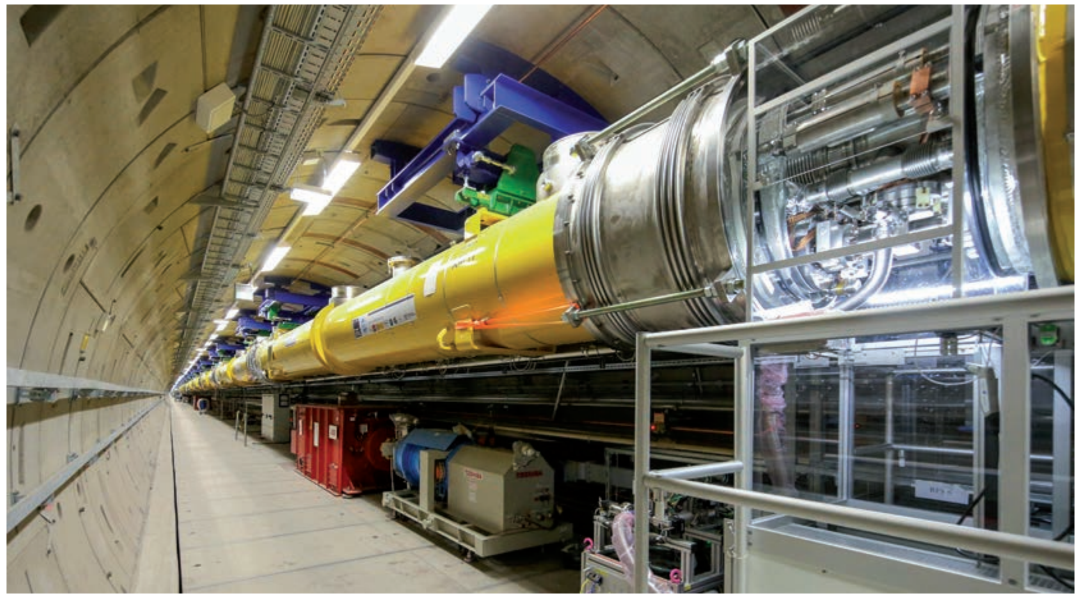


Figure 1

Accelerator tunnel of the European XFEL (April 2015)

Figure 2

In a symbolic ceremony, the two FLASH experimental halls were named after the Nobel laureates Albert Einstein and Kai Siegbahn by Beatrix Vierkorn-Rudolph of the German Federal Ministry of Education and Research (BMBF), the Swedish secretary of state Anders Lönn, DESY director Helmut Dosch, Hamburg's mayor Olaf Scholz and Hans Siegbahn, son of Kai Siegbahn (from left to right).

After a two-year upgrade, the Large Hadron Collider (LHC) at CERN near Geneva in Switzerland started up again in 2015. Scientists all around the world are now eagerly waiting for new discoveries from the collider, which was operated close to its design energy. At the same time, DESY is preparing for the high-luminosity upgrade of the facility, due to start in 2022. The research centre will host the national detector assembly facility for the tracking detector end-caps of the upgraded ATLAS and CMS experiments.

All these activities take place in extensive international cooperation. At DESY, we take pride in our open-mindedness and in the great national and cultural diversity of our staff, which currently includes colleagues from more than 60 nations. Curiosity and passion for research clearly build bridges between people – here at DESY, we demonstrate, every day, that integration works!

Lately, we have witnessed an unprecedented immigration of refugees, many of whom now live in shelters or camps very close to the DESY campus. As a publicly funded research centre, DESY cannot grant direct financial support or reduce its employees' working hours to compensate for voluntary work with refugees. However, DESY can, to a certain extent, grant access to its infrastructures and facilities, and we are trying our best to do so. I would like to use this opportunity to thank all those who, in their often limited spare time, have started a wide range of activities and efforts to make the refugees feel welcome and to relieve their distress.

I am aware that our many and diverse activities and projects are a challenge for all staff members at DESY – a challenge that, I am proud to say, we handle admirably. I cannot extend a big enough "thank you" to fully express the appreciation I have for the excellent work and continued commitment of our staff members and external collaborators. I am very much looking forward to their results in 2016!

Helmut Dosch
Chairman of the DESY Board of Directors

Particle and astroparticle physics at DESY.

Introduction

For particle and astroparticle physics, 2015 was again an eventful year. If, back in 2013, we wondered whether the Nobel Prize for François Englert and Peter Higgs might have been the last for our field, we were surprised to learn that, in 2015, particle physics was awarded another such distinction, this time for the discovery of neutrino oscillations. This recognition shows that our field is full of surprises and potential. And DESY, with its many diverse activities in particle and astroparticle physics, is contributing to numerous exciting developments.

A prime example is DESY's contribution to the experiments at the Large Hadron Collider (LHC) at CERN near Geneva. The LHC had a very successful restart in 2015, providing a total integrated luminosity of around $4\ \text{fb}^{-1}$ for each of the two multipurpose experiments, ATLAS and CMS. The prospects for 2016 are excellent, and the plans for the full exploitation of the LHC raise great hopes for future discoveries.

DESY is an important player in the LHC, delivering significant contributions to both multipurpose experiments – in detector operation, data analysis, upgrade activities and management – and to the theoretical exploitation of the LHC physics. DESY particle physicists were involved in the production of a large fraction of the close to 1000 experimental papers published by the ATLAS and CMS collaborations so far.

As one of the largest laboratories involved in the LHC and a national hub for particle physics, DESY plays a central role in numerous upgrade activities for the LHC experiments. One example is the module production for the CMS pixel detector, which is to be installed in the experiment in 2016. After some teething troubles, the project is now well on track, and module production will be completed in spring 2016 (Fig. 1). Another major enterprise is DESY's contribution to the LHC detectors for the high-luminosity LHC: DESY is constructing one tracker end-cap for each experiment, ATLAS and CMS. This 10-year project will enhance DESY's visibility in the international community even further. The project has already attracted significant funding from the German Federal Ministry of Education and Research (BMBF) for the planned university contributions, and DESY is prepared to invest the funds required for setting up the necessary laboratory infrastructure. The DESY Directorate is optimistic that it will be able to soon secure the required investment funds from the Helmholtz Association.

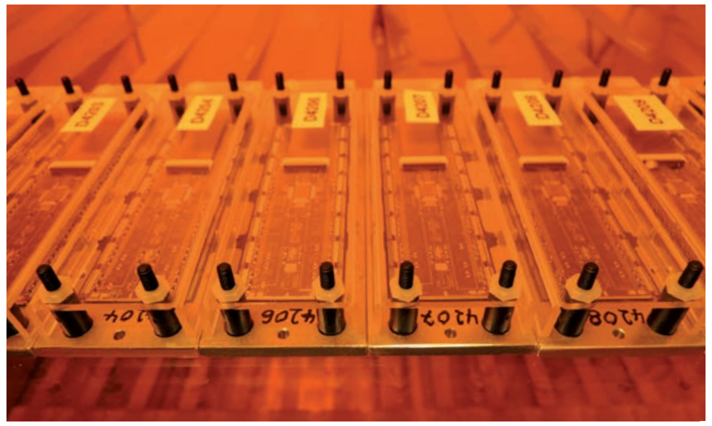


Figure 1

CMS silicon pixel modules in their storage

The DESY activities in particle physics extend well beyond the LHC. The worldwide community planning the International Linear Collider (ILC) is making progress in the site-specific design, and Japan is continuing its serious investigations into hosting the ILC. In 2015, Japanese representatives visited DESY and other large particle physics laboratories around the globe several times to gauge the status and significance of the project in all the world regions. The DESY physicists involved in the ILC are now waiting for a – hopefully positive – evaluation of the project by the Japanese expert committees. The year 2016 promises to be very interesting in this respect.

DESY is also holding numerous responsibilities in the Belle II experiment at the SuperKEKB collider at the Japanese particle physics laboratory KEK. As part of the DEPFET collaboration, which is building a novel pixel vertex detector for the experiment, DESY contributes a full one-to-one thermo-mechanical copy of the entire vertex detector system, used to verify and optimise the complex thermal management concept, and designs and constructs the remote vacuum connection (RVC, see Fig. 2) that forms the interface between the fragile vertex detector and the superconducting final-focus quadrupoles of the SuperKEKB accelerator. New data from the Belle II detector will only become available in the next years. However, DESY physicists are currently busy analysing the large data set from the former Belle experiment, which provides a good testing ground for the upcoming Belle II analyses.

Beyond its contributions to the LHC, the ILC and Belle II, DESY is exploring future opportunities and contributing to a coherent global strategy for particle physics. In the near future, and in the light of the LHC findings and of developments in Asia and the USA, particle physicists worldwide will have to sketch their vision for the future of the field. Be it CERN's Future Circular Collider, Chinese ideas on new large accelerators, or new developments in neutrino physics – DESY will remain open-minded and invest its efforts to the best of particle physics. In fact, the next update of the European strategy for particle physics – which is intended to pave the way for the long-term future of the field – is expected to be published around 2018. Germany is starting to prepare input for this European strategy process, with a series of dedicated workshops beginning in spring 2016, and DESY will play an important role in the development of the strategy at the national and international level.

DESY is also a major player in astroparticle physics, where the next large project is progressing swiftly towards realisation: The Cherenkov Telescope Array (CTA) – the next-generation gamma-ray observatory – will substantially increase our knowledge of the non-thermal high-energy universe. Currently, the CTA management is engaged in negotiations for hosting CTA with the nations and organisations responsible for the two potential CTA sites on the northern and southern hemisphere (Spain for the La Palma location and European Southern Observatory (ESO) for the Paranal location in Chile). In parallel, DESY is applying to be selected as host laboratory for the CTA headquarters – a privilege that would boost the DESY Zeuthen site and increase DESY's influence in astroparticle physics nationally and internationally. A decision on the location of the CTA headquarters is expected for 2016.

CTA is not DESY's only project in astroparticle physics. DESY physicists are currently upgrading the cameras of the H.E.S.S. telescope in Namibia, with the aim of extending the experiment's lifetime. DESY is also strongly involved in the IceCube neutrino telescope at the geographic South Pole, which continues to deliver high-quality data. In 2015, the highest-energy neutrino event so far was observed, new measurements of the energy spectrum and flavour composition of the diffuse astrophysical neutrino flux were published and, while still no source could be detected, strong constraints on the origin of these neutrinos could be derived using a multimessenger approach. The DeepCore subdetector allowed neutrino mixing parameters to be measured with a precision approaching dedicated neutrino oscillation experiments. Planning of the IceCube-Gen2 project, which will comprise an extended high-energy array and the low-energy extension PINGU, is well under way, with DESY playing a leading role in sensitivity studies and in the development of new photosensors.

Recruiting in 2015 was particularly successful, resulting in a significant number of new leading scientists and joint professorships with universities: Kerstin Borras, Elisabetta Gallo, Christophe Grojean, Krisztian Peters, Christian Schwanenberger and Géraldine Servant will now contribute to shaping particle and astroparticle physics at DESY. The DESY Directorate extends its congratulations to former leading scientist Eckhard Elsen, who took up his new position as Director for Research and Computing at CERN at the beginning of 2016. During his 25 years at DESY, Eckhard Elsen significantly advanced research and development in particle physics projects, both at DESY und internationally, particularly in connection with the ILC.

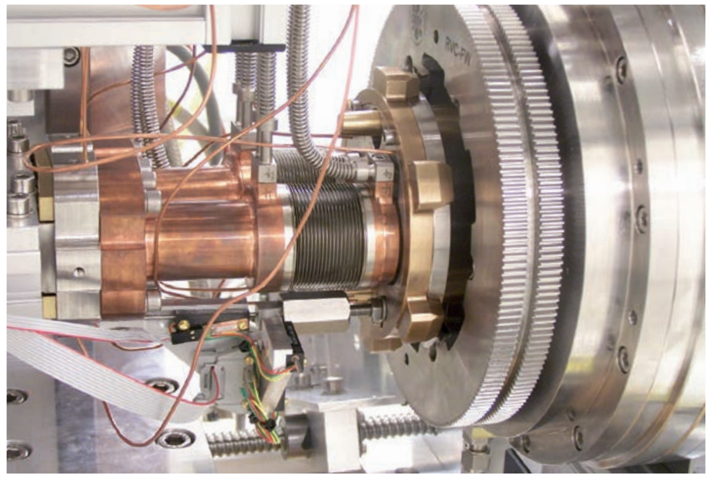


Figure 2

One of the two RVC systems constructed at DESY before closing the vacuum system of the Belle II interaction region

The DESY management also congratulates the following DESY particle and astroparticle physicists on prestigious grants: Alexander Westphal and Walter Winter each obtained a European Research Council (ERC) Consolidator Grant (Westphal was also awarded the J. Hans D. Jensen Award of the Institute for Theoretical Physics of the University of Heidelberg in Germany for his outstanding contributions to string theory), while Kerstin Tackmann was offered an ERC Starting Grant; DESY fellow Katharina Behr received a grant from the Helmholtz postdoctoral programme; and theorist Elli Pomoni was awarded an Emmy Noether grant from Deutsche Forschungsgemeinschaft (DFG).

These developments, together with our success in obtaining prizes and other EU grants – for example for AIDA2020, E-JADE and JENNIFER – clearly demonstrate DESY's attractiveness to particle and astroparticle physicists worldwide, to the funding agencies and to the scientific community at large. I am sure that, in 2016, our dedication and commitment will similarly bear fruit.

Joachim Mnich

Joachim Mnich
Director in charge of Particle Physics
and Astroparticle Physics

News and Events.

A busy year 2015

January

DESY welcomes three new leading scientists

At the beginning of 2015, DESY welcomed three new leading scientists for particle physics, appointed within the framework of the Helmholtz recruitment initiative.

Elisabetta Gallo, an experimental physicist appointed together with the University of Hamburg, joined the CMS group at DESY. Prior to her appointment, she coordinated particle physics at the Istituto Nazionale di Fisica Nucleare (INFN) in Florence, Italy, and taught at the University of Florence. With her research focusing on Higgs physics, she is continuing work she began at the Large Hadron Collider (LHC) at CERN and building a bridge to research at the planned International Linear Collider (ILC).

Elisabetta Gallo

Géraldine Servant, who was also appointed together with the University of Hamburg, joined the DESY theory group. She came from Barcelona, where she was a professor at the Catalan Institution for Research and Advanced Studies (ICREA). Her research focuses on the interplay of particle physics and cosmology, in particular on dark matter and the origin of the matter–antimatter asymmetry in the universe. She works on models of new physics at the TeV scale and their collider phenomenology and is eagerly awaiting the avalanche of new data coming from the LHC and from direct searches of dark matter.

Géraldine Servant

Christophe Grojean

Christophe Grojean also joined the DESY theory group coming from Barcelona. As a specialist in the physics and dynamics of the Higgs boson and its possible incarnations in various theories beyond the Standard Model, he is collaborating closely with experimentalists to establish the profile of this new particle. He is also involved in various working groups defining the physics case for the next generation of colliders after the LHC.

Third round of programme-oriented funding (POF III) starts

The third round of the programme-oriented funding (POF III) of the Helmholtz research field “Matter”, which includes DESY, started at the beginning of 2015. The efforts made to present the many facets of research at DESY to the reviewers in writing and at on-site inspections in 2014 paid off. From 2015 to 2019, DESY will receive funds amounting to 1050 million euros. Starting with an initial value of 193 million euros in 2015, this corresponds to an average annual increase of about 3%. This financial framework gives the DESY scientists and their colleagues at other Helmholtz centres in the research field “Matter” the means to realise their concepts, which are reflected in the reviewers’ recommendations.

DESY is engaged in three programmes in the research field “Matter”: the programme “Matter and the Universe”, which comprises particle and astroparticle physics; the newly established programme “Matter and Technologies”, which focuses on the development of a long-term perspective in the field of detector technologies and systems; and the programme “From Matter to Materials and Life”, which includes all activities in photon science. In addition to the programme-specific research activities, it is foreseen to continuously strengthen the management of large amounts of data for the three programmes.

February

Youth science competition “Jugend forscht” turns 50

Participants in the youth science competition “Jugend forscht” at the DESY school lab

On 19 and 20 February, the regional round of the youth science competition “Jugend forscht” took place at DESY in Hamburg. A total of 119 participants presented 66 projects at the DESY school lab. The competition, which celebrated its 50th anniversary in 2015, and the related experiments competition “Schüler experimentieren” invite young people from fourth grade to age 21 to experiment in mathematics, the natural sciences and technology within an individual research project.

Christian Schwanenberger appointed as leading scientist

Christian Schwanenberger was appointed as leading scientist at DESY and visiting professor at the University of Manchester in the UK. He is a member of the CMS collaboration at the LHC at CERN in Geneva and of the DØ collaboration at the Tevatron collider at Fermilab in Chicago. His main topics of research are elementary particle physics, in particular precision measurements of the properties of the top quark and its electroweak and strong couplings, the interaction between the top quark and the Higgs boson, searches for supersymmetric and other exotic extensions of the Standard Model and searches for dark matter.

Christian Schwanenberger

Helmholtz programme “Matter and Technologies” launched

At the end of February, approximately 200 scientists, including 50 PhD students and postdocs, met at DESY in Hamburg for the kick-off meeting of the new Helmholtz research programme “Matter and Technologies”. The various talks on accelerator and detector technology clearly showed that developers of instrumentation won’t run out of work for years to come. The meeting gave the participants the opportunity to better define the goals of the new programme, get to know each other and take a major step forward towards turning the “Matter and Technologies” concept into an functioning programme.

A meeting of PhD students from the “Matter and Technologies” programme, dubbed “MT student retreat”, took place prior to the actual kick-off meeting. It provided a forum for students to present their work and network with colleagues from other centres in order to develop a better understanding of the research done within the programme.

Participants in the kick-off meeting of the Helmholtz programme “Matter and Technologies”

February

European XFEL celebrates topping out of headquarters building

The topping-out ceremony for the European XFEL headquarters building was celebrated on 18 February. The event marked a milestone in the construction of the X-ray free-electron laser, which is one of Europe's largest new international research facilities. Over 350 guests, including representatives from the German federal government, the German states of Schleswig-Holstein and Hamburg, the consular corps, local politics and administration, the European XFEL Council and European XFEL employees and their colleagues from DESY, recognised the accomplishments of the construction workers over the past year.

The headquarters building is constructed atop an underground experimental hall. The complex is 3.4 km away from the starting point of the facility on the DESY campus in Hamburg and is linked by a system of tunnels. When complete, the European XFEL will be a user facility open to scientists around the world.

Work will continue throughout 2015 on the completion of the headquarters building. European XFEL employees will move into the building in 2016 as they prepare for the beginning of user operation in 2017.

Traditional foreman's toast at the topping-out ceremony of the European XFEL headquarters building

March

Negotiations for CTA northern site to start

On 26 March, the partner countries involved in the Cherenkov Telescope Array (CTA), the next-generation gamma-ray observatory, decided to start negotiations for the location of the telescope array in the northern hemisphere. At a meeting in Heidelberg in Germany, representatives of ministries and funding agencies agreed to begin negotiations with Spain for a possible location on La Palma and with Mexico for one in San Pedro Mártir. Another candidate site in Arizona (USA) is being considered as a possible back-up site. Following the site selection, the project will move forward with the construction of the first telescopes on the site, planned for 2016.

The CTA gamma-ray observatory will be built on two sites, one in the northern and one in the southern hemisphere.

DESY in Zeuthen participates in IceCube Masterclass

In March, DESY in Zeuthen participated in the IceCube Masterclass for the first time. The masterclass was created by the IceCube cooperation partners of the University of Wisconsin-Madison (USA) in 2014 based on the model of the International Particle Physics Outreach Group (IPPOG) Masterclasses.

Ten research institutions in Europe and the USA opened their doors for the programme, inviting school students to learn about current astroparticle physics research. On the day, 20 ninth-grade pupils attended the DESY campus in Zeuthen. They were given the opportunity to analyse real measurement data from the IceCube neutrino telescope at the South Pole – neutrino signals that deliver information about extreme objects in the universe, such as black holes or gamma-ray bursts. The students also met scientists of the Zeuthen IceCube group and communicated via live broadcasting with scientists working at the South Pole and at other institutes.

April

LHC restart opens up new territories

After a two-year shutdown, the world's largest particle accelerator, the LHC at CERN, restarted in early April 2015. During the shutdown, the LHC was upgraded in order to increase the particle collision energy to a new world record of 13 TeV. These particle collisions will provide particle physicists around the globe with insights into previously uncharted territory. At DESY, two large groups of scientists are involved in the LHC experiments ATLAS and CMS.
The high-energy collisions might uncover the avidly looked-for supersymmetric particles – or something completely different. One of the biggest unanswered questions is the nature of dark matter, an invisible form of matter that is revealed only through its gravitational interaction. Even though dark matter is five times more common than the matter we are familiar with, its nature is a complete mystery. Many physicists hope that the revamped LHC will uncover possible candidates for dark matter.

Designated Helmholtz President visits DESY

Otmar Wiestler, a board member of the German Cancer Research Centre in Heidelberg and the designated President of the Helmholtz Association, visited DESY in April prior to taking up office. Wiestler and his attendants were not only impressed by the research carried out at DESY, but also by the liveliness and dynamics of the centre.

Apart from discussions with the directorate and leading scientists, one highlight in the late afternoon was a round of talks with young researchers, which illustrated the versatility of the centre and its staff members. The interest of the future Helmholtz President in the perspectives and ideas of the younger generation was so great that, long after the end of the subsequent reception at the Center for Free-Electron Laser Science (CFEL), he was still engaged in conversations with PhD students and postdocs.

Otmar Wiestler, designated President of the Helmholtz Association (right), conversing with DESY Director Helmut Dosch (left)

May

DESY creates new research opportunities at FLASH

After a comprehensive technological upgrade and expansion, DESY's pioneering soft X-ray free-electron laser facility FLASH opens up new vistas into the nanocosm, providing the international scientific community with novel experimental opportunities and groundbreaking technologies. At a symbolic ceremony on 20 May, Olaf Scholz, First Mayor of Hamburg, and Anders Lönn, State Secretary to Sweden's Minister for Higher Education and Research, named the two FLASH experimental halls after the pioneer physicists and Nobel Prize laureates Albert Einstein and Kai Siegbahn.

The new Flash2 experimental hall, named after Nobel laureate Kai Siegbahn

In the future, scientists will be able to peer into the nanocosm using FLASH at up to 12 different experimental stations – twice as many as before – to record films of chemical reactions, for instance, examine the dynamics of new types of data storage device or observe biomolecules at work. The X-rays delivered by the new beamline FLASH2 will further be used for experiments in the field of plasma acceleration, enabling novel activities in accelerator research.

June

ATLAS Award for Nicholas Styles

DESY scientist Nicholas Styles was awarded one of the 2015 ATLAS Outstanding Achievement Awards for his contributions to the improvement of the ATLAS detector at the LHC. As outlined by the award committee, Styles wrote essential software for the reconstruction and simulation of particle tracks and contributed significantly, through detailed studies, to the design of the planned ATLAS detector upgrade.

Nicholas Styles

The award recognises outstanding contributions to the detector; scientific data analyses are excluded. The ATLAS collaboration has more than 3000 members, 57 of them at DESY in Hamburg and Zeuthen. Twelve such awards were conferred in 2015.

Emmy Noether grant for Elli Pomoni

Elli Pomoni, a postdoctoral researcher in DESY'stheory group, received almost 1 million euros through an Emmy Noether grant from the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG). The Emmy Noether Programme supports young researchers in achieving independence at an early stage of their scientific career. The grant will allow Elli Pomoni to lead a young investigator group involving two PhD students and one postdoc. Starting in June 2015 for a period of five years, Pomoni and her team will investigate methods that can be used in gauge theories with less supersymmetry and aim to obtain exact results for more realistic gauge theories.

Elli Pomoni

July

Colloquium in honour of Wilfried Buchmüller

In July, DESY held a two-day colloquium, attended by the "Who's Who" of theoretical particle physics, in honour of the 65th birthday of Wilfried Buchmüller, a professor at the University of Hamburg and leading scientist within the DESYtheory group.

Participants of the colloquium in honour of DESY theorist Wilfried Buchmüller (first row, second from right)

The first day was devoted to the work of Wilfried Buchmüller himself and his fundamental contributions to modern particle physics. Following a welcoming address by Joachim Mnich, DESY director in charge of particle and astroparticle physics, further lectures were given by Christian Schwanenberger, leading scientist at DESY and member of the CMS collaboration at the LHC, Tsutomu Yanagida of the Kavli Institute for the Physics and Mathematics of the Universe at the University of Tokyo, Japan, Andrei Linde of Stanford University, USA, and Roberto Peccei, formerly of the University of California Los Angeles, USA.

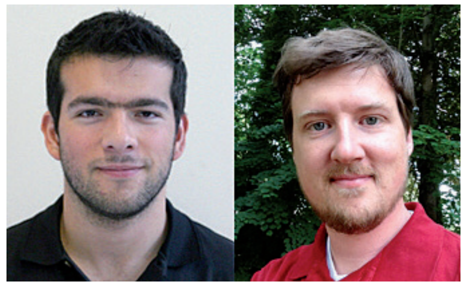
The second day gave an overview of the current areas of research, including many interesting papers presented in particular by Wilfried Buchmüller's former PhD students.

Two 2015 GNN dissertation prizes for DESY PhD students

Juan Pablo Yáñez and Jakob van Santen of the IceCube group at DESY in Zeuthen were awarded two of the three dissertation prizes of the Global Neutrino Network (GNN), which were presented in 2015 for the first time.

Juan Pablo Yáñez wrote his PhD thesis "Measurement of neutrino oscillations in atmospheric neutrinos with the IceCube DeepCore detector" at DESY as a student of Humboldt University Berlin. Analysing neutrino events taken with the IceCube neutrino telescope at the South Pole, he was able to constrain the allowed region for two parameters governing neutrino oscillation.

Jakob van Santen wrote his thesis as a student of the University of Wisconsin, USA, and was later recruited as a postdoc for the Zeuthen group. For his thesis "Neutrino Interactions in IceCube above 1 TeV: Constraints on Atmospheric Charmed-Meson Production and Investigation of the Astrophysical Neutrino Flux with 2 Years of IceCube Data taken 2010-2012", he analysed the energy spectrum and angular distribution of neutrinos recorded with IceCube.



GNN prize winners Juan Pablo Yáñez (left) und Jakob van Santen (right)

Chadwick Medal for Amanda Cooper-Sarkar

The Institute of Physics (IOP) in the UK awarded particle physicist Amanda Cooper-Sarkar the Chadwick Medal and Prize 2015 for her research into the structure of the proton using deep-inelastic scattering of leptons on nuclei. The award is made biennially for distinguished research in particle physics.

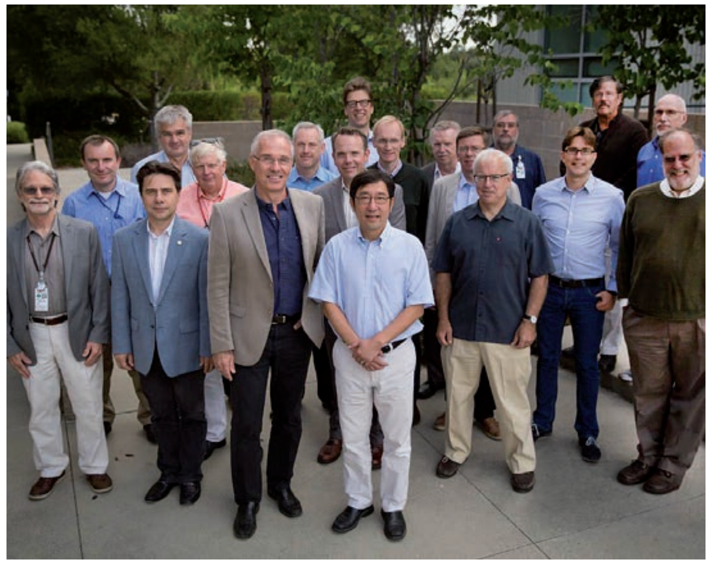
Amanda Cooper-Sarkar

Amanda Cooper-Sarkar is one of the most renowned physicists in this field. As a long-time member of the ZEUS collaboration at DESY's former HERA electron–proton collider, she worked mainly with data from the HERA experiments. Among others, she played a leading role in the analysis for a 2015 publication by the H1 and ZEUS experiments for which the two collaborations combined all their collision data taken at HERA. According to the IOP, the results will be the reference data for the proton structure for decades to come.

Amanda Cooper-Sarkar has worked for decades on the optimisation of techniques for interpreting experimental data and on the theory of quantum chromodynamics. She was one of the primary developers of the analysis software HERAfitter, used to analyse data on deep-inelastic scattering processes at H1 and ZEUS. Today, as a member of the ATLAS collaboration, she uses this knowledge to refine the data analysis at the LHC.

SLAC and DESY join forces at bilateral strategy meeting

The US research centre SLAC and DESY will work closer together in the future: That was the outcome of a meeting of senior managers of both labs who convened on 16–17 July at SLAC to discuss a joint strategy for more collaboration.



Attendees of the SLAC–DESY bilateral strategy meeting

SLAC and DESY representatives talked about their labs' current research activities and future plans, exposing a variety of commonalities and also differences between the research centres. This led to discussions that identified areas where the labs can best collaborate with each other. The meeting's attendees found plenty of common ground. They compiled a comprehensive list of common interests, including advancements in X-ray laser technology, particle physics detectors, future compact accelerators and computing methods to handle ever-increasing amounts of scientific data produced in X-ray, particle physics and cosmology experiments.

The meeting was the first of its kind, kicking off future regular collaboration meetings of the two labs.

Kerstin Borras appointed as leading scientist

Within the framework of the Helmholtz recruitment initiative, Kerstin Borras was jointly appointed as leading scientist at DESY and professor at RWTH Aachen University in Germany. The experimental particle physicist investigated various aspects of the Standard Model, particularly special features of the strong interaction, with experiments at the HERA collider at DESY and the Tevatron collider at Fermilab in the USA. Kerstin Borras headed the DESY CMS research group for many years and is now deputy spokesperson of the CMS experiment at the LHC.

Kerstin Borras

August

DESY welcomes 115 summer students from 28 nations

For eight weeks, 115 students were given the opportunity to gain practical insight into research at DESY in Hamburg and Zeuthen as part of the DESY summer student programme, which is one of the largest and most international summer schools in Germany. In 2015, the young researchers came from 28 nations.

The DESY summer student programme is extremely popular among students, both because of the practical experience it provides in genuine research projects and because of its internationality. The students were integrated into various DESY groups in the fields of particle and astroparticle physics, accelerator physics and photon science, where they experienced everyday life in science at first hand. A series of lectures providing the necessary theoretical background complemented the practical experience.

DESY summer students 2015

September

Eckhard Elsen to become research director at CERN

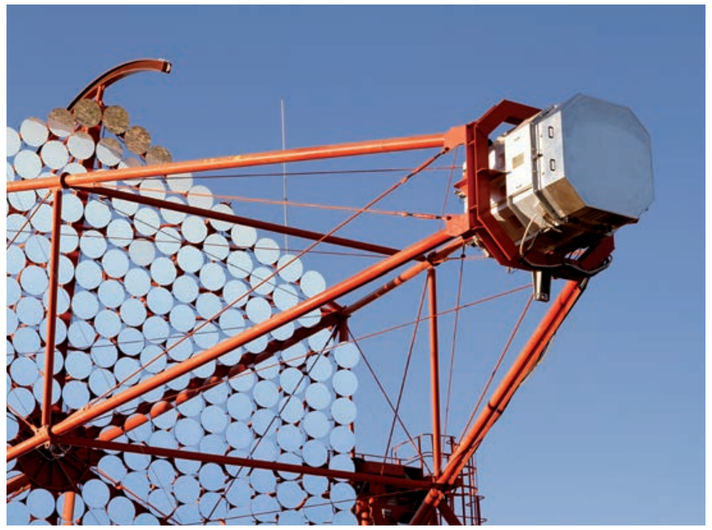
DESY particle physicist Eckhard Elsen will be the next Director for Research and Computing at CERN. Elsen was appointed by the designated Director General of CERN, the Italian particle physicist Fabiola Gianotti. The CERN Council approved Gianotti's proposals for the new directorate.

Eckhard Elsen

Eckhard Elsen, a professor at the University of Hamburg, has been working at DESY since 1990. His career has taken him from Hamburg via Stanford and Heidelberg to DESY, participating in various particle physics experiments along the way, such as JADE and H1 at DESY, OPAL at CERN as well as DELCO and BaBar at SLAC. For over ten years, he has been advancing research and development in high-energy physics projects, both at DESY und internationally, particularly in connection with the planned International Linear Collider (ILC). As the project manager for several EU-funded research projects and a member of many international committees, Elsen knows his way around international research policies. In his role as chairman of the Large Hadron Collider Committee (LHCC), he has gained deep insights into the challenges of the LHC experiments.

First gamma-ray images from new H.E.S.S. camera

At the end of September, the first of four new gamma-ray cameras recorded its first light at the High Energy Stereoscopic System (H.E.S.S.) gamma-ray observatory in Namibia. In July, a team from DESY had upgraded the camera and installed 200 electronic boards and a new ventilation system. After integration into the network and data acquisition system, first cosmic gamma-ray images could be acquired.

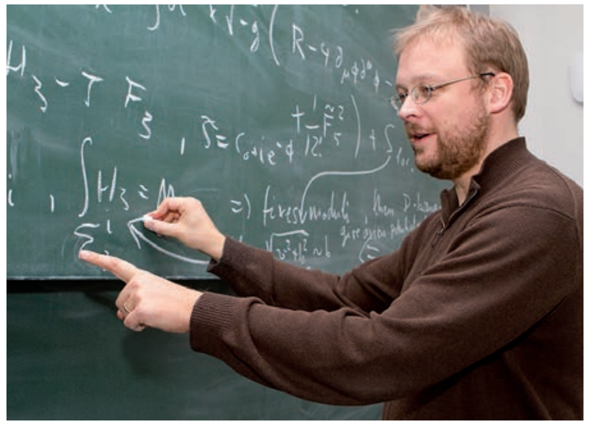


New camera for the H.E.S.S. gamma-ray observatory, mounted at telescope CT1

The new, faster camera can resolve and digitise the light flashes produced by gamma rays in the atmosphere, which only last a few nanoseconds. The images demonstrate the basic functionality of the camera, thereby giving the go-ahead for the production of the remaining three cameras, which are to be installed in 2016.

Jensen Prize goes to Alexander Westphal

DESY scientist Alexander Westphal was awarded the J. Hans D. Jensen Prize by the University of Heidelberg in Germany for his outstanding contributions to string theory. Alexander Westphal is particularly interested in the phenomenon known as inflation, which is believed to have caused the size of the universe to increase by a factor of at least one hundred septillion within the first fraction of a second after the big bang. Westphal is examining how the various models of inflation can be incorporated in string theory.

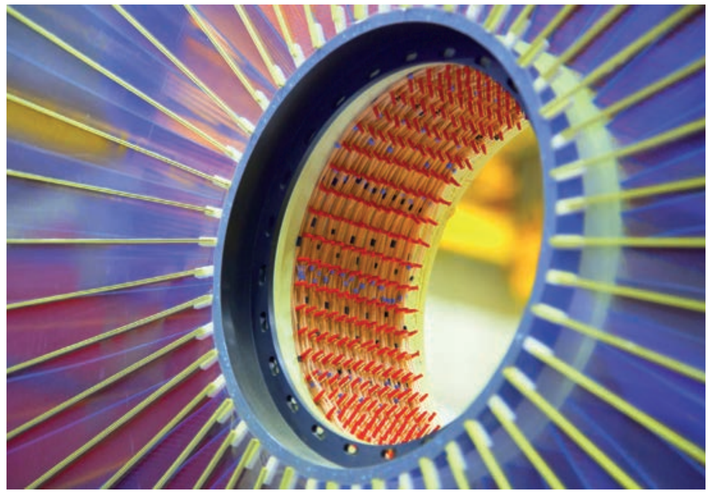


Alexander Westphal

The J. Hans D. Jensen Prize was called into being to mark the 100th birthday of the Heidelberg physicist and Nobel Prize winner, and has been awarded annually since 2008 to outstanding scientists working in the field of theoretical physics.

DESY Photowalk

At the end of September, DESY in Hamburg welcomed 45 amateur and professional photographers participating in the DESY Photowalk. The event was part of the Global Physics Photowalk, which took place on the same weekend at seven other research centres around the globe. The photographers had the opportunity to take pictures of the HERA tunnel, the PETRA III „Max von Laue“ experimental hall, the FLASH2 „Kai Siegbahn“ experimental hall and the CFEL building.



Detail of the radial tracking chamber of the H1 experiment at DESY's former HERA collider

Hinrich Meyer becomes HAP Senior Fellow

In recognition of his abundant merits regarding the progress of physics, particularly astroparticle physics, DESY scientist Hinrich Meyer was elected Senior Fellow of the Helmholtz Alliance for Astroparticle Physics (HAP). The emeritus physics professor of the University of Wuppertal, Germany, carried out particle physics research in several DESY groups for decades and substantially contributed to the development of astroparticle physics.

Hinrich Meyer

Meyer is still working with colleagues at an experiment at DESY, developed at the University of Wuppertal, to measure gravitation with high precision.

October

Krisztian Peters appointed as leading scientist

In October, Krisztian Peters was appointed as leading scientist at DESY within the ATLAS group. His current research activities focus on understanding the nature of electroweak symmetry breaking and on searching for dark matter and other phenomena beyond the Standard Model of particle physics using the ATLAS experiment at the LHC.

Krisztian Peters

Krisztian Peters graduated with a thesis based on electroweak and quantum chromodynamics phenomenology, in which he developed and computed resummed higher-order corrections to vector boson scattering. From 2005 to 2010, he was a member of the D0 experiment at the Tevatron collider at Fermilab near Chicago. Afterwards he moved to CERN, where he was co-leading the Higgs boson property measurements in the diphoton decay channel at ATLAS.

Science on Tap

A completely new way of learning about science was tested in Hamburg for the first time. On 15 October, 30 pubs and bars around the city offered “Science on Tap”. Particle accelerators, lasers and black holes, strings and nanoparticles, proteins and dark matter, Higgs particles and quarks – researchers talked about their field of interest in vivid and easily understandable terms, for about half an hour each, and discussed their subjects with the audience in a convivial atmosphere. The response was overwhelming: Virtually all the pubs were packed; the audiences listened with great enthusiasm and asked many questions. The scientists too enjoyed the Science on Tap experiment enormously. And the publicans were pleased to welcome new patrons to their premises.

The event was organised by DESY, the Hamburg Centre for Ultrafast Imaging (CUI), the Partnership for Innovation, Education and Research (PIER) and the Special Research Field (SFB) 676 of the University of Hamburg. It is to be held every year.

Learning about science in the pub: the Science on Tap event was a big success.

November

Helmholtz Young Investigator Group for ATLAS

The Helmholtz Association awarded DESY grants to implement three new Young Investigators Groups, allowing three young scientists to set up their own research groups at DESY. They will receive annual funds of 250 000 euros each over a period of five years, half of which will be provided by DESY.

Sarah Heim

Sarah Heim set up a group of young investigators to search for dark matter and other new physics phenomena using the ATLAS detector at the LHC. The group plans to use two different approaches to look for dark-matter candidates: through the decay of the Higgs boson into invisible particles that do not leave any trace in the detector; and indirectly by comparing the properties of the Higgs boson with the predictions of the Standard Model of particle physics.

Colloquium in honour of Eckhard Elsen

In November, DESY held a colloquium in honour of Eckhard Elsen, who was to leave DESY at the beginning of 2016 to take up his new position as Director for Research and Computing at CERN. As a long-time DESY scientist, Elsen made numerous scientific contributions to particle physics at DESY and beyond.

Speakers at the colloquium recalled Elsen's past achievements: Vera Lüth of SLAC, USA, talked about his activities at SLAC, Siggi Bethke of the Max Planck Institute of Physics in Munich, Germany, spoke about his involvement in the JADE experiment at DESY’s PETRA accelerator and Joël Feltesse of CEA in Saclay, France, detailed his role in the H1 experiment at the former HERA collider at DESY. Sachio Komamiya of the University of Tokyo, Japan, reviewed the path towards the ILC and Rolf Heuer, then Director General of CERN, speculated about Elsen’s future at CERN.

From left to right: Rolf Heuer, then CERN Director General,
Eckhard Elsen, designated CERN Director for Research and Computing,
and Sergio Bertolucci, Elsen’s predecessor at CERN.

EU funds design study for European plasma accelerator

EuPRAXIA

The European Union supports the development of a novel plasma particle accelerator with three million euros from the Horizon2020 programme. The EU project EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) will produce a design study for a European plasma research accelerator focusing on applications of the new technology. Plasma acceleration promises to significantly shrink the costs and size of particle accelerators for science, medical applications and industry.

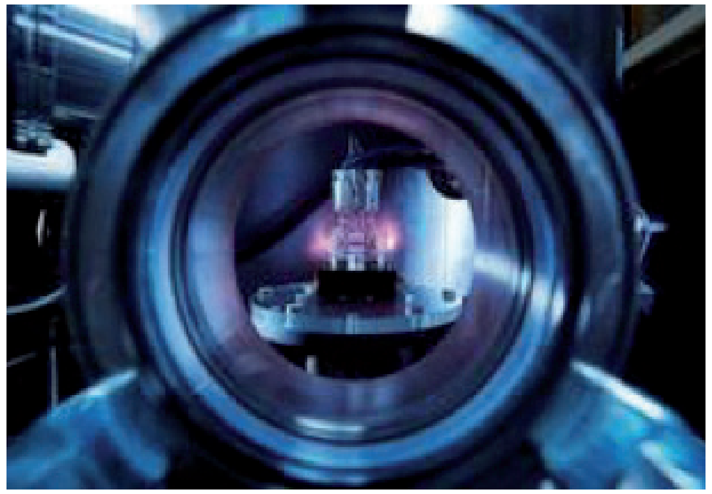


Image of a plasma cell

By the end of 2019, EuPRAXIA will produce a conceptual design report for the worldwide first 5 GeV plasma-based accelerator with industrial beam quality and dedicated user areas. EuPRAXIA is the required intermediate step between proof-of-principle experiments and versatile ultracompact accelerators for industry, medicine or science, e.g. at the energy frontier of particle physics as a plasma linear collider.

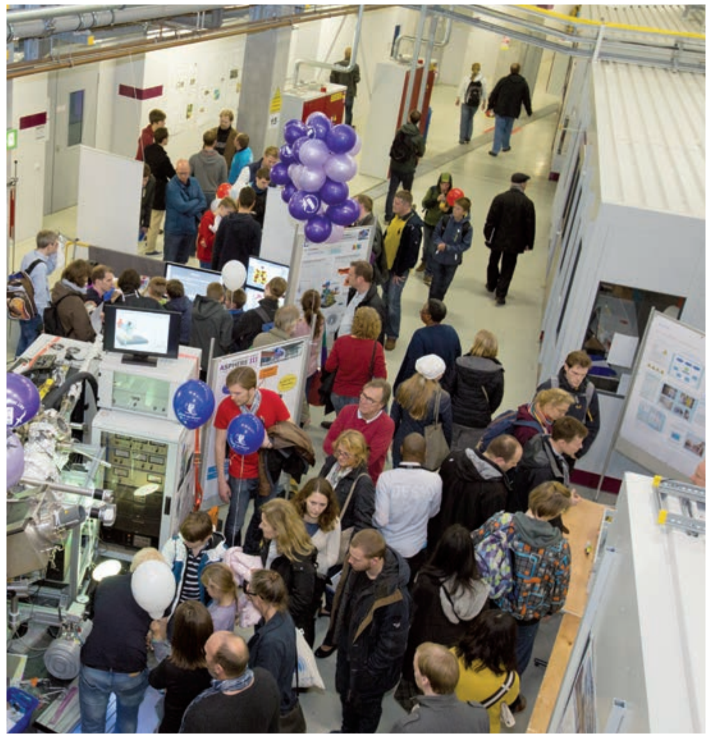
Honorary professorship for Volker Gülzow

Volker Gülzow, head of DESY's IT department, was awarded a honorary professorship on big data at the HTW University of Applied Sciences in Berlin, Germany. This professorship underlines the intense cooperation between DESY and the HTW on research in the field of advanced computing for large scientific experiments.

Volker Gülzow

Open Day at DESY in Hamburg

The DESY campus in Hamburg opened its doors to the public on 7 November for twelve hours, from noon to midnight. More than 100 attractions were presented to more than 18 000 visitors, with more than 1200 helpers participating in the event. In addition to unique insights into the large-scale accelerators and light sources, DESY and its campus partners offered a colourful children's programme and fascinating lectures – from particles in the universe to molecules as movie stars.



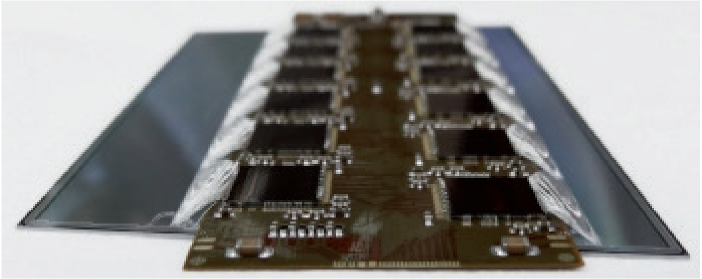
Impressions from DESY's Open Day in November

Impressions from DESY's Open Day in November

December

Detector assembly facility for LHC upgrades becomes reality

A major milestone on the way towards the construction of silicon strip tracker end-caps for the ATLAS and CMS experiments at the high-luminosity LHC was reached in December 2015: The DESY Directorate and Foundation Council approved the investment of 8.5 million euros for the realisation of the detector assembly facility (DAF) on the DESY campus. The facility will serve, until at least 2026, for all construction steps, from module production through series tests to the integration and system test of the complete end-caps.



Prototype of a silicon strip module for use in the new ATLAS tracker end-cap

PhD thesis award 2015

The 2015 PhD thesis award of the Association of the Friends and Sponsors of DESY (VFFD) was shared by Denise Erb und Timon Mehrling, both of DESY and the University of Hamburg. The association presents the prize every year for one or two outstanding PhD theses from the two previous university terms.

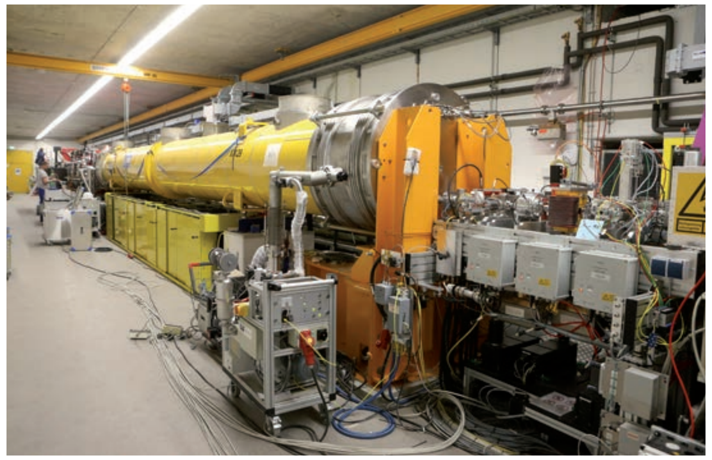
For her thesis, Denise Erb developed a method to produce nanomaterials through self-organisation. Timon Mehrling worked on the conservation of beam emittance in novel plasma accelerators.

Denise Erb and Timon Mehrling together with DESY Director Helmut Dosch (left) und Friedrich-Wilhelm Büßer, President of the Association of the Friends and Sponsors of DESY (right)

First electrons accelerated in the European XFEL

A crucial component of the European XFEL X-ray free-electron laser took up operation in December: The injector – the first part of the 2-km-long superconducting linear accelerator that will drive the X-ray laser – accelerated its first electrons to nearly the speed of light. This is the first beam ever accelerated at the European XFEL and represents a major advancement toward the completion of the facility. As the main shareholder of European XFEL, DESY is responsible for the construction and operation of the linear accelerator.

The injector, which is located on the DESY campus in Hamburg and has been under construction since 2013, produced a series of tightly packed electron bunches that passed through the 45-m-long injector beamline. The injector shapes the highly charged electron bunches and gives them their initial energy. This energy is then gradually increased across the main linear accelerator, which is still being assembled.



View into the injector area of the European XFEL

ERC Grant for Kerstin Tackmann

DESY particle physicist Kerstin Tackmann is to receive over 1.3 million euros from the European Research Council (ERC) to carry out research aimed at a more detailed characterisation of the Higgs boson. She will use the ERC Starting Grant to set up a research group investigating the properties of the Higgs boson in detail, as part of the ATLAS collaboration. The group's focus will lie especially on the decay of the Higgs boson into two photons or four leptons, which allows very accurate measurements. The five-year project is scheduled to begin in 2016.

Kerstin Tackmann

Physics with protons.

Physics with protons has been at the heart of DESY's particle physics activities since the start-up of its electron–proton collider HERA in 1992. Today, almost 10 years after the shutdown of the accelerator and the H1, ZEUS and HERMES detectors, flagship HERA data analyses are being finalised, ensuring a unique heritage, e.g. in the form of combined quantum chromodynamics (QCD) and electroweak measurements and parton distribution functions of the proton (p. 38).

The discovery of the Higgs boson by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN in 2012 would not have been possible without the precise knowledge of the proton structure as the principal input. In 2015, the ATLAS and CMS collaborations furthered their analysis of the new particle, using their full LHC Run 1 data sets and combining their results (p. 22). While Run 1 analyses were pursued and to a large extent finished – for example searches for new physics at CMS (p. 31) and ATLAS (p. 32) – Run 2 started very successfully in 2015 at a record centre-of-mass energy of 13 TeV, raising new expectations towards exciting discoveries at the LHC (p. 24). The unprecedented centre-of-mass energy opens up completely new windows for so far unobserved phenomena that might show up directly as signals in searches for new physics (p. 32) or in deviations from Standard Model expectations, e.g. in top-quark measurements (p. 26). On the other hand, the new energy also requires a new understanding of the collision environment and thus dedicated QCD studies (pp. 28, 30).

While physics analyses of LHC Run 1 and Run 2 are progressing, developments towards upgrades of the experiments have also been forging ahead. For example, CMS physicists are working hard to finalise their contributions to the pixel detector extension to be installed in 2016 (p. 34). And both experiments are concluding, together with German university partners, their preparations towards new silicon tracker end-caps (p. 36).

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Higgs-boson properties: Exceeding precision.

LHC Run 1 ATLAS and CMS combinations, and prospects for LHC Run 2

Since, in 2012, the ATLAS and CMS collaborations at the LHC announced the discovery of a new particle consistent with the Higgs boson predicted by the Standard Model, both experiments have independently performed high-precision measurements of various properties of this new state, which is the crucial element in the breakdown of the electroweak symmetry. By now, the ATLAS and CMS collaborations have joined their efforts to further improve the precision of the measurements of the mass of the Higgs boson, its production and decay rates, and its couplings to Standard Model particles. The collaborations are using their complete LHC Run 1 data sets, which comprise the data collected in proton–proton collisions at centre-of-mass energies of 7 and 8 TeV during the years 2011 and 2012.

In the Standard Model (SM), the breakdown of electroweak symmetry is achieved through the introduction of a complex doublet scalar field, leading to the prediction of the Higgs boson H whose mass m_H is a fundamental parameter of the theory. An improved knowledge of m_H would also allow more precise predictions to be made for the other properties of the Higgs boson, such as production rates or couplings to SM particles. The ATLAS and CMS experiments at the LHC were designed to help elucidate the electroweak symmetry breaking mechanism. In 2012, they announced the observation of a new particle resembling the Higgs boson predicted by the SM, and since then, they have been measuring several of its properties. Recently, the two experiments combined their analyses using the full LHC Run 1 data set to further improve the precision of the measurements of the mass, the production and decay modes and their rates, and the couplings of this new state to SM particles.

Higgs-boson mass

The measurement of the Higgs-boson mass is performed using only the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay channels, because of their superior mass resolution. Figure 1 presents the results of the individual analyses together with their combinations, which yield a value of the Higgs-boson mass of $m_H = 125.09 \pm 0.24$ GeV. This combined measurement of the Higgs-boson mass improves the results from the individual experiments and decay channels and is the most precise measurement to date of this fundamental parameter of the newly discovered particle.

Production and decay rates

The global signal strength μ is the simplest and most precisely measured parameter facilitating a comparison of Higgs-boson production and decays with SM predictions. Several production modes are considered in measurements of μ: gluon fusion (ggF), vector-boson fusion (VBF), and associated production with vector bosons (WH, ZH) or a pair of top quarks (ttH). Similarly, several decay channels into bosons ($H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ and $H \rightarrow \gamma\gamma$) and into fermions ($H \rightarrow \tau\tau$, $H \rightarrow bb$ and $H \rightarrow \mu\mu$) were investigated. The measurement of the global signal strength μ assumes that the individual signal strengths of all productions modes and decay channels take their SM values. The combined ATLAS and CMS data of Run 1 result in a best-fit value of $\mu = 1.09 \pm 0.11$, which is consistent with the SM expectation of $\mu = 1$.

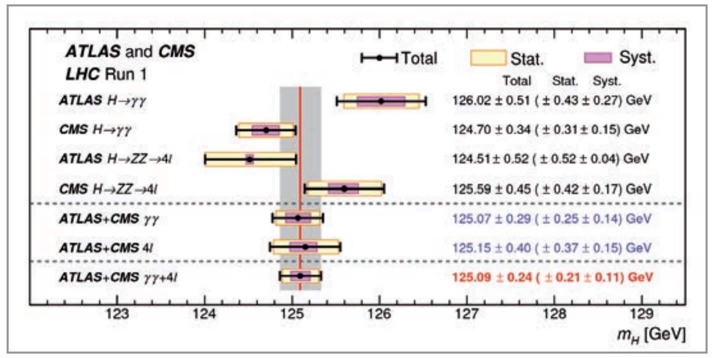

Figure 1

Summary of Higgs-boson mass measurements from the individual analyses of ATLAS and CMS and from the combination of the two experiments

The measurement of the global signal strength is very model-dependent, and dedicated measurements of coupling-related observables that are specifically designed for the individual production and decay channels may provide stronger tests of the compatibility of the experimental results with the SM.

Figure 2 shows the ATLAS and CMS measurements of the signal strengths for the various production processes (left) and decay modes (right) together with the result of a combination of the two experiments. In all cases, the signal strengths are consistent with unity within the experimental uncertainties, demonstrating the very good agreement of the results with the SM predictions. Moreover, the combination of the data from ATLAS and CMS confirms the observations of the VBF production mode and of the decay $H \rightarrow \tau\tau$ with significances of 5.4 and 5.5 standard deviations, respectively.

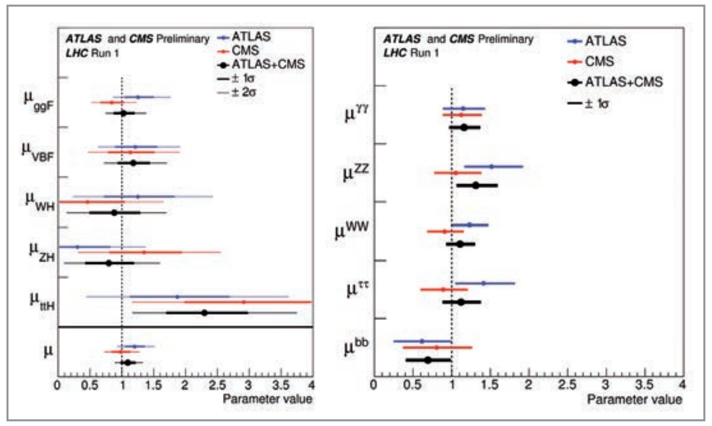

Figure 2

Best-fit results for the production (left) and decay (right) signal strengths obtained individually by ATLAS and CMS and by the combination of the two experiments

Higgs couplings

The direct couplings of the Higgs boson to the SM particles are well defined in the SM: They relate directly to the masses of the fermions and gauge bosons. Therefore, the precise measurement of the couplings is an essential test of the SM. By combining the measurements of all the production and decay channels from ATLAS and CMS, the measurement precision of the coupling strengths κ_Z, κ_W, κ_t, κ_b, κ_τ and κ_μ of the Higgs boson to the W and Z bosons, the t and b quarks, and the τ and μ leptons, respectively, could be taken to unprecedented levels. The coupling–mass relation obtained from this combined measurement is shown in Fig. 3; it is found to be in very good agreement with the SM prediction of a linear relation between particle mass and coupling strength.

The effective couplings κ_g and κ_γ describing the loop-induced processes of ggF production and $H \rightarrow \gamma\gamma$ decay, respectively, are particularly interesting: They are sensitive to loop contributions from new heavy particles, and any deviation from their SM predictions would be indicative of new physics beyond the Standard Model (BSM). Two scenarios are considered in the LHC analyses: In one scenario, the Higgs boson is assumed not to decay into BSM particles (e.g. because of their mass being too high), while in the other scenario, this assumption is relaxed, i.e. a branching fraction BR_{BSM} greater than zero is possible. Figure 4 depicts the couplings measured for both scenarios. Good agreement with the SM predictions is observed. However, when considering possible BSM decays, an upper limit on BR_{BSM} of 0.34 at 95% confidence level is obtained, which still leaves significant room for new physics that might be inaccessible at 8 TeV.

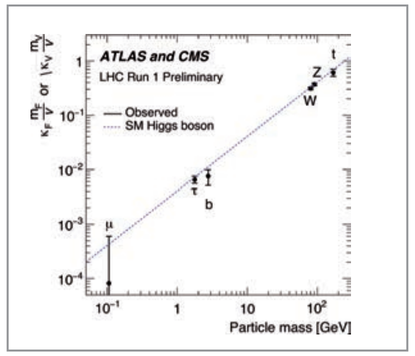

Figure 3

Coupling–mass relation obtained from the combined ATLAS and CMS measurements of the coupling strengths of SM particles to the Higgs boson. The measurements are compared to the SM prediction of a linear relation.

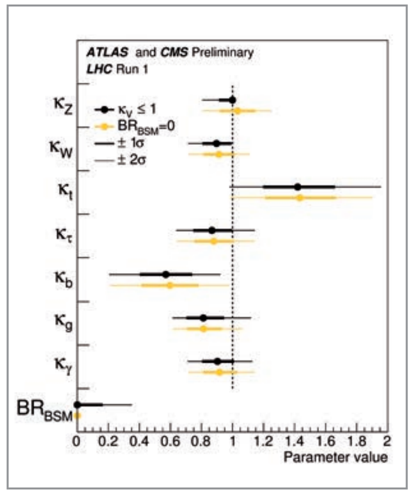

Figure 4

Combined ATLAS and CMS fit results for the Higgs couplings for the two different scenarios discussed in the text

Prospects for LHC Run 2

In 2015, Run 2 started with proton–proton collisions at the unprecedented centre-of-mass energy of 13 TeV, which brings with it an increase of Higgs-boson production by a factor of 2.5 compared to the 8 TeV data taking. Furthermore, Run 2 will deliver four times more luminosity than Run 1 did. Run 2 will thus drastically improve our knowledge of the Higgs-boson properties (mass, couplings), and it will bring the confirmation of the decay $H \rightarrow bb$ as well as evidence of the ttH process. Moreover, Run 2 will allow the Higgs-boson properties to be scrutinised for any sign of new physics that might become accessible at the new energy frontier.

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Yanping Huang, yanping.huang@desy.de

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Successful start of LHC Run2 at 13 TeV.

... with new detector components provided by DESY

After a two-year shutdown, the LHC at CERN restarted operation in 2015 very successfully and provided a first set of data at an unprecedented proton–proton centre-of-mass energy of 13 TeV. An initial integrated luminosity of 4 fb^{-1} was delivered to the ATLAS and CMS experiments. For those searches for physics beyond the Standard Model that involve heavy particles, the new data at high energy already exceed the sensitivity of the LHC Run1 data set recorded in the years 2010–2012. ATLAS and CMS used the long shutdown for maintenance and upgrades of several detector components, including the equipment for monitoring the LHC beam conditions as well as the trigger systems, to which DESY is contributing substantially.

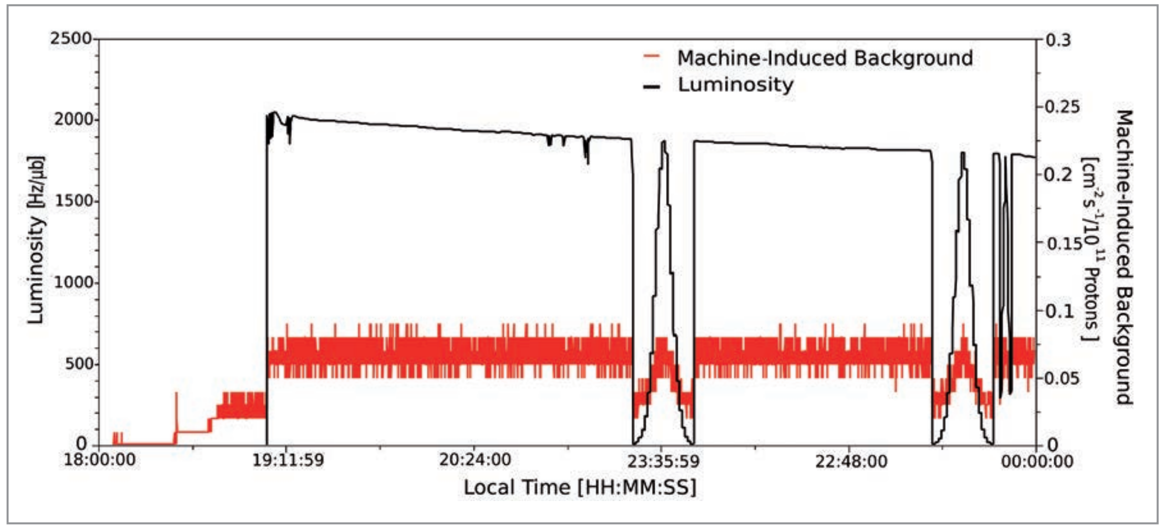

Figure 2

Luminosity and machine-induced background in the CMS experiment as a function of time during a Van-der-Meer scan

LHC operation in 2015

After initial accelerator studies in spring 2015, the first LHC beam with protons at an energy of 6.5 TeV was circulated in April 2015. Soon afterwards, in May 2015, a new world record was established with colliding beams at a centre-of-mass energy of 13 TeV. Subsequently, in June, a first data-taking run with stable beam conditions was delivered to all LHC experiments. Over the course of the year, the intensity of the LHC beams was carefully ramped up to a peak luminosity of about 5 x 10^{33} $\text{cm}^{-2}\text{s}^{-1}$ in November (Fig. 1). The proton–proton collision period was followed by a data-taking period with heavy ions in December.

In total, the LHC delivered an integrated luminosity of 4 fb^{-1} to the experiments and demonstrated readiness for the high-luminosity production running foreseen for the coming three years until 2018, when a total integrated luminosity of 150 fb^{-1} is envisioned.

New detector for luminosity measurements at CMS

The luminosity is a key parameter for collider experiments that quantifies the number of collisions. At the LHC, the luminosity is measured precisely using a technology originally invented by Nobel laureate Simon van der Meer. In this technique, steering magnets are used to displace the two colliding proton beams with respect to each other, enabling the effective beam size to be determined and thus leading to an evaluation of the beam luminosity at the intersection point. Dedicated detector systems are required for these measurements.

One of the detectors used for such Van-der-Meer scans in 2015 is the CMS fast beam conditions monitor BCM1F, which was developed at DESY. BCM1F provides information on the conditions of the beams and ensures that the CMS inner detector occupancy is sufficiently low for data taking. In addition to providing beam information, BCM1F also detects collisions and can thus be used for Van-der-Meer scans. It consists of 24 single-crystal diamond sensors of 5 x 5 mm^2 area each, positioned in two rings of 6.5 m radius from the beam centre, located at 1.8 m on either side of the interaction point. A dead-time-free real-time histogramming unit (RHU) is installed so the BCM1F can, thanks to its excellent time resolution, deliver online information on instantaneous luminosity and machine-induced background to the LHC and CMS control rooms. Signals from the proton collisions can be distinguished from backgrounds bunch-by-bunch using their arrival time.

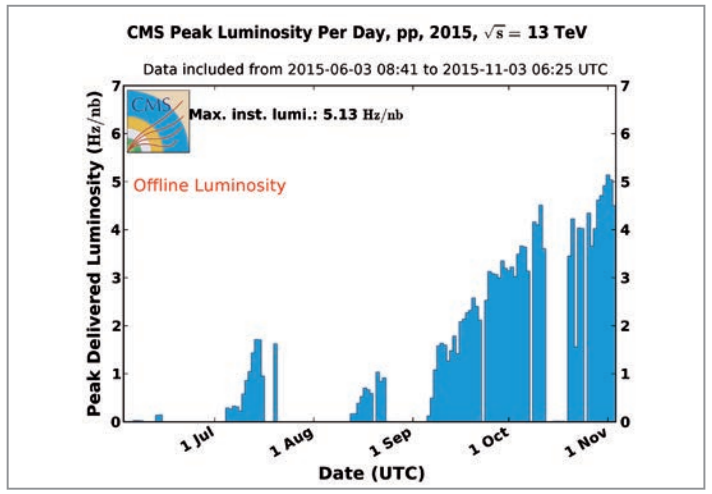

Figure 1

Maximum daily instantaneous proton–proton luminosity as recorded by CMS between June and November 2015

In Fig. 2, both the instantaneous luminosity and the machine-induced background rates are shown as a function of time [1]. In the Van-der-Meer scan, the relative positions of the two beams are changed, creating the strong variation as a function of time seen in the centre and towards the right of the figure. From this information, the size of the beams and hence the luminosity is determined.

New trigger stage for ATLAS

At the LHC, the experiments have to cope with a bunch-crossing frequency of 40 MHz, which requires sophisticated trigger electronics that decide in real time which events are good enough to be stored for final analysis. The trigger system of the ATLAS experiment is designed to reduce the event rate from the LHC nominal bunch crossing at 40 MHz to about 1 kHz. In the coming years, with ever increasing luminosity, more sophisticated algorithms will be needed to achieve higher background rejection while maintaining good efficiency for interesting signals.

DESY is involved in the development, installation and commissioning of the fast tracker (FTK) [2], a new trigger stage designed to reduce the data volume significantly. The FTK is a first step towards an advanced trigger on particle tracks (track trigger). In previous trigger systems at the LHC, information from the inner tracking system was not used. In the FTK, a hardware processor is utilised that provides a trigger decision within 0.1 ms for tracks down to momenta as low as 1 GeV. The track trigger decision is calculated using data from the silicon strip tracker. The algorithm comprises two main steps. The first step consists of pattern recognition in the associative memory. In the second step, the tracks are fitted using full-resolution hits in each candidate road to determine the optimal track parameters and reject false pattern matches.

Providing fast, extensive access to tracking information, with a resolution comparable to the offline reconstruction, the FTK will facilitate the precise detection of primary and secondary vertices and ensure robust selections and improved trigger performance.

In 2015, the design of the FTK was finalised and a first prototype was installed in the ATLAS detector. In 2016, this system will successively be extended, with full deployment scheduled for 2017.

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[1] CMS Collaboration, Machine Induced Background with BCM1F 2015, CMS-DP-2016-003 ; CERN-CMS-DP-2016-003, http://cds.cern.ch record/2121275?ln=en
[2] M. Shochet et al., Fast TracKer (FTK) Technical Design Report, CERN-LHCC-2013-007; ATLAS-TDR-021, https://cds.cern.ch/record/1552953?ln=de

Exploring top-quark physics at a new energy frontier.

First top-quark pair production cross sections measured at 13 TeV

Shortly after the start of the LHC Run 2 at CERN, the ATLAS and CMS groups at DESY performed important initial tests of the Standard Model of particle physics at the new energy frontier of 13 TeV, exploring the heaviest of all known particles: the top quark. The measured inclusive and differential $t\bar{t}$ cross sections were found to agree with the Standard Model prediction.

Introduction

The restart of the LHC at CERN in June 2015 marked the beginning of a new era in particle physics. After a two-year shutdown, the LHC is now operating at a centre-of-mass energy of 13 TeV, enabling the probing of smaller distances and larger energies than ever before. The ATLAS and CMS groups at DESY have played a leading role in the first exploration of this unknown territory. Both groups are deeply involved in the quest to understand the heaviest of all known elementary particles, the top quark, and performed the first measurements of the top-quark pair production cross section in the new energy regime of 13 TeV.

Since its discovery in 1995 by the CDF and DØ collaborations at the Tevatron in the USA, the top quark has been measured with ever higher precision. The large amount of data from the two accelerators, the Tevatron at 2 TeV and the LHC at 7 and 8 TeV, have pinned down its properties with high precision, and no deviations from the Standard Model have been found. Due to its high mass, the top quark has the strongest connection to the Higgs boson, suggesting that it might play a special role in electroweak symmetry breaking. Speaking more generally, the top quark is a very good candidate for guiding the way towards new physics beyond the Standard Model and thus a particularly interesting object to study at 13 TeV. Top quarks are predominantly produced as quark–antiquark pairs. As top quarks decay almost always into a bottom quark and a *W* boson, top-quark final states are classified according to the decay channel of the *W* bosons. For their measurements of the $t\bar{t}$ production cross sections, the DESY ATLAS and CMS groups focused on the case where both *W* bosons decay into a lepton (electron, *e*, or muon, *μ*) and the corresponding neutrino.

Inclusive cross section

One of the principal advantages of the higher centre-of-mass energy is that, for many processes, the production cross section increases. At 13 TeV, the $t\bar{t}$ cross section is enhanced by a factor of three relative to the one at 8 TeV and a factor of almost five relative to 7 TeV. Thus, with a rather low integrated luminosity (compared to the amount of data recorded at lower energies), statistically powerful measurements can be performed. Early measurements of the $t\bar{t}$ cross section are crucial, not only to test the Standard Model at a higher energy than ever before, but because the $t\bar{t}$ process is a dominant background in many searches for physics beyond the Standard Model.

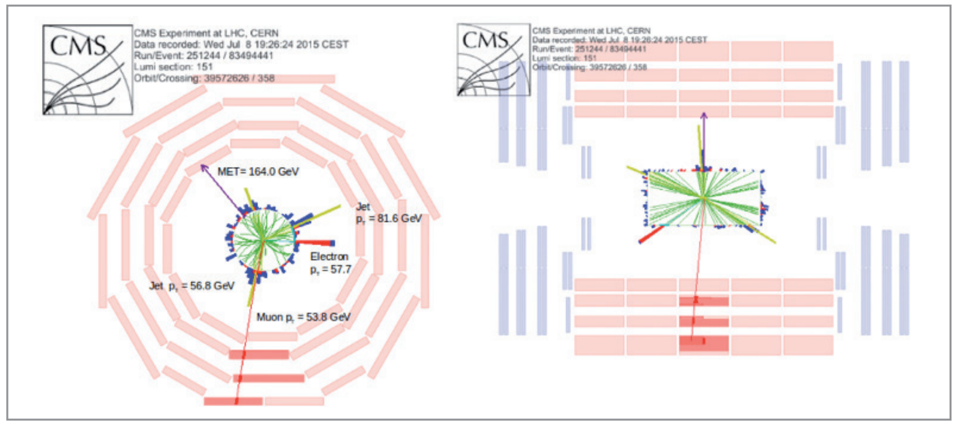

Figure 1

Event display of a top-quark pair candidate in *x–y* (left) and *r–z* (right) views. This event has one isolated muon, one isolated electron and two hadronic jets (from CERN-CMS-DP-2015-019).

During summer 2015, the DESY ATLAS and CMS groups performed measurements of the $t\bar{t}$ production cross section in the dilepton channel, beginning with "first evidence" studies, which were presented at the EPS-HEP conference of the European Physical Society in July, and culminating in detailed measurements of the dilepton cross section. The cross section was measured in five different channels, shown in Fig. 2. The DESY ATLAS group studied the *ee*/*μμ* dilepton channel, the DESY CMS group the *eμ* dilepton channel. The precision of the results is of the order of 15% and dominated by uncertainties in the understanding of the luminosity. The results will be updated to include the ~3 fb^{-1} recorded by both ATLAS and CMS in 2015 and are expected to reach a precision of significantly better than 10%.

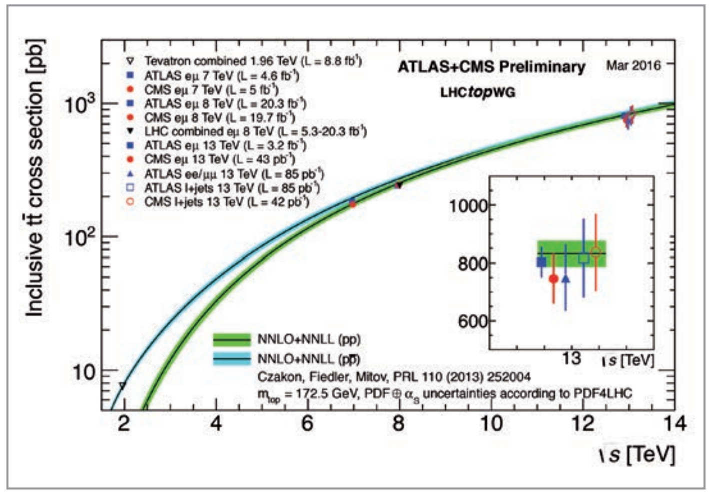

Figure 2

Inclusive cross section measurements by ATLAS and CMS at 7 TeV, 8 TeV and 13 TeV, compared to the Standard Model prediction

Differential cross section

Measurements of the $t\bar{t}$ cross section in different regions of phase space are an important next step towards a deeper understanding of perturbative QCD and for enhancing the sensitivity to new physics beyond the Standard Model. The DESY ATLAS and CMS groups have performed the first differential measurements of $t\bar{t}$ production at 13 TeV in the dilepton channels, measuring the cross section as a function of kinematic quantities of the top quarks and the $t\bar{t}$ system, such as the transverse momentum (p_T) of the top quark or the $t\bar{t}$ system, and as a function of the number of hard jets in the event. The kinematics of the top quarks are sensitive to higher-order effects in perturbative QCD, and possible deviations in the shapes of all distributions can hint to physics beyond the Standard Model. At the LHC, more than 60% of all $t\bar{t}$ events are produced with additional hard jets in the final state. A detailed understanding of these processes is crucial as multijet processes represent important backgrounds for many new-physics searches.

Figure 3 shows two examples of these distributions, in particular the top p_T (upper panel) and the number of additional jets accompanying the $t\bar{t}$ system (lower panel). The measurements are corrected for detector and migration effects back to parton or particle level and normalised to the measured inclusive cross section. The results are compared to state-of-the-art theory models, many of which are used during Run 2 for the first time. Therefore, these first measurements will help to tune the theory predictions in order to improve the description of the data. Furthermore, the new LHC energy and the large data samples expected will allow the previous measurements to be extended into further regions in phase space and higher multiplicities.

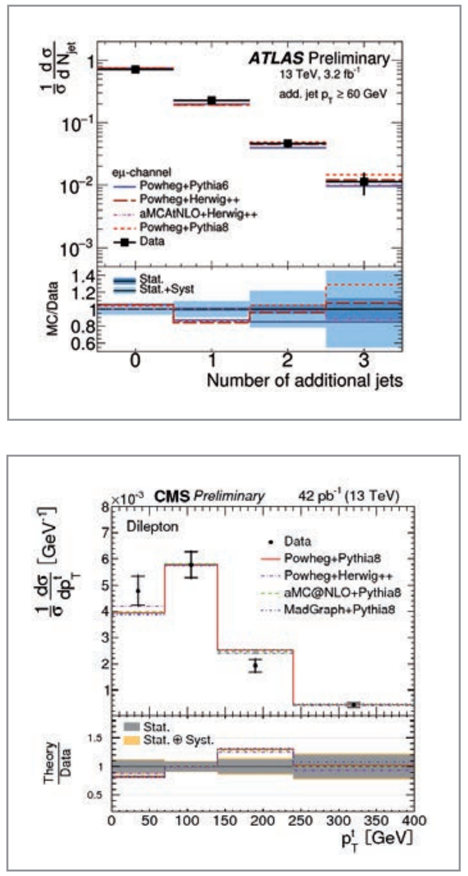

Figure 3

Differential cross section of top-quark pair production at 13 TeV as a function of the p_T of the top quarks (top, ATLAS) and the number of additional jets accompanying the $t\bar{t}$ system (bottom, CMS) in the dilepton decay channel. The measurements are compared to different Standard Model predictions.

Summary

The restart of the LHC at 13 TeV marked the beginning of a new area in particle physics. The DESY ATLAS and CMS groups performed first inclusive and differential measurements of $t\bar{t}$ production. A small fraction of the data collected in 2015 has been analysed, and no hints of new physics beyond the Standard Model were found. For now, the Standard Model prevails.

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References:

[1] CMS Collaboration, Phys. Rev. Lett. 116 (2016) 052002
[2] ATLAS Collaboration, ATLAS-CONF-2015-049
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[4] ATLAS Collaboration, ATLAS-CONF-2015-065

Inclusive QCD measurements with the ATLAS detector.

Testing pile-up modelling and tracker performance

Using the early LHC Run 2 data taken at a centre-of-mass energy of 13 TeV, the DESY ATLAS group led a measurement of primary charged particles. The resulting distributions are corrected for detector effects and presented as inclusive-inelastic distributions in a well-defined fiducial region. They are then compared to the most commonly used generators in particle physics (Pythia 8 and Herwig++) and astroparticle physics (EPOS and QGSJET-II). These comparisons are crucial for simulating the more than 20 pile-up interactions that happen during every bunch crossing and for helping to understand air showers induced by cosmic rays.

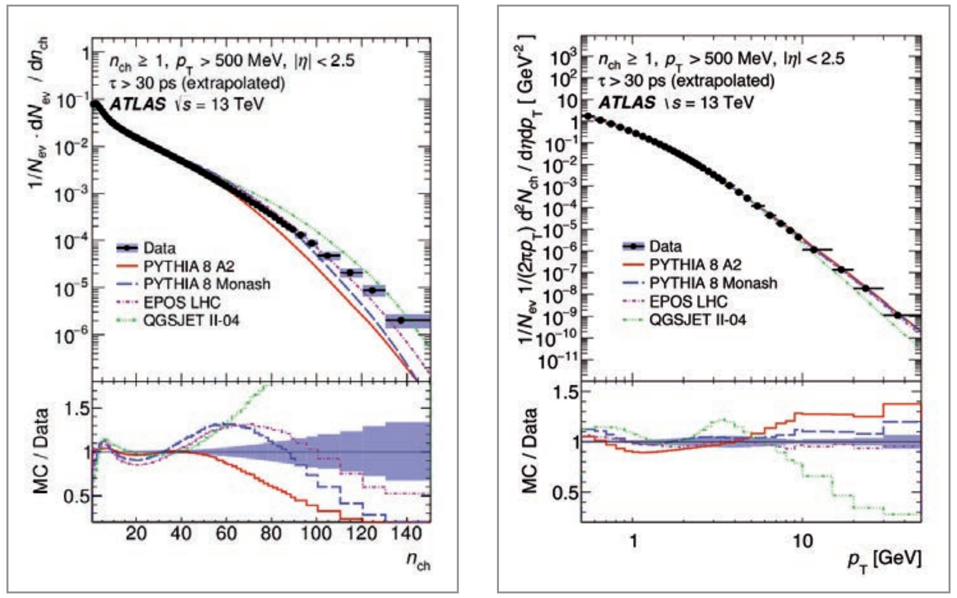

Figure 2

Unfolded distribution of the number of tracks per event (left) and the momentum distribution of tracks (right) in the fiducial tracking volume for data and several Monte Carlo predictions

Introduction

Inclusive charged-particle measurements in proton–proton collisions provide insights into the low-energy, non-perturbative region of quantum chromodynamics (QCD). Particle interactions at these energy scales are typically described by QCD-inspired models implemented in Monte Carlo event generators with free parameters that have to be constrained by measurements (“tuned”). The ATLAS experiment recorded about 10 million events at a centre-of-mass energy of 13 TeV in a special run at low instantaneous luminosity. These events were fully corrected for detector effects in the fiducial phase space and compared to commonly used generator tunes.

Analysis strategy

The data were recorded in May 2015 using a nearly fully efficient scintillator trigger. A vertex requirement was applied to remove the remaining background from events with multiple interactions. Events containing at least one track with a momentum above 500 MeV and a pseudorapidity $|\eta| < 2.5$ were selected, and the background stemming from tracks produced in interactions with the detector material and in decays of short-lived particles was removed. Then the sample was corrected for the tracking efficiency of primary particles, which is the most important correction.

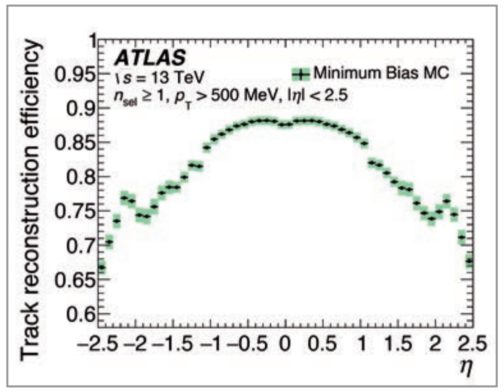

Figure 1

Tracking efficiency versus η for primary tracks. The systematic uncertainty is dominated by the incomplete knowledge of the material in the inner detector.

Figure 1 shows the tracking efficiency as a function of η, determined from Monte Carlo simulations. The uncertainties are dominated by the limited knowledge of the material distribution in the tracking detector, which includes the active detector material as well as support structures, cables and cooling pipes. In the Run 1 data taking from 2010 to 2012, the material content of the detector was known to better than 5%. Before the start of Run 2, an additional innermost silicon pixel layer (insertable b-layer, IBL) was installed and parts of the support services (cables, printed circuit boards) were moved outside of the tracking volume. To validate the changes, extensive data-to-Monte Carlo comparisons were performed using the vertices of hadronic interactions and photon conversions in the material. The IBL was fully included in the Monte Carlo simulations, and an additional data-driven correction for the material between the pixel detector and the strip detector was developed. This reduced the systematic uncertainty for the tracking efficiency resulting from incomplete knowledge of the material of the tracking devices to less than 1.5% in the forward direction, compared to more than 3% in previous publications.

Studies of unfolded distributions

Figure 2 shows the primary charged particle multiplicity distribution n_{ch} (left) of the events and the transverse momentum (p_T) distribution of the primary charged particles (right). The high-multiplicity region contains significant contributions from events with numerous multiparton interactions or hard interactions that cannot be described by leading-order calculations. The Pythia 8 A2 tune, a dedicated ATLAS tune used for pile-up modelling, describes the bulk of the data in the $n_{ch} < 50$ region well, but predicts too few events at larger n_{ch} values. The more universal Pythia 8 tune Monash – as well as EPOS and QGSJET-II, two generators widely used in astroparticle physics – aim to describe the data in a wider range by predicting too many events in the mid-n_{ch} region. The QGSJET-II prediction is also higher than the data at high $n_{ch,}$ because it incorporates no mechanism such as colour reconnection to suppress the production of particles in dense jets. The momentum distribution is best described by EPOS, the best generator for describing single-particle properties, but both Pythia 8 tunes show a reasonable agreement as well.

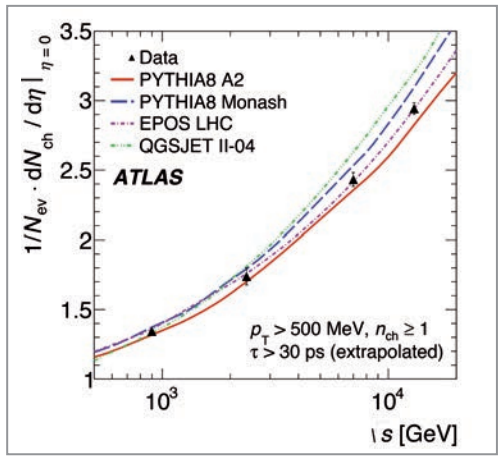

Figure 3

Comparison of the unfolded data with different Monte Carlo predictions for the number of tracks per unit in η in the central detector at different centre-of-mass energies

Figure 3 shows a comparison of the mean number of particles per unit of η in the central detector region at different LHC centre-of-mass energies. The mean number of primary charged particles increases by a factor of 2.2 when the centre-of-mass energy increases by a factor of about 14 from 0.9 TeV to 13 TeV. EPOS and Pythia 8 A2 describe the centre-of-mass energy dependence very well, while Pythia 8 Monash and QGSJET-II predict a steeper rise in multiplicity with the centre-of-mass energy. The comparison thus shows that energy interpolation in inclusive QCD events works, but that the quality depends on the generator tuning.

Summary

The measurement of inclusive QCD events in the early Run 2 data helps to better understand inclusive charged-particle production in QCD. It is an important contribution to the understanding of the detector material, to the tuning of Monte Carlo generators and to the modelling of pile-up in high-energy hadron interactions. Our results show that the generators tuned to the Run 1 data taken at centre-of-mass energies of 900 MeV to 7 TeV describe the new Run 2 data collected at 13 TeV reasonably well. However, the agreement in the differential distributions strongly depends on the distributions used for the parameter tuning of the generators.

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LHC Run 2 QCD highlights.

Jets at large transverse momenta and underlying-event simulations

With the high-energy LHC Run 2, experimental investigations of the theory of strong interactions, quantum chromodynamics (QCD), have entered a new and exciting phase. Jet production at large transverse momenta can be used to test QCD at the highest collider energies. A measurement of the inclusive jet cross section as a function of jet transverse momentum and rapidity, the latter of which is related to the polar angle of the produced jets, was released by CMS [1] using first data from proton–proton collisions at 13 TeV. The results, shown in Fig. 1, cover a large range in jet transverse momentum from 114 GeV up to 2 TeV, in seven rapidity bins. The predictions from next-to-leading order QCD calculations are in good agreement with the measurement, giving confidence in the validity of the theory at highest energies.

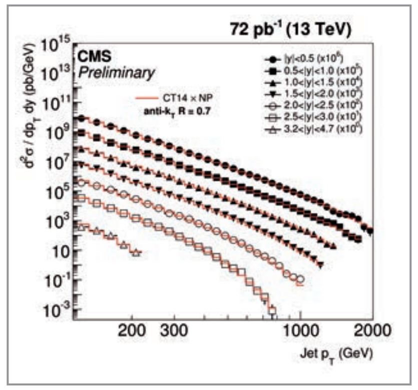

Figure 1

Double-differential inclusive jet cross sections as a function of jet transverse momentum compared to predictions from calculations at next-to-leading order in the strong coupling

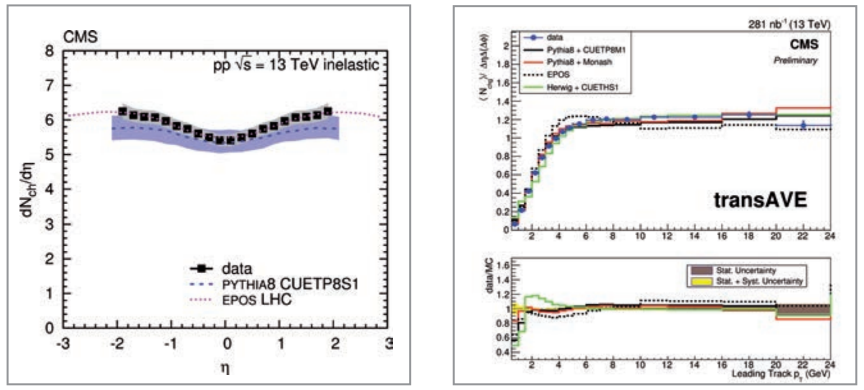

Figure 2

Left: Charged-particle multiplicity as a function of pseudorapidity.
Right: Average charged-particle multiplicity in the region transverse to the direction of the hard scattering as a function of the leading transverse momentum. Measurements are compared to the latest predictions.

In a high-energy hadron–hadron collision, the underlying event (UE) is defined as the activity that is not part of the final-state activity originating from the most energetic parton scattering of the collision. An accurate understanding of the UE is required for precise measurements of Standard Model processes at high energies and for searches for new physics. First measurements at 13 TeV show that the most recent predictions [2] of the underlying-event simulation are able to correctly describe the event content in terms of charged-particle multiplicity as a function of pseudorapidity [3] (Fig. 2, left) and as a function of the transverse momentum of the leading charged particle [4] (Fig. 2, right). These simulations are of crucial importance as they are used to model additional proton–proton interactions ("pile-up") that are generated as a by-product during high-luminosity LHC operation.

QCD measurements at the highest collision energies challenge the theoretical and phenomenological description of QCD and are essential benchmarks for any search for new phenomena.

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References:

[1] CMS Collaboration, CMS-PAS-SMP-15-007
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[3] CMS Collaboration, Phys. Lett. B751 (2015) 143
[4] CMS Collaboration, CMS-PAS-FSQ-15-007

Higgs and SUSY – a beauty-ful couple.

Searching for supersymmetric Higgs bosons in the *b*-quark final state

After the Higgs-boson discovery in July 2012, the physicists at the LHC revealed many properties of this newfound particle. Within the current precision, the findings are consistent with the expectations from the Standard Model of particle physics (SM). However, there is still sizable room for non-SM phenomena. Supersymmetric models predict additional Higgs bosons, which might be detectable in the *b*-quark final state. The CMS Higgs group at DESY performs comprehensive searches for such Higgs bosons, at both very low and very high masses.

The SM provides an impressively precise description of electroweak and strong interactions. Its success culminated in 2012 with the discovery of a Higgs boson with a mass of 125 GeV, so far found to be consistent with SM expectations. Nevertheless, the exact nature of the Higgs sector remains still unclear. There might be additional Higgs bosons, as predicted e.g. by supersymmetry (SUSY), a theory solving several known shortcomings of the SM. Two well-motivated implementations of SUSY are the minimal and the next-to-minimal supersymmetric Standard Model, shorthanded MSSM and NMSSM. Two analyses strongly driven by the CMS Higgs group at DESY probe important features of these models.

Even rather light Higgs bosons that have so far escaped detection in experiments are thinkable. As pointed out in Ref. [1], this is possible through a large admixture of the elusive Higgs singlet field of the NMSSM, which has strongly reduced couplings to SM particles, rendering it invisible in classical production mechanisms. However, the unprecedented high energies reached by the LHC at CERN enable production modes via intermediate heavy SUSY particles that finally decay into light Higgs bosons and invisible light SUSY particles. The former decay predominantly into *b* quarks, and the latter show as an imbalance in the transverse momentum, which is crucial for controlling the SM background. A signal would look like the red peak in the invariant-mass distribution of the *b*-quark jets in Fig. 1 [2]. The measured data do not show such a signal at this point; the distribution is well described by the backgrounds expected from the SM. This novel and unique analysis excludes Higgs masses within 30–100 GeV assuming certain model parameters.

Searches for additional Higgs bosons in the mass range above 125 GeV are also motivated by SUSY models. These particles might show as an enhancement in the *b*-quark pair final state, accompanied by additional *b* quarks. Such a scenario was studied in a dedicated analysis [3], covering a large fraction of the MSSM parameter space. This analysis was only possible thanks to a dedicated trigger developed by the DESY group. No signal was observed, and stringent upper limits up to 900 GeV were derived. In addition, the results were interpreted in several MSSM scenarios (Fig. 2). This analysis provides the world-best limits in this channel and is the only one of its kind at the LHC.

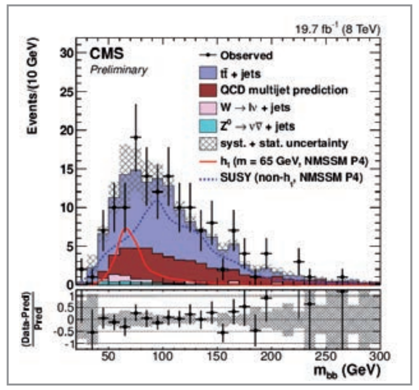

Figure 1

Background-only fit result of the invariant mass of the selected *b*-tagged jets in the NMSSM analysis [2]. Good agreement between the data and the SM prediction is observed, with no indication of a signal.

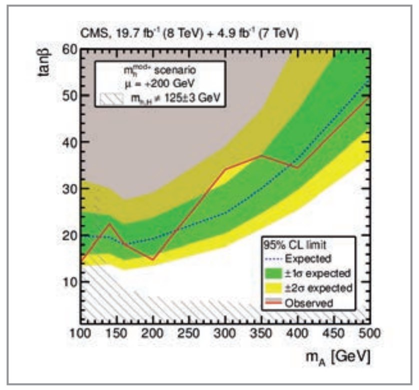

Figure 2

Expected and observed upper limits for the MSSM parameters tan β versus m_A [3]. The shaded area is the parameter space excluded by this analysis. The hatched area indicates the parameter space region excluded by requiring the model to provide a Higgs boson with a mass of 125 GeV.

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References:

[1] O. Stål, G. Weiglein, JHEP 1201 (2012) 071
[2] CMS Collaboration, CMS-HIG-14-030 (2015)
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Searches for new physics with ATLAS.

Looking for physics beyond the Standard Model of particle physics

The unprecedented Run 2 centre-of-mass energies at the LHC offer unique opportunities for searches for new phenomena. Although many scenarios of physics beyond the Standard Model (BSM) have been excluded by previous experiments and measurements, the high-energy regime made accessible for the first time at the LHC facilitates searches for many proposed BSM signatures and increases the sensitivity to SM processes that have not previously been observed.

Using W and Z bosons to search for dark matter

Dark matter (DM) accounts for a large part of the mass of the universe, but its nature and interactions with the SM as well as many of its properties remain unknown. Existing direct and indirect detection experiments suffer from large astrophysical uncertainties that would not be present if DM particles could be created at a collider. Searches at the LHC look for one or more SM particles recoiling against weakly interacting DM particles that are not observed in the detector, resulting in a distinctive energy imbalance termed “missing transverse momentum”. The DESY ATLAS group is playing a leading role in the search for DM recoiling against a W or Z boson using the latest 13 TeV proton–proton collisions recorded by the ATLAS detector [1]. Specifically, this search looks for W or Z bosons produced with high transverse momentum, meaning that their decay products are collimated into a jet of particles that is balanced against a large amount of missing transverse momentum. No statistically significant excess over the SM prediction is observed. Figure 1 provides an interpretation of the data in terms of an effective field theory (EFT) model, showing a lower limit on the mass scale of possible DM particles of this type.

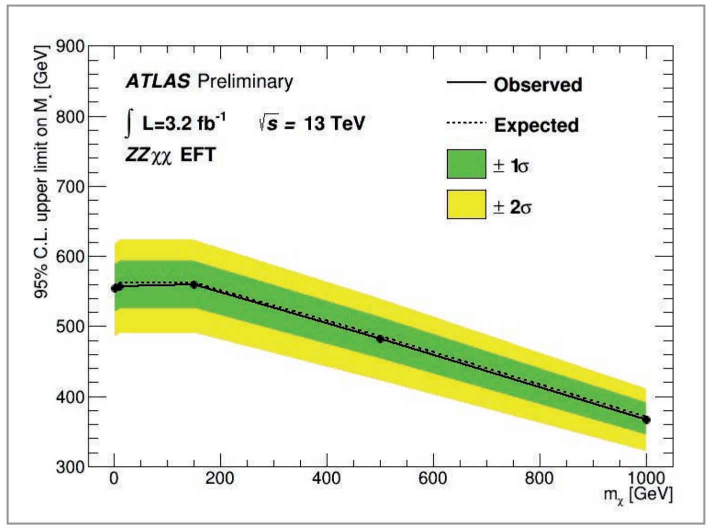

Figure 1

Limit on the mass scale M_* in the $ZZ\chi\chi$ EFT model. The higher the mass scale, the better the ability to probe dark matter.

Using Higgs bosons to search for dark matter

In a way similar to the W/Z search described above, the SM Higgs boson can be used as a probe to look for DM. The Higgs is less likely than the W or Z boson to have been produced through radiation from known SM particles, and so this search would give insight into the way in which DM particles couple to SM particles. The DESY ATLAS group is strongly involved in the search for DM production in association with a Higgs boson using the full 8 TeV data set collected by ATLAS [2]. The most probable decay of the Higgs boson is to two b quarks, and two techniques are used to identify decays of this type. The first, “resolved” technique looks for two small-radius jets of particles that each contain known b-type hadrons. The second, “boosted” technique looks for a single, larger, jet of particles, under the assumption that all of the decay products from the Higgs are travelling in the same direction. Figure 2 shows a comparison between the observed data and the expected SM background, which are found to be consistent with one another.

High-mass diphoton resonances

Many BSM models contain an extended Higgs sector, which predicts new scalar particles with masses larger or smaller than the mass of the SM Higgs boson. If such particles exist, they may decay into two photons; this would result in a narrow resonance in the diphoton final state, centred on the mass of the new particle. A search in this final state benefits from a clean experimental signature with excellent mass resolution and a well-controlled background. Using strict identification criteria to select photon pairs means that backgrounds from sources other than direct SM production of photons can be suppressed. This continuum background can be parameterised using a smooth function with several free parameters that are adjusted to fit the observed data. The DESY ATLAS group has been heavily involved in this search for additional Higgs-like resonances manifesting themselves as localised excesses of events on top of the smooth background. Figure 3 shows the diphoton mass spectrum observed in 13 TeV data with the result of an unbinned, background-only fit superimposed. The most significant deviation from the background-only hypothesis is observed for a mass of around 750 GeV.

Higgs pairs decaying to $bb\gamma\gamma$

In the SM, the predicted rate for the production of Higgs-boson pairs is several orders of magnitude lower than the rate for the single-Higgs process. The production of Higgs pairs is therefore not expected to be observable with current LHC data sets. However, a variety of extensions to the SM predict an enhancement of Higgs-pair production. In particular, the two-Higgs-doublet model proposes a heavier neutral scalar Higgs boson that can decay to a pair of SM Higgs bosons. The production of Higgs pairs could also be increased without resonant enhancements if the Higgs boson self-coupling parameter deviates from the value predicted in the SM. In the analysis presented here, ATLAS searched for a pair of Higgs bosons decaying into a pair of bottom quarks ($b\bar{b}$) and a pair of photons ($\gamma\gamma$), respectively [3]. Figure 4 shows the combined, unbinned signal-plus-background fit for the non-resonance analysis using 8 TeV data. Within a mass window around the Higgs-boson mass, 1.5 events are expected, mostly coming from the continuum background. Five events are observed, providing an intriguing excess that is being further studied using the data collected at 13 TeV – an analysis in which DESY is playing a leading part [4].

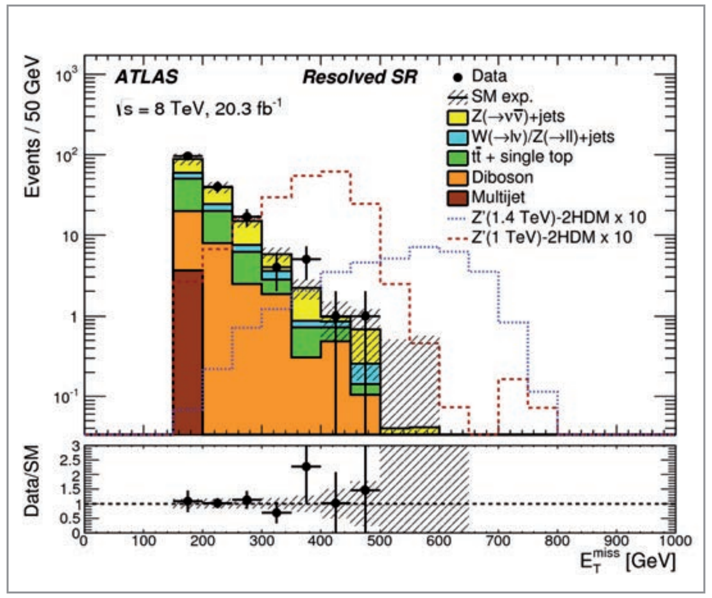

Figure 2

Distribution of missing transverse energy using the “resolved” method for the estimated backgrounds (solid histograms) and the observed data (points). The distributions that would be expected if DM signals were present are overlaid as dashed lines for comparison.

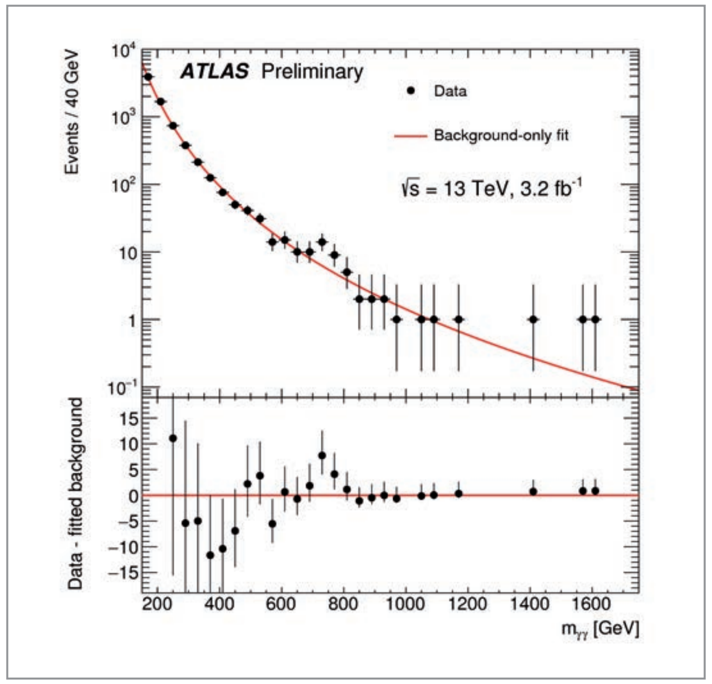

Figure 3

Invariant-mass distribution of selected diphoton events at 13 TeV. Residual numbers of events with respect to the fit result are shown in the bottom panel.

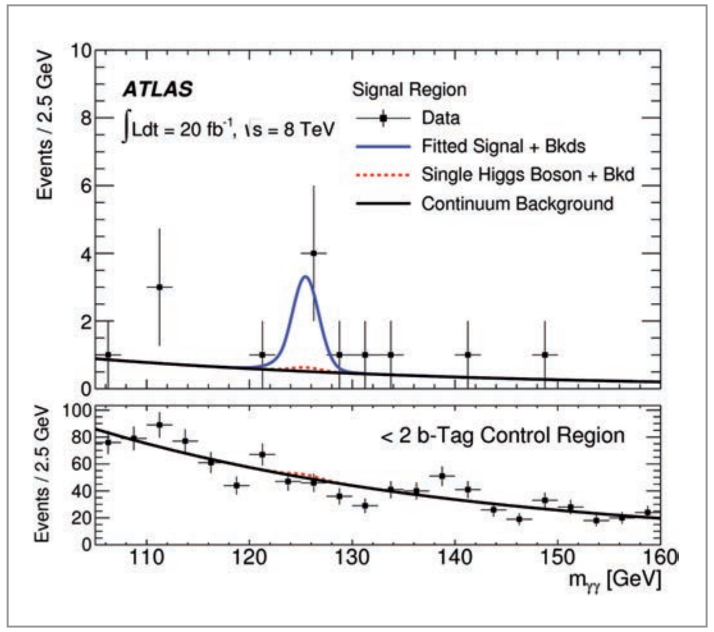

Figure 4

Diphoton invariant-mass spectrum for data and the corresponding fitted signal and background in the signal region for the non-resonance search. The control region has more statistics, which is useful to determine the functional shape of the background in the signal region.

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References:

[1] ATLAS Collaboration, ATLAS-CONF-2015-080
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Module production for the new CMS pixel detector.

Flip-chip and wire bonding, tests and calibration

The CMS collaboration is building a new pixel detector system to be installed in the 2016/17 extended year-end technical stop of the LHC at CERN. Together with the University of Hamburg, DESY is contributing 300 modules to half of the fourth barrel pixel layer. An in-house flip-chip bump-bonding procedure has been developed together with testing and calibration procedures that ensure high production quality.

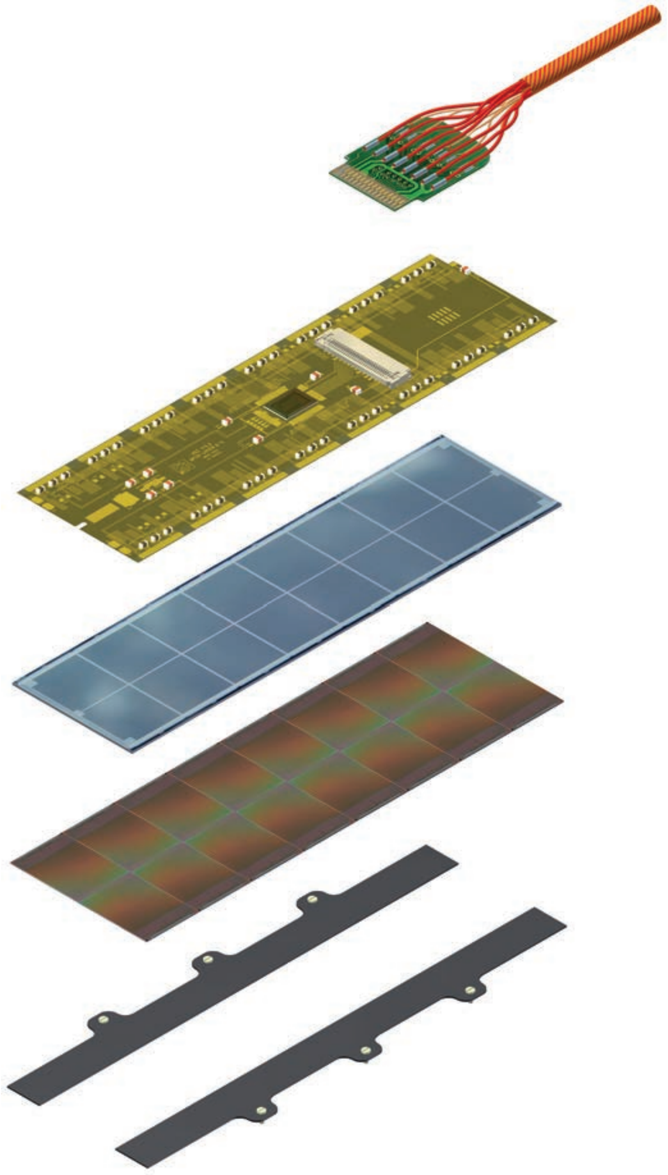

Figure 1

Module components: thin HDI, silicon sensor (area 10 cm^2), ROCs and base strips (from top to bottom)

The present CMS pixel detector, which has been successfully in operation since 2009, was designed 15 years ago for the nominal LHC luminosity of 10^{34} cm^{-2} s^{-1}, without further safety margin. The LHC is expected to exceed the design luminosity by a factor of two within this decade and before the high-luminosity upgrade takes place. To maintain a good efficiency at higher particle rates, the pixel readout chips (ROCs) must be extended to provide more data buffering. In the hybrid pixel architecture used, the silicon sensor is bump-bonded to ROCs covering the entire active area. To improve the tracking capabilities of CMS, it was decided to replace the entire pixel detector by an extended system with four instead of three barrel layers.

The standard pixel cell on the sensor has a size of 100 x 150 µm^2, and each cell must make contact to a readout channel. In a cleanroom at DESY, an in-house procedure has been established in which precision tin spheres of 40 µm diameter are placed individually on the sensor and soldered by melting with a short laser pulse. A rate of four balls per second is routinely achieved, allowing one sensor to be filled with 66 592 balls in less than five hours. A total of 18 million balls were placed in 2015. The random failure rate is 0.0002 and the placement accuracy is 1 µm, as determined from high-resolution microscope images.

A second machine is used to place selected ROCs of 175 µm thickness precisely on the solder-balled sensor. A robotic arm picks up a chip, aligns it using optical image recognition, moves it to a needle card for a quick electrical test and presses it onto the sensor with 160 N force and at elevated temperature but below the melting point. Once all 16 chips are placed, an in-situ reflow process under formic acid atmosphere is used to establish the final solder connection.

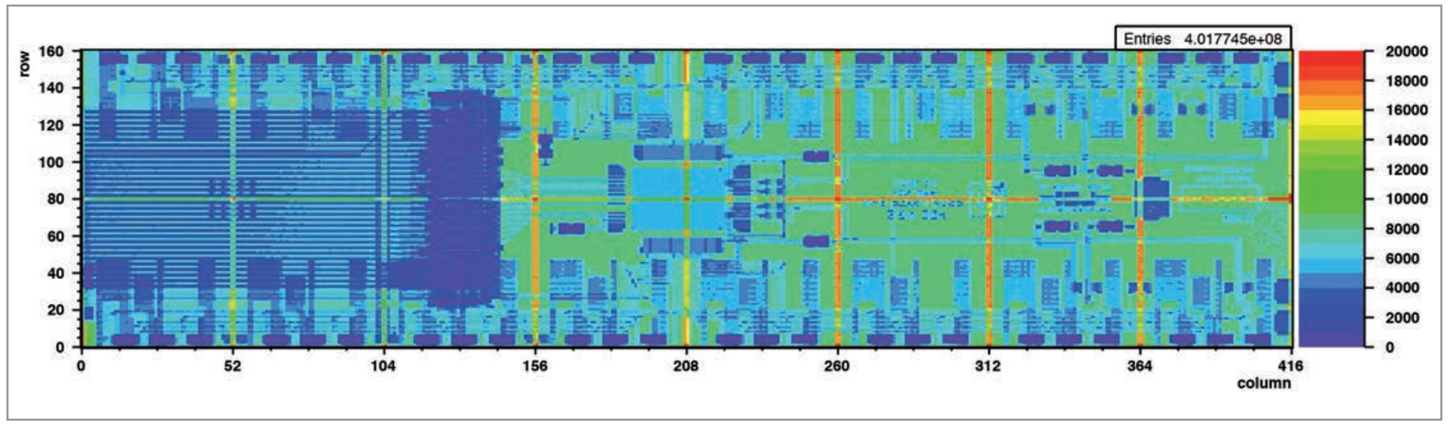

Figure 2

High-rate X-ray response map of a completed module illuminated through the HDI. Columns with double rate correspond to larger sensor pixels covering the gaps between ROCs. Capacitors, cables, connectors and copper traces create shadows.

The resulting bare modules undergo a full electrical test on a probe station in an adjacent cleanroom. A special procedure has been developed to test the bump bond quality by pulsing across the 25 µm air gap between ROC and sensor. In about 8% of the modules, one ROC develops a defect (typically high current and a dead column), probably due to mechanical stress. Individual chips can be removed from a bare module by local heating and underpressure force, creating a clean break at the last soldered interface and leaving enough material on the sensor to place a new chip with good yield. In 2015, 250 bare modules using 4000 ROCs have been made and tested.

For powering, signal distribution and readout, each bare module is connected to a thin high-density interconnection (HDI) circuit carrier, which is glued to the sensor side of the bare module (at the University of Hamburg, Fig. 1) and then wire-bonded to the ROC pads (at DESY). The HDI is equipped beforehand, again through glueing and wire-bonding, with a token bit manager (TBM) chip, which coordinates the readout and issues signals via the HDI to the ROCs. For good thermal contact, a pair of ceramic base strips is glued underneath the outer regions of the ROCs, and their six "ears" (the three bulges on each strip) will be used for mounting the modules on a carbon fibre frame for installation in CMS.

The operating temperature foreseen for the new pixel detector in CMS is -15°C, with one or two thermal cycles per year. At DESY, a cold box has been designed and built that allows rapid thermal cycling of four modules using Peltier elements and stable operation at -20°C and +17°C for threshold and gain calibration. The FPGA-based core software for these tests has been developed at DESY and is used in all the production centres.

As a final test, all modules are operated under high-rate illumination with X-rays generated using a 35 kV, 1 mA electron gun on a tungsten target. Rates of up to 150 MHz cm^{-2} as expected from multiple proton–proton collisions in CMS are created, and the module response is measured as shown in Fig. 2.

A central database collects the calibration data from all production centres and applies a common grading scheme for the module quality. Half of the required modules were produced and calibrated by the end of 2015, and the second half has to be completed by mid 2016. Until then, modules are stored in cabinets flushed with nitrogen to prevent corrosion.

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Towards new inner tracking detectors for ATLAS and CMS.

Designing upgraded tracker end-caps for both experiments

Both the ATLAS and the CMS group at DESY play a leading role in the design and construction of the tracker upgrades for their respective experiments, in particular of the end-cap regions. In collaboration with other institutions in Germany and abroad, the two groups follow an ambitious programme to deliver one end-cap each for the high-luminosity LHC (HL-LHC) trackers of ATLAS and CMS.

The ATLAS end-cap

The forward regions of the ATLAS detector consist of six disks per side, made up of low-mass wedge-shaped structures called petals. One of the tasks of the DESY ATLAS group is the development of petal support structures, called cores. The cores, to which the silicon modules are directly glued, provide precise mechanical support and integrate services like cooling, power rails and high-speed data links to the outside world. The cores consist of carbon fibre with integrated titanium cooling pipes that are surrounded by thermal carbon-based foam to enhance the cooling power along the structure. The core structure is enclosed by a carbon fibre skin that is co-cured together with thin, flexible polyimide-copper-based printed circuit boards (PCBs) called bus tapes. Power, data and control lines run along the bus tapes, which are electrically connected to the modules by wire bonds and electrically conductive glue. The first batch of high-precision core prototypes was manufactured at DESY using custom-made mechanical tools that guarantee high precision and tight tolerances.

As a first step to produce the first fully functional petals, thermo-mechanical modules and petals were manufactured to validate the layout. Custom-made thermo-mechanical modules were manufactured at DESY, with laser-cut silicon in the place of the silicon detectors, FR-4 boards as chip carriers, and glass-patterned application-specific integrated circuits (ASICs) with heaters to simulate the heat loads of the electronic components. Figure 1 shows a petal core partially loaded with thermo-mechanical modules. Thermal simulations of the prototypes are planned for the near future.

An important milestone was reached in the design of the end-cap modules with the conclusion of the petalet programme, to which DESY was one of the main contributors. The single-sided, split-module layout – the option preferred by DESY – was selected over the double-sided transmission line alternative. After this decision, the design and testing effort was put in place to develop the next family of modules, with a set of binary ASICs consisting of an ABC130 and a hybrid controller chip (HCC). Some of the first module prototypes with the new ASIC set, including the new hybrid designs, were manufactured at DESY and are currently being tested, e.g. in several test beam campaigns. Figure 2 shows a so-called DAQ load, consisting of an end-cap hybrid PCB including one ABC130 and one HCC ASIC.

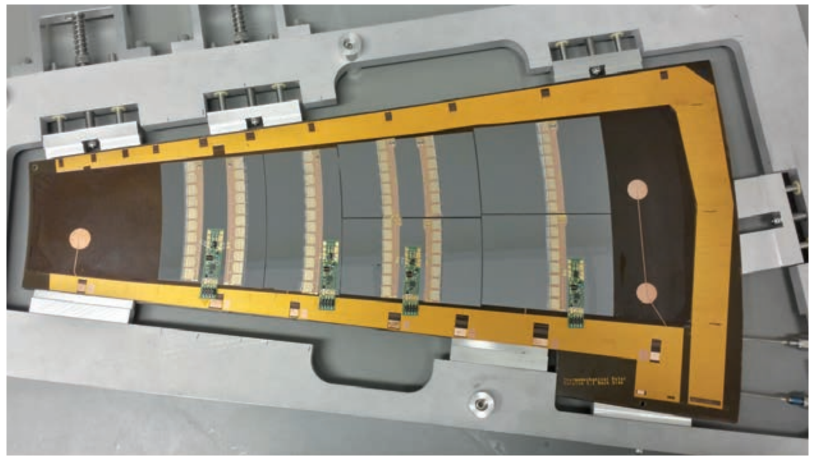

Figure 1

Petal core partially loaded with thermo-mechanical modules

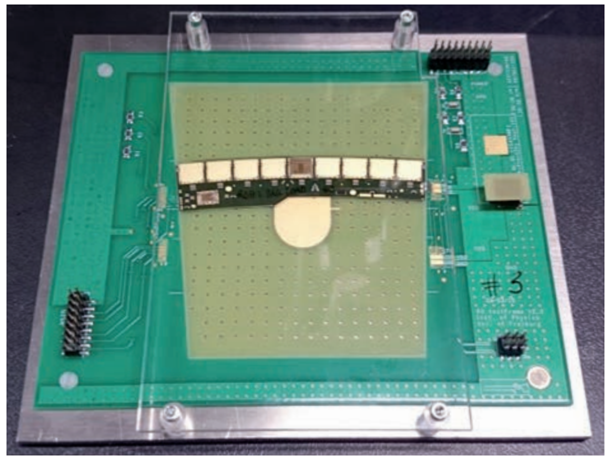

Figure 2

ABC130–HCC DAQ load prototype

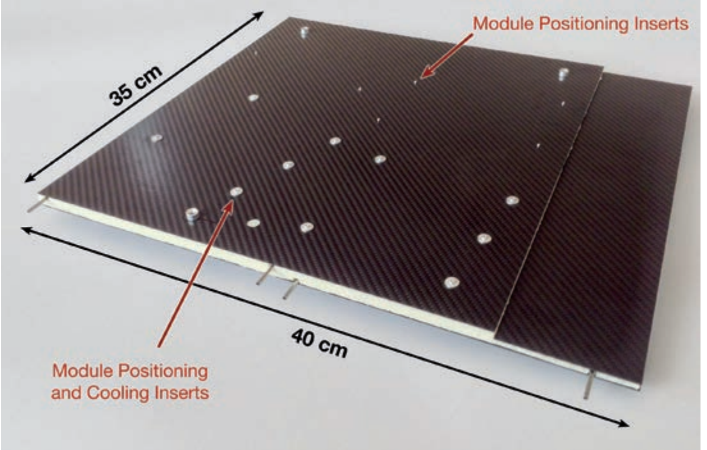

Figure 3

CMS small-scale dee prototype

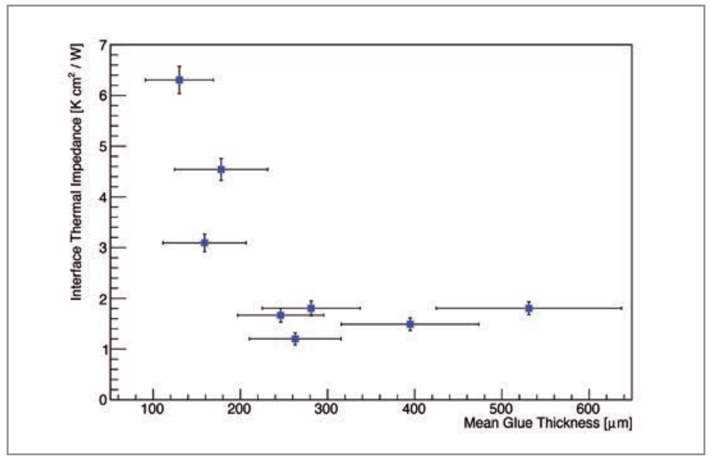

Figure 4

Thermal impedance of an interface between a solid and carbon foam as a function of glue layer thickness

The CMS end-cap

DESY is planning to build one of the end-caps of the new CMS silicon inner tracking detector. The experiment will utilise two different module types throughout its future tracker. Above radii of 60 cm, the end-caps will be equipped with modules composed of two closely spaced silicon strip sensors, whereas at smaller radii, they will be equipped with modules made of a silicon strip and pixel sensor. The support structures foreseen in the CMS end-caps are half-disks of 2.4 m diameter, which will be equipped with modules on both sides. A combination of four half-disks with alternating module positions ensures hermetic coverage for particles originating from the interaction point. These so-called dees are highly integrated sandwich structures that provide the necessary mechanical support and, at the same time, integrate cooling and positioning inserts for the modules.

To verify the concept, a small-scale dee prototype was developed and built at DESY. Figure 3 shows a photograph of the prototype structure, which has a size of 35 cm x 40 cm. The positioning precision of the inserts – indicated in Fig. 3 – was measured at the DESY quality assurance group (ZMQS). The results show that the deviation of the in-plane position from its nominal value is on average about 25 µm with a standard deviation of 20 µm, which is much better than the required precision and proves that the assembly concept works as expected. Currently, the DESY CMS group is carrying out thermal measurements on the prototype in order to investigate the thermal coupling of the cooling elements to the cooling pipe. In addition, a second version of the prototype is being prepared, which will incorporate recent changes in the global design and utilise an improved assembly scheme.

In their upgrades, both experiments rely on materials and technologies that have not been used in the previous tracking detectors. The feasibility of these technologies is currently being investigated in both collaborations. One example is chemically vapour-deposited carbon foam, which has become popular throughout high-energy physics experiments as thermal management material. It provides a high thermal conductivity at low density and large radiation length. Due to the porous nature of the foam and hence the limited contact surface, the thermal coupling of a solid object to the foam is challenging. The CMS group has optimised the thermal coupling to the carbon foam by filling the pores with highly conductive glue to increase the contact surface to the foam. Results show that a minimum thermal impedance is reached above a glue layer thickness of 250 µm (Fig. 4). This result is taken into account in the improved assembly scheme of the CMS end-cap prototype and the ongoing performance studies of the designs based on finite-element analyses.

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Probing electroweak and new physics in the proton.

HERA data deepens our understanding of the Standard Model

Almost a decade after the final shutdown of DESY's electron–proton collider HERA, flagship analyses are being finalised – revealing a "HERA heritage" that will shape our understanding of the proton and the fundamental forces of nature for many years to come. In 2015, the high-precision HERA data on deep-inelastic scattering were used to extract a deeper understanding of the Standard Model and to search for new physics.

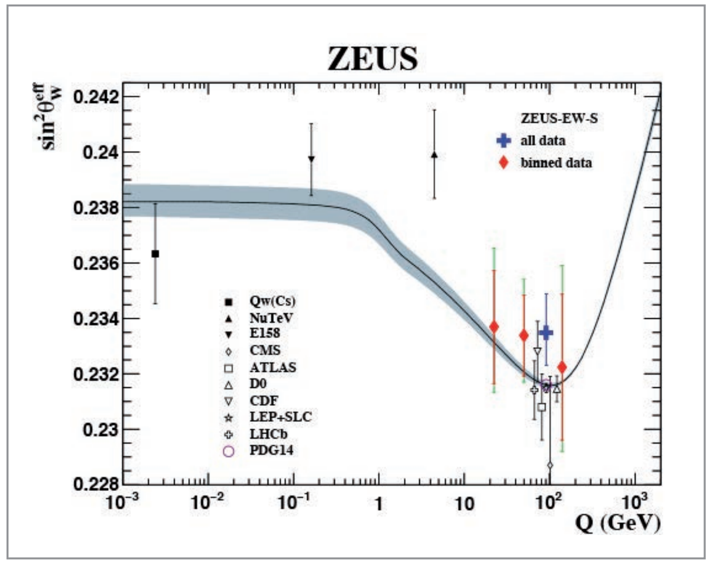

Figure 1

Energy scale dependence of sin^2 θ_W. The ZEUS extraction is compared to those from other experiments and to predictions from the Standard Model (grey band).

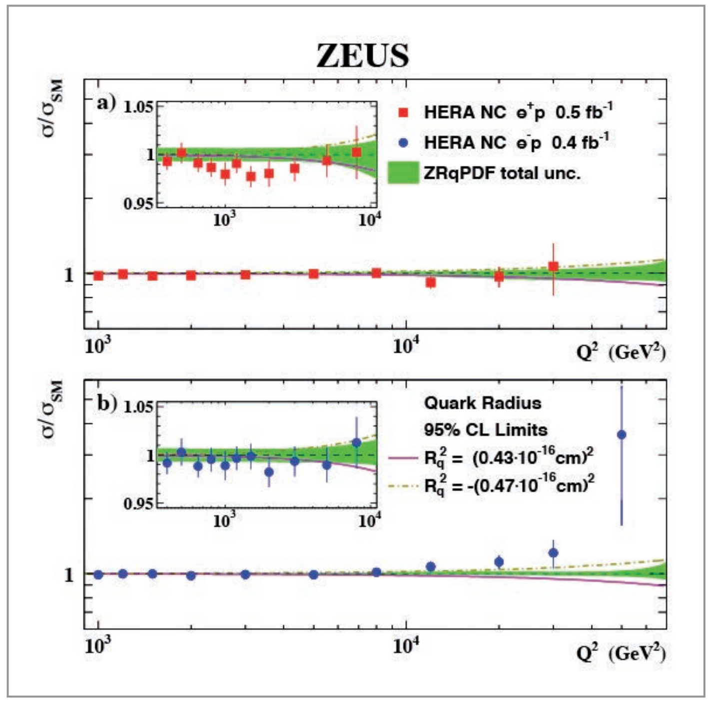

Figure 2

HERA data for (a) e^+p and (b) e^-p scattering compared to the Standard Model (green band) as well as limits on the radius of quarks (lines)

The final HERA heritage

The recent combination of all data on inclusive deep-inelastic scattering from the HERA experiments H1 and ZEUS was a major triumph of the HERA programme [1], providing the so far most detailed understanding of the structure of the proton. The data yield a detailed picture of quantum chromodynamics (QCD) and the dynamics of quarks and gluons, a precise extraction of the strong coupling constant and a demonstration of the chiral structure of the weak interaction. The similarity of the weak and electromagnetic interactions at high energies is also beautifully demonstrated, supporting the hypothesis of unification into one electroweak force. In addition, the combined data were used in an analysis of the structure of the proton, leading to a new set of parton distribution functions, HERAPDF2.0. These data provide the most significant constraints on the partonic content of the proton, the precise knowledge of which is essential for physics at the LHC.

Electroweak effects in electron–proton scattering

The ZEUS collaboration extended the QCD analysis of the structure of the proton to include electroweak effects [2]. The polarisation of the electron beam was exploited in the ZEUS data taken at the highest energies in the final years of HERA running, yielding results on the strengths of the couplings of the *Z* boson to *u*-type and *d*-type quarks, on the value of the electroweak mixing angle, and on the mass of the *W* boson. The results on the couplings are compared to measurements from the Large Electron–Positron (LEP) collider at CERN, the Stanford Linear Collider (SLC) at SLAC and the Tevatron collider at Fermilab, as well as to previous H1 values and the Standard Model. Consistency between the different measurements and theory is observed, with the new measurements of the couplings to the *u*-type quarks being the most precise published single values.

The ZEUS extraction of the weak mixing angle (θ_W), which is related to the masses of the *W* and *Z* bosons and which provides a measure of the relative strengths of the electromagnetic and weak forces, is shown in Fig. 1 in comparison with many other measurements and the Standard Model prediction. From the very different processes and measurements, a consistent picture of the mixing angle is obtained. The result presented here is the first time that data from a single experimental configuration were used to determine sin^2 θ_W at different energy scales.

Searching for new physics

Given the high precision of the measurements and the wide kinematic range covered, the data were also used to look for effects beyond the Standard Model [3]. Measurements of deep-inelastic scattering at HERA have produced exquisite knowledge of the structure of the proton, allowing for investigations into the question whether the quarks themselves have a structure or are pointlike particles. Should quarks have a structure, then this would be revealed as a deviation of the measured data cross sections from the Standard Model predictions. Such new physics can be parameterised by modifying the Standard Model to include the concept of the quarks having a radius.

The ZEUS collaboration performed a simultaneous fit of the parton distribution functions in the proton and this new physics. A comparison of the Standard Model and the modified theory is shown in Fig. 2. The Standard Model describes the data well, and so limits on the quark radius were extracted. An upper limit of $R_q < 0.43 \times 10^{-18}$ m was determined, which is similar to values extracted elsewhere and to measurements investigating structure in electrons. The result shows that, at these (tiny) scales, quarks are still elementary and have no structure.

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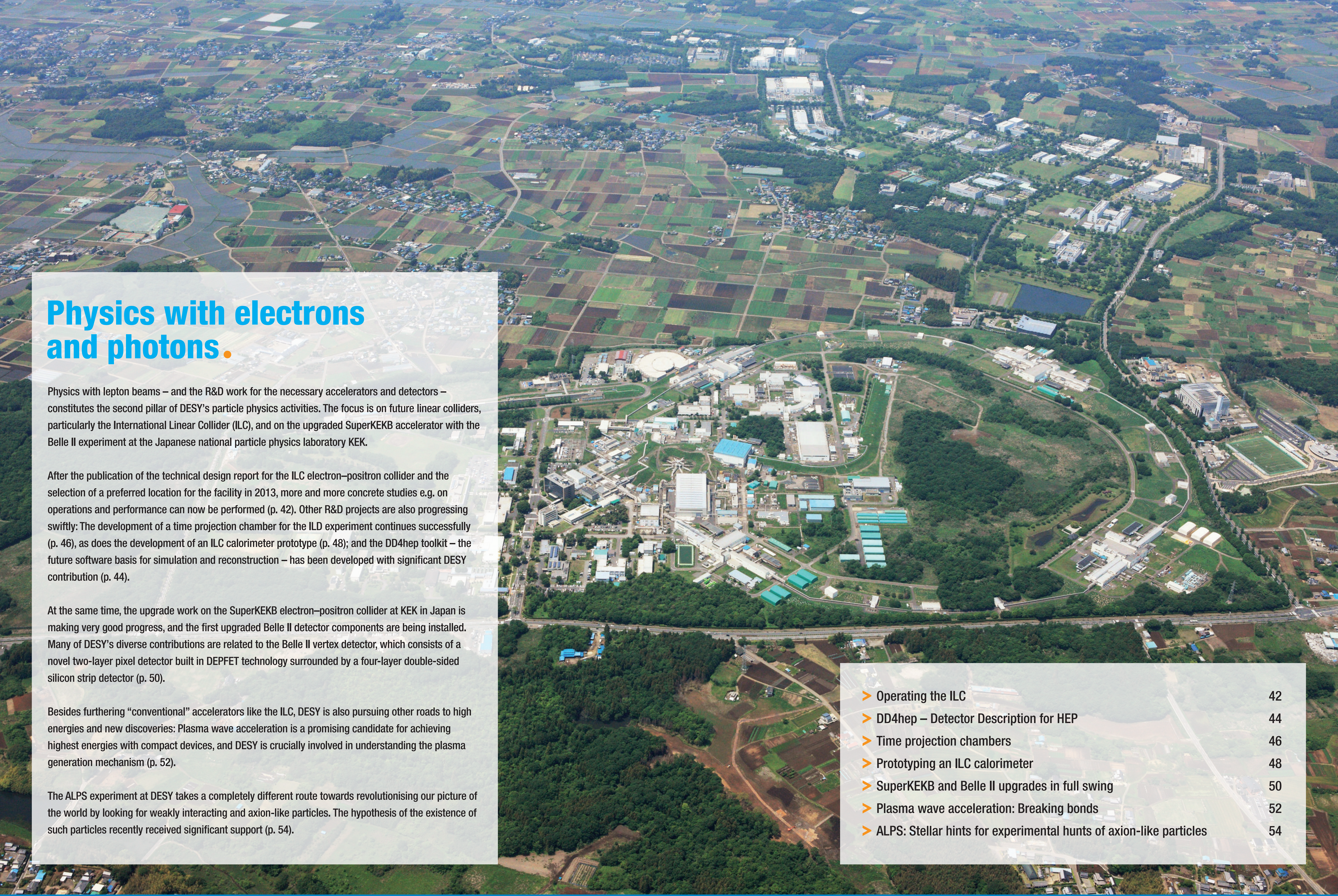

Physics with electrons and photons.

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 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.

After the publication of the technical design report for the ILC electron–positron collider and the selection of a preferred location for the facility in 2013, more and more concrete studies e.g. on operations and performance can now be performed (p. 42). Other R&D projects are also progressing swiftly: The development of a time projection chamber for the ILD experiment continues successfully (p. 46), as does the development of an ILC calorimeter prototype (p. 48); and the DD4hep toolkit – the future software basis for simulation and reconstruction – has been developed with significant DESY contribution (p. 44).

At the same time, the upgrade work on the SuperKEKB electron–positron collider at KEK in Japan is making very good progress, and the first upgraded Belle II detector components are being installed. Many of DESY's diverse contributions are related to the Belle II vertex detector, which consists of a novel two-layer pixel detector built in DEPFET technology surrounded by a four-layer double-sided silicon strip detector (p. 50).

Besides furthering "conventional" accelerators like the ILC, DESY is also pursuing other roads to high energies and new discoveries: Plasma wave acceleration is a promising candidate for achieving highest energies with compact devices, and DESY is crucially involved in understanding the plasma generation mechanism (p. 52).

The ALPS experiment at DESY takes a completely different route towards revolutionising our picture of the world by looking for weakly interacting and axion-like particles. The hypothesis of the existence of such particles recently received significant support (p. 54).

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Operating the ILC.

How to run the ILC for best physics results

The Linear Collider Collaboration recently established two working groups: the LCC Physics Working Group and the Joint Working Group on ILC Beam Parameters. Both groups worked hand in hand to identify the most important physics drivers and develop so-called running scenarios for the International Linear Collider (ILC). In 2015, the parameter working group defined new, realistic standards for benchmarking the physics performance of the ILC, while the physics working group updated and sharpened the ILC physics case in view of the new standard running scenario.

Realistic operation assumptions

The ILC technical design report (TDR) [1] defines beam parameters for the most important centre-of-mass energies for a future electron–positron collider, in particular 250 GeV, 350 GeV, 500 GeV and 1 TeV. While the TDR baseline foresees to build a 500 GeV machine right away, various staging and upgrade scenarios have been discussed since. Most of the physics performance studies in the TDR assumed very moderate integrated luminosities, corresponding to only a few years of ILC operation. In 2014, the Joint Working Group on ILC Beam Parameters was assigned the task to study different running scenarios and their physics impact and to propose a new standard running scenario [2].

The resulting scenarios were based on the following assumptions: Per calendar year, the ILC is operated for eight months with an average efficiency of 75%. During the first four years of physics operation, 10%, 30%, 60% and 100% of the design luminosity are assumed to be collected, respectively. After major changes to the configuration, analogous learning curves are assumed. When the two linear accelerators are operated at gradients significantly below their maximum, the spare cryogenic and radio-frequency (RF) power is used to increase the repetition rate and thus the luminosity of the collider. After some years, the luminosity is upgraded by doubling the number of colliding bunches per pulse, which requires the installation of additional RF power (klystrons and modulators) as well as the possible addition of a new positron damping ring.

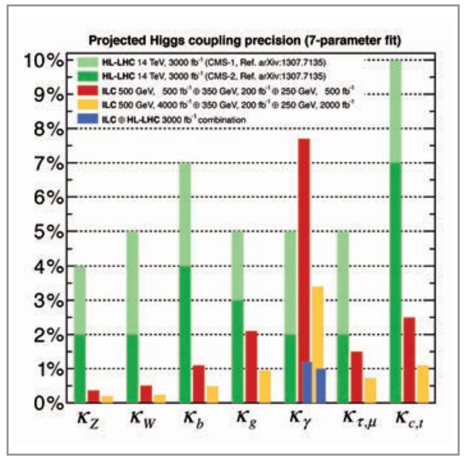

Figure 1

Relative precisions on the Higgs-boson couplings extracted from projected HL-LHC and ILC measurements in a model-dependent 7-parameter fit [3]. Apart from the coupling to photons, a combination of HL-LHC and ILC would be completely dominated by the ILC results.

A time span of roughly 20 years before an energy upgrade to 1 TeV is dedicated to operation at 250 GeV, 350 GeV and 500 GeV. For other energies, including the 1 TeV upgrade but also operation on the *Z* pole and at the *WW* threshold, target integrated luminosities and polarisations are given, but no detailed operation plan is proposed.

Optimising the physics impact

Within these boundary conditions, a huge variety of running scenarios have been considered, including the sharing of running time not only between different energies, but also between the different beam helicity configurations (e.g. mostly left-handed electrons and right-handed positrons "-+" versus mostly right-handed electrons and left-handed positrons "+-"). For each of these scenarios, the early and the final physics potential have been evaluated with respect to some of the most important direct and indirect searches for new phenomena beyond the Standard Model (SM). Among the latter, a model-independent precision study of the properties of the Higgs boson is of particular importance. It is also a tricky case to optimise, since different properties of the Higgs boson are studied best at different centre-of-mass energies. For example, while its coupling to the *Z* boson and the Higgs-boson mass are measured most efficiently at 250 GeV near the *ZH* production threshold, its coupling to the *W* boson can be measured much better at higher centre-of-mass energies. Since the knowledge of the Higgs–*W* coupling is important to access the total decay width of the Higgs boson, its precision also feeds into the determinations of the couplings to the fermions. A detailed comparison of the reachable precision on the Higgs–*W* coupling in different scenarios clearly demonstrates that starting the operation at 250 GeV significantly reduces the early physics performance of the ILC.

New standard running scenario

The new standard running scenario for the ILC as proposed by the parameter working group and endorsed by the Linear Collider Board is named "H-20" and assumes an initial running period of four years at 500 GeV, accumulating an integrated luminosity of 500 fb^{-1} with a sharing between beam helicity configurations of (40%, 40%,10%,10%) for (-+, +-, ++, --). This run provides a multi-purpose data set that maximises the early physics performance not only for Higgs coupling measurements, but also for top physics, for the determination of triple gauge couplings and for direct searches for physics beyond the SM.

Unless the results of this initial run call for immediate collection of more data at 500 GeV or the scan of new physics thresholds, a short run at 350 GeV is foreseen to determine the top mass in a theoretically clean way by measuring the top-quark production cross section at several energies close to the production threshold. Then, the collision energy is lowered to 250 GeV to collect a special-purpose data set of 250 fb^{-1} with a helicity sharing of (67.5%, 22.5%, 5%, 5%) to boost the precision on the Higgs–*Z* coupling and the Higgs recoil mass determination, before the ILC is shut down for 1.5 years to implement the luminosity upgrade. After the luminosity upgrade, a large-statistics data set of another 3500 fb^{-1} is collected at 500 GeV to gain precision on rare processes such as associated top–Higgs production (which gives access to the Yukawa coupling of the top quark), to double the Higgs production (which allows the extraction of the Higgs self-coupling) and to study potential new particles with high precision. Finally, in a second run near the *ZH* threshold, a large data set of 1500 fb^{-1} is collected for ultimate precision on the Higgs–*Z* coupling and on the Higgs mass.

ILC physics case and new running scenario

Based on the plethora of detailed simulation studies that have been done in the past with very moderate assumptions on the integrated luminosity (e.g. typically 500 fb^{-1} at 500 GeV), the most important measurements to be performed at the ILC have been projected to the full H-20 running scenario by the LCC Physics Working Group [3]. Figure 1 shows, as an example, the projected precisions before the luminosity upgrade (red) and after the full 20-year programme (yellow) compared to corresponding projections for the high-luminosity LHC (HL-LHC, green). Only in the case of the coupling to photons (κ_γ) does the combination of the results of both colliders lead to a significant improvement beyond the ILC results alone (blue).

In many extensions of the SM, deviations of maximally a few percent from the SM prediction for the Higgs couplings are expected. Therefore, the precision achievable with the ILC bears a substantial discovery potential complementary to the LHC. Another important way to probe for new physics is the precise investigation of the top quark. Due to its extraordinarily large mass (about the mass of a gold atom), the top quark may be tightly connected to phenomena beyond the SM. Yet it has so far never been produced in electron–positron collisions. Thus mostly its production via the strong interaction has been studied, while little is known about the details of its chiral electroweak couplings, which are difficult to access at hadron colliders. At the ILC, the polarised beams are a key tool to disentangle the couplings of left-handed and right-handed top quarks. This is illustrated in Fig. 2, which compares the precision achievable on the chiral couplings of the top quark with the deviations in these couplings expected in various extensions of the SM. The precision achievable at the ILC enables not only the discovery of such deviations, but also the ability to discriminate between different types of models.

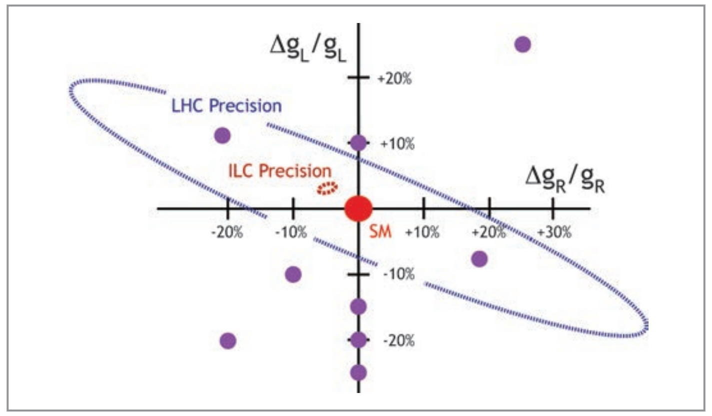

Figure 2

Uncertainty ellipses on the chiral top-quark couplings extracted from projected LHC and ILC measurements, compared to the SM prediction (red dot) and various proposed alternative models (violet dots) [3]. The precision expected from the ILC can be used to distinguish between different models of new physics.

Beyond the two examples given here, the ILC offers many more unique opportunities to search for new phenomena directly or indirectly. These are complementary to searches at the LHC or, for example, at dedicated dark-matter experiments, and include such phenomena as hidden Higgsinos from natural supersymmetry, additional gauge bosons (*Z'*), hidden pseudoscalar Higgs bosons as well as different kinds of dark-matter scenarios. The update and summary documents drawn up by the physics working group provided important input to the ongoing review of the ILC project by the Japanese science ministry.

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DD4hep – Detector Description for HEP.

A software tool for the optimisation of new particle physics detectors

Developing a complex particle physics detector for a new accelerator would not be possible without detailed Monte Carlo simulations that allow the expected physics performance of a given design to be predicted. A key ingredient for the validity of these simulations is the description of the complete detector, including its geometry, its material properties and sensor technologies. As this is a complex and recurring software task, CERN and DESY groups working on linear collider software decided to develop a toolkit that addresses this problem in a generic and reusable way. DD4hep was developed in the context of AIDA, a project funded by the 7th Framework Programme of the EU, and is now being used to design and optimise the detectors at all proposed future accelerators: ILC, CLIC, FCC and CEPC.

Overview

A detailed and realistic description of the detector geometry and material properties is essential for the development of almost all data-processing applications in high-energy physics (HEP) experiments. This is particularly evident in Monte Carlo simulations, where the exact knowledge of the position, shape and material content of every detector component is crucial for the accuracy of the simulated detector response and underlying physics. For the subsequent processing steps of digitisation and reconstruction, it is equally important to have an accurate description of the detector geometry, which should ideally be created from the same source to avoid inconsistencies. The DD4hep (Detector Description for HEP) software package is a generic geometry toolkit that builds on the two most widely used software packages in HEP: ROOT and Geant4. Even though DD4hep was developed in the context of the linear collider project with other future accelerator projects in mind, it has been designed from the start to support the full experiment life cycle, meaning that it can be used continuously also beyond the project-planning phase or be adopted by running experiments.

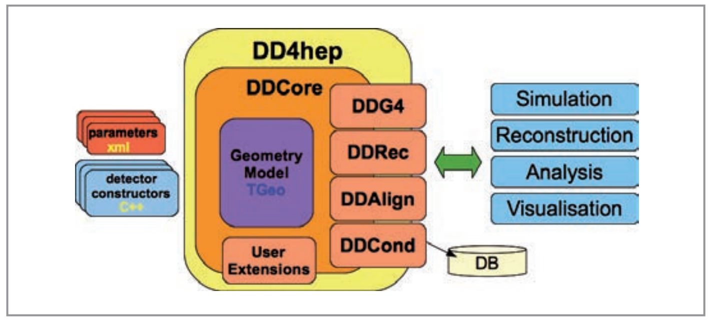

Figure 1

Schematic view of the component structure of DD4hep with the core component DDCore and optional extensions such as DDG4 and DDRec

Software design

The DD4hep toolkit follows a component-based design that provides a high level of flexibility for the users. The core functionality is implemented in DDCore, where the geometry of the detector is represented in memory as a hierarchy of geometrical objects holding material properties (implemented using ROOT). An extension mechanism allows additional data structures to be attached in order to incorporate relevant physical properties of individual detector components, such as alignment constants, measurement surfaces or visualisation. Different components, like DDG4 or DDRec, support different tasks in HEP data processing, such as simulation, reconstruction or analysis, and can optionally be included in an application or extended by custom components as needed (Fig. 1).

Simulation and reconstruction

Since the simulation of the interaction of particles with the detector is typically done using Geant4, DD4hep allows its geometry to be converted to Geant4. The DDG4 component provides all the necessary configuration methods and handling of input and output files as well as matching of detector hits to Monte Carlo truth particles. DD4hep also offers a palette of generic detector constructors that can be directly applied to create a first conceptual detector model by defining their parameters in corresponding XML files. This offers the possibility to start investigating a new detector concept in full simulation with relatively little effort.

The reconstruction of physics events – created in simulation or measured in a real detector – requires a consistent but different view of the detector geometry. This is addressed in the component DDRec, which adds relevant data structures to the detailed geometry model hierarchy. Of particular importance here are the measurement surfaces needed in the reconstruction of charged-particle tracks and momenta. Objects of a dedicated surface class are attached to the sensitive volumes of the tracking detectors and provide geometrical as well as material properties, which are crucial for the correct treatment of energy loss and multiple scattering. These material properties are automatically sampled and averaged from the detailed model, making this approach very flexible with respect to studying different detector variants. An example of these two different views of the same geometry is shown in Fig. 2 for the ILD detector.

Figure 2

Inner tracking detectors of the ILD detector concept for the ILC in a DD4hep-based geometry model. Left: Detailed detector geometry model used for simulation. Right: Measurement surfaces attached to the sensitive detector elements by DDRec and used for track reconstruction.

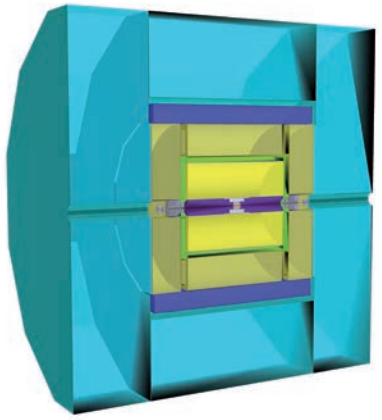

Figure 3

3D model of the ILD detector implemented in DD4hep. Only envelope volumes of the individual subdetectors are shown.

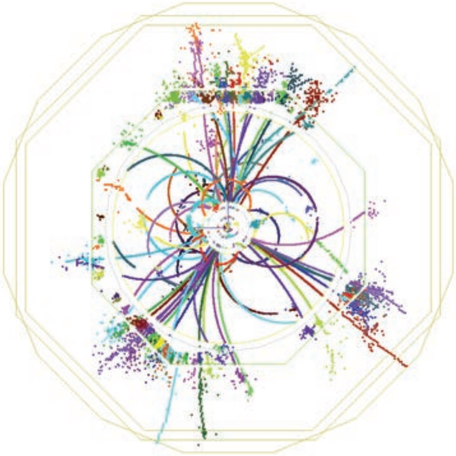

Figure 4

Hadronic $t\bar{t}$ event at 500 GeV in the ILD detector simulated and reconstructed using DD4hep

DDAlign and DDCond complete the DD4hep toolkit by providing methods to describe the misalignment of individual detector components and to access their corresponding conditions data, respectively. These are indispensable features for a real experiment but also useful in the design phase, as they allow the investigation of alignment and calibration schemes early on.

Application to detectors at linear colliders

DD4hep has been developed in the context of the ILD and CLICdp detector concepts for the linear colliders ILC and CLIC. Both detector groups fully adopted DD4hep as their single source of detector geometry for simulation and reconstruction. A new package, called lcgeo, collects the specialised detector constructors for the two concepts, mostly containing more engineering-level details than the generic ones from DD4hep are able to provide. For ILD, pre-existing code from a previous simulation program has been ported to DD4hep, thereby keeping all necessary details but simplifying the overall structure as much as possible. In particular, the introduction of mandatory envelope volumes for every subdetector (Fig. 3) should help to speed up the simulation and facilitate a potential scaling or replacement of the detectors. These are important features in the process of optimising the overall layout of the ILD detector as well as in selecting the individual subdetector technologies through direct comparisons in simulation.

The existing reconstruction algorithms in the Marlin framework, which is used throughout the linear collider community, have been adapted to use the classes provided by DDRec as their only source of geometry information. An example for an event in the ILD detector that was fully simulated and reconstructed using DD4hep is shown in Fig. 4.

The validation of the new simulation models and reconstruction tools for ILD and CLICdp is currently ongoing. As soon as this is completed, they will be used to further optimise these detector concepts for their planned physics programme.

Recently, several other R&D groups have started to use DD4hep for their detector development at the future facilities ILC, FCC and CEPC. This and the fact that DD4hep has been included as an incubator project in the recently founded HEP Software Foundation demonstrate the necessity and the validity of common software developments in particle physics.

Contact:

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Time projection chambers.

Developing high-precision tracking detectors

Tracking detectors are a central part of any modern particle physics experiment. Over the last years, a time projection chamber concept has been developed and tested by the international Linear Collider Time Projection Chamber (LCTPC) collaboration. DESY is playing a central role in the design and test of a gas electron multiplier (GEM)-based readout system.

For a detector at a future linear collider, highly efficient tracking in a high-multiplicity environment is a key challenge. A time projection chamber (TPC) as a central part of such a tracking system offers a robust option, providing a large number of 3D space points with high precision. Such a TPC is a candidate tracker for the International Large Detector (ILD) at the ILC.

DESY is at the forefront of developing a GEM-based readout system for such a TPC. In the years 2013 and 2014, extensive test beam campaigns took place using the DESY test beam infrastructure. Several types of modules were constructed and tested in the large TPC prototype infrastructure that is available at DESY as part of the EU-funded AIDA programme.

These tests yielded a number of promising results and interesting conclusions. During several weeks, large data samples of overall excellent quality were recorded.

The large sample of single-track data with very low noise was used to calibrate and align the three modules used in the campaign. The Millepede-II toolkit was used to determine the alignment constants for each module and to correct for field distortions primarily at the edges of the modules. Figure 1 shows the residual distribution as a function of the coordinate along the track for raw data, for data corrected for alignment and for data corrected for alignment and field distortions. The significant improvement of the data quality is clearly visible.

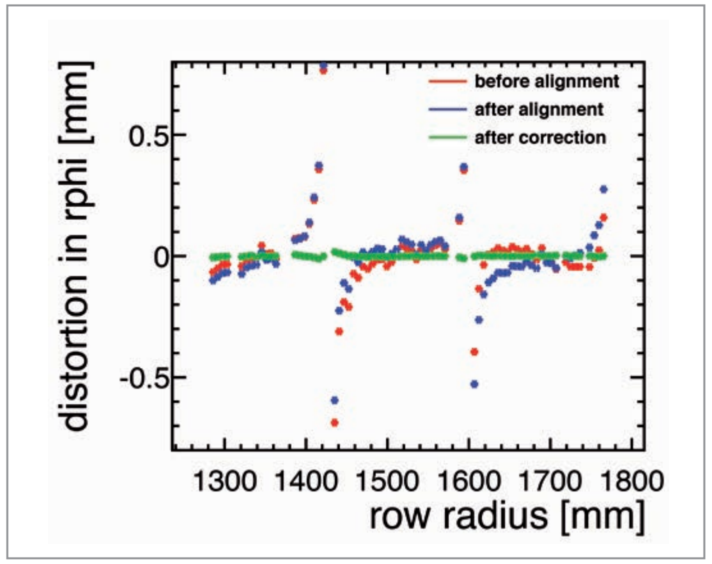

Figure 1

Residuals along a track for raw data (blue), data corrected for alignment effects (red) and data after alignment and distortion corrections (green)

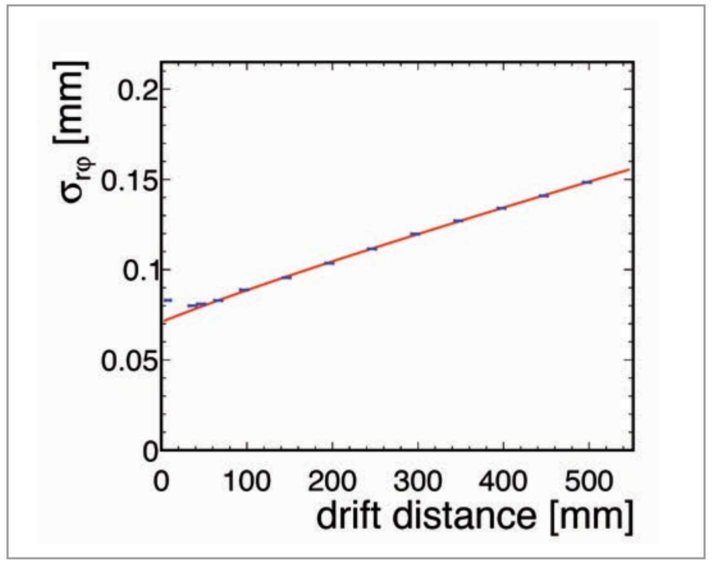

Figure 2

Spatial resolution as a function of drift distance measured in the TPC prototype at the DESY test beam

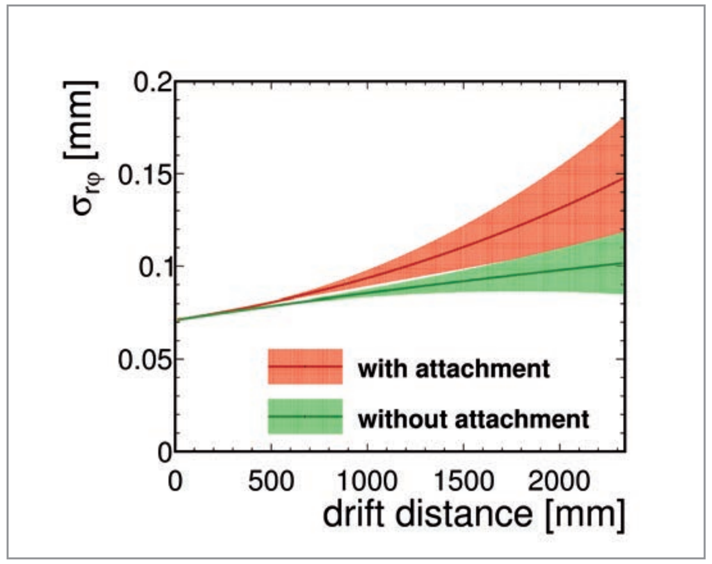

Figure 3

Extrapolation of the point resolution to a magnetic field of 3.5 T over 2.35 m drift distance including 1σ error bands

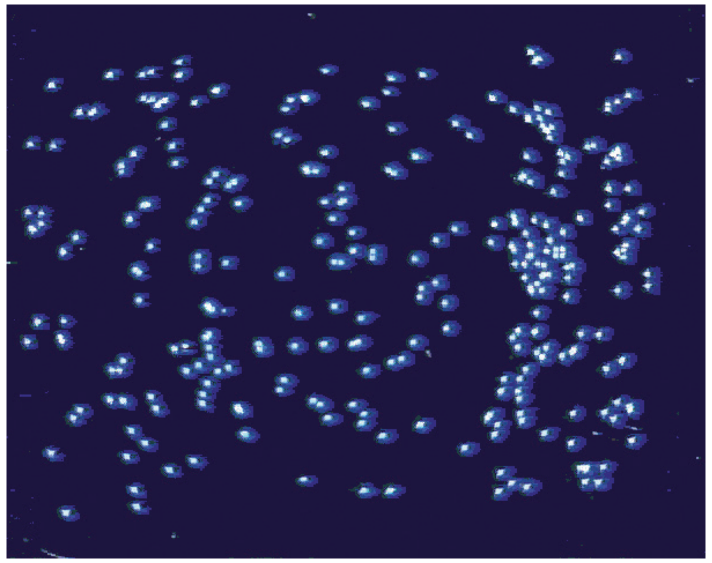

Figure 4

Long-term monitoring of sparks on a complete GEM plane with four sectors. Each dot corresponds to a spark.

Figure 2 shows the measured point resolution in the transverse plane as a function of drift distance. The red curve is the result of the theoretical resolution curve, fitted to the data. Extrapolated to zero drift, a point resolution of 70 µm is achieved, which then rises with drift distance as expected from the increasing diffusion.

The measured resolution results have been used to extrapolate the resolution to a TPC with a drift length of over 2 m operated in a magnetic field of 3.5 T. The result is presented in Fig. 3. A point resolution of below 100 µm for the complete drift can be reached if the gas properties are tightly controlled. Systematic studies are being performed on the long-term high-voltage stability of the GEM readout modules. To this end, a setup was built that optically monitors a GEM plane for discharges. The plane was operated at elevated potentials to increase the spark rate artificially. The system was run over several weeks, and sparks were recorded. Figure 4 shows the result of such a long-term observation. Each blue spot represents a discharge.

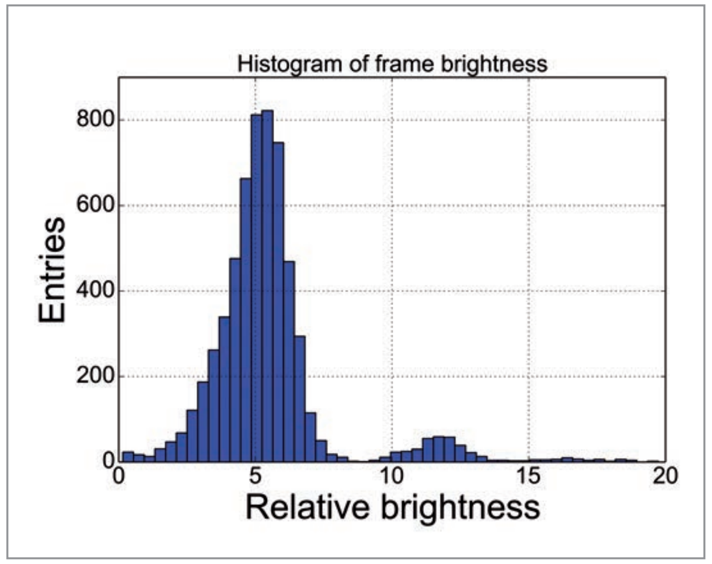

Figure 5

Distribution of the intensity of sparks in a module. Visible is the majority of sparks and a small secondary peak due to correlated double sparks.

Figure 5 shows a distribution of the intensity of the signal. In a small fraction of cases, two or more sparks happen nearly simultaneously, though always in different sectors. No significant correlation between the double-spark rate and the rate of destructive discharges was found, indicating that the overall protection of the modules against discharges works as designed. Further studies are ongoing to better understand the behaviour of the sparks and find ways to further minimise the spark rate.

During the first half of 2016, the next generation of readout modules will be designed and built. In particular, the new modules will have an improved high-voltage protection circuitry and better control of the electric fields to minimise distortions, and they will provide better control of the mechanical tolerances. It is planned to expose these new modules to a test beam in 2016 in order to perform the final demonstration of the feasibility of the GEM-based TPC readout for the ILC TPC.

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Prototyping an ILC calorimeter.

Advancing the electronics for an analogue hadron calorimeter

The development of front-end electronics for an analogue hadron calorimeter for the International Linear Collider (ILC) is an inspiring task. In 2015, following successful tests of single units, the developed concept had to prove its suitability on a large scale. The single prototype was therefore extended to a multilayer setup with several thousand detector channels and tested extensively in two test beam periods at the CERN Super Proton Synchrotron (SPS). In addition, efforts to reduce the power dissipation to the envisaged low limits progressed essentially in the lab with a dedicated setup. The electronics development is accomplished within the CALICE collaboration with major contributions from DESY.

Within the CALICE collaboration, the prototype of an analogue hadron calorimeter is being developed in several extension steps. The calorimeter is designed to follow the particle flow concept, which requires among other properties high granularity and the integration of the electronics into the detector volume. Both requirements were addressed by the use of 3 x 3 x 0.3 cm^3 scintillating tiles as active detector cells, which are read out by novel silicon photomultipliers (SiPMs). Several small prototypes with different tile architectures and SiPMs were realised that allowed us to study and compare the performances of the respective components.

Further aspects have to be considered to qualify the concept as a possible candidate for an ILC detector. In addition to stable operation of the prototype in a realistic environment, a small series production has to show whether all constraints concerning dimensions, power consumption and costs can be met. For this purpose, a prototype with 15 active detector layers was developed and tested in two two-week test beam periods at the hadron SPS test beam facility at CERN (Fig. 1).

All detector modules are based on the so-called HCAL base unit (HBU) with 144 detector channels and a size of 36 x 36 cm^2. The analogue signals of the SiPMs are read out by four dedicated front-end application-specific integrated circuits (ASICs, SPIROC2b) mounted on each HBU. The prototype consists of four layers with four HBUs in a 2 x 2 configuration each, as shown in Fig. 1 (left), and 11 layers with one HBU, resulting in more than 3800 detector channels. For the synchronous operation of the 15 detector layers, a new data acquisition (DAQ) system was developed and optimised that enabled stable data taking in both test beam periods. Valuable data could be obtained that are currently being analysed.

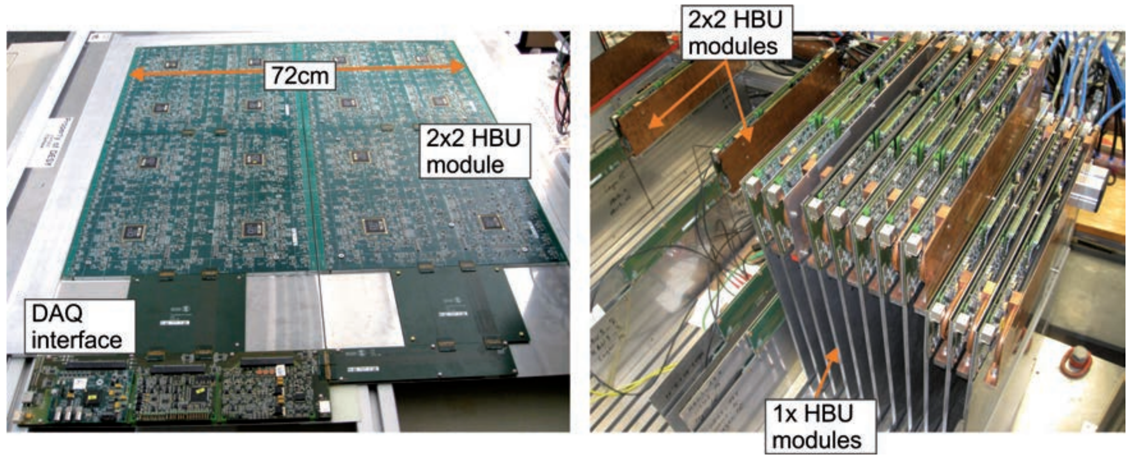

Figure 1

2 x 2 HBU detector prototype module with 576 detector channels (left) and CERN 2015 test beam setup (right) with four 2 x 2 HBU modules and 11 single HBU/EBU modules with 144 detector channels each

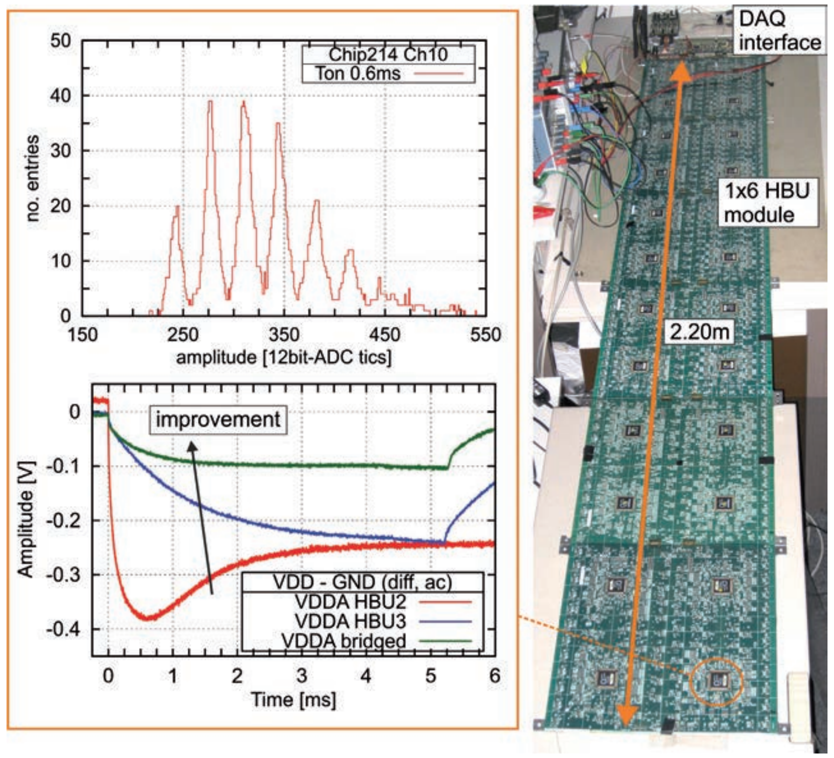

Figure 2

Achieved performance of the full-scale extension (photo, right) in power-pulsing mode: single-pixel spectrum (top left) and improvement of the power supply stability (bottom left)

To achieve best possible physics performance and keep the mechanical calorimeter setup as simple as possible, no active cooling system can be placed inside the detector. As a consequence, the inner detector electronics must operate with smallest possible power dissipation (40 µW/channel is aimed for), which can be achieved only if the electronics are switched off during inactive intervals of the ILC bunch train structure. This mode of operation, where the consumers are switched on and off with a rate of up to 5 Hz, is called “power pulsing” and is a key feature of the proposed concept. Power pulsing was successfully tested in the lab with a 1 x 6 HBU module with 864 detector channels. With a length of 2.20 m, this is the longest detector extension in a possible ILC calorimeter. A photo of the setup is shown in Fig. 2 (right).

The operation of sensitive analogue front-end electronics across 2.20 m long structures is not trivial. All control signals, including the operation clocks and the power supply voltages, have to be transferred from the DAQ interface to the HBU at the end of the structure without significant degradation. Due to the limited height of the structure, this transfer can be accomplished between the HBUs only through thin flex leads and tiny connectors (1.2 mm total height). In addition to the challenging length of the structure, the electronics are switched on and off every 200 ms in power-pulsing mode, following the expected bunch train rate of the ILC.

Results for the successful commissioning of the 2.20 m long calorimeter prototype in power-pulsing mode are shown in Fig. 2 (left). The single-pixel spectrum (top left) is the smallest signal that has to be detected. It shows the individual pixels of the SiPMs firing at low light intensities. The distances of the pixels are used for gain calibration and monitoring. As shown, single-pixel spectra can be obtained in high quality also at the end of the structure.

Important aspects in power-pulsing mode are the voltage drop and how fast the supply voltages stabilise after switching on the detector. As shown in Fig. 2 (bottom left), both issues have already been improved significantly with the new generation of HBUs (comparison red to blue curve) and by using bypass lines for the supply voltages in parallel to the flex leads (comparison blue to green curve).

Together with the very stable operation of the detector prototypes during the CERN test beam periods, important milestones have thus been reached in the prototype development for a potential calorimeter concept for the ILC. In 2016, a redesign of the HBU with the newest generation of readout ASICs and surface-mounted SiPMs will be realised. The DAQ interface modules have been redesigned for a further optimisation of the power-pulsing mode, and their first commissioning will also take place in 2016.

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https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

SuperKEKB and Belle II upgrades in full swing.

Analyses of Belle data at DESY are also progressing well

SuperKEKB is a next-generation *B* factory that is currently under construction at the Japanese national particle physics laboratory KEK. The upgrade of the electron–positron collider is making very good progress, and the first phase of commissioning of parts of the accelerator is scheduled for the beginning of 2016. In parallel, the former Belle detector is undergoing a major upgrade to Belle II. DESY has assumed key responsibilities in the integration and installation of the novel Belle II vertex detector as well as in computing and software development. In addition, several interesting physics analyses of the large Belle data set are nearing completion at DESY.

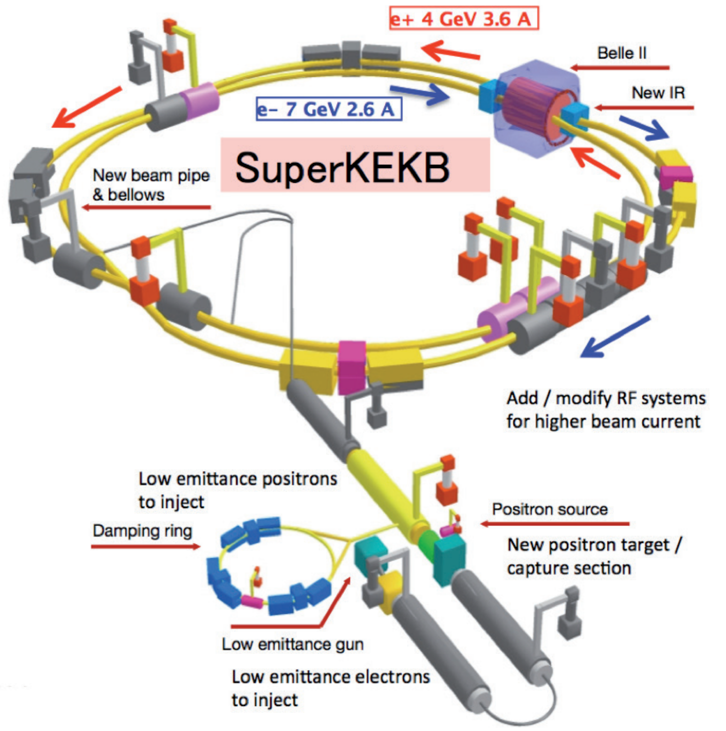

Figure 1

Schematics of the upgraded SuperKEKB accelerator complex. Key components that need to be rebuilt for an increase in peak luminosity by a factor of 40 are indicated by labels. The first phase of the accelerator commissioning is scheduled to start in February 2016, however still without final-focus quadrupoles and without the Belle II detector, which will stay in its parking position until the end of 2016.

Project status

Since 2011, a major upgrade programme has been under way at KEK in Japan with the aim to increase the peak luminosity of the SuperKEKB collider by a factor of 40. Figure 1 shows which of the main components of SuperKEKB have to be replaced to reach this very ambitious goal. In the fall of 2015, the construction of most elements of the accelerator was finished, so the vacuum system of the main ring could be closed in the Belle II experimental hall. Phase I commissioning of the accelerator is scheduled to start in February 2016, but without the superconducting final-focus quadrupoles that are currently still being produced and tested. The Belle II detector will stay in its parking position, where the upgraded subdetectors will be installed in parallel. Only the installation of the vertex detector will be delayed until the accelerator background is under control. Roll-in of the main detector is scheduled for the end of 2016.

Thermal studies for the Belle II vertex detector

The main contribution of the German institutes to Belle II is the two-layer pixel vertex detector (PXD), which is based on the DEPFET technology developed at the Semiconductor Laboratory Munich (HLL). Belle II is the first particle physics experiment to employ this novel technology. The PXD and the surrounding four-layer silicon strip detector (SVD) form the Belle II vertex detector (VXD). Figure 2 (top) shows the first complete PXD module, which is based on a sensor from a pilot run production equipped with almost final readout chips developed in Heidelberg and Bonn.

One of the key features of the DEPFET technology is its low material budget: the sensors can be kept very thin and the readout electronics can be placed almost entirely outside the physics acceptance. This is a major advantage, in particular for the application at a *B* factory where typical particle momenta are relatively low and it is thus essential to minimise the effect of multiple scattering. The substantial amount of heat dissipated by the readout electronics of the VXD has to be efficiently removed from the very confined VXD volume without spoiling its low material budget by introducing too much extra dead material. This required the design of a complicated thermal management scheme based on two-phase CO_2 cooling. DESY is in charge of verifying and optimising the VXD cooling concept. To this end, DESY is building a full VXD mock-up with the same mechanical and thermal properties as the final detector. Figure 2 (bottom) shows the inner two layers of the PXD thermal mock-up during assembly at DESY. The very fragile thermal dummy sensors are made of 75 µm thick silicon exactly in the same way as the real detector. Measurements with this setup are ongoing and have already produced extremely valuable insights into how to operate this sensitive device in its complicated environment. Studies including the SVD thermal mock-up will follow soon.

Physics analysis of Belle data

The huge data sample collected by the predecessor experiment Belle is an ideal basis to search for candidates for dark matter, dark forces or other signals of new physics that would most likely manifest themselves first as tiny deviations from Standard Model (SM) predictions. Particularly good candidate channels for such searches are the production of a dark photon A' with subsequent decays into lepton or hadron pairs through A'–γ mixing, or strongly suppressed rare processes like the flavour-changing neutral-current decay $B \rightarrow K^{(*)}\mu\mu$, which in the SM can only proceed through higher-order loop or box diagrams.

The LHCb collaboration recently reported tantalising findings where, for the latter reaction, they compared the dependence of angular observables on the squared invariant mass of the muon pair (q^2) with theoretical predictions. Figure 3 shows one of these comparisons for the variable P_5', which exhibits the largest discrepancy. The overall significance of the difference of LHCb data to the SM corresponds to more than three standard deviations. Among other possible explanations, this observation could be interpreted as a first hint of a so far undetected new particle appearing virtually in the loop. Clearly, such a finding has to be confirmed by other experiments.

DESY has performed a "blind" analysis, i.e. without looking into the signal region, of the channels $B \rightarrow K^{(*)}ll$ ($l = e, \mu$) to determine whether or not the full Belle data set would yield sufficient sensitivity to make a meaningful statement. Although the final comparison of real Belle data with the theoretical prediction has to wait for the unblinded analysis, the expected statistical Belle sensitivity can already be inferred from Fig. 3. While for the plot the vertical positions of the Belle points are arbitrarily fixed to the predicted values, the vertical errors are derived from extensive Monte Carlo toy studies and reflect what precision can realistically be expected. The most significant deviation between data and theory in the case of LHCb occurs at q^2 values around 6 GeV^2 and is about twice as large as the expected Belle error. Thus, there are good prospects that, using Belle data, it will be possible to make a meaningful statement on the discrepancy observed by LHCb. After intense scrutiny by the Belle collaboration of the analysis procedure developed at DESY, the data will be unblinded at the beginning of 2016. It will be very interesting to see if the LHCb discrepancy can be confirmed with the Belle data or not.

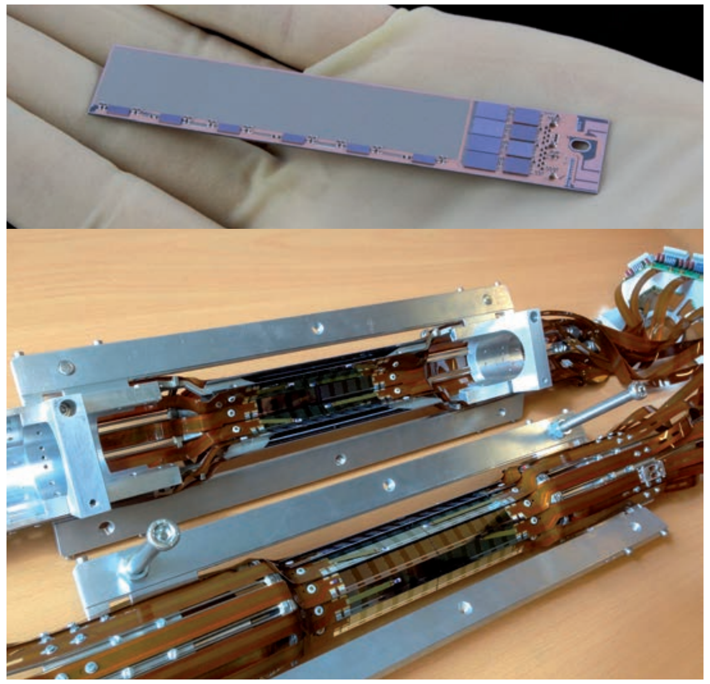

Figure 2

Top: First complete PXD module with almost final readout chips (HLL).

Bottom: The two layers of the PXD thermal dummy during assembly at DESY.

Another very interesting DESY analysis on Belle data that is also nearing completion is a search for so-called long-lived dark photons in the mass range from 0.2 to 10 GeV/c^2.

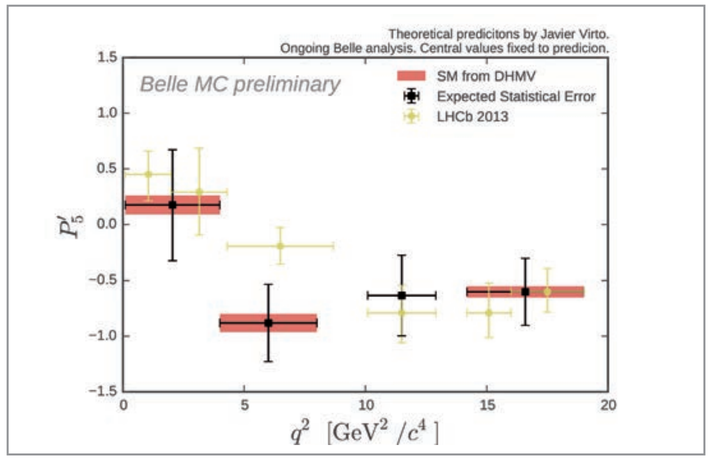

Figure 3

Comparison of recent LHCb results (yellow) with theoretical predictions (red). The expected Belle sensitivity as estimated from Monte Carlo toy studies can be inferred from the size of the vertical black error bars. Note that the vertical position of the Belle Monte Carlo points is fixed to the prediction.

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Breaking bonds.

Assessing the importance of molecular ionisation on plasma generation

In plasma wave acceleration, strong electric fields beyond 10 GV/m can accelerate electrons to GeV energies within distances of just a few centimetres. In this process, the plasma density distribution plays a crucial role for the determination of accelerating and focusing field strengths and for the phase velocity of the plasma wakefield. The plasma acceleration group at DESY is studying the underlying processes of plasma generation. To this end, the group examined a simple theoretical model to compute plasma electron density profiles based on the ionisation properties of molecular hydrogen. The presented approach shows a dependence on laser pulse duration owing to the characteristic time scale of the breaking of the molecular bond. To our knowledge, this effect has been neglected in numerical simulations of plasma wakefield accelerators so far.

The FLASHForward project

FLASHForward [1], a wakefield accelerator beamline at DESY's free-electron laser facility FLASH, uses plasmas formed through ionisation of hydrogen gas by a multi-terawatt femtosecond laser. The generated plasma electrons can be excited to perform a collective periodic motion, the plasma wave, which is powered by an electron bunch from the FLASH linear accelerator, generating electric fields on the order of 10 to 100 GV/m. In these fields, a second electron beam may be boosted to multi-GeV energies. One of the primary goals of the FLASHForward project is to demonstrate sufficient electron bunch quality from a plasma accelerator to allow the beams to be used in first photon science experiments, in particular for the demonstration of free-electron laser gain. FLASHForward separates plasma generation and wave excitation, in principle providing improved control over the plasma structure and thus the wakefield properties. Hence, an in-depth understanding of the ionisation processes affecting the initial electron density distribution is mandatory. Moreover, tailoring the gas ionisation locally will enable the possibility of structured plasma density profiles to control the acceleration process in great detail.

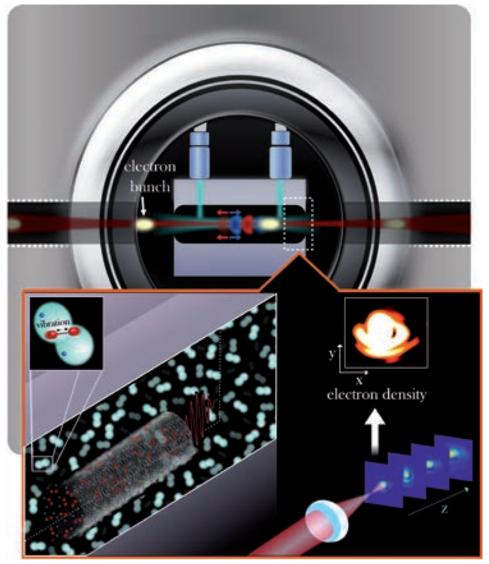

Figure 1

Scheme of the FLASHForward central interaction area. An ultrashort and intense laser is focused into a gas cell situated inside a vacuum chamber. The laser pulse ionises the gas target and creates a plasma. Subsequently, an electron bunch from the FLASH linear accelerator is injected, driving a wakefield that allows for electron acceleration. The local electron density of the plasma can theoretically be predicted by a careful description of the ionisation rates of the gas molecules and knowledge of the laser properties.

Figure 1 illustrates the basic concept of the experimental setup. The TW laser is focused into a gas cell situated inside a vacuum chamber. This cell consists of a sapphire capillary with an inner diameter of 1.5 mm. Gas inlets supply the capillary with hydrogen, which is ionised by the incoming laser beam. Subsequently, a single electron bunch from FLASH is injected, driving a plasma wakefield at a repetition rate of 10 Hz. Our goal is to create a comprehensive theoretical description of the initial ionisation event, which may be used to predict the generated electron density profile based either on simulations of realistic laser pulse propagation or on an experimentally measured laser pulse evolution.

Laser releases electrons

Molecular hydrogen possesses two electrons, which may leave the molecule under absorption of energy, e.g. from a laser pulse. Hydrogen decomposes into its constituents through three possible fragmentation scenarios, each requiring a different amount of energy:

$$\text{a)}\quad H_2 \xrightarrow{15.4\text{ eV}} H_2^+ \xrightarrow{30.0\text{ eV}} H_2^{++},$$

$$\text{b)}\quad H_2 \xrightarrow{15.4\text{ eV}} H_2^+ \xrightarrow{2.8\text{ eV}} H + H^+ \xrightarrow{13.6\text{ eV}} H^+ + H^+,\ \text{or}$$

$$\text{c)}\quad H_2 \xrightarrow{4.5\text{ eV}} H + H \xrightarrow{2\cdot 13.6\text{ eV}} H^+ + H^+ .$$

The favoured channel depends on the laser pulse duration and peak intensity [2]. Laser pulses with durations shorter than the characteristic molecular vibrational oscillation period, referred to as the *short-pulse regime* (associated with scenario a), may double-ionise the molecule directly before dissociation can occur. If, in contrast, molecular dissociation precedes ionisation, the scenario is called *long-pulse regime* (in its pure form associated with scenario c). The dominating ionisation process expected for FLASHForward parameters is tunnelling ionisation. In this scheme, the laser pulse distorts the electric binding potential in such a way that the bound electrons can escape by tunnelling through the potential barrier. The presented ionisation model is based on the calculation of *static tunnelling ionisation rates* [3] of hydrogen in strong laser fields under consideration of a specific temporal and spatial laser intensity profile. These rates are implemented into rate equations assuming instantaneous ionisation.

Figure 2 depicts the expected electron density n_e normalised to the initial molecular density n_0 after a laser pulse with peak intensity I_0 has passed. Complete ionisation for a purely atomic treatment compared to the molecular model is reached at lower peak intensities and for longer pulse durations. An example evolution of ionisation products is shown in the inset. These analytic tools allow for the prediction of electron density profiles from a measured or simulated evolution of the laser profile.

Predicting plasma shapes: the impact of molecular bonds

In the following, the theoretically expected plasma shape, as generated by the focused 5 TW FLASHForward laser beam reaching a peak intensity of ~2 x 10^{15} W/cm² under the assumption of a static temporal profile with a pulse duration of 25 fs FWHM, is computed. We simulate the associated evolution of the laser focus along the laser propagation axis *z* in the ionisation setup. The result of the radial average of an image plane perpendicular to the laser propagation direction (cf. Fig. 1) at each sampling point along *z* is shown in Fig. 3A. Using the ionisation model, we convert these intensity planes into electron density distributions in Fig. 3B. The plot on top of Figure 3A shows the on-axis intensity lineout as well as the laser energy loss. The laser power is depleted more strongly for atomic ionisation treatment due to the more rapid consumption of energy for ionisation. The upper halves in Figs. 3A and 3B show ionisation calculations on the basis of a simple atomic ionisation model, whereas the bottom halves depict the molecular ionisation case (plotted against negative radius *r*). The plot to the right of Figure 3B presents the transverse electron density at different locations in *z*. The molecular electronic structure, in particular, influences the shape of the plasma compared to pure atomic ionisation for intensities close to the ionisation threshold. These thresholds, ~2.5 x 10^{14} W/cm² for H_2^+ and ~0.7 x 10^{14} W/cm² for H_2/H, are crucial parameters when targeting a certain radial and longitudinal plasma density profile. The developed ionisation model incorporates ionisation dynamics of molecules for plasma generation and thereby allows for realistic predictions and an optimisation of the laser focusing geometry for the upcoming FLASHForward project.

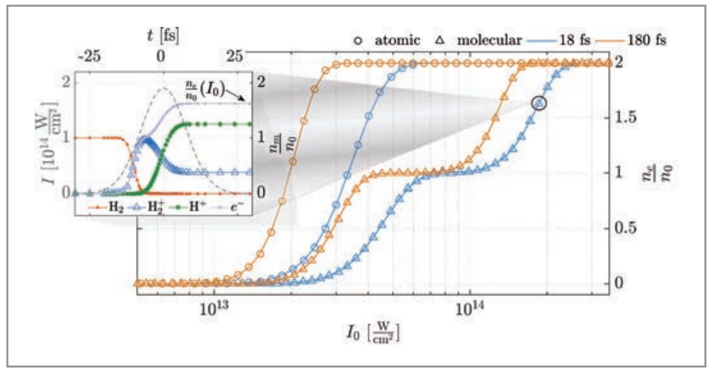

Figure 2

Calculated electron densities as a function of laser peak intensities. Each data point represents the expected electron density after a laser pulse has passed. Computed are incoming Gaussian laser pulses with pulse durations of 18 fs (blue line) and 180 fs (orange line) FWHM for the presented molecular ionisation model (triangles) and assuming atomic ionisation (circles). Inset: Hydrogen ionisation products according to rate equations for fully molecular fragmentation. The hydrogen ionisation products vary depending on the interaction time.

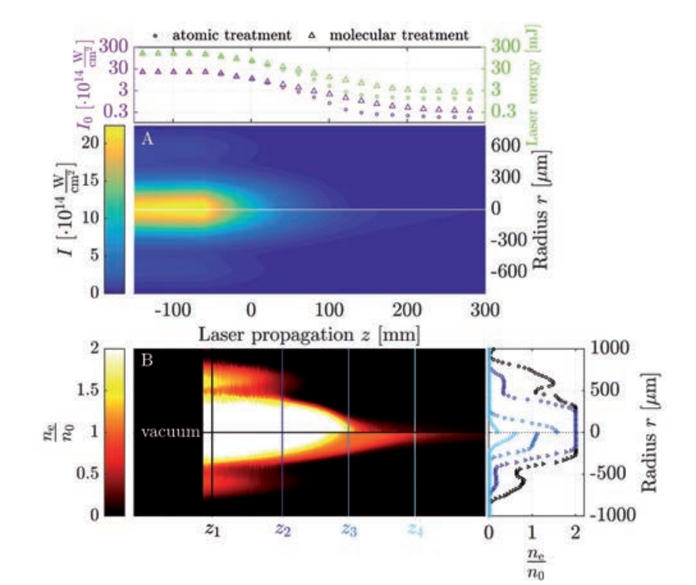

Figure 3

Simulated laser profile and expected electron density evolution for the FLASHForward laser focusing geometry. Plot A shows radially averaged intensity lineouts of image planes perpendicular to the laser propagation direction simulated by ZEMAX. The on-axis intensity and laser energy along the laser propagation are shown on top. Plot B presents the associated electron density distributions. The upper half of this plot shows hydrogen treated atomically, whereas the bottom half takes the molecular binding potentials into account. On the right, the transverse electron density is depicted at several locations in *z*.

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Stellar hints for experimental hunts of axion-like particles.

ALPS II experiment may shed light on excessive cooling of stars

The Any Light Particle Search collaboration is preparing the ALPS II experiment at DESY, which aims to discover hypothetical very weakly interacting ultralight particles, in particular axion-like particles (ALPs). Their existence is predicted in extensions of the Standard Model based on string theory. Intriguingly, additional support for their possible existence accumulates from observations of stars in various stages of their evolution, pointing to an excessive cooling mechanism that can be best explained by the stellar production and emission of ALPs. This hypothesis can be decisively tested at ALPS II.

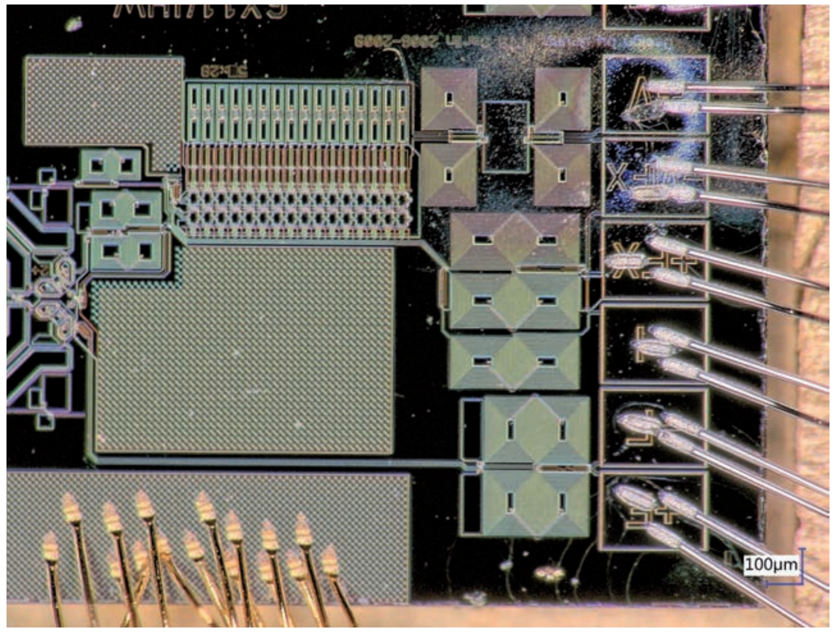

Figure 3
Detailed view of the wire bonds of the SQUID electronics that are used to read out the TES (thanks to the DESY CMS detector laboratory)

ALPS II aims for both the production and the detection of ALPs in the laboratory. This is done by sending laser photons along a strong magnetic field, allowing for their conversion into ALPs, towards a blocking wall, behind which the ALPs may then reconvert, again in a strong magnetic field, into photons; these are susceptible to detection, eventually giving the impression of "light shining through a wall". Details of the planned ALPS II setup were given in *DESY Particle Physics 2012*. In 2013, the collaboration demonstrated the feasibility of the detector and magnet concept. In 2014, ALPS II reached an important milestone regarding the optical resonator generating the high photon flux in front of the wall. As a highlight in 2015, the collaboration demonstrated the feasibility of the method chosen to keep this optical resonator frequency-locked with the optical resonator behind the wall – a key requirement for reaching the envisaged sensitivity in ALP–photon coupling strength.

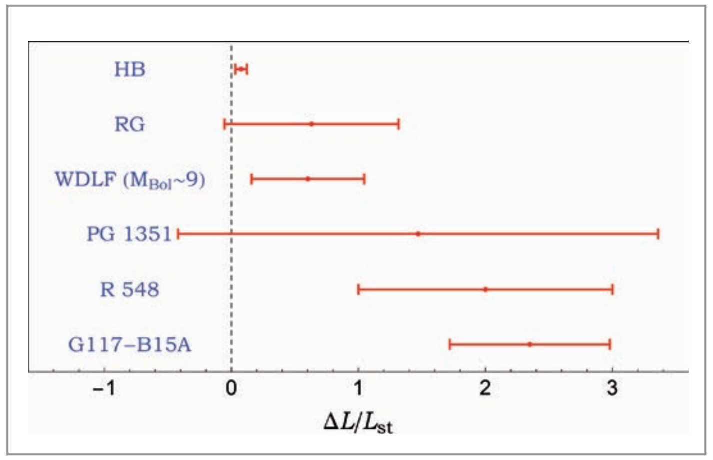

Figure 1
Luminosity excess ΔL normalised over a reference luminosity L_{st} for different types of stars and observational data: number counts of helium-burning (HB) stars and red giants (RG) in globular clusters; white-dwarf luminosity function (WDLF), i.e. the space density of white dwarfs (WDs) per brightness interval; period decrease of the variable white dwarfs PG 1351+489, R548 and G117-B15A.

This sensitivity is required in order to decisively test the hypothesis that ALPs explain the increasing number of observational hints of excessive cooling of stars in various stages of their evolution: red giants, helium-burning stars, white dwarfs and neutron stars. Unfortunately, with the astronomical data presently at hand, one cannot exclude the possibility that all these individual observations are the result of an inadequate understanding or of poor statistics. Together, however, they overwhelmingly indicate a systematic tendency of stars to cool more efficiently than predicted, as evident from Fig. 1.

The observed additional cooling could be due to a novel weakly interacting slim particle (WISP), produced in the interior of stars and leaving them unimpeded, thus being responsible for efficiently carrying energy away. Given the very different properties of the stars that show anomalous cooling – red giants having a dense, degenerate core and a non-degenerate burning shell, helium-burning stars having a non-degenerate helium-burning core, white dwarfs having an inactive degenerate core – the new production mechanism should have a quite peculiar dependence on temperature and density. Remarkably, this favours an ALP over other potential WISP candidates such as a hidden photon. In fact, all the observed cooling excesses can be explained at one stroke if one postulates the existence of an ALP with a non-vanishing coupling to photons, electrons and quarks. Importantly, the hinted ALP couplings are accessible to ALPS II at DESY and the proposed International Axion Observatory (IAXO) supported by CERN, which aims to search for solar ALPs (Fig. 2).

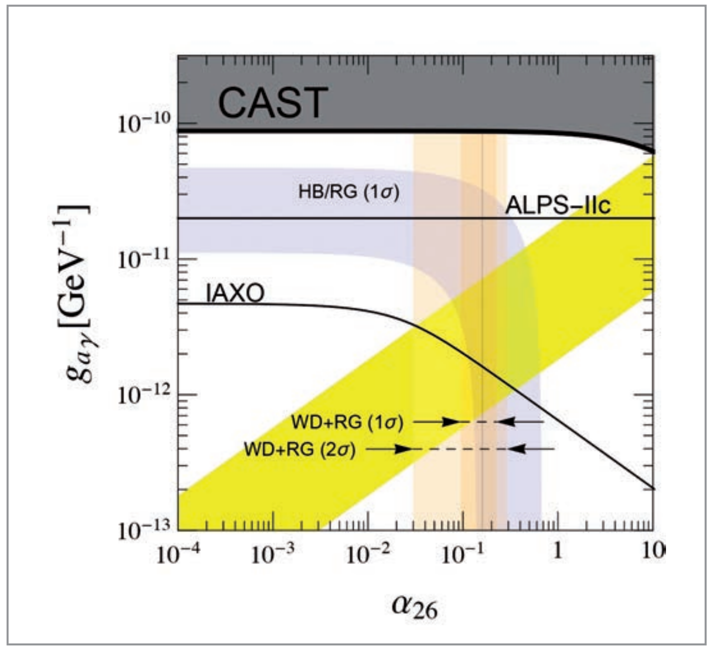

Figure 2
Summary of the region in the ALP parameter space (ALP–photon coupling $g_{a\gamma}$ / ALP–electron coupling α_{26}) required to explain the observed energy loss excesses of red giants (RG), helium-burning (HB) stars and white dwarfs (WD). The yellow band indicates the prediction of axion models solving the strong charge–parity (CP) problem. The projected sensitivities of ALPS IIc and IAXO are also shown.

On the experimental side, the preparations towards a first search for hidden photons (ALPS IIa) progressed in 2015. Long-standing issues with the high-power cavity in front of the wall could be traced back to faulty high-reflectivity mirrors. A new batch of mirrors will be delivered in early 2016. Detailed studies of the transition edge sensor (TES) detector system (Fig. 3) continued with the aim to optimise its detection efficiency.

With the University of Florida in Gainesville joining the ALPS collaboration and significant investments for the ALPS IIc infrastructure approved by the Heising–Simons Foundation in Los Altos, California, the funds that had been missing for the ALPS IIc setup in the HERA tunnel are now available. A corresponding project plan is under development.

In November 2015, a workshop funded by the Hamburg Partnership for Innovation, Education and Research (PIER) took place at DESY to investigate possibilities of using the ALPS IIc infrastructure to measure the vacuum magnetic birefringence predicted in 1936 by Hans Euler and Werner Heisenberg (see **https://indico.desy.de/conferenceDisplay.py?confId=12654**). First R&D activities with third-party funds have started.

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Astroparticle physics.

Astroparticle physics at DESY spans a very broad range, from profound theoretical studies to a slew 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 physics preparation. Most importantly, DESY is applying to host the CTA headquarters at its Zeuthen site (p. 58).

DESY has since long collected 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. Currently, H.E.S.S. is being equipped with new camera systems designed and built at DESY (p. 60). H.E.S.S. continues to contribute important physics results, as are other groups at DESY working on the ground-based gamma-ray observatories MAGIC on La Palma, Spain, and VERITAS in Arizona, USA, as well as on the Fermi Large Area Telescope (Fermi-LAT, p. 61).

The second large field of experimental activities in astroparticle physics is neutrino physics. The IceCube neutrino telescope at the south pole continues to deliver high-quality data. Here too, the future is in clear focus, with the IceCube-Gen2 project being pursued at full steam. DESY plays a leading role in sensitivity studies and the development of photosensors for IceCube-Gen2 (p. 64).

The astroparticle theory activities bundle the results from the experiments mentioned above, together with those from particle physics and cosmology. One focus currently is on the interpretation of all these data in terms of dark matter (p. 62).

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CTA takes off.

Towards construction and data analysis

The Cherenkov Telescope Array (CTA) is the next-generation gamma-ray observatory, due to explore the highly active non-thermal universe at energies above 30 GeV with unprecedented precision and sensitivity, with the aim of understanding the sources and acceleration mechanisms of cosmic particles and the nature of dark matter. CTA will be built by a worldwide consortium, with major contributions from DESY. The CTA consortium is ready to begin construction in 2016.

Project milestones

A major milestone of CTA was the critical design review (CDR) in June 2015, for which each work package produced an extensive technical design report on the technical and planning status. The Scientific and Technical Advisory Committee (STAC) then reviewed a total of more than 3000 pages, coming to the conclusion that the science case for CTA is as strong and robust as ever and that the overall technical design and prototyping of the telescopes and cameras are mature. To conclude the CDR, however, the final site selection and a funding plan are still needed. The CTA project office and the international funding agencies are working towards resolving these issues.

In July 2015, contract negotiations started for hosting CTA South on the Paranal grounds of the European Southern Observatory (ESO) in Chile and CTA North at the Instituto de Astrofísica de Canarias (IAC) of Roque de los Muchachos Observatory in La Palma, Spain. A decision is expected in early 2016.

The council of the CTA gGmbH has become the legal body for major decisions on CTA, such as the funding start or the site choice. The CTA project office is getting ready to develop the site for the preproduction telescopes and the control and readout of the observatory. At the same time, the CTA consortium is preparing for the early CTA science programme.

Finalising prototypes

Under the leadership of DESY, the prototype of the medium-sized telescopes (MSTs) is being further optimised towards a final design for the preproduction telescopes. The main focus is now on developing the telescope control software, characterising the telescope optics and competing mirror designs, and performing extensive drive tests to verify the reliability of operation (Fig. 1). The positioner of the MST was also chosen for the Schwarzschild-Couder Telescope (SCT), a proposed US contribution to CTA. A positioner for the SCT prototype was produced and assembled in cooperation with US partners.

Software architecture for array control and data acquisition

DESY is leading the effort to define the software architecture for the CTA array control and data acquisition, that is, the fundamental organisation of the software system, the relationship between its individual components and with their wider environment, and the principles guiding the design and evolution of the whole software project. Together with CTA collaborators from INAF in Italy and software experts from the Fraunhofer Institute for Experimental Software Engineering in Germany, the DESY team is shaping the software environment using state-of-the-art industrial methods.

Figure 1

The MST prototype near DESY in Berlin at night in rapid movement

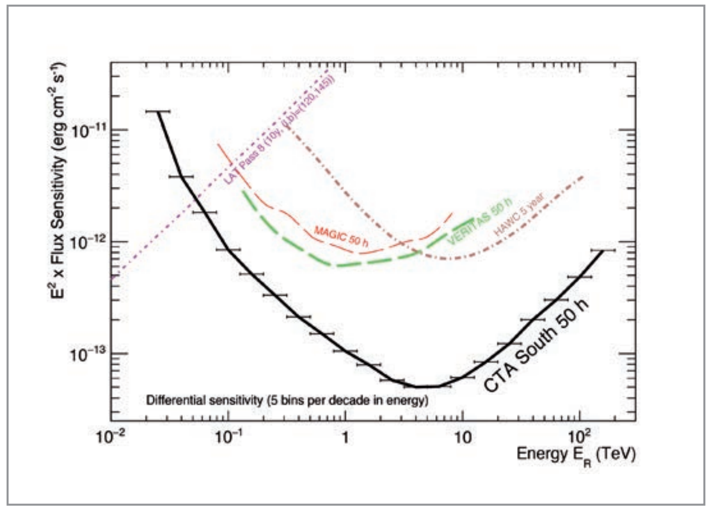

Figure 2:

Differential flux sensitivity of CTA in comparison to existing gamma-ray observatories. The CTA energy range extends from about 30 GeV to 300 TeV. CTA is much more sensitive in the region between 1 and 10 TeV than any existing observatory.

Optimising CTA science performance

CTA will consist of an arrangement of numerous imaging atmospheric Cherenkov telescopes of three different sizes. DESY has contributed to the optimisation of the array layout and the improvement of the analysis methods to achieve a significantly improved angular resolution and flux sensitivity over four decades in energy (Fig. 2) compared to existing gamma-ray detectors. With CTA, it will become feasible for the first time to perform a sensitive survey of a large portion of the sky in gamma light and to resolve extended objects, such as supernova remnants or pulsar wind nebulas, with arc minute resolution.

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https://www.cta-observatory.org

New exceptional cosmic accelerators discovered.

... and a new H.E.S.S. Cherenkov camera

In 2015, the H.E.S.S. collaboration presented the first survey of TeV particle accelerators in the Large Magellanic Cloud. In parallel, a major hardware upgrade has begun: under the leadership of DESY, the first of four H.E.S.S. I Cherenkov cameras was improved and commissioned. The upgrade, which is due to be finished in 2016, will lead to enhanced reliability and sensitivity of the H.E.S.S. array in its final years of operation before the Cherenkov Telescope Array (CTA) gamma-ray observatory will take over.

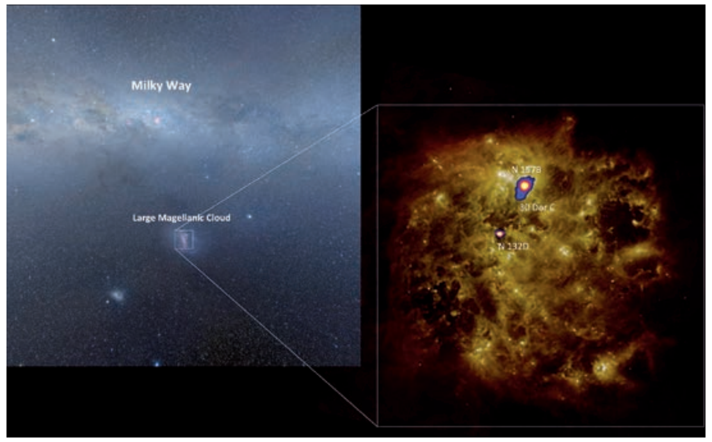

Figure 1

Optical image of the Milky Way and infrared zoom into the Large Magellanic Cloud with superimposed H.E.S.S. images

Figure 2

Commissioning the new front-end electronics of one of the H.E.S.S. I cameras

The Large Magellanic Cloud (LMC) is a nearby satellite of the Milky Way. At a distance of only 163 000 light years, it is one of the few galaxies that can be resolved and surveyed with present-day Cherenkov telescopes. As the LMC is only visible from the southern hemisphere, the H.E.S.S. gamma-ray telescope in Namibia is the only instrument that can currently perform this survey. After 210 hours of observation, first results were published in *Science* [1]: Three TeV gamma-ray sources, including the most luminous pulsar wind nebula ever seen (N 157B), and a so-called super bubble (30 Dor C) were discovered. The latter is a source type that had never been seen in gamma rays before (Fig. 1).

In July 2015, 10 DESY Zeuthen staff members travelled to Namibia to completely refurbish the first of four 10-year-old H.E.S.S. I cameras (Fig. 2). The necessary electronics and mechanical components were designed and produced at DESY in Zeuthen and Hamburg. The upgrade campaign was finished on time, and first cosmic gamma rays were detected already in August. While high-level commissioning is still ongoing, the upgrade of the remaining three cameras has started. It will be completed in autumn 2016.

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[1] H.E.S.S. Collaboration, The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud, DOI: 10.11.26/science.1261313

The variable gamma-ray sky.

... as seen with the Fermi Large Area Telescope

The Large Area Telescope (LAT) onboard the Fermi Gamma-Ray Space Telescope is the most sensitive instrument observing the sky at gamma-ray energies between 100 MeV and about 100 GeV. Since 2008, the LAT has been scanning the whole sky every three hours. Many new source types emitting gamma rays have been found, and many sources – such as white dwarfs and pulsars – have unexpectedly proved to be variable on time scales down to a few hours [1,2], revealing rapid particle acceleration in these systems.

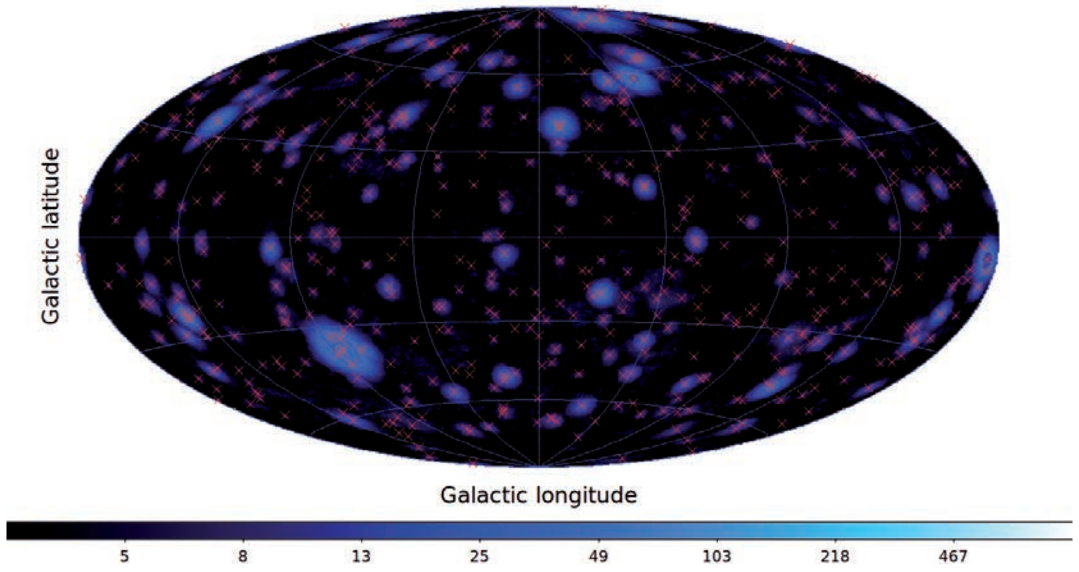

Figure 1

Red crosses indicate the positions of sources in the second catalogue of flaring gamma-ray sources. The background shows, for each position in the sky, the maximum significance for all flares detected in seven years.

In summer 2015, the LAT sensitivity was significantly enhanced through new event reconstruction and analysis techniques. At DESY, the improved reconstruction was used to perform a major upgrade to the Fermi All-sky Variability Analysis (FAVA), which searches the entire gamma-ray sky for flares every week. FAVA was used to define the second catalogue of flaring gamma-ray sources, which contains 527 sources, 136 of which are previously unknown gamma-ray emitters. The distribution of these sources in the sky is shown in Fig. 1.

In collaboration with NASA, the DESY LAT team developed a public web interface for FAVA, which was recently released (http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/). It automatically runs the catalogue pipeline every week. The results are made public in real time. Furthermore, the flux as a function of time is available for every point in the sky. Astronomers around the globe are now able to scan the gamma-ray sky for flares and to correlate their data obtained at other wavebands to the LAT observations. This will hopefully lead to further surprises in the variable gamma-ray sky.

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To be or not to be.

Constraining the concept of dark matter

The search for dark matter is a major challenge for modern physics at the frontier of astrophysics, cosmology and particle physics. The existence of dark matter might be indirectly confirmed by astroparticle experiments such as neutrino and gamma-ray telescopes. Scientists at DESY are striving to find evidence for dark matter in data from these instruments, thereby helping to constrain theoretical models of dark matter.

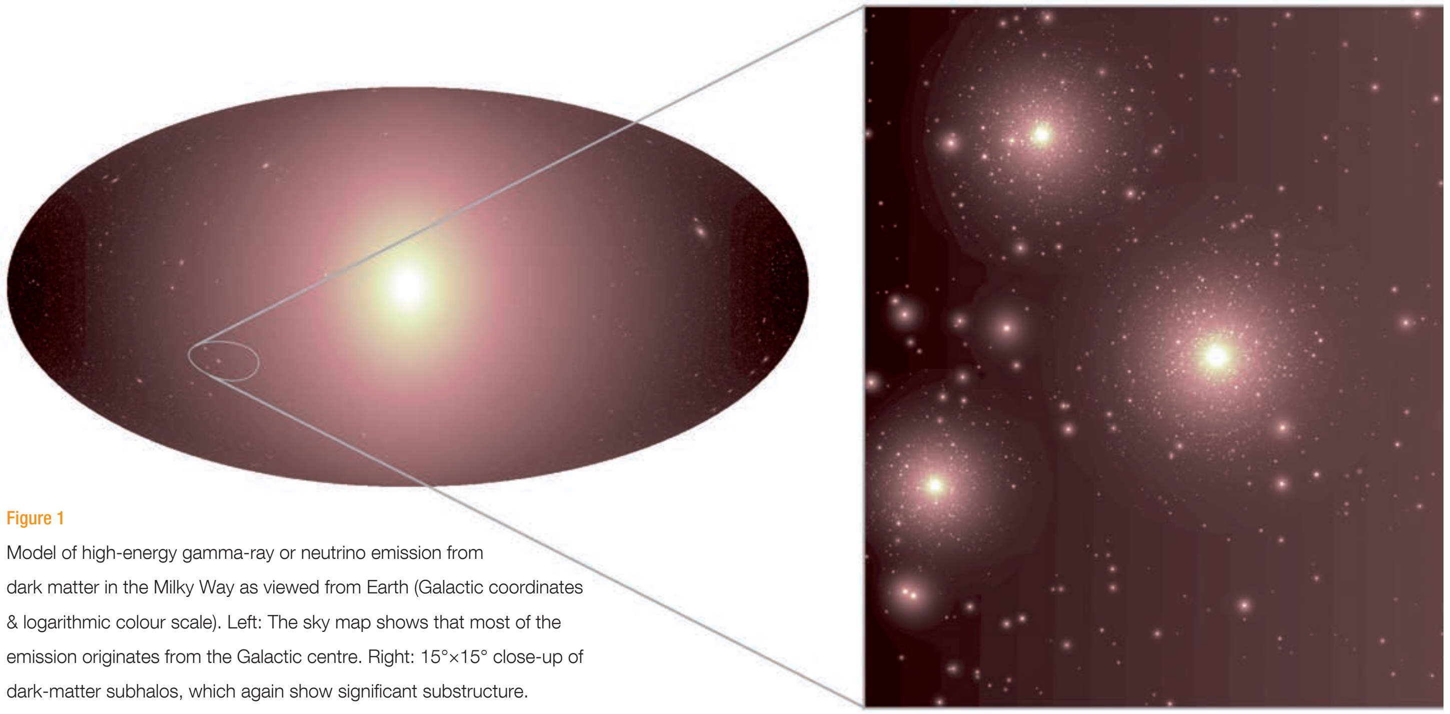

Figure 1

Model of high-energy gamma-ray or neutrino emission from dark matter in the Milky Way as viewed from Earth (Galactic coordinates & logarithmic colour scale). Left: The sky map shows that most of the emission originates from the Galactic centre. Right: 15°×15° close-up of dark-matter subhalos, which again show significant substructure.

Revealing the nature of dark matter is one of the most challenging tasks for modern astrophysics and cosmology. Diverse observations indicate that there is about five times more mass present in the universe than visible matter can account for [1]. This indicates the presence of invisible mass, called dark matter. So far, dark matter manifests itself only through gravitational effects. The possibility remains that instead of being due to a new type of matter, the observations might be explained by a fundamental lack of understanding of gravitational dynamics at astronomical scales. To distinguish between these scenarios, it is important to find an alternative, non-gravitational indication for dark matter. Conversely, the non-detection of predicted signals may rule out plausible dark-matter models.

The most promising candidate to explain the observational evidence is a long-lived, only weakly interacting massive particle (WIMP), as predicted by many theories for physics beyond the Standard Model of particle physics. An important characteristic of such WIMPs is that they are predicted to self-annihilate or decay into a variety of Standard Model particles. Detecting these secondary products may provide an unambiguous – though indirect – signature for the existence of dark matter. As the mass of the WIMPs is expected to be in the range of giga- to teraelectronvolts (GeV–TeV, the mass scale of the weak interaction), the secondary products will have similar energies. Therefore, astroparticle observatories are suitable instruments for the indirect detection of dark matter.

Different strategies exist for the indirect search for dark matter. Cosmic-ray experiments search for telltale secondary products in the composition and the energy spectrum of cosmic rays. At DESY, scientists strive to detect astrophysical regions of high dark-matter density, which emit a high rate of secondary particles, using gamma-ray [2] and neutrino telescopes [3]. In the last decades, extensive simulations have provided a good picture of how dark matter forms density clusters throughout the universe. The heaviest dark-matter clusters are the galaxies themselves, with the highest dark-matter density located at their centres. Therefore, the centre of our Galaxy is a promising target to detect indirect signals from dark matter. Dark-matter clumps are also expected on smaller scales. For example, dwarf galaxies – small companions surrounding the Milky Way – are thought to be subhalos of the Galactic dark-matter distribution (Fig. 1). Only dark matter could provide a reasonable explanation for a detection of high-energy particles from these objects. Finally, the many small and distant extragalactic dark-matter clusters may leave an imprint in the diffuse gamma-ray background, or they may be an origin of the recently discovered astrophysical neutrino flux.

DESY is involved in the dark-matter programmes of the observatories CTA, H.E.S.S., MAGIC, VERITAS, IceCube and Fermi. So far, no clear evidence for dark matter could be found. However, the mentioned experiments were already able to constrain the parameter space of possible WIMP dark-matter scenarios. Figure 2 shows up-to-date upper limits on the annihilation cross section of WIMP dark matter, obtained by H.E.S.S. (magenta line) and Fermi-LAT (blue line). These limits already reach the cosmologically most favoured cross section (black dashed line) for masses below 100 GeV, which excludes a variety of prominent models for a dark-matter particle lighter than 100 GeV. The figure also shows the parameter space reached with the planned CTA gamma-ray observatory. Observing the Galactic centre with CTA will provide sensitivity to the most favourable dark-matter models between 200 GeV and 40 TeV. Thus, indirect evidence for dark matter might soon be found. If CTA does not detect a signal, the WIMP dark-matter hypothesis will be severely challenged.

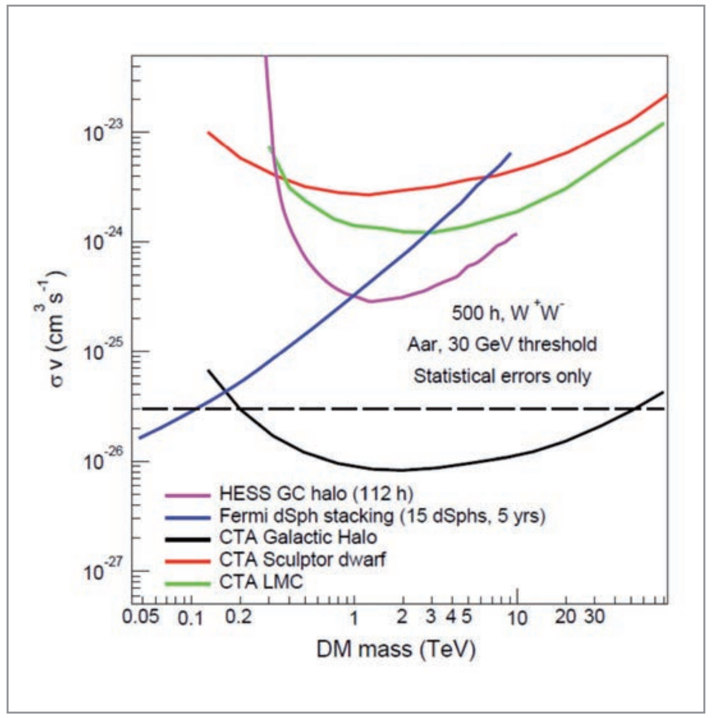

Figure 2:

Up-to-date limits by H.E.S.S. [4] and Fermi-LAT [5] on the velocity-averaged annihilation cross section of WIMP dark matter as a function of WIMP mass, and sensitivity of CTA for dark-matter detection for the Galactic centre (black), a typical dwarf galaxy (red) and the Large Magellanic Cloud (green) [6].

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Cosmic neutrinos.

IceCube and beyond

The neutrino telescope IceCube at the South Pole continues to deliver high-quality data. In 2015, the highest-energy neutrino event so far was observed, new measurements of the energy spectrum and the flavour composition of the diffuse astrophysical neutrino flux were presented, and strong constraints could be placed on the origin of these neutrinos. Planning of the IceCube-Gen2 project, which includes an extended high-energy array, the low-energy extension PINGU and a large surface array, is well under way, with DESY playing a leading role in sensitivity studies and the development of new photosensors.

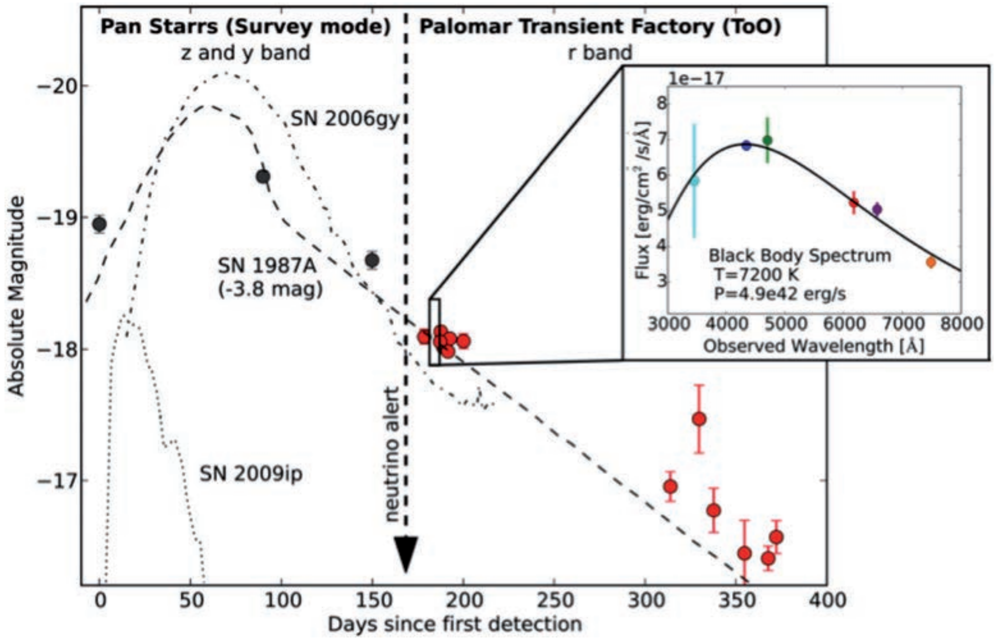

Figure 2

Light curve of PTF12csy, a Type IIn supernova detected by the Palomar Transient Facility as a result of the most significant alert sent by IceCube. The insert shows the photometric data as a function of wavelength for a narrow range in time, fitted with the expectation for a black-body spectrum. The total bolometric energy released is estimated to be at least 10^{50} ergs.

The DESY IceCube group led the analysis [1] of a combined set of astrophysical neutrinos, in which information from all detection channels (through-going muons, contained events and events starting in the detector) was used to characterise the spectral shape and the flavour content of the neutrinos (Fig. 1). The data are consistent with the expectation of a flavour ratio of 1:2:0 for electron, muon and tau neutrinos at the source. Oscillation effects turn this into a ratio of 1:1:1 at Earth. The data are still consistent with a ratio of 0:1:0, which is expected when muons are damped due to strong magnetic fields in the astrophysical sources. The scenario that the astrophysical neutrinos are produced in neutron decay (1:0:0 at the source) can already be ruled out.

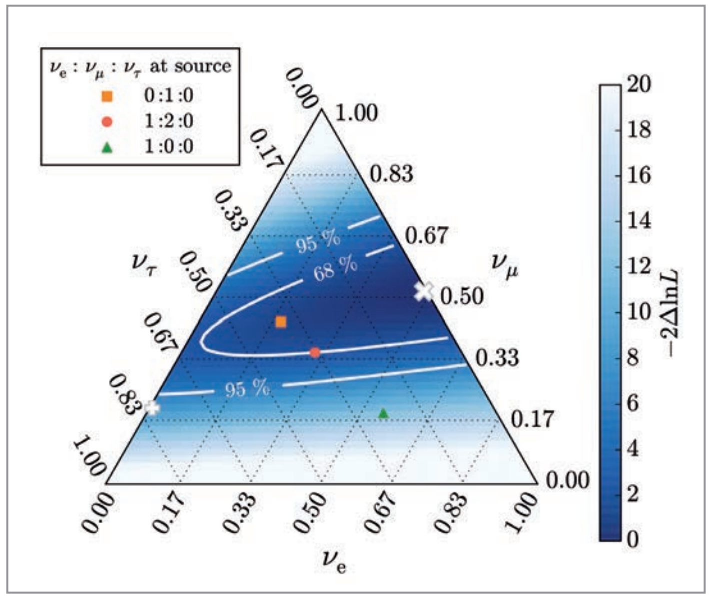

Figure 1

Profile likelihood scan of the neutrino flavour composition at Earth [1]. The best-fit composition is marked with “×”.

The DESY IceCube group is leading the follow-up of interesting neutrino events to identify prospective electromagnetic counterparts. Searches are being performed in the optical, X-ray and gamma range. A first tantalising observation was made with the 1.2 m telescope of the Palomar Transient Factory in California: PTF12csy, a bright supernova (SN) in coincidence with the most significant neutrino alert sent by IceCube so far (two neutrinos detected only 1.6 s apart) [2]. Spectroscopic observations showed that PTF12csy is a SN of Type IIn detected at a redshift of 0.068, i.e. rather distant for a prospective source.

The light curve of PTF12csy is shown in Fig. 2. The probability for this observation to be a chance coincidence – i.e. two atmospheric neutrinos accidentally aligning with a SN – is estimated at 1.4%. However, based on archival data from Pan-STARRS in Hawaii as well as spectral information, the SN was established to be already more than 170 days old at the time of the neutrino detection, ruling out most models for neutrino production. An exception could be the delayed collapse of a neutron star to a black hole, also postulated to explain short radio bursts [3]. Unlike in the original Blitzar model for short radio bursts, the magnetic shock wave would not accelerate electrons in almost empty space, but protons in a denser/dirtier environment. For the IceCube-Gen2 project, DESY is developing novel optical sensors and technologies for a large-area surface veto. One sensor option, the wavelength-shifting optical module (WOM, Fig. 3) developed in collaboration with the University of Mainz in Germany, uses wavelength-shifting and light-guiding techniques to achieve a large photo-sensitive area while using small-diameter photomultiplier tubes (PMTs), which have low noise rates, for readout. The use of wavelength shifters opens the UV band for the detection of Cherenkov light, the intensity of which is high in the UV range. The WOM has a cylindrical module design with a diameter of 14 cm, which promises a significant cost reduction for IceCube-Gen2 as it allows narrower holes to be drilled for deployment. Prototype studies show that capture and transport efficiencies of 50% for UV light can be achieved.

Figure 3

Wavelength-shifting optical module (WOM) for the IceCube-Gen2 project. The light collected in a wavelength-shifting coated tube (blue) is transported to two small PMTs at the ends of the tube. The whole setup is protected by a UV-transparent quartz pressure housing.

A 75 km² surface veto array currently foreseen for IceCube-Gen2 requires new developments for power generation and distribution, communication and time synchronisation under the harsh conditions in Antarctica. The Transportable Array for eXtremely large area Instrumentation studies (TAXI) is a modular and transportable air shower array of four autonomous stations. It enables in-situ studies of the engineering challenges that come with this type of detector. TAXI is a joint project of DESY and KIT within the Helmholtz Alliance for Astroparticle Physics. In November 2015, the first autonomous TAXI station was installed and commissioned at the DESY location in Zeuthen.

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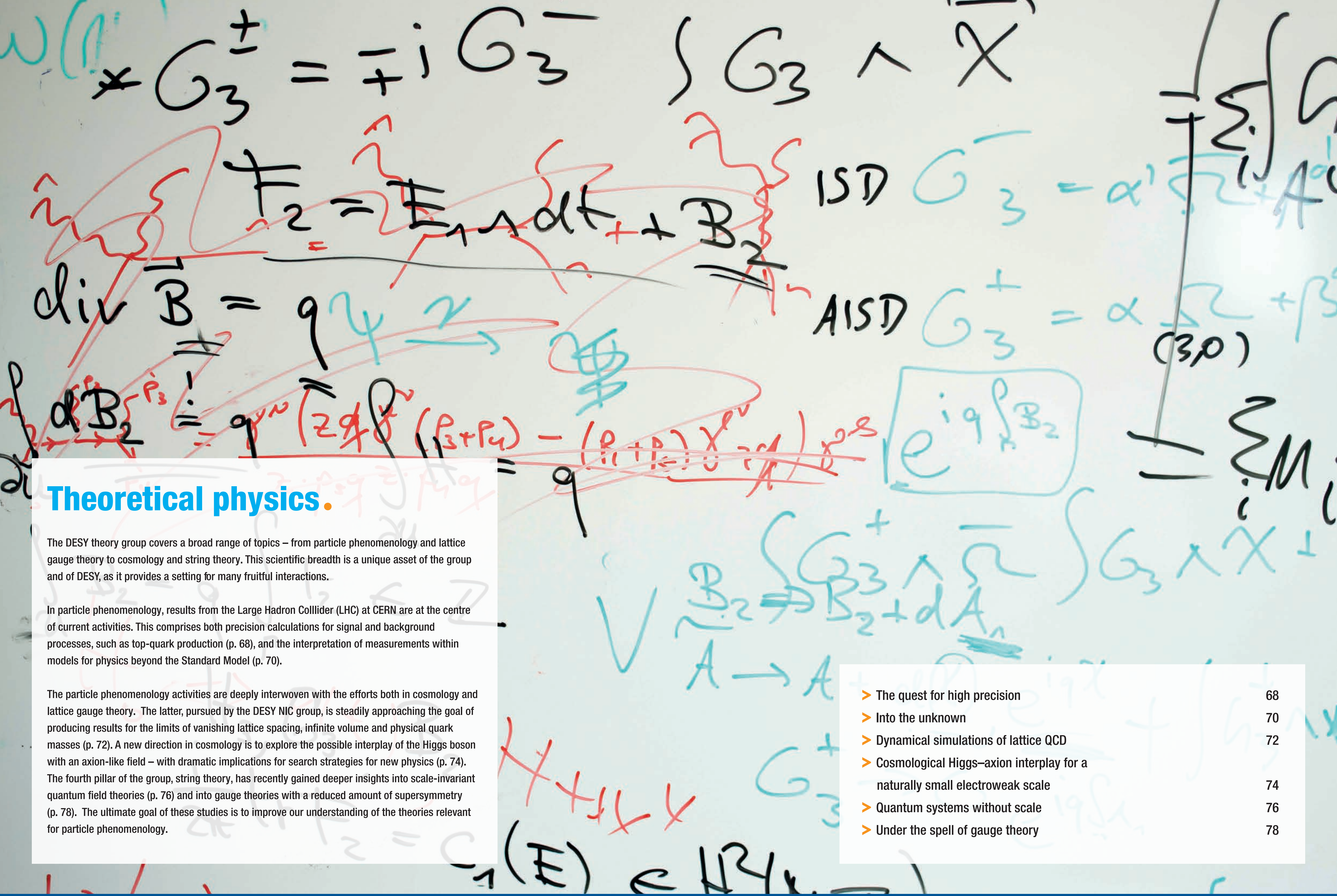

Theoretical physics.

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 Colllider (LHC) at CERN are at the centre of current activities. This comprises both precision calculations for signal and background processes, such as top-quark production (p. 68), and the interpretation of measurements within models for physics beyond the Standard Model (p. 70).

The particle phenomenology activities are deeply interwoven with the efforts both in cosmology and lattice gauge theory. The latter, pursued by the DESY NIC group, is steadily approaching the goal of producing results for the limits of vanishing lattice spacing, infinite volume and physical quark masses (p. 72). A new direction in cosmology is to explore the possible interplay of the Higgs boson with an axion-like field – with dramatic implications for search strategies for new physics (p. 74). The fourth pillar of the group, string theory, has recently gained deeper insights into scale-invariant quantum field theories (p. 76) and into gauge theories with a reduced amount of supersymmetry (p. 78). The ultimate goal of these studies is to improve our understanding of the theories relevant for particle phenomenology.

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The quest for high precision.

Improving heavy-quark mass relations

Quark masses can theoretically be defined in many different ways depending on the physical situation at hand. To match the experimental precision, the theoretical prediction for the relations between the different mass schemes also has to improve. To this end, the DESY theory group calculated the relation between $\overline{\mathrm{MS}}$ and on-shell mass up to next-to-next-to-next-to-leading order in perturbative quantum chromodynamics (QCD).

The masses of the quarks are free parameters entering the Lagrange density of the Standard Model. They receive radiative corrections and need to be renormalised. For the renormalisation, different prescriptions can be used, the most common ones being the $\overline{\mathrm{MS}}$ and the on-shell scheme. In the $\overline{\mathrm{MS}}$ scheme, only the appearing divergences are subtracted, while in the on-shell scheme, one requires in addition that the quark propagator $S_q(q)$ has a pole at the position of its mass for $q^2 = m^2$. In addition to these schemes, several threshold mass definitions exist. The most prominent ones are the so-called potential-subtracted (PS) mass and the 1S mass. They share features of both the $\overline{\mathrm{MS}}$ and the on-shell mass definition; in particular, they have a physical interpretation at threshold. The PS mass is defined by $M_{\mathrm{PS}} = M - \delta m(\mu_F)$, with $\delta m(\mu_F) = \mu_F C_F \frac{\alpha_s}{\pi}(1 + \cdots)$, where the ellipsis denotes higher-order corrections in perturbation theory. The 1S mass is defined as half of the mass of the hypothetical 1S bound state.

The transition between these schemes can be calculated in perturbation theory. We will illustrate the status for the case of the top quark. Up to three loops, the relation between $\overline{\mathrm{MS}}$ mass $m_t(m_t)$ and on-shell mass M_t is given by $M_t = (163.643 + 7.557 + 1.617 + 0.501)$ GeV, where we used $m_t(m_t) = 163.643$ GeV as the starting point and showed the one-, two- and three-loop contribution separately. Taking half of the three-loop contribution as an error estimate, this implies an error of 250 MeV, which is not negligible compared to the current measurement precision of the top-quark mass. In order to reduce the theoretical uncertainty, we calculated the four-loop corrections [1]. We obtained $M_t = (163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005)$ GeV, where the indicated error stems from numerical integrations. The four-loop correction of about 200 MeV is of the same order as the intrinsic renormalon-induced uncertainty, which is of the order of Λ_{QCD}.

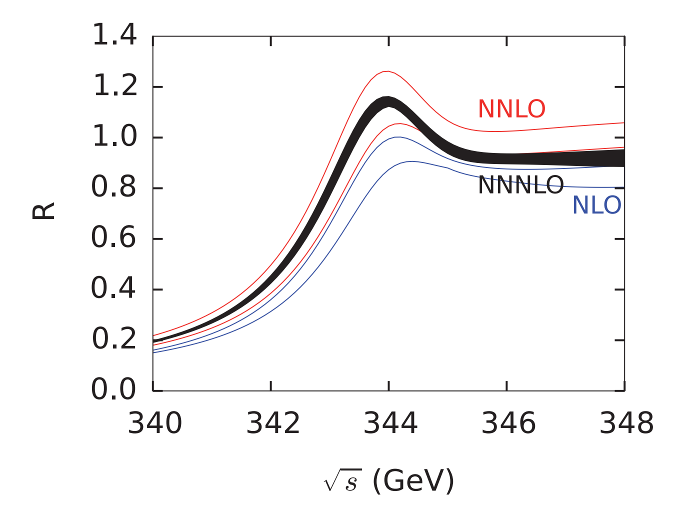

Figure 1

Total cross section for top–antitop production at a linear electron–positron collider [2]. The error bands are obtained by varying the renormalisation scale between 80 and 350 GeV.

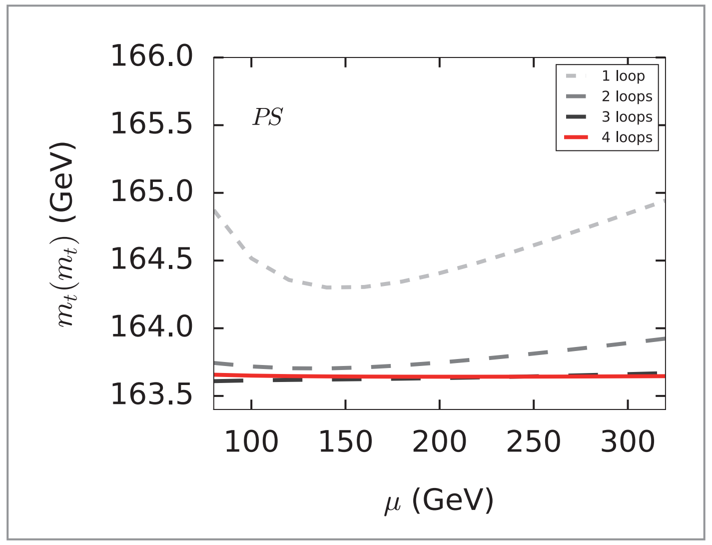

Figure 2

$m_t(m_t)$ obtained after first calculating $m_t(\mu)$ and then evolving to $m_t(m_t)$ [3]

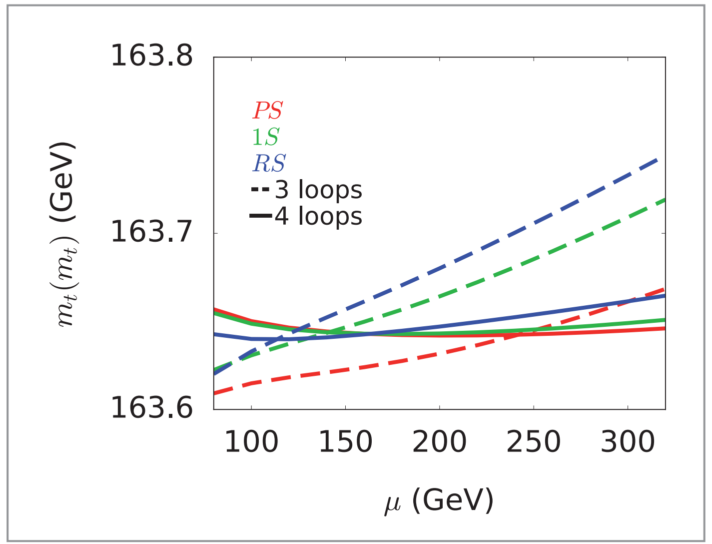

Figure 3

Same as Fig. 2, but now focusing on three- and four-loop results and in addition showing results for the 1S and RS masses [3]

The PS (or 1S) mass enters the theoretical prediction for the total cross section for top–antitop production near threshold at a future electron–positron linear collider (Fig. 1). The next-to-next-to-next-to-leading order (NNNLO) corrections have recently been calculated [2]. The result is shown in Fig. 1, where the predictions for different orders of the perturbative series are displayed. As can been seen, the NNNLO corrections are stable concerning height and position of the maximum and lead to a reduced error estimate. The width of the error band is about 3%. With the recent progress on the theory side, measuring the mass of the top quark at a future linear collider with an error of 100 MeV becomes feasible. The mass measured there will be either the PS or the 1S mass and has to be converted to the $\overline{\mathrm{MS}}$ mass.

For the conversion between PS and 1S mass on one side and the $\overline{\mathrm{MS}}$ mass on the other side, we find

- PS to $\overline{\mathrm{MS}}$ mass
  $m_t(m_t) = (168.204 - 3.893 - 0.598 - 0.088 + 0.018 \pm 0.006)$ GeV
- 1S to $\overline{\mathrm{MS}}$ mass
  $m_t(m_t) = (172.227 - 7.182 - 1.184 - 0.210 - 0.008 \pm 0.006)$ GeV

In both cases, we find that NNNLO accuracy is needed in order not to spoil the precision of the measurement. A possible error estimate is half the four-loop correction, which in both cases leads to an error of below 20 MeV.

Another way to estimate the impact of higher-order effects is to look at the behaviour under variation of the renormalisation scale. This is shown in Fig. 2 for the PS mass. Here, first $m_t(\mu)$ is calculated and in a second step $m_t(m_t)$ employing four-loop renormalisation group evolution. In Fig. 3, we only show the three- and four-loop results in order to better visualise the impact of the new four-loop corrections. We also include, in Fig. 3, the results for the and PS and RS masses. We find that, at four loops, all curves are essentially flat and intersect with the corresponding three-loop ones.

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Into the unknown.

Upcoming LHC results will greatly advance our understanding of nature

Presently, our understanding of the fundamental laws of nature is such that the known experimental data are compatible with various descriptions corresponding to very different underlying physics. Exploring the LHC Run 2, which takes place at the highest energies ever reached in a collider experiment, will allow us to enter new territory, challenging and shaping our understanding of nature at its most fundamental level.

The highlight of the LHC Run 1 at energies of 7 and 8 TeV was the spectacular discovery of a signal at about 125 GeV in the Higgs searches at the ATLAS and CMS experiments. While at the present accuracy, the properties of the observed particle are compatible with the ones predicted for the Higgs boson of the Standard Model (SM) of particle physics, a variety of other interpretations are possible as well, corresponding to very different underlying physics. In particular, the new particle could be part of an extended Higgs sector, implying the presence of further Higgs bosons, with masses either above or below the one of the detected signal. Another possibility could be that the detected signal is not a fundamental particle but a composite state, which would point to a new kind of strong interaction.

Together with searches for further states of new physics, the investigation of the properties of the observed particle with high precision, both of the experimental measurements and theoretical predictions, paves the way towards identifying the mechanism that is responsible for providing elementary particles with the property of mass. In the SM, this is achieved through the Brout–Englert–Higgs mechanism, according to which elementary particles receive their masses as a consequence of a non-trivial structure of the vacuum, i.e. of the state of lowest energy of our universe. Higgs physics at the LHC and at possible future colliders can therefore provide a window to the quantum structure of the vacuum.

Since the SM is incomplete – it does not include gravity and therefore describes only three of the four known fundamental interactions of nature – some kind of physics beyond the SM must exist. In view of this and various other shortcomings of the SM, supersymmetric extensions of the SM are particularly attractive. Based on a new symmetry between fermions and bosons, they predict that the SM particles should be accompanied by superpartners that share the properties of the SM particles but have different spin. Supersymmetric extensions of the SM offer the fascinating possibility that the strong, electromagnetic and weak interactions unify at a high energy scale and provide a natural candidate for the cold dark matter in the universe. An extended Higgs sector is a firm prediction of this class of models.

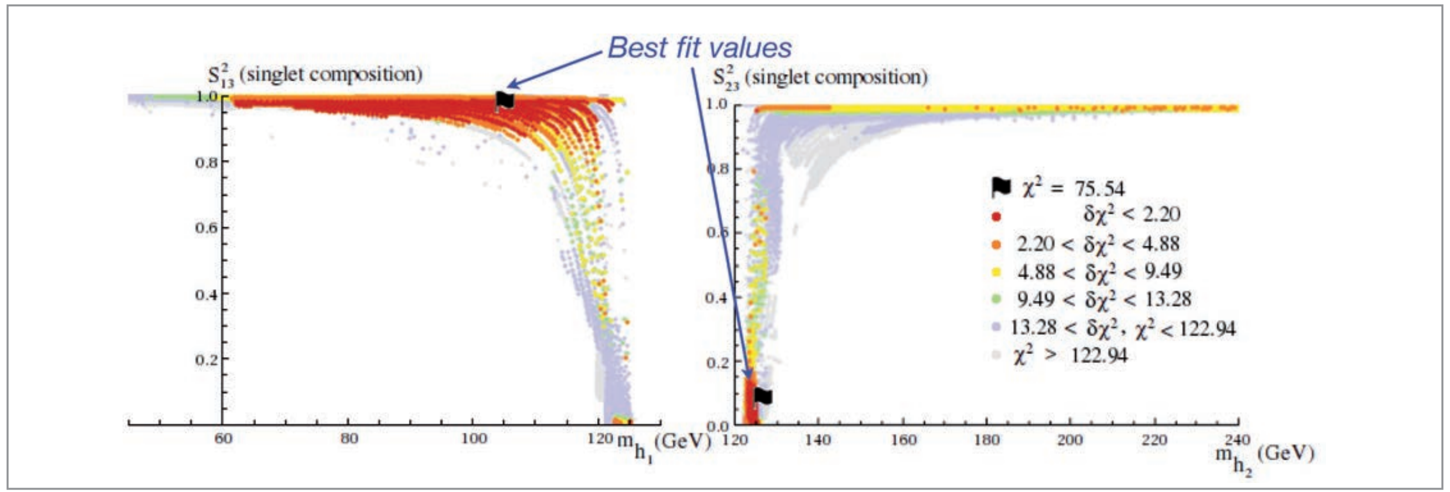

Figure 1
Results of a parameter scan in the next-to-minimal supersymmetric extension of the SM (NMSSM) for the two lightest neutral Higgs bosons. The regions that are preferred by the fit in the vicinity of the indicated best points are shown in red. The state at 125 GeV has a small singlet component and can be identified with the Higgs signal observed at the LHC. The model predicts an additional lighter Higgs boson, which has a mass of about 105 GeV in this case, with a large singlet component giving rise to suppressed couplings to the gauge bosons and fermions of the SM.

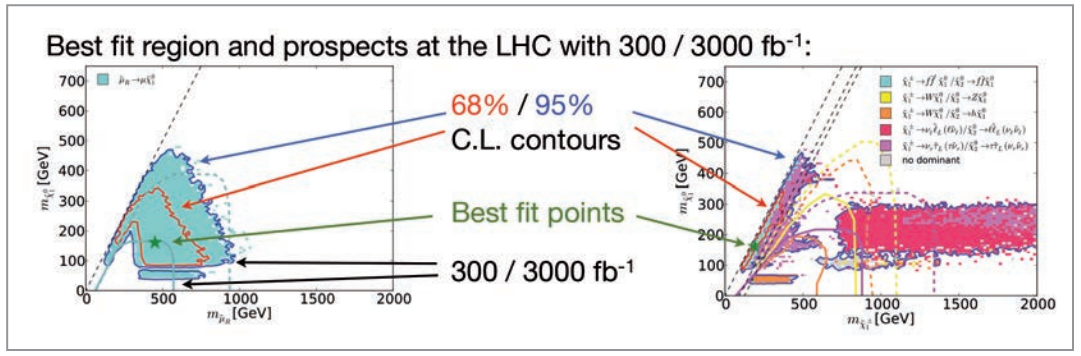

Figure 2
Preferred regions for superpartner masses obtained from a global fit in the minimal supersymmetric extension of the SM (MSSM). The best fit regions at (approximately) 68% and 95% confidence level are shown together with the sensitivities of the searches at LHC Run 2 with 300 and 3000 fb^{-1}.

Figure 1 shows, as an example, the case of the next-to-minimal supersymmetric extension of the SM (NMSSM), in which the signal observed at 125 GeV may generically appear not as the lightest but the next-to-lightest neutral state in the Higgs sector. Instead of the single Higgs boson of the SM, the Higgs sector of the NMSSM contains five neutral Higgs bosons. In the example shown, the Higgs boson at 125 GeV, which can be identified with the detected signal, is accompanied by a lighter Higgs boson with a mass of about 105 GeV. Because of its large singlet component, which suppresses the couplings to the gauge bosons and fermions of the SM, searches at the LHC and at previous colliders have not been sufficiently sensitive to detect such a light Higgs boson.

Concerning the superpartners predicted in supersymmetric models, Figure 2 shows the results obtained from a global fit in the minimal supersymmetric extension of the SM (MSSM) [2]. The simultaneous fit of ten free parameters has been carried out using the MasterCode framework. In this fit, limits from the searches for supersymmetric particles and Higgs bosons at the LHC and other colliders have been taken into account together with the experimental information on the detected Higgs signal as well as constraints from a comprehensive set of electroweak precision measurements, observables in the flavour sector, the dark-matter relic density and other cosmological data. The preferred regions at (approximately) 68% and 95% confidence level for the example of the lightest neutralino, the lightest chargino and the right-handed smuon are shown together with the dominant decay channels of the indicated particle and the search prospects at the LHC with 300 and 3000 fb^{-1}. While the LHC searches will have sensitivities for the superpartners of the quarks and the gluon up to 2–3 TeV, the plot shows that for the right-handed smuon almost the whole 95% confidence region can be covered with the highest achievable luminosities at the LHC. For the lightest neutralino and chargino, rather small mass values are preferred, with best fit values for the masses below 200 GeV, offering good prospects for a future electron–positron linear collider.

After a shutdown during which the LHC was upgraded to run at a collision energy of 13 TeV – the highest energy ever reached in a collider experiment to date – the LHC restarted operation in 2015. Since the amount of data accumulated in 2015 was relatively small, the sensitivity of many searches at 13 TeV was still below the limits that were achieved with more data at lower energies. This will change with the LHC run in 2016, where the expected amount of data will allow us to explore a wide new territory. This journey into the unknown will for sure enable us to exclude many of the possibilities for the physics underlying the fundamental laws of nature that exist according to our present knowledge, and it may lead to groundbreaking new discoveries.

The presented examples of an extended Higgs sector predicting additional Higgs bosons, which could be heavier but also lighter than the discovered signal at 125 GeV, and of new partner particles of the SM particles will be probed in the upcoming LHC run. The data taken in 2016 will also clarify the possible hint for a new particle at about 750 GeV related to an excess in two-photon final states in the 2015 data recently reported by ATLAS [3] and CMS [4]. If confirmed, the discovery of such a particle would have far-reaching consequences for our understanding of nature at its most fundamental level.

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Dynamical simulations of lattice QCD.

Working towards vanishing lattice spacing, infinite volume and physical quark masses

Simulations of quantum chromodynamics (QCD) on a discrete lattice have progressed substantially in the past decade, thanks not only to faster computers, but also to the development of algorithms that make better use of properties of the underlying physics of QCD. The John von Neumann Institute for Computing (NIC) group at DESY is engaged in two international lattice QCD simulation efforts, with the goal of ultimately being able to predict results at vanishing lattice spacing, in the infinite volume and at physical quark masses.

Decisive progress

Lattice QCD computations have come a long way from the parameters at which they were performed at the beginning of the 2000s to the control that can be achieved today. In these computations, QCD is formulated on a four-dimensional lattice with a lattice constant *a*, and to be able to treat it on the computer, only a finite volume is considered. As they are computationally much "cheaper", quark masses larger than the physical ones are frequently employed.

In a famous analysis presented at the Lattice 2001 conference in Berlin, Akira Ukawa of the University of Tsukuba in Japan predicted that with the algorithms of the time, even using the computers that we have today, it would be impossible to do computations at quark masses close to the physical ones, or on lattices fine and large enough to have the effects of finite lattice spacing and size under control. Realistic simulations seemed to be confined to the distant future.

Nowadays, a number of groups are performing computations on lattices that are fine and have a large volume, using quark masses close to their physical values. All these parameters are varied between simulations to study their impact. Not only have computers become faster – at least equally important are the many improvements to the algorithms: While in 2001 general-purpose algorithms were used, today's algorithms incorporate significant insight into the physics of the underlying system. They can, for example, separate long-distance physics from effects at short distances, and the computational cost of numerically solving the Dirac equation was reduced drastically by taking into account physical properties in the preconditioning of the system.

A lattice simulation is split in two parts: the generation of the gluon fields and a "measurement", i.e. the computation of observables for the generated fields. The NIC group at DESY contributes in leading positions to two such simulation efforts, which include members from all over Europe: the European Twisted Mass Collaboration (ETMC) and the Coordinated Lattice Simulations (CLS) initiative. Both are generating gluon field configurations at many values of the lattice spacing and volume and for different quark masses in order to study the effects of these parameters on the observables and to ultimately predict results at vanishing lattice spacing, in the infinite volume and at physical quark masses.

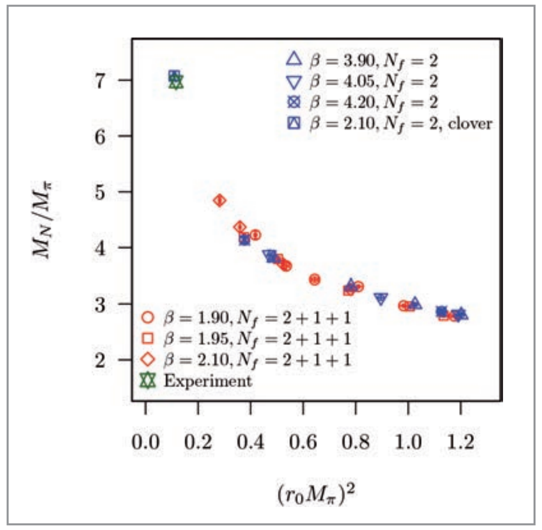

Figure 1

Ratio of the nucleon mass over the pion mass, indicating that in contrast to earlier simulations, the physical values are now met.

ETMC

Along with the $N_f = 2 + 1 + 1$ simulations pursued by ETMC in recent years, there has been a renewed interest in $N_f = 2$ flavour simulations [1]. The leading discretisation effects of twisted-mass fermions at maximal twist always come at $O(a^2)$, but by adding the clover term with a suitably tuned coefficient, their magnitude has been reduced. These simulations are performed at the physical value of the masses of the up and down quark.

So far, the simulations are restricted to one lattice spacing and a relatively small volume ($m_\pi L \approx 3$ at the physical point). However, varying the lattice size *L* allows the volume effects to be studied and estimates for their relevance to be given. An example of how much closer the current simulations are to the physical masses compared to previous simulations is given in Fig. 1.

CLS

CLS has a programme to simulate $N_f = 2 + 1$ flavours of non-perturbatively improved Wilson fermions. The project, which started in 2013, has by now generated lattices at four different lattice spacings between 0.085 fm and 0.05 fm and for a range of quark masses [2]. Both parameters can bring significant corrections with respect to the physical situation. An example is given in Fig. 2, where the product of the pion decay constant with the gluonic scale parameter $t_0 \approx (0.15 \text{ fm})^2$ is displayed. As can be seen, the accuracy that can be reached in such a quantity is at the level of 1%.

The extrapolation towards the continuum limit $a = 0$ fm agrees with leading scaling violations of $O(a^2)$, as expected for this non-perturbatively $O(a)$-improved theory. From Fig. 2, it is also obvious that only the fine lattices used here can lead to such a 1% accuracy – the points at 0.085 fm and 0.065 fm being approximately 5% away from the continuum result.

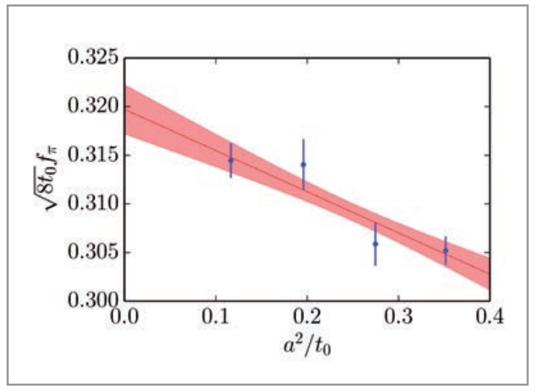

Figure 2

Continuum extrapolation of the dimensionless product $f_\pi (8t_0)^{1/2}$ of the pseudoscalar decay constant f_π and the gluonic scale t_0 along the line $m_\pi = m_K \approx 420$ MeV. Fine lattices are needed to reach a percent-level result.

Conclusion

These lattice simulations have laid the foundation for a large variety of projects currently pursued by a number of European groups. First results have been published, and many more are expected for the next years. The progress of the past decade highlights that it is worth investing in the improvement of computational methods, which now allow us to determine many quantities at percent-level accuracy.

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Cosmological Higgs–axion interplay for a naturally small electroweak scale.

New twist in the fruitful interplay of particle physics and cosmology

Recently, a new mechanism to generate a naturally small electroweak scale has been proposed, relying on the cosmological evolution of the Higgs mass parameter rather than new symmetries at the electroweak scale. The mechanism exploits the coupling of the Higgs boson to an axion-like field and a long era in the early universe where the axion unchains a dynamical screening of the Higgs mass. This very change of paradigm has dramatic implications for strategies to search for new physics linked to the understanding of the weak scale.

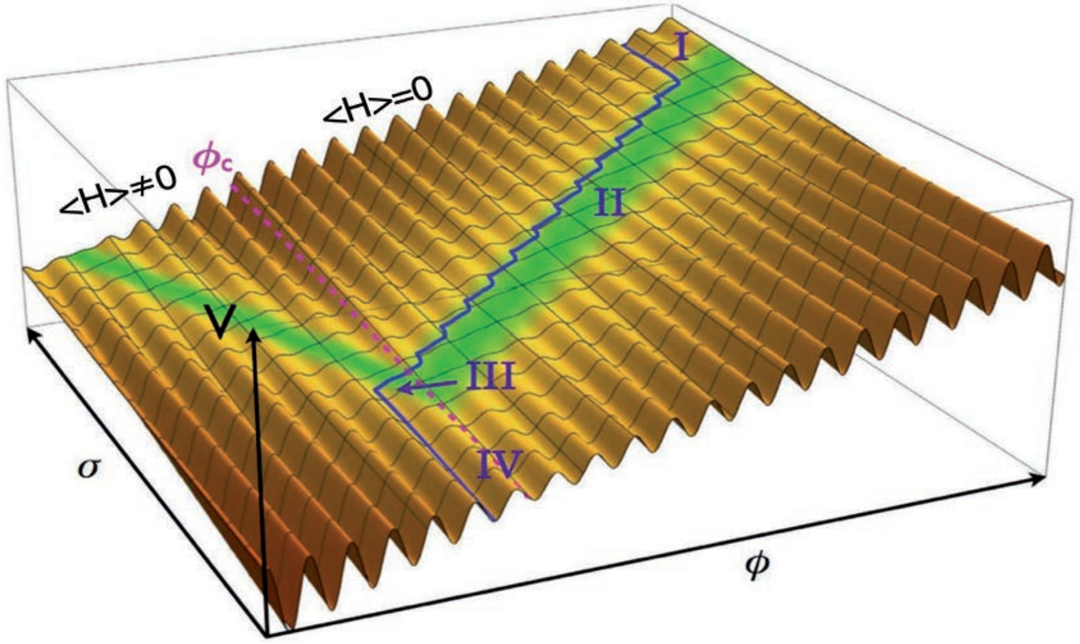

Figure 1

Scalar potential in the two-field $\{\varphi, \sigma\}$ plane. The blue line shows a possible slow-roll cosmological trajectory of the fields along the green band free of barriers. The fields start at stage I and end at stage IV, close to the pink critical line where electroweak symmetry gets broken.

Our understanding of nature is based on the empirical evidence that natural phenomena taking place at very different energy or distance scales do not influence each other. The parameters of an effective theory are *natural* if they do not require any special tuning of the parameters of the theory at higher energies. In the late 1970s and early 1980s, Kenneth Wilson, John Kogut and Gerard 't Hooft gave a quantitative meaning to this naturalness principle by demanding that all dimensionless parameters controlling the different effective theories should be of order unity unless they are associated to the breaking of a symmetry. The Higgs-boson mass and the value of the cosmological constant have long been recognised as two notorious challengers of this naturalness principle. Supersymmetry or Higgs compositeness are two prime examples of models trying to associate the Higgs mass to a small symmetry breaking.

In high-energy completions of the Standard Model where the Higgs potential can be computed in terms of new parameters in the underlying theory, understanding the hierarchy between the electroweak scale and the Planck scale M_{Pl} consists in understanding why the Higgs vacuum resides so close to the critical line separating the phase with unbroken (<*H*> = 0) from the phase with broken (<*H*> ≠ 0) electroweak symmetry. The Higgs mass squared parameter m_H^2 is expected to be of order M_{Pl}^2, and therefore either <*H*> ~ M_{Pl} or <*H*> = 0 depending on the sign of m_H^2. So, why are the parameters such as to lie practically on the critical line?

One simple way to understand this is to postulate that $|m_H^2|$ is field-dependent and that these fields have local minima populating the broken phase, then the cosmological evolution naturally settles them in a minimum close to the critical line. In Ref. [1], a new paradigm along those lines was implemented to explain the hierarchy between the electroweak scale and the cutoff scale of the Standard Model in terms of the cosmological evolution of the Higgs mass. In this framework, the Higgs mass squared parameter depends on the vacuum expectation value of an axion-like scalar field φ, which evolves in time in the early universe and eventually relaxes the Higgs mass squared to a small negative value. The key feature is that the time evolution is stopped by electroweak symmetry breaking, due to the back-reaction of the Higgs vacuum expectation value on the axion potential that necessarily stops its cosmological evolution close to the critical line where electroweak symmetry is unbroken (in analogy with the phenomenon of self-organised criticality in dynamical systems). This radically new approach to explain the smallness of the Higgs mass beautifully intertwines cosmology and particle physics. It is reminiscent of the relaxation mechanism proposed by Larry Abbott in 1985 for explaining the smallness of the cosmological constant. The idea that hierarchies in interaction strengths could have something to do with cosmological evolution actually goes back to Paul Dirac, who hypothesised in 1937 a relation between the ratio of universe sizes to the ratio of force scales.

In Ref. [2], we presented a new realisation of this idea with the new feature that it leaves no sign of new physics at the electroweak scale, and up to a rather large scale of 10^9 GeV. The aim was to offer a proof of principle that it is indeed possible to devise a model that dynamically generates a large mass gap between the Higgs mass and the new-physics threshold. The only new states are ultralight axion-like states, φ and σ, with masses below the weak scale and very weakly coupled to the Standard Model, making them very difficult to detect at present and future experiments. Interestingly, they could provide the source of dark matter in the universe. Part of the parameter space of this model can be tested through observations of the diffuse gamma-ray backgrounds, black-hole superradiance, and even in pulsar timing arrays. In addition, there is a rather rich big bang nucleosynthesis and cosmic microwave background phenomenology, which motivates further studies.

These ideas represent a new twist in the long and fruitful history of the interplay between particle physics and cosmology, and many variants could be envisioned (for instance, the axion field could be scanning the supersymmetry-breaking scale rather than the Higgs mass parameter). While in the past, particle physics has been a crucial ingredient to understanding the cosmological history of our universe, if these new ideas were correct, cosmological evolution would be a key ingredient in the understanding of some key parameters of particle physics.

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Quantum systems without scale.

Solving the hydrogen atom(s) of quantum field theory

Quantum systems that look the same on all length scales may provide important insights into more realistic models, at least at sufficiently low energies. The situation can be compared to the highly symmetric hydrogen atom, whose solution prepared the grounds for a deep understanding of the entire periodic table of elements in the early days of quantum physics. Scientists from all over the world, including a group at DESY, are joining forces to address the important challenge of solving such scale-invariant quantum field theories through a combination of new mathematical developments and the investigation of some concrete models.

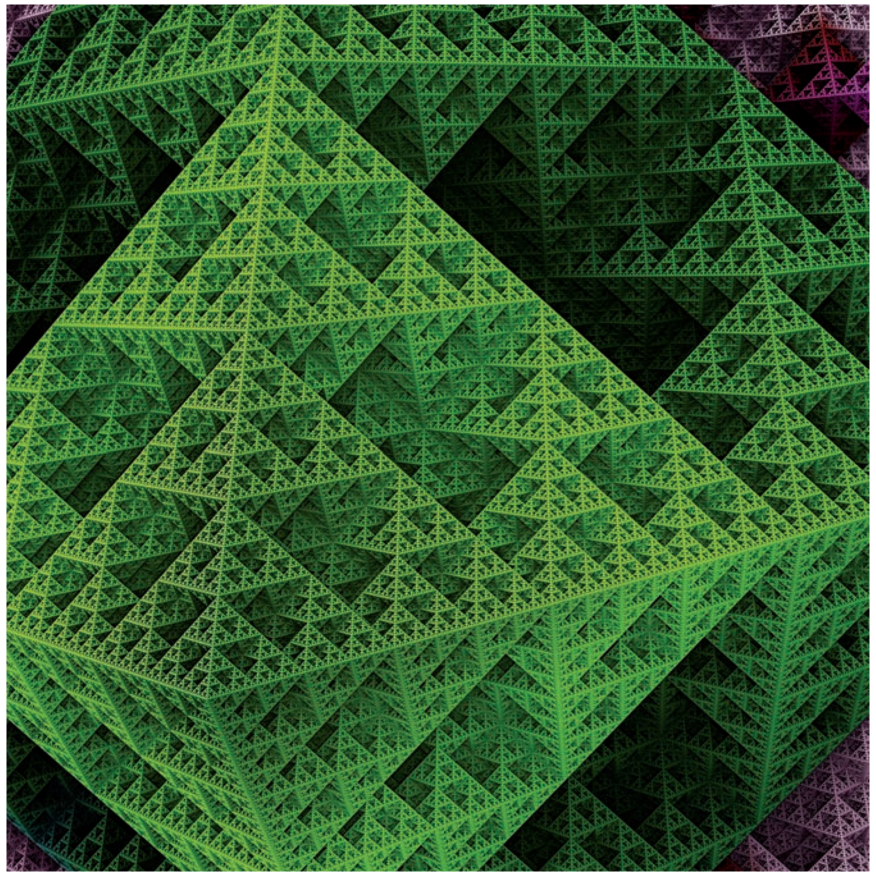

Figure 1

Scale-invariant quantum systems resemble fractals in that they look the same no matter how much one zooms in.

Many systems in physics possess one or more scales that determine their behaviour. As an example, let us consider quantum chromodynamics (QCD), the theory of strong interactions. The characteristic energy scale of QCD is a few hundred MeV. It separates the low-energy regime of hadronic bound states, such as protons, neutron, pions etc., from the high-energy description of QCD in terms of (weakly) interacting quarks and gluons. So the physics of QCD depends on the scale, i.e. QCD is not scale-invariant.

A scale-invariant system looks quite different: No matter how much you zoom into the details of the system, it will always appear to be the same. A useful image to keep in mind is that of a fractal, which is infinitely self-similar when magnified (Fig. 1). Quite a few scale-invariant quantum systems have been produced and investigated, in particular in condensed-matter physics. There are materials that, in a carefully adjusted (critical) external magnetic field or doping density, display scale invariance at zero temperature. If one changes the conditions a little bit compared to the critical ones, scale invariance may no longer be exactly realised. Yet the scale-invariant model can still be a very good approximation and explain features of systems in the vicinity of the critical point.

In particle physics, we do not have the same control over parameters. For example, we cannot simply adjust the value of the electric charge to drive a system into a more accessible regime. On the other hand, even without such possibilities, the behaviour of real-life quantum field theories may still be well described by a scale-invariant model as long as one is interested in physics well below the characteristic scale of the system. Even in the “vicinity” of QCD or at least QCD-like theories, one can find scale-invariant quantum theories that could capture the behaviour at sufficiently low energies.

What makes this way of addressing quantum systems so powerful is that scale-invariant systems seem much more accessible than generic quantum field theories. Computations in QCD, for example, quickly become so complicated that making reliable predictions even at high energies requires tremendous experience and computer power, and low-energy physics can only be addressed through numerical simulation on the lattice. On the other hand, beautiful and powerful novel methods were devised for scale-invariant theories, such as the celebrated holographic duality with string theory in Anti-deSitter space or the so-called conformal bootstrap, a programme that was designed in the 1970s but that is only now beginning to bear fruit beyond two-dimensional models.

To fully appreciate the recent progress, let us briefly recall a useful analogy from atomic physics where the hydrogen atom, which can be solved through the aid of its symmetries, taught us very important lessons about the entire periodic table. In the solution of the hydrogen atom, rotational symmetry plays an important role. All quantities factor into pieces that are determined by the mathematics of the rotation group and a much smaller number of reduced matrix elements encoding all the dynamical content of the hydrogen atom. This rotational symmetry is further enhanced by the famous Runge–Lenz vector. With its help, the spectrum of the hydrogen atom can be determined, based on algebra alone without ever solving the Schrödinger wave equation.

The situation with scale-invariant quantum systems is very similar, except that the relevant mathematics is not fully developed yet. As in atomic physics, the correlation functions of scale-invariant quantum field theories factor into building blocks from the mathematics of the so-called conformal group and some dynamical data that is similar to the reduced matrix elements of atomic physics. In Ref. [1], we addressed the group-theoretic building blocks and uncovered a very remarkable connection with a quantum mechanical Schrödinger problem. In fact, we were able to show that the most important mathematical building blocks of scale-invariant quantum systems may be interpreted as wave functions of a very special interacting two-particle system. It belongs to a family of systems that was first considered by Francesco Calogero, Jürgen Moser and Bill Sutherland in the early 1970s. The case that happens to appear in scale-invariant quantum systems has been studied extensively, both in physics and in mathematics. It actually has many features in common with the quantum mechanics of the hydrogen atom, including a Runge–Lenz-like symmetry enhancement. This puts the understanding of the group-theoretic building blocks in a scale-invariant quantum system on firm mathematical grounds and will help to address the dynamical content of such theories, just as in the hydrogen atom.

Besides such investigations concerning the mathematical foundations of scale-invariant quantum systems, members of the DESYtheory group have also continued to pursue the analysis of scattering amplitudes in the maximally supersymmetric four-dimensional Yang–Mills theory. This model is one of the most famous examples of a scale-invariant quantum system. In Ref. [2], we were able to determine the high-energy limit of two-loop amplitudes for any number of external gluons, at least up to terms of lower mathematical complexity. This represents an important progress towards the ultimate goal of finding all-loop expressions for such amplitudes.

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Under the spell of gauge theory.

Holography, integrability and exact results

The DESY theory group is investigating methods and techniques that could be used to formulate gauge theories with less supersymmetry and obtain exact results for more realistic gauge theories.

The physical world as we understand it today consists of (matter) particles that interact through four different types of interactions. Three of these interactions are described by gauge theories: electromagnetism, weak interactions and strong nuclear interactions. The fourth interaction, gravity, does not quite fit in this picture. Gauge theories are compatible with quantum mechanics, while gravity is not.

The quantum theory of strong interactions, quantum chromodynamics (QCD), asserts that nuclear matter is composed of quarks and gluons. However, up to date, it has not been possible to explain the experimental fact that quarks can never be isolated, but are always confined inside the nucleons. This phenomenon, called confinement, is one of the biggest open problems in theoretical physics. It relates to the general problem of not knowing how to handle gauge theories that interact strongly (at strong coupling).

Significant progress has been achieved in the study of gauge theories in the last decades. Theoretical physicists have been able to not only learn about the strong coupling regime of gauge theories using holography (the anti-de Sitter/conformal field theory correspondence, AdS/CFT). They could also calculate a plethora of processes exactly, thanks to the discovery of hidden symmetries (integrability) and other modern mathematical techniques (like localisation), which previously seemed unreachable.

Holography or gauge theory/gravity duality is probably one of the deepest ideas in theoretical physics, in that it gives us the possibility not only to attack the notoriously difficult problem of dynamical properties of non-Abelian gauge theories, but also to understand quantum gravity; in principle, gauge theories provide a reformulation of gravity as an “emergent” phenomenon. The AdS/CFT correspondence is a concrete example of a gauge theory/gravity duality and provides tools to explore strongly coupled gauge theories using weakly coupled gravity (string theory), and, inversely, to learn about the non-perturbative regime of string theory using weakly coupled gauge theory.

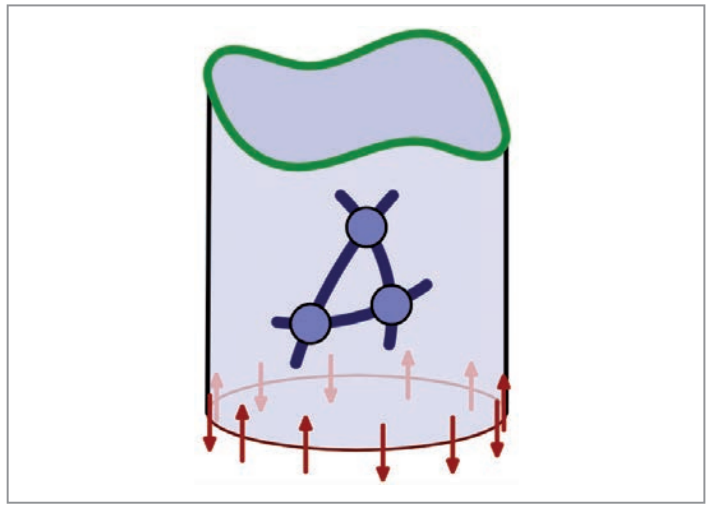

Figure 1

The AdS/CFT correspondence for $N = 4$ SYM could have been discovered “bottom-up”, from the perturbative analysis of the field theory dilation operator. At one loop, the dilation operator can be mapped to the Hamiltonian of an integrable spin chain, while at strong couplings it captures the energies of string states.

But how general is the AdS/CFT correspondence? There are many “phenomenological” models inspired by the AdS/CFT correspondence (which give, for example, a qualitative geometric understanding of confinement and chiral symmetry breaking), but there is quantitative evidence of an “exact” duality only for a sparse set of four-dimensional gauge theories. The basic paradigm is the duality between the maximally symmetric gauge theory in four dimensions, $N = 4$ super Yang–Mills (SYM), and a particular closed string theory on a given geometric space. Although there are several other conjectured “exact” dualities, they are all close cousins of this basic paradigm and as unrealistic as the $N = 4$ SYM mother theory is.

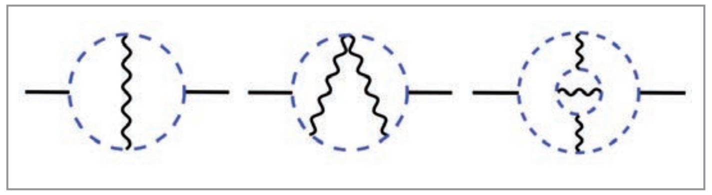

Figure 2

Sample Feynman diagrams that contribute to the relative (between $N = 2$ and $N = 4$ SYM) finite renormalisation of the coupling constant $\lambda \to f(\lambda)$

One of the main objectives of our research within the DESY theory group is to search for exact string dual pairs for gauge theories that are more realistic and have less supersymmetry. In Ref. [1], we made some progress in this direction. We studied what is arguably the simplest gauge theory outside the $N = 4$ universality class, namely $N = 2$ superconfomal QCD, and found evidence that its string dual is a non-critical string background.

With regard to understanding AdS/CFT but also to obtaining exact results, the discovery of integrability and the application of the techniques it comes with have proven extremely powerful tools. Integrability refers to the fact that the theories under study have more symmetries than originally expected. They have enough symmetry for us to be able to completely solve them. For $N = 4$ SYM, the discovery of integrability led to the complete determination of the exact operator spectrum of the planar $N = 4$ SYM. What’s more, the same integrability structures arise both on the gauge theory and the dual string theory side, allowing for a very precise check of the AdS/CFT correspondence. In fact, even though it historically happened otherwise, the AdS/CFT correspondence for $N = 4$ SYM could have been discovered “from the bottom up”, i.e. from the perturbative analysis of the gauge theory dilation operator.

It is very important to understand which particular properties of a gauge theory make it integrable, how necessary planarity, conformality and supersymmetry are (and how much supersymmetry is needed). Some answers to these questions have already been obtained by studying the structure of the dilation operator (Hamiltonian) in sectors in which the operators are composed of fields only in the vector multiplet. In Ref. [2], we were able to show that these sectors have Hamiltonians that are identical to the $N = 4$ SYM to all loops up to a redefinition (renormalisation) of the coupling constant $\lambda \to f(\lambda)$ and are thus integrable by just planarity, gauge invariance and only $N = 1$ supersymmetry. On the other hand, sectors with operators that include bi-fundamental hypermultiplets (quarks) have Hamiltonians and scattering matrices that are very particular deformations of the $N = 4$ ones.

Finally, another powerful technique that leads to exact results in gauge theories is localisation. Thanks to the groundbreaking work of Vasily Pestun, we can now compute many interesting observables to all orders in the coupling constant. What is more, localisation is a technique that is not bound to the planar limit and allows us to obtain results for any number of colours. In Refs. [3,4], we were able to compute a few different observables like Wilson loops, the radiation emitted by an accelerating heavy quark, as well as the entanglement entropy for a large class of $N = 2$ theories. Comparing these results with their $N = 4$ SYM counterparts, we discovered that they can be obtained to all loops from the $N = 4$ ones by the same replacement $\lambda \to f(\lambda)$ as above, which is equal to the relative renormalisation between the $N = 2$ and the $N = 4$ gluon propagator.

However, the majority of these impressive results have been obtained only for $N = 4$ SYM, the most symmetric and most unrealistic gauge theory in four dimensions. We aim to break this impasse and investigate which of the methods and techniques described above, or generalisations of them, can be used to formulate gauge theories with less supersymmetry and obtain exact results for more realistic gauge theories. We believe that our field of research is by now mature enough to move forward and unravel the mysteries of gauge theory.

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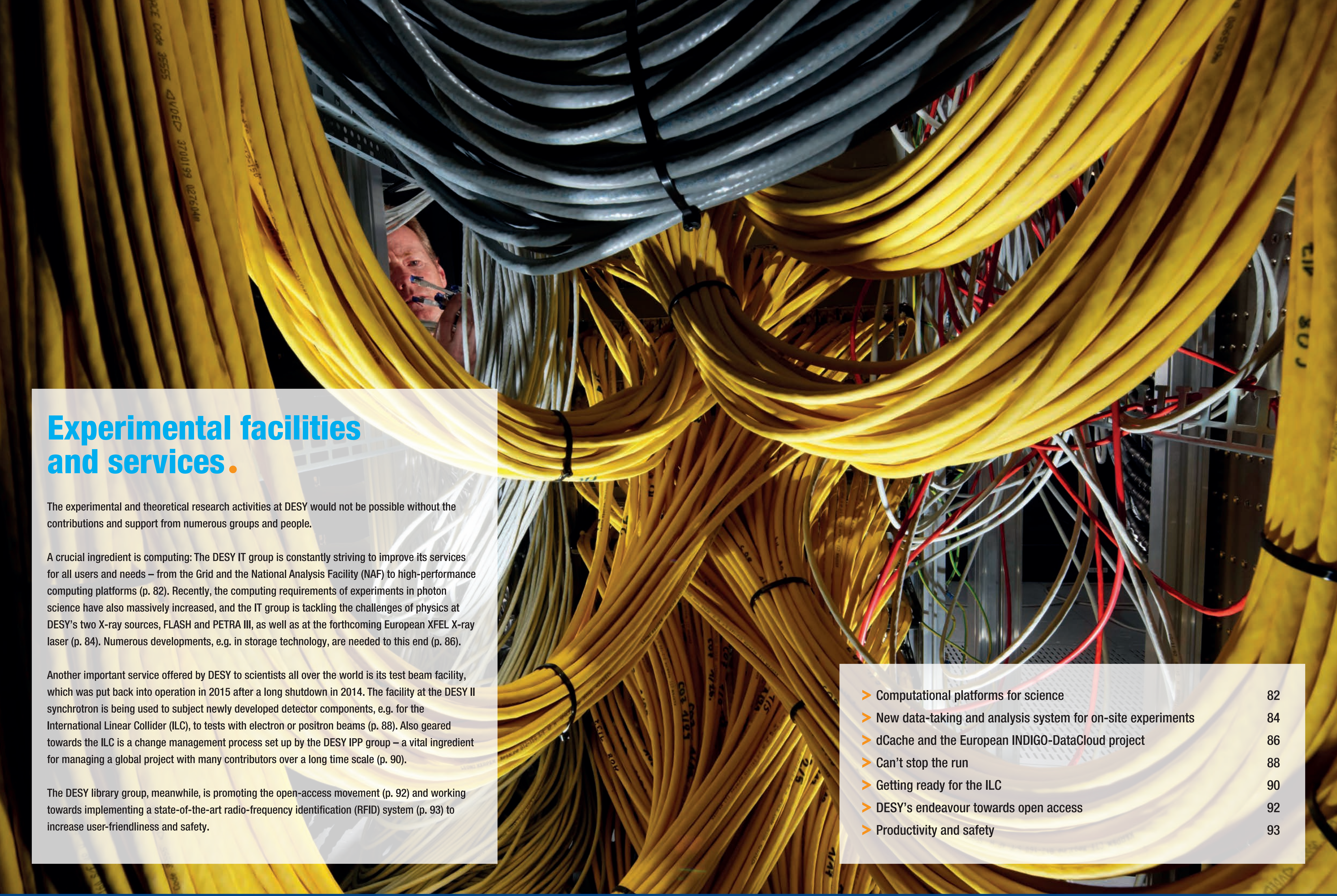

Experimental facilities and services.

The experimental and theoretical research activities at DESY would not be possible without the contributions and support from numerous groups and people.

A crucial ingredient is computing: The DESY IT group is constantly striving to improve its services for all users and needs – from the Grid and the National Analysis Facility (NAF) to high-performance computing platforms (p. 82). Recently, the computing requirements of experiments in photon science have also massively increased, and the IT group is tackling the challenges of physics at DESY's two X-ray sources, FLASH and PETRA III, as well as at the forthcoming European XFEL X-ray laser (p. 84). Numerous developments, e.g. in storage technology, are needed to this end (p. 86).

Another important service offered by DESY to scientists all over the world is its test beam facility, which was put back into operation in 2015 after a long shutdown in 2014. The facility at the DESY II synchrotron is being used to subject newly developed detector components, e.g. for the International Linear Collider (ILC), to tests with electron or positron beams (p. 88). Also geared towards the ILC is a change management process set up by the DESY IPP group – a vital ingredient for managing a global project with many contributors over a long time scale (p. 90).

The DESY library group, meanwhile, is promoting the open-access movement (p. 92) and working towards implementing a state-of-the-art radio-frequency identification (RFID) system (p. 93) to increase user-friendliness and safety.

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Computational platforms for science.

Serving all DESY user communities

Today’s demands for computational platforms for science are diverse in terms of communities, quantity and usage profiles. To best serve these demands, DESY has set up different platforms, each with its own strength. While the Grid and the National Analysis Facility (NAF) platforms were described in detail in previous annual reports, this article focuses on the DESY High-Performance Computing (HPC) platform, which, over the past few years, has been successfully used and constantly enlarged to map rising demands.

Overview

In the past decade, the DESY Grid sites [1] have played a major role as members of the European Grid Infrastructure (EGI) [2] and as Tier-2 centres in the Worldwide LHC Computing Grid (WLCG) [3]. The facilities, complemented by the NAF [4], allowed physicists from ATLAS, CMS and LHCb as well as from the ILC community and Belle II to benefit from first-class computing and storage resources that have been reliably operated over the years.

In 2011, the DESY IT group started to commission an HPC cluster [5] for dedicated applications, such as plasma wakefield simulations, which could not be served by the existing Grid and NAF infrastructure. The continuously growing HPC cluster and the associated fast storage systems allow scientists from the large variety of scientific communities at DESY to perform high-performance computing tasks.

Grid and NAF

The DESY Grid infrastructure provides a large portfolio of computing and storage services and handles user authorisation by way of the Virtual Organization Management Service (VOMS). Hence, no DESY account is required to access the Grid. Other services are distributed file catalogues and job workflow management. For the NAF, specialised DESY accounts are automatically created via a self-registration portal, based on Grid certificates and the membership in the virtual organisations that are supported by DESY.

The actual workhorses are the large Grid batch systems and the high-capacity dCache storage elements in Hamburg and Zeuthen. These resources, pooled together in one common infrastructure in Hamburg and in Zeuthen, serve different projects:

- WLCG Tier-2 for the ATLAS, CMS and LHCb experiments
- Additional share of resources for researchers of German institutes participating in the Helmholtz Alliance “Physics at the Terascale” – mainly ATLAS, CMS and ILC
- Legacy HERA analysis effort
- Current high-energy physics (HEP) collaborations beyond LHC: ILC and BELLE
- Astroparticle physics: Tier1 for IceCube computing, CTA simulations and analysis
- Numerous small communities

The NAF has been in operation at DESY since 2007. It complements the DESY and German Grid resources. The facility was set up in the framework of the Helmholtz Alliance “Physics at the Terascale” and initially intended for researchers of German institutes working for ATLAS, CMS, LHCb and ILC. In the meantime, however, legacy HERA analysis efforts are also being supported, as well as German Belle activities.

As the NAF supports direct interactive access, it allows for fast-response workflows necessary for development, debugging, testing and small-scale private production – important complements to the large-scale Grid infrastructure. Regarding the dCache storage elements, NAF and Grid users are provided with identical access rights; however, NAF users are offered additional fast scratch space for more direct and interactive work, realised in IBM SONAS technology.

Although there is a natural difference between job profiles running on the NAF and those running on the Grid, there are convenient commonalities arising from the intrinsic trivial parallelism in most HEP data analysis and simulation jobs.


Figure 1
DESY provides first-class computing and storage resources to many different communities through its Grid centre, the National Analysis Facility and the Maxwell HPC cluster.

This trivial parallelism is based on the fundamental independence of individual HEP physics events – an independence that can be exploited during both simulation and data analysis. Consequently, no communication between different jobs is needed.

Historically, HEP analysis jobs only utilised a single CPU core. However, with the availability of affordable multicore CPU systems and the support of multithreaded workflows in physics frameworks, an increased number of HEP jobs can now efficiently run on multiple computing cores at the same time.

High-performance computing

At DESY in Hamburg, a new HPC system called “Maxwell” was set up in the past five years and will grow following user demands. It is based on 16-node AMD Interlagos technology, totalling 1024 CPU cores and 3072 GByte of memory, and the low-latency QDR InfiniBand interconnect.

Besides a very fast local cluster storage system, users have access to the DESY dCache systems for experiment data and permanent file space. Many different applications have been run on the cluster. Amongst the first ones were simulations of plasma wakefield acceleration (Fig. 2), based on particle-in-cell methods using the software OSIRIS, and radiation simulations for European XFEL, also based on particle-in-cell methods using the software GENESIS. Beside these simulation codes, the HPC system is also intended to serve analysis codes, as these too will be parallelised in the future due to the amount of data being processed. In 2015, older systems have been replaced by eight new nodes (512 cores) in the HPC cluster for lattice QCD calculations and simulations in theoretical astroparticle physics in Zeuthen.

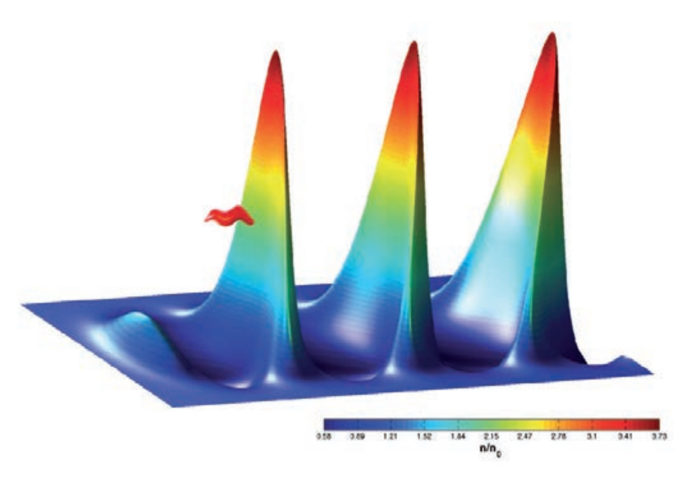

Figure 2
Visualisation of a plasma wakefield simulation carried out on the new HPC cluster at DESY

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[3] http://wlcg.web.cern.ch/
[4] http://naf.desy.de/
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New data-taking and analysis system for on-site experiments.

Based on high-performance computing industry components

Data taking and analysis infrastructures in particle physics have evolved over many years into a “well-known-problem” domain. In contrast, third-generation synchrotron radiation sources as well as existing and upcoming free-electron lasers are confronted to an explosion in data rates and volumes primarily driven by recent developments in 2D/3D pixel array detectors. The next generation of these facilities will produce data at a rate upwards of 50 GB/s. This article presents the selected components, overall architecture and experience gained with the new data-taking and analysis architecture and services deployed at DESY’s PETRA III synchrotron radiation source, which have been in full operation since April 2015.

Technology choices for the new system were undertaken over a period of 10 months. The work involved a close collaboration between the central DESY IT group, the beamline control group and beamline support staff. In addition, a cooperation on core technical and technological areas was established between DESY-IT and IBM to include industrial R&D experience and skills. The chosen approach integrates leading-edge high-performance computing (HPC) technologies for storage systems and protocols. In particular, the solution uses a multiple-file-system instance with a multiple-protocol access, while operating within a single name space and with automated data management operations behind the scenes, for archive and data export purposes.

Challenges

The development of detectors at third-generation light sources is currently outpacing the development of experimental methods and data acquisition capabilities. Single clients will produce data rates of 0.5 GB/s, and the next generation is already pushing for 6 GB/s. For 30 beamlines, the expected averaged aggregated rate is 50 to 80 GBs/s, depending on detector deployments.

In addition, measurements last from a few hours to a few days, resulting in many single data sets of up to tens of terabytes each. From next-generation detectors, multi-GB/s data rates are expected, spread over many 10-GE connections.

Furthermore, these facilities are characterised by a very dynamic experimental setup with inherent burst nature and a very heterogeneous environment regarding technology, social context and requirements. To support better data control and shorter turnaround cycles, the new system has to allow high-speed access within seconds after data production by the detector. Within minutes, the data must be ready for full-scale data analysis using multiple CPUs, and within hours, they must be available for archiving to tape media and for external (remote) access.

Industry cooperation

To benefit from high-end technologies and the experience of the HPC market, DESY started a cooperation with IBM to develop and build a system based on IBM’s General Parallel File System (GPFS) technology. IBM sponsored its related internal activities for beta hardware and, more importantly, the time various teams in its R&D groups spent working on the project.

The new system

Figure 1 depicts the overall composition of the new system. Together with the transactional characteristics for starting and ending a new experiment, it covers the whole life cycle for experimental data taking and analysis. During data taking, the controlled access is through the Network File System (NFS), Server Message Block (SMB) and a specialised ZeroMQ-based channel. The initial physical media for taken data are solid-state drive (SSD)-based storage pools, allowing high bandwidth and low-latency access. Getting matured, data migrate to spinning-disk-based resources, still residing in the beamline file system (Beamline-FS) specially configured for that purpose (access rights and modes, IO pattern and access protocols). After a few minutes of data aging, the next automated process generates copies to the Core-FS, built with a different configuration to support full authentication, access control list (ACL), high availability etc.

Once the experiment ends and all data from the Beamline-FS are proved to be copied over to the Core-FS, all resources at the Beamline-FS will be removed, readying it for the next experiment at the same experimental station. As soon as the data arrive in the Core-FS, they can be accessed (at very high speed) in parallel from the analysis cluster (Windows & Linux platform), automatically copy-selected to the tape archive (using the existing on-site dCache system installations and preserving ACLs) and made available for external access through HTTP (browser-based access) and FTP. An additional benefit of using dCache as an archive is the ability to allow seamless and controlled data access, through NFS, to the archived data to and from any host on site.

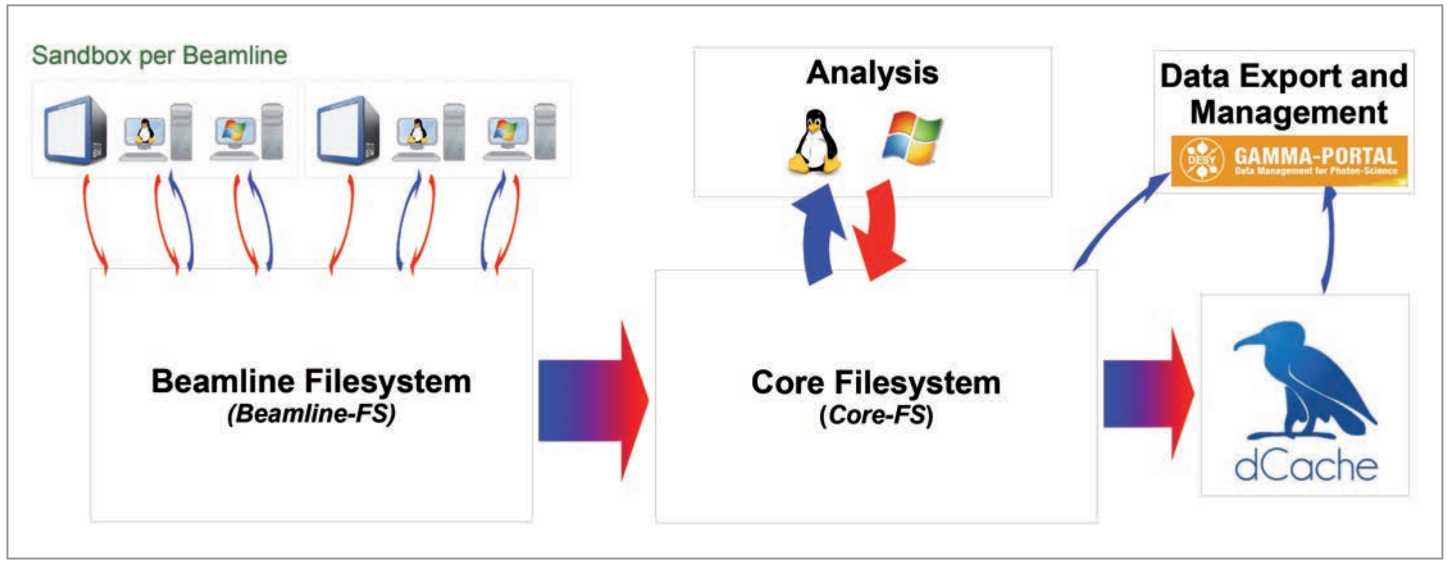

Figure 1

New data-taking and analysis architecture and services deployed at DESY’s PETRA III synchrotron radiation source

Initial deployment and further developments

The new system has been initially deployed for experiments at the on-site PETRA III synchrotron radiation source and used in full operation since April 2015. Since then, in-depth tests have been performed by the European XFEL computing group to verify the applicability of this architecture as a blueprint for the data-taking and analysis system at the European XFEL X-ray free-electron laser, which is currently under construction. Initial deployments for the European XFEL system have already started and will be the main focus in early 2016. Both PETRA III and European XFEL will require even higher data rates and volumes compared to existing experimental setups and detector technologies. The IO profile is expected to change with higher demands in burst capturing and recursive selected reads while data analyses run.

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dCache and the European INDIGO-DataCloud project.

Incorporating Cloud mechanisms into DESY computing services

In 2015, the dCache.org collaboration further consolidated its leadership role in the worldwide management of scientific data by incorporating cloud mechanisms in the context of INDIGO-DataCloud (or INDIGO for short), a large European Horizon 2020 project. dCache and INDIGO, in collaboration with the Research Data Alliance and the Storage Networking Industry Association, are pushing forward an approach to programmatically support “quality of service” in storage and “data life cycle management” in public and private systems.

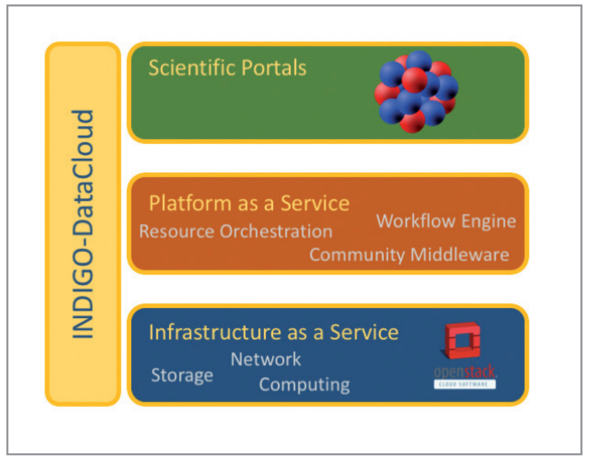

Figure 1

Virtualised service layers, supported by INDIGO-DataCloud

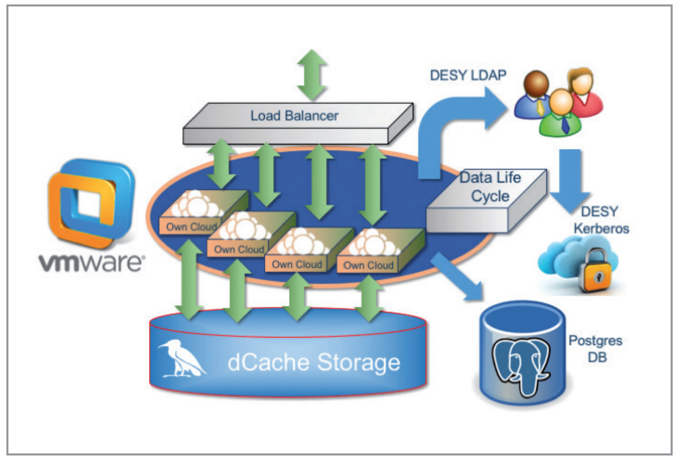

Figure 2

Design of the OwnCloud-dCache hybrid system

The INDIGO-DataCloud project

The INDIGO-DataCloud project was launched in April 2015. It is funded in the context of the European Horizon 2020 framework programme; 26 partners from 11 European countries, including DESY, are receiving more than 11 million euros in total, spread over 30 months. The extremely ambitious objective of the project is to develop an open-source platform for computing and data, deployable on public and private cloud infrastructures.

Requirements and use cases have been collected from 11 communities, either directly associated to INDIGO or indirectly represented by the European Grid Infrastructure (EGI), which is itself an INDIGO partner. The project aims at making computing middleware a commodity product – easy to deploy and easy to use by scientific communities, ranging from very big initiatives like the Human Brain Project down to very small projects comprising only a handful of scientists. Especially initiatives from the “long tail of science” can’t afford spending time and resources on the development of computing middleware.

Although at present almost all components to create a scientific-community-specific computing solution are available, it still takes significant efforts to compose a scalable computing platform serving the needs of the average scientist. Infrastructures such as the Google and Amazon public clouds, the Telekom cloud or the traditional Grid systems, provided by EGI or the US Open Science Grid (OSG), offer storage and computing facilities, but not solutions. Sophisticated open-source cloud management software stacks, like OpenStack and OpenNebula, can be operated on those platforms, but skills are needed to connect them to scientific portals and to make them robust and easy to use.

This is where INDIGO-DataCloud steps in. Starting from the portals (the entry point for the scientists) via “platform as a service” components (which execute the scientific workflow) down to the infrastructures (where the actual computing and storage horsepower is provided), INDIGO offers complete solutions that only have to be customised using standardised orchestration languages. The final version of the INDIGO software stack will allow computing and storage resources from different cloud providers – private and public – to be federated, enabling the use of infrastructure brokers to get the best value for money without changing neither the user portal nor the experiment-specific analysis software.

INDIGO and dCache

dCache.org started in 2000 as a collaboration of computer scientists from Fermilab, the Nordic Data Grid Facility (NDGF) and DESY. dCache.org is developing and deploying dCache, a highly scalable open-source storage system, which is being continuously improved to match the data management requirements of the majority of scientific communities. dCache supports a variety of storage media, including spinning disks, tape archives and solid-state media. It provides access to data through standard industry protocols, like NFS4.1/pNFS, GridFTP and http/WebDAV, and through community-specific mechanisms. The dCache technology is deployed at about 70 sites worldwide, with single sites reaching the 20 PB mark.

Financial support is essentially provided by the three main partners. Over the previous decade, however, dCache.org acquired significant funding from European and German projects and initiatives, such as D-GRID, the European Middleware Initiative (EMI) and the Helmholtz Large Scale Data Management and Analysis project (LSDMA). In April 2015, dCache.org, through DESY, became a partner of the INDIGO-DataCloud project, within which it will receive funding of approximately 800 000 euros over the project lifetime of 30 months. Within INDIGO, dCache.org is mainly involved in providing storage “infrastructure as a service” (IaaS) and, to some extent, higher-level storage federations, generally referred to as “platform as a service” (PaaS).

The main objective for dCache.org within INDIGO is to extent the dCache feature set by offering fine-grained “quality of service” (QoS) and “data life cycle” functionality accessible through cloud protocols. The work is based on the observation that modern scientific communities envision storing their data in public or private clouds, brokering the price based on different service-level agreements (SLAs). A typical scientific use case would be to store data, produced by a data source like a particle detector, a CCD chip or an antenna, on high-speed, low-latency media for fast analysis. As a next step, the data could be moved to media more appropriate for wide-area transfers and finally migrated to long-term archives.

As with the modern cloud offerings the data location, the associate SLA and the prices are brokered, storage systems must expose their supported storage quality properties through a well-defined protocol or application programming interface (API). Moreover, cloud storage systems must allow the user or the higher-level platforms to select different storage qualities and to migrate data between those. A popular example is Amazon S3 for high-throughput, low-latency storage versus Amazon Glacier for archival storage.

Within INDIGO, dCache.org is in charge of defining QoS criteria under the umbrella of the international Research Data Alliance (RDA). Currently, an RDA QoS working group is being created, composed of representatives from scientific communities and laboratories. To standardise appropriate QoS negotiation protocols, dCache.org is collaborating with the Storage Networking Industry Association, a non-profit trade organisation. The current proposal is to extend the already existing Cloud Data Management Interface (CDMI) protocol for the described purposes.

dCache.org and the big-data cloud at DESY

Historically, dCache has been used as a scientific storage management system, giving access to experiment frameworks through either community-specific protocols or industry standards like GridFTS, NFS or HTTP. However, with the upcoming importance of cloud and big-data computing, dCache has been extending its services in that direction, incorporating cloud protocols like WebDAV and CDMI, similar to public cloud services like Amazon or Google or scientific private clouds like the EGI Federated Cloud (FedCloud).

However, besides big-data access to storage, today’s scientists are expecting DropBox-like features – essentially, to be able to synchronise their computers and mobile devices with cloud systems and share data with friends, colleagues or the public in an easy and intuitive way. To provide this functionality at DESY, dCache.org integrated OwnCloud with dCache, where dCache provides the mass storage capabilities and OwnCloud enables sync-and-share functionalities. In 2015, the dCache-OwnCloud hybrid system underwent an intensive preproduction phase. Based on user feedback, dCache.org and the DESY Information Fabrics team will improve the current service and bring the system into production in 2016.

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OwnCloud: https://owncloud.org/
dCache: https://www.dcache.org/

Can’t stop the run.

DESY II test beam facility is back in operation

DESY operates the DESY II test beam facility for detector R&D projects from a wide range of communities. After a long shutdown in 2014, the facility re-opened for user operation in January 2015; since then, it has been as popular as ever. User groups of all sizes pursuing projects ranging from the upcoming LHC upgrades to generic R&D made extensive use of the facility, appreciating the big improvements implemented in the 2014 shutdown. User operation in 2016 will resume in March, and many weeks of beam time are already booked.

Introduction

The DESY II test beam facility is located on the DESY Hamburg site and makes use of the DESY II synchrotron, which is predominantly serving as an injector for the synchrotron radiation source PETRA III. DESY II delivers electron and positron beams of 1–6 GeV to three test beamlines via a secondary target.

All beamlines are fully controllable by the users. The ease of use and the excellent infrastructure available to the user groups make the DESY II test beam a very popular facility with a global user community. The DESY test beam team constantly adds improvements to the beamlines and strives to keep it a world-class facility for detector R&D. With the AIDA-2020 project, the EU continues to support test beam activities around Europe, including at the DESY facility.

AIDA-2020

The AIDA-2020 project, which is funded within the Horizon 2020 framework programme of the EU, started in June 2015. AIDA-2020 will run for four years, bringing together the leading institutes and infrastructures in the field of detector development. It comprises 38 institutes from 24 countries plus CERN.

Besides common research projects and networking activities, AIDA-2020 supports access to the DESY II test beam facility for testing detector systems under the project’s transnational access programme. This programme helps users from outside Germany to come to Hamburg and perform their beam tests at the DESY II facility. In 2015, 16 users from two user groups were supported within this programme.

Furthermore, AIDA-2020 provides funding for additional improvements to the DESY II facility, including continuing support for the pixel telescopes, the addition of an advanced slow-control and monitoring infrastructure as well as an external silicon tracker for the 1 T PCMAG solenoid. Both will become available to users in 2017.

Improving the beam areas

During the 2014 shutdown, many improvements were made, including the introduction of the DACHS access system, which proved very well suited for handling the access of the approx. 300 users of the facility in 2015. The primary beam targets inside the DESY II vacuum were also replaced in 2014, and the new targets performed very well throughout 2015. Additional monitoring of the beam, in particular using the beam rate monitor at the end of the beamline, is now available to the users through the DESY TINE accelerator controls and monitoring system.

With the start of the current shutdown in November 2015, another round of improvements started. The gas warning system was replaced, and the spill counter system in the DESY II tunnel was completely overhauled, including new cabling and power supplies. The targets were further upgraded, and additional enhancements to the electrical and network installation were implemented.

Introducing a second pixel telescope

The pixel telescopes have proved tremendously successful, and the DATURA telescope, which is permanently installed at DESY, has been heavily overbooked in the past. Two thirds of the user groups coming to DESY requested the usage of a telescope during their test beam time. Therefore, a second telescope for the DESY II facility was built in 2015. The new telescope, named DURANTA, was installed in the test beam area T22 in fall 2015. Right after commissioning, it was already used by the LHC user groups, which were very eager to have more test beam slots with a telescope available. Having two telescopes permanently installed is a huge advantage and will make the facility even more versatile.

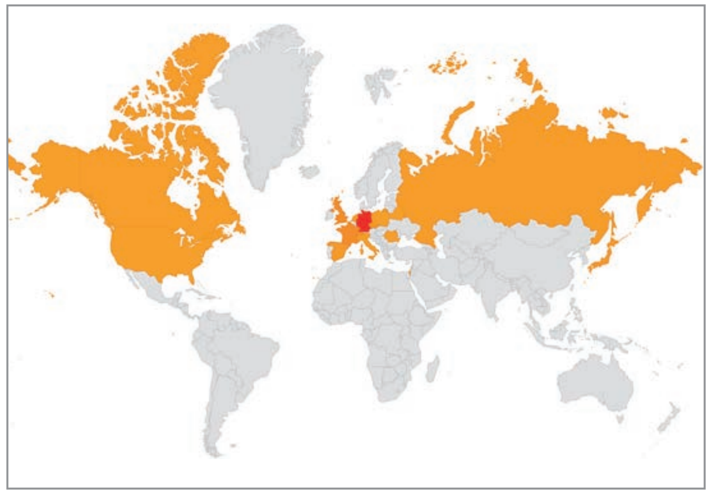

Figure 1

The global DESY test beam user community

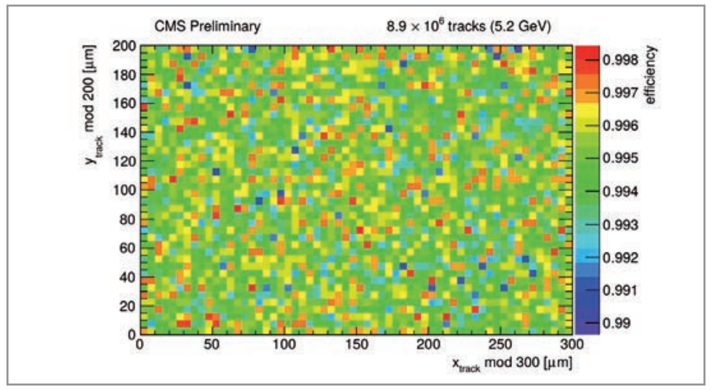

Figure 2

Tracking efficiency of the new front-end chip for the CMS pixel detector, exceeding 99% throughout

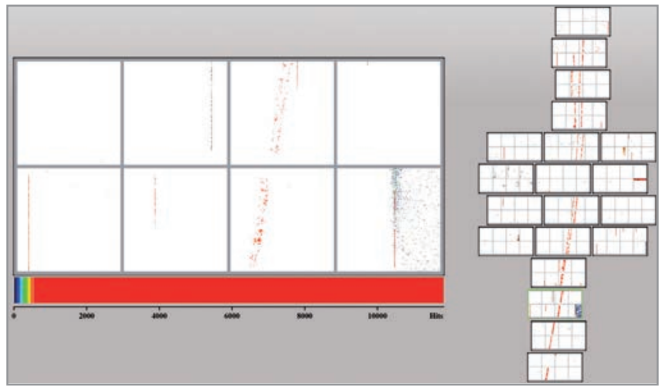

Figure 3

Event display of a double-track event: complete event on the right, zoom into an 8 GridPix group on the left

Highlights from 2015

The 2015 run was again very successful; the test beam was operated for 43 weeks. Of the 129 week-long slots that were available for the users, 56 slots were allocated, and 60% of the beam time available in these slots was used by the groups; this is a very high value for such a facility. Overall, 275 users from 16 countries came to the test beam facility, among them 62% from Germany, 25% from other EU countries and 13% from outside the EU (Fig. 1). 28% of the users came to DESY for the first time.

The DESY II test beam facility is an important and vital infrastructure for training the next generation of detector experts for particle physics and other disciplines. Therefore, it is very encouraging that about half of the users were students. Also, every year, DESY summer students are given the opportunity to take part in several test beam measurements.

Concerning the user communities, the LHC experiments are clearly dominating, with a share of 62% of the user groups, while the remainder ranges from generic detector R&D to preparing detectors for future linear colliders, in particular the ILC. One of the highlights of 2015 was the testing of the new front-end chip for the CMS Phase I pixel detector, which is due to be installed during the extended LHC winter shutdown in 2016/2017. The new chip comes with several improvements, particularly more buffers and a faster data transmission. The front-end design and performance was evaluated at the DESY II test beam facility, and the upgraded modules were found to provide a tracking efficiency of 99.7 + 0.3 - 0.5% with a point resolution of 4.8 ± 0.3 µm (Fig. 2).

Another highlight was the successful test of a newly developed readout module in a large time projection chamber prototype operated in the 1 T PCMAG solenoid in test beam area T24/1. The new modules use GridPix for the readout, which are built of a Timepix pixel chip with an aligned Micromegas gas amplification structure on top. With this readout structure, every single electron of the ionisation trail of a passing particle can be detected.

Three modules were operated simultaneously; one of them was equipped with 96 GridPix, the other two with 32, resulting in close to 10.5 million readout channels and a maximal track length of over 50 cm. An example event is shown in Fig. 3.

Outlook for 2016

The DESY II test beam facility will resume operation in March 2016 and run until Christmas 2016. So far, 39 weeks of beam time have been requested by 24 different user groups. The majority of the users come again from the LHC community, and the telescopes continue to be a success story with 75% of the groups requesting to use either DATURA or DURANTA. The DESY test beam team is also looking forward to the final system test of the BELLE II silicon tracking system, which is going to be installed at KEK in Japan towards the end of the year.

Summary

2015 has been another successful year for the DESY II test beam facility, and 2016 promises to be just as productive. The success of the DESY II facility would not have been possible without the support from many individuals and groups from the DESY particle physics and accelerator divisions, and we would like to take this opportunity to thank everybody involved for their efforts.

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Getting ready for the ILC.

Design collaboration and change management at a global scale

The Global Design Effort for the planned International Linear Collider (ILC) has defined the baseline design of the accelerator and demonstrated its technical feasibility. Now the international community is waiting for a political decision from the most likely host nation, Japan, to enter the next phase of the project. In the meantime, under the guidance of the global Linear Collider Collaboration (LCC) many institutes continue detailing the design by further investigating critical aspects and by starting to adapt the facility layout to the specifics of the expected site. A change management process ensures that the overall design evolves in a coordinated fashion.

Change management

Current ILC design activities focus on adding detail to the baseline design. Critical systems are further studied, available options and alternatives are examined for potential performance gain and cost savings, and the layout of the facility is adapted to the specifics of the preferred mountain site in the Kitakami region of Japan. With different teams in different regions investigating different ideas in parallel, one challenge is to keep dependencies and side effects under control.

Following a DESY initiative, a formal change management process has been established that organises design activities systematically into four phases: proposal of a change, review, decision and implementation. The process is coordinated by the newly established Change Management Board (CMB), which comprises experts from all relevant stakeholders and ensures un-biased review and decision-making, an essential foundation for reaching the necessary broad consensus on the design.

The challenge was to set up a process that involves minimal bureaucracy, respects the culture of the community, reaches out to all ILC collaborators around the world and is practicable with the global distribution of the participants. Twelve successfully processed change requests of widely varying scope confirm that the objectives have been met.

One size does fit all

Already the second change request submitted to the CMB turned out to be a challenge: The final-focus magnet, the last magnet of the accelerator before the interaction point (IP), is an accelerator component that sits inside the detectors. Its distance from the interaction point, L^*, defines the free space available for instrumentation in the most sensitive area. L^* is one of the major design constraints for each detector and goes to the very heart of the detector concept.

The two detector concepts SiD and ILD, which have been developed independently, were optimised to different values of L^*. But as supporting two different L^* in one facility requires compromises in the accelerator that are suboptimal for both solutions, the accelerator designers called for a harmonisation of L^* between the two detector concepts.

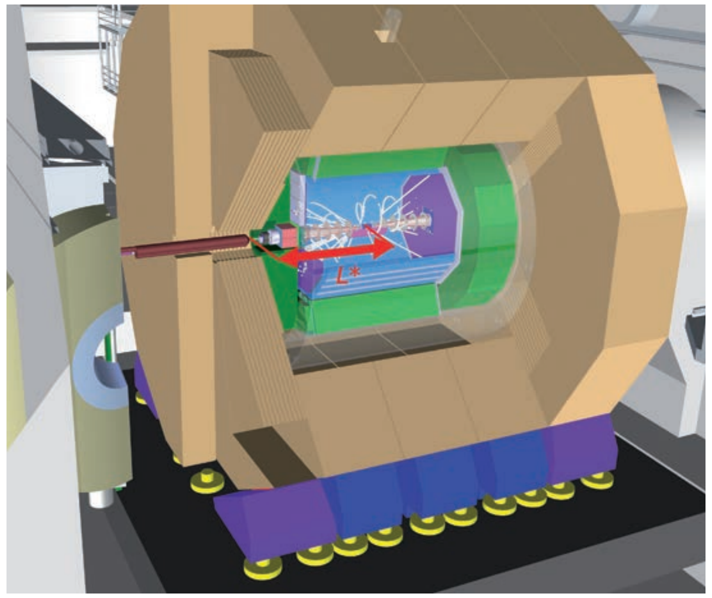

Figure 1

Schematic view of the ILD detector with a Higgs event: L^*, the distance from the last accelerator magnet to the interaction point, has been harmonised for both ILC detector concepts.

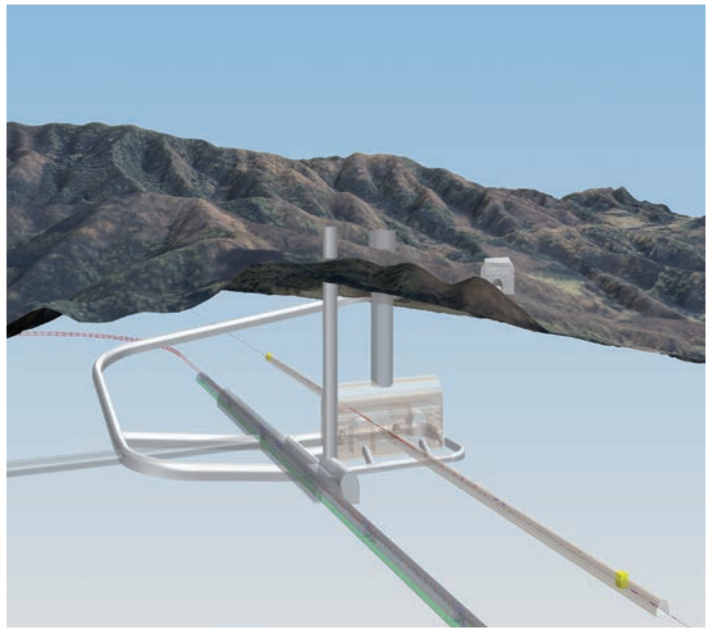

Figure 2

Illustration of the ILC accelerator complex in a fictitious mountainous area: Design evolution uses change requests to adapt the general layout of the facility to the specifics of the most probable host site. The figure shows the experimental hall with the original sloped access tunnel and the newly added vertical access shafts. The accelerator is shown to illustrate the complexity and dependencies that have to be taken into account when changing the design of any component.

Changing L^* requires significant engineering work, preceded by careful physics studies. The change request triggered a review phase that took over a year, with several dedicated workshops that weighed the pros and cons. Finally, a solution was found that suited all parties, the accelerator and both experiments, with a common L^* value of 4.1 m.

Accessing the mountain hall

In return, the detector groups approached the accelerator siting team with a change request asking for a modification of the access scheme to the experimental hall: The detectors will be housed in an experimental hall deep under the mountain, and the planners have foreseen a kilometre-long, slightly sloped access tunnel for bringing detector components and equipment into the hall. The detector groups would prefer to pre-assemble large parts of the detectors on the surface and lower them into the pit through a vertical access shaft with a gigantic gantry crane for pieces of up to 4000 t.

This change request meant that the interaction point at the preferred site had to be moved by about 800 m to a point where the overburden was low enough to allow for a vertical shaft. The request also took about a year of discussions, but in this case the proposers chose to work out the details before submitting the change request. After the CMB had convinced itself that all stakeholders had been involved in the preparation and were satisfied with the proposed solution, the change request was quickly approved.

More accelerator at not more cost

The most expensive change request so far called for an extension of the main linear accelerator tunnels by 1.5 km on each side, adding 3 km to the total length of the accelerator. Although the proposal was triggered by a machine requirement that the round of the positrons from damping ring (DR) to IP has to be an integer multiple of the DR circumference, the real reason for this costly solution came from physics: At 500 GeV centre-of-mass energy, the ILC operates just above the threshold for associate production of a top pair and a Higgs boson, an eminently important physics case of the ILC. Failure to reach 500 GeV would jeopardise this goal, and the 1.5 km additional tunnels add space that could be equipped with additional cryomodules. This option may be needed in case it turns out that it is more economic to produce more cryomodules at a relaxed gradient rather than require the full design gradient of 31.5 MV/m for all modules.

The CMB has accepted this change request, but only under the condition that the ensuing cost increase will be compensated by another change that saves at least the same amount of money. Such a change request is currently being reviewed: A new change request proposes to reduce the shield wall thickness in the main linear accelerator tunnel from 3.5 m to 1.5 m, which would finance the longer tunnel.

Experience

The change management process has been well adopted by the LCC. Ongoing change requests serve as crystallisation points for discussion, are naturally focusing workshops and meetings, and lead to coordinated and thorough studies of any upcoming design issues. Design activities emerge bottom-up as often as top-down, and as such activities typically change the baseline design, managing the change is almost tantamount to managing the project. The benefit for the project is an increased efficiency, as design activities are conducted in a transparent way. Consensus is reached on a broad basis, and changes are less likely to be challenged or reversed again. A documented and systematic implementation ensures that design documents are up-to-date and that pending changes are known. The reduced waste from confusion is not to be underestimated in a global project.

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DESY’s endeavour towards open access.

Promoting free online access to publications

The global open-access (OA) movement, which promotes the free and unrestricted online access to research publications, has gained more and more momentum. DESY committed itself to supporting OA early on and is well on track to fulfil the declared objectives. At the same time, a few challenges remain.

The Helmholtz Association, of which DESY is a member, is one of the first signees of the 2003 Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities (http://openaccess.mpg.de/Berlin-Declaration). In addition, the DESY Directorate decided that DESY “shall be entitled to make the contents of the article freely accessible to the general public on the Internet or in some other form at the time of publication (alternatively 3 or 6 months after the article’s publication).”

In 2012, the European Commission set the goal that 60% of European publicly funded research articles be available under OA by 2016. Where does DESY stand today?

In 2014 and 2015, more than 60% of DESY papers were OA and easily accessible through DESY’s institutional repository PubDB (http://pubdb.desy.de/), whereas the respective average percentage at the Helmholtz centres was around 30%. One important reason for this leading role is that the DESY library actively encourages authors to provide full texts. But the OA percentage depends on the research topic (Fig. 1): Accelerator and detector research slightly missed the mark, with 50–60% OA papers in PubDB, and photon science reached a rate of roughly 45% in 2015. In contrast, particle physics exceeded 90% – based on the two “pillars” arXiv (http://arxiv.org/) and SCOAP^3 (http://scoap3.org/). But even there, a closer look reveals that more papers could easily be made OA in PubDB if the authors provided the post-referee arXiv paper. This is even truer for astroparticle physics publications, where only one third of the articles in PubDB is OA, while more than 80% of the non-OA papers are available on arXiv.

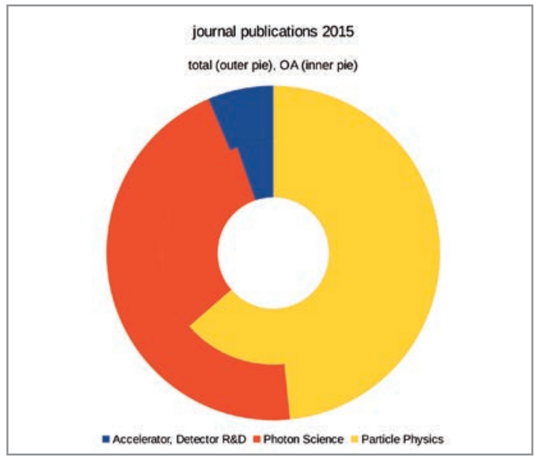

Figure 1
DESY journal publications by research topic in 2015

But even without arXiv, many publishers allow the archiving of the post-referee paper or even of the publisher’s version in PDF form in institutional repositories like PubDB. Authors can check the corresponding journal policies using the RoMEO service (http://www.sherpa.ac.uk/romeo). Under specific circumstances, the 2014 amendment to German copyright law grants a “secondary publication right” independently of agreements between authors and publishers (http://www.allianzinitiative.de/de/handlungsfelder/rechtliche-rahmenbedingungen/faq-zvr.html).

Another option is to publish directly in OA journals (https://doaj.org/). In that case, as a rule, the authors or their home institutions have to pay for the publication. But there are also models where OA journals are funded through scientific societies or other sponsors – such as *Physical Review Accelerators and Beams*, which is financed by DESY together with other industrial and institutional sponsors. At a larger scale, the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) project bundles resources of 47 countries and intergovernmental organisations to finance OA in particle physics. In the last two years, close to 9000 articles were published at an average article-processing charge of 1106 euros.

The DESY library group not only runs PubDB, but also counsels researchers wishing to publish in OA journals or to turn their traditional publications into OA. Moreover, the group is pushing the OA idea in different OA committees.

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Productivity and safety.

Implementing a state-of-the-art RFID system in the DESY library

In 2015, the DESY central library switched from the old barcodes and electromagnetic theft protection to a modern radio-frequency identification (RFID)-based system. RFID allows rapid charging and discharging in circulation, offers simplified and cost-effective self-check-in and -check-out and has a higher reliability than the old system. As a further unique advantage, RFID allows high-speed inventorying by simple in-shelf scanning of the media. The RFID implementation is one step towards the migration of the DESY library from the current commercial library system to the open-source software INVENIO.

Figure 1
New RFID self-check-out station at the DESY central library in Hamburg

For more than a decade, the DESY library used an integrated library system as an enterprise resource planning system to track items, make orders and manage patrons. To identify the items, barcode labels were used, and an electromagnetic (EM) theft protection system ensured that only correctly checked-out items could be taken outside the library. Although RFID was already available at that time, the price for the RFID labels was much too high compared to barcode labels and Tattle-Tape EM strips. The combination of barcode and Tattle-Tape strips allowed the library group to set up a self-check-out station at the DESY central library in Hamburg (Fig. 1), but the price of the hardware together with the high license fees unfortunately prevented such a well-tried setup at the DESY site in Zeuthen.

After relocation of the DESY central library into Building 1d, the reliability of the EM theft protection decreased dramatically due to the areal conditions in the new premises. A lot of false alarms occurred, or no alarms at all. Amendments of the manufacturer were unsuccessful. In the fourth quarter of 2015, DESY published a call for tender for migrating the library to RFID (Fig. 2). The tender was successful, and the library group was able to migrate 20 000 media in the central library within only two month. The migration of the media at DESY in Zeuthen will begin shortly. During the migration, the group collected data for making an inventory, but these data have not yet been analysed.

The RFID implementation is part of the strategy towards the migration from the commercial library system ALEPH by ExLibris to the open-source system INVENIO. By using INVENIO for the library system, the publication database and the high-energy physics literature database INSPIRE, the DESY library group will be able to exploit synergies within the library. The migration to RFID will allow a self-check-out system to be set up in Zeuthen and other branches, as soon as the switch to INVENIO has been carried out.

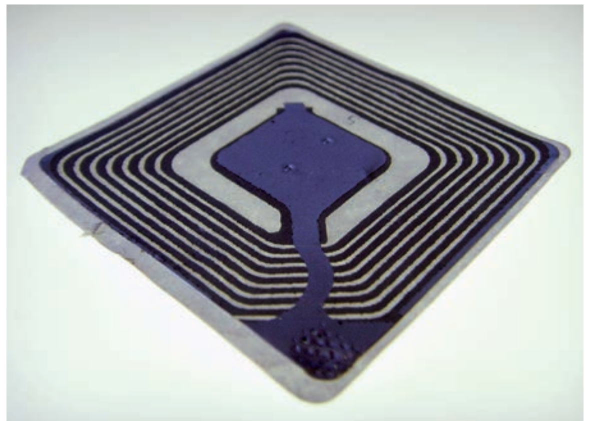

Figure 2
RFID chip

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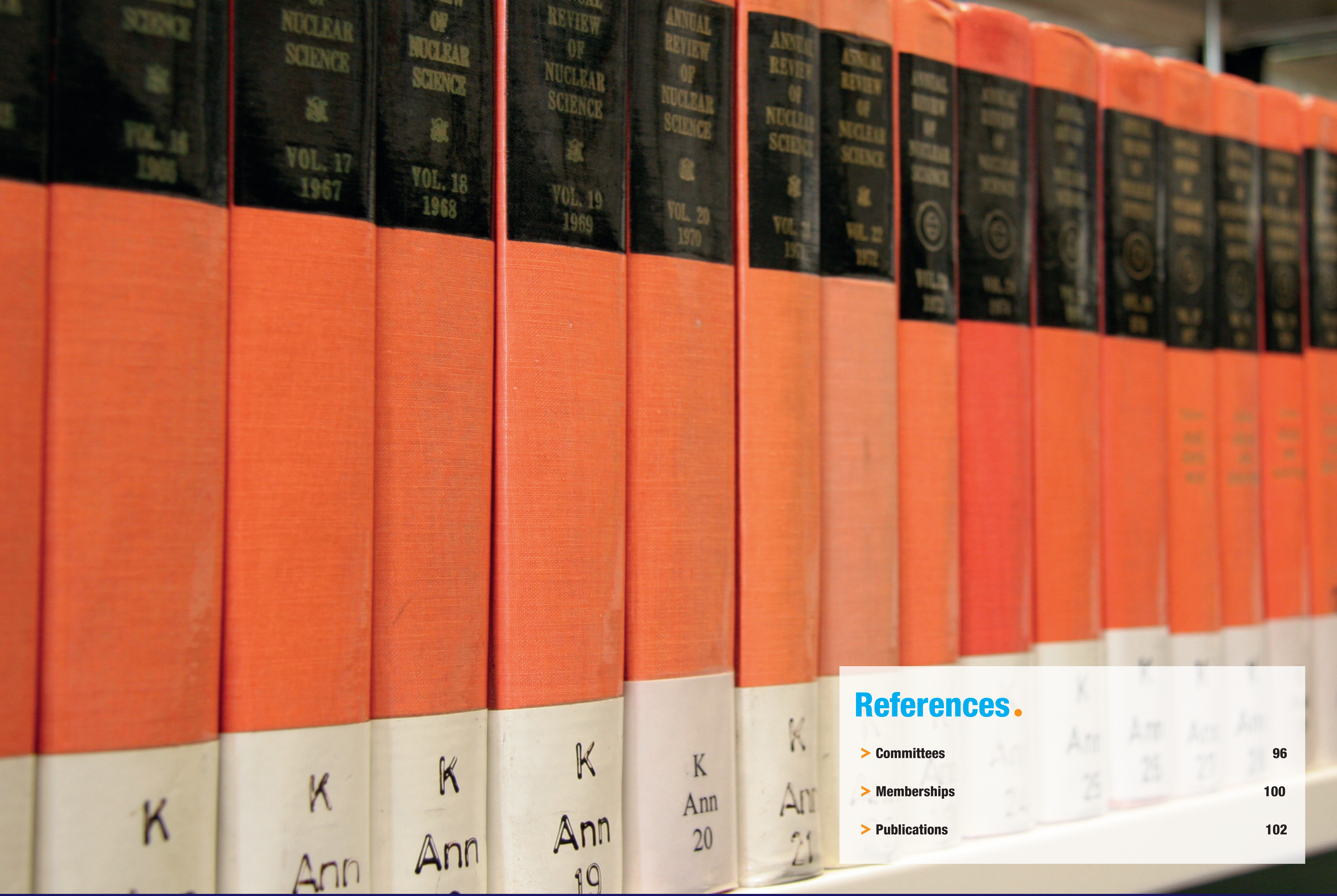

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