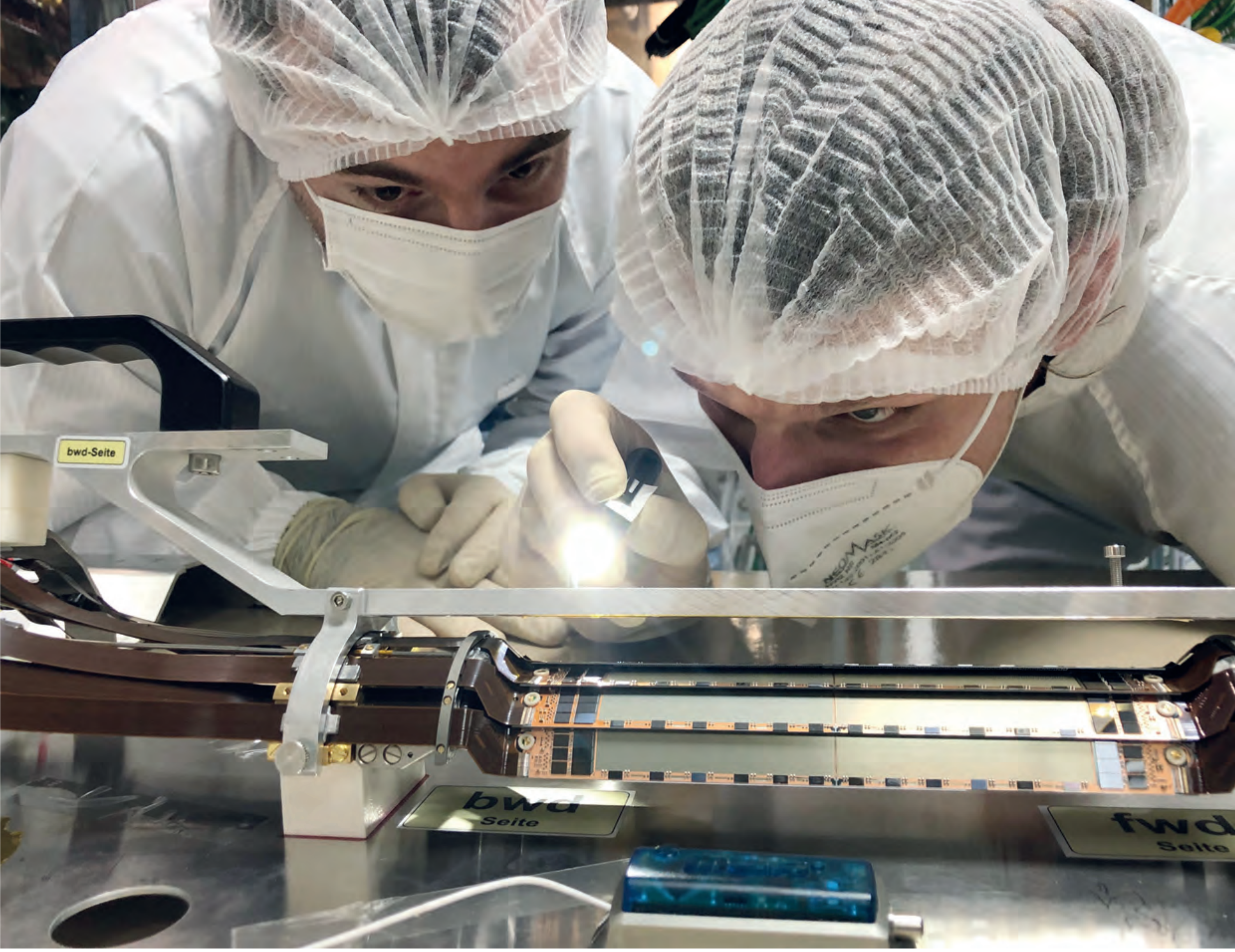


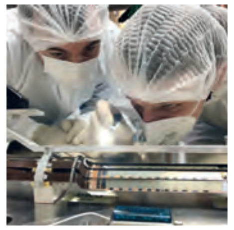
PARTICLE PHYSICS 2023.

Highlights and Annual Report

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

PARTICLE PHYSICS 2023.

Highlights and Annual Report



Cover
First visual inspection of the Belle II pixel vertex detector for possible transport damage after transport to KEK in Japan

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The year 2023 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

The world is facing unprecedented challenges. The consequences of climate change are becoming increasingly evident in devastating extreme weather events. Even as the aftershocks of the COVID-19 pandemic continue, we are still exposed to potential new viral and bacterial pathogens whose effects we do not know. Concurrently, the global community is shaken by geopolitical upheavals: Putin's horrifying war in Ukraine and the brutal terrorist attacks on Israel, just to name a few. Now more than ever, we must advocate for a sustainable and peaceful future so that we do not leave a ruined world for future generations.

What role can a research centre like DESY play in shaping a liveable future in Germany, Europe and the world? How can DESY contribute to limiting climate change and to preventing future pandemics and other health issues? And how do we navigate international collaborations with partners from nations that challenge democratic values, such as China?

Preliminary answers to these questions can be found in our draft of the DESY Strategy 2030 Loop. Under the guiding principle "The Decoding of Matter", DESY remains deeply rooted in fundamental research. Our commitment as a national centre to the international particle physics organisation CERN remains unchanged, and we continue to expand astroparticle physics. A significant move in this direction is the establishment of the German Center for Astrophysics (DZA) in the Lausitz region – a political decision to which Christian Stegmann, Director in charge of Astroparticle Physics at DESY, has made significant contributions. By 2024, decisions should be made regarding DESY's position within the DZA.

In recent months, we have vigorously advocated for the timely realisation of DESY's flagship project, PETRA IV. The conversion of our existing synchrotron radiation source PETRA III into a state-of-the-art fourth-generation X-ray light source is essential to remain competitive worldwide.

Figure 1
DESY researcher Johannes Hagemann (left) shows German Health Minister Karl Lauterbach (right) the experiments at the PETRA III beamline P06 together with Helmut Dosch (second from left), Hamburg Science Senator Katharina Fegebank ((middle) and Gesa Miehe-Nordmeyer from the Federal Chancellery (second from right).

In particular, the USA and Asia are already heavily investing in similar research infrastructures. All our endeavours regarding PETRA IV have received substantial local political backing from the Hamburg Parliament, which committed to funding 10% of the project's investment costs. This strong support continues at the national level: During the Federal Budget Committee session on 16 November 2023, a decisive step was taken with the approval of 40 million euros in seed funding for the project – highlighting the pivotal relevance of PETRA IV for future science.

Over the past months, we have seen remarkable support from the high-tech and deep-tech industries. Our industrial dialogue partners recognise that they stand at the brink of a profound transformation: Climate change solutions demand a shift towards sustainable materials and processes, while precision data emerges as the new currency in international competition. Those with the best databases will lead AI-driven developments, be it in custom materials or pharmaceuticals. Fourth-generation synchrotron radiation facilities are globally recognised as vital for generating this invaluable pool of data.

The coming decade will be pivotal for our research centre. For DESY, it is crucial to ensure the swift implementation of PETRA IV and further advance photon science, uphold our leadership in plasma-based particle acceleration developments, expand new methods in astroparticle physics and make a significant national contribution to the High-Luminosity Large Hadron Collider (HL-LHC) at CERN. Concurrently, we must ambitiously drive our vision of creating a dynamic research innovation ecosystem with DESY at the core of the Science City Hamburg Bahrenfeld, incorporating innovative and sustainable digital structures and processes.

Realising this master plan is in itself a monumental challenge. The current financial situation, with volatile energy and gas prices among other effects leading to rising inflation, poses significant difficulties for the DESY management. We face a new reality at DESY: the need to craft a globally competitive research programme with diminishing resources, which is achievable only with stringent prioritisation. The dramatic rise in the construction cost index in recent years has jeopardised several of our planned construction projects. However, we were able to successfully launch the civil engineering work for our DESYUM visitor centre in Hamburg as the first major construction initiative. Construction is progressing swiftly, giving us hope that we will meet all set milestones on time. Up next is the new accelerator centre CAST, which will also house the accelerator control room and the DESY Innovation Factory, a centre for start-ups. Ideally, we would like to implement these projects before the intensive construction phase of PETRA IV.

Figure 2
Visualisation of the DESY visitor centre DESYUM, close to the main entrance on the DESY campus in Hamburg

DESY is held in high international regard in fundamental research. It is imperative to emphasise that our success would be inconceivable without talented researchers and engineers who consistently pioneer the development of new technologies. My special thanks therefore go to them and all the DESY staff, our national and international users as well as our partners for their dedicated work. This is also reflected in the numerous awards they have earned.

The crucial message is: We must persistently strive to cultivate an attractive and innovative environment for the world's brightest minds, or risk falling behind in the international competition – and this is not just about DESY. In challenging times, the ability to provide answers to difficult questions is needed more than ever, and this is precisely where the strength of fundamental science lies. The scientific results in this annual report are good examples of what we can achieve when we work together for a better future!

Yours

Helmut Dosch
Chairman of the DESY Board of Directors

Particle physics at DESY

Introduction

Figure 2
Pupils enjoying experiments at the DESY school lab "physik.begreifen"

Dear Colleagues and Friends of DESY,

It's the science that drives us, and the scientific and technological challenges we need to master in order to extract fascinating scientific results.

In the past year, 2023, two very demanding and exciting projects were successfully brought to an – intermediate – end: In March, the new pixel vertex detector for the Belle II experiment at the KEK research centre in Japan was pre-commissioned at DESY, in cooperation with numerous German university colleagues, and shipped to KEK. After its successful installation in the experiment in summer and the subsequent commissioning and cosmic-ray data taking, these early days of 2024 are seeing the first collision data taking of the new component in the Belle II detector. And in late May – thanks in particular to the perseverance of Axel Lindner and his vision for axion experiments at DESY – we could celebrate the start of data taking of the ALPS II axion search experiment on our Hamburg campus (Fig. 1), 20 years after Andreas Ringwald first proposed the idea in *Physics Letters B* (569, pp. 51–56, 2003). We are now eagerly looking forward to first physics results from this experiment, expected for summer 2024!

Figure 1
Start of data taking at the ALPS II experiment on 24 May 2023

The upgrades for the Large Hadron Collider (LHC) at CERN near Geneva and our contributions to the tracker endcaps of the LHC experiments ATLAS and CMS – topics we have been involved in for close to 10 years now! – are entering the production phase: Almost all R&D has been carried out, and the collaborations are about to start the actual production. ATLAS has constructed its first petal from final components and is preparing a full system test. CMS could demonstrate, at DESY and with international partners, the successful integration of modules into one half disk of the mechanical substructure – the so-called "Dee".

All these detector and technological enterprises are technologically fascinating, but we embark on them primarily in order to achieve potentially revolutionary scientific results. While not all individual results by experimentalists and theorists at DESY are scientific game changers, they all contribute to building up our knowledge and laying the groundwork for a deeper understanding of our universe and its history and future. Perseverance and patience are just as important as innovation to ensure steady progress while also enabling novel developments.

Let me mention four highlight results from 2023: Belle II could establish first evidence for the rare decay of B mesons into a kaon and two neutrinos, $B \rightarrow K\nu\nu$. With the measured value being somewhat higher than predicted by the Standard Model, this result has already sparked considerable interest in the theory community. A new measurement of the tau-lepton mass – performed by DESY scientists at Belle II based on a method originally developed at the ARGUS experiment at DESY's former electron–positron collider DORIS – is the most precise single determination of this quantity ever achieved. On the LHC side, 15 years into operation, ATLAS and CMS are still making important observations. In particular, they are detecting ever rarer processes! Events containing four top quarks were observed, and, also for the first time, events with a W boson, a Z boson and a high-energy photon, i.e. three different bosons – in both cases with major DESY contributions!

In 2023, two events at DESY and in Hamburg offered excellent opportunities for getting in closer touch with other scientists: In August, the university campus was occupied by the over 800 participants of the European Physical Society Conference on High Energy Physics (EPS-HEP2023), co-organised together with Universität Hamburg. And in November, the 13th seminar of the International Committee for Future Accelerators (ICFA) took place at DESY, under the title "Future Perspectives in High-Energy Physics". Around 200 renowned scientists assembled in the auditorium for a week of presentations and intense discussions, surveying the entire field of particle physics worldwide.

Conveying science, curiosity and the scientific method to the general public, and particularly to children, is very important for our future. One example that is especially dear to me is the DESY school lab "physik.begreifen" (Fig. 2). In existence for now more than 25 years, the classes have attracted more than 7000 pupils per year – and we aim to increase this number to as many as 10 000 pupils per year in the future! Another important format that addresses young children is the federal foundation "Kinder Forschen", where we work as a network partner with kindergarden educators to implement research in the daily kindergarden routine. These are fantastic formats to foster curiosity and help establish scientific thinking in society as one of the pillars of our civilisation.

Unfortunately, we are also living in difficult times, with many challenges and uncertainties that also affect DESY and its employees. I am confident though that – thanks to our outstanding competences, creativity and devotion – we will be able to overcome them and adapt DESY so that we emerge even stronger than before. We should embrace our role as Germany's premier lab for fundamental science and trust that this role will continue to be appreciated locally, nationally and internationally.

Let me close by thanking each and every one of you at DESY and at our partner institutions around the world for your sustained effort and commitment to excellent science – it is much appreciated!

Enjoy the reading!

Yours,

Beate Heinemann
Director in charge of Particle Physics

News and events

A busy year 2023

January

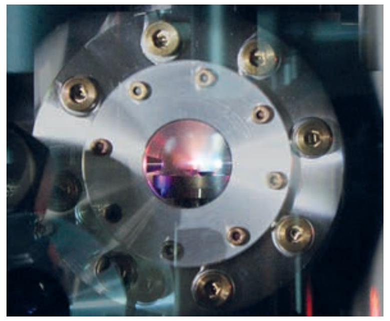
DESY school lab celebrates 25th anniversary

The name says it all, and the concept is more relevant today than ever: The DESY school lab "physik.begreifen", in the sense of "touching", "trying out", but also "understanding" physics, aims to raise pupils' interest in the natural sciences and reduce prejudices. More than 110 000 school kids have already conducted research in what was the first school lab in the Helmholtz Association. "physik.begreifen" celebrated its 25th anniversary in a ceremony attended by Hamburg's Senator for Schools Ties Rabe and physics entertainer, book author and former DESY scientist Michael Büker. The guest of honour was DESY's former administrative director Helmut Krech, who founded the school lab.

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

Unique live view into plasma acceleration

For the first time, an international research team led by DESY accurately measured the acceleration process in a plasma without disturbing the process itself. The findings, published in the journal *Physical Review Letters*, open up a new possibility to understand the acceleration process in plasmas more precisely – a result that is key to developing this novel acceleration technology more quickly.



Light from the one-millimetre-long helium plasma in which the electrons were accelerated

ERA Chair awarded to Karl Jansen

Karl Jansen started the project QUEST.

The European Research Executive Agency (ERA) awarded DESY scientist Karl Jansen DESY's first ERA Chair, which is worth 2.5 million euro. Jansen will start the Quantum Computing for Excellence in Science and Technology (QUEST) project to establish a new centre for quantum computing at the Cyprus Institute. The centre will work closely with the Centre for Quantum Technology and Applications at DESY in Zeuthen in order to develop practical applications, algorithms and methods of quantum computing through common projects, thus bridging the gap between academia and industry. QUEST will also provide training for students and test novel quantum hardware.

February

DESY–Ukraine Winter School creates opportunities

The DESY–Ukraine Winter School was held from 31 January to 10 March. A total of 22 students from Ukrainian universities worked on DESY research projects on the Hamburg and Zeuthen campuses for six weeks. The projects enabled the students to interact with scientists in research areas that would otherwise have been out of reach given the current geopolitical situation. No distance was too far: Some of the students were picked up from the Polish–Ukrainian border by bus transport organised by DESY.

Students from Ukrainian universities who joined the DESY–Ukraine Winter School in Hamburg and Zeuthen

Jugend forscht 2023

Under the motto "Mach Ideen groß" ("Make ideas great"), 137 pupils presented themselves at this year's "Jugend forscht" regional science competition. DESY hosted the Hamburg-Bahrenfeld regional competition for the 11th time. A total of 14 projects from technology, mathematics, informatics, biology and chemistry were awarded prizes.

ATLAS PhD Award for Emily Thompson

DESY student Emily Thompson received an award for her PhD thesis from the ATLAS collaboration at CERN in Geneva, Switzerland. Thompson's award-winning search for long-lived supersymmetric particles used a feature called displaced vertices. With lifetimes ranging from picoseconds to nanoseconds, massive long-lived particles could decay to several electrically charged particles within the inner tracking volume of the ATLAS detector, resulting in a displaced secondary vertex. But these particles are hard to find as they decay on a longer timescale than other particles measured by ATLAS, i.e. they would not match the timing structure provided by the detector. Thompson adjusted many algorithms for the identification of the particles and showed with her thesis that these searches are technically possible.

ATLAS PhD award winner Emily Thompson with her supervisor, DESY Particle Physics Director Beate Heinemann

March

Kerstin Tackmann is awarded visiting professorship in Berkeley

DESY particle physicist Kerstin Tackmann took up a four-month visiting professorship at the University of California in Berkeley in March. The Miller Institute for Basic Research in Science has been promoting basic research since the 1950s. Every year, "Visiting Miller Research Professorships" are awarded to eminent and aspiring scientists to bring them to the university campus for a few months and promote collaboration with researchers on site.

Kerstin Tackmann was a visiting professor at the University of California in Berkeley for four months.

Research team detects first neutrinos made by a particle collider

An international team at the FASER experiment at the Large Hadron Collider (LHC) at CERN in Geneva detected neutrinos created by a particle collider for the first time. The discovery promises to deepen scientists' understanding of the nature of neutrinos, first spotted in 1956, which are the most abundant particles in the cosmos and a key participant in the process that makes stars burn. DESY theorist Felix Kling, who was a member of the team that proposed the experiment back in 2018, contributed significantly to the findings by conducting simulations about the number of expectable neutrinos.

The FASER detector is located deep underground in a side tunnel at the LHC near the ATLAS detector.

April

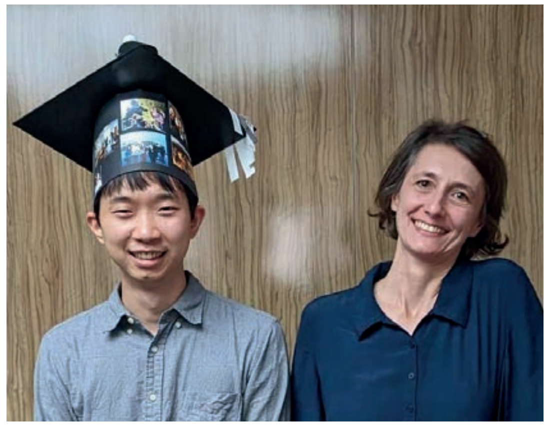
Music, religion and science meet in an opera about creation

On 27 April, fragments of the opera "Schöpfung" ("Creation") by composer and singer Gloria Bruni had their German premiere at St. Catherine's Church in Hamburg. Inspired by conversations with scientists at DESY, the music is intended as a contribution to the human search for answers to questions about the birth of the universe, life and humanity and shares current concerns about creation and the future of our planet as a place worth living in. A DESY particle physicists' choir founded especially for this purpose was also part of the event.

May

Helmholtz PhD Award for Peera Simakachorn

The Helmholtz Association awarded DESY PhD student Peera Simakachorn the PhD Prize for Mission-Oriented Research in the research field "Matter".



Awardee Peera Simakachorn together with his tutor, DESY physicist Géraldine Servant

Simakachorn received the award on 3 May at a meeting of the Strategic Advisory Board of the research field, where he also presented his work. His doctoral thesis entitled "Charting Cosmological History and New Particle Physics with Primordial Gravitational Waves" covers a broad spectrum of topics in the cosmology of the early universe, so-called primordial gravitational waves, axion physics and particle physics beyond the Standard Model in general. He was one of two awardees in the Helmholtz research field "Matter".

Interactive exhibition: How it all began

The interactive exhibition "How it all began: Of galaxies, quarks and collisions" at the Hamburg Museum der Arbeit (Museum of Labour) provided interesting insights into the latest findings in particle physics, astroparticle physics and cosmology. The exhibition took place from 26 October 2022 to 7 May 2023 and was visited by 26 500 people.
In the exhibition, visitors could explore several thematic stations that offered exciting insights into the development of the universe. The unique joint project of Universität Hamburg, the Cluster of Excellence Quantum Universe, DESY and Museum der Arbeit made the latest findings of cutting-edge research in Hamburg visible and tangible.

ALPS starts searching for dark matter

The "light-shining-through-a-wall" experiment ALPS II – the world's most sensitive model-independent experiment to search for particularly light particles of which dark matter might be composed – took up operations at DESY. Scientific calculations predict that this ominous form of matter should occur five times as often in the universe as normal, visible matter. So far, however, no experiment has been able to identify such particles; the ALPS experiment could provide the first evidence.

Panoramic picture of the 250 m long ALPS II experiment, with the first magnet installed in the tunnel for ALPS II in the centre

Foundation stone laid for DESY visitor centre

Hamburg Science Senator Katharina Fegebank, DESY Director Helmut Dosch and other guests of honour laid the foundation stone for the new DESY visitor centre, called DESYUM. Alongside a large atrium, a cafeteria and offices, the six-storey building will host a lively multimedia exhibition that makes DESY's research and innovations accessible to the general public. The DESYUM will be a landmark on the campus, serving as a public meeting point and a forum for everyone. Its opening is planned for 2025.

Inserting the time capsule into the DESYUM foundation stone

June

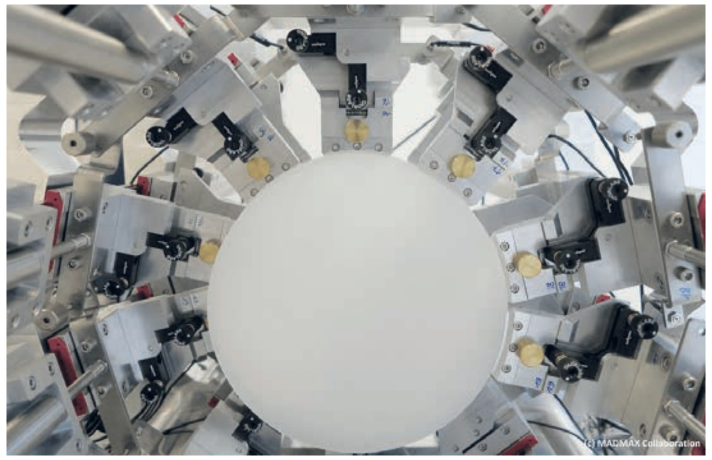
CMS Awards for six scientists from Hamburg

Every year, the CMS Award committee honours some of the collaboration's members for their outstanding work. In 2023, six of the winners came from Hamburg! They were:

- Freya Blekman (DESY and Universität Hamburg) for her outstanding activity on communicating CMS physics to a more general audience through physics briefings
- Sandra Consuegra Rodriguez (DESY) for her outstanding contributions to the ultimate alignment of the CMS tracker in LHC Run 2 and to the excellent performance of the tracker during the start-up of LHC Run 3
- Jonas Rübenach (DESY) for his outstanding contribution to the construction, commissioning and operation of the online luminosity detector BCM1F during the start of LHC Run3 and throughout the first year of data taking
- Mathias Reinecke (DESY) for his long-standing technical and collaborative contributions to the HGCAL project
- Younes Otarid (DESY) for his competence and dedication to the development of the data acquisition for the CMS tracker upgrade, which allowed the tracker prototypes to perform successfully in many beam tests and the path of the tracker upgrade to be secured
- Karla Josefina Pena Rodriguez (Universität Hamburg) for her outstanding dedication in validating and improving the performance of track reconstruction at the CMS high-level trigger

German–French laboratory for dark-matter research founded

The French research organisation CNRS and three centres of the Helmholtz Association joined forces to form the Dark Matter Lab (DMLab), an international research laboratory dedicated to the study of the mysterious dark matter. The DMLab, which will be heavily involved in the planned MADMAX experiment at DESY, is coordinated on the German side by DESY.



The axion experiment MADMAX is one of the experiments in which the DMLab will play a major role.

Helmholtz AI Conference 2023 hosted by DESY

For the annual Helmholtz AI Conference, around 400 scientists and experts gathered at DESY from 12 to 14 June to share cutting-edge research in artificial intelligence for science. The event brought together AI enthusiasts and AI researchers from the Helmholtz Association and beyond to exchange knowledge and discover the latest advancements and insights in AI, which can enhance and accelerate future discoveries in all areas of science.

German Health Minister Karl Lauterbach visits DESY

Participants of the Life Science Forum with Hamburg Science Senator Katharina Fegebank and German Health Minister Karl Lauterbach (centre)

Using the experience from the COVID-19 pandemic to accelerate health research: Karl Lauterbach, the German Federal Minister of Health, visited DESY in Hamburg on 30 June. Lauterbach recognised DESY's unique expertise and the diverse possibilities for application of the centre's accelerator-based light sources, including in health research, and emphasised DESY's prominent role for the future of Germany as a leader in science.

July

Hamburg Prize for Theoretical Physics awarded to Edward Witten

The string theorist Edward Witten was awarded the Hamburg Prize for Theoretical Physics 2023, one of the most valuable science prizes for physics in Germany. The professor emeritus at the Institute for Advanced Study in Princeton, USA, was recognised for his groundbreaking contributions to a unified mathematical description of the fundamental forces of nature. His outstanding research on string and quantum theory has had a profound impact on our understanding of space, time, matter and the structure of the cosmos. The influence of his work extends far into other disciplines, especially mathematics.

Edward Witten received the Hamburg Prize for Theoretical Physics 2023

Preparing for a quantum (computing) leap

Researchers published a pioneering white paper that identifies activities in particle physics where emerging quantum computing technologies could be applied. These applications, for example in the context of quantum dynamics or experiment simulation, could help to tackle computing challenges associated with the upgrade programme for the LHC at CERN as well as with other colliders and low-energy experiments worldwide, including several in which DESY plays a major role.

IBM is leading the development of quantum computers.

Summer students are back in town

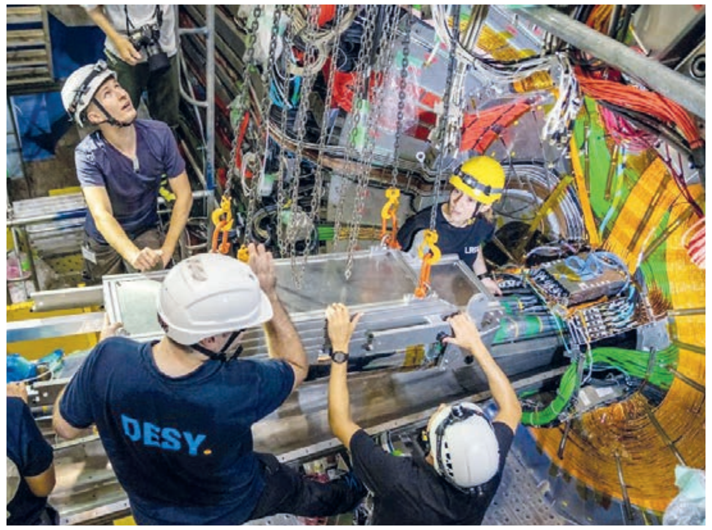
The DESY summer student programme, which was held from 18 July to 7 September 2023, included full-time work in established research groups, a lecture programme on DESY research topics and visits to facilities operated by DESY. Some of the projects also took place on the European XFEL campus in Schenefeld. Each of the projects provided the students with in-depth hands-on experience of real-world scientific investigations, analysis, theory and experiment design and offered networking opportunities.

Summer students at DESY in Hamburg

August

World's thinnest pixel vertex detector installed in Japan

After travelling a long way from its production site in Munich to its final destination in Japan, the pixel vertex detector – the innermost sub-detector of the Belle II experiment – was successfully installed at its final location at the SuperKEKB electron–positron collider at the KEK laboratory. The device, which is about the size of a soda can, is designed to detect the signals of certain particle decays that could shed light on the origin of the observed imbalance of matter and antimatter in the universe.



The pixel vertex detector being installed in the Belle II experiment in Japan

Dieter Trines (1942–2023)

DESY mourns the loss of its former Accelerator Director Dieter Trines. Dieter Trines was in charge of the DESY Accelerator division from 1995 to 2007 and, with his strong commitment to international collaboration, advanced the development of particle accelerators worldwide.

Dieter Trines in 1993

His involvement in the design and development of DESY's electron–proton collider HERA and his significant contribution to its successful construction and commissioning, the preparation of the PETRA III synchrotron radiation source project, the paving of the way for the European XFEL X-ray laser project and his major contribution to the recent launch of the ALPS II axion search experiment after his retirement are just a few examples of his many achievements. He passed away on 27 July 2023 at the age of 81.

Europe's largest particle physics conference comes to Hamburg

The EPS-HEP conference was held in Hamburg for the second time.

DESY and Universität Hamburg hosted the 2023 Conference on High Energy Physics on behalf of the European Physical Society (EPS-HEP). At the conference, scientists from around the world met to present their latest results from different areas across the field of high-energy physics: from experiments at particle accelerators to the search for dark matter and for particles not yet known to science. Almost 900 participants registered for the conference, which was rounded off by an attractive supporting programme.

September

Retreat of the Particle Physics division

The annual retreat of the DESY Particle Physics division took place on 1 September in the Mozartsäle in downtown Hamburg. The goal of the retreat was to jointly discuss the current challenges and opportunities in the division and to benefit from each other's ideas and thoughts.

DESY Particle Physics Director Beate Heinemann at the annual retreat of the division

Beamline for Schools winners at DESY

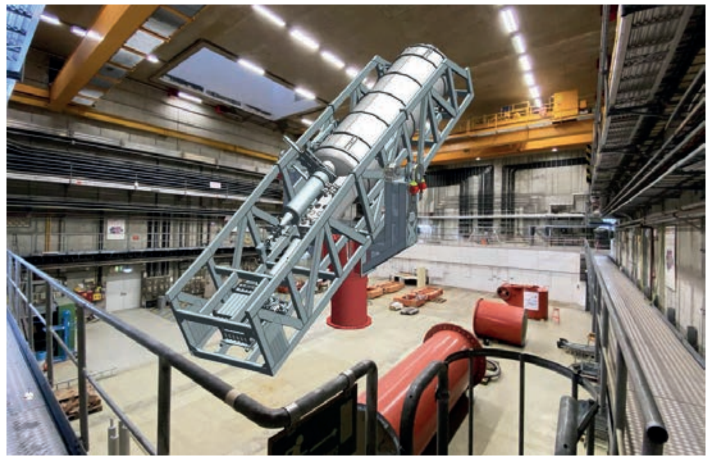
In 2023, for the second time in the history of the CERN Beamline for Schools competition, the evaluation committee selected three winning teams. Two teams, from the USA and from Pakistan, travelled to CERN to carry out their experiments. The third team, "Wire Wizards" from the Augustinianum in Eindhoven, the Netherlands, was hosted by DESY to perform its experiment. Preparing a proposal for a particle physics experiment is a very challenging task for secondary school pupils, but with the right support, participants design very creative experiments. The Wire Wizards' experiment focused on detector development. The Dutch students designed and built a multiwire proportional chamber, a gas detector that can measure the position of a particle interacting with it, which they characterised using the electron beam of the DESY II Test Beam Facility.

Pupils of the winning team Wire Wizards from Eindhoven in the Netherlands

October

ERC project to provide quantum detectors for DESY dark-matter experiment

The European Research Council (ERC) bestowed a prestigious ERC Synergy Grant for developing novel quantum sensors for experiments searching for dark matter. The DarkQuantum project, coordinated by the University of Zaragoza in Spain, was granted funding of almost 13 million euros. The aim of the project is the development of new quantum sensors and their application in experiments to search for axions – hypothetical particles that could make up dark matter. One of the benefitting experiments is BabyIAXO, a dark-matter observatory under preparation at DESY.



Visualisation of the BabyIAXO experiment

November

PhD Thesis Prize 2023

The PhD Thesis Prize of the Association of the Friends and Sponsors of DESY (VFFD) was awarded in equal parts to Annika Lena Rudolph for her thesis "Emission of Multiple Messengers from Gamma-Ray Bursts" and to Dennis Mayer for his thesis "Time-resolved X-ray Spectroscopy of 2-Thiouracil". Congratulations!

Annika Lena Rudolph

Dennis Mayer

WPC Theoretical Physics Symposium

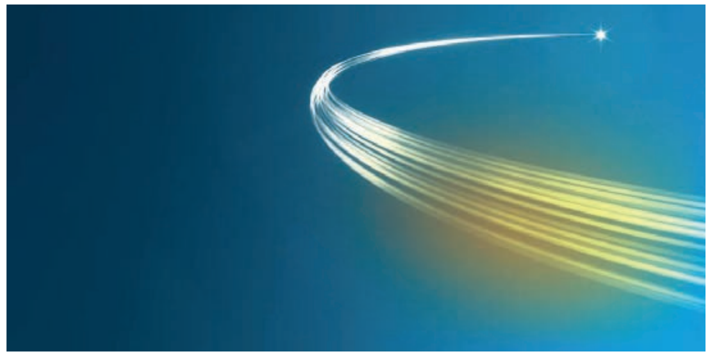
The WPC Theoretical Physics Symposium, organised by the Wolfgang Pauli Centre (WPC) for Theoretical Physics, a joint forum of Universität Hamburg and DESY, took place on 8–10 November at DESY. The three-day symposium brought together leading international experts from different areas of theoretical physics, particularly mathematical physics, high-energy physics, quantum field theory and string theory. Among the attendees was Edward Witten, one of the most prominent and most cited physicists of all times, who received the Hamburg Prize for Theoretical Physics at the meeting.

From left to right: Volker Schomerus, Chairman of the jury of the Hamburg Prize for Theoretical Physics, senior scientist at DESY and speaker of the Wolfgang Pauli Centre, Edward Witten, winner of the 2023 prize, and Sabine Kunst, Chairwoman of the Joachim Herz Foundation

Lecture of the WPC Symposium at DESY

Groundbreaking decision for PETRA IV

The budget committee in charge of the 2024 German federal budget decided to finance an important preparatory project for the fourth-generation synchrotron radiation source PETRA IV at DESY, for which DESY will receive 40 million euro in start-up funding. The funds can be used for preparatory measures for PETRA IV, in particular for the design and prototype of an innovative, energy-saving accelerator technology and the transformation of the business model.

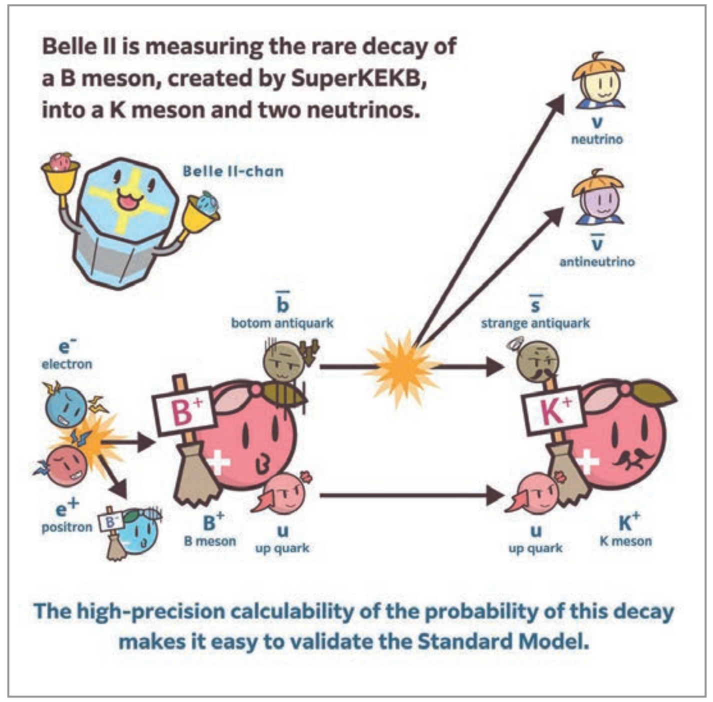


DESY hosts ICFA Seminar

The 13th ICFA Seminar on Future Perspectives in High-Energy Physics, which is held every three years, was organised by DESY on behalf of the International Committee for Future Accelerators (ICFA). The four-day international exchange of information focused on plans for future facilities in particle physics. The meeting, which is by invitation only, was attended by the directors of most of the world's major laboratories in the field, senior particle and accelerator physicists and science officials from several countries.

Belle II detects rare particle decay

For the first time ever, the Belle II experiment detected a charged *B* meson, a particle consisting of a quark and an anti-*b*-quark, decaying into a kaon (another particle consisting of a quark and an antiquark), a neutrino and an antineutrino. The discovery did not come as a surprise: The decay was predicted with high precision by the Standard Model of particle physics, the theory that describes the constituents and forces in the universe. Until now, this event simply could not be observed because of technological limitations. What did come as a bit of a surprise, however, was the frequency with which Belle II researchers observed it.

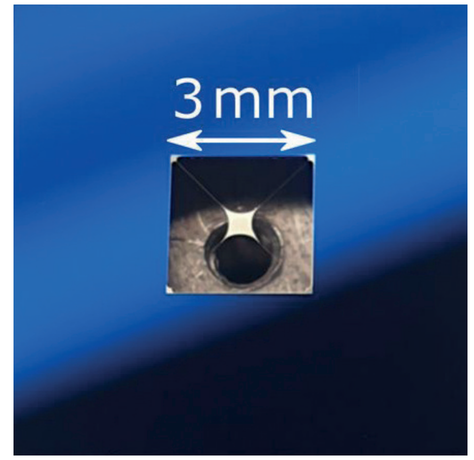


Artist's interpretation of the new decay seen by Belle II

December

Broadly applicable gas pressure sensor filed for patent

New technology from the world of gravitational-wave detectors: DESY researcher Christoph Reinhardt from the ALPS II experiment and PhD student Hossein Masalehdan from Universität Hamburg developed a pressure sensor that can be used over extremely large pressure and temperature ranges and, as a variant, can even identify which gas is flowing around it. The invention, which was filed for patent, was honoured with the DESY Innovation Award. The development of the sensor towards market maturity will also be supported by the DESY Generator Programme, an internal start-up funding programme for transfer projects.



An 80 nm thick trampoline membrane made of silicon nitride is the central element of the pressure sensor.

New Emmy Noether Research Group

DESY theorist Johannes Braathen received 1.59 million euro from the German Research Foundation (DFG) to set up an Emmy Noether Independent Junior Research group. His project, called "Cornering New Physics with Generic Precision Calculations", aims at preparing extremely precise theoretical predictions for phenomena beyond the Standard Model that can then be investigated by experiments. The group's particular attention will be on the Higgs boson, which is at the interface of many aspects of particle physics and early-universe evolution.

Johannes Braathen, new Emmy Noether group leader at DESY

Experimental particle physics

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

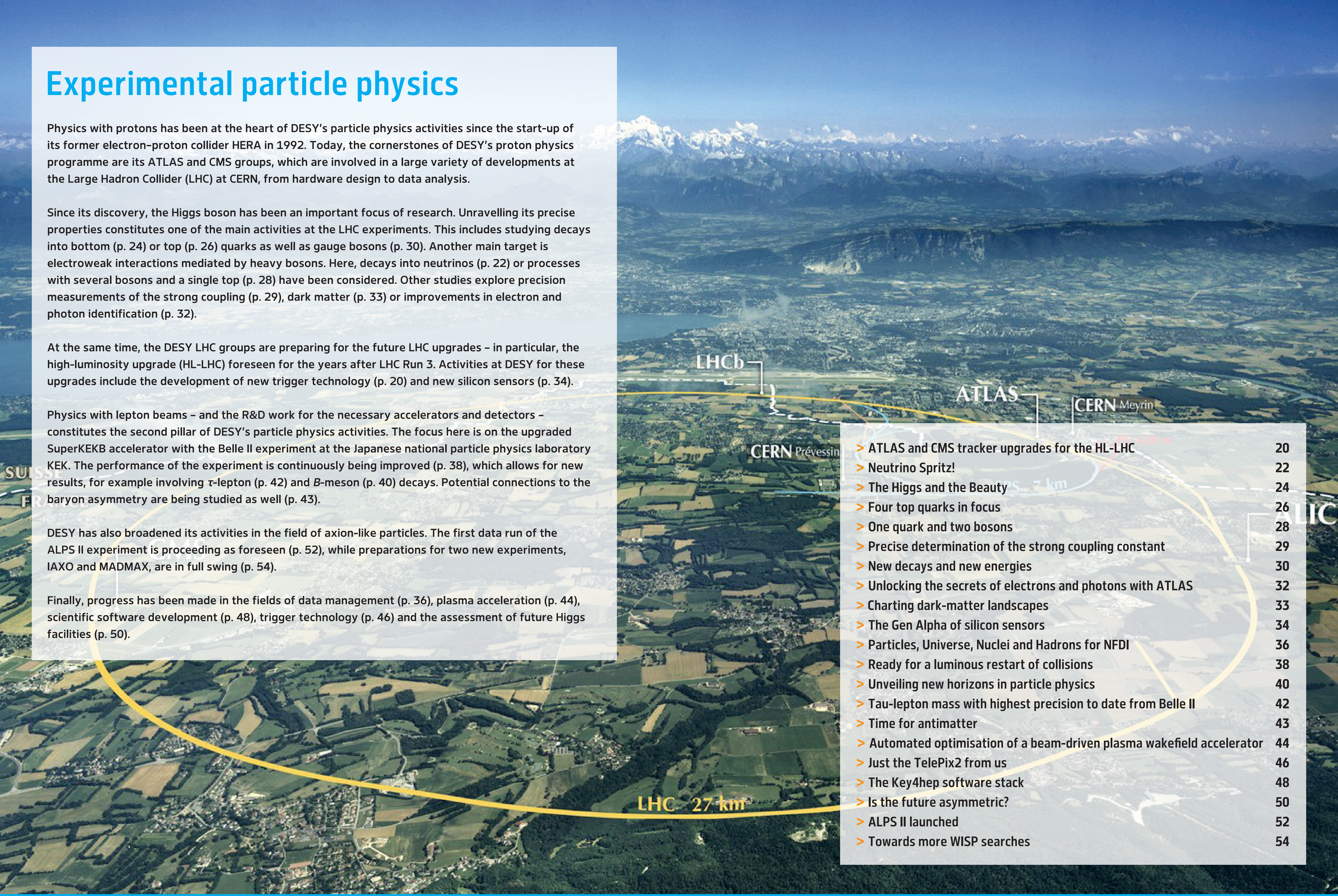
Since its discovery, the Higgs boson has been an important focus of research. Unravelling its precise properties constitutes one of the main activities at the LHC experiments. This includes studying decays into bottom (p. 24) or top (p. 26) quarks as well as gauge bosons (p. 30). Another main target is electroweak interactions mediated by heavy bosons. Here, decays into neutrinos (p. 22) or processes with several bosons and a single top (p. 28) have been considered. Other studies explore precision measurements of the strong coupling (p. 29), dark matter (p. 33) or improvements in electron and photon identification (p. 32).

At the same time, the DESY LHC groups are preparing for the future LHC upgrades – in particular, the high-luminosity upgrade (HL-LHC) foreseen for the years after LHC Run 3. Activities at DESY for these upgrades include the development of new trigger technology (p. 20) and new silicon sensors (p. 34).

Physics with lepton beams – and the R&D work for the necessary accelerators and detectors – constitutes the second pillar of DESY's particle physics activities. The focus here is on the upgraded SuperKEKB accelerator with the Belle II experiment at the Japanese national particle physics laboratory KEK. The performance of the experiment is continuously being improved (p. 38), which allows for new results, for example involving τ-lepton (p. 42) and *B*-meson (p. 40) decays. Potential connections to the baryon asymmetry are being studied as well (p. 43).

DESY has also broadened its activities in the field of axion-like particles. The first data run of the ALPS II experiment is proceeding as foreseen (p. 52), while preparations for two new experiments, IAXO and MADMAX, are in full swing (p. 54).

Finally, progress has been made in the fields of data management (p. 36), plasma acceleration (p. 44), scientific software development (p. 48), trigger technology (p. 46) and the assessment of future Higgs facilities (p. 50).



ATLAS and CMS tracker upgrades for the HL-LHC

Assembly, integration and production

Both the tracker of the CMS experiment and the inner detector of the ATLAS experiment at the LHC will be completely rebuilt in the coming years. The DESY ATLAS and CMS groups are strongly involved in the construction of the ATLAS strip tracker and the CMS outer tracker, respectively. The assembly and integration of the main structures for both of these endcaps will occur in the DESY laboratories. The production phase will start in the near future or has already started for some of the detector components.

ATLAS ITk production at DESY in full swing

The DESY ATLAS group is one of the major players in the construction of the new inner tracker (ITk) for the ATLAS detector, in particular the subdetectors of the ITk strip endcap. The production of multiple elements of the tracker is currently in full swing, aiming for final installation in the ATLAS spectrometer in 2027.

The final assembly procedure of the local support structures of the ITk strip endcaps, also called "petals", was developed at DESY and transferred to industry. DESY is still the main institute responsible for delivering the key components of the petal assembly:

- The "facesheets" or "skins", which consist of a polyimide–copper stack-up circuit board co-cured together with three thin layers of unidirectional, high-modulus pre-preg carbon fibre in 0-90-0 orientation
- The "cooling loops", an assembly of thin, 2.27 mm outer diameter, 160 µm wall thickness titanium pipes, bent to shape and with ceramic-based (Al_2O_3) insulating breaks connected to the inlet and outlet with orbital welds
- The "thermal foam sets", sets of carbon-based foam material with low density (ρ ~ 0.23 g/cm^3) and high thermal conductivity (K ~ 30 W/Km), machined to shape with high precision.

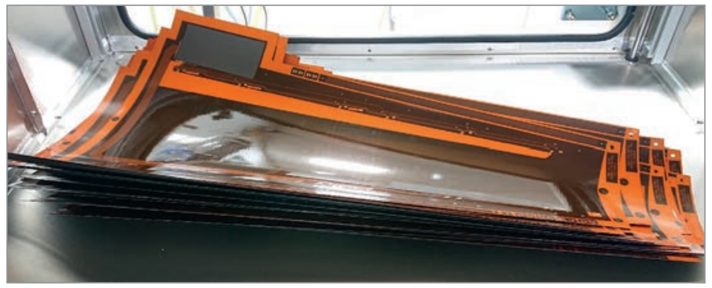


Figure 1
Set of co-cured facesheets after undergoing QC, ready to be shipped to the industrial assembly partner AVS

An ambitious quality control (QC) programme was developed and exercised at DESY and other collaborating institutes to ensure the suitability of all these components for the final detector. The QC programme includes geometrical, mechanical, electrical and thermal performance checks on all of these DESY deliverables.

The production of the DESY deliverables was successfully initiated in 2023. More than 200 facesheets were produced at DESY. As an example, Fig. 1 shows a completed set of co-cured facesheets, ready to be sent to the industrial partner. A high yield of approximately 97% has been achieved so far. Up to 35 foam sets and 13 cooling loops were also delivered in 2023, with a yield higher than 90% after QC. This enabled the industrial partner to stock up for the beginning of the assembly production, which is currently ongoing. The first local support units will be delivered in the first quarter of 2024. Figure 2 shows a completed petal.

The ITk strip petals are populated with the main sensing units of the strip tracker, the "modules", assemblies of a silicon microstrip sensor and its associated readout, power and control electronics. This population of the petal supports is referred to as "module loading", and it is another key activity in which DESY plays a major role: As one of the four endcap module loading sites across the ITk production, 25% of the fully loaded petals for the experiment are assembled at DESY, up to a total of 100 double-sided petals.

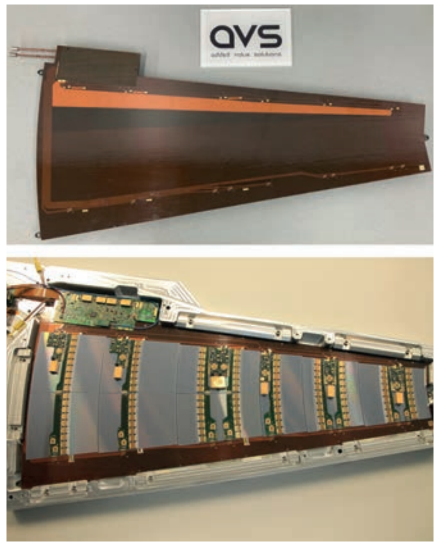


Figure 2
Top: Petal support structure. Bottom: First fully loaded petal assembled at DESY.

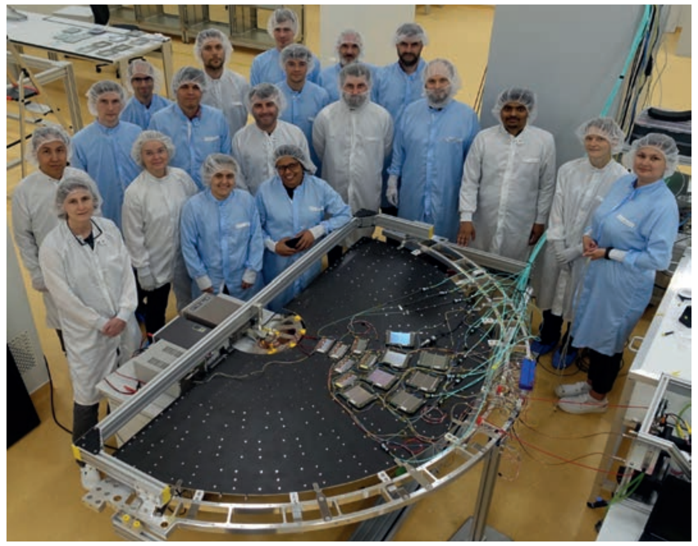


Figure 4
Participants of the integration exercise gather around a CMS outer tracker endcap Dee in the DAF cleanroom after having successfully mounted 13 silicon tracking modules onto the large carbon fibre support structure.

The module loading process was developed by DESY in collaboration with three other partner institutes: TRIUMF in Vancouver, Canada, IFIC in Valencia, Spain, and the University of Freiburg, Germany. This process allows the positioning of the modules with micrometre precision onto the local support structures by means of a custom-made pick-and-place gantry: The gantry provides automated glue dispensing, module placement and module survey. Four fully loaded petals with preproduction modules have been assembled in the collaboration, with DESY producing its first petal in 2023, marking an important milestone for the DESY ATLAS group. Figure 2 shows the "main" side of the DESY petal.

CMS PS module assembly

The DESY CMS group is in charge of the assembly of 1120 silicon detector modules for the upgraded CMS tracker. Each module consists of two closely stacked silicon sensors glued onto a thin carbon fibre base plate. The module is completed by attaching electronic printed circuit boards for readout and powering.

Figure 3
Five bare PS modules for the CMS outer tracker on their support plates, ready for attaching the electronics and readout components

In anticipation of the upcoming series production phase, five sensor stacks were assembled in summer 2023. Figure 3 shows the fragile objects, stored on aluminium carrier frames for mechanical support.

So far, one of the five stacks could be completed into a full module. This module performs very well, passed all qualification tests and was successfully operated and characterised in the DESY II Test Beam Facility.

Dee integration test

DESY is also an integration centre for the endcap of the new CMS outer tracker. The building blocks of the endcap are half-discs, named Dees. A Dee is a carbon fibre sandwich with embedded cooling structures, to which silicon detector modules are mounted.

A major step on the way to the production phase was an integration test with multiple silicon detector modules on a Dee, which took place in June 2023. Collaborators from several European CMS institutes visited DESY for a week to exercise the delicate task of installing detector modules on the large structure, to evaluate ways of connecting them to the power and readout services and to gain experience in operating the modules on the Dee. In total, 13 detector modules were available, enough to populate a small section of a Dee. Figure 4 shows the participants next to the partially populated Dee in the cleanroom of the Detector Assembly Facility (DAF) in Building 26 at DESY.

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Neutrino Spritz!

Mixing heavy neutrinos at the LHC

Neutrinos distinguish themselves among the particles of the Standard Model (SM) of particle physics due to their minuscule mass and exceptionally feeble interaction probabilities. A plausible theory aiming to elucidate these distinctive properties proposes additional heavy neutrinos that mix with the SM neutrinos. The ATLAS and CMS collaborations searched their data sets for signs of heavy neutrinos produced in proton–proton collisions using novel search methods for the first time at the LHC. The investigations explore the production of heavy neutrinos in the decays of *W* bosons and in *WW* scattering events.

Introduction

During the formulation of the Standard Model, neutrinos were initially proposed to be massless. However, the observation of neutrino oscillations has revealed that at least two of the three neutrinos observed in nature must possess mass, albeit a tiny one compared to all other fundamental particles. A favourable theory to explain these neutrino masses is the Type I Seesaw model. It introduces three heavy neutrinos, which can be either Majorana or Dirac particles, with the former implying that the particles are their own antiparticles. By mixing with the SM neutrinos, these heavy neutrinos give mass to the SM neutrinos. The Seesaw model gains additional significance as one of the three heavy neutrinos could potentially serve as a candidate for dark matter. Moreover, the mixing angles in this model can be adjusted to replicate the observed matter–antimatter asymmetry of the universe. Even if these new particles are kinematically inaccessible, the Majorana nature of active neutrinos can still be probed indirectly using effective field theories, with the lowest-dimensional operator being the so-called dimension $d = 5$ Weinberg operator.

Exploring the high-mass region

Searches for neutrinoless double-beta decay are very sensitive probes of these models. However, due to the limited energy in nuclear decays, only final states with electrons can be probed. The Feynman diagram in Fig. 1 is essentially the high-energy equivalent of neutrinoless double-beta decay. A team with strong DESY involvement studied the phenomenology of this process and explored the sensitivity of the LHC experiments using a fast simulation of the ATLAS detector implemented in the DELPHES simulation tool [1, 2]. Even though the LHC can access all three lepton flavours, the study focused on final states with two muons, since they are experimentally more accessible than tau leptons.

Majorana neutrinos in same-sign *WW* scattering have a very distinct signature. The analysis targeted final states including exactly two same-sign muons and at least two hadronic jets well separated in rapidity. The requirement for a very high transverse momentum of the second-hardest muon was used to explore the sensitivity for signals originating from a heavy Majorana neutrino. Previous searches, where heavy neutrinos were produced resonantly, are only sensitive up to masses of 1.4 TeV. The *WW* scattering channel can greatly extend this mass range covered by current LHC searches and, particularly, adds invaluable sensitivity above a few hundred GeV.

Encouraged by the results of the phenomenological study, a search for heavy Majorana neutrinos produced in same-sign *WW* scattering was performed with a leading contribution from the DESY ATLAS group using the full LHC Run 2 data set [3]. The modelling of the main backgrounds, from SM same-sign *WW* scattering and *WZ* production, was constrained with data in dedicated signal-depleted control regions. Since signal events typically have a significantly higher muon transverse momentum than those arising from SM backgrounds, the entire shape of the transverse-momentum distribution of the subleading muon was used to discriminate between signal and background.

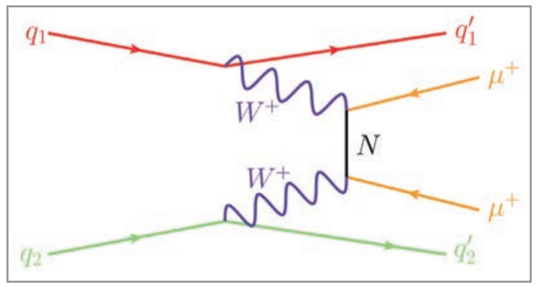

Figure 1

Diagrammatic representation of same-sign $\mu^\pm\mu^\pm$ production in $W^\pm W^\pm$ scattering mediated by a Majorana neutrino *N* in proton–proton collisions

No significant excess was observed over the background expectation. Upper limits on the neutrino mixing element at 95% confidence level were computed for signals with Majorana neutrino masses between 50 GeV and 20 TeV based on a Phenomenological Type I Seesaw model. As shown in Fig. 2, constraints on the muon-neutrino mixing element were extended from previous results at masses on the order of 1 TeV in the resonant production channels to values of up to 20 TeV in this analysis. In addition, limits were set on the $d = 5$ Wein-berg operator, which translate to an observed (expected) upper limit of 16.7 (13.1) GeV on the effective $\mu\mu$ Majorana neutrino mass, which cannot be probed in nuclear decays.

Long-lived heavy neutrinos

An experimentally intriguing phenomenon arises when heavy neutrinos are light, i.e. with a mass below 20 GeV. Due to their lifetime being proportional to $m^{-5}\,|V_{lN}|^{-2}$, they can travel macroscopic distances within the detector before undergoing decay, provided the mixing element V_{lN} with the SM leptons *l* is sufficiently small. A recent analysis by the CMS collaboration, led by a team deeply involved with DESY, has zeroed in on these long-lived signatures [4]. In the study, the heavy neutrino was considered to traverse distances from a few hundred micrometres up to about one metre away from the proton–proton collision at the centre of the detector. Its decay to a SM electron, muon or tau lepton and at least one jet, originating from an intermediate *W* boson, results in trajectories that are displaced and do not align with the point of the collision.

This novel analysis was designed to be sensitive to a broad spectrum of scenarios involving heavy Majorana or Dirac neutrinos. For the first time at the LHC, arbitrary mixing scenarios involving all three SM lepton generations were explored. Events featuring two leptons (electrons/muons) in any flavour or charge combination, along with jets, were selected from the LHC Run 2 data set.

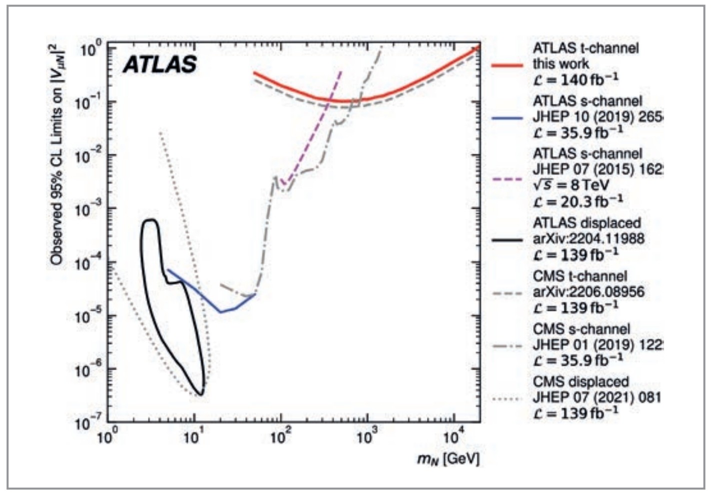

Figure 2

Overview of the most stringent 95% CL limits set on the heavy Majorana neutrino mixing element $|V_{\mu N}|^2$ as a function of m_N, as observed by ATLAS and CMS

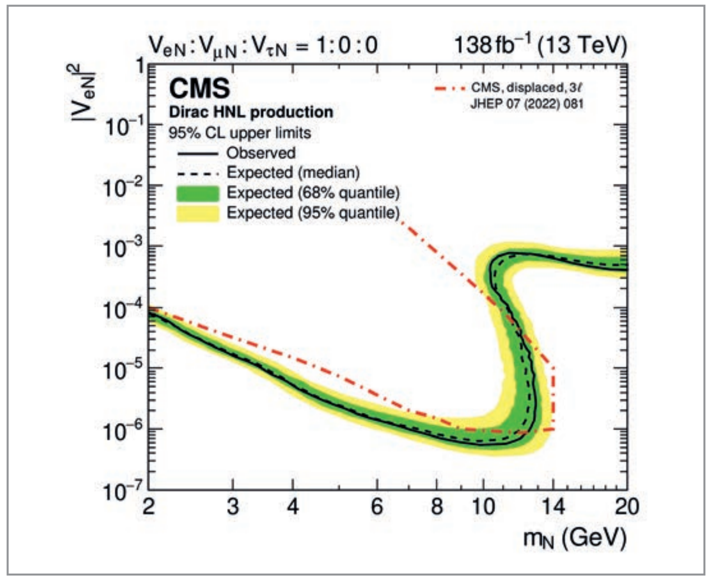

Figure 3

Two-dimensional 95% CL exclusion limits on the heavy Dirac neutrino mixing element with electrons $|V_{eN}|$ as a function of its mass. A comparison with an orthogonal CMS analysis targeting the pure leptonic decay channel is overlaid.

A central aspect of the analysis involved the identification of displaced jets, arising from the decay of the heavy neutrino, through a deep neural network. The network uses various properties of the jet and its constituents as inputs, incorporating information on particle tracks and their displacements. A technique called "domain adaptation" was implemented to ensure that only features well described in the data are used to decide whether a jet originated from a heavy-neutrino decay. This was accomplished by simultaneously training the network on both simulated and real data events, forcing the resulting classifier to be insensitive to any subtle differences between them.

No excess was observed in the data, and exclusion limits were determined for various heavy-neutrino lifetime, mass and mixing scenarios. Figure 3 illustrates the two-dimensional limit on the mixing element as a function of the heavy Dirac neutrino mass, exclusively mixing with electron neutrinos. The employed displaced jet identification resulted in competitive bounds similar to those obtained in a previous CMS analysis focused on an orthogonal final state involving three leptons. Additional results can be found in Ref. [4].

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References:

[1] B. Fuks, J. Neundorf, K. Peters et al., Phys. Rev. D 103, 5 (2021)
[2] B. Fuks, J. Neundorf, K. Peters et al., Phys. Rev D 103, 11 (2021)
[3] ATLAS Collaboration, Eur. Phys. J. C 83, 9 (2023)
[4] CMS Collaboration, JHEP 03, 105 (2024)

The Higgs and the Beauty

Beauty quarks add clarity to Higgs portrait

The decay of the Higgs boson into a pair of bottom quarks, also referred to as beauty or *b* quarks, is one of the key probes of both the Standard Model (SM) and potential new physics phenomena beyond it (BSM). Using advanced analysis techniques, physicists from the DESY CMS group, together with colleagues from other institutes, have delved into the properties of the Higgs boson as it decays into *b* quarks, thereby offering deeper insights into the Higgs mechanism. The results are based on partial (91 fb^{-1}) and full (138 fb^{-1}) LHC Run 2 data sets of proton–proton collisions at a centre-of-mass energy of 13 TeV, collected with the CMS experiment.

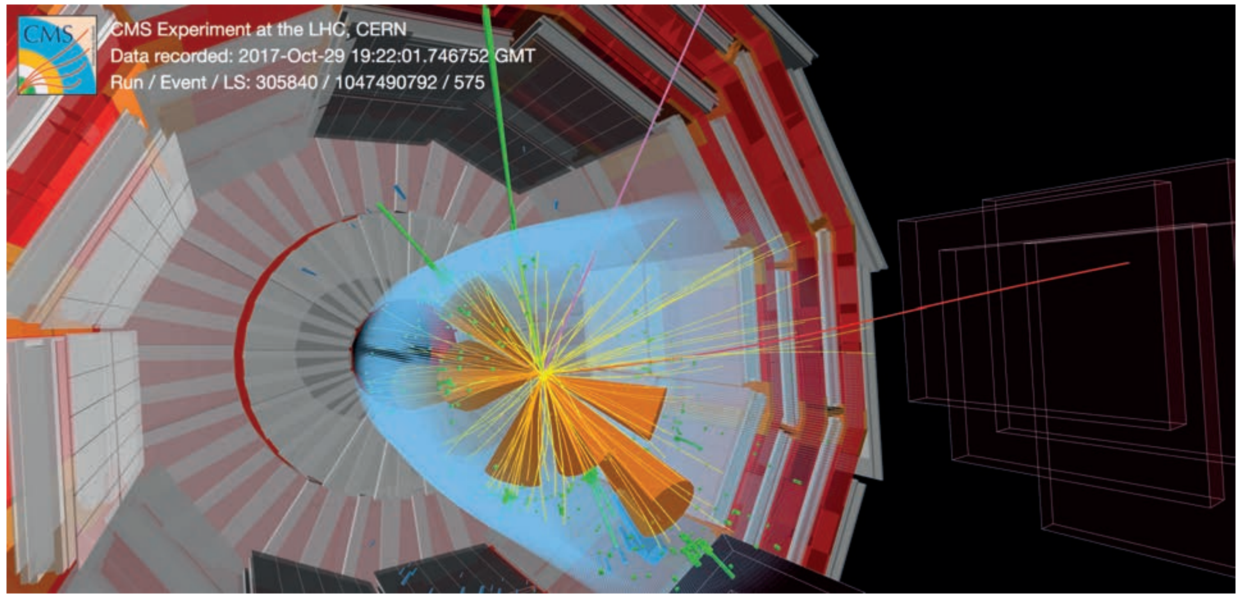

Figure 3
Display of a dilepton candidate *ttH* ($H \to bb$) event [4]

Despite constituting the largest branching fraction at 58%, the exploration of the Higgs-boson decay into beauty quarks ($H \to bb$) poses significant experimental challenges. In the dominant gluon–gluon fusion production mode, the Higgs-boson signature is overwhelmed by background from quantum chromodynamics (QCD) multijets. Much higher sensitivity to the $H \to bb$ decay is provided by other production modes, albeit with lower rates, due to more favourable background conditions. Scientists from the DESY CMS group, in collaboration with other institutes, have scrutinised the properties of the Higgs boson in the $H \to bb$ decay using three distinct processes: the production of the Higgs boson i) in the vector boson fusion process (VBF), (ii) in association with *Z* or *W* bosons (*VH*) and (iii) in association with top-quark pairs (*ttH*).

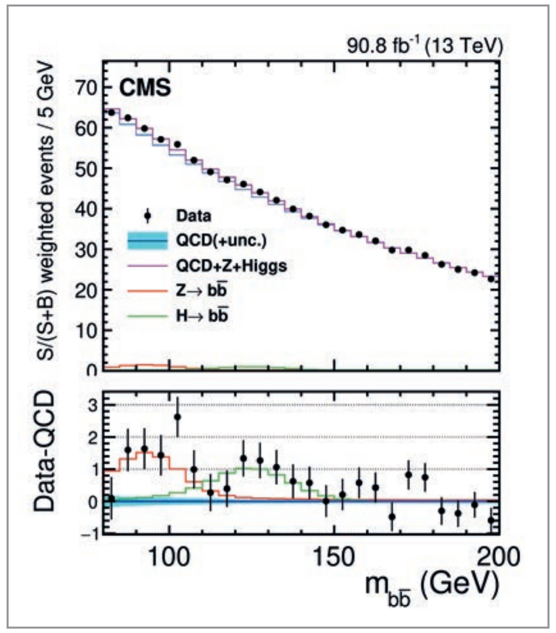

Figure 1
m_{bb} distribution after weighted combination of all categories in the analysis weighted with S/(S+B) (S: signal, B: background)

VBF

The VBF production followed by the $H \to bb$ decay gives rise to a four-jet final state. Two of the jets, from the $H \to bb$ decay, typically lie in the central region of the detector. The other two jets, from the light quarks, are produced mainly in the forward and backward directions relative to the beamline and consequently have a large rapidity separation between them as well as high dijet invariant mass. The DESY CMS group participated both in the development of a dedicated VBF trigger and in the analysis of the data recorded with this trigger. The VBF($H \to bb$) signal manifests as a resonant peak in the mass spectrum of *b* quarks (Fig. 1) with a significance of 2.4 standard deviations above the background expectation. The signal rate was measured to be 1.01±0.51 relative to the SM prediction.

VH

The *VH* production followed by the $H \to bb$ decay and the vector boson decay into leptons is often referred to as the "$H \to bb$ golden channel", as it has the largest sensitivity among all Higgs-boson production modes despite a relatively low production rate. The secret lies in the leptons from the *V* decays, which help to select events during the data-taking and are reconstructed with relatively good resolution. Precise differential measurements of this process, especially in regions with high transverse momentum (p_T) of the produced particles, are very important for indirect BSM searches. The DESY CMS group, together with colleagues from other institutes, measured the *VH* production cross section differentially as a function of the p_T of the vector boson as well as of the number of additional jets in the event, as shown in Fig. 2. The measured cross section values were found to be compatible with the SM prediction.

ttH

The *ttH* production with subsequent $H \to bb$ decays produces final states involving nearly all physics objects that particle physicists deal with in their analyses. The complex signal signature comprises multiple *b* quarks originating from both the *tt* and the Higgs-boson decays, and its production rate is about two thousand times less likely than the irreducible *tt+bb* background. Depending on the *W*-boson decays from the top quarks, the *b* quarks can be accompanied by additional jets (fully hadronic channel), one charged lepton and two jets (semileptonic channel), or two charged leptons (dilepton channel). The DESY CMS group focused on investigating the dilepton channel. Figure 3 shows an event display of a *ttH*($H \to bb$) candidate in this final state.

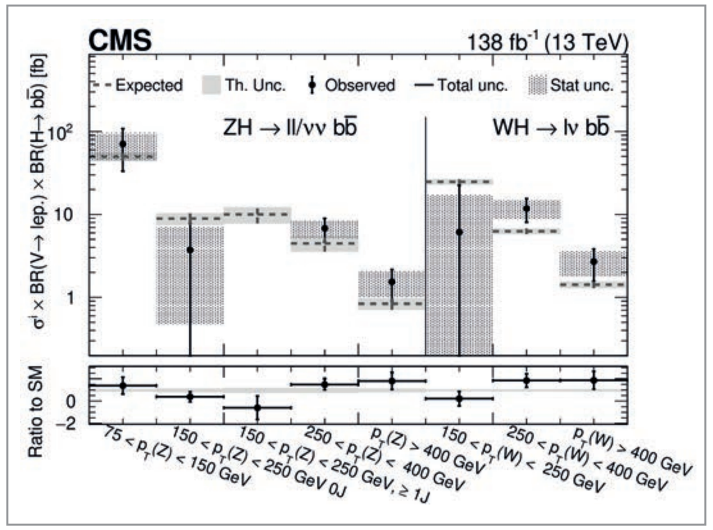

Figure 2
Measured values of σB, defined as the product of the *VH* production cross sections multiplied by the branching fractions of $V \to$ leptons and $H \to bb$.

Events were classified into signal and background categories based on jet and *b*-jet multiplicities, the output of an artificial neural network and the reconstructed Higgs-boson p_T. State-of-the-art simulation of the *tt+bb* background was used, and its rate was calibrated in situ by the fit. The production rate of the *ttH* process was measured to be 0.36±0.23 relative to the SM prediction. The result is consistent with a similar measurement performed by the ATLAS collaboration. Additionally, the study provided measurements of the *ttH* cross section in bins of the reconstructed Higgs-boson p_T.

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References:

[1] CMS Collaboration, JHEP 01, 173 (2024)
[2] CMS Collaboration, arXiv:2312.07562
[3] CMS Collaboration, CMS-PAS-HIG-19-011, https://cds.cern.ch/record/2868175?ln=en
[4] CMS Collaboration, https://cds.cern.ch/record/2680325

Four top quarks in focus

Observation of four-top-quark production creates new opportunities for ATLAS and CMS

The production of four top quarks is even rarer than that of the Higgs boson, with 4000 collisions producing Higgs bosons expected for each collision producing four top quarks. So why do DESY physicists want to study this elusive production mode? The reason is loops and quantum chromodynamics.

Production of top quarks can occur in various ways. While top quark–antiquark pairs are the most common, single top quarks have also been observed by ATLAS and CMS in most production modes that the Standard Model predicts. However, it is much rarer for four top quarks to be produced simultaneously. This would entail two top quarks and two top antiquarks originating from the same collision. The Standard Model predicts the cross section for four-top-quark production to be very small: only 12 fb, significantly smaller than the cross section for top-quark pairs of about 831 000 fb.

The potential (even when off-shell) exchange of new particles or variations in the interaction between the top quark and the Higgs boson will alter the frequency of four-top-quark production, and the process is particularly sensitive to these virtual contributions. As top quarks are so massive, producing four top quarks is particularly sensitive to particles that preferentially interact with top quarks or heavy particles in general, including axion-like particles and heavy Higgs bosons. Four-top-quark production is a precise test of quantum chromodynamics (QCD), the quantum field theory of the strong interaction and one that can be calculated relatively accurately nowadays.

Besides, events involving four top quarks lead to spectacular outcomes, as each top quark decays into a *W* boson and a bottom quark, resulting in many, many jets (Fig. 1 and Fig. 2). The resulting detector signatures vary drastically, from zero to four charged leptons and up to 12 jets. This makes the study of four top quarks very diverse and experimentally interesting, as it is one of the most complex signatures studied at the LHC, which is particularly challenging when dealing with signatures that feature a low number of charged leptons. Extracting the signal when studying four top quarks demands some of the most ambitious machine learning used in LHC physics analysis.

Multiple teams at DESY are working on studying four top quarks. In new results released in 2023, both ATLAS and CMS achieved a five-sigma observation of the process in signatures with many leptons. These signatures have a relatively low background, but represent only a tiny fraction of all four-top-quark signatures, and, due to the many energetic neutrinos, it is difficult to study the physics.

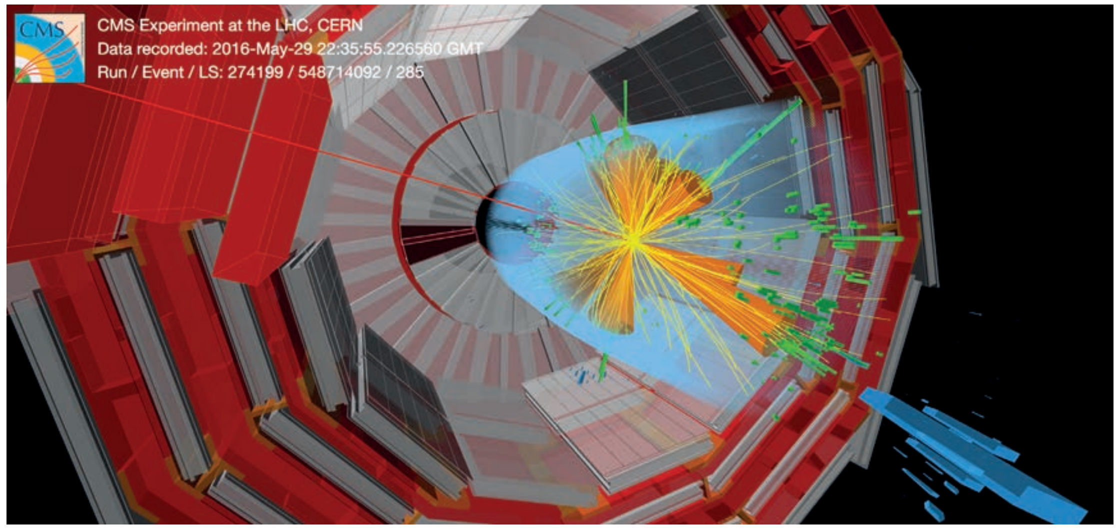

Figure 1

Event display of a candidate *tttt* event recorded by CMS. This event contains one muon and ten jets, four of which are *b*-tagged jets. One of the four top quarks is expected to have produced leptons and a *b* quark, while the other three decayed to jets.

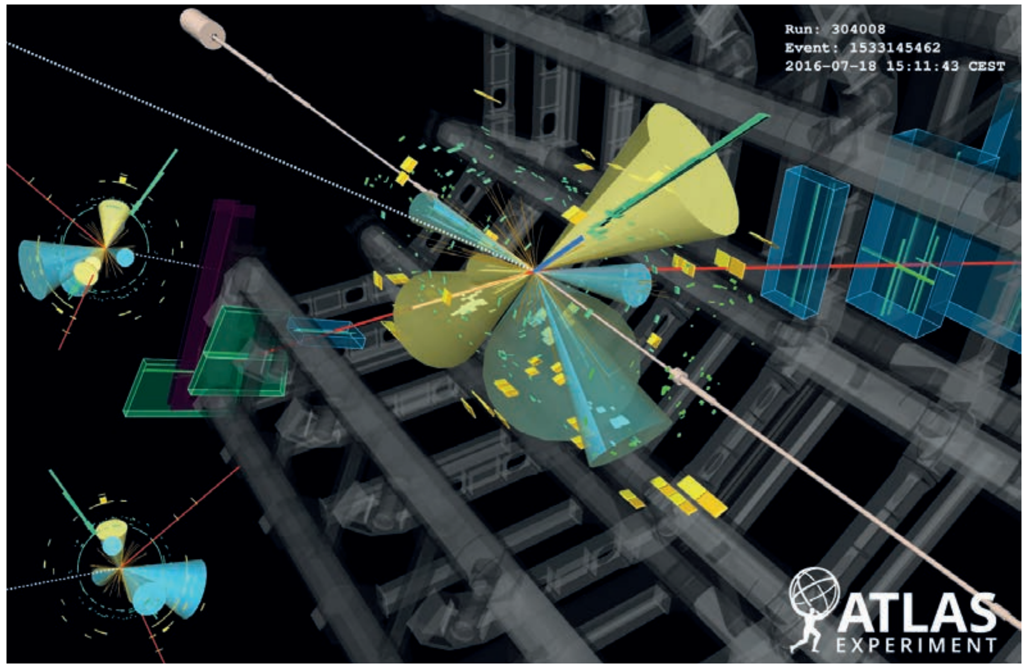

Figure 2

Event display of a candidate *tttt* event recorded by ATLAS. This event contains two muons, one electron and seven jets, four of which are *b*-tagged jets. Three of the four top quarks are expected to have produced leptons and a *b* quark, while the fourth decayed to jets.

The DESY CMS group was additionally involved in the first three-sigma evidence for four-top-quark production in signatures without many leptons. These new results focused on final states with zero, one and two opposite-charge leptons, and, for the first time, scenarios where only jets are produced were also considered. To do so, new machine learning algorithms were employed, not only to differentiate the four-top-quark events from the background but also, for the first time at the LHC, to predict the behaviour of that background using measured data, after the algorithms had been trained on simulated events to predict background properties.

Combining all these various CMS searches for four-top-quark events, the sensitivity for observing Standard Model production of four top quarks already surpasses the three standard deviations typically required by particle physicists to claim evidence for a new production mechanism. The observed number of collisions consistent with four-top-quark production modestly exceeds the Standard Model prediction at four sigma, but remains compatible within the broad measurement uncertainties (Fig. 3).

CMS physicists at DESY will now pursue the elusive signature in the context of new undiscovered particles in the LHC Run 3 data. At DESY, physicists are now examining the next challenge: the search for new particles in signatures with three top quarks, which are predicted to be even rarer than four top quarks.

Four (and three) top quark production is one of the exciting topics to be investigated during LHC Run 3 and with the High-Luminosity LHC, which is slated to generate 20 times more top quarks than currently available.

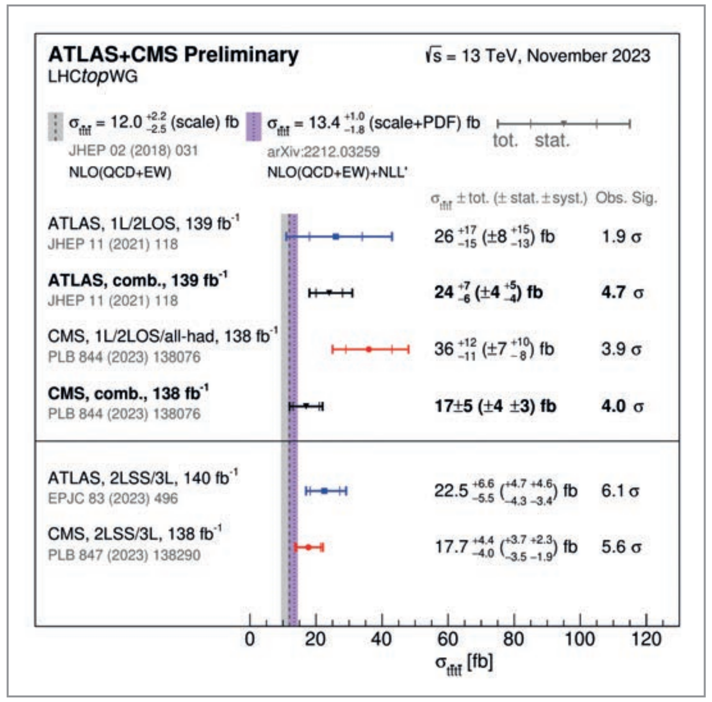

Figure 3

Summary of all measurements of four-top-quark production at the LHC

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References:

[1] CMS Collaboration, Phys. Lett. B 844, 138076 (2023)
[2] CMS Collaboration, Phys. Lett. B 847, 138290 (2023)
[3] ATLAS Collaboration, Eur. Phys. J. C 83, 496 (2023), Eur. Phys. J. C 84, 156 (2024) (erratum)

One quark and two bosons

CMS reports first evidence for *tWZ* production

The top quark, the Higgs boson, the *Z* boson and the *W* bosons are the heaviest elementary particles currently known. At the LHC, production processes involving top quarks in association with one boson have become experimentally well-established facts. In 2023, the DESY CMS group, together with colleagues from other institutes, found the first evidence for *tWZ* production comprising one top quark, one *Z* and one *W* boson. A key to success was the use of deep neural networks and extensive categorisations to distinguish the rare signal from the more likely background processes.

Searches for rare processes are an important way to study the validity and the limits of the Standard Model (SM) of particle physics. The SM makes precise predictions for the production of the known particles; deviations from the predictions could uncover the unexpected. As such, the search for and measurement of rare SM processes are complementary to precision measurements or direct searches for new particles.

The DESY CMS group has pioneered the search for the *tWZ* production process, in which a top quark is produced together with a *W* and a *Z* boson. One of the interesting aspects of this process is its sensitivity to new physics, which could modify the interaction between the top quark and the two bosons, thus altering the *tWZ* production rate. The analysis makes use of events with at least three leptons (electrons or muons): The *Z* boson decays into two leptons, and at least one other lepton comes from the decay of the top quark or the *W* boson.

In practice, most selected events come from other sources, e.g. from the *ttZ* process, which is five times more likely than the *tWZ* process. Subtle differences between the processes have to be used to separate the signal from the backgrounds.

The data samples were divided into several categories, according to the number of jets and leptons in the events. In each category, state-of-the-art deep neural networks (DNN) were trained to recognise *tWZ* and to tell them from *ttZ* and other backgrounds. The output of the DNN quantifies the probability for an event to belong to the signal (higher score) or to the background (lower score). In the distribution, shown in Fig. 1, it can be seen that the contribution from *tWZ* (red) is enriched towards higher score values.

The results of the DESY analysis provided the first evidence for the *tWZ* process, and the cross section was measured to be 0.37 ± 0.11 pb [1].

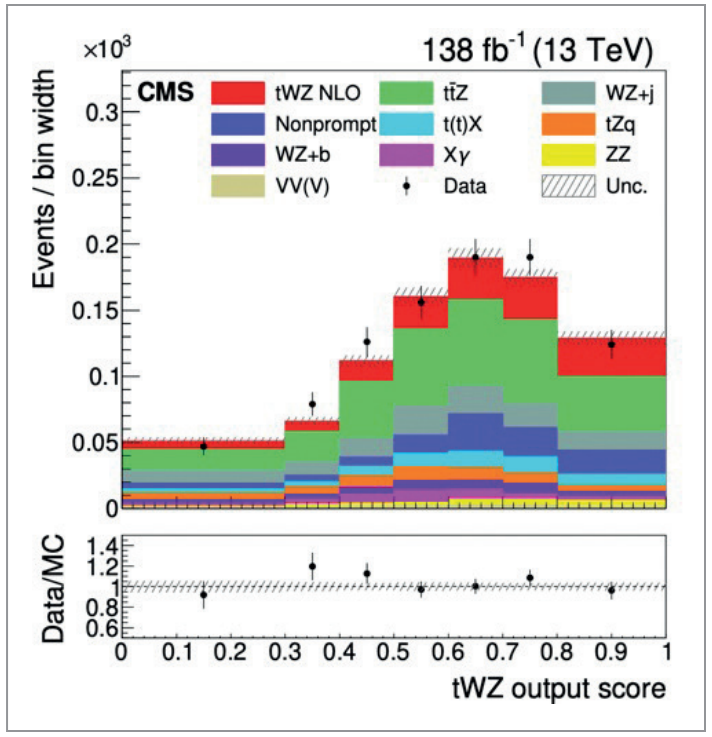

Figure 1

Output of the deep neural network classifier. The *tWZ* signal distribution, shown in red, is enhanced towards larger output values.

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Reference:

[1] CMS Collaboration, arXiv:2312.11668, submitted to Phys. Lett. B

Precise determination of the strong coupling constant

ATLAS measures the least precisely known SM coupling using *Z*-boson transverse momentum spectra

In a first at the LHC, the DESY ATLAS team has released a precise measurement of the rate (or cross section) of *Z*-boson production across the entire spectrum of possible outcomes for the decay products, using data from proton–proton collisions collected by the ATLAS experiment in 2012 at a centre-of-mass energy of $\sqrt{s}$ = 8 TeV. This result has enabled DESY scientists, in collaboration with other colleagues from the ATLAS collaboration, to extract the strength of the strong force. The final result, with less than 1% uncertainty, is the most precise determination of the strong force ever achieved by a single experiment.

The measurements of *W* and *Z* bosons at the LHC have provided valuable new insights into the fundamental parameters of the Standard Model (SM) of particle physics. Notably, *Z* bosons have become one of the most successful probes at the LHC. Their distinct properties render them indispensable instruments in unravelling the theoretical foundations of particle physics, extending beyond the SM. Whether in finely tuning the parameters of the SM or exploring new physics models, the study of the properties of *Z* bosons plays an important role in the present and future ATLAS physics programme.

The DESY ATLAS team played a pivotal role in the recent, highly precise measurement of *Z*-boson decays to two leptons (electrons or muons) [1]. The analysis achieved a precision in measuring the *Z*-boson transverse momentum from the decay products of better than 1%. The measurement was extended by a measurement of the *Z* boson's rapidity, a quantity related to the emission angle of the *Z* boson with respect to the beam axis. The double differential cross section of *Z*-boson production versus transverse momentum and rapidity (Fig. 1) allowed the ATLAS collaboration to precisely determine the coupling strength of the strong force [2]. The strong coupling constant, denoted α_S, is one of the fundamental parameters of the SM and describes the intensity of the strong interaction. It governs the extent of interaction among quarks and gluons, the basic building blocks of protons and neutrons.

The value $\alpha_S(m_Z) = 0.1183 \pm 0.0009$ was determined by concurrently adjusting it alongside other theoretical modelling parameters to match the observed data. To extract α_S, DESY ATLAS physicists used cutting-edge theory calculations of the production of the *Z* boson. The precision of the result depends on several factors, including the accuracy of the theoretical description and the precision to which the decay products of the *Z* boson can be measured in the detector. The new ATLAS result is compatible with the world average and is the most precise single measurement to date. It showcases that competitive precision physics is possible at a proton–proton collider.

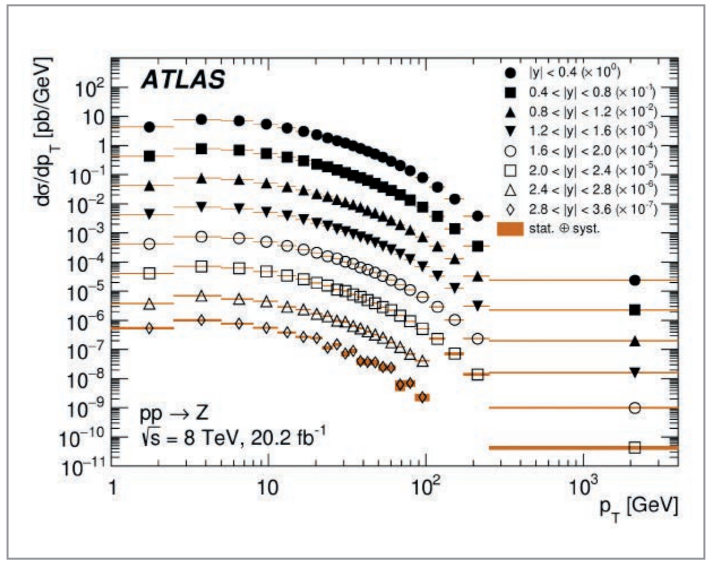

Figure 1

Measured transverse momentum of the *Z* boson produced in 8 TeV proton–proton collisions, in different rapidity (*y*) regions. The rapidity is linked to the polar scattering angle. From [1].

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References:

[1] ATLAS Collaboration, arXiv:2309.09318, accepted by Eur. Phys. J. C
[2] ATLAS Collaboration, arXiv:2309.12986, submitted to Nat. Phys.

New decays and new energies

New ways to probe the Higgs boson at the LHC

With a full Run 2 and a growing Run 3 data set, LHC physicists have produced exciting new Higgs-boson results. The DESY ATLAS group has played a pivotal role in presenting the first evidence for the rare $H \rightarrow Z\gamma$ decay. This evidence, with a significance of 3.4 standard deviations, stems from a combination of ATLAS and CMS analyses during the LHC's Run 2. In Run 3, the group achieved another milestone by measuring the inclusive Higgs-boson production rates in the $\gamma\gamma$ and $ZZ \rightarrow 4l$ decay channels in ATLAS, at an unprecedented centre-of-mass energy of 13.6 TeV. The combination of the $\gamma\gamma$ and $ZZ \rightarrow 4l$ measurements yields a total cross section of $\sigma(pp \rightarrow H) = 58.2 \pm 8.7$ pb, in agreement with the Standard Model prediction.

$H \rightarrow Z\gamma$, rare but finally revealed

Since the discovery of the Higgs boson by the ATLAS and CMS collaborations in 2012, a comprehensive programme of measurements has found its couplings and other properties to be largely in line with the predictions of the Standard Model (SM). However, several rare Higgs-boson decay channels, including $H \rightarrow Z\gamma$, remain unobserved. This decay, which occurs via loop diagrams (Fig. 1), is sensitive to modifications in several scenarios beyond the SM. ATLAS physicists therefore hope to use these loops as a magnifying glass to search for physics beyond the SM (BSM).

During the LHC's Run 2, the ATLAS detector collected approximately 30 times more Higgs-boson events than at the time of the Higgs-boson discovery, helping scientists study ever rarer decays. The DESY ATLAS group played a significant role in searching for the $H \rightarrow Z\gamma$ decay using 139 fb^{-1} of data at 13 TeV [1]. The Z boson was reconstructed through its decays into electron or muon pairs. This provides a clean signature with a good invariant-mass resolution for the final-state products of the Higgs-boson decay. After the reconstruction and selection of candidate events, the signal would show up as a narrow resonant peak at m_H in the invariant-mass distribution and stand out over the falling background. To further enhance the significance, the team assigned events to categories with different signal-to-background ratios by exploiting the kinematic features of different Higgs-boson production modes, including the vector-boson fusion topology, which was optimised using a dedicated boosted decision tree. As a result, the observed (expected) local significance of the $H \rightarrow Z\gamma$ signal with respect to the background-only hypothesis was found to be 2.2 (1.2) standard deviations, σ.

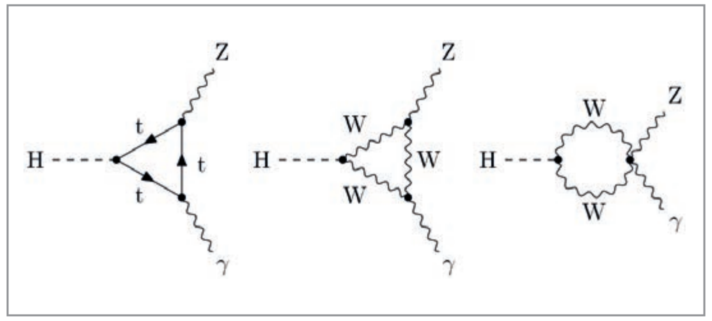

Figure 1
Examples of Feynman diagrams for the $H \rightarrow Z\gamma$ decay [3]

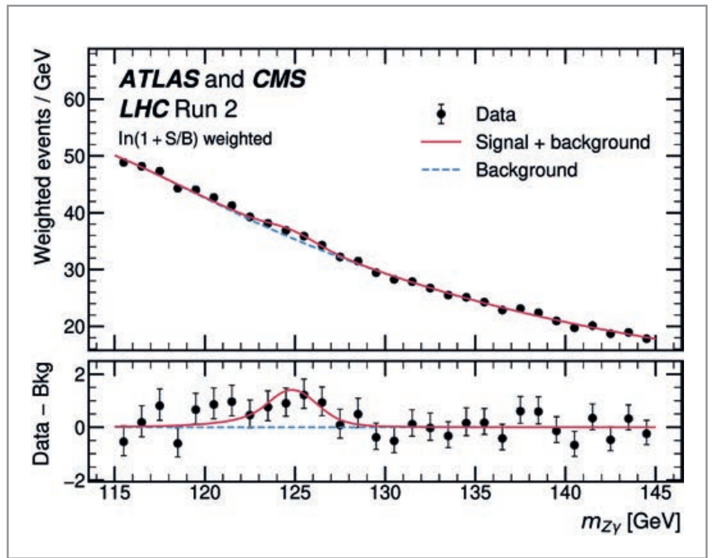

Figure 2
The $Z\gamma$ invariant-mass distribution. The signal-plus-background (background) probability density function is represented by a red solid (blue dashed) line. The lower panel shows the background-subtracted results. From [3].

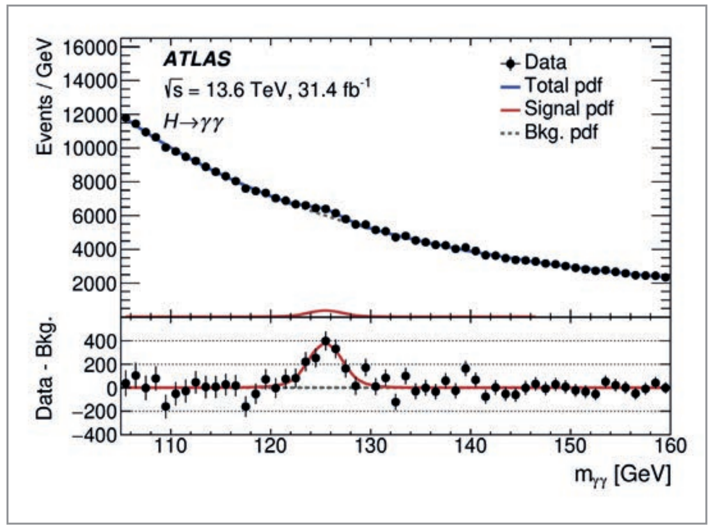

Figure 3
Di-photon invariant-mass spectrum from the $H \rightarrow \gamma\gamma$ measurement, using data from 2022. The Higgs-boson signal peak is shown by a red line. From [4].

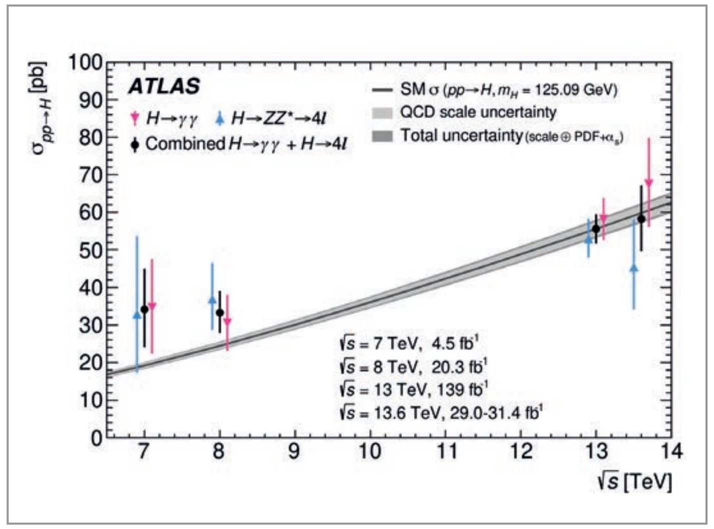

Figure 4
Total ATLAS Higgs-boson cross section measurements as a function of the centre-of-mass energy. They can be compared to the SM prediction and associated uncertainties in the grey band. From [4].

The CMS collaboration presented a similar analysis with a significance of 2.6 (1.1) σ [2].

As a natural extension of this work, the DESY ATLAS group contributed to a combination of the ATLAS and CMS searches, which provided the first evidence for the $H \rightarrow Z\gamma$ decay, with an observed (expected) significance of 3.4 (1.6) σ (Fig. 2) [3]! The team measured a signal yield of $2.2 \pm 0.6(stat.)^{+0.3}_{-0.2}(syst.) = 2.2 \pm 0.7$ times the SM prediction. The measured branching fraction for the decay is $(3.4 \pm 1.1) \times 10^{-3}$. The result agrees with the SM prediction and opens a new channel for the study of Higgs-boson properties and possibly of BSM effects.

Higgs-boson production at unprecedented energies

In July 2022, the LHC started Run 3 operations at a record-breaking centre-of-mass energy of 13.6 TeV.

The ATLAS collaboration, including members of the DESY ATLAS group, immediately started to analyse the new data and published a new measurement of the production rate of Higgs bosons using data collected in the second half of 2022 [4]. The measurement is a combination of two Higgs decay modes with distinctive signatures: the $H \rightarrow \gamma\gamma$ process and the $H \rightarrow ZZ \rightarrow 4l$ process. With similar final states to the $H \rightarrow Z\gamma$ process, but either higher branching fraction or better signal-to-background ratios, these two processes were the most sensitive channels in the discovery of the Higgs boson and are the "golden" channels to study its properties precisely. They were therefore the first ones used to measure Higgs production rates in Run 3. In both measurements, the Higgs boson was observed as an excess at m_H over the background prediction in the invariant-mass distribution of its decay products (Fig. 3, an example in the $H \rightarrow \gamma\gamma$ decay channel).

The cross sections times branching fractions (σ_X) in phase-space regions defined by the kinematics of the final-state photons or leptons were measured to be $\sigma_{\gamma\gamma} = 76^{+14}_{-13}$ fb and $\sigma_{4l} = 2.80 \pm 0.74$ fb. These results are in good agreement with the SM predictions of 67.6 ± 3.7 fb and 3.67 ± 0.19 fb, respectively.

By assuming that the Higgs boson decay rates to $H \rightarrow \gamma\gamma$ and $H \rightarrow \gamma\gamma \rightarrow 4l$ and the fraction of Higgs-boson events that the ATLAS detector can observe are those predicted by the SM, these results can be extrapolated to estimate the total rate of Higgs bosons produced in proton–proton collisions. The estimates from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ are combined to yield a Higgs-boson cross section of 58.2 ± 8.7 pb at 13.6 TeV. This result is also in agreement with the SM prediction (Fig. 4).

The new measurements allow the ATLAS collaboration to study the Higgs boson at a world-record energy and serve as great ways to study the performance of the ATLAS detector under the new conditions of the LHC's Run 3.

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References:
[1] ATLAS Collaboration, Phys. Lett. B 809, 135754 (2020)
[2] CMS Collaboration, JHEP 05, 233 (2023)
[3] ATLAS and CMS Collaboration, Phys. Rev. Lett. 132, 021803 (2024)
[4] ATLAS Collaboration, Eur. Phys. J. C 84, 78 (2024)

Unlocking the secrets of electrons and photons with ATLAS

Achieving unparalleled accuracy in calibrating electrons and photons

Electrons and photons play a crucial role in several fields of the analysis programme of the ATLAS collaboration at the LHC. Many analyses, such as Standard Model precision measurements, measurements in the Higgs sector and searches for new phenomena beyond the Standard Model of particle physics, rely on excellent electron and photon reconstruction efficiencies together with small misidentification probability, excellent momentum resolution and small uncertainties. The DESY ATLAS group was a strongly involved in the latest measurements of electron and photon performance, using the full LHC Run 2 data set collected by the ATLAS experiment from 2015 to 2018.

The ATLAS collaboration has reached an unprecedented level of precision in its understanding of the electron and photon object performance by analysing the complete Run 2 data set [1,2]. The ATLAS DESY team made substantial contributions to the comprehensive review of the energy calibration chain and the reassessment of all major sources of uncertainty. This effort led to an overall reduction of the calibration uncertainty by a factor of 2–3 compared to previous iterations, depending on the particle type, position and energy. The obtained calibration uncertainties typically stand at 0.05% for electrons originating from *Z*-boson decays (Fig. 1), while for photons with a transverse energy of 60 GeV, they average at 0.2%. This remarkable achievement enabled the ATLAS collaboration to measure the Higgs-boson mass in the di-photon channel with a precision of 1.1 per mille [3].

The DESY ATLAS group was also heavily involved in the latest electron and photon identification efficiency calibration [2]. The new measurement of the electron identification efficiency correction factor provides uncertainties at the 0.1% level in the central region. For electrons originating from *Z*-boson decays, these are the most precise measurements ever achieved within ATLAS, and they will have a significant impact on future ATLAS precision measurements. The improvements were achieved by employing new techniques to reduce the impact of particles misidentified as electrons on the efficiency measurement and by comparing different methods used to extract the efficiency measurement.

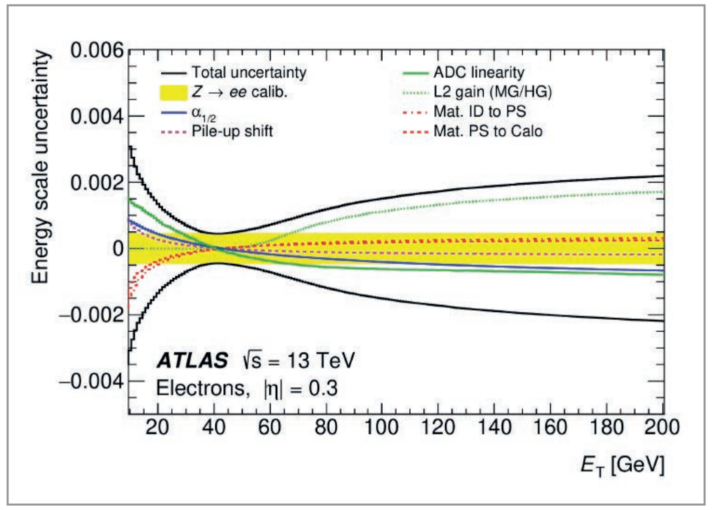

Figure 1

Relative energy scale calibration uncertainty for electrons as a function of transverse momentum (E_T). The total uncertainty is shown along with the main contributions. From [1].

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References:

[1] ATLAS Collaboration, JINST 19, P02009 (2024)
[2] ATLAS Collaboration, arXiv:2308.13362, submitted to JHEP
[3] ATLAS Collaboration, Phys. Lett. B 847, 138315 (2023)

Charting dark-matter landscapes

ATLAS searches set stringent constraints on DM interactions with an extended Higgs sector

Around 85% of all matter in the universe is non-luminous and not described by the Standard Model (SM) of particle physics, the successful theoretical framework that accurately describes the elementary particles and interactions making up the remaining 15% percent of visible matter in the universe. Unravelling the nature of this dark matter (DM) is one of the key goals of particle physics in the 21st century. The DESY ATLAS group plays a leading role in searches for dark matter in the data collected with the ATLAS experiment at the LHC. A key strength of collider searches lies in the fact that the high-energy collisions of SM particles may not only produce dark matter directly under controlled experimental conditions, but provide access to particles mediating the interactions between dark matter and the SM sector. These mediators could either decay invisibly into dark matter or visibly into quarks or leptons.

The ATLAS collaboration, with leading contributions from the DESY ATLAS group, published a comprehensive summary and combination of DM searches on proton–proton collision data at a centre-of-mass energy of 13 TeV collected by the ATLAS experiment during LHC Run 2 (2015–2018), corresponding to a total integrated luminosity of 139 fb^{-1}. These searches were interpreted in a benchmark model that not only predicts the existence of DM but, additionally, a second Higgs doublet and a pseudoscalar mediator (called *a*). A pseudoscalar was chosen primarily due to the reduced constraints from direct detection experiments, making LHC searches particularly relevant. This ultraviolet-complete benchmark model, referred to as 2HDM+*a*, was developed in part by members of the DESY Theory group [1] and used to define various representative benchmarks for LHC DM searches by the LHC DM Working Group [2], with significant input from members of the DESY ATLAS and CMS groups.

For the first time at the LHC, the region of small mediator masses in 2HDM+*a* was probed, where decays of the SM Higgs boson to a pair of pseudoscalars ($h \to aa$) are kinematically allowed. Constraints were placed as a function of the mediator and DM masses (Fig. 1). Searches targeting exotic Higgs decays to a pair of pseudoscalars with subsequent decays to fermions, $h \to aa \to 4f$, constrain a triangular region in the $m_a - m_X$ plane, where the mediator cannot decay invisibly to dark matter ($m_a < 2m_X$). This region is almost fully excluded by these searches, except for two bands where m_a is close to the masses of the J/ψ and Υ mesons. For $m_a > 2m_X$, invisible mediator decays are possible, and constraints were derived based on the latest stringent constraints on the invisible branching fraction of the Higgs boson derived with major contributions from the DESY ATLAS group [4]. For larger values of m_a, the region $m_a > 2m_X$ is excluded up to $m_a < 600$ GeV by a search for DM produced in association with a Higgs boson decaying to a pair of *b* quarks, another ATLAS search conducted with strong contributions from the DESY ATLAS group. The still unexcluded high-m_a, high-m_X region can be probed by searches for the mediator or heavy Higgs-boson states in signatures such as $a/A/H \to tt$ or $tbH^{\pm}(tb)$.

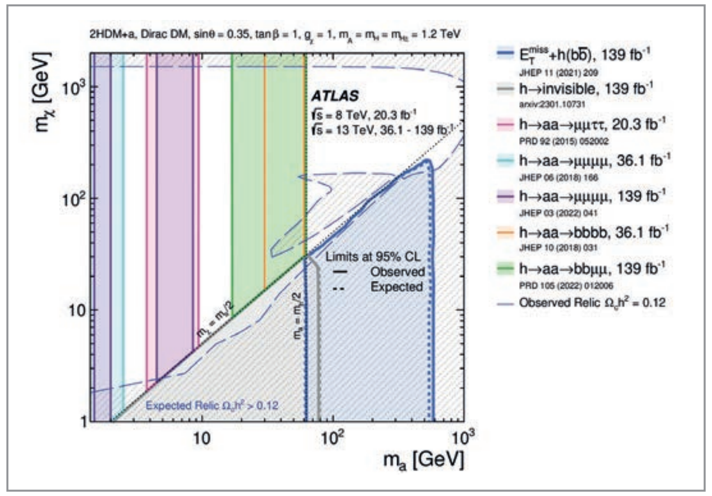

Figure 1

Exclusion regions in the plane of the masses of the pseudoscalar mediator *a* and the DM particle *X* obtained from ATLAS searches targeting exotic decays of the Higgs boson to a pair of mediators

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References:

[1] ATLAS Collaboration, arXiv:2306.00641
[2] M. Bauer et al., JHEP 1705, 138 (2017)
[3] LHC DM WG, Phys. Dark Univ. 27, 100351 (2020)
[4] ATLAS Collaboration, Phys. Lett. B 842, 137963 (2023)

The Gen Alpha of silicon sensors

Investigating commercial CMOS technologies for future solid-state detectors

The European Committee for Future Accelerators (ECFA) defined a Detector R&D Roadmap in 2021. In the context of solid-state detectors, CMOS sensors and 4D-tracking have been identified, among others, as key technologies required to meet the very challenging conditions at future experiments in high-energy physics. Several R&D activities are already under way at DESY in this context. The 4D-tracking performance of a digital silicon photomultiplier prototype fully developed at DESY is currently being investigated. Through simulations, development and characterisation of prototypes, the Helmholtz Innovation Pool project TANGERINE, in synergy with other institutes, is evaluating the potential of 65 nm CMOS imaging technology.

CMOS technology potential

Low material budgets, low power, few-micrometre spatial resolution and sub-nanosecond timing are among the main requirements for future tracking detectors. Commercial CMOS imaging technologies are well suited to meet these requirements and can also represent a cost-effective solution in solid-state detector development. R&D groups in the DESY Particle Physics division are gaining expertise with these technologies, being involved in all stages of new sensor development: from simulation and design to prototype characterisation.

MIP 4D-tracking with digital SiPM

Silicon photomultipliers (SiPMs) are a state-of-the-art technology in single-photon detection. The key element of SiPMs are single-photon avalanche diodes (SPADs), which can nowadays be produced in CMOS foundries, allowing the development of SiPMs with in-chip electronics. Designed at DESY using 150 nm CMOS technology [1], a prototype digital SiPM (dSiPM) is currently being investigated. The design allows masking, hitmap readout, fast timestamping and digitisation within the same silicon that contains the sensing part.

These features, typical of tracking detectors, can make the DESY dSiPM suitable not only for light detection and photon-counting contexts, but also as a possible candidate for 4D-tracking applications of charged particles, where excellent spatial and temporal performance is required. A laser setup and an electron beam at the DESY II Test Beam Facility [2] are being used to investigate the performance of the sensor. Spatial resolutions on the order of 20 µm and efficiencies of over 30% were achieved in direct minimum ionising particle (MIP) detection, confirming the expected performance in particle tracking [3]. Furthermore, in Fig. 1, the time resolution is shown to be as low as 50 ps while detecting particles in the SPAD active area. Performance improvement in terms of MIP detection efficiency will be the main focus of study in the coming months.

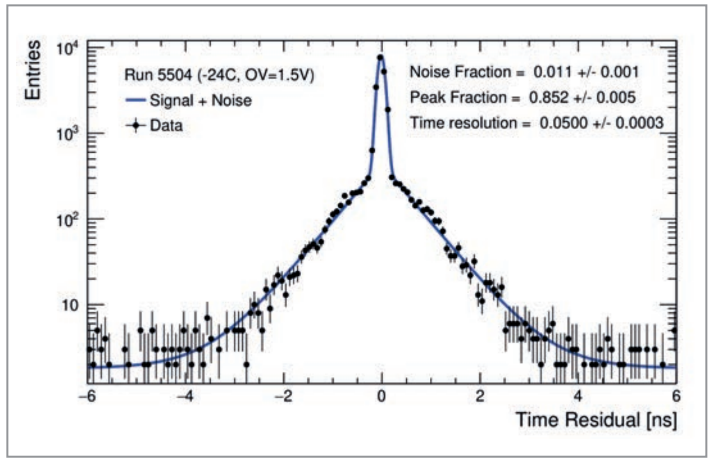

Figure 1

Example of timestamp difference between two dSiPMs detecting the same particle. A model containing signal and noise is fitted to the data. 85% of the events are contained in the main peak with a dSiPM time resolution of 50 ps. Events in the tails come from low-efficiency regions.

Towards 65 nm CMOS imaging technology from design to testing

Within the TANGERINE project, the Helmholtz centres DESY, GSI and KIT, in collaboration with international partners, are developing next-generation silicon pixel detectors for tracking charged particles, focusing in particular on monolithic sensors based on a novel 65 nm CMOS imaging technology with a small collection electrode design.

The first fully integrated prototype detector in the TANGERINE project is called H2M (Hybrid-to-Monolithic). It was designed by a collaboration of DESY, CERN and IFAE in Barcelona, Spain, with the design following a digital-on-top workflow known from hybrid detector application-specific integrated circuits (ASICs). The sensor of H2M comprises a matrix of 64 x 16 pixels, with a total sensitive area of 2.24 x 0.56 mm^2, and each pixel has a pitch size of 35 µm. The thickness of the sensor is 50 µm. H2M offers four acquisition modes for different measurement purposes. The second test chip, DESY-ER1, features the same analogue pixel front-end as H2M, but allows direct access to the analogue amplifier output, which is useful for gaining a deeper understanding of the sensor and the technology.

In 2023, the H2M and DESY-ER1 prototypes from the second submission in 65 nm CMOS imaging technology were received from manufacturing. Figure 2 shows the full sensor matrix of an H2M prototype under a microscope. First measurements confirmed that both chips are fully functional, and a detailed characterisation is ongoing.

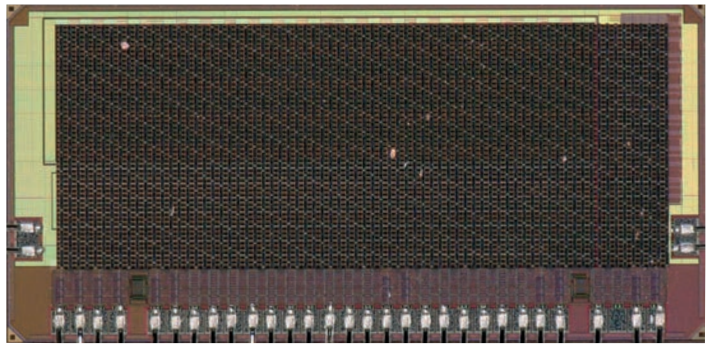

Figure 2

Full sensor matrix of an H2M prototype under a microscope

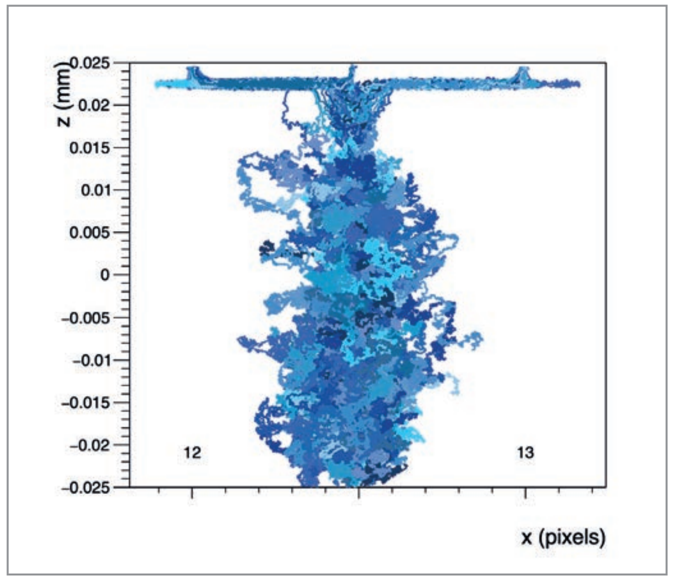

Figure 3

Propagation of the electrons in an H2M sensor simulated with the Allpix^2 framework. Each line indicates the path of a single electron. In this event, the electrons are generated in the interpixel region between pixel 12 and pixel 13, and both pixel 12 and pixel 13 are contributing to the charge collection.

Highlight on simulation tools for sensor design

A technology-independent approach using generic doping profiles is being developed at DESY for simulating sensors produced in CMOS imaging technology. Detector performance is simulated by integrating a detailed electric-field model from finite element simulations with TCAD into a Monte-Carlo-based simulation with the Allpix^2 framework [4]. This combined simulation approach makes it possible to study the sensor response with both high statistics and reduced computational cost compared to using only TCAD. The simulation procedure can be applied in multiple cases and has been proven to provide accurate predictions of the sensor behaviour, so it can be used to inform decisions in future sensor design [5].

The sensor simulations were done for H2M during the design stage. Figure 3 shows an example of electron propagation in an H2M sensor model simulated with the Allpix^2 framework using an electric-field model and generic doping profile from TCAD. The diffusion and drift process of the electrons is visualised. Comparisons with measurements are currently ongoing.

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References:

[1] I. Diehl et al., JINST 19 P01020 (2024)
[2] R. Diener et al., Nucl. Instrum. Methods Phys. Res. A 922, 265 (2019)
[3] F. Feindt et al., arXiv:2402.12305
[4] S. Spannagel and P. Schütze, JINST 17 C0902 (2022)
[5] A. Simancas et al., arXiv:2404.14524

Particles, Universe, Nuclei and Hadrons for NFDI

PUNCH4NFDI – Status update with a specific glance at metadata

In 2023, the German National Research Data Infrastructure (NFDI) reached its full volume after welcoming seven new disciplinary consortia in the third round. As a consortium of the second round, PUNCH4NFDI [1] took off in October 2021 to provide infrastructure and services to foster FAIR (findable, accessible, interoperable and reusable) data for particle, astroparticle, astro-, hadron and nuclear physics in Germany. In line with its high-level milestones, the consortium focuses on a few distinct developments: i) a science data platform and a corresponding portal that provides access via single sign-on to federated, heterogeneous storage and computing resources, ii) a workflow management engine, iii) a definition and workable implementation of a digital research product (DRP) and a registry for DRPs, iv) solutions for the handling of big data within the PUNCH communities and v) a software marketplace and software repositories for the exchange of FAIR software solutions within the NFDI and beyond.

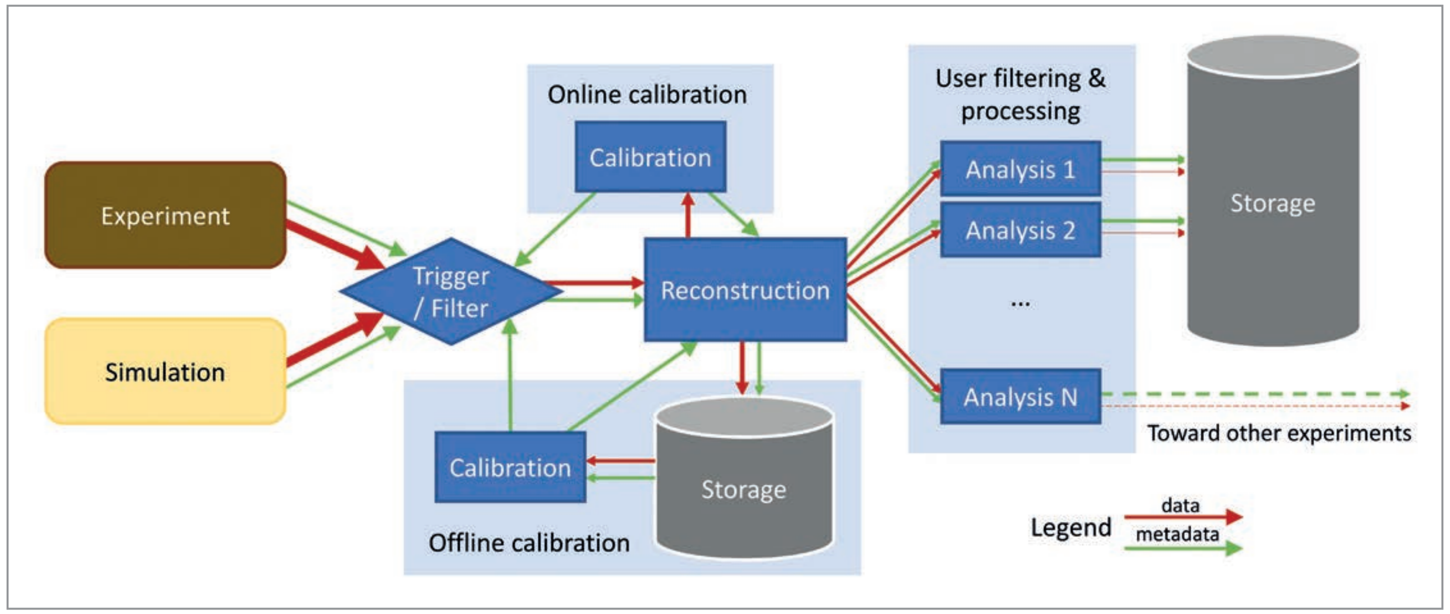

Figure 1

General data-processing graph for particle and astroparticle experiments. Variations of the data flow and triggering scheme are possible. The arrow width gives a qualitative indication of the data rate.

A lot of technical progress was achieved in 2023 towards the realisation of the milestones mentioned above – for example, more locations were connected to the federated Compute4PUNCH and Storage4PUNCH resources, and access to the resources was simplified through the adoption of MyToken, a technical solution to refresh access tokens automatically. This enables the execution of jobs on Compute4PUNCH that last longer than the initial lifetime of access tokens provided by the PUNCH authentication and authorisation infrastructure (AAI). Furthermore, new features provided by the Unity IAM authentication service and available on the Helmholtz-AAI were enabled in the PUNCH-AAI. These finally allow the enrichment of tokens with group claims – a feature that is crucial for restricting access to research data or digital research products to a group of users, e.g. members of a specific experiment.

Metadata are an important issue in the work of PUNCH4NFDI and beyond, and work is progressing on many fronts:

- Members of the consortium have been leading the effort to extend and modernise the International Lattice Data Grid (ILDG), in particular the metadata and file catalogue services. This includes support for multiple collections of metadata with freely configurable schema, token-based access control, a new REST application programming interface and containerised deployment. So far, three instances of the new catalogues were deployed at DESY in Zeuthen, the University of Bielefeld in Germany and the University of Tsukuba in Japan.
- The use of the ILDG metadata catalogue for data other than those stemming from gauge field theorists is currently being evaluated for example data from astrophysics and high-energy physics (HEP).
- On a more abstract basis, work on a coherent metadata schema for the PUNCH sciences in general is progressing. This project is significantly larger than "only" PUNCH4NFDI: The ideas for and implementation of e.g. metadata schemas in PUNCH4NFDI connect directly to similar work in the DAPHNE4NFDI project [2].
- Concrete work is also closely related to the PATOF project [3] of the Helmholtz Metadata Collaboration (HMC), where direct steps for implementing metadata schemas for small- and medium-size PUNCH experiments are taken. Here, similarly to PUNCH4NFDI, the mapping of different metadata schemas to the DataCite schema is being pursued, an effort in which the DESY Library is also involved. To truly capture the needs with regard to metadata from the different communities within PUNCH4NFDI, the mapping is carried out for specific use cases. The HEP use case, provided by consortium members at DESY, comprises a transformation of CMS and ATLAS open data to a common simplified data format, a combined "Higgs to 4 leptons" analysis of these data as well as a unified treatment of the related metadata in the PUNCH metadata catalogue. This prototype analysis, which partially reproduces results related to the original Higgs discovery, is the first to combine data from two different HEP experiments at basic reconstruction level.
- The metadata schema developed within PUNCH4NFDI does not stop at the level of DataCite, however, but foresees the addition of further levels of metadata that are more and more discipline- and experiment-specific. This metadata schema is being developed for DRPs in general, which can consist of any combination of research data, analysis software, workflow information, instrument or facility information and publications.

Furthermore, metadata play a key role in reducing the loss of information through online filtering and thus for the reproducibility of results in PUNCH sciences. A first metadata concept [4] has been developed within the consortium and will be advanced in the coming years (Fig. 1).

Altogether, different aspects of metadata and metadata handling are being discussed in several task areas within PUNCH4NFDI. Bringing all these aspects together and creating a common vision for metadata will be the next major task.

Finally, the consortium has conducted training workshops on several tools for data analysis, such as pyhf or BAT.jl. A joint workshop with European XFEL on "Machine Learning and Data Processing on FPGAs" was held in June 2023 at DESY to enhance the exchange of experience and best practices, subsequent to which further channels for communication were established. A second workshop of this kind is foreseen for 2024. Furthermore, a mentoring service for early-career scientists was established within PUNCH4NFDI and kicked off in March 2023.

PUNCH4NFDI, like all other consortia of the second NFDI round, is now preparing for its mid-term evaluation, with a report due in September 2024. This will indicate the continuation of the NFDI consortia after their first five-year funding period. Important players here will most probably be the NFDI sections and – the new kid on the block – the Base4NFDI initiative [5] formed by all funded NFDI consortia, which is charged with defining and implementing base services that are useful to the entire science system and with bringing them to production level. The PUNCH4NFDI consortium will closely monitor the developments in order to remain at the forefront of data management solutions for our scientific community also in the future.

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References:

[1] https://www.punch4nfdi.de
[2] https://www.daphne4nfdi.de
[3] https://helmholtz-metadaten.de/en/inf-projects/patof-from-the-past-to-the-future-legacy-data-in-small-and-medium-scale-a-blueprint-for-punch-and-other-disciplines
[4] A. Redelbach et al., Zenodo (2024), doi:10.5281/zenodo.10692169
[5] https://base4nfdi.de

Ready for a luminous restart of collisions

High hopes for entry into a new luminosity regime

While the first years of operation of the SuperKEKB electron–positron collider and its Belle II experiment at KEK in Japan have been quite successful, they have also revealed a number of areas where improvements are needed. To this end, in summer 2022, accelerator operation was stopped for the first Long Shutdown (LS1), which lasted until the end of 2023. In addition to maintenance work on several Belle II subdetectors, the collaboration used the break to replace the pixel vertex detector (PXD), which had been operating very successfully since 2019, with the complete two-layer PXD2. In order to enter the luminosity regime beyond 10^{35} $cm^{-2}s^{-1}$ after LS1, several significant modifications had to be made on the accelerator side as well.

Installation and commissioning of PXD2

The main objective of the Belle II collaboration during LS1 was to install the complete PXD2, needed to maintain excellent vertexing performance at the higher luminosities expected in Run 2. However, as mentioned in the 2022 edition of this report, unforeseen thermomechanical problems significantly delayed the precommissioning of the two half-shells at DESY in 2022 and early 2023. After very detailed investigations into the causes of these problems and the development of a number of mitigation measures, the first of the two half-shells, consisting of 10 ladders made from 75 µm thin silicon wafers, was completely disassembled. After replacing the defective ladders with spare ones, the half-shell was reassembled in the clean-room of the detector laboratory in Hall West at DESY in close cooperation with technicians from MPP Munich, where the half-shell had originally been assembled. The second half-shell required only minor modifications.

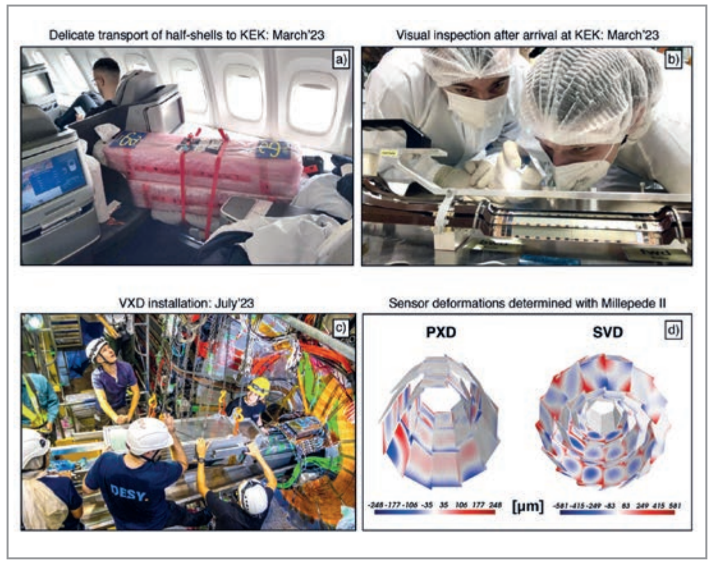

Figure 1

Important milestones of the PXD2 installation and commissioning

The safest way to transport the highly sensitive half-shells to KEK was considered to be flying the detector on an additional seat in the passenger cabin (Fig. 1a). Fortunately, visual inspection of the device on arrival at KEK revealed no mechanical damage during the delicate long-distance transport (Fig. 1b and [1]). Only after successful mounting of the detector on the newly built central beampipe at KEK in April did the Belle II collaboration decide to remove the existing vertex detector (VXD), which consists of the PXD and the four-layer strip vertex detector (SVD), from the Belle II detector. After verification of the full functionality of the PXD2 and the reused SVD after reassembly, the reinstallation of the VXD took place at the end of July (Fig. 1c) [2].

Cosmic rays recorded without magnetic field were used to perform an initial alignment of all the sensors of the PXD2 and SVD. The sophisticated alignment procedure is based on the Millepede II program [3] originally developed at Universität Hamburg and further developed by DESY. In addition to measuring pure displacements of the individual sensors from their nominal position, the procedure is able to determine small deviations from the ideal flat sensor geometry (Fig. 1d). The timely and accurate determination of these parameters is important, as movements and deflections of the thin PXD sensors were already observed in 2022 as a result of tiny deformations of the beampipe on which the high-precision device is mounted. Such deformations are due to the beam-current-dependent thermal load caused by the unavoidable synchrotron radiation in the machine. As a significant increase in beam currents is still required to reach the target luminosity of SuperKEKB, the final operating conditions of the PXD2 will be defined only once sufficient experience has been gained after the collider is restarted in 2024.

SuperKEKB improvements in LS1

During LS1, which lasted throughout 2023, SuperKEKB experts made significant progress in implementing a number of modifications to the machine to address some of the major issues that had slowed down the ramp-up of peak luminosity in the first years of operation.

Serious problems included so-called sudden beam losses (SBLs) and the accidental firing of kicker magnets, which damaged several collimators and quenched the superconducting final focus magnets. Due to its proximity to the beamline, the high radiation dose rate around the Belle II interaction point caused by these SBL events was also the main contributor to the loss of readout channels in the sensitive PXD during Run 1. The SBL phenomenon is characterised by sudden transverse kicks of the beam bunches, which led to significant beam loss on a very short time scale on the order of 10 µs, corresponding to the beam revolution time in the Main Ring of SuperKEKB.

An example of a damaged collimator in the Low Energy Ring (LER) is displayed in Fig. 2a, which shows grooves from the incident beam and debris from molten tantalum, one of the metals used as collimator head material along with titanium or tungsten. It is obvious that such an uneven surface can no longer be effective in protecting the downstream machine components or the Belle II experiment in a controlled manner. Moreover, the increased total impedance that the LER beam experiences due to the narrow opening of the collimators leads to an effect known as transverse mode coupling instability, which causes single-beam blow-up once the bunch current exceeds ~0.6 mA.

To date, the preferred explanation for the occurrence of SBLs that is consistent with observations is the so-called "fireball" hypothesis [4]. It is based on the idea that sputtered metal particles with a high sublimation point, such as tungsten or tantalum, are heated by the beam and, after landing on a metal surface with a low sublimation point, such as copper, lead to the formation of a plasma around the landing point, which can grow into a macroscopic vacuum arc that interacts with the passing bunches. Countermeasures for the problems mentioned above therefore include:

- Replacement and partial repositioning of all damaged collimators
- Copper plating of collimator heads
- Introduction of a more robust low-*Z* (carbon) collimator to intercept the beam in the event of accidental kicker firing without melting
- Installation of a novel non-linear collimator (NLC) with large aperture in the LER
- Addition of a variety of new sensors around the ring, including acoustic sensors to locate the source of SBLs

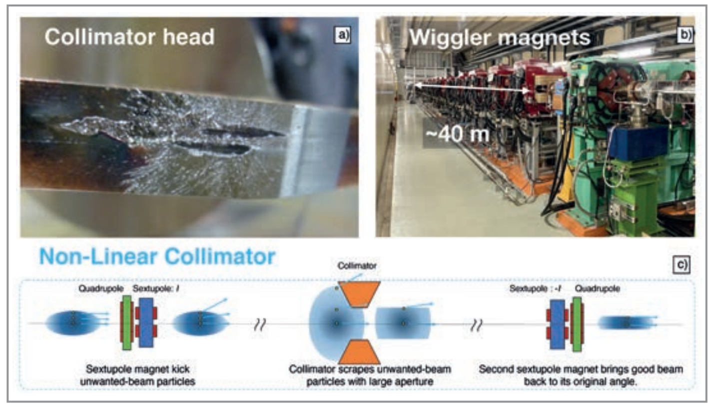

Figure 2

(a) Example of a damaged collimator head in Run 1. (b) SuperKEKB tunnel before NLC installation. (c) Schematic illustration of the NLC concept.

- Faster beam abort after detection of beam instability or excessive loss rates

The purpose of the NLC is to efficiently scrape unwanted beam particles in the tail of the distribution without requiring a very small collimator aperture, which relaxes the conditions for transverse mode coupling instability. This was achieved by inserting a pair of newly designed sextupole magnets that kick the unwanted beam particles to larger amplitudes, which can easily be scraped by a vertical collimator with a comparatively large aperture placed between the sextupoles (Fig. 2c).

This major installation first required the removal of approximately 50 wiggler magnets from the 40 m long straight section upstream of the Belle II interaction point (Fig. 2b). A number of additional modifications were made to the beam transport line between the linear accelerator and the Main Ring in order to improve injection efficiency and reduce the associated injection background, which had already caused some performance degradation in some of the Belle II subdetectors in Run 1. The experience gained with these modifications during the upcoming 2024 run will be essential in deciding on possible upgrade options for the machine, which will be necessary to reach the SuperKEKB target luminosity of 6 x 10^{35} $cm^{-2}s^{-1}$.

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References:
[1] https://www.belle2.de/detail/belle-ii-bekommt-ein-neues-herzstueck-pixeldetektor-pxd2-ist-in-japan-eingetroffen
[2] https://interactions.org/press-release/made-germany-worlds-thinnest-pixel-vertex-detector-installed
[3] Physics at the Terascale, Millepede II, https://www.terascale.de/wiki/millepede_ii/
[4] T. Abe et al., Phys. Rev. Accel. Beams 21, 122002 (2018)

Unveiling new horizons in particle physics

Pioneering study of the $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay with Belle II data

In an international partnership, a DESY team recently explored the elusive $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay process, leveraging data from the Belle II experiment at KEK in Japan. This initiative, led by DESY scientists, used an inclusive tagging method developed in house, showcasing DESY's innovative contributions to particle physics research. The study's observations hint at intriguing discrepancies with Standard Model expectations, potentially opening doors to new physics. This effort underscores DESY's integral role in pushing the boundaries of our current understanding and paves the way for future explorations in the realm of subatomic phenomena.

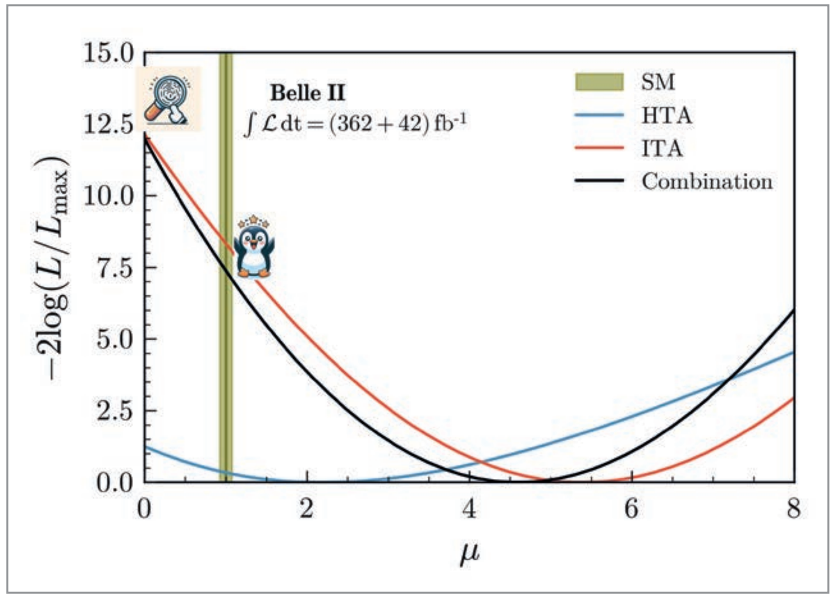

Figure 2

Twice the negative logarithm of the likelihood L compared to the point with the maximum likelihood L_{max} for the signal strength μ, illustrating the search for $B^+ \rightarrow K^+ \nu\bar{\nu}$ decays. The three lines show the results from the ITA, the HTA and their combination. The vertical band at unity shows the SM expectation with its uncertainty. From [1].

Particle physics aims to understand the universe at its most fundamental level, and the study of rare decay processes like $B^+ \rightarrow K^+ \nu\bar{\nu}$ is crucial in this endeavour. These processes are sensitive to new physics beyond the Standard Model (SM), making their observation and measurement key to potentially discovering new particles and forces.

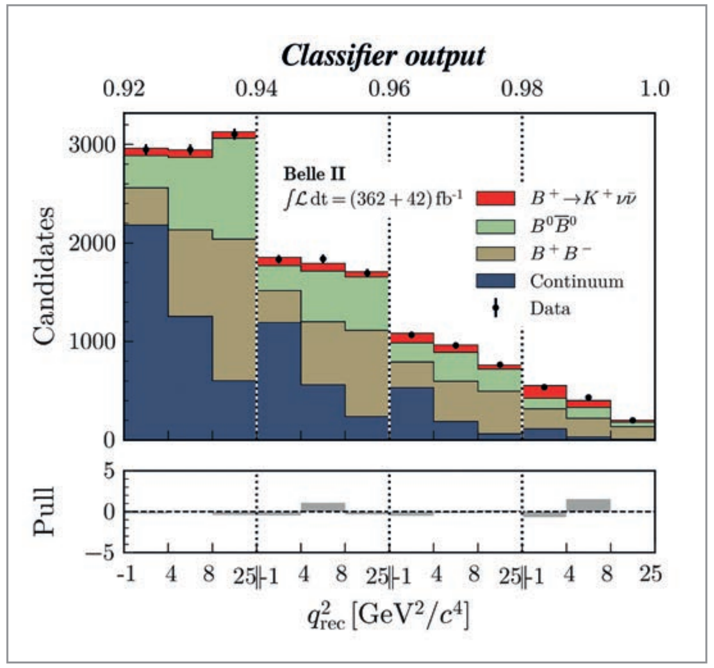

Figure 1

Observed yields and fit results in bins of the ITA classifier output and the invariant mass of the dineutrino pair, q^2_{rec}. The yields are shown for the data and individually for the signal (red) and different background components. From [1].

A recent study by a DESY team led by Sasha Glazov [1], in collaboration with physicists from Italy and France, used data from the Belle II collaboration to examine this decay. The team's work has been pivotal in advancing the search for these rare processes. It employed an advanced multivariate technique known as inclusive tagging analysis (ITA), which has been shown to be in agreement with traditional hadronic tagging analysis (HTA). ITA is a significant development in particle detection sensitivity and accuracy, as was demonstrated by the DESY team's analysis of early Belle II data [2] – a result that was also discussed as a DESY highlight in the 2021 issue of this report. The main idea of ITA is to use all available information in a single classifier that uses machine learning methods to separate the signal from the background. The current analysis represents an update based on a sixfold increase in the data sample.

The study's findings indicate evidence for the $B^+ \rightarrow K^+ \nu\bar{\nu}$ decay process. Figure 1 shows the ITA results. For all kinematic regions, the background contributions are large; however, for the region with the highest classifier output, the data are visibly above the background and consistent with the presence of the signal.

A comparison of the ITA and HTA results, together with their combination, is summarised in Fig. 2. The results are given in terms of a "signal strength" μ, which measures the signal in terms of the SM expectation: $\mu = 1$ corresponds to the SM, while $\mu = 5.4$, which is preferred by the ITA, corresponds to more than five times the SM expectation. The figure shows the variation of twice the negative logarithm of a likelihood ratio for a given μ compared to the likelihood at its maximum value. The square roots of the values on the y-axis act as a measure of consistency, expressed in terms of the number of standard deviations, providing a quantitative evaluation of the signal's significance. For example, values around 1 indicate consistency at 1 σ level, while values above 9 correspond to evidence with significance more than 3 σ. The figure shows the agreement between the ITA and the HTA and their combination. The point where the combined analysis line crosses 1 indicates some departure from the SM expectation, marked by an excited penguin, while the point where the line crosses zero, indicative of evidence, is highlighted accordingly.

The observed decay events align with the SM predictions, but they also display a deviation. This deviation, quantified at a statistical significance of 2.7 σ, opens up intriguing possibilities for new physics, although further data and analysis are needed for a definitive conclusion.

To ensure the reliability and validity of the findings, the team conducted a comprehensive series of checks on the analysis. The rigorous verification processes included a range of auxiliary measurements designed to test the robustness of the result from multiple angles. Each of the tests confirmed the integrity of the observation, reinforcing the confidence in the accuracy of the data and the methodologies employed.

The research has garnered substantial interest within the theoretical physics community, reflected in several citations and discussions. The slight deviation from the SM predictions has prompted further investigation and debate about the potential for new particles or interactions that could be revealed through these decay processes.

The implications of these findings for new physics scenarios are broad and varied. They may point to phenomena such as additional Higgs bosons, supersymmetric particles, leptoquarks or other yet undiscovered aspects of particle physics that could significantly impact our theoretical framework. Last but not least, the deviation may be explained by the creation of dark-matter particles, since these have similar properties to the pair of neutrinos.

The study, while underscoring the importance of further research, also highlights the need for more sensitive detection techniques and data analysis methods. The findings serve as a stepping stone for future studies, potentially leading to breakthroughs that could reshape our understanding of particle physics.

As we continue to probe deeper into the world of subatomic particles, each discovery, whether it confirms existing theories or reveals new phenomena, brings us closer to a more comprehensive understanding of the cosmos.

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References:

[1] Belle II Collaboration, arXiv:2311.14647, accepted by Phys. Rev. D
[2] Belle II Collaboration, Phys. Rev. Lett. 127 18, 181802 (2021)

Tau-lepton mass with highest precision to date from Belle II

Delving into the nature of the tau lepton

DESY researchers working on the Belle II experiment at KEK in Japan have carried out an analysis that led to the most precise measurement of the τ-lepton mass to date. To conduct this measurement, the researchers studied the decays of the τ leptons to three pions and a τ neutrino, using a technique initially developed by the ARGUS collaboration at DESY back in 1992. Through the analysis of these decays, they determined the mass of the τ lepton to be 1777.09 ± 0.14 MeV. This advancement improves the sensitivity of lepton flavour universality tests and further constrains possible extensions of the Standard Model.

The Belle II experiment and τ decays

Compared to its lighter cousins – the electron and the muon – the properties of the τ lepton, such as its mass, have not yet been measured with the same precision. The main reason for that is the shorter lifetime of the τ lepton. Researchers from DESY have led an analysis to determine the τ mass using a sample of about 175 million $e^+e^- \to \tau^+\tau^-$ events recorded with the Belle II detector at the SuperKEKB collider. The data were collected in 2019 and 2021 and correspond to an integrated luminosity of 190 fb^{-1}. The τ mass, m_τ, was determined from the hadronic decays $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using the pseudomass endpoint method. The key challenge in this method lies in accurately determining the kinematics of the decay products and the energy of the e^+e^- collisions. Any inaccuracy in either of these directly impacts the τ-mass determination. By studying these decays, the team was able to measure the mass of the τ lepton to be m_τ = 1777.09 ± 0.14 MeV, which has the best single-measurement precision to date. This result is consistent with previous measurements (Fig. 1), moving the new world average value to a slightly higher value of 1776.96 ± 0.09 MeV.

Knowing the properties of the τ lepton as precisely as possible is important for testing the Standard Model and looking for signs of new physics beyond it. For instance, there exists a predicted relation between the decay rate of the τ into lighter leptons, $B'(\tau \to e\bar{\nu}\nu)$, and its lifetime τ_τ, which is very sensitive to the value of the τ mass Previously, a slight discrepancy was observed between the measured values of $B'(\tau \to e\bar{\nu}\nu)$ and τ_τ and the prediction when using the average value of the τ mass from previous measurements. However, with the new averaged value that incorporates the latest τ-mass measurement from Belle II, that discrepancy has further decreased. This once again demonstrates the success of the Standard Model, while the researchers continue their quest for indications of new physics.

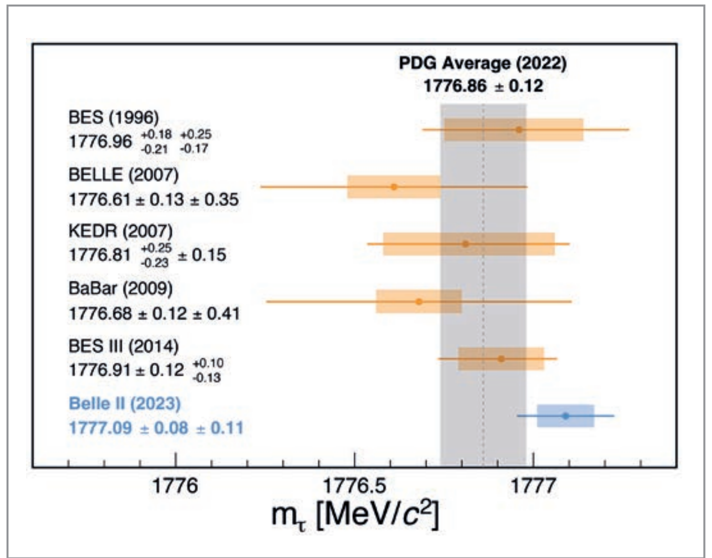

Figure 1

Previous τ-mass measurements (orange), compared with the result of this work (blue). The vertical grey band indicates the average value of previous measurements [1]. For each result, the inner error represents the statistical uncertainties, while the outer is the total uncertainty.

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References:

[1] Particle Data Group, R. Workman et al., PTEP 2022, 083C01 (2022)

[2] ARGUS Collaboration, Phys. Lett. B 292, 221 (1992)

Time for antimatter

Pinpointing the mechanism of matter–antimatter asymmetry

The research of the Helmholtz Young Investigator Group (YIG) "Time for Antimatter" is motivated by two of the major open questions in particle physics. The first one is about the origin of the huge imbalance between matter and antimatter in the universe. The second one concerns a series of measurements that deviate from the prediction for certain decay modes of *B* mesons. These phenomena are summarised in the literature under the term "*B* anomalies".

CP violation as the key to the abundance of matter

The YIG will use the data from the Belle II experiment at KEK in Japan to shed light on one of the most pressing questions in fundamental physics: What is the origin of the enormous imbalance between matter and antimatter in the universe, which cannot be explained by the small charge conjugation parity (CP) asymmetry contained in the Standard Model (SM)? The YIG will search for hints of new sources of asymmetry between B^0 meson and anti-B^0 meson decays, which will be produced in substantial amounts at Belle II in the coming years. The YIG will first of all perform a high-precision measurement of the asymmetry between the number of B^0 and anti-B^0 mesons both decaying to $J/\Psi K^0$. This gives access to the angle β in the famous Cabibbo–Kobayashi–Maskawa (CKM) unitarity triangle. The knowledge of β, in combination with other flavour measurements, constitutes a very precise test of the CKM mechanism, through which CP asymmetry arises in the SM.

The B^0 decay time is a critical input for these measurements. Its precision will be improved using the new Belle II pixel vertex detector, developed in great part at DESY, and new vertexing techniques. In addition, the YIG will use the same experimental techniques to measure, for the first time, the CP asymmetry in electroweak B^0 decays. Such decays have been under scrutiny in recent years due to anomalies seen in several independent measurements, such as $B^0 \to K_{str}\mu\mu$ at the LHCb experiment at CERN and $B^+ \to K^+\nu\bar{\nu}$ at Belle II. If interactions beyond the Standard Model are the cause of these anomalies, it is likely that they also induce anomalous sources of CP violation in these decays.

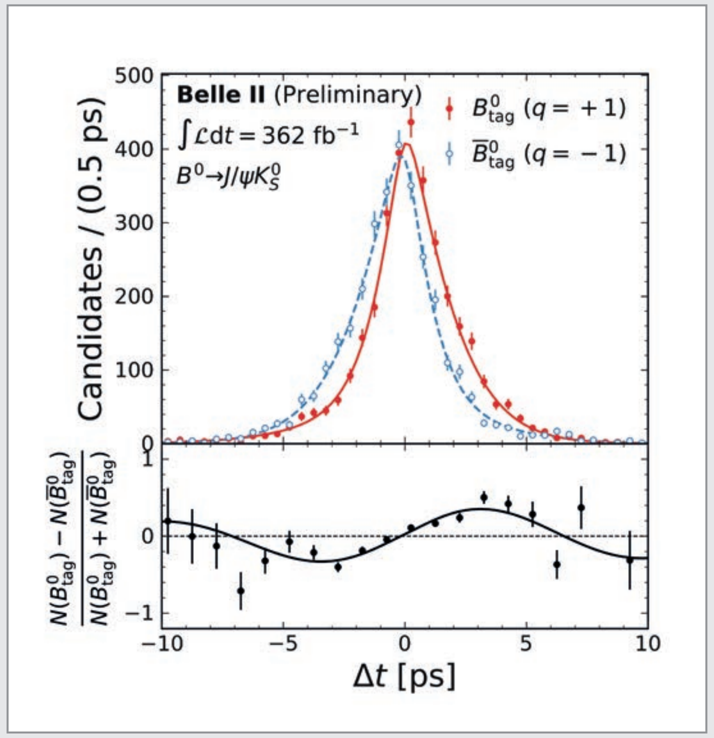

Figure 1

Decay time distributions for B^0 and anti-B^0 mesons decaying to $J/\Psi K_S$ (top). The left–right asymmetry between the two is due to CP violation, and the amplitude of the asymmetry (bottom) is proportional to sin2β.

Helmholtz Young Investigator Group

"Time for Antimatter"

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HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Automated optimisation of a beam-driven plasma wakefield accelerator

Multiparameter tuning for the best plasma-accelerated beams

Plasma wakefield accelerators have the potential to achieve the particle energies required by high-energy physics and photon science experiments at a fraction of the cost of conventional technology. FLASHForward – DESY's own beam-driven plasma wakefield accelerator experiment, run by the FTX group and the Accelerator division – has made great progress towards demonstrating a plasma acceleration stage that could truly be used for such applications. However, the setup of this stage often requires extreme fine-tuning, with a large number of parameters to choose from. The FTX group at DESY is therefore investigating how a machine-learning-based approach can help in the optimisation of a beam-driven plasma wakefield accelerator.

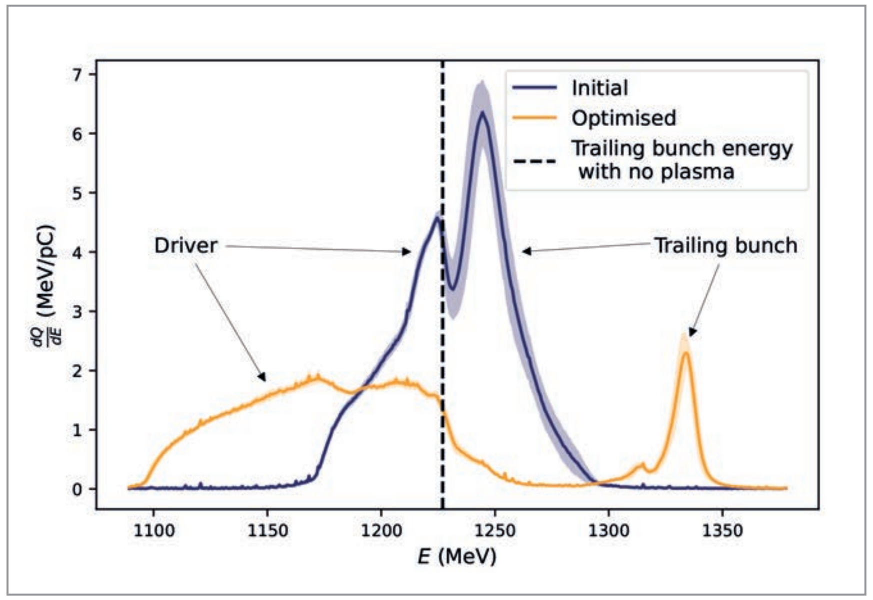

Figure 2

Energy spectra of the driver and trailing bunches are shown for both the initial working point (navy curve) and for the best settings found by the optimiser (orange curve). At the optimised working point, the energy of the accelerated bunch was around 1330 MeV, 100 MeV higher than the energy of the bunch in the absence of plasma (black dashed line). Note that the measurement of the absolute energy spread of the bunches in this case was resolution-limited, which in the future will be mitigated by measuring the spectrum with higher dispersion.

Why plasma accelerators?

By surfing the charge density waves driven by an intense laser pulse or particle beam travelling through a plasma, particles can be accelerated at gradients of GV/m – orders of magnitude higher than that achievable in radio frequency accelerator technology. Using the electron bunches from the FLASH linear accelerator [1] at DESY, the FLASHForward experiment [2] aims to demonstrate a plasma accelerator stage that can significantly boost the energy of a conventional accelerator whilst also at least matching its performance in terms of beam quality, repetition rate and stability. Achieving this requires careful tuning of both the incoming beam and the properties of the plasma itself, which necessarily involves changing many parameters. This has made the setup and optimisation of this stage tough in the past [3]; machine learning, however, may hold the key to solving this issue.

Bayesian optimisation

Bayesian optimisation is a popular machine-learning-based technique, especially for optimising systems such as plasma accelerators [4, 5] where there are multiple variables to change, where the underlying problem is largely a "black box" and where the output is often contaminated by noise. Simply put, this approach involves efficiently predicting the output of a system – known as the objective – as a function of multiple inputs. Using this prediction, the optimiser attempts to find the optimum point in the parameter space by striking a balance between exploring areas that it hasn't investigated before and those it believes are most likely to contain the best result. In this way, the optimiser aims to find the best point with relatively few samples, whilst also building a model that can provide insights into the relationships between the individual input and output parameters.

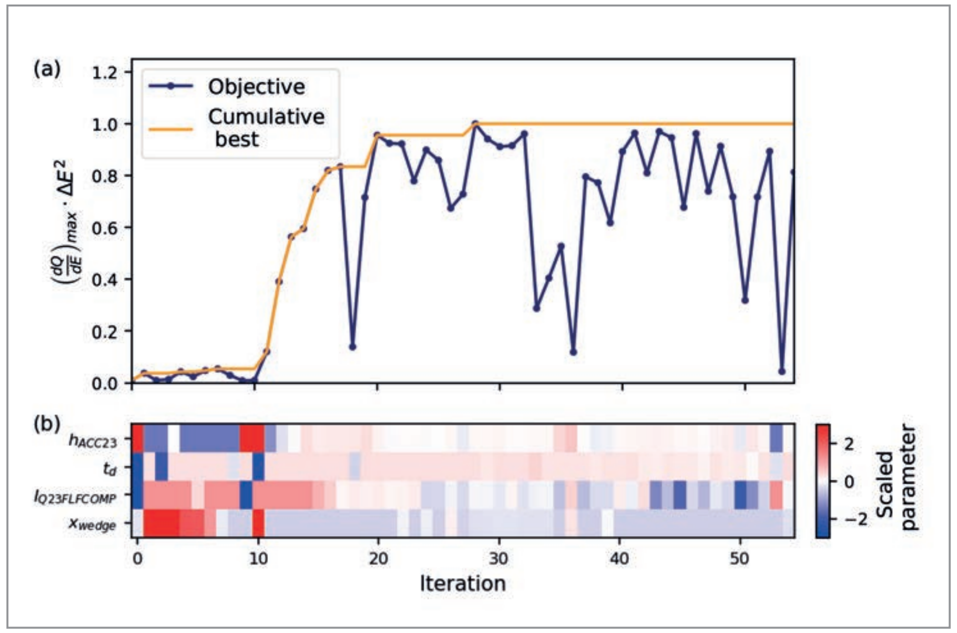

Figure 1

The evolution of the normalised objective function, which is maximised for high energy gain and high peak spectral density, is represented by the navy line in (a), whilst the optimum value reached so far at each iteration is shown by the orange line. Changes in the input parameters, each scaled relative to their mean values from across all iterations, are shown in (b).

Application at FLASHForward

Bayesian optimisation was used for the first time at FLASHForward to optimise the acceleration of a trailing bunch over a distance of 50 mm, aiming to achieve high energy gain ΔE whilst also maintaining a high charge and low energy spread, implying a high peak spectral density $(dQ/dE)_{max}$. For the results presented here, the Bayesian optimisation library Optimas [6] was used, of which DESY is a major developer.

In this case, four important parameters were selected for tuning: the timing t_d of the discharge pulse that determines the plasma density, the position of the wedge scraper x_{wedge} that cuts the beam into two bunches, the chirp h_{ACC23} in one of the accelerator modules that controls the bunch compression and finally the strength $I_{Q23FLFCOMP}$ of a quadrupole magnet that affects the tilt of the bunches entering the plasma. In the example shown in Fig. 1, the optimiser begins from a point where the objective function is low (Fig. 1(a)). After a period of exploration where the input parameters are changed simultaneously in relatively large steps (iterations 0–10 in Fig. 1(b)), the optimiser begins to converge towards the settings that maximise the objective function, reaching an optimum after 28 iterations. In Fig. 2, the energy spectrum at this working point is compared to that at the initial point, demonstrating that the optimiser, starting from a working point with around 20 MeV energy gain, was able to automatically find a setting that produced an energy gain of approximately 100 MeV, corresponding to an accelerating gradient of around 2 GV/m.

What next?

Following these promising initial studies, the potential of Bayesian optimisation for the plasma acceleration of electron bunches will continue to be explored at FLASHForward, especially as the experiment looks to tackle the challenge of going to even longer acceleration lengths and thus higher energies. As well as aiming for maximum energy gain of high-quality trailing bunches, such optimisation techniques may also prove useful in improving the stability of plasma accelerators, which has so far been unable to match that of conventional machines. It may then be the case that tools such as Bayesian optimisation become not only helpful but also necessary in the setup and operation of plasma accelerators in the future.

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References:

[1] S. Schreiber and B. Faatz, High Power Laser Sci. Eng. 3, e20 (2015)
[2] R. D'Arcy et al., Phil. Trans. R. Soc. A 377, 20180392 (2019)
[3] C. A. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)
[4] R. J. Shalloo et al., Nat. Commun. 11, 6355 (2020)
[5] S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)
[6] A. Ferran Pousa et al., Phys. Rev. Accel. Beams 26, 084601 (2023)

Just the TelePix2 from us

Timing and region-of-interest triggering for the beam telescopes of the DESY II Test Beam Facility

The TelePix2 chip is a fast region-of-interest trigger and timing plane, which is on its way to becoming an important addition to the treasure trove of infrastructure components at the DESY II Test Beam Facility. After successful characterisation at the facility, TelePix2 is now undergoing initial test user operation.

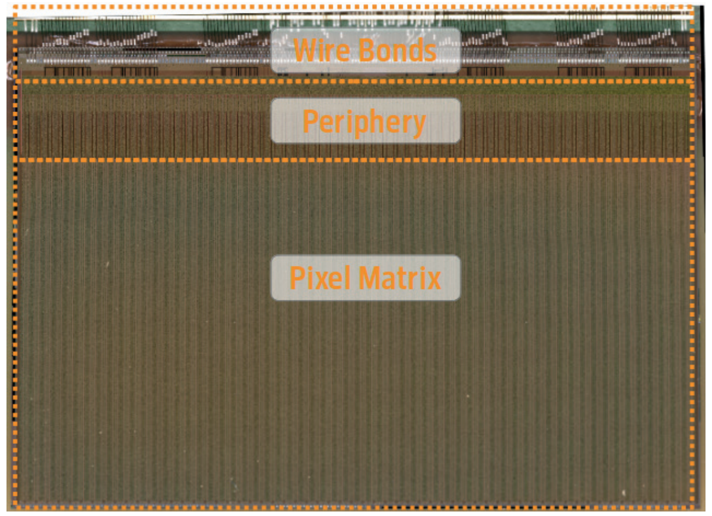

Figure 2

TelePix2 pictured under the microscope. The wire bonds transmit data and voltages to and from the sensor. The periphery is where additional processing takes place. Electrons are detected in the pixel matrix.

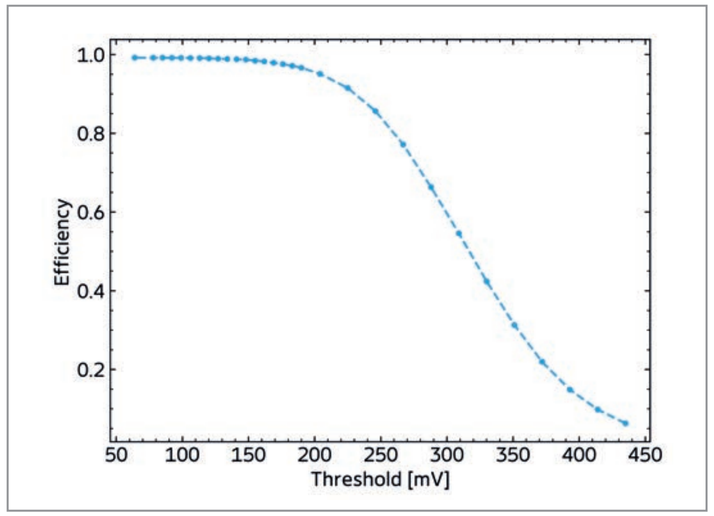

Figure 3

TelePix2 particle detection efficiency as a function of detection threshold

The research and development of new detector prototypes drives the need for test facilities that allow the properties and response of these detectors to be assessed. Understanding this performance is crucial for their later operation in different experiments and for directing future R&D efforts. The DESY II Test Beam Facility provides electrons with a user-selectable energy of 1–6 GeV at three beamlines used for detector testing purposes.

At the heart of each DESY II test beamline are important components to test and characterise detectors. These include beam telescopes to trace the paths of individual electrons as well as triggers, which, when crossed by an electron, start the data acquisition and allow the synchronisation of different data streams.

Figure 1

TelePix2 hitmap with pixels masked outside the DESY logo

Trigger with masking

Many data acquisition systems rely on trigger signals to know when to record data. If one of these systems is particularly slow, they can become quickly overwhelmed by too many trigger signals. Hence, it is vital to only trigger on interesting events, for instance when an electron has passed through the sensitive area of the detector being tested.

Matching the surface area of the trigger perpendicular to the beam to the detector under test is crucial. If the trigger is too small, an electron may pass through the detector under test but miss the trigger. If it is too large, uninteresting events are recorded.

The DESY II Test Beam Facility hosts a large number of varied campaigns every year, with some groups bringing prototype sensors that require trigger areas as wide as a human hair, whereas others need the full size of the beam telescopes of approximately 1 cm x 2 cm.

In addition to providing a fast output signal that can be used as a trigger, the TelePix2 chip also allows for the masking of pixels, preventing signals that lie outside of a desired region to be transmitted.

Figure 1 shows a hitmap, a map where the colour scale represents the number of signals detected. Pixels that lie outside of the DESY logo have been masked. TelePix2 is completely versatile in its region-masking capabilities, allowing the masking not only of rectangular regions but of any shape that can be drawn within the available pixel resolution. By providing a trigger that can be configured to match a region of interest, the DESY II Test Beam Facility can thus adapt to all of its users' requirements.

Precise timing with position information

The telescopes provide highly precise spatial information on the electron path [1, 2]. This yields precise knowledge on exactly where the electron intersected the detector under test, enabling detailed studies on the in-pixel level.

However, multiple electrons may cross the telescope system within one readout frame, the time period in which all hits are read out together from the telescope. The telescope assigns time stamps not on a hit-by-hit basis, but rather by the time the readout was initiated. This lack of individual time stamps makes it impossible to associate which electron crosses the system when, creating ambiguities in the association of hits to particle trajectories.

The use of a timing plane, a layer with both timing and position information as provided by TelePix2, adds an extra level of information that helps to detangle these tracks by enabling better time stamping of the tracks.

TelePix2 from R&D to user operation

TelePix2, pictured in Fig. 2, was designed by the Karlsruhe Institute of Technology (KIT), with the readout and data acquisition system developed jointly by Heidelberg University and DESY. The sensor design stands on the shoulders of developments towards the Mu3e chip family (MuPix) and AtlasPix [3]. DESY is now closely evaluating the performance of the TelePix2 sensor and putting it into user operation. After successful testing of TelePix [4], a small prototype sensor, it was decided to proceed with the full-scale TelePix2 chip. Since then, extensive work has been done to reach successive milestones, from seeing the successful masking of pixels to decoding time stamps and then assessing the behaviour of TelePix2.

The performance of TelePix2 has been evaluated at the DESY II Test Beam Facility. The results show a time resolution below 5 ns at an efficiency of how likely TelePix2 is to detect an electron above 99%, an impressive result for a sensor of this type and size.

Figure 3 shows the effect of the detection threshold on detection efficiency. The higher the detection threshold, the larger the amount of charge deposited by an electron within TelePix2 needs to be for successful detection.

The further the threshold can be raised without a significant drop in efficiency, the greater the flexibility to achieve performance improvements in other areas. For example, an increase in threshold is expected to decrease the amount of noise, enhancing one aspect of performance. Further work is now ongoing on how performance can be improved even further by optimising the operating conditions.

First initial tests with user groups using TelePix2 within their setup at the DESY II Test Beam Facility took place in late November 2023. Analysis of the data collected by these groups is currently under way.

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References:

[1] H. Jansen et al., EPJ Techn. Instrum. 3, 7 (2016)
[2] Yi Liu et al., JINST 18, P06025 (2023)
[3] I. Perić, Nucl. Instrum. Meth. A 582, 876 (2007)
[4] H. Augustin et al., Nucl. Instrum. Meth. A 1048, 167947 (2023)

The Key4hep software stack

A construction toolkit for future colliders

Modern particle physics experiments rely on large and complex software stacks to perform all the tasks that are part of their lifecycle. This includes not only data reconstruction and analysis but also detector simulation, which is especially important for the development of future particle physics experiments. Developing and maintaining such a software stack is a highly non-trivial task due the sheer number of software packages involved and the fact that they are highly interdependent. The Key4hep project, with key contributions from DESY, aims to provide such a software stack for use by future particle physics experiments.

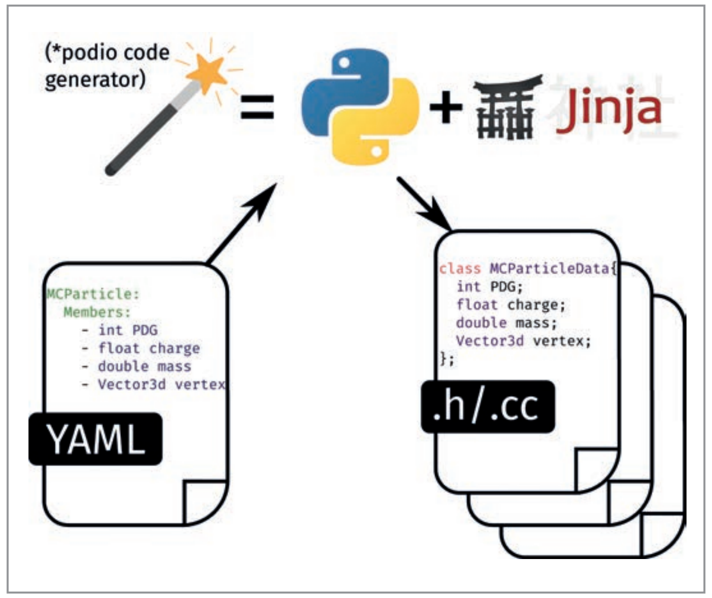

Figure 2

Flow diagram of the podio code generator, which reads a data model definition YAML format and produces an efficient implementation in C++ as output

The challenge

The software stack for a typical high-energy physics (HEP) experiment comprises not only experiment-specific software and tools but also libraries that are commonly used throughout the particle physics or data science communities. Additionally, many of these have dependencies on software that is commonly distributed as part of the operating system (OS), e.g. compilers or build tools (Fig. 1). Counting all transitive dependencies, the resulting software stack can easily reach a size of several hundred individual packages. Even when simply counting the packages that are somewhat experiment-specific, this size typically ranges somewhere between 50 and 100. All of this is complicated by the fact that the packages do not live in isolation but rather form an ecosystem of interdependent components, where compatibility doesn't usually come for free. Hence, changes to one piece of software might break several other packages further up the stack. Given that many of the algorithms for future colliders are still under very active development, seemingly simple changes can bind significant parts of the already scarce person power that is available for these projects.

Sharing the burden

The Key4hep project aims to provide a common software stack for all future collider projects that are currently under study. Members of the DESY FTX Software for Future Experiments (SFT) group have been involved in the project since the beginning when it was initiated by members of the ILC, CLIC, FCC and CEPC communities in June 2019. Since then, it has attracted contributions from other communities as well, and (parts of) Key4hep are now also used by the MuonCollider, Electron Ion Collider (EIC) and LUXE communities. Some packages that are part of the Key4hep stack, such as DD4hep for geometry description, are now even used by LHC experiments, such as CMS and LHCb. The key goal of the Key4hep project is not to build experiment-specific software but rather to develop common standards and approaches that are useful for all the parties involved – thus reducing the burden for the individual groups and allowing all of them to profit from the common developments.

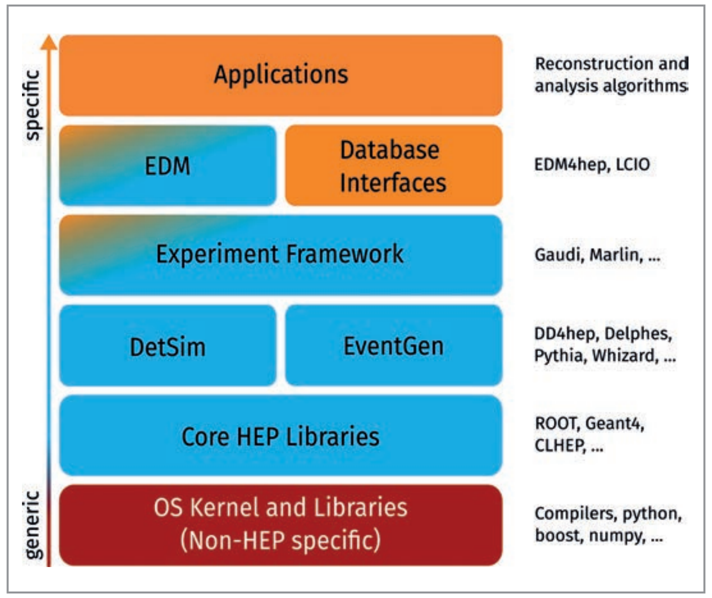

Figure 1

Schematic depiction of a typical software stack for a HEP experiment, comprising commonly available software at the base and becoming more and more experiment-specific towards the top of the stack

Key4hep software stacks are currently released at roughly a monthly pace. For these releases, the FTX SFT group builds the latest tagged versions of all the software packages involved. Additionally, the complete stack is built on a nightly basis using the latest available version of the code for all packages that are developed within the Key4hep software stack. This approach makes it possible to do larger-scale physics productions using the tagged releases, while still allowing the rapid prototyping and developments that are necessary for studying novel detector concepts. Both the releases and the nightly builds are distributed through the CernVM File System and are available for several different operating systems.

Common data model

The FTX SFT group keeps playing an integral role in Key4hep, bearing responsibility for the overall architecture as well as key parts of the implementation. One of these parts is the development of a common event data model (EDM) for the Key4hep project, EDM4hep. The EDM is a central piece of the Key4hep software stack, as it serves as both the common language in which different parts of the software chain communicate with each other and the language used by physicists to express their ideas. Since it is such a key part of the Key4hep project, usability and efficient implementation are crucial aspects.

EDM4hep is largely based on the experience gained with LCIO, which has been used for linear collider studies over the last two decades. One of the key aspects of EDM4hep that sets it apart from LCIO is thread safety, which has become imperative for leveraging modern computing resources. Rather than implementing the complete data model manually, the FTX SFT group has developed the podio EDM toolkit, which offers to generate an efficiently implemented, thread-safe and easy-to-use data model in C++, starting from a high-level description of the necessary data types in a simple grammar based on the YAML format (Fig. 2). DESY has made crucial efforts towards a first stable release of the podio toolkit and is currently central to the finalisation of EDM4hep version 1.0.

Unified future

While a lot of work for Key4hep is still ahead, the software stacks it provides are already being used by all the communities involved. It has also served as an excellent community building and bonding tool, as now all of the future collider projects can easily share knowledge, data samples or even full reconstruction algorithms. This shows that a common approach is key to leveraging the full potential of all the parties involved.

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References:

[1] Key4hep Collaboration, PoS EPS-HEP2021, 844 (2022)
[2] Key4hep Collaboration, arXiv: 2312.08151
[3] V. Volkl et al., EPJ Web Conf. 251, 03056 (2021)
[4] M. Frank et al., J. Phys. Conf. Ser. 513, 022010 (2014)
[5] Key4hep Collaboration, EPJ Web Conf. 251, 03026 (2021)

Is the future asymmetric?

Studying the Higgs boson at an asymmetric collider

There is a wide agreement in the worldwide particle physics community that, for deciphering the mysteries of the Higgs boson, it will be necessary to collide electrons and positrons at sufficiently high energies. In spring 2023, a group of scientists with strong ties to DESY proposed the Hybrid Asymmetric Linear Higgs Factory (HALHF), which would collide a conventionally accelerated positron beam with a higher-energetic but less intense plasma-accelerated electron beam. Such a facility could be much shorter and cheaper than classic Higgs factories, but it also comes with many accelerator challenges. But could it even deliver the demanding precision physics programme of a Higgs factory? And what would experiments at such a facility need to look like?

Next stop: Higgs factory

Recently, the US strategy process for particle physics re-emphasised the conclusion of the last update of the European Strategy for Particle Physics in 2020: An electron–positron collider for precision studies of the Higgs boson is the highest-priority next collider project. For decades, DESY has been a leading player in R&D for such Higgs factories, in particular for the ILC, which would be based on the same linear acceleration technology as the European XFEL X-ray laser, but more recently also for storage-ring-based proposals such as CERN's FCC-ee.

However, all Higgs factory projects so far rely on equal energies of the colliding electrons and positrons, leading to a symmetric experimental setting, as was the case with LEP, the predecessor of the LHC at CERN. This will be different with the partially plasma-acceleration-based concept of HALHF [1], which was first proposed in 2023 based on ideas developed in the FLASHForward team at DESY. The FTX group at DESY therefore started to explore the experimental consequences of such an asymmetric setting for precision studies of the Higgs boson.

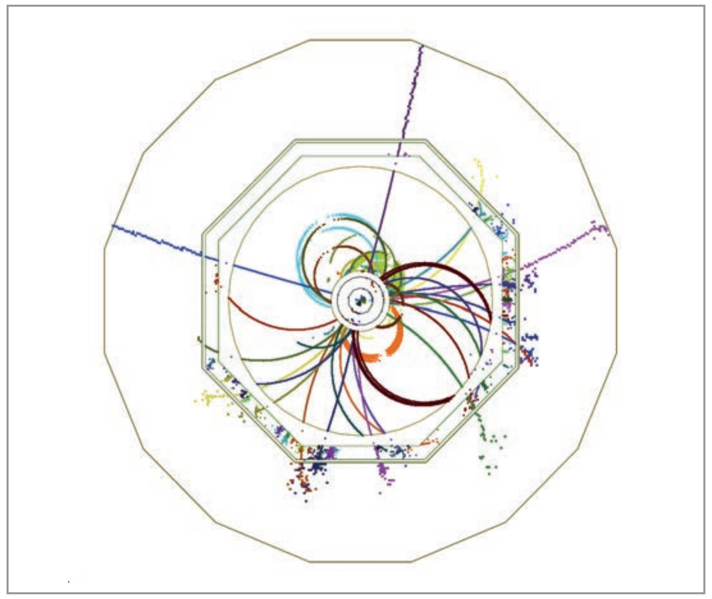
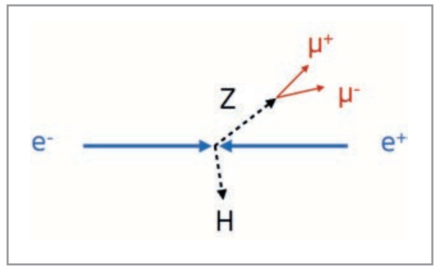


Figure 1

Higgs bosons can be recognised independently of their decay mode from the two muons of the decay of the accompanying *Z* boson. In the detector (here a cross section view perpendicular to the beam axis), these muons can be easily recognised as the rather straight and isolated traces at one and ten o'clock, respectively.

In general, asymmetric experiments are not uncommon: SuperKEKB at KEK in Japan exploits asymmetric electron and positron beam energies to enlarge the boost and therefore the flight distance of *B* hadrons, facilitating the detection of their decay, and the experiments at DESY's former electron–proton collider HERA were highly asymmetric due to both different colliding particle species and energies. However, the physics goals and thus the detector requirements at a Higgs factory are quite different from any previous experiments. The flagship measurement at any Higgs factory will be the measurement of the total production rate of a Higgs boson in association with a *Z* boson. This process can be identified from the decay products of the *Z* boson without any prior assumption on the Higgs-boson properties, especially when the *Z* boson decays into a pair of muons, as illustrated in Fig. 1.



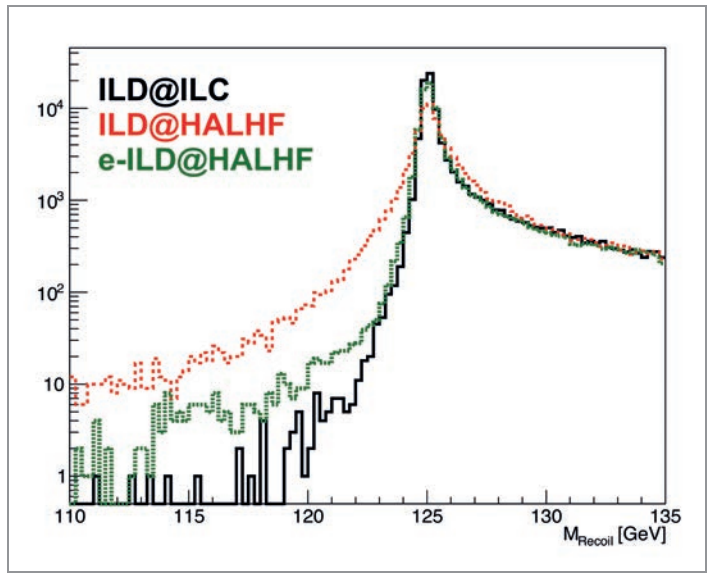


Figure 2

Recoil mass spectrum as expected with the ILD detector at a symmetric Higgs factory like the ILC (black), with the unmodified ILD detector at HALHF (red) and when extending the central part of the ILD detector along the flight direction of the higher-energetic electron beam of the collider (green).

The Higgs boson is then recognised by calculating the momentum recoiling against the two muons given the known initial momenta of the colliding beams – a unique advantage of lepton colliders. The invariant mass of the recoiling object should then coincide with the Higgs-boson mass of around 125 GeV – up to the precision to which the detector measures the momenta of the muons! An example of such a recoil mass distribution assuming the ILD detector concept [2], developed with leading contributions from DESY for symmetric Higgs factories like the ILC, is shown as the black histogram in Fig. 2.

Going asymmetric

At HALHF, however, colliding a 500 GeV electron beam with a 30 GeV positron beam, the collision products will be boosted in the direction of the higher-energetic beam, referred to as the forward direction. This means that the two muons from the *Z*-boson decay also tend to fly into the more forward parts of the detector. In any particle detector, the momenta of charged particles are determined from the curvature of the particles' trajectories in a magnetic field due to the Lorentz force. This magnetic field is usually parallel to the beam axis, which maximises the lever arm for particles flying perpendicular to the beam into the central parts of the detector.

For the more forward-flying muons at HALHF, this means that the momentum measurement becomes less precise due to the shallower angle with respect to the magnetic field of the detector. The loss in precision is drastic, as can be seen in the red histogram in Fig. 2, which shows the recoil mass distribution expected when placing the unmodified ILD detector at HALHF. The change from black to red would imply a factor of 2–3 worse precision on all Higgs measurements – clearly not an attractive prospect.

Towards a detector for HALHF

Can this be rectified? In a first exploration [3], the central part of the ILD detector was simply prolonged into the forward direction (green histogram in Fig. 2). While this is not a realistic detector design, it serves as a proof of concept that the loss in precision can indeed be nearly mitigated. This result provides encouragement to address the next challenges towards a proper detector design for HALHF. These include considering the – also highly asymmetric – beam backgrounds, exploring special magnetic field configurations in the forward region, investigating the impact on flavour tagging, measuring the luminosity, and many more.

While many questions need to be answered to arrive at a performance- and cost-optimised detector design for HALHF, so far there seems to be no fundamental show-stopper to performing Higgs precision physics at an asymmetric facility.

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References:

[1] B. Foster, R. D'Arcy, C.A. Lindstrom, New J. Phys. 25, 093037 (2023)
[2] T. Behnke et al., ILD Interim Design Report, arXiv:2003.01116
[3] A. Laudrain, M. Berggren, J. List et al., PoS EPS-HEP2023, 556 (2024)

ALPS II launched

New elementary-particle searches at DESY have begun

At the end of May 2023, 11 years after the evaluation of its technical design report, the ALPS II experiment, located in the North area of the old HERA tunnel, started its initial science run. While the main purpose of this first run is to understand systematics and backgrounds, it has already reached uncharted parameter regions with significant discovery potential. First results regarding the performance of the experiment and its prospects to reach the design sensitivity are encouraging.

A new particle frontier

The Any-Light-Particle-Search experiment ALPS II, situated in a straight section of the tunnel of DESY's former HERA accelerator, targets new elementary particles far beyond the reach of accelerator-based experiments. Any new particle found at ALPS II would be a strong candidate for explaining the dark matter in our universe. Figure 1 shows its sensitivity goal for axions and axion-like particles.

For the first time, ALPS II will reach a parameter region in a model-independent fashion where the axion – motivated primarily by the charge conjugation parity (CP) conservation of quantum chromodynamics (QCD) – could also explain the dark matter in our universe and astrophysical anomalies. However, this requires improving the axion–photon coupling sensitivity by three orders of magnitude, which translates into 12 orders of magnitude in terms of the signal-to-noise ratio. The international ALPS II collaboration is on its way to do just that.

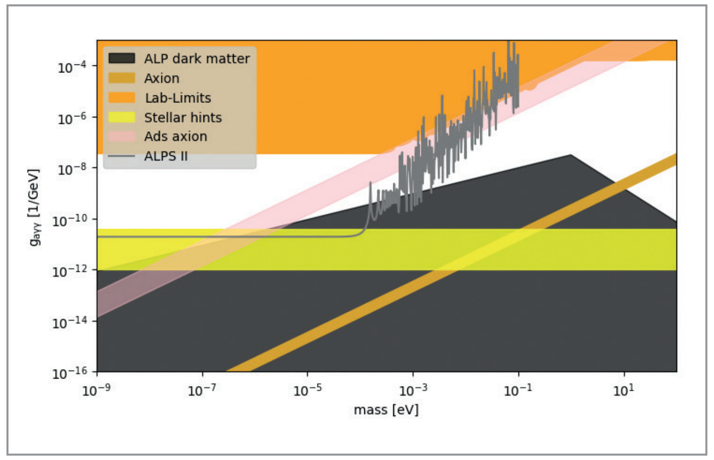

Figure 1

Coupling strength vs. mass for axions and axion-like particles: The dark grey area indicates the region where dark matter could exist, the golden line shows the parameter space for traditional axion models, the orange area is the parameter space excluded by earlier model-independent experiments (above 1 eV: accelerator-based experiments, below: predecessors of ALPS II), the yellow band displays hints on axions from stellar evolutions, the pink band is a more recent axion model [1], and the grey line shows the ALPS II sensitivity. The exclusion data were partly taken from https://cajohare.github.io/AxionLimits/.

First light in ALPS II

ALPS II will realise this leap in sensitivity increase by driving the light-shining-through-a-wall approach to its limits in the HERA environment. The 250 m long experiment combines a string of 24 modified superconducting HERA dipole magnets with two 124 m long high-precision optical cavities and extremely low-power light detectors. Details of the setup were described in earlier issues of this report. The optical system is sketched in Fig. 2.

The operation of this complex system requires relative length control of the cavities with sub-atomic precision and relative phase stabilities of the different laser light sources of less than 0.1 cycle over the course of up to 20 days. A second sensing scheme based on photon counting with a transition edge sensor [4], not sketched in Fig. 2, has made very good progress and is essentially ready to potentially confirm a detection based on the current sensing scheme.

On 23 May 2023, ALPS II started its initial science run [5]. This run did not include the production cavity. The HPL shone its light directly against the light-tight wall: This configuration increases the intensity of potential stray light – the most serious background source – by a factor of about 40, thus allowing for easier tracking of such spurious light. Indeed, first investigations hint at stray-light backgrounds with intensities below 10^{-22} W and coherence times larger than 10 000 s. At the time of writing, data analyses are in progress to identify stray-light sources and mitigate them. Despite the simplified setup, ALPS II has already reached an axion–photon coupling sensitivity roughly 30 times larger than earlier experiments. The performance of the control system for the complex optical system was much better than expected and reached duty cycles above 80%.

On 30 May 2023, an ALPS Fest was held in the HERA North hall to celebrate the start-up. Figure 3 shows a collection of colleagues who helped to make ALPS II a reality. Unfortunately, Dieter Trines, who was the driving force for the modification of the superconducting magnets and their installation in the HERA tunnel, passed away in July 2023 [6]. The collaboration will miss him and regrets very much that he was not able to see the first ALPS II results.

Echo in the media

The start-up of ALPS II was very much noticed in public media: Newspapers, print and online magazines, radio and television stations reported very positively about the new search for dark-matter candidates. A (not exhaustive) collection of articles is available at: https://alps.desy.de/news_and_media/.

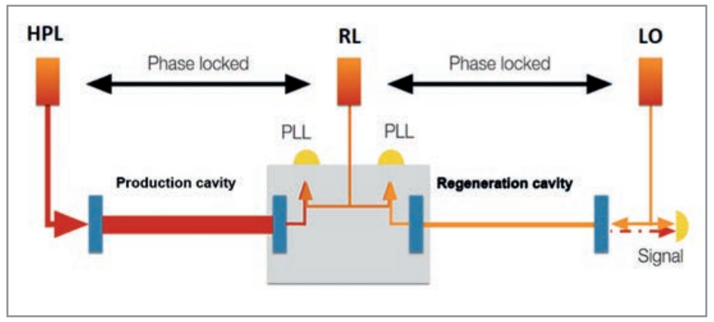

Figure 2

The optical system of ALPS II [2] from right to left: The local oscillator laser LO is resonantly coupled to the regeneration cavity to sense the relative mirror (blue rectangles) movements induced by seismic noise. The reference laser RL is tracking LO with a shifted frequency so that its light is not in resonance with the regeneration and production cavities. The high-power laser HPL is following RL, again with a frequency shifted with respect to RL and LO, so that its light will resonate in the regeneration cavity: Light from axions converting in the regeneration cavity would have exactly the same properties as the HPL light. At the signal diode (lower right), the photons from axion reconversion and the LO light are mixed to exploit a heterodyne sensing scheme [3].

Figure 3

Happy faces: Random selection of DESY colleagues and members of the international ALPS II collaboration who helped to build the experiment

The road ahead

The ALPS II collaboration plans to finish the initial data taking without the production cavity in spring 2024. First results on the search for new particles beyond the Standard Model will be published soon afterwards. The rest of the year 2024 will be used for a shutdown to implement and commission the production cavity and instigate various measures according to the "lessons learned" in 2023. In 2025, axion and other new particle searches will continue with the full optics configuration. A further upgrade is planned for late 2025 to reach the design sensitivity (as shown in Fig. 1) in 2026.

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References:

[1] A. V. Sokolov, A. Ringwald, JHEP 06, 123 (2021)
[2] M. Diaz Ortiz et al., Phys. Dark Univ. 35, 100968 (2022)
[3] A. Hallal et al., Phys. Dark Univ. 35, 100914 (2022)
[4] J. A. Rubiera Gimeno et al., Nucl. Instrum. Meth. A 1046, 167588 (2023)
[5] https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2758
[6] https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2881

Towards more WISP searches

Solar and galactic axions, high-frequency gravitational waves

While the ALPS II experiment at DESY is searching for axions and other weakly interacting slim particles (WISPs) in a purely laboratory-based fashion, the future experiments (Baby)IAXO and MADMAX will look for WISPs emitted by the sun and making up the local dark matter in our Milky Way. Another new experimental frontier, the search for high-frequency gravitational waves as signature of new elementary particle physics, is approached by novel ideas.

(Baby)IAXO

The collaboration of the International Axion Observatory (IAXO) intends to construct its prototype, called BabyIAXO, in the South hall of DESY's former HERA collider. BabyIAXO will search for axions and other similar particles emitted by the sun. Like in ALPS II, axions will be detected through their conversion into photons in a strong magnetic field. BabyIAXO was basically ready for construction to start already in 2022, but experienced a serious setback after the Russian invasion of Ukraine and the subsequent discontinuation of collaborations with Russian partner institutes. This mainly affected the BabyIAXO magnet. Thanks to the collaboration and commitment of CERN and DESY, the magnet seems to be within reach again. A review of its conceptual design is planned for spring 2024.

Figure 1

CAD model of BabyIAXO in the HERA South hall. The magnet (upper right) and the X-ray optics, beamlines and shielded detectors (lower left) are mounted on a movable platform that enables tracking of the sun. The red components on the hall floor (right) are the tower and drive system of a CTAO mid-sized telescope prototype, which are to be reused for BabyIAXO.

Details of the BabyIAXO setup are sketched in the *DESY Particle Physics 2022* annual report. Figure 1 shows a visualisation of the experiment in the HERA South hall. Apart from the magnet, all components of the experiment are nearly ready for construction.

The physics case of BabyIAXO keeps expanding significantly. As solar axions might be produced not only by the axions' couplings to photons, but also by axion–electron and axion–nucleon coupling, BabyIAXO data might make it possible to narrow down on the specific axion model once an axion is discovered (especially if combined with ALPS II results). New physics targets include supernova axions and solar physics: Axions could allow the tracing of the sun's magnetic fields, temperature and chemical composition [1]. In addition, the large BabyIAXO magnet might accommodate haloscopes to search for dark-matter axions in a low-mass region not accessible by existing experiments. The collaboration therefore decided to include the RADES project [2] in its baseline programme.

In autumn 2023, the ERC Synergy Grant application "DarkQuantum" led by IAXO spokesperson Igor Irastorza from the University of Zaragoza in Spain was approved. The grant includes contributions to the BabyIAXO magnet and focuses on new quantum sensing methods that would allow the haloscope sensitivities of BabyIAXO to be boosted significantly.

MADMAX

The MAgnetized Disc and Mirror Axion eXperiment (MADMAX) will search for galactic axion dark matter in the mass region around 100 µeV using an innovative detection method. A so-called booster of dielectric disks inside a huge dipole magnet will resonantly amplify the very weak axion-to-photon conversion signals to detectable levels.

In 2023, major breakthroughs were achieved in key technologies: The superconducting cable concept for the magnet was verified [3], funds for two test coils were granted, and test results of the tuning mechanism at cryogenic temperatures and high magnetic fields were published [4]. Methods to calibrate MADMAX boosters were developed and successfully applied to prototypes [5]. This last achievement was a breakthrough that allowed first physics results to be derived from test campaigns at CERN (Fig. 2) and in the SHELL laboratories of Universität Hamburg. The latter measurements were strongly supported by a DESY international fellowship award that enabled Stefan Knirck from Fermilab, USA, to join the collaboration.

High-frequency gravitational waves

High-frequency gravitational waves (HFGWs) are characterised by a signal frequency above 10 kHz. They offer a potential pathway towards new physics as, unlike their lower-frequency (≤10 kHz) counterparts, they cannot originate from established physical phenomena (see *DESY Particle Physics 2022*). In addition to axions and other lightweight particles, the ALPS II experiment is also sensitive to HFGWs by converting them into photons inside its strong magnetic field. In a similar fashion, the axion experiments BabyIAXO and MADMAX will be sensitive to HFGWs. The frequencies covered by these three setups lie within the range of 10^{10}–10^{19} Hz. Another line of work at DESY targets dedicated on-site HFGW experiments for frequencies between 10^4 and 10^9 Hz.

DESY is currently following two dedicated approaches (Fig. 3). One relies on superconducting radio frequency (SRF) cavities. The (former) MAGO collaboration, led by INFN Genoa in Italy, has in the past developed SRF cavities to study their prospects for gravitational-wave searches. In a collaborative effort, DESY / Universität Hamburg and Fermilab are continuing this R&D programme [6, 7]. From July to November 2023, the MAGO cavity was at DESY for characterisation at room temperature. This included detailed measurements of the cavity geometry, wall thickness and mechanical resonances as well as RF measurements. These measurements were compared with detailed simulations and calculations. Work started to develop the cavity control and a suitable low-noise cryostat. The cavity is now at Fermilab for surface treatment, tuning and cryogenic characterisation.

Additional efforts are aimed at realising another type of HFGW detector, which relies on optically trapped membranes. Here, chip-scale mechanical oscillators are coupled to the strong light field inside an optical cavity. Work towards the design of a related prototype detector is in progress at DESY. In 2023, R&D studies on such membranes led to a patent application for an innovative pressure sensor [8].

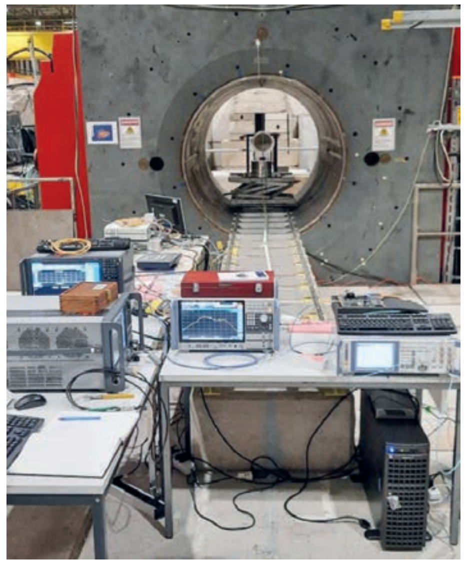

Figure 2

MADMAX prototype booster during a test campaign in CERN's MORPURGO magnet

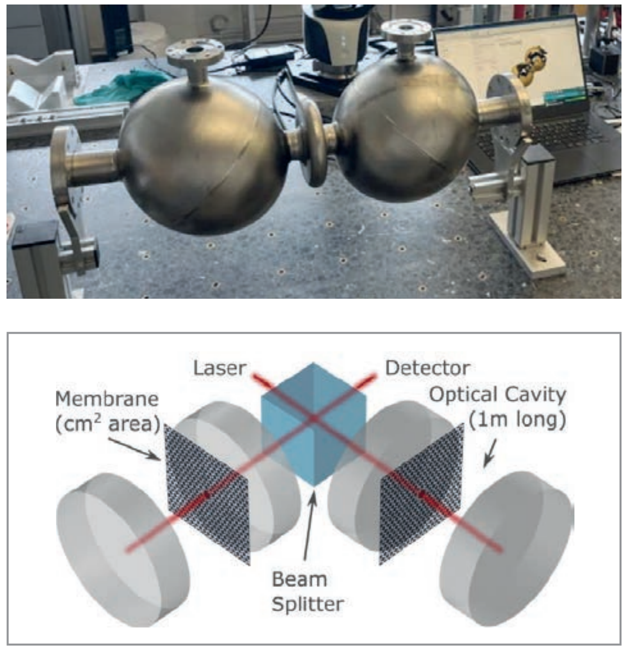

Figure 3

Top: The MAGO SRF cavity, built as part of a CERN–INFN collaboration around the year 2000, being characterised at DESY in 2023. The cavity comprises two nearly spherical coupled cells. Bottom: Conceptual design of a membrane-based prototype HFGW detector.

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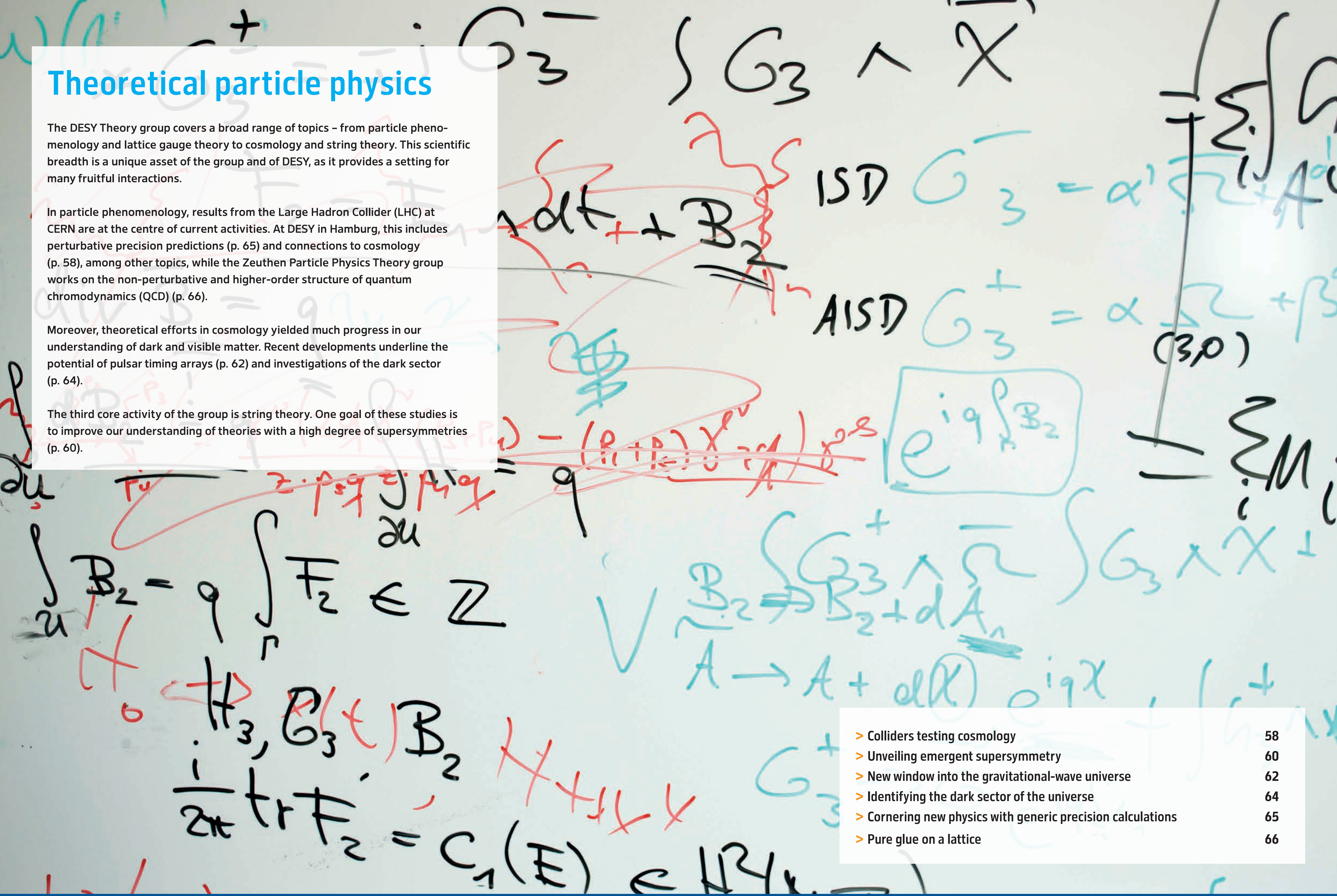
References:

[1] S. Hoof et al., JCAP 10, 024 (2023)
[2] S. Ahyoune et al., Ann. Phys. 535, 2300326 (2023)
[3] C. Lorin et al., IEEE Trans. Appl. Supercond. 34, 4500106 (2024)
[4] E. Garutti et al., JINST 18 , P08011 (2023)
[5] J. Egge et al., arXiv: 2311.13359
[6] R. Löwenberg et al., Eur. Phys. J. C 83, 1153 (2023)
[7] https://indico.cern.ch/event/1257532/contributions/5668679/
[8] https://indico.cern.ch/event/1257532/contributions/5586586/
C. Reinhardt et al., ACS Photonics 11, 1438-1446 (2024)



Theoretical particle physics

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

In particle phenomenology, results from the Large Hadron Collider (LHC) at CERN are at the centre of current activities. At DESY in Hamburg, this includes perturbative precision predictions (p. 65) and connections to cosmology (p. 58), among other topics, while the Zeuthen Particle Physics Theory group works on the non-perturbative and higher-order structure of quantum chromodynamics (QCD) (p. 66).

Moreover, theoretical efforts in cosmology yielded much progress in our understanding of dark and visible matter. Recent developments underline the potential of pulsar timing arrays (p. 62) and investigations of the dark sector (p. 64).

The third core activity of the group is string theory. One goal of these studies is to improve our understanding of theories with a high degree of supersymmetries (p. 60).

Colliders testing cosmology

How searches for long-lived particles probe the history of our universe

We lack observational data on the state of the universe before big bang nucleosynthesis occurred. In particular, it is unknown which form of energy dominated at these early times. While the naive expectation is the domination of radiation, well-motivated scenarios suggest a period of matter domination instead. Recently, DESY theorists pointed out for the first time that searches for long-lived particles at existing and foreseen colliders could directly test the dynamics responsible for a period of early matter domination. Their study provides new physics justifications for long-lived particle searches and offers a fresh direction for obtaining otherwise inaccessible insights into our universe.

In cosmology, the evolution of the universe is characterised by different phases dominated by different forms of energy: radiation (relativistic species), matter (non-relativistic species) and vacuum energy. These different forms of energy can be shown to scale differently with time (or equivalently with the size of the universe parameterised by the scale factor *a*), see Fig. 1.

We have a good understanding of the evolution of our universe back to about 1 s after the big bang (corresponding to temperatures of about 1 MeV), when primordial nucleosynthesis took place. At these early times, the universe was in a state of radiation domination. As the universe continued to expand and cool, the energy density associated with matter eventually surpassed that of radiation, shortly before the emission of the cosmic microwave background radiation. Very recently, the expansion of the universe has entered a phase where dark energy dominates, leading to the observed accelerated expansion.

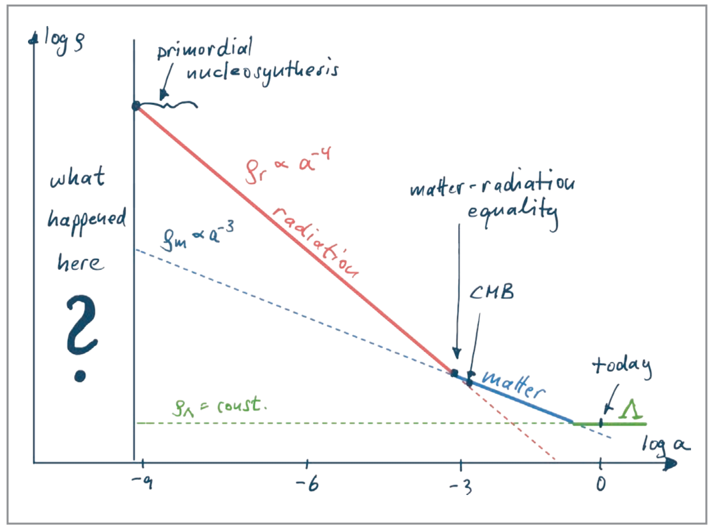


Figure 1

Different forms of energy scale differently with the size of the universe parameterised by the scale factor *a*.

As of today, we do not know the form of energy that dominated for temperatures above the MeV scale. While the Standard Model (SM) in isolation predicts radiation domination, a period of early matter domination (EMD) is instead predicted in some models that address shortcomings of the SM.

EMD would imply a large abundance of non-relativistic massive particles. These particles should have an appreciable lifetime in order to sustain an extended period of EMD. On the other hand, to be consistent with observations, these particles need to decay before the onset of primordial nucleosynthesis. Once these particles decay back to radiation, they will effectively lead to a dilution of other species that are not in thermal equilibrium (basically because the universe cools down more slowly while it still expands quickly). As the abundance of particles in thermal equilibrium depends only on the temperature, additional particles are created, while decoupled relics only become more dilute due to the expansion. The corresponding dilution factor *D* can therefore be interpreted as a measure of the amount of matter domination.

Overall, it would be highly desirable to have experimental tests of these early epochs. Recently, DESY theorists showed that a period of EMD may be probed in the laboratory by means of collider searches for the long-lived particles (LLPs) that induce it.

One may think that the long lifetimes tested in the laboratory are enough to directly test EMD. However, the couplings needed to produce enough LLPs in the laboratory are often large enough to keep them, in the early universe, in equilibrium with the bath of surrounding particles until they become non-relativistic. If this is the case, their number density becomes Boltzmann-suppressed, so that they do not dominate the energy in this case.

There are cases, however, where this does not happen. One example, examined in [1], corresponds to a dark confining SU(*N*) gauge group similar to quantum chromodynamics (QCD). With no light dark fermions, the lightest states at low temperatures are glueballs – composite objects made up of gluons. Assuming no couplings to the SM, the lightest of these glueballs is stable and a good dark-matter candidate. For small couplings instead, these glueballs will typically be long-lived (with a lifetime determined by the coupling strength) and may lead to a phase of EMD. The simplest coupling structure to the SM involves the Higgs boson. This induces decays of the lightest glueballs into light SM states.

Cosmology

At high temperatures, the dark sector consists of a gas of weakly interacting dark gluons. As the universe cools, the coupling grows stronger and, at some critical temperature, the dark sector will undergo a phase transition, in which massless gluons are confined into massive glueballs. As the glueball mass is significantly larger than the critical temperature, the glueballs are immediately non-relativistic and hence behave as matter. After the phase transition, the glueballs will undergo number-changing 3 → 2 interactions, where part of the mass is converted to kinetic energy. As the dark and visible sectors are decoupled, this leads to a relative temperature increase of the dark sector. This process will continue for some time and then cease to be efficient. Taking this cosmological evolution into account,

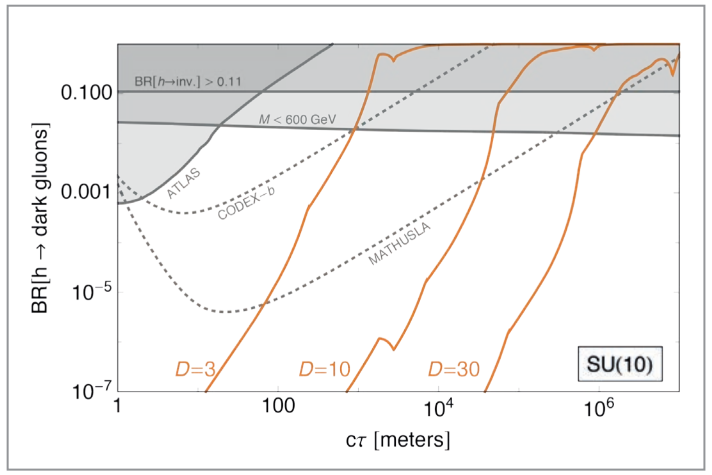


Figure 2

Dilution factor *D* of energy in the dark sector as a function of the lifetime and coupling strength of glueballs to the SM

DESY theorists could deduce the resulting dilution factor *D* as a function of the lifetime and the coupling strength of the glueballs to the SM.

Collider signatures

The coupling between dark gluons and the SM will generally also lead to Higgs decays into dark gluons. These gluons then hadronise and produce glueballs, which can be searched for at colliders. Depending on the lifetime, the produced glueballs will either decay outside the detector or with a displaced vertex. As no dedicated searches exist, collider constraints were estimated through Higgs decays to two LLPs, which in turn result in displaced jets. Though these constraints should only be considered indicative, it is clear from Fig. 2 that colliders are able to probe significant dilutions. The result by DESY theorists strongly motivate further collider searches for LLPs. More details can be found in [1].

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Reference:

[1] F. Bishara, F. Sala, K. Schmidt-Hoberg, arXiv:2401.12278

Unveiling emergent supersymmetry

Emergent (super-)symmetry from non-Lagrangian theories

Symmetry provides one of the central concepts in modern physics. Often, while a physical system may appear to have a certain symmetry, the symmetry may, in fact, be much larger than is apparent, and this has important consequences towards being able to compute physical quantities. The string theory group at DESY has studied four-dimensional minimally supersymmetric quantum field theories that undergo symmetry enhancement at low energies to the well-studied maximally supersymmetric quantum field theories. This allows the group to use powerful tools developed for highly symmetric theories to understand theories with much less symmetry.

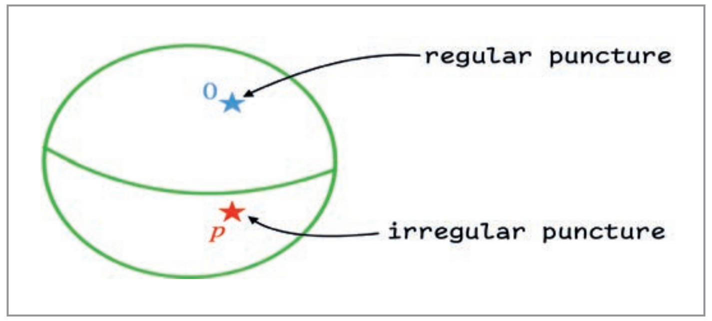

Figure 2

The string theoretic geometric origin of the Argyres–Douglas theories that we consider involves two-punctured spheres, with one regular and one irregular puncture, as depicted here.

Symmetry is the fundamental organising principle used to characterise physical systems. Symmetry is such a central concept as it provides constraints that allow one to answer physical questions that appear intractable without symmetry. Along renormalisation group flows, connecting physical systems at different energy scales, symmetries can be spontaneously broken, or, alternatively, new symmetries can be emergent. A particularly potent type of symmetry is supersymmetry, which forces bosonic and fermionic degrees of freedom to come in pairs, as it often leads to delicate cancellations of quantum corrections, rendering certain quantities equal to their classical, uncorrected values even in the full quantum theory.

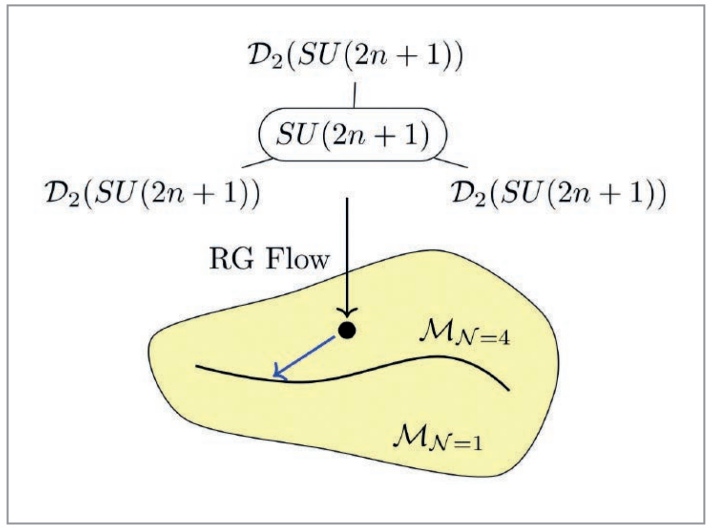

Figure 1

The top shows the gauging of three Argyres–Douglas theories, yielding a minimally supersymmetric QFT. At low energies, this theory flows to (the conformal manifold of) the maximally supersymmetric QFT (depicted as the yellow region).

While supersymmetry is typically regarded as a high-energy symmetry that exists in the ultraviolet, there are a variety of examples where supersymmetry emerges at low energies from a non-supersymmetric theory. Supersymmetry has been observed to emerge in the dilute Ising model at the tri-critical point (and in the generalisation to quantum critical points of higher-dimensional lattice models). It has also been suggested that supersymmetry can emerge at the edges of a topological superconductor – something that may even be observed experimentally in the lab. In our recent work, we have explored quantum field theories (QFTs) with a small amount of supersymmetry at high energies, but which have a larger, emergent supersymmetry at low energies.

The textbook approach to QFT involves writing down a “Lagrangian” in terms of fundamental fields, and this can be taken as a definition of the QFT. Then, one can consider a perturbative analysis around a Gaussian fixed point to understand the physical behaviour. However, most known QFTs do not have a known Lagrangian description. How, then, do we know that they exist? How can we describe their physics? In these cases, string theory comes to the rescue. String theory, in addition to being a theory of quantum gravity, can be thought of as a machine to produce QFTs. String theory is a ten-dimensional theory, and one way to produce a four-dimensional QFT is to compactify six out of ten dimensions; the geometry of these compact dimensions then fixes the physics of the resulting QFT. This geometric approach also captures strong-coupling physics, which is related to some of the most fascinating features of QFT, such as confinement in quantum chromodynamics (QCD) or the quark–gluon plasma that existed in the early stages of the universe.

One example of such non-Lagrangian theories that can be engineered from string theory are the so-called Argyres–Douglas theories; and their non-perturbative physics is well-understood from their string theory origin. Given these theories, it is possible to construct new QFTs via bottom-up operations, such as gauging them together; we refer to this class of theories as gauged Argyres–Douglas theories. While this construction can provide a rich source of novel physical behaviour, such theories can be especially hard to study, as they are both non-Lagrangian and they lack a direct construction from string theory. In our work, we find that some of these theories have emergent maximal supersymmetry; this unexpected symmetry enhancement then allows us to use the tools developed for maximal supersymmetry to study the gauged Argyres–Douglas theories, and even the Argyres–Douglas building block theories themselves.

In fact, this emergent supersymmetry is only the most extreme example of the surprising relationship between minimally supersymmetric gauged Argyres–Douglas theories and maximally supersymmetric Yang–Mills theory. In particular, these theories have identical central charges, something that is enforced by maximal supersymmetry, but that is unexpected when there is less supersymmetry. In general, the difference of the central charges has an infinite number of contributions, and these contributions must all miraculously conspire to cancel. Is this remarkable cancellation an accident, or is there some structure, such as an (emergent) symmetry that, in the general case, protects the difference of central charges from correction? Given the central importance of symmetry in physics, this tantalising hint of a novel symmetry in these non-Lagrangian theories is something we aim to unveil in the near future.

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References:

[1] M. J. Kang et al., Phys. Rev. Lett. 130, 231601 (2023)
[2] M. J. Kang et al., Phys. Rev. D 105, 126006 (2022)
[3] M. J. Kang et al., Phys. Rev. D 104, 105005 (2021)

New window into the gravitational-wave universe

First evidence of a gravitational-wave background from pulsar timing

By tracking the arrival times of radio pulses from a collection of pulsars in the Milky Way, DESY members of the NANOGrav collaboration have contributed to the first evidence for a background of gravitational waves permeating our galaxy. The origin of this background is still unknown. One possibility is that it stems from the collective and overlapping gravitational emissions from a population of supermassive black hole binaries residing at the centre of galaxies. An alternative and possibly even more intriguing possibility is that it was produced in the early universe, fractions of a second after the big bang.

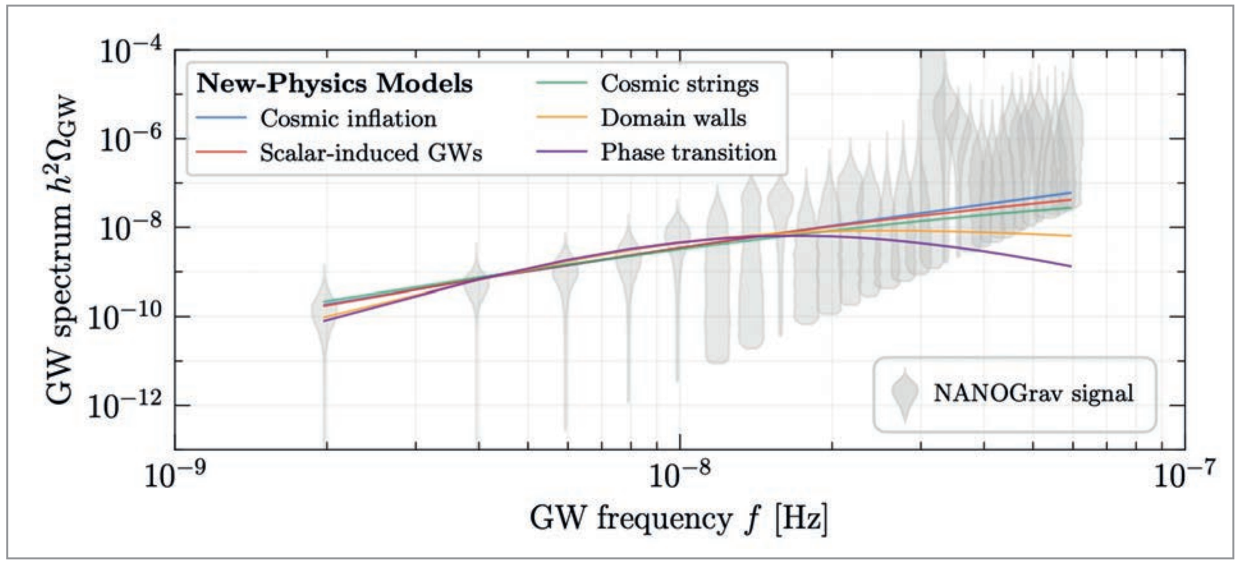


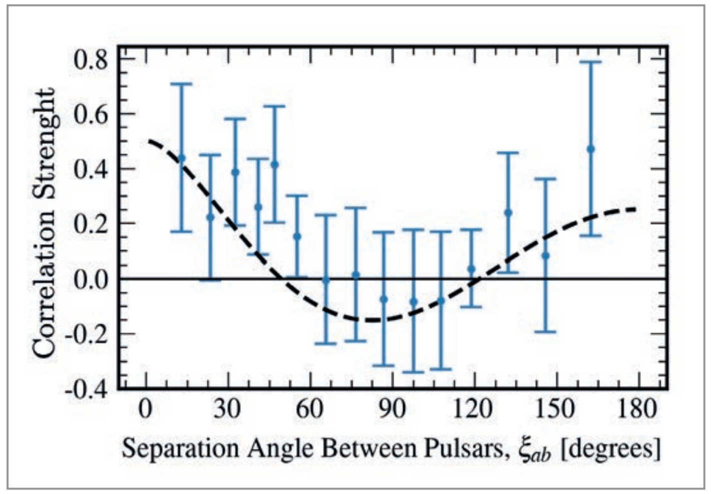
Figure 2

Comparison between the GW spectra of potential cosmological sources and the spectrum of the observed signal (grey contours). Each model ties to an extension of the Standard Model of particle physics: cosmic inflation (blue – exponential expansion of the universe), scalar-induced GWs (red – large density fluctuations in the primordial plasma) and cosmological phase transitions (purple – changes in the vacuum state of the universe, similar to the phase transition from liquid water to steam). Cosmic strings and domain walls (green and orange lines, respectively) are cosmic defects, like cracks in an ice cube that occur as water freezes.

The gravitational-wave background

The ability to detect gravitational waves (GWs) is changing how we look at the universe and ushering us into a new era of astronomy. Several pulsar timing array (PTA) collaborations, which use precisely timed millisecond pulsars to detect ripples in space-time induced by passing GWs, have recently found convincing evidence for the presence of a gravitational-wave background (GWB) permeating our galaxy (see for example Ref. [1]).

This evidence consists of correlated perturbations in the arrival times of the radiation pulses emitted by the pulsars, which are caused by the stretching and squeezing of the fabric of space induced by passing GWs (Fig. 1). DESY scientists involved in the NANOGrav collaboration played a central role in this effort. They were especially involved in the study of possible sources for such a GWB. Indeed, while we have strong evidence for its existence, the origin of the GWB still remains unknown.



Astrophysical sources

One possibility is that we are seeing an astrophysical background generated by the collective and overlapping GW emissions from a population of supermassive black hole binaries (SMBHB) residing at the centre of most massive galaxies. These binaries are believed to form during the hierarchical merging of galaxies. However, we still lack direct evidence of their existence, and a long-standing debate persists about whether such binaries can efficiently form during galaxy mergers and which mechanisms bring them to sufficiently small orbits to produce a detectable GWB.

The results of our preliminary analysis suggest that, in order to explain the observed GWB signal, these binaries should be more massive and common than we previously expected [2]. The data also seem to suggest a turnover in the GWB power at low frequencies – which might be an indication of sizable interactions between the binaries and the stars and gas of their host galaxies.

Figure 1

A background of gravitational waves should imprint a distinctive pattern of correlated timing variations on pulsars, indicated here by the black dashed line. The blue dots show the correlations measured by NANOGrav after binning and averaging the correlation measurements of all pulsar pairs.

Cosmological sources

An alternative and perhaps even more intriguing possibility is that the GWB was produced in the early universe, fractions of a second after the big bang. Such a GWB, usually referred to as cosmological GWB, should be thought of as the gravitational analogue of the cosmic microwave background (CMB).

Little is known about the physical processes that took place during this early stage of cosmological evolution, therefore detecting a cosmological GWB could provide a direct glimpse into the universe's dynamics at unprecedented high energies and at times that are not accessible to us by other means.

DESY scientists led the search for such a cosmological GWB. The results of this analysis showed how many cosmological sources could produce a GWB signal compatible with the one that we observed in PTA data (Fig. 2) [3].

Moreover, independently from the origin of the GWB, the analysis of PTA data allowed us to set novel and stringent constraints on several models for physics beyond the Standard Model. These included constraints on the tensor power spectrum produced by inflationary dynamics, the magnitude of primordial density fluctuations at scales smaller than the ones probed by CMB measurements, the properties of cosmological defects like cosmic strings and domain walls, models of ultralight dark matter (DM) and the abundance of DM substructures in the Milky Way. With the analysis of future data sets, these constraints will become even more stringent and constitute one of the primary scientific results of PTA observations.

The path forward

Identifying the origin of the GWB is one of the main objectives of future PTA observations. Several properties of the GWB can be used to achieve this goal. These include the GWB power spectrum, which describes the distribution of the background's power in the frequency domain, GWB anisotropies, which describe the distribution of the GWB in the sky, and the presence of continuous GW signals on top of the underlying GWB.

A small team at DESY is currently collaborating with researchers from the NANOGrav and IPTA collaborations to develop and improve the data analysis and theoretical frameworks needed to use the GWB properties to identify the origin of the signal. This effort includes simulations of large libraries of SMBHB populations to understand the level of GWB anisotropies and the strength of GW signals they typically produce. These tools will then be used to analyse future data sets from the NANOGrav and IPTA collaborations.

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References:

[1] NANOGrav Collaboration, Astrophys. J. Lett. 951, L8 (2023)
[2] NANOGrav Collaboration, Astrophys. J. Lett. 952, L37 (2023)
[3] NANOGrav Collaboration, Astrophys. J. Lett. 951, L11 (2023)

Identifying the dark sector of the universe

Imprints from early dynamics to late time signatures

Explaining the enigmatic presence of dark matter is one of the greatest challenges of modern physics. Supported by the German Research Foundation (DFG), a newly established Emmy Noether Independent Junior Research Group (ENG) at DESY is dedicated to investigating the properties and signatures of elusive forms of new physics connected to dark matter, known as the "dark sector". Between the phenomenology and cosmology subgroups of the DESY Theory group, this ENG explores the imprints left on cosmological observables by dynamics of the dark sector during the early stages of our universe.

Post-inflationary dynamics

Cosmic inflation is our best theory for simultaneously explaining the quasi-homogeneity of our universe at large scales and the primordial size of inhomogeneities. At the end of inflation, the energy density carried by the inflaton (the scalar field driving inflation) is converted into Standard Model plasma ("radiation"). Parametric resonance effects during this stage can give rise to a substantial increase in inhomogeneities, which can be accompanied by the formation of primordial black holes and the production of gravitational waves as clear evidence of these effects. The ENG investigates such dynamics in conjunction with dark-matter production.

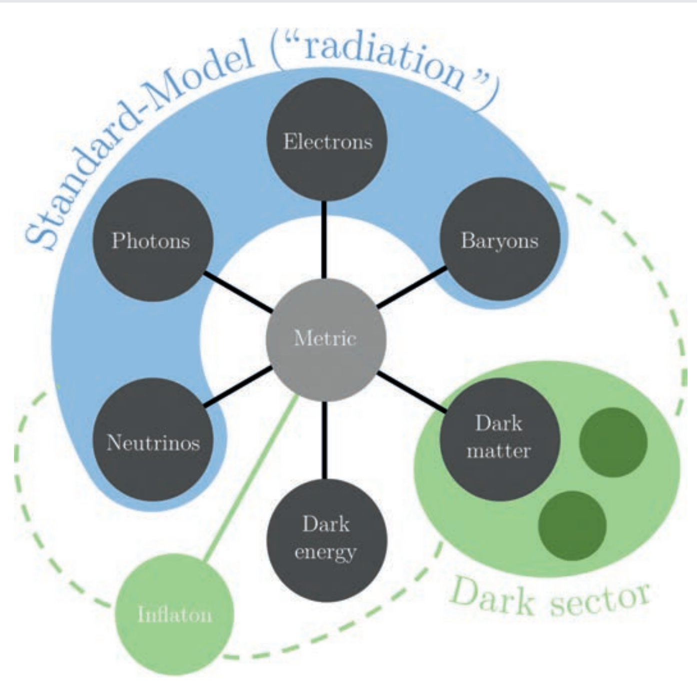

Figure 1

Most relevant interactions in the ΛCDM cosmological model. The ENG focuses on the elements beyond ΛCDM represented in green.

Cosmological signatures of dark sectors

The nature of dark matter is imprinted in the inhomogeneities currently observed in our universe. One of the best ways to test the properties of dark matter is to understand the dynamics of such inhomogeneities. In this context, the ENG explores two main lines of research: (i) the consequences of microscopic interactions and dark-matter production on primordial inhomogeneities and (ii) the possibility that our universe has undergone a cosmological phase transition within an extended dark sector. The ENG focuses on identifying signatures associated with these effects in order to deepen our understanding of the dark sector of the universe.

Emmy Noether Independent Junior Research Group

"Identifying the dark sector of the Universe: Imprints from early dynamics to late time signatures"

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Cornering new physics with generic precision calculations

High-precision theory predictions to exploit data from current and future experiments

Within our current understanding of particle physics, many questions, such as the origin of the asymmetry between matter and antimatter, remain unanswered. This signals the need for some new physics, the nature of which eludes us so far however. In this context, the Higgs boson offers a unique opportunity to search for indirect signs of this new physics through precision studies of its properties. Funded by the German Research Foundation (DFG), a new Emmy Noether Independent Junior Research Group (ENG) in the DESY Theory group is performing precision theoretical calculations to make optimal use of experimental data awaited from high-energy colliders and of cosmological observations to probe the Higgs sector.

Probing new physics with the Higgs boson

We are witnessing the dawn of an area of precision measurements of Higgs properties at high-energy colliders. Theory therefore needs to provide high-accuracy predictions of these observables to reliably interpret measurements in terms of viable scenarios of new physics. The new ENG participates in this effort and delivers precise results for general theories, for use by the community. Of particular interest is the trilinear Higgs coupling, which controls the shape of the Higgs potential (Fig. 1) and was shown by DESY theorists to provide a strong tool to probe new physics [1, 2]. The trilinear Higgs coupling is one of the main focuses of the ENG, with support of the development of the public tool anyH3 [3], together with other Higgs couplings (e.g. to two photons) or its decays.

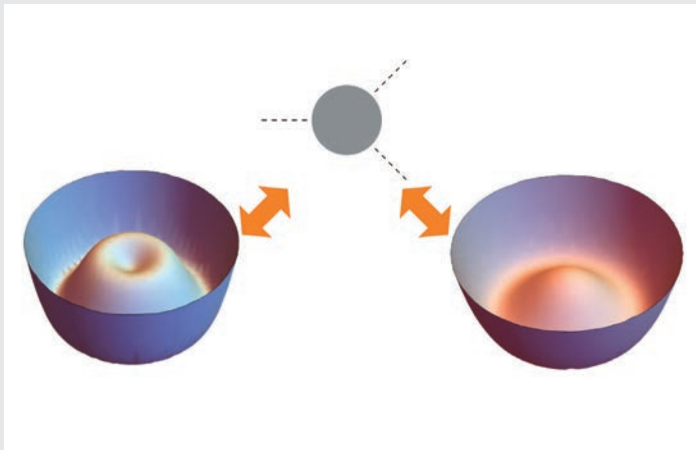

Figure 1

The trilinear Higgs coupling gives information about the shape of the Higgs potential.

Relics of the early universe

Cosmological observations also represent a powerful complementary probe of early universe evolution. Indeed, strong first-order phase transitions could source a stochastic background of primordial gravitational waves (GWs) or primordial black holes (PBHs), which can be investigated with GW interferometers (e.g. LISA) or microlensing observations. In this direction, the ENG investigates how GWs or PBHs can be produced in theories of new physics and what can be learned about the Higgs sector of such theories from cosmological observations.

Emmy Noether Independent Junior Research Group

"Cornering New Physics with Generic Precision Calculations"

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References:

[1] H. Bahl, J. Braathen, G. Weiglein, Phys. Rev. Lett. 129, 231802 (2022)
[2] H. Bahl, J. Braathen, M. Gabelmann, G. Weiglein, Eur. Phys. J. C 83 12, 1156 (2023)
[3] https://gitlab.com/anybsm/anybsm
[4] https://www.desy.de/~braathen/emmy-noether-research-group.html

Pure glue on a lattice

The quest for new algorithms for finding balls of glue

Glueballs are elusive particles thought to consist primarily of gluons, but so far they have not been identified beyond doubt in experiments. Fortunately, this strong-interaction physics can in principle be studied by simulating quantum chromodynamics on a computer. As these numerical computations are very demanding in terms of resources, progress in algorithms is essential to address difficult problems that are out of reach of current methods, such as the existence and nature of glueballs, as well as to keep this line of research sustainable.

Some problems become classic because – significant long-time efforts notwithstanding – they are still considered hard and have not been solved to a satisfactory level. One such question is the existence of glueballs in nature, which, despite considerable efforts from both experiment and theory, have not yet been identified.

Why are glueballs interesting? When it comes to strong interactions, we usually observe only protons and neutrons in nature, which consist of quarks held together by gluons. These two particles are known as baryons, which in the simple picture have three valence quarks. In addition, mesons with two valence quarks have long been observed, and they are an important part of our understanding of strongly interacting matter. In this picture, glueballs are particles made up of gluons only. They were hypothesised half a century ago, and so far only glueball candidates have been found in experiments.

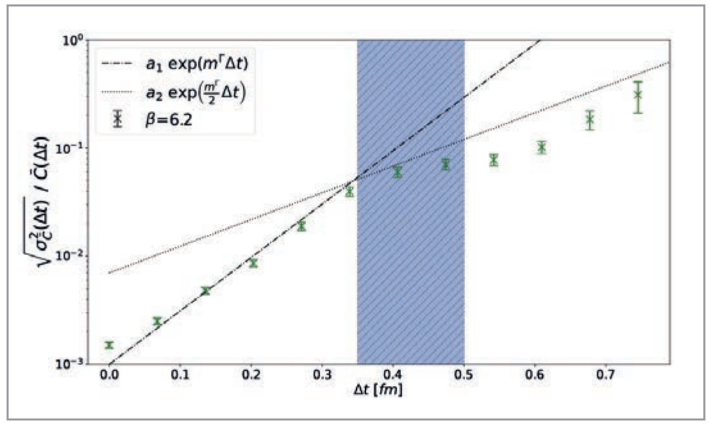

Figure 1

Relative error of the correlation between two glueball operators from which the mass is extracted. The dashed-dotted line gives the standard scaling of the noise-to-signal ratio with increasing distance. Where the standard method would lose the signal at around 0.4 fm/c, the domain-decomposed multilevel sampling stabilises the relative uncertainty. These distances are needed for reliable extraction of the signal in the full theory including quarks.

The best evidence for glueballs comes from numerical calculations that solve quantum chromodynamics, the best theory of strong interactions, on a discrete space–time lattice. Here, in a theory without quarks, these pure glue states were clearly identified in the 1990s. At the time, states starting at one and a half times the mass of the proton were found with various quantum numbers. The catch is that a theory with gluons only is not what we observe in nature. Quarks are inseparably linked to gluons and vice versa. To answer the question of the existence of glueballs, numerical studies are therefore required in the full theory of interacting quarks and gluons, unless experimentalists find no clear signal for such a state in their data. At the current stage, it is even not clear whether and how the idea of states made up primarily of gluons will hold once quarks are included in the picture.

Algorithms

Despite tremendous progress in numerical lattice quantum chromodynamics calculations, glueball states are elusive in computations with the full theory including quarks. The source of the problem is the presence of many other, lighter states that have the same quantum numbers, mixing with the states of interest. These states consist of mesons, quark bound states not present in the purely gluonic theory that provided the evidence in the earlier studies. One task is to identify all these states and their mixing with each other. This alone is daunting. Worse, the presence of many light states also causes severe deterioration of the signal when using state-of-the-art techniques of Monte Carlo sampling of the relevant integrals.

To improve this situation, a research unit was formed by scientists at the University of Wuppertal, Trinity College Dublin and DESY, funded by the German Research Foundation (DFG) under grant number FOR5269. The goal of the research unit is the development of new algorithms to improve the signal in numerical lattice quantum chromodynamics calculations.

One particular approach is domain-decomposed sampling. As the task is to compute correlations between glueball fields separated in time, these algorithms use the locality of the theory to average locally around these space–time points. The sampling in the different domains is to a large extent independent and therefore more efficient than one that samples at all space–time points at once. This strategy has the potential to improve the scaling with the number of field samples N from the inverse square root of this number to its inverse. If one takes $N = 100$ of such sub-samples, the total speed-up of the calculation is therefore ideally a factor of $\sqrt{N} = 10$.

Figure 1 demonstrates that this strategy works in the case of glueballs in the theory with gluons only [1, 2]. At short time distances, the signal deteriorates rapidly and exponentially with respect to noise. The domain-decomposed multi-level sampling is effective at larger distances, where we clearly see that the deterioration can be mitigated with these advanced techniques. These findings will be essential for the next step, the simulation of the full theory including fermions.

Machine learning

In a lattice quantum chromodynamics calculation, gluon field configurations are drawn from a distribution that is prescribed by the theory under investigation, quantum chromodynamics in our case. This is usually done in the context of a Markov Chain, where an update algorithm produces a time series of such fields, deforming them in small steps in a probabilistic way. The problem we face is that this procedure becomes increasingly inefficient as the resolution of the space–time lattice is increased.

Methods for drawing samples from a given probability distribution have been extensively studied in the machine learning community. One promising approach are so-called normalising flows, which generate the field configuration by continuously deforming completely unordered starting configurations to target configurations that represent the full theory.

Researchers at DESY, TU Berlin and the Cyprus Institute have explored such an approach and found a significant improvement compared to other groups' setups [3]. The model that gives the deformation from the trivial, unordered distribution to the target has to be determined and trained in the language of machine learning. In two-dimensional quantum chromodynamics, this approach can be successful, as shown in Fig. 2. It gives the probability to generate a relevant field configuration with this method as a function of the computer time invested in training the model. Depending on the theories' parameters, the model we have studied can be adjusted in such a way that this probability is sufficiently high for the method to work.

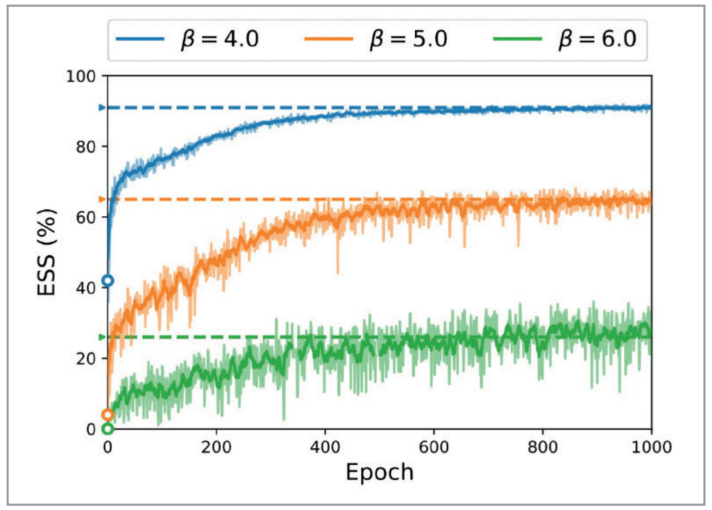

Figure 2

Field configurations drawn at the target distribution parametrised by the inverse coupling β starting from completely unordered configurations. x-axis: Training time of the parameters of the model that generates the transformation. y-axis: Effective sampling size, i.e. the percentage of "relevant" configurations. The training makes the model much more efficient.

While this finding is promising, full four-dimensional quantum chromodynamics is a much more challenging candidate, and it will take significant effort to make such an approach part of the toolbox to solve quantum chromodynamics by numerical computations.

Summary

Computations in quantum chromodynamics on the lattice use significant computer resources. Still, many problems, such as the existence of glueballs in nature, are out of reach. To address such a problem in a sustainable way, with limited use of available computers, new algorithms have to be developed. This has been a particular focus of the DESY lattice group in the recent years, as highlighted in this article. Such research will not only make new results possible, but also lead to new insights into the theory itself, as algorithmic progress without detailed physics knowledge is virtually impossible. This progress will hopefully put us in the position to decide whether glueballs do exist – or not.

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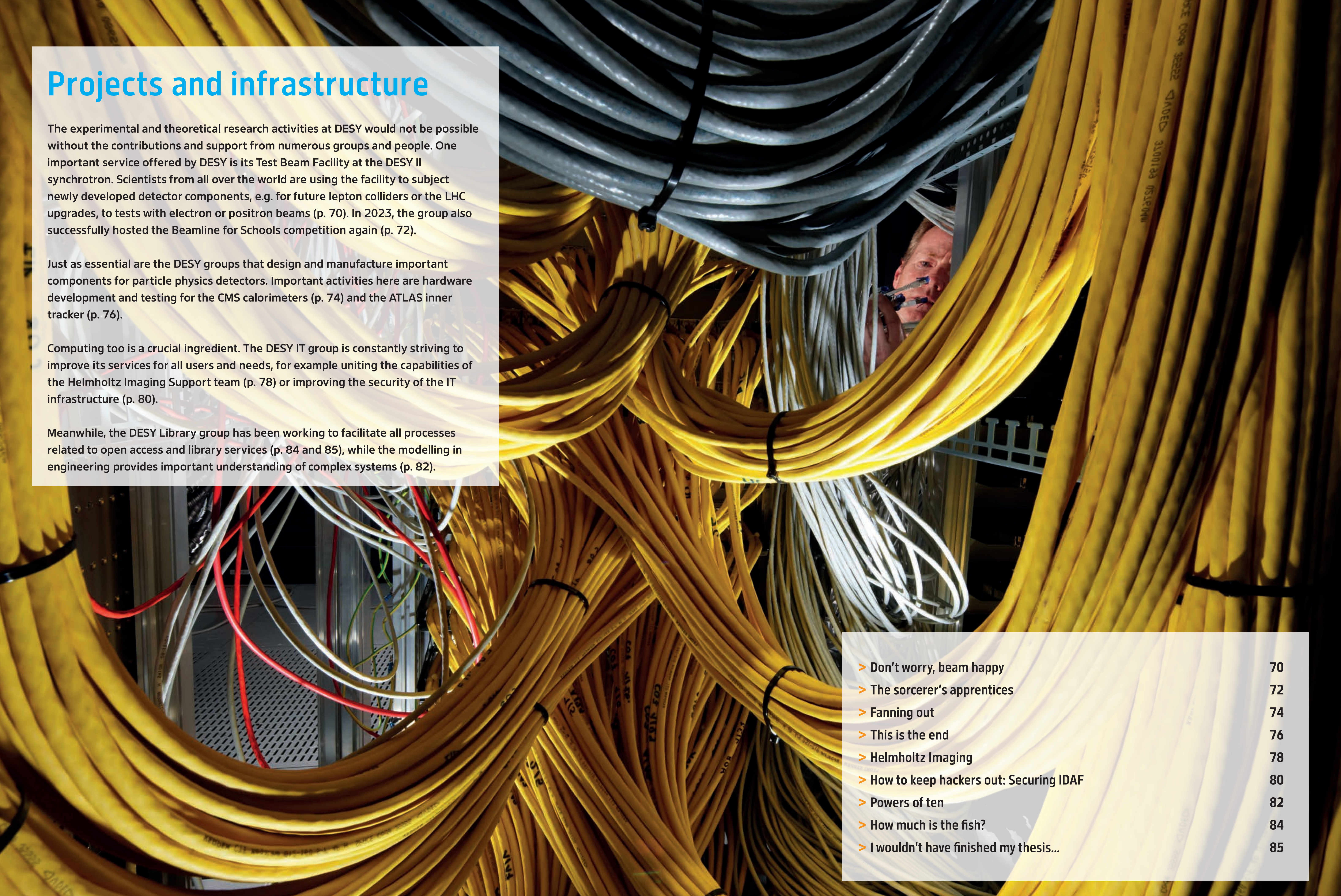
References:
[1] L. Barca et al., PoS LATTICE2023, 030 (2024)
[2] L. Barca et al., to be published
[3] S. Bacchio, P. Kessel, S. Schaefer, L. Vaitl, Phys. Rev. D 107, L051504 (2023)



Projects and infrastructure

The experimental and theoretical research activities at DESY would not be possible without the contributions and support from numerous groups and people. One important service offered by DESY is its Test Beam Facility at the DESY II synchrotron. Scientists from all over the world are using the facility to subject newly developed detector components, e.g. for future lepton colliders or the LHC upgrades, to tests with electron or positron beams (p. 70). In 2023, the group also successfully hosted the Beamline for Schools competition again (p. 72).

Just as essential are the DESY groups that design and manufacture important components for particle physics detectors. Important activities here are hardware development and testing for the CMS calorimeters (p. 74) and the ATLAS inner tracker (p. 76).

Computing too is a crucial ingredient. The DESY IT group is constantly striving to improve its services for all users and needs, for example uniting the capabilities of the Helmholtz Imaging Support team (p. 78) or improving the security of the IT infrastructure (p. 80).

Meanwhile, the DESY Library group has been working to facilitate all processes related to open access and library services (p. 84 and 85), while the modelling in engineering provides important understanding of complex systems (p. 82).

Don't worry, beam happy

DESY II Test Beam Facility delivers beam like clockwork to its international users

In 2023, the DESY II Test Beam Facility continued to highly reliably deliver electron and positron beams with gigaelectronvolt energy to 400 users from experiments and R&D projects of the global particle detector community and beyond. The world-class infrastructures, such as the EUDET-type pixel beam telescopes and the new ALPIDE-based telescope, continued to be in strong demand.

The DESY II Test Beam Facility

The DESY II Test Beam Facility is located in Hall 2 on the DESY campus in Hamburg. The three beamlines are fed by the DESY II synchrotron and offer electron or positron beams in the energy range from 1 to 6 GeV for detector prototype tests. Each beamline can be individually controlled by the user groups and provides single-particle rates up to several 10 kHz. The test beam crew offers support to the international user groups and constantly improves the beamlines and infrastructure to keep the facility a world-class venue for detector R&D.

Operations in 2023

To support the nationwide energy-saving efforts during the winter 2022/23, the start-up of the facility was moved three weeks back, so that user runs started on 6 March 2023 instead of 13 February. This was possible as no time-critical measurements were requested for this period. In addition, to optimise efficiency, the schedule was regularly rearranged to avoid weeks in which the DESY II synchrotron would deliver beam for only one beamline.

Figure 1

Countries of the test beam users' home institutes

Despite this reduced availability, 58 groups used 80 measurement weeks at the three beamlines, resulting in a facility booking of 78%. The user groups came from institutes across 16 countries (Fig. 1). Since many international collaborations involve German groups, the majority of scientists (about 60%) came to DESY from German institutes.

As in previous years, the largest fraction of the groups (44%) worked on detectors for the experiments at the LHC at CERN. Work on general R&D for the next generation of detector technologies accounted for 40%, the second largest fraction.

Of the 396 users, 42% were under- and post-graduate students, 28% came for the first time to the DESY test beam and about 50% were below 30 years old. These numbers underline the importance of the facility as a training ground for the next generation of detector experts.

Beam telescopes

The test beam facility has a beam telescope installed at each of the three beamlines. The telescopes are essential instruments used to measure the trajectories of passing beam particles very precisely. This makes it possible to extrapolate the exact position where a beam particle traverses the detector under test. As in previous years, the telescopes stayed in high demand, with 83% of the groups requesting them.

After successful testing in 2022/23, a new ALPIDE-based telescope prototype called Adenium, shown in Fig. 2, was moved to Beamline 22, which delivers the highest rates out of the three beamlines. Thanks to its ten times shorter readout frames, Adenium allows data taking at higher rates with much less ambiguities than the EUDET-type telescopes installed at the other two beamlines. Since the move, this beamline and telescope have been in very high demand, and the DESY team is working to finalise the design and equip all three beamlines with this new type of telescope.

In April, the 11th Beam Telescopes and Test Beams workshop was held at DESY. The local beamline experts offered the participants hands-on tutorials, teaching them the effective use of the DESY beamlines with a strong focus on the beam telescopes and the common data acquisition framework.

Test beam registration system

In 2023, the move to a new beamtime registration system was successfully completed (Fig. 3). The transition started in 2022 with the single-user registration. In 2023, the complete workflow, from user groups applying for beamtime to the final scheduling and the organisation of the beamtimes, was put into operation. The new system is integrated in the DESY computing infrastructure and connected to the central systems for person and safety handling. By collecting all information in one place and offering essential tools, the registration system facilitates beamtime registration and organisation for the visiting groups and for the facility coordination.

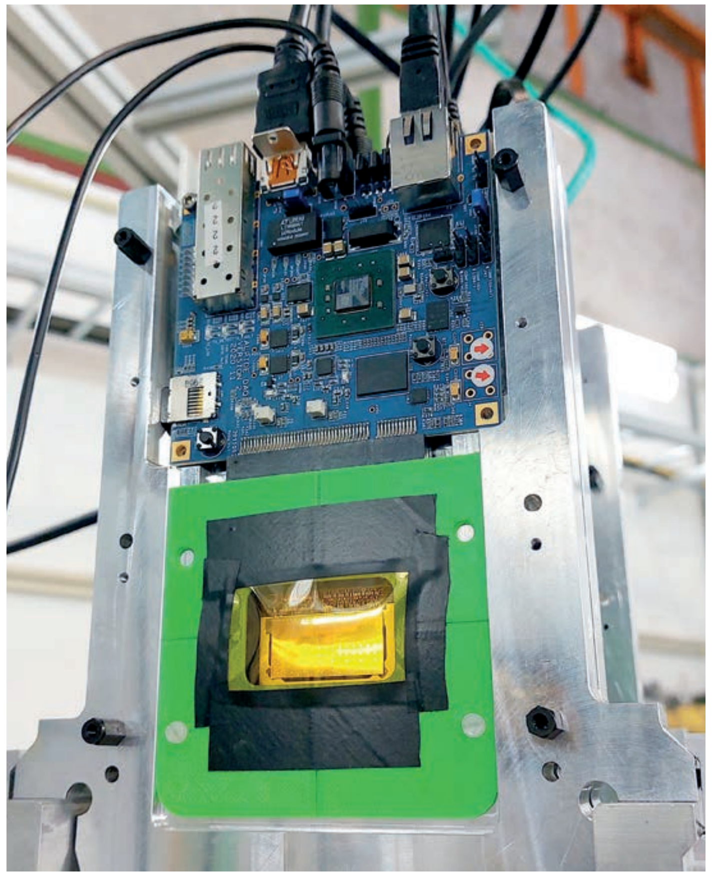


Figure 2

A layer of the new Adenium telescope prototype, with the ALPIDE pixel sensor visible behind the orange Kapton foil and the readout board on top

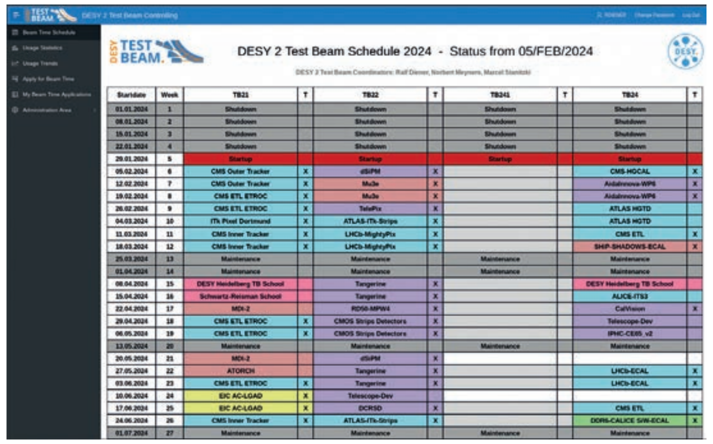


Figure 3

Beamtime schedule 2024 in the test beam registration system

Outlook for 2024 and beyond

The winter shutdown 2023/24 was used for maintenance and upgrades before the user runs started again on 5 February 2024. The call for beamtime in the first half of 2024 met with a great response: The first three months, February to April, are 100% fully booked, and the following two months are already over 90% full. As usual, requests received after the official call will be scheduled on a first-come, first-served basis.

A major ongoing task at the test beam facility is the planning of its future in view of the upgrade of the PETRA III X-ray radiation source to PETRA IV. These efforts were intensified in 2023 with the start of a new team member focusing on the development of solutions to provide and improve the test beamlines at the planned pre-accelerator complex. The collaboration with the PETRA IV project team was intensified, and several options are being explored and optimised in detail.

Summary

2023 was another year in which the DESY II Test Beam Facility reliably provided much-needed beam to the international detector development community, and we are looking forward to a successful year 2024. The success of the facility would not have been possible without the support from many individuals and groups from the DESY Particle Physics and Accelerator divisions. We would like to take this opportunity to thank everybody involved.

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The sorcerer's apprentices

Beamline for Schools competition celebrates its 10th edition

The 2023 edition of Beamline for Schools marked the 10th edition of the competition, which is hosted by CERN and DESY and offers beamtime to high-schools students. This year's winning teams that travelled to CERN were the "Myriad Magnets" from the USA and the "Particular Perspective", who represented Pakistan for the first time. DESY hosted the "Wire Wizards" from the Netherlands, who tested their own home-made wire chambers.

Worldwide particle physics competition for high-school students

As a high-school student, have you ever dreamed about building a particle physics experiment and testing it at a real particle accelerator? Since 2014, this dream can become reality: The winning teams of the Beamline for Schools (BL4S) competition are offered a two-week stay at CERN or DESY to test their experiment at CERN's Proton Synchrotron (PS) or the DESY II test beams. The main constraint: The experiment must fit the fixed-target setup at the test beams and be built by the students themselves or with hardware available there. In 2023, 379 teams totalling more than 2500 students from 68 countries submitted a project, once again surpassing the record from the previous year.

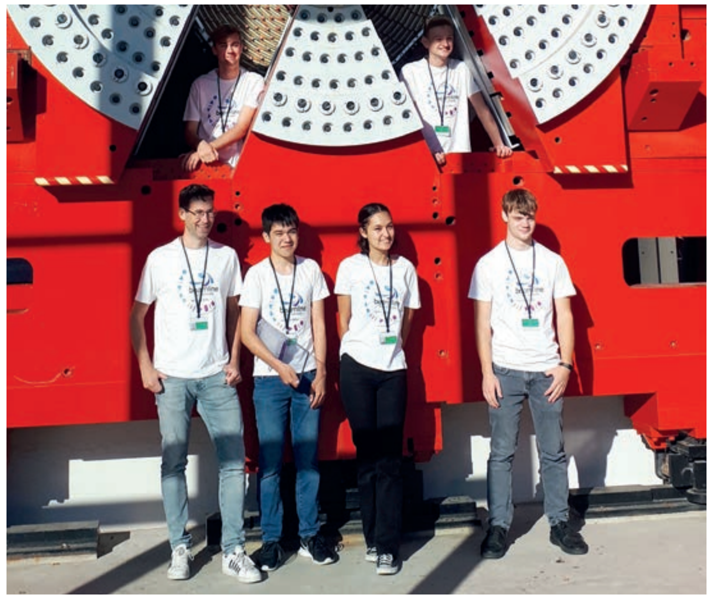

Figure 1
The Wire Wizards from Eindhoven, the Netherlands, in (front of) the ARGUS detector at DESY

At the start of the competition on the occasion of CERN's 60th anniversary, two teams were originally selected to go to CERN. In 2019, CERN's accelerator complex entered a shutdown phase and the two teams were hosted by DESY instead. In 2022, CERN's accelerators were back in operation and the cooperation with DESY continued, allowing for a third team to be selected: Two would go to CERN and one would be hosted by DESY.

Winning teams in 2023

Out of the 27 teams shortlisted this year, the winners came from the USA, Pakistan and the Netherlands. CERN hosted the "Particular Perspective" team, comprising students from several schools across Pakistan, and the "Myriad Magnets" team from Phillips Exeter Academy in New Hampshire, USA. The first team studied the particle composition of the beam at CERN'S PS Beamline T9, while the second designed a modular magnet setup that could be used in future accelerators.

The "Wire Wizards" (Fig. 1) from the Augustinianum in Eindhoven, the Netherlands, who were invited to DESY, designed multiwire proportional chambers that can be built using widely available tools and materials. Their goal was to publish the design as an open-hardware project in order to allow other students to build their own detectors based on this design. The project, initiated as an outstanding high-school project, fitted in with the BL4S competition, and the students could eventually test their prototypes at Beamline 21 at the DESY II Test Beam Facility.

Home-made detector at Beamline 21

Wire chambers consist of an enclosed volume of gas surrounded by two cathode plates under high voltage, with anode wires in between. When an incoming high-energy particle traverses the volume, it ionises the gas. The ionisation electrons drift towards the closest wire, creating an electron avalanche in its vicinity. This signal is transmitted by the wires to the outside of the chamber and can be recorded by the readout electronics.

The challenges reside in making the chamber air-tight and avoiding spikes on all surfaces that could create electric discharges caused by the high voltage. The operation of the chamber is also not an easy task: The high voltage must be controlled in such a way as to maximise the signal strength while limiting the noise on the wires.

Upon their arrival at DESY, the Wire Wizards used the first days to meticulously assemble their four chambers, drilling, gluing and soldering the last pieces together. After some tuning, the chambers were placed in the DESY test beam and saw their first particles (Fig. 2). Over the following days, the chambers were characterised using various gases and high-voltage settings.

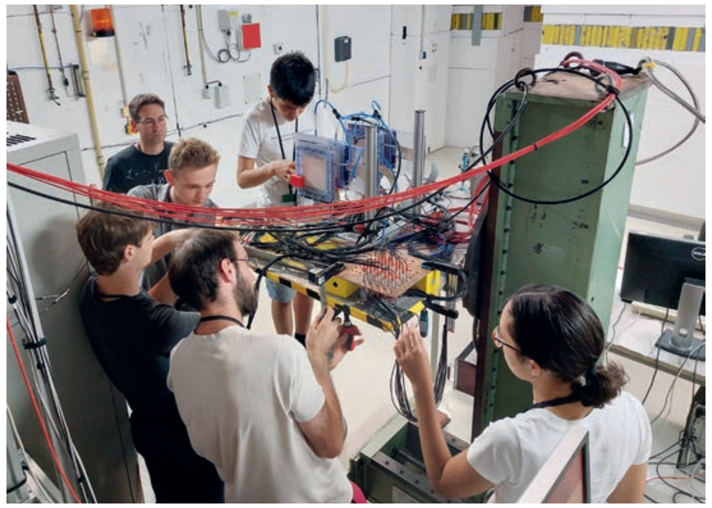

Figure 2
The Wire Wizards assembling and connecting their detector at Beamline 21

Living the real test beam experience

Test beam campaigns are always full of surprises, and both the students and the DESY supporting team experienced their fair share: They learned step by step how to operate the setup and overcome all data-taking issues. The team eventually managed a smooth operation of the detector and started analysing the data with the help of volunteer DESY PhD students and postdocs.

Daily morning online meetings between CERN and DESY allowed all teams to share their progress and experience. A live video connection between the two control rooms also provided support in frustrating moments and enabled shared joy over major successes on both sides.

At the end of their stays, the teams prepared conference-style presentations that were given in front of all other teams and support scientists. This *almost* concluded their first research experience: All the teams were invited to present their experiment and results at the 12th Beam Telescopes and Test Beams workshop in April 2024.

BL4S celebrates its 10th edition

In 2023, BL4S celebrated its 10th edition with a special VIP and sponsors event featuring short talks from the CERN and DESY Directorates (Manfred Krammer and Beate Heinemann), from the sponsors (Rolex and the Wilhelm and Else Heraeus Foundation), from this year's winning teams as well as from previous winning teams, coaches and local supporting teams, who provided a recollection of their experience at BL4S. The event was co-hosted by CERN and DESY, with VIP delegations from the US, Pakistani and Dutch embassies attending on-site, while around 80 additional participants connected online. This marked a 10th successful BL4S edition for both CERN and DESY and their cooperation in the event.

At DESY, the celebration was concluded with a barbecue to which the test beam group had invited all participants and helpers: The Wire Wizards shared a relaxed time with the VIPs and the former and current organising and supporting team at DESY.

Acknowledgments

Beamline for Schools is an education and outreach project funded by the CERN & Society Foundation. The 2023 edition was supported by Rolex and the Wilhelm and Else Heraeus Foundation. The BL4S competition is only possible thanks to the contributions and support of a large number of groups and individuals at CERN and DESY. We would like to take this opportunity to thank the volunteers, colleagues and groups who have contributed their time and expertise for their invaluable support.

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Fanning out

Towards the series production of the scintillator tile modules for the CMS high-granularity calorimeter

Like all detectors at the LHC, the CMS detector will also be upgraded for the high-luminosity phase of the collider (HL-LHC). Part of the CMS upgrade includes two new endcaps with novel, highly granular calorimeters. The hadronic part of the calorimeter contains complex detector modules based on silicon photomultipliers and scintillating tiles, the scintillator tile modules. Following the successful prototyping phase, the tile modules now have to be realised in 32 geometrical variants. Each tile module design requires careful verification to avoid mechanical conflicts in the detector. With the installation planned in 2027, the preparation of the series production is picking up speed also at DESY.

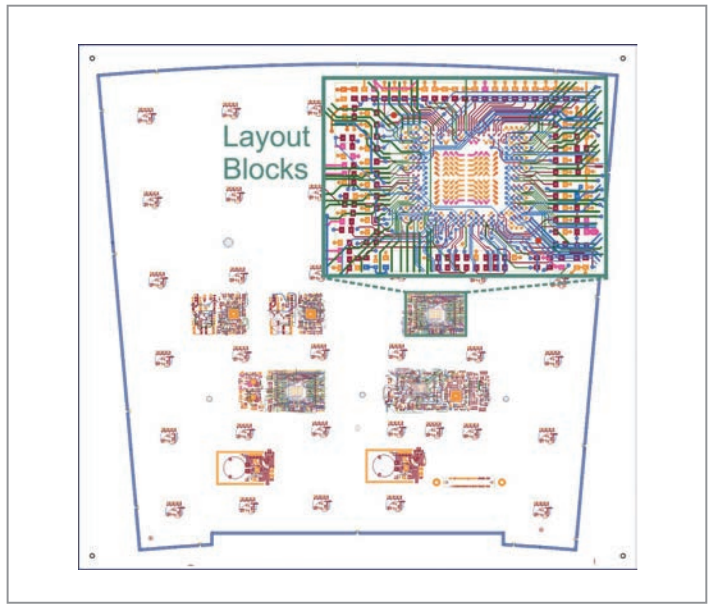

Figure 2
Tileboard layouts: High-density areas around the ASICs are merged to layout blocks.

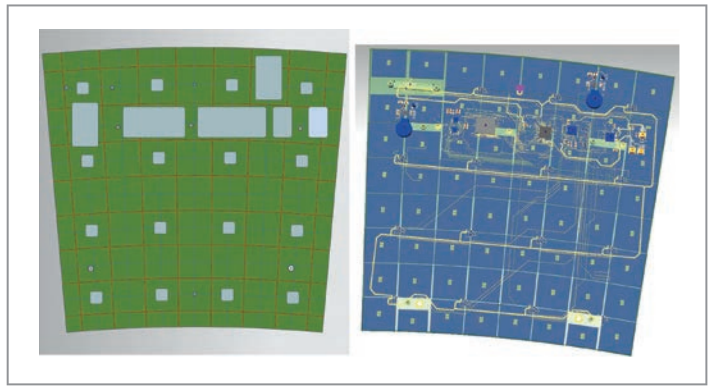

Figure 3
Tile module envelope (left) and detailed, final design model (right)

In its downstream half, the high-granularity calorimeter (HGCAL) of the new endcaps of CMS [1] contains 14 active detector layers in two different technologies. The inner part in radial direction is formed by hexagonal silicon modules, while the outer part is covered by up to five adjacent tile modules of different geometries (Fig. 1). To fill the circular structure of the endcaps, the tile modules are of trapezoidal shape, each covering 10° of the endcaps' circumference.

For the 14 detector layers of the HGCAL, 32 geometrically different tile module variants now have to be realised. Of these 32 variants, however, only eight main variants differ significantly from each other in size and electrical setup. The main variants have sizes between 15 x 21 cm^2 and 42 x 45 cm^2. All remaining tile modules differ only slightly from their respective main variant.

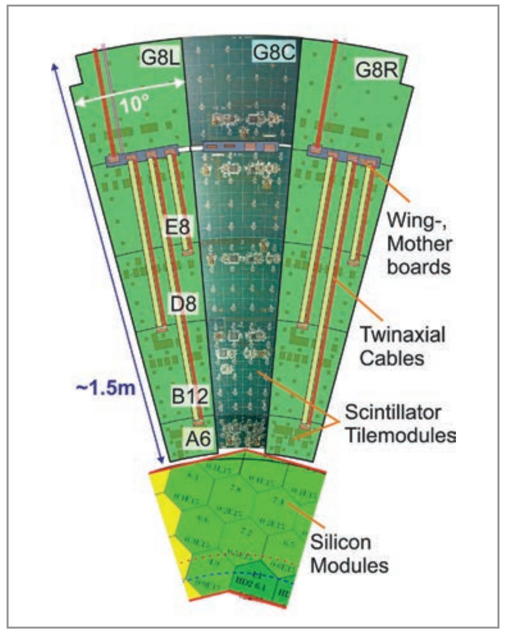

Figure 1
Top view of a 30° section of a CMS HGCAL mixed cassette

Although most of the main tile module variants come with very similar circuit diagrams (schematic), generating the layouts for the printed circuit boards (PCBs) proved to be rather time-consuming: Alongside the outer dimensions, the positions of the connectors and the application-specific integrated circuits (ASICs) on the tile modules also vary between the variants (Fig. 1).

In consequence, in 2023, the DESY FE group finalised the use of layout blocks in the ECAD tool Mentor Xpedition. From a layout design that proved to be good in tests of the realised tile module prototype, the most complex areas around the ASICs are merged to layout blocks (Fig. 2). The blocks contain components, vias and traces across all signalling layers of the PCB. As the blocks can be moved and rotated as a whole, they allow efficient optimisation of the tile module designs. Once validated, the electrical behaviour within the layout blocks does not change any more, enabling a reliable transition from one tile module design to the next. The introduction of the layout blocks has simplified and accelerated the layout design effort significantly.

Before new tile module layouts are designed, their underlying envelopes are created. Envelopes are mechanical models of the tile modules that contain, next to the layout block contours (Fig. 3 left, grey boxes), the PCB itself and important components with their positions and dimensions. Through import into the respective ECAD tools, the envelopes allow the layout design of new tile module variants in parallel with the mechanical design of the detector cassette. For the latter task, the envelopes are integrated into the overall 3D detector model by members of CMS at CERN and Fermilab. In 2023, the FE group finalised the envelopes for most of the tile modules.

As soon as a tile module layout is completed, a detailed 3D model is created (Fig. 3 right). In a final integration step, the envelopes are replaced in the global 3D detector model by the detailed tile module models so that any mechanical conflicts can be excluded in the most reliable way.

In 2023, the DESY FTX, FE and ZE groups jointly produced several pre-series tileboards of five main variants (Fig. 1 centre). In ongoing tests, many pre-series boards have already been successfully checked on a test bench and at the DESY II Test Beam Facility (Fig. 4).

In contrast to previous prototypes, the pre-series modules are close to the final versions foreseen for installation at CMS. An important task for DESY and its partners during commissioning is therefore to optimise the test methods and the subsequent automatic test scripts for quality control (QC) in preparation of the upcoming production.

The QC involves tests at room temperature as well as measurements in a climate chamber at -30°C, the final operating temperature at CMS.

Along with the tile modules, the size of the scintillating tiles also grows every second or third detector row in radial direction, resulting in 35 different tile sizes between 2.3 x 2.3 cm^2 and 5.5 x 5.5 cm^2. For the wrapping of the tiles into reflector foil, the FTX group developed a dedicated machine that was successfully commissioned. To place and glue the wrapped tiles to the tile modules, the ZE group uses a standard pick-and-place machine.

In 2024, all pre-series tileboards will be equipped with scintillating tiles produced in the USA and wrapped at DESY. Finally, a further test stand is in preparation that will allow parallel testing of up to eight tile modules with cosmic muons. The experience gained from the construction and operation of the pre-series tile modules will be essential for a smooth transition to the series production.

Figure 4
Tile module in the DESY II Test Beam Facility

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Reference:
[1] CMS Collaboration, CERN-LHCC-2017-023, doi: 10.17181/CERN.IV8M.1JY2

This is the end

… of the ATLAS inner tracker substructure

The upgrade of the ATLAS detector requires a new design of the inner tracker. Its electronics will need to operate reliably for a period of 10–15 years without access for repairs. For the end-of-substructure (EoS) cards – a high-speed interface with fine-pitch chips – the quality requirements are even higher, because a failure will lead to a loss of signals from all 14 sensors. Also, flexibility in production is an advantage and speeds up the design phase. The experience gained with the EoS boards produced so far can be used for feedback into the production. This article presents the challenges associated with the flexible and reliable production of 1700 individual printed circuit boards (PCBs) and the demanding quality control.

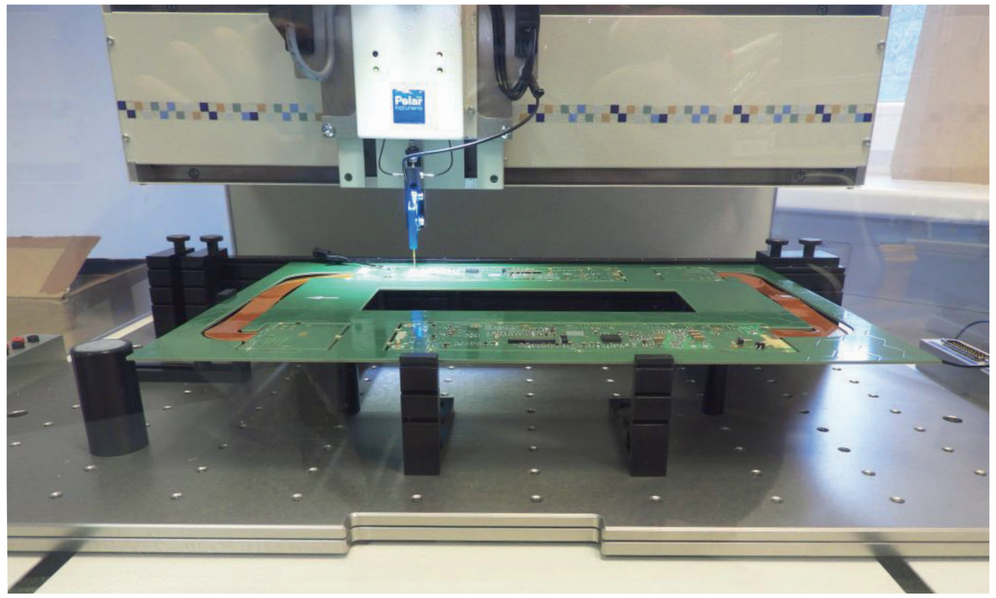

Figure 3
Flying probe testing of a multipanel with long flex leads

A new silicon tracker

For the upgrade of the ATLAS experiment at the LHC, the inner tracker (ITk) will be rebuilt. For the strip tracker, four to six layers of silicon detectors for particle crossings will be constructed from 776 substructures. Each substructure for up to 2.7 m^2 of silicon strips is equipped at its end with a pair of EoS interface boards. Their task is data multiplexing (at 10 Gb/s) and supply filtering in the neighbourhood of the sensitive silicon detectors.

For the design of the EoS boards, it is important to accommodate a 0.5 mm fine-pitch ball grid array (BGA) chip to allow bonding and to provide the freedom to position a robust connector on the detector mechanics. The cylindrical geometry requires 12 dedicated designs for different positions within the ITk, so the total amount of about 1700 boards can be split into small batches.

Each EoS is a possible single-point-of-failure candidate for a large area of sensors. Therefore, the designs must be kept robust, manufacturing needs have to be well controlled and a dedicated process of quality control (QC) must catch any weakness in design and manufacturing. The process must also cope with the concurrent engineering of the application-specific integrated circuits (ASICs), sensors and opto-devices used and with learning from QC on a growing number of available boards. This requires starting production with small quantities in order to have the flexibility to stop production and await further investigations necessary to understand any detected unexpected behaviour.

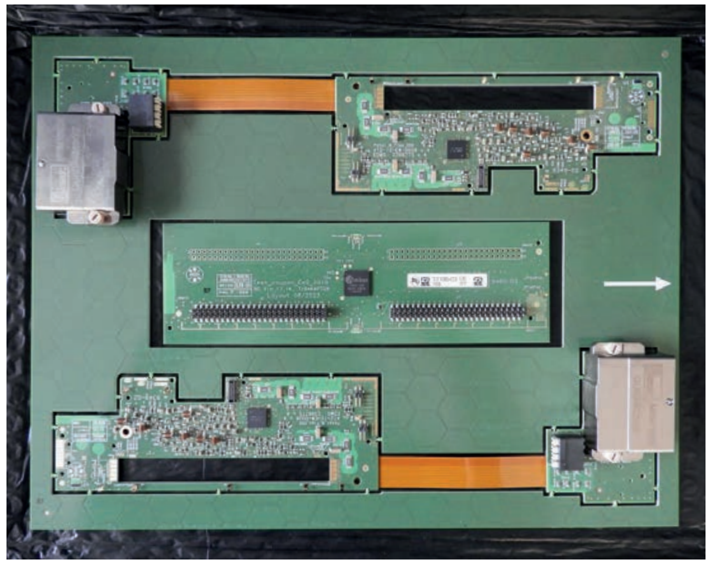

Figure 1
Two boards and a test coupon in a multipanel

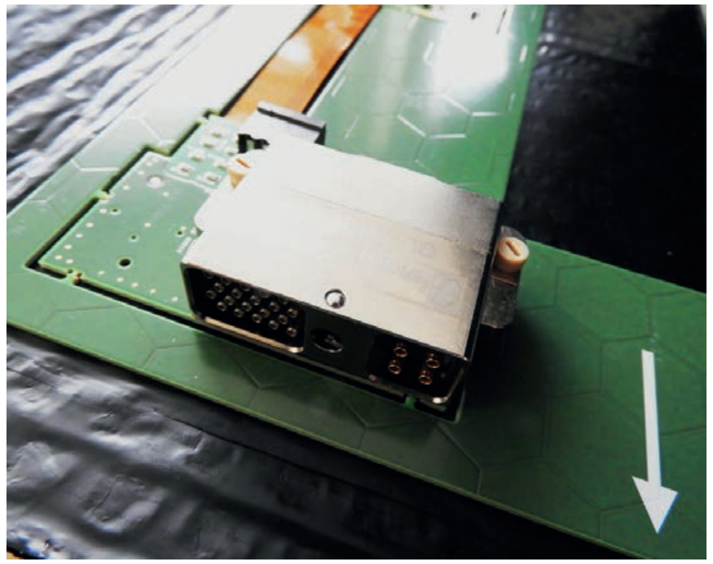

Figure 2
Space is limited: a special connector for the EoS boards

Challenges

A major challenge is the fact that, when the detector is in operation, nobody will have access to any of its parts for about 15 years. This means that the components produced now must run absolutely reliably. Quality and reliability have to be ensured before, during and after production of the boards. For the EoS boards, a very elaborate process has been developed. To understand it, let's take a closer look at the boards first.

The project starts with the naked PCBs, ordered by the DESY ZE group – about 1700 boards carrying electronic components, as well as 650 test coupons. To save money and material and optimise board handling and population, the individual boards are put together in a multipanel of two or three boards per panel, which also contains a test coupon. This test coupon allows the whole PCB manufacturing process to be tracked down to two or three individual boards. This is very important, because if the test coupon is already faulty or shows signs of premature degeneration, the remaining boards of the multipanel must be discarded. It would be too risky to use them without having access to them for a long time.

The test coupons thus have to be populated first. Only two connectors and a solder dummy for the BGA – to control the solder quality through a long chain of soldered contacts – are populated. After optical inspections at DESY ZE, they are wire bonded and go through several temperature cycles for accelerated aging, with testing between cycles: The wire bonds are pulled, and the boards are tested using a special software-controlled setup. If the results are OK and the surface of the test coupons is not damaged, the rest of the board is approved for production and can be populated at DESY ZE.

The PCBs are a bit unusual (Fig. 1) in that they are not only simple green boards but have a flex lead connection between two individual parts. This requires special handling: All the components must be mounted while they are still in the panel frame. The flex lead connections are highly sensitive and may break without mechanical support, so they should be kept in the frame as long as possible.

Manufacturing and testing

If the test coupons are approved, the boards can be populated with surface-mounted devices (SMDs). With every PCB containing about 200 to 220 components, it takes only about 90 s to populate a multipanel of two to three boards.

After populating and soldering the SMDs, the boards are inspected twice at DESY ZE: An automatic optical inspection is followed by a flying probe test to ensure that no connection is faulty (Fig. 3). Additionally, the BGA is inspected with X-rays. After the boards have passed the tests, the through-hole mounting is performed. The connectors have been specially designed for the boards for several reasons: They must be radiation-hard, sturdy and quite small, and it's important that they can be disconnected quickly when dismounting the activated detector components.

This demanding production was challenging for everyone in the DESY ZE, FE and ATLAS groups!

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Helmholtz Imaging

Capturing the world of science

DESY is hosting Helmholtz Imaging, one of the five Helmholtz Information & Data Science platforms. DESY IT hosts one of the three Helmholtz Imaging Support Units to provide services to imaging scientists from all centres of the Helmholtz Association. These services include the development and provision of modern deep learning methods for image analysis and reconstruction. The services offered by Helmholtz Imaging cover the entire imaging pipeline from the sensor to the validated results.

The mission of Helmholtz Imaging is to unlock the potential of imaging science in the Helmholtz Association. Image data make up a substantial part of the data generated in scientific research. As one of the five Helmholtz Information & Data Science platforms (alongside Helmholtz.AI, HIDA, HIFIS and HMC), Helmholtz Imaging is the overarching platform to better leverage the innovative modalities, methodological richness and data treasures of the Helmholtz Association and make them accessible to all. The Research and Support Units of Helmholtz Imaging are hosted by DESY, MDC in Berlin and DKFZ in Heidelberg.

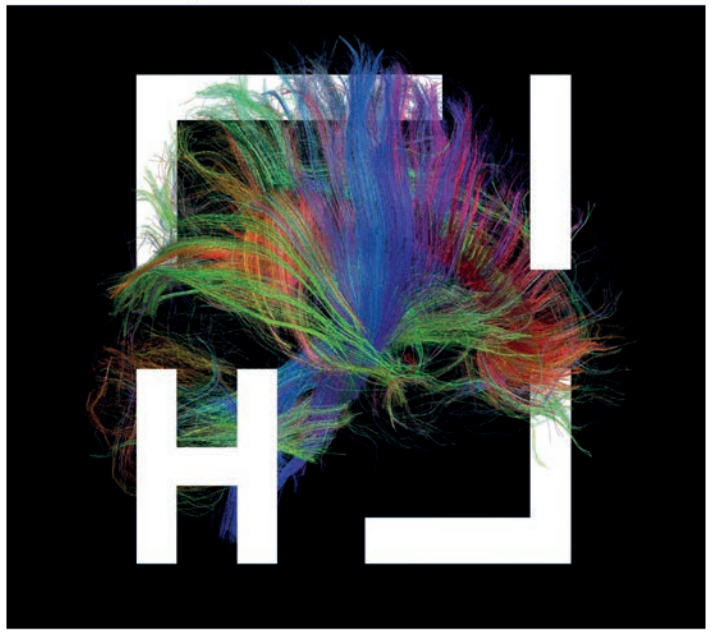

Figure 1

Helmholtz Imaging key visual

Helmholtz Imaging: successful evaluation

Three years after its foundation, Helmholtz Imaging was thoroughly reviewed at an event at DESY in April 2023 by an independent review panel of experts from academia and research institutions around the world.

Across the young platform, staff and scientists have published more than 90 papers, delivered more than 400 hours of training, conducted more than 50 short-term consulting projects and won 30 awards and prizes. Helmholtz Imaging has managed to build a community from scratch (with over 900 imaging enthusiasts from all 18 Helmholtz centres and over 70 other institutions), which spans extremely heterogeneous research areas. Helmholtz Imaging is proud to have enabled, for the first time, a lively and regular exchange between domain scientists and methodologists on common topics.

The feedback from the review panel was overwhelmingly positive. The panel commended Helmholtz Imaging for fulfilling its mission with extraordinary activity and enthusiasm of the whole team. They emphasised that Helmholtz Imaging is a unique and novel structure, without precedent in its scope, and highlighted its outstanding progress through collaboration and networking, producing cutting-edge research in a very short period of time.

Helmholtz Imaging Conference at DESY

In 2023, DESY also hosted the annual Helmholtz Imaging Conference in Hamburg. Participants from various backgrounds came together for engaging talks, thought-provoking unconference sessions and the sharing of research and ideas among peers. The captivating presentations related to image analysis, visualisation of research data and modern reconstruction methods in imaging.

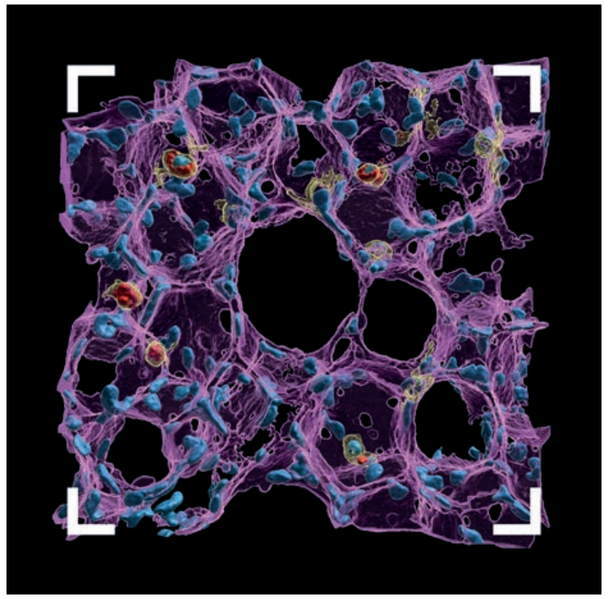

Figure 2

Lung health and immunity by Lin Yang (CPC/LHI, HMGU), first place in the category "Jury Award" of the Helmholtz Imaging Best Scientific Image 2023 contest

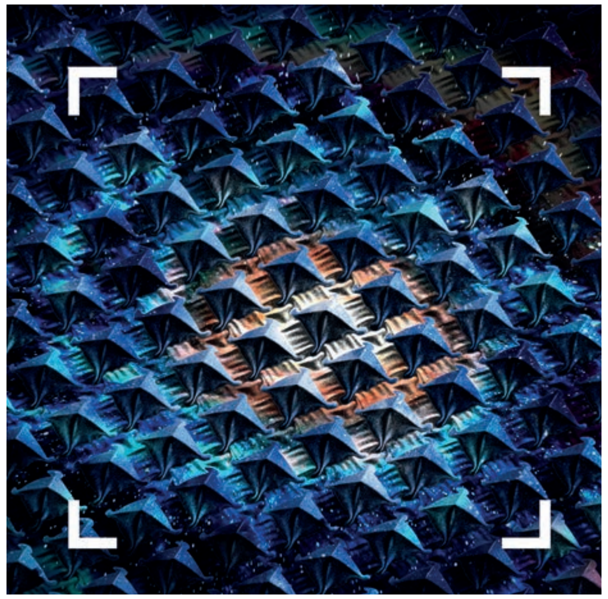

Figure 3

Small-pyramids Harvesting Big-universe Energy by Gan Huang and Bryce Richards (KIT), first place in the category "Public Choice Award" of the Helmholtz Imaging Best Scientific Image 2023 contest

One highlight was the award ceremony to honour the Best Scientific Image 2023 within the Helmholtz community. The 162 high-quality, stunning images submitted show the world from the nanoscale to the global scale and cover all Helmholtz research domains and almost all Helmholtz centres. The winning images in the categories "Jury Award" and "Public Choice Award" are shown in Fig. 2 and 3, respectively.

Helmholtz Imaging at DESY

The Research and Innovation in Computing (RIC) group at DESY IT in the Particle Physics division is home to the Helmholtz Imaging Support Team at DESY, while the Management Unit and the Computational Imaging group, led by Martin Burger, are part of the Photon Science division.

The Support Team, led by Philipp Heuser of DESY IT, collaborates with imaging scientists across the Helmholtz Association and beyond to enable them to solve challenges in image reconstruction and data analysis. All scientists from the Association can benefit from this service by getting in touch through the Helmholtz Imaging Support Hub [3].

Examples for collaborations of the DESY Helmholtz Imaging Support Team in 2023 are the development of the PickYOLO detector with the group of Thomas Marlovits from CSSB/UKE in Hamburg and the long-standing collaboration with the Helmholtz centre Hereon in Geesthacht on the development of deep learning methods for the analysis of synchrotron-radiation-based microtomography data. PickYOLO is a deep-learning-based particle detector for cryo electron tomography (cryo-ET) images. Localising individual molecular particles within a busy tomogram is known as picking, which is a laborious and time-intensive process. PickYOLO now automates this step and can be used to optimise cryo-ET workflows [1]. The essence of the long-standing collaboration with Hereon on artificial intelligence for synchrotron radiation tomography, including the development of segmentation and active learning approaches, were presented by Julian Moosmann from Hereon at the SPIE conference 2023 [2].

In addition, the DESY Helmholtz Imaging Support Team is developing a platform to connect all Helmholtz activities related to imaging. The platform Helmholtz Imaging CONNECT [4] presents all the instruments, modalities, solutions and experts from the Association, as well as their connections with each other.

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References:

[1] E. Genthe et al., J. Struct. Biol. 215:107990 (2023)
[2] J. Moosmann et al., Proc. SPIE. PC12655, Emerging Topics in Artificial Intelligence (ETAI) 2023
[3] https://helmholtz-imaging.de/support-hub/
[4] https://connect.helmholtz-imaging.de

How to keep hackers out: Securing IDAF

Introducing multifactor authentication in the Interdisciplinary Data and Analysis Facility

In response to escalating cyber threats, DESY IT undertook a proactive initiative to fortify the security infrastructure of the centre's Interdisciplinary Data and Analysis Facility (IDAF). Recognising the vulnerability of user passwords, e.g. to social engineering or technical threats, the group swiftly implemented multifactor authentication (MFA) across its systems. Leveraging integration of the open-source two-factor authentication system privacyIDEA, users were seamlessly equipped with MFA tokens, enhancing both security and user experience. Despite initial challenges, the transition proved successful, paving the way for continuous improvement and collaboration in safeguarding research data and computing resources.

Global accessibility to the data and computing resources offered by the IDAF is indispensable for researchers across various domains. However, ensuring robust security measures to prevent misuse of resources or unauthorised access is of paramount importance. The escalating cyber threats present significant challenges to the integrity and confidentiality of data stored within such facilities.

Addressing security threats

The recent increase in successful intrusions into computer systems within centres of the Helmholtz Association and several universities in Germany and elsewhere underscores the urgency of bolstering security measures. These incidents, often resulting in prolonged service downtime, highlight the evolving sophistication of cyber attackers, who operate in organised teams and exploit vulnerabilities with precision. The advent of ransomware attacks further accentuates the need for proactive security measures, as academic institutions become prime targets for malicious actors seeking financial gain or data theft.

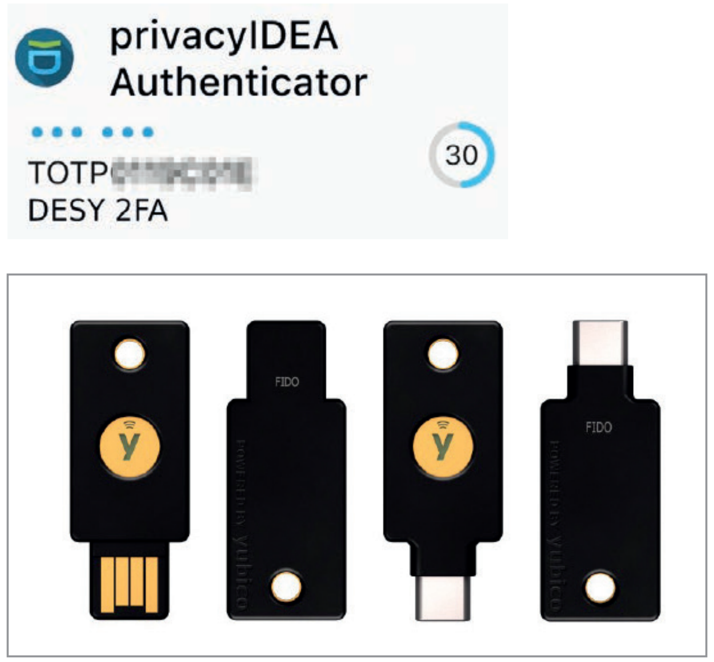

Figure 1

Different factors can be configured, e.g. a time-based one-time password (TOTP) generated by a smartphone app (top) or a hardware token (bottom).

Implementing MFA

Recognising the critical need to enhance security protocols, DESY IT embarked on a comprehensive initiative to fortify its services with multifactor authentication (MFA). These factors can be for example a tamper-resistant hardware token or a smartphone app producing time-based one-time password (TOTP) tokens, as shown in Fig. 1. This decision stemmed from a thorough analysis of successful hacking attempts, which revealed user passwords as a primary vulnerability. While DESY employs robust password storage mechanisms, attackers often resort to phishing, fraudulent websites or keyloggers to obtain user credentials directly. To counteract this threat, the introduction of MFA emerged as a pivotal strategy to augment traditional authentication methods.

```
scientist@remote ~ % ssh scientist@naf-atlas.desy.de
(scientist@naf-wgs.desy.de) Password:
(scientist@naf-wgs.desy.de) OTP(mfa.desy.de):

naf-wgs::~> █
```

Figure 2

Typical ssh login session of a remote user

Rolling out MFA

The deployment of MFA entailed a meticulous process of documentation, user training and system configuration. MFA tokens had to be provided to users. By mid-September 2023, the first systems were configured to require MFA, marking a significant milestone in DESY's security enhancement endeavour. Despite the logistical difficulties arising from DESY's diverse user base and complex network structure, the transition to MFA was met with positive user feedback and a noticeable decrease in compromised accounts.

Integration with privacyIDEA and DESY Registry

A central component of DESY's MFA implementation was the setup of the two-factor authentication system DESY privacyIDEA and the integration of the MFA setup and management into the DESY Registry. This integration not only facilitated the setup of custom second factors, but also streamlined the authentication process across multiple DESY web services. The introduction of single sign-on capabilities represents a significant advancement in user convenience and security, reducing the need for repeated authentication prompts.

Integrating MFA into the IDAF infrastructure

Building on the success of DESY's MFA rollout, efforts were made to extend these security measures to the IDAF infrastructure. Coordination with key stakeholders, including representatives of the National Analysis Facility (NAF) user committee and the Maxwell HPC cluster, facilitated the smooth integration of MFA into the NAF and Maxwell HPC infrastructures. Dedicated user documentation and test systems were prepared to ensure a seamless transition, with specific access methods tailored to different IDAF services.

As a result of these efforts, users accessing the IDAF need to provide their user name, their password and an additional MFA token. An example ssh session is shown in Fig. 2. Using Jupyter and FastX for accessing the IDAF works in similar ways.

Conclusion

The implementation of MFA represents a significant step forward in fortifying the security posture of the IDAF. By proactively addressing vulnerabilities and leveraging industry-proven security practices, DESY demonstrated its commitment to safeguarding sensitive data and ensuring uninterrupted access to computing resources for researchers worldwide. As threats continue to evolve, ongoing vigilance and collaboration with users remain paramount to maintaining the resilience and efficacy of IDAF's security infrastructure.

IDAF – Status in a nutshell

Maxwell HPC cluster: ~50 000 CPU cores, ~250 GPUs, ~2700 registered users, mostly photon science incl. European XFEL as well as accelerator R&D and operations.
Grid cluster: 20 000 CPU cores, integrated into federated WLCG experiment production frameworks, mostly serving ATLAS, CMS and Belle II.
NAF – National Analysis Facility: ~9000 CPU cores, serving experiments of the Terascale Alliance as well as smaller DESY-based communities, optimised for fast turn-around times.
Data – dCache systems: ~20 PB for particle physics, ~140 PB for photon science, including European XFEL.
Data – GPFS systems: Speed optimised for integration into data-taking and project space: 60 PB (incl. European XFEL)
Network: WAN: up to 2 x 50 Gbit/s. Internally: InfiniBand in Maxwell HPC cluster for ultrafast data access and parallel jobs.
Services: Scientific software provisioning, Jupyter portal availability, remote graphical login and desktop sharing, container execution in batch systems, extensive documentation, support and consulting.

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Links:
https://grid.desy.de/
https://maxwell.desy.de/
https://naf.desy.de/

Powers of ten

Designing large-scale scientific infrastructures using hierarchical 3D models across several orders of magnitude

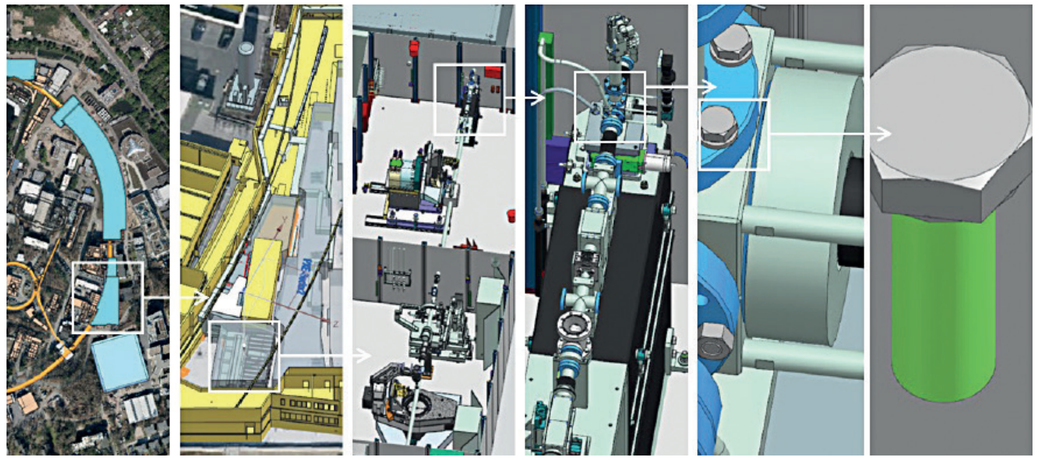

Figure 3
Coherent engineering model of a large-scale scientific facility spanning six orders of magnitude

From universe to molecule to elementary particle, from population to organism to cell, from facility to unit to part: Coherent models across several orders of magnitude help to understand how complex systems are built from smaller building blocks and how small-scale building blocks organise themselves to produce large-scale structures, organisms and behaviour. In science, models are deduced from investigating systems. In engineering, models are developed for building systems.

Science develops models to understand how complex nature is hierarchically built from smaller and smaller building blocks. Models at different scales help to understand the building blocks' interplay and interdependencies: How, for example, collective small-scale behaviour generates emergent global behaviour; or how global events may impact small-scale structures.

In engineering, unlike in nature, complex systems are designed and artificially produced from small-scale parts, and engineering models are created upfront. Engineering models pre-define the intended structures and behaviour, comprehend and define the required building blocks and make the overall system match the intended purpose.
In both cases, the models have to be refined from a global system view down to the elementary parts. They have to be adapted to the specific needs of every scale, for example by only showing an adequate level of detail, and avoid overloading or oversimplifying. And they have to be and be kept compliant across several orders of magnitude – which is a challenge of its own, as we will see.

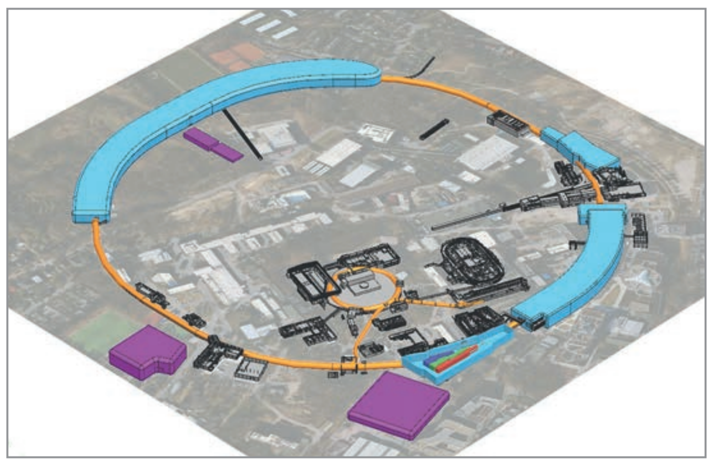

Figure 1
Overview of the PETRA IV programme and its decomposition into complexes: accelerator complex (orange), photon science complex (blue), technology complex (purple) and building complex (grey)

10^3 (1000 m): The world view

The world view provides a top-level overview of a scientific programme – such as the next-generation synchrotron light source PETRA IV, which is planned at DESY in Hamburg. Top-level model elements can reach the order of kilometres, such as accelerators, large experimental halls, construction sites or campus development. The world view defines what's in and what's out. What are the major elements of the programme? How are they arranged, where are they located? What are their major connections, such as roads and supply lines? Top-level models allow the investigation of how to access and move around, how to organise e.g. transportation and logistics.

10^2 (100 m): The business view

In a first step, programmes are decomposed into major business segments. Business segments express what is happening in the programme, what is going on. They manifest the major activities and responsibilities. They embody different domains and contribute the respective mandatory expertise to the programme. Examples include accelerators, experiments, buildings and infrastructure, campus, technology or management. Business segments are also termed "complex". Complex models show how the complex is situated. Complexes can extend to several hundreds of metres. The global view shows the arrangement and connections of the complexes in an overall layout. Figure 1 gives an example of the PETRA IV programme and its decomposition into complexes.

10^1 (10 m): Production centres

Business segments are realised by means of production centres and systems. Production centres are the centres of activity, the buzzing hot spots where things are produced and work is done. They provide the major activities to the programme. They describe how things are done in a business segment and comprise the required systems and services. For example, an accelerator complex has sources, pre-accelerators, transfer lines and the main accelerator, which comprise machine elements and various kinds of supply systems. A science complex has experimental, computing and service centres, which contain various experimental stations and computing systems.

Facilities and systems represent the environment in which we live and that we experience directly. Facility and system models enable envisioning, understanding and optimisation of our environment and workflow. Facilities mostly extend over a few tens of metres. The business view shows how the various facilities and systems interact. Figure 2 provides an example of the "Ada Yonath" photon science centre.

10^0 (1 m): Functional units, processors and cells

Systems are made of functional units, or processors, or cells, which are doing the work. They are what humans operate and interact with. Functional units provide the functions and services that make a facility operate, and they define how systems and facilities behave. For example, an accelerator beamline has cells, an experimental station has detectors. Unit models explain the shape of the functional units, their handling and their interfaces. Units extend to about a few metres. Facility models show how the functional units are connected.

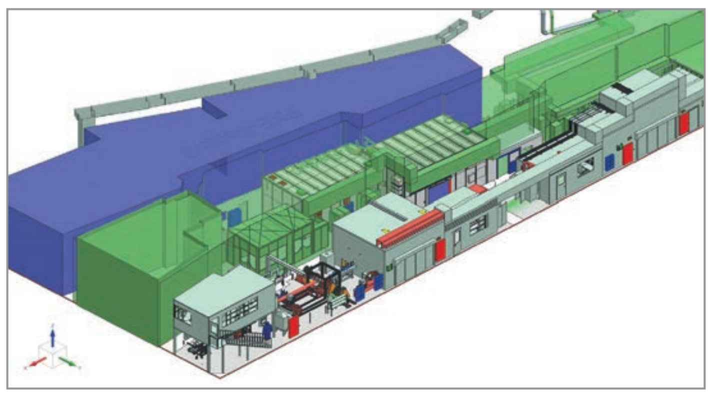

Figure 2
"Ada Yonath" photon science centre: overview of the facility structure, with the experimental sectors highlighted

10^{-1} (10 cm): Components

Units are built from standardised components. Technical components are things that are available, ideally in stock, or, if not, that can be easily contracted. They are general-purpose building blocks, which are often automatically performing dedicated functions. For examples, accelerator cells contain magnets for focusing the beam, detectors contain sensors and readout electronics. Component models define how components are manufactured. Unit models show how units are assembled from components.

10^{-2} (1 cm): Elementary parts and fundamental forces

Components are manufactured from basic parts and materials. Parts and materials are synonymous with the wide range of basic ingredients for building any technical device, including metal sheets, conductors, pumps, fasteners, you name it. Part models define how parts are created. Component models define how fundamental forces make the parts stick together as a component (Fig. 2).

Conclusion

Coherent models across several orders of magnitude provide an understanding of complex systems at different scales (Fig. 3). They allow the impact of effects and changes at one scale to be followed across all other scales. They explain how observations at large scales can be caused by events at small scales and how dedicated action at small scales can influence what is happening at large scales. The latter is the foundation for developing dedicated components to precisely control large-scale systems, generate wanted behaviour and protect against harm and damage. Coherent models across several orders of magnitude are an exciting achievement in engineering, as in science.

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How much is the fish?

openCost for cost transparency and sustainable and fair scientific publishing

The Open Access transformation calls for restructuring the field of scientific publishing: The openCost project of the DESY Library and Documentation group is taking on a pioneering role in realising publication cost transparency and examining publication structures in the interests of a fair scientific landscape. In 2023, openCost thus brought the DESY Library further into the public focus with regard to the scientific topics of Open Science and Open Access. The takeaway – and promising news for scientific libraries that have to deal with the organisational structure related to scholarly publication costs: With the openCost standard, monitoring can be automated and simplified for each participating institution.

The Open Access (OA) transformation has been a political goal for some time now, set by the EU and the German federal government as well as by scientific and funding organisations.

So-called transformative agreements are currently attracting a lot of attention within the transforming publishing scene. These contracts require that part of the content of subscription journals will be converted to OA, with the expectation that the rate will gradually rise to 100%. While it is not entirely obvious whether such a conversion is binding, the financial scope of the publish and read agreements is currently growing.

In fact, OA can certainly pay off financially as well. But the desired transformation from subscriptions to OA is only sustainable if it is accompanied by the achievement of cost transparency. As authors and contractual partners, we must now demand our right to be informed. Only once the financial flows have been disclosed can we enter into fact-based negotiations with publishers. With its technical exchange format, openCost provides a strategy to enable this transparency and to structurally support the establishment of the so-called information budget in scientific institutions.

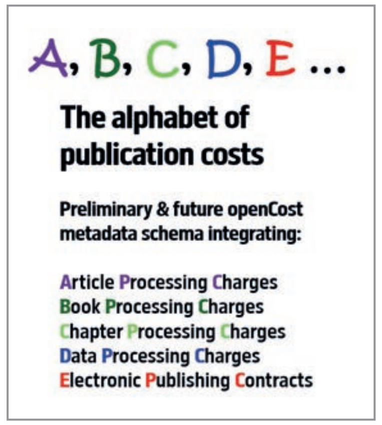

Figure 1
Publication cost types, ranging from "article", "book", "chapter" or "data processing fees" to "electronic publishing contracts"

Figure 2
openCost at conferences

In 2023, the openCost team finalised the metadata schema for article-based fees, which has also undergone technical optimisations, and prepared a schema for contract-based costs. From now on, the aim is to further capture the alphabet of publication costs, as these may be not only opaque but also very diverse (Fig. 1).

As the necessity of the project is perceived both nationally and internationally, the openCost team was invited to many conferences and other events, such as Open Repositories in South Africa, BiblioCon in Hannover or Open-Access-Tage in Berlin (Fig. 2).

Alongside major progress to expand the Electronic Journals Library (EZB) in order to include information on publishing, the first data transfer in openCost format as part of the Germany-wide German Research Foundation (DFG) project OA-Publication Costs was another key success of 2023.

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I wouldn't have finished my thesis…

…without coming to the library

The COVID-19 pandemic had a significant impact on the DESY Library, with a sharp decline in in-person enquiries at the information desk and a shift to email communication due to the closure of the main reading room. This made it more difficult for users to access the library's collection and eliminated the usual on-site usage and serendipitous findings while browsing the shelves. However, in 2023, the situation improved and the main reading room was fully reopened in March. This led to a lively use of the library, with many DESY users returning.

During the pandemic, the library initially saw a sharp drop in visitor numbers and in-person enquiries, particularly at the information desk. Once mobile working became commonplace, usage of the library normalised somewhat, but there was of course a significant shift from face-to-face contact to email as well as electronic and postal delivery due to the closure of the main reading room. This made it more difficult for users to access the collection. The usual in-library usage, which does not show up in any statistics, was basically eliminated, as was the possibility to make serendipitous discoveries while browsing the shelves. This could be compensated only partially by electronic resources. Furthermore, for quite some time, it was not possible to use the workspaces provided within the library. In particular, the favoured quiet corners behind the shelves had to remain closed for a long time.

Fortunately, the pandemic situation improved in 2023, and we were finally able to fully reopen the main reading room in March. As could be seen from the lively use that developed shortly afterwards, this obviously met a strong need. Many DESY employees are now using the library again as usual. Our collection of (inter)national newspapers is regularly used during breaks over a cup of coffee, as is our public bookshelf.

Figure 1
Imagine a library… [1, 2]

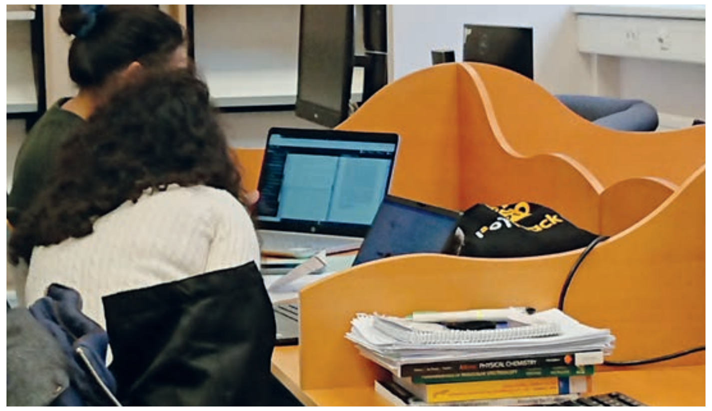

Figure 2
Lively discussions in the final stages of a thesis. "Of course you can use this photo. I wouldn't have finished my thesis without coming to the library!"

The library is also being used again by many people for on-site research and work on various projects. We know from personal feedback, for example, that a number of doctoral and master's theses have been completed and essays written at our workspaces. Quiet but lively discussions also happen again (Fig. 2), while the new shelving invites users to easily browse the collection by subject.

In short, we are very happy to have you back and to be able to serve you again as we used to.

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References:
[1] Image by Lorena Klein, apprentice at the DESY Library
[2] L. Klein, M. Piegler,: "Shhh ......: Did you know that about the DESY library?" doi: 10.3204/PUBDB-2023-07757

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M. Schumacher (U Freiburg)
F. Simon (MPP München)

Publications

ALPS

Published

M. Meyer et al.
A first application of machine and deep learning for background rejection in the ALPS II TES detector.
1. 17th Patras Workshop on Axions, WIMPs and WISPs, Mainz (Germany), 8 Aug 2022 - 12 Aug 2022.
Annalen der Physik, vol. 5361:2200545, and PUBDB-2022-06682.
Wiley-VCH, Berlin.
doi: 10.1002/andp.202200545.

L. Diehl et al.
Comparison of the time resolution of unirradiated and irradiated LGADs and 3D sensors.
Nuclear instruments & methods in physics research / Section A, 1046:167691, and PUBDB-2023-07644.
doi: 10.1016/j.nima.2022.167691.

E. Garutti et al.
Qualification of piezo-electric actuators for the MADMAX booster system at cryogenic temperatures and high magnetic fields.
Journal of Instrumentation, 18(08):P08011, and PUBDB-2023-03451, arXiv:2305.12808. DESY-23-069.
doi: 10.1088/1748-0221/18/08/P08011.

C. Lorin et al.
Development, Integration, and Test of the MACQU Demo Coil Toward MADMAX Quench Analysis.
IEEE transactions on applied superconductivity, 33(7):4500711, and PUBDB-2023-00283.
doi: 10.1109/TASC.2023.3273734.

J. A. Rubiera Gimeno et al.
The TES detector of the ALPS II experiment.
The 16th Vienna Conference on Instrumentation, Vienna (Austria), 21 Feb 2022 - 25 Feb 2022.
Nuclear instruments & methods in physics research / A, vol. 1046:167588, and PUBDB-2022-01677.
North-Holland Publ. Co., Amsterdam.
doi: 10.1016/j.nima.2022.167588.

A. V. Sokolov and A. Ringwald.
Generic Axion Maxwell Equations: Path Integral Approach.
Annalen der Physik, 536(1):2300112, and PUBDB-2023-01308, DESY-23-031. arXiv:2303.10170v2.
doi: 10.1002/andp.202300112.

M. Tobar et al.
Searching for GUT-scale QCD Axions and Monopoles with a High Voltage Capacitor.
Physical review / D, 108(3):035024, and PUBDB-2023-03900, DESY-23-084. arXiv:2306.13320.
doi: 10.1103/PhysRevD.108.035024.

ATLAS

Published

ATLAS Collaboration.
Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector.
Journal of high energy physics, 2023(7):40, and PUBDB-2023-04719, arXiv:2209.10910. CERN-EP-2022-109.
doi: 10.1007/JHEP07(2023)040.

ATLAS Collaboration.
Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ decay channel using 139 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions recorded by the ATLAS detector at the LHC.
Physics letters / B, 843:137880, and PUBDB-2023-04945, arXiv:2207.00320. CERN-EP-2022-135.
doi: 10.1016/j.physletb.2023.137880.

ATLAS Collaboration.
Measurement of the inclusive $t\bar{t}$ production cross section in the lepton+jets channel in pp collisions at $\sqrt{s}$= 7 TeV with the ATLAS detector using support vector machines.
Physical review / D, 108(3):032014, and PUBDB-2023-05282, arXiv:2212.00571. CERN-EP-2022-191.
doi: 10.1103/PhysRevD.108.032014.

ATLAS Collaboration.
Combination of searches for invisible decays of the Higgs boson using 139 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS experiment.
Physics letters / B, 842:137963, and PUBDB-2023-05379, arXiv:2301.10731. CERN-EP-2022-289.
doi: 10.1016/j.physletb.2023.137963.

ATLAS Collaboration.
Search for flavor-changing neutral-current couplings between the top quark and the Z boson with LHC Run 2 proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physical review / D, 108(3):032019, and PUBDB-2023-05382, arXiv:2301.11605. CERN-EP-2022-044.
doi: 10.1103/PhysRevD.108.032019.

X. Ai et al.
A non-linear Kalman filter for track parameters estimation in high energy physics.
Nuclear instruments & methods in physics research / A, 1049:168041, and PUBDB-2023-00507, arXiv:2112.09470. DESY-21-218.
doi: 10.1016/j.nima.2023.168041.

S. Ali et al.
Performance in beam tests of carbon-enriched irradiated Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector.
Journal of Instrumentation, 18(05):P05005, and PUBDB-2023-03167.
doi: 10.1088/1748-0221/18/05/P05005.

J.-H. Arling et al.
Test beam measurement of ATLAS ITk Short Strip module at warm and cold operational temperature.
Journal of Instrumentation, 18(03):P03015, and PUBDB-2023-03143, arXiv:2302.10950.
doi: 10.1088/1748-0221/18/03/P03015.

ATLAS Collaboration.
A search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):200, and PUBDB-2023-04803, arXiv:2211.02617. CERN-EP-2022-187.
doi: 10.1007/JHEP07(2023)200.

ATLAS Collaboration.
Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
Physical review / D, 108(5):052009, and PUBDB-2023-06722, arXiv:2306.03637. CERN-EP-2023-045.
doi: 10.1103/PhysRevD.108.052009.

ATLAS Collaboration.
ATLAS flavour-tagging algorithms for the LHC Run 2 pp collision dataset.
The European physical journal / C, 83(7):681, and PUBDB-2023-04835, arXiv:2211.16345. CERN-EP-2022-226.
doi: 10.1140/epjc/s10052-023-11699-1.

ATLAS Collaboration.
Calibration of the light-flavour jet mistagging efficiency of the b-tagging algorithms with Z+jets events using 139 fb^{-1} of ATLAS proton–proton collision data at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(8):728, and PUBDB-2023-08000, arXiv:2301.06319. CERN-EP-2022-211.
doi: 10.1140/epjc/s10052-023-11736-z.

ATLAS Collaboration.
Charged-hadron production in pp, p+Pb, Pb+Pb, and Xe+Xe collisions at $\sqrt{s_{NN}} = 5$ TeV with the ATLAS detector at the LHC.
Journal of high energy physics, 07(7):74, and PUBDB-2023-04791, arXiv:2211.15257. CERN-EP-2022-221.
doi: 10.1007/JHEP07(2023)074.

ATLAS Collaboration.
Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV pp collision data with two top quarks and missing transverse momentum in the final state.
The European physical journal / C, 83(6):503, and PUBDB-2023-04804, arXiv:2211.05426. CERN-EP-2022-133.
doi: 10.1140/epjc/s10052-023-11477-z.

ATLAS Collaboration.
Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at s=13 TeV.
Physics letters / B, 843:137745, and PUBDB-2023-04802, arXiv:2211.01216. CERN-EP-2022-149.
doi: 10.1016/j.physletb.2023.137745.

ATLAS Collaboration.
Correlations between flow and transverse momentum in Xe+Xe and Pb+Pb collisions at the LHC with the ATLAS detector: A probe of the heavy-ion initial state and nuclear deformation.
Physical review / C, 107(5):054910, and PUBDB-2023-04869, arXiv:2205.00039. CERN-EP-2022-052.
doi: 10.1103/PhysRevC.107.054910.

ATLAS Collaboration.
Cross-section measurements for the production of a Z boson in association with high-transverse-momentum jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):80, and PUBDB-2023-04872, arXiv:2205.02597. CERN-EP-2022-075.
doi: 10.1007/JHEP06(2023)080.

ATLAS Collaboration.
Determination of the strong coupling constant from transverse energy-energy correlations in multijet events at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):85, and PUBDB-2023-04415, arXiv:2301.09351. CERN-EP-2022-282.
doi: 10.1007/JHEP07(2023)085.

ATLAS Collaboration.
Differential $t\bar{t}$ cross-section measurements using boosted top quarks in the all-hadronic final state with 139 fb^{-1} of ATLAS data.
Journal of high energy physics, 04(4):80, and PUBDB-2023-04873, arXiv:2205.02817. CERN-EP-2022-026.
doi: 10.1007/JHEP04(2023)080.

ATLAS Collaboration.
Evidence for the charge asymmetry in pp → $t\bar{t}$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 08(8):077, and PUBDB-2024-00177, arXiv:2208.12095. CERN-EP-2022-166.
doi: 10.1007/JHEP08(2023)077.

ATLAS Collaboration.
Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector.
Physics letters / B, 846:138223, and PUBDB-2023-07135, arXiv:2304.01532. CERN-EP-2023-023.
doi: 10.1016/j.physletb.2023.138223.

ATLAS Collaboration.
Exclusive dielectron production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ATLAS.
Journal of high energy physics, 06(6):182, and PUBDB-2023-04953, arXiv:2207.12781. CERN-EP-2022-130.
doi: 10.1007/JHEP06(2023)182.

ATLAS Collaboration.
Fast b-tagging at the high-level trigger of the ATLAS experiment in LHC Run 3.
Journal of Instrumentation, 18(11):P11006, and PUBDB-2023-07553, arXiv:2306.09738. CERN-EP-2023-111.
doi: 10.1088/1748-0221/18/11/P11006.

ATLAS Collaboration.
Fiducial and differential cross-section measurements for the vector-boson-fusion production of the Higgs boson in the $H \to WW^* \to e\nu\mu\nu$ decay channel at 13 TeV with the ATLAS detector.
Physical review / D, 108(7):072003, and PUBDB-2023-07032, arXiv:2304.03053. CERN-EP-2023-025.
doi: 10.1103/PhysRevD.108.072003.

ATLAS Collaboration.
Inclusive and differential cross-sections for dilepton $t\bar{t}$ production measured in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 07(7):141, and PUBDB-2023-05259, arXiv:2303.15340. CERN-EP-2023-016.
doi: 10.1007/JHEP07(2023)141.

ATLAS Collaboration.
Inclusive-photon production and its dependence on photon isolation in pp collisions at $\sqrt{s}$ = 13 TeV using 139 fb^{-1} of ATLAS data.
Journal of high energy physics, 07(7):86, and PUBDB-2023-04417, arXiv:2302.00510. CERN-EP-2022-247.
doi: 10.1007/JHEP07(2023)086.

ATLAS Collaboration.
Measurement of $Z\gamma\gamma$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 83(6):539, and PUBDB-2023-04792, arXiv:2211.14171. CERN-EP-2022-192.
doi: 10.1140/epjc/s10052-023-11579-8.

ATLAS Collaboration.
Measurement of cross-sections for production of a Z boson in association with a flavor-inclusive or doubly b-tagged large-radius jet in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment.
Physical review / D, 108(1):012022, and PUBDB-2024-00477, arXiv:2204.12355. CERN-EP-2021-140.
doi: 10.1103/PhysRevD.108.012022.

ATLAS Collaboration.
Measurement of electroweak $Z(\nu\bar{\nu})\gamma jj$ production and limits on anomalous quartic gauge couplings in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):082, and PUBDB-2023-04957, arXiv:2208.12741. CERN-EP-2022-138.
doi: 10.1007/JHEP06(2023)082.

ATLAS Collaboration.
Measurement of exclusive pion pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector.
The European physical journal / C, 83(7):627, and PUBDB-2023-04790, arXiv:2212.00664. CERN-EP-2022-140.
doi: 10.1140/epjc/s10052-023-11700-x.

ATLAS Collaboration.
Measurement of muon pairs produced via $\gamma\gamma$ scattering in nonultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector.
Physical review / C, 107(5):054907, and PUBDB-2023-03164, arXiv:2206.12594. CERN-EP-2022-047.
doi: 10.1103/PhysRevC.107.054907.

ATLAS Collaboration.
Measurement of single top-quark production in the s-channel in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):191, and PUBDB-2023-04836, arXiv:2209.08990. CERN-EP-2022-116.
doi: 10.1007/JHEP06(2023)191.

ATLAS Collaboration.
Measurement of substructure-dependent jet suppression in Pb+Pb collisions at 5.02 TeV with the ATLAS detector.
Physical review / C, 107(5):054909, and PUBDB-2023-04829, arXiv:2211.11470. CERN-EP-2022-182.
doi: 10.1103/PhysRevC.107.054909.

ATLAS Collaboration.
Measurement of suppression of large-radius jets and its dependence on substructure in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector.
Physical review letters, 131(17):172301, and PUBDB-2023-07999, arXiv:2301.05606. CERN-EP-2022-250.
doi: 10.1103/PhysRevLett.131.172301.

ATLAS Collaboration.
Measurement of the $B_s^0 \to \mu\mu$ effective lifetime with the ATLAS detector.
Journal of high energy physics, 09(9):199, and PUBDB-2023-07551, arXiv:2308.01171. CERN-EP-2023-139.
doi: 10.1007/JHEP09(2023)199.

ATLAS Collaboration.
Measurement of the $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s}$ = 5.02 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):138, and PUBDB-2023-04949, arXiv:2207.01354. CERN-EP-2022-119.
doi: 10.1007/JHEP06(2023)138.

ATLAS Collaboration.
Measurement of the $t\bar{t}$ cross section and its ratio to the Z production cross section using pp collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS detector.
Physics letters / B, 848:138376, and PUBDB-2023-07872, arXiv:2308.09529. CERN-EP-2023-166.
doi: 10.1016/j.physletb.2023.138376.

ATLAS Collaboration.
Measurement of the charge asymmetry in top-quark pair production in association with a photon with the ATLAS experiment.
Physics letters / B, 843:137848, and PUBDB-2023-04778, arXiv:2212.10552. CERN-EP-2022-260.
doi: 10.1016/j.physletb.2023.137848.

ATLAS Collaboration.
Measurement of the CP properties of Higgs boson interactions with τ-leptons with the ATLAS detector.
The European physical journal / C, 83(7):563, and PUBDB-2023-04787, arXiv:2212.05833. CERN-EP-2022-244.
doi: 10.1140/epjc/s10052-023-11583-y.

ATLAS Collaboration.
Measurement of the cross-sections of the electroweak and total production of a $Z\gamma$ pair in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Physics letters / B, 846:138222, and PUBDB-2023-07896, arXiv:2305.19142. CERN-EP-2023-098.
doi: 10.1016/j.physletb.2023.138222.

ATLAS Collaboration.
Measurement of the Higgs boson mass with $H \to \gamma\gamma$ decays in 140 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Physics letters / B, 847:138315, and PUBDB-2023-07555, arXiv:2308.07216. CERN-EP-2023-160.
doi: 10.1016/j.physletb.2023.138315.

ATLAS Collaboration.
Measurement of the nuclear modification factor of b-jets in 5.02 TeV Pb+Pb collisions with the ATLAS detector.
The European physical journal / C, 83(5):438, and PUBDB-2023-03713, arXiv:2204.13530. CERN-EP-2022-043.
doi: 10.1140/epjc/s10052-023-11427-9.

ATLAS Collaboration.
Measurement of the polarisation of W bosons produced in top-quark decays using dilepton events at s = 13 TeV with the ATLAS experiment.
Physics letters / B, 843:137829, and PUBDB-2023-04721, arXiv:2209.14903. CERN-EP-2022-197.
doi: 10.1016/j.physletb.2023.137829.

ATLAS Collaboration.
Measurement of the production of a W boson in association with a charmed hadron in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector.
Physical review / D, 108(3):032012, and PUBDB-2023-05383, arXiv:2302.00336. CERN-EP-2022-291.
doi: 10.1103/PhysRevD.108.032012.

ATLAS Collaboration.
Measurement of the properties of Higgs boson production at $\sqrt{s}$ = 13 TeV in the H → γγ channel using 139 fb^{-1} of pp collision data with the ATLAS experiment.
Journal of high energy physics, 07(7):88, and PUBDB-2023-04418, arXiv:2207.00348. CERN-EP-2022-094.
doi: 10.1007/JHEP07(2023)088.

ATLAS Collaboration.
Measurement of the Sensitivity of Two-Particle Correlations in pp Collisions to the Presence of Hard Scatterings.
Physical review letters, 131(16):162301, and PUBDB-2023-07137, arXiv:2303.17357. CERN-EP-2023-036.
doi: 10.1103/PhysRevLett.131.162301.

ATLAS Collaboration.
Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):19, and PUBDB-2023-04959, arXiv:2209.00583. CERN-EP-2020-018.
doi: 10.1007/JHEP06(2023)019.

ATLAS Collaboration.
Measurement of the total and differential Higgs boson production cross-sections at $\sqrt{s}$ = 13 TeV with the ATLAS detector by combining the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels.
Journal of high energy physics, 05(5):028, and PUBDB-2023-04951, arXiv:2207.08615. CERN-EP-2022-143.
doi: 10.1007/JHEP05(2023)028.

ATLAS Collaboration.
Measurement of the total cross section and ρ-parameter from elastic scattering in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 83(5):441, and PUBDB-2023-04952, arXiv:2207.12246. CERN-EP-2022-129.
doi: 10.1140/epjc/s10052-023-11436-8.

ATLAS Collaboration.
Measurements of W^+W^- production in decay topologies inspired by searches for electroweak supersymmetry.
The European physical journal / C, 83(8):718, and PUBDB-2024-00168, arXiv:2206.15231. CERN-EP-2022-087.
doi: 10.1140/epjc/s10052-023-11508-9.

ATLAS Collaboration.
Measurements of $Z\gamma$+jets differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 07(7):072, and PUBDB-2023-07061, arXiv:2212.07184. CERN-EP-2022-240.
doi: 10.1007/JHEP07(2023)072.

ATLAS Collaboration.
Measurements of differential cross sections of Higgs boson production through gluon fusion in the $H \to WW^* \to e\nu\mu\nu$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 83(9):774, and PUBDB-2023-08001, arXiv:2301.06822. CERN-EP-2022-228. arXiv:2301.06822. CERN-EP-2022-228.
doi: 10.1140/epjc/s10052-023-11873-5.

ATLAS Collaboration.
Measurements of Higgs boson production by gluon-gluon fusion and vector-boson fusion using $H \to WW^* \to e\nu\mu\nu$ decays in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physical review / D, 108(3):032005, and PUBDB-2024-00186, arXiv:2207.00338. CERN-EP-2022-078.
doi: 10.1103/PhysRevD.108.032005.

ATLAS Collaboration.
Measurements of multijet event isotropies using optimal transport with the ATLAS detector.
Journal of high energy physics, 10:060, and PUBDB-2023-06723, arXiv:2305.16930. CERN-EP-2023-079.
doi: 10.1007/JHEP10(2023)060.

ATLAS Collaboration.
Measurements of observables sensitive to colour reconnection in $t\bar{t}$ events with the ATLAS detector at $\sqrt{s}$ = 13 TeV.
The European physical journal / C, 83(6):518, and PUBDB-2023-04841, arXiv:2209.07874. CERN-EP-2022-167.
doi: 10.1140/epjc/s10052-023-11479-x.

ATLAS Collaboration.
Measurements of the suppression and correlations of dijets in Pb+Pb collisions at $\sqrt{s_{NN}}$ = TeV.
Physical review / C, 107(5):054908, and PUBDB-2023-03166, arXiv:2205.00682. CERN-EP-2022-046.
doi: 10.1103/PhysRevC.107.054908.

ATLAS Collaboration.
Measuring tau g-2 using ATLAS Pb+Pb collisions.
Journal of Instrumentation, 18(09):C09005, and PUBDB-2023-05759.
doi: 10.1088/1748-0221/18/09/C09005.

ATLAS Collaboration.
Model-independent search for the presence of new physics in events including $H \to \gamma\gamma$ with $\sqrt{s}$ = 13 TeV pp data recorded by the ATLAS detector at the LHC.
Journal of high energy physics, 07(7):176, and PUBDB-2023-05380, arXiv:2301.10486. CERN-EP-2022-232.
doi: 10.1007/JHEP07(2023)176.

ATLAS Collaboration.
New techniques for jet calibration with the ATLAS detector.
The European physical journal / C, 83(8):761, and PUBDB-2023-07146, arXiv:2303.17312. CERN-EP-2023-028.
doi: 10.1140/epjc/s10052-023-11837-9.

ATLAS Collaboration.
Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector.
Physical review letters, 131(15):151902, and PUBDB-2023-07031, arXiv:2304.08962. CERN-EP-2023-035.
doi: 10.1103/PhysRevLett.131.151902.

ATLAS Collaboration.
Observation of electroweak production of two jets and a Z-boson pair.
Nature physics, 19(2):237, and PUBDB-2023-07060, arXiv:2004.10612. CERN-EP-2020-016.
doi: 10.1038/s41567-022-01757-y.

ATLAS Collaboration.
Observation of four-top-quark production in the multilepton final state with the ATLAS detector.
The European physical journal / C, 83(6):496, and PUBDB-2023-05027, arXiv:2303.15061. CERN-EP-2023-055.
doi: 10.1140/epjc/s10052-023-11573-0.

ATLAS Collaboration.
Observation of gauge boson joint-polarisation states in W±Z production from pp collisions at s=13 TeV with the ATLAS detector.
Physics letters / B, 843:137895, and PUBDB-2023-04785, arXiv:2211.09435. CERN-EP-2022-202.
doi: 10.1016/j.physletb.2023.137895.

ATLAS Collaboration.
Observation of Single-Top-Quark Production in Association with a Photon Using the ATLAS Detector.
Physical review letters, 131(18):181901, and PUBDB-2024-00174.
doi: 10.1103/PhysRevLett.131.181901.

ATLAS Collaboration.
Observation of the $\gamma\gamma \to \tau\tau$ Process in Pb+Pb Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment with the ATLAS Detector.
Physical review letters, 131(15):151802, and PUBDB-2024-00183, arXiv:2204.13478. CERN-EP-2022-079.
doi: 10.1103/PhysRevLett.131.151802.

ATLAS Collaboration.
Production of Y(nS) mesons in Pb+Pb and pp collisions at 5.02 TeV.
Physical review / C, 107(5):054912, and PUBDB-2023-04874, arXiv:2205.03042. CERN-EP-2022-045. arXiv:2205.03042. CERN-EP-2022-045.
doi: 10.1103/PhysRevC.107.054912.

ATLAS Collaboration.
Pursuit of paired dijet resonances in the Run 2 dataset with ATLAS.
Physical review / D, 108(11):112005, and PUBDB-2023-07895, arXiv:2307.14944.
doi: 10.1103/PhysRevD.108.112005.

ATLAS Collaboration.
Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):203, and PUBDB-2023-05423, arXiv:2211.01136. CERN-EP-2022-170.
doi: 10.1007/JHEP07(2023)203.

ATLAS Collaboration.
Search for a light charged Higgs boson in $t \to H^{\pm}b$ decays, with $H^{\pm} \to cb$, in the lepton+jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 09(9):004, and PUBDB-2024-00181, arXiv:2302.11739. CERN-EP-2022-207.
doi: 10.1007/JHEP09(2023)004.

ATLAS Collaboration.
Search for a new heavy scalar particle decaying into a Higgs boson and a new scalar singlet in final states with one or two light leptons and a pair of τ-leptons with the ATLAS detector.
Journal of high energy physics, 10:009, and PUBDB-2023-06720, arXiv:2307.11120. CERN-EP-2023-125.
doi: 10.1007/JHEP10(2023)009.

ATLAS Collaboration.
Search for a new scalar resonance in flavour-changing neutral-current top-quark decays $t \to qX$ ($q = u, c$), with $X \to b\bar{b}$, in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 07(7):199, and PUBDB-2023-07861, arXiv:2301.03902. CERN-EP-2022-176.
doi: 10.1007/JHEP07(2023)199.

ATLAS Collaboration.
Search for a new Z' gauge boson in 4μ events with the ATLAS experiment.
Journal of high energy physics, 07(7):90, and PUBDB-2023-04583, arXiv:2301.09342. CERN-EP-2022-251.
doi: 10.1007/JHEP07(2023)090.

ATLAS Collaboration.
Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS.
Journal of high energy physics, 07(7):234, and PUBDB-2023-07030, arXiv:2304.10953. CERN-EP-2023-049.
doi: 10.1007/JHEP07(2023)234.

ATLAS Collaboration.
Search for boosted diphoton resonances in the 10 to 70 GeV mass range using 138 fb^{-1} of 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 07(7):155, and PUBDB-2023-05426, arXiv:2211.04172. CERN-EP-2022-183.
doi: 10.1007/JHEP07(2023)155.

ATLAS Collaboration.
Search for boosted diphoton resonances in the 10 to 70 GeV mass range using 138 fb^{-1} of 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 07(7):155, and PUBDB-2023-05428, arXiv:2211.04172. CERN-EP-2022-183.
doi: 10.1007/JHEP07(2023)155.

ATLAS Collaboration.
Search for dark matter produced in association with a dark Higgs boson decaying into W^+W^- in the one-lepton final state at $\sqrt{s}$=13 TeV using 139 fb^{-1} of pp collisions recorded with the ATLAS detector.
Journal of high energy physics, 07(7):116, and PUBDB-2023-04805, arXiv:2211.07175. CERN-EP-2022-147.
doi: 10.1007/JHEP07(2023)116.

ATLAS Collaboration.
Search for dark matter produced in association with a Higgs boson decaying to tau leptons at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 09(9):189, and PUBDB-2023-06726, arXiv:2305.12938. CERN-EP-2023-072.
doi: 10.1007/JHEP09(2023)189.

ATLAS Collaboration.
Search for dark matter produced in association with a single top quark and an energetic W boson in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
The European physical journal / C, 83(7):603, and PUBDB-2023-04834, arXiv:2211.13138. CERN-EP-2022-146.
doi: 10.1140/epjc/s10052-023-11582-z.

ATLAS Collaboration.
Search for dark photons from Higgs boson decays via ZH production with a photon plus missing transverse momentum signature from pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):133, and PUBDB-2023-04783, arXiv:2212.09649. CERN-EP-2022-237.
doi: 10.1007/JHEP07(2023)133.

ATLAS Collaboration.
Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W-boson mass in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 2023(6):31, and PUBDB-2023-04720, arXiv:2209.13935. CERN-EP-2022-132.
doi: 10.1007/JHEP06(2023)031.

ATLAS Collaboration.
Search for displaced photons produced in exotic decays of the Higgs boson using 13 TeV pp collisions with the ATLAS detector.
Physical review / D, 108(3):032016, and PUBDB-2023-07090, arXiv:2209.01029. CERN-EP-2022-096.
doi: 10.1103/PhysRevD.108.032016.

ATLAS Collaboration.
Search for doubly charged Higgs boson production in multi-lepton final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
The European physical journal / C, 83(7):605, and PUBDB-2023-04807, arXiv:2211.07505. CERN-EP-2022-212.
doi: 10.1140/epjc/s10052-023-11578-9.

ATLAS Collaboration.
Search for excited τ-leptons and leptoquarks in the final state with τ-leptons and jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):199, and PUBDB-2023-05021, arXiv:2303.09444. CERN-EP-2023-008.
doi: 10.1007/JHEP06(2023)199.

ATLAS Collaboration.
Search for flavour-changing neutral current interactions of the top quark and the Higgs boson in events with a pair of τ-leptons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2306(6):155, and PUBDB-2023-04956, arXiv:2208.11415. CERN-EP-2022-123.
doi: 10.1007/JHEP06(2023)155.

ATLAS Collaboration.
Search for Heavy Neutral Leptons in Decays of W Bosons Using a Dilepton Displaced Vertex in $\sqrt{s}$ = 13 TeV pp Collisions with the ATLAS Detector.
Physical review letters, 131(6):061803, and PUBDB-2023-07262, arXiv:2204.11988. CERN-EP-2022-017.
doi: 10.1103/PhysRevLett.131.061803.

ATLAS Collaboration.
Search for heavy resonances decaying into a Z or W boson and a Higgs boson in final states with leptons and b-jets in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 06(6):016, and PUBDB-2023-03999, arXiv:2207.00230. CERN-EP-2022-115.
doi: 10.1007/JHEP06(2023)016.

ATLAS Collaboration.
Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset.
Journal of high energy physics, 2306(6):158, and PUBDB-2023-04064, arXiv:2205.06013. CERN-EP-2022-029.
doi: 10.1007/JHEP06(2023)158.

ATLAS Collaboration.
Search for Higgs boson pair production in association with a vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.

The European physical journal / C, 83(6):519, and PUBDB-2023-04725, arXiv:2210.05415. CERN-EP-2022-159.
doi: 10.1140/epjc/s10052-023-11559-y.

ATLAS Collaboration.
Search for high-mass Wγ and Zγ resonances using hadronic W/Z boson decays from 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):125, and PUBDB-2023-07029, arXiv:2304.11962. CERN-EP-2022-241.
doi: 10.1007/JHEP07(2023)125.

ATLAS Collaboration.
Search for lepton-flavour violation in high-mass dilepton final states using 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 23(10):082, and PUBDB-2023-06721, arXiv:2307.08567. CERN-EP-2023-089.
doi: 10.1007/JHEP10(2023)082.

ATLAS Collaboration.
Search for leptonic charge asymmetry in $t\bar{t}W$ production in final states with three leptons at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):33, and PUBDB-2023-04775, arXiv:2301.04245. CERN-EP-2022-249.
doi: 10.1007/JHEP07(2023)033.

ATLAS Collaboration.
Search for leptoquarks decaying into the bτ final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 10:001, and PUBDB-2023-06724, arXiv:2305.15962. CERN-EP-2023-033.
doi: 10.1007/JHEP10(2023)001.

ATLAS Collaboration.
Search for light long-lived neutral particles that decay to collimated pairs of leptons or light hadrons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 06(6):153, and PUBDB-2023-04881, arXiv:2206.12181. CERN-EP-2022-054.
doi: 10.1007/JHEP06(2023)153.

ATLAS Collaboration.
Search for long-lived, massive particles in events with displaced vertices and multiple jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2306(6):200, and PUBDB-2023-04067, arXiv:2301.13866. CERN-EP-2023-002.
doi: 10.1007/JHEP06(2023)200.

ATLAS Collaboration.
Search for magnetic monopoles and stable particles with high electric charges in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 11(11):112, and PUBDB-2023-07891, arXiv:2308.04835. CERN-EP-2023-150.
doi: 10.1007/JHEP11(2023)112.

ATLAS Collaboration.
Search for magnetic monopoles and stable particles with high electric charges in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 11(11):112, and PUBDB-2023-07892, arXiv:2308.04835. CERN-EP-2023-150.
doi: 10.1007/JHEP11(2023)112.

ATLAS Collaboration.
Search for Majorana neutrinos in same-sign WW scattering events from pp collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(9):824, and PUBDB-2023-06725, arXiv:2305.14931. CERN-EP-2023-099.
doi: 10.1140/epjc/s10052-023-11915-y.

ATLAS Collaboration.
Search for new phenomena in final states with photons, jets and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 07(7):21, and PUBDB-2023-04413, arXiv:2206.06012. CERN-EP-2022-012.
doi: 10.1007/JHEP07(2023)021.

ATLAS Collaboration.
Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton and two jets using $\sqrt{s}$ = 13 TeV proton–proton collision data collected by the ATLAS detector.
Journal of high energy physics, 07(7):202, and PUBDB-2023-07059, arXiv:2211.08945. CERN-EP-2022-179.
doi: 10.1007/JHEP07(2023)202.

ATLAS Collaboration.
Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physical review / D, 108(5):052003, and PUBDB-2023-07998, arXiv:2301.03212. CERN-EP-2022-235. arXiv:2301.03212. CERN-EP-2022-235.
doi: 10.1103/PhysRevD.108.052003.

ATLAS Collaboration.
Search for pair-produced scalar and vector leptoquarks decaying into third-generation quarks and first- or second-generation leptons in pp collisions with the ATLAS detector.
Journal of high energy physics, 2306(6):188, and PUBDB-2023-04723, arXiv:2210.04517. CERN-EP-2022-145.
doi: 10.1007/JHEP06(2023)188.

ATLAS Collaboration.
Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector.
The European physical journal / C, 83(8):719, and PUBDB-2023-05429, arXiv:2212.05263. CERN-EP-2022-201.
doi: 10.1140/epjc/s10052-023-11790-7.

ATLAS Collaboration.
Search for pair-production of vector-like quarks in pp collision events at s=13 TeV with at least one leptonically decaying Z boson and a third-generation quark with the ATLAS detector.
Physics letters / B, 843:138019, and PUBDB-2023-04726, arXiv:2210.15413. CERN-EP-2021-207.
doi: 10.1016/j.physletb.2023.138019.

ATLAS Collaboration.
Search for pairs of muons with small displacements in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physics letters / B, 846:138172, and PUBDB-2023-07028, arXiv:2305.02005. CERN-EP-2023-038.
doi: 10.1016/j.physletb.2023.138172.

ATLAS Collaboration.
Search for resonant WZ production in the fully leptonic final state in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
The European physical journal / C, 83(7):633, and PUBDB-2023-04950, arXiv:2207.03925. CERN-EP-2022-093.
doi: 10.1140/epjc/s10052-023-11437-7.

ATLAS Collaboration.
Search for single production of vector-like T quarks decaying into Ht or Zt in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 08(8):153, and PUBDB-2023-07027, arXiv:2305.03401. CERN-EP-2023-058.
doi: 10.1007/JHEP08(2023)153.

ATLAS Collaboration.
Search for supersymmetry in final states with missing transverse momentum and three or more b-jets in 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 83(7):561, and PUBDB-2023-04818, arXiv:2211.08028. CERN-EP-2022-213.
doi: 10.1140/epjc/s10052-023-11543-6.

ATLAS Collaboration.
Search for the charged-lepton-flavor-violating decay $Z \to e\mu$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physical review / D, 108(3):032015, and PUBDB-2024-00172, arXiv:2204.10783. CERN-EP-2022-007.
doi: 10.1103/PhysRevD.108.032015.

ATLAS Collaboration.
Search for third-generation vector-like leptons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 07(7):118, and PUBDB-2023-05170, arXiv:2303.05441. CERN-EP-2022-236. arXiv:2303.05441. CERN-EP-2022-236.
doi: 10.1007/JHEP07(2023)118.

ATLAS Collaboration.
Search in diphoton and dielectron final states for displaced production of Higgs or Z bosons with the ATLAS detector in $\sqrt{s}$ = 13 TeV pp collisions.
Physical review / D, 108(1):012012, and PUBDB-2023-05162, arXiv:2304.12885. CERN-EP-2023-044.
doi: 10.1103/PhysRevD.108.012012.

ATLAS Collaboration.
Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon using 139 fb^{-1} of ATLAS $\sqrt{s}$ = 13 TeV proton–proton collision data.
The European physical journal / C, 83(9):781, and PUBDB-2024-00173, arXiv:2208.03122. CERN-EP-2022-128.
doi: 10.1140/epjc/s10052-023-11869-1.

ATLAS Collaboration.
Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 07(7):166, and PUBDB-2023-07056, arXiv:2302.05225. CERN-EP-2022-279.
doi: 10.1007/JHEP07(2023)166.

ATLAS Collaboration.
Searches for new phenomena in events with two leptons, jets, and missing transverse momentum in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
The European physical journal / C, 83(6):515, and PUBDB-2023-03996, arXiv:2204.13072. CERN-EP-2022-014. arXiv:2204.13072. CERN-EP-2022-014.
doi: 10.1140/epjc/s10052-023-11434-w.

ATLAS Collaboration.
Strong constraints on jet quenching in centrality-dependent p+Pb collisions at 5.02 TeV from ATLAS.
Physical review letters, 131(7):072301, and PUBDB-2023-04880, arXiv:2206.01138. CERN-EP-2022-086. arXiv:2206.01138. CERN-EP-2022-086.
doi: 10.1103/PhysRevLett.131.072301.

ATLAS Collaboration.
Studies of the muon momentum calibration and performance of the ATLAS detector with pp collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(8):686, and PUBDB-2024-00187, arXiv:2212.07338. CERN-EP-2022-274. arXiv:2212.07338. CERN-EP-2022-274.
doi: 10.1140/epjc/s10052-023-11584-x.

ATLAS Collaboration.
Test of CP Invariance in Higgs Boson Vector-Boson-Fusion Production Using the $H \to \gamma\gamma$ Channel with the ATLAS Detector.
Physical review letters, 131(6):061802, and PUBDB-2023-04954, arXiv:2208.02338. CERN-EP-2022-134.
doi: 10.1103/PhysRevLett.131.061802.

ATLAS collaboration.
A search for new resonances in multiple final states with a high transverse momentum Z boson in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 2023(6):36, and PUBDB-2023-04722, arXiv:2209.15345. CERN-EP-2022-180.
doi: 10.1007/JHEP06(2023)036.

ATLAS Collaboration and CMS Collaboration.
Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s}$ = 7 and 8 TeV.
Journal of high energy physics, 07(7):213, and PUBDB-2023-04875, arXiv:2205.13830. CERN-EP-2021-222. CMS-TOP-18-014. CERN-LPCC-2022-03.
doi: 10.1007/JHEP07(2023)213.

L. A. Beresford et al.
Destructive breakdown studies of irradiated LGADs at beam tests for the ATLAS HGTD.
Journal of Instrumentation, 18(07):P07030, and PUBDB-2023-04248, arXiv:2306.12269.
doi: 10.1088/1748-0221/18/07/P07030.

A. Boebel et al.
Current status of the end-of-substructure (EoS) card project for the ATLAS strip tracker upgrade using final ASICs.
03. Topical Workshop On Electronics For Particle Physics , Bergen (Norway), 19 Sep 2022 - 23 Sep 2022.
Journal of Instrumentation, vol. 1803:C03016, and PUBDB-2022-05224.
Inst. of Physics, London.
doi: 10.1088/1748-0221/18/03/C03016.

A. Crippa et al.
Quantum Algorithms for Charged Particle Track Reconstruction in the LUXE Experiment.
Computing and software for big science, 7(1):14, and PUBDB-2023-07901, arXiv:2304.01690. DESY-23-045. MIT-CTP/5481.
doi: 10.1007/s41781-023-00109-6.

L. Nozka et al.
Upgraded Cherenkov time-of-flight detector for the AFP project.
Optics express, 31(3):3998, and PUBDB-2023-07260.
doi: 10.1364/OE.480624.

K. Tackmann.
10 years of Higgs boson measurements at ATLAS and CMS.
Letters in High Energy Physics, 2023(440):1, and PUBDB-2023-01834, DESY-23-053.
doi: 10.31526/LHEP.2023.440.

Ph.D. Thesis

B. Brueers.
Searches for dark matter and single top-quarks with the ATLAS experiment.
Humboldt U., Berlin, 2023.

A. Hrynevich.
The three-jets and Z+jets cross-section measurements in proton-proton collisions data collected with the ATLAS experiment at the LHC.
Universität Hamburg, Hamburg, 2023.

M. Liberatore.
Top of the tops: Combining searches for Dark Matter with top quarks at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Humboldt-Universität zu Berlin, 2023.

G. Mania.
A Multi-purpose Framework for Efficient Parallelized Execution of Charged Particle Tracking.
University of Hamburg, 2023.

Belle

Published

Belle Collaboration.
Search for the decay B0→K*0τ+τ- at the Belle experiment.
Physical review / D, 108(1):L011102, and PUBDB-2023-04247.
doi: 10.1103/PhysRevD.108.L011102.

Belle-II Collaboration.
Determination of $|V_{cb}|$ using $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with Belle II.
Physical review / D, 108(9):092013, and PUBDB-2023-07368, arXiv:2310.01170. Belle II Preprint 2023-014. KEK Preprint 2023-28. arXiv:2310.01170. Belle II Preprint 2023-014. KEK Preprint 2023-28.
doi: 10.1103/PhysRevD.108.092013.

Belle-II Collaboration.
Measurement of CP violation in $B^0 \to K^0_S\pi^0$ decays at Belle II.
Physical review letters, 131(11):111803, and PUBDB-2023-07370, arXiv:2305.07555. Belle II Preprint 2023-006. KEK Preprint 2023-2.
doi: 10.1103/PhysRevLett.131.111803.

Belle-II Collaboration.
Measurement of CP asymmetries in $B^0 \to \phi K^0_S$ decays with Belle II.
Physical review / D, 108(7):072012, and PUBDB-2023-07741, arXiv:2307.02802. Belle II preprint: 2023-012. KEK preprint: 2023-10. arXiv:2307.02802. Belle II preprint: 2023-012. KEK preprint: 2023-10.
doi: 10.1103/PhysRevD.108.072012.

Belle-II Collaboration.
Measurement of Lepton Mass Squared Moments in $B \to X_c\ell\bar{\nu}_\ell$ Decays with the Belle II Experiment.
Physical review / D, 107(7):072002, and PUBDB-2023-01941, arXiv:2205.06372.
doi: 10.1103/PhysRevD.107.072002.

Belle-II Collaboration.
Measurement of the Λ_c^+ lifetime.
Physical review letters, 130(7):071802, and PUBDB-2023-00907, arXiv:2206.15227. Belle II Preprint 2022-003. KEK Preprint 2022-13.
doi: 10.1103/PhysRevLett.130.071802.

Belle-II Collaboration.
Measurement of the Ω_c^0 lifetime at Belle II.
Physical review / D, 107:L031103, and PUBDB-2023-00909, arXiv:2208.08573. Belle II Preprint 2022-005. KEK Preprint 2022-26.
doi: 10.1103/PhysRevD.107.L031103.

Belle-II Collaboration.
Measurement of the B^0 lifetime and flavor-oscillation frequency using hadronic decays reconstructed in 2019-2021 Belle II data.
Physical review / D, 107(9):L091102, and PUBDB-2023-03710, arXiv:2302.12791. Belle II Preprint 2023-001. KEK Preprint 2022-56. arXiv:2302.12791. Belle II Preprint 2023-001. KEK Preprint 2022-56.
doi: 10.1103/PhysRevD.107.L091102.

Belle-II Collaboration.
Measurement of the τ-lepton mass with the Belle II experiment.
Physical review / D, 108(3):032006, and PUBDB-2023-05206, arXiv:2305.19116. Belle II Preprint 2023-008. KEK Preprint 2023-6.
doi: 10.1103/PhysRevD.108.032006.

Belle-II Collaboration.
Measurement of the branching fraction and CP asymmetry of $B^0 \to \pi^0\pi^0$ decays using 2019-2021 Belle II data.
Physical review / D, 107(11):112009, and PUBDB-2023-04077, arXiv:2303.08354. Belle II Preprint 2023-004. KEK Preprint 2022-59.
doi: 10.1103/PhysRevD.107.112009.

Belle-II Collaboration.
Novel method for the identification of the production flavor of neutral charmed mesons.
Physical review / D, 107(11):112010, and PUBDB-2023-04076, arXiv:2304.02042. Belle II Preprint 2023-005. KEK Preprint 2023-1.
doi: 10.1103/PhysRevD.107.112010.

Belle-II Collaboration.
Precise Measurement of the Ds+ Lifetime at Belle II.
Physical review letters, 131(17):171803, and PUBDB-2023-06461, arXiv:2306.00365. Belle-Preprint-2023-007. KEK-Preprint-2023-5. UCHEP-23-03.
doi: 10.1103/PhysRevLett.131.171803.

Belle-II Collaboration.
Search for a $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events with the Belle II experiment.
Physical review letters, 131(12):121802, and PUBDB-2023-05940, arXiv:2306.12294. KEK preprint: 2022-32. Belle II preprint: 2022-006.
doi: 10.1103/PhysRevLett.131.121802.

Belle-II Collaboration.
Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment.
Physical review letters, 130(7):071804, and PUBDB-2023-00908, arXiv:2207.00509. Belle II Preprint 2022-001. KEK Preprint 2022-6.
doi: 10.1103/PhysRevLett.130.071804.

Belle-II Collaboration.
Search for a long-lived spin-0 mediator in $b \to s$ transitions at the Belle II experiment.
Physical review / D, 108(11):L111104, and PUBDB-2023-08132, arXiv:2306.02830. Belle II Preprint 2023-009. KEK Preprint 2023-7.
doi: 10.1103/PhysRevD.108.L111104.

Belle-II Collaboration.
Search for an invisible Z' in a final state with two muons and missing energy at Belle II.
Physical review letters, 130(23):231801, and PUBDB-2023-03708, arXiv:2212.03066. Belle II Preprint 2022-008. KEK Preprint 2022-40.
doi: 10.1103/PhysRevLett.130.231801.

Belle-II Collaboration.
Search for lepton-flavor-violating τ decays to a lepton and an invisible boson at Belle II.
Physical review letters, 130(18):181803, and PUBDB-2023-03709, arXiv:2212.03634. Belle II Preprint 2022-007. KEK Preprint 2022-39. arXiv:2212.03634. Belle II Preprint 2022-007. KEK Preprint 2022-39.
doi: 10.1103/PhysRevLett.130.181803.

Belle-II Collaboration.
Test of Light-Lepton Universality in the Rates of Inclusive Semileptonic B-Meson Decays at Belle II.
Physical review letters, 131(5):051804, and PUBDB-2023-04740, arXiv:2301.08266. Belle II Preprint 2022-009 KEK Preprint 2022-45.
doi: 10.1103/PhysRevLett.131.051804.

Belle-II Collaboration.
Tests of light-lepton universality in angular asymmetries of $B^0 \to D^{*-}\ell\nu$ decays.
Physical review letters, 131(18):181801, and PUBDB-2023-06555, arXiv:2308.02023. Belle II Preprint 2023-013. KEK Preprint 2023-18.
doi: 10.1103/PhysRevLett.131.181801.

Belle-II Collaboration and Belle Collaboration.
Measurement of CP asymmetries and branching-fraction ratios for $B^\pm \to DK^\pm$ and $D\pi^\pm$ with $D \to K^0_S K^\pm\pi^\mp$ using Belle and Belle II data.
Journal of high energy physics, 09(9):146, and PUBDB-2023-05941, arXiv:2306.02940. Belle II Preprint 2023-010. KEK Preprint 2023-8. arXiv:2306.02940. Belle II Preprint 2023-010. KEK Preprint 2023-8.
doi: 10.1007/JHEP09(2023)146.

Y. Chen et al.
Implementation and verification of the CEPC baseline tracker using a modern track reconstruction software.
Radiation detection technology and methods, 7(3):392, and PUBDB-2023-05754.
doi: 10.1007/s41605-023-00405-0.

T. M. Kraetzschmar et al.
Generalised Known Kinematics (GKK): an approach for kinematic observables in pair production events with decays involving invisible particles.
Journal of high energy physics, 07(7):101, and PUBDB-2023-07865, arXiv:2109.14455. MPP-2021-137.
doi: 10.1007/JHEP07(2023)101.

A. Natochii et al.
Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider.
Nuclear instruments & methods in physics research / Section A, 1055:168550, and PUBDB-2023-07487, arXiv:2302.01566.
doi: 10.1016/j.nima.2023.168550.

A. Novosel et al.
Identification of light leptons and pions in the electromagnetic calorimeter of Belle II.
Nuclear instruments & methods in physics research / Section A, 1056:168630, and PUBDB-2023-07619.
doi: 10.1016/j.nima.2023.168630.

Master Thesis

M. Konstantinova.
Studying the pedestal current ageingand pedestal compression for the pixelvertex detector in the Belle II experiment.
University of Hamburg, 2023.

Ph.D. Thesis

H. Svidras.
Measurement of the photon energy spectrum in inclusive radiative B meson decays using the hadronic-tagging method.
Universität Hamburg, Hamburg, 2023.

CMS

Published

CMS Collaboration.
Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 846:137713, and PUBDB-2023-06313, arXiv:2208.09700. CMS-B2G-21-004. CERN-EP-2022-153.
doi: 10.1016/j.physletb.2023.137713.

S. Amoroso et al.
Probing the weak mixing angle at high energies at the LHC and HL-LHC.
Physics letters / B, 844:138103, and PUBDB-2023-00875, DESY-23-028. arXiv:2302.10782.
doi: 10.1016/j.physletb.2023.138103.

ATLAS Collaboration and CMS Collaboration.
Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s}$ = 7 and 8 TeV.
Journal of high energy physics, 07(7):213, and PUBDB-2023-04875, arXiv:2205.13830. CERN-EP-2021-222. CMS-TOP-18-014. CERN-LPCC-2022-03.
doi: 10.1007/JHEP07(2023)213.

S. Cerci et al.
Extraction of the strong coupling with HERA and EIC inclusive data.
The European physical journal / C, 83(11):1011, and PUBDB-2024-00287, arXiv:2307.01183.
doi: 10.1140/epjc/s10052-023-12176-5.

CMS Collaboration.
A search for decays of the Higgs boson to invisible particles in events with a top-antitop quark pair or a vector boson in proton-proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(10):933, and PUBDB-2023-06439, arXiv:2303.01214. CMS-HIG-21-007. CERN-EP-2023-004.
doi: 10.1140/epjc/s10052-023-11952-7.

CMS Collaboration.
Azimuthal anisotropy of dijet events in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.
Journal of high energy physics, 07(7):139, and PUBDB-2023-05330, arXiv:2210.08325. CMS-HIN-21-002. CERN-EP-2022-199.
doi: 10.1007/JHEP07(2023)139.

CMS Collaboration.
Azimuthal correlations in Z +jets events in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(8):722, and PUBDB-2023-05333, arXiv:2210.16139. CMS-SMP-21-003. CERN-EP-2022-178.
doi: 10.1140/epjc/s10052-023-11833-z.

CMS Collaboration.
Azimuthal Correlations within Exclusive Dijets with Large Momentum Transfer in Photon-Lead Collisions.
Physical review letters, 131(5):051901, and PUBDB-2023-05217, arXiv:2205.00045. CMS-HIN-18-011. CERN-EP-2021-071.
doi: 10.1103/PhysRevLett.131.051901.

CMS Collaboration.
CMS pythia 8 colour reconnection tunes based on underlying-event data.
The European physical journal / C, 83(7):587, and PUBDB-2023-04359, arXiv:2205.02905. CMS-GEN-17-002. CERN-EP-2022-005.
doi: 10.1140/epjc/s10052-023-11630-8.

CMS Collaboration.
Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the ττ final state.
Physical review / D, 108(3):032013, and PUBDB-2023-05218, arXiv:2205.05120. CMS-HIG-20-007. CERN-EP-2022-021.
doi: 10.1103/PhysRevD.108.032013.

CMS Collaboration.
Evidence for four-top quark production in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 844:138076, and PUBDB-2023-05338, arXiv:2303.03864. CMS-TOP-21-005. CERN-EP-2023-014.
doi: 10.1016/j.physletb.2023.138076.

CMS Collaboration.
First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV.
Physical review / D, 108(9):092004, and PUBDB-2023-07740, arXiv:2301.07630. CMS-HIN-18-019. CERN-EP-2022-164.
doi: 10.1103/PhysRevD.108.092004.

CMS Collaboration.
First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s}$ = 13.6 TeV.
Journal of high energy physics, 08(8):204, and PUBDB-2023-06440, arXiv:2303.10680. CMS-TOP-22-012. CERN-EP-2023-021.
doi: 10.1007/JHEP08(2023)204.

CMS Collaboration.
Measurement of differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review / D, 108(5):052004, and PUBDB-2023-06308, arXiv:2205.02872. CMS-SMP-19-009. CERN-EP-2021-175.
doi: 10.1103/PhysRevD.108.052004.

CMS Collaboration.
Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):046, and PUBDB-2023-04365, arXiv:2208.00924. CMS-TOP-21-010. CERN-EP-2022-158.
doi: 10.1007/JHEP07(2023)046.

CMS Collaboration.
Measurement of the $t\bar{t}$ charge asymmetry in events with highly Lorentz-boosted top quarks in pp collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 846:137703, and PUBDB-2023-06312, arXiv:2208.02751. CMS-TOP-21-014. CERN-EP-2022-155.
doi: 10.1016/j.physletb.2023.137703.

CMS Collaboration.
Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 842:137955, and PUBDB-2023-03853, arXiv:2212.10311. CMS-BPH-21-006. CERN-EP-2022-270.
doi: 10.1016/j.physletb.2023.137955.

CMS Collaboration.
Measurement of the cross section of top quark-antiquark pair production in association with a W boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):219, and PUBDB-2023-05327, arXiv:2208.06485. CMS-TOP-21-011. CERN-EP-2022-168.
doi: 10.1007/JHEP07(2023)219.

CMS Collaboration.
Measurement of the dependence of the hadron production fraction ratio f_s/f_u and f_d/f_u on B meson kinematic variables in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review letters, 131(12):121901, and PUBDB-2023-06316, arXiv:2212.02309. CMS-BPH-21-001. CERN-EP-2022-248.
doi: 10.1103/PhysRevLett.131.121901.

CMS Collaboration.
Measurement of the differential $t\bar{t}$ production cross section as a function of the jet mass and extraction of the top quark mass in hadronic decays of boosted top quarks.
The European physical journal / C, 83(7):560, and PUBDB-2023-04371, arXiv:2211.01456. CMS-TOP-21-012. CERN-EP-2022-222.
doi: 10.1140/epjc/s10052-023-11587-8.

CMS Collaboration.
Measurement of the electroweak production of $W\gamma$ in association with two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review / D, 108(3):032017, and PUBDB-2023-06436, arXiv:2212.12592. CMS-SMP-21-011. CERN-EP-2022-223.
doi: 10.1103/PhysRevD.108.032017.

CMS Collaboration.
Measurement of the Higgs boson inclusive and differential fiducial production cross sections in the diphoton decay channel with pp collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):091, and PUBDB-2023-04369, arXiv:2208.12279. CMS-HIG-19-016. CERN-EP-2022-142.
doi: 10.1007/JHEP07(2023)091.

CMS Collaboration.
Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell–Yan production in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(7):628, and PUBDB-2023-04360, arXiv:2205.04897. CMS-SMP-20-003. CERN-EP-2022-053.
doi: 10.1140/epjc/s10052-023-11631-7.

CMS Collaboration.
Measurement of the top quark mass using a profile likelihood approach with the lepton + jets final states in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(10):963, and PUBDB-2023-07742, arXiv:2302.01967. CMS-TOP-20-008. CERN-EP-2022-245.
doi: 10.1140/epjc/s10052-023-12050-4.

CMS Collaboration.
Measurement of the top quark pole mass using $t\bar{t}$+jet events in the dilepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):077, and PUBDB-2023-04364, arXiv:2207.02270. CMS-TOP-21-008. CERN-EP-2022-112.
doi: 10.1007/JHEP07(2023)077.

CMS Collaboration.
Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(7):562, and PUBDB-2023-04357, arXiv:2204.12957. CMS-HIG-19-010. CERN-EP-2022-027.
doi: 10.1140/epjc/s10052-023-11452-8.

CMS Collaboration.
Measurements of inclusive and differential cross sections for the Higgs boson production and decay to four-leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 08(8):040, and PUBDB-2023-06486, arXiv:2305.07532. CMS-HIG-21-009. CERN-EP-2023-065.
doi: 10.1007/JHEP08(2023)040.

CMS Collaboration.
Measurements of jet multiplicity and jet transverse momentum in multijet events in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(8):742, and PUBDB-2023-05332, arXiv:2210.13557. CMS-SMP-21-006. CERN-EP-2022-144.
doi: 10.1140/epjc/s10052-023-11753-y.

CMS Collaboration.
Measurements of the azimuthal anisotropy of prompt and non-prompt charmonia in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
Journal of high energy physics, 10(10):115, and PUBDB-2023-06487, arXiv:2305.16928. CMS-HIN-21-008. CERN-EP-2023-052.
doi: 10.1007/JHEP10(2023)115.

CMS Collaboration.
Measurements of the Higgs boson production cross section and couplings in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(7):667, and PUBDB-2023-05224, arXiv:2206.09466. CMS-HIG-20-013. CERN-EP-2022-120.
doi: 10.1140/epjc/s10052-023-11632-6.

CMS Collaboration.
Observation of τ lepton pair production in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
Physical review letters, 131(15):151803, and PUBDB-2023-07736, arXiv:2206.05192. CMS-HIN-21-009. CERN-EP-2022-098.
doi: 10.1103/PhysRevLett.131.151803.

CMS Collaboration.
Observation of electroweak W^+W^- pair production in association with two jets in proton-proton collisions at $\sqrt{s} = 13$TeV.
Physics letters / B, 841:137495, and PUBDB-2023-03256, arXiv:2205.05711. CMS-SMP-21-001. CERN-EP-2022-038.
doi: 10.1016/j.physletb.2022.137495.

CMS Collaboration.
Observation of four top quark production in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 847:138290, and PUBDB-2023-07746, arXiv:2305.13439. CMS-TOP-22-013. CERN-EP-2023-090.
doi: 10.1016/j.physletb.2023.138290.

CMS Collaboration.
Observation of same-sign WW production from double parton scattering in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review letters, 131(9):091803, and PUBDB-2023-06309, arXiv:2206.02681. CMS-SMP-21-013. CERN-EP-2022-092.
doi: 10.1103/PhysRevLett.131.091803.

CMS Collaboration.
Observation of the rare decay of the η meson to four muons.
Physical review letters, 131(9):091903, and PUBDB-2023-06485, arXiv:2305.04904. CMS-BPH-22-003. CERN-EP-2023-071.
doi: 10.1103/PhysRevLett.131.091903.

CMS Collaboration.
Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Nature physics, 19(3):338, and PUBDB-2023-00858, arXiv:2111.05370. CMS-BPH-21-004. CERN-EP-2021-215.
doi: 10.1038/s41567-022-01838-y.

CMS Collaboration.
Performance of the local reconstruction algorithms for the CMS hadron calorimeter with Run 2 data.
Journal of Instrumentation, 18(11):P11017, and PUBDB-2023-07750, arXiv:2306.10355. CMS-PRF-22-001. CERN-EP-2023-093.
doi: 10.1088/1748-0221/18/11/P11017.

CMS Collaboration.
Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 842:137563, and PUBDB-2023-03673, arXiv:2206.07110. CMS-SMP-18-014. CERN-EP-2022-088.
doi: 10.1016/j.physletb.2022.137563.

CMS Collaboration.
Probing heavy Majorana neutrinos and the Weinberg operator through vector boson fusion processes in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review letters, 131(1):011803, and PUBDB-2023-04250, arXiv:2206.08956. CMS-EXO-21-003. CERN-EP-2022-105.
doi: 10.1103/PhysRevLett.131.011803.

CMS Collaboration.
Reconstruction of decays to merged photons using end-to-end deep learning with domain continuation in the CMS detector.
Physical review / D, 108(5):052002, and PUBDB-2023-06307, arXiv:2204.12313. CMS-EGM-20-001. CERN-EP-2022-028.
doi: 10.1103/PhysRevD.108.052002.

CMS Collaboration.
Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s} =$ 13 TeV.
Journal of high energy physics, 09(9):032, and PUBDB-2023-06310, arXiv:2207.01046. CMS-HIG-21-010. CERN-EP-2022-125.
doi: 10.1007/JHEP09(2023)032.

CMS Collaboration.
Search for a heavy composite Majorana neutrino in events with dilepton signatures from proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 843:137803, and PUBDB-2023-04005, arXiv:2210.03082. CMS-EXO-20-011. CERN-EP-2022-181.
doi: 10.1016/j.physletb.2023.137803.

CMS Collaboration.
Search for a high-mass dimuon resonance produced in association with b quark jets at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 10(10):043, and PUBDB-2023-07752, arXiv:2307.08708. CMS-EXO-22-016. CERN-EP-2023-122.
doi: 10.1007/JHEP10(2023)043.

CMS Collaboration.
Search for a massive scalar resonance decaying to a light scalar and a Higgs boson in the four b quarks final state with boosted topology.
Physics letters / B, 842:137392, and PUBDB-2023-03666, arXiv:2204.12413. CMS-B2G-21-003. CERN-EP-2022-034.
doi: 10.1016/j.physletb.2022.137392.

CMS Collaboration.
Search for a vector-like quark $T' \rightarrow$ tH via the diphoton decay mode of the Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 09(9):057, and PUBDB-2023-06438, arXiv:2302.12802. CMS-B2G-21-007. CERN-EP-2022-253.
doi: 10.1007/JHEP09(2023)057.

CMS Collaboration.
Search for CP violating top quark couplings in pp collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 07(7):23, and PUBDB-2023-04361, arXiv:2205.07434. CMS-TOP-18-007. CERN-EP-2021-143.
doi: 10.1007/JHEP07(2023)023.

CMS Collaboration.
Search for CP violation in $t\bar{t}$H and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 07(7):092, and PUBDB-2023-04366, arXiv:2208.02686. CMS-HIG-21-006. CERN-EP-2022-157.
doi: 10.1007/JHEP07(2023)092.

CMS Collaboration.
Search for CP violation using $t\bar{t}$ events in the lepton+jets channel in pp collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 06(6):081, and PUBDB-2023-03861, arXiv:2205.02314. CMS-TOP-20-005. CERN-EP-2022-051.
doi: 10.1007/JHEP06(2023)081.

CMS Collaboration.
Search for direct pair production of supersymmetric partners of τ leptons in the final state with two hadronically decaying τ leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 108(1):012011, and PUBDB-2023-05226, arXiv:2207.02254. CMS-SUS-21-001. CERN-EP-2022-032.
doi: 10.1103/PhysRevD.108.012011.

CMS Collaboration.
Search for electroweak production of charginos and neutralinos at $\sqrt{s}$=13 TeV in final states containing hadronic decays of WW, WZ, or WH and missing transverse momentum.
Physics letters / B, 842:137460, and PUBDB-2023-03671, arXiv:2205.09597. CMS-SUS-21-002. CERN-EP-2022-031.
doi: 10.1016/j.physletb.2022.137460.

CMS Collaboration.
Search for exotic Higgs boson decays H $\rightarrow \mathcal{A}\mathcal{A} \rightarrow 4\gamma$ with events containing two merged diphotons in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review letters, 131(10):101801, and PUBDB-2023-06314, arXiv:2209.06197. CMS-HIG-21-016. CERN-EP-2022-151.
doi: 10.1103/PhysRevLett.131.101801.

CMS Collaboration.
Search for heavy resonances and quantum black holes in eμ, eτ, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 05(5):227, and PUBDB-2023-03669, arXiv:2205.06709. CMS-EXO-19-014. CERN-EP-2022-033.
doi: 10.1007/JHEP05(2023)227.

CMS Collaboration.
Search for Higgs Boson and Observation of Z Boson through their Decay into a Charm Quark-Antiquark Pair in Boosted Topologies in Proton-Proton Collisions at $\sqrt{s}$=13 TeV.
Physical review letters, 131(4):041801, and PUBDB-2023-05336, arXiv:2211.14181. CMS-HIG-21-012. CERN-EP-2022-233.
doi: 10.1103/PhysRevLett.131.041801.

CMS Collaboration.
Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review letters, 131(6):061801, and PUBDB-2023-05219, arXiv:2205.05550. CMS-HIG-21-008. CERN-EP-2022-081.
doi: 10.1103/PhysRevLett.131.061801.

CMS Collaboration.
Search for Higgs boson decays into Z and J/ψ and for Higgs and Z boson decays into J/ψ or Υ pairs in pp collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 842:137534, and PUBDB-2023-03672, arXiv:2206.03525. CMS-HIG-20-008. CERN-EP-2022-074.
doi: 10.1016/j.physletb.2022.137534.

CMS Collaboration.
Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 05(5):233, and PUBDB-2023-03667, arXiv:2204.12945. CMS-HIG-19-014. CERN-EP-2022-019.
doi: 10.1007/JHEP05(2023)233.

CMS Collaboration.
Search for Higgs boson pairs decaying to WW*WW*, WW*$\tau\tau$, and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 07(7):095, and PUBDB-2023-04362, arXiv:2206.10268. CMS-HIG-21-002. CERN-EP-2022-113.
doi: 10.1007/JHEP07(2023)095.

CMS Collaboration.
Search for light Higgs bosons from supersymmetric cascade decays in pp collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 83(7):571, and PUBDB-2023-04358, arXiv:2204.13532. CMS-HIG-20-018. CERN-EP-2022-010.
doi: 10.1140/epjc/s10052-023-11581-0.

CMS Collaboration.
Search for long-lived particles decaying to a pair of muons in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 05(5):228, and PUBDB-2023-03670, arXiv:2205.08582. CMS-EXO-21-006. CERN-EP-2022-080.
doi: 10.1007/JHEP05(2023)228.

CMS Collaboration.
Search for long-lived particles using out-of-time trackless jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):210, and PUBDB-2023-05340, arXiv:2212.06695. CMS-EXO-21-014. CERN-EP-2022-276.
doi: 10.1007/JHEP07(2023)210.

CMS Collaboration.
Search for medium effects using jets from bottom quarks in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.
Physics letters / B, 844:137849, and PUBDB-2023-05331, arXiv:2210.08547. CMS-HIN-20-003. CERN-EP-2022-190.
doi: 10.1016/j.physletb.2023.137849.

CMS Collaboration.
Search for narrow resonances in the b-tagged dijet mass spectrum in proton-proton collisions at $\sqrt{s}$ =13 TeV.
Physical review / D, 108(1):012009, and PUBDB-2023-04249, arXiv:2205.01835. CMS-EXO-20-008. CERN-EP-2022-037.
doi: 10.1103/PhysRevD.108.012009.

CMS Collaboration.
Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 844:137813, and PUBDB-2023-05329, arXiv:2210.00043. CMS-B2G-20-009. CERN-EP-2022-152.
doi: 10.1016/j.physletb.2023.137813.

CMS Collaboration.
Search for new physics in multijet events with at least one photon and large missing transverse momentum in proton-proton collisions at 13 TeV.
Journal of high energy physics, 10(10):046, and PUBDB-2023-07753, arXiv:2307.16216. CMS-SUS-21-009. CERN-EP-2023-127.
doi: 10.1007/JHEP10(2023)046.

CMS Collaboration.
Search for new physics in the τ lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 09(9):051, and PUBDB-2023-06437, arXiv:2212.12604. CMS-EXO-21-009. CERN-EP-2022-268. arXiv:2212.12604. CMS-EXO-21-009. CERN-EP-2022-268.
doi: 10.1007/JHEP09(2023)051.

CMS Collaboration.
Search for new physics using effective field theory in 13 TeV pp collision events that contain a top quark pair and a boosted Z or Higgs boson.
Physical review / D, 108(3):032008, and PUBDB-2023-05328, arXiv:2208.12837. CMS-TOP-21-003. CERN-EP-2022-172.
doi: 10.1103/PhysRevD.108.032008.

CMS Collaboration.
Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 842:137531, and PUBDB-2023-03674, arXiv:2206.09401. CMS-HIG-20-010. CERN-EP-2022-117.
doi: 10.1016/j.physletb.2022.137531.

CMS Collaboration.
Search for nonresonant Higgs boson pair production in the four leptons plus twob jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 06(6):130, and PUBDB-2023-04363, arXiv:2206.10657. CMS-HIG-20-004. CERN-EP-2022-114.
doi: 10.1007/JHEP06(2023)130.

CMS Collaboration.
Search for Nonresonant Pair Production of Highly Energetic Higgs Bosons Decaying to Bottom Quarks.
Physical review letters, 131(4):041803, and PUBDB-2023-05223, arXiv:2205.06667. CMS-B2G-22-003. CERN-EP-2022-090.
doi: 10.1103/PhysRevLett.131.041803.

CMS Collaboration.
Search for pair production of vector-like quarks in leptonic final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):020, and PUBDB-2023-04370, arXiv:2209.07327. CMS-B2G-20-011. CERN-EP-2022-175.
doi: 10.1007/JHEP07(2023)020.

CMS Collaboration.
Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):161, and PUBDB-2023-05225, arXiv:2206.09997. CMS-EXO-21-010. CERN-EP-2022-103.
doi: 10.1007/JHEP07(2023)161.

CMS Collaboration.
Search for supersymmetry in final states with a single electron or muon using angular correlations and heavy-object identification in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 09(9):149, and PUBDB-2023-06031, arXiv:2211.08476. CMS-SUS-21-007. CERN-EP-2022-169.
doi: 10.1007/JHEP09(2023)149.

CMS Collaboration.
Search for the exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):148, and PUBDB-2023-05326, arXiv:2208.01469. CMS-HIG-21-003. CERN-EP-2022-095.
doi: 10.1007/JHEP07(2023)148.

CMS Collaboration.
Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physics letters / B, 846:137783, and PUBDB-2023-06311, arXiv:2208.00265. CMS-HIG-21-015. CERN-EP-2022-131.
doi: 10.1016/j.physletb.2023.137783.

CMS Collaboration.
Search for the lepton-flavor violating decay of the Higgs boson and additional Higgs bosons in the eμ final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review / D, 108(7):072004, and PUBDB-2023-06488, arXiv:2305.18106. CMS-HIG-22-002. CERN-EP-2023-061.
doi: 10.1103/PhysRevD.108.072004.

CMS Collaboration.
Search for top squark pair production in a final state with at least one hadronically decaying tau lepton in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):110, and PUBDB-2023-05339, arXiv:2304.07174. CMS-SUS-21-004. CERN-EP-2023-019.
doi: 10.1007/JHEP07(2023)110.

CMS Collaboration.
Search for top squarks in the four-body decay mode with single lepton final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 06(6):060, and PUBDB-2023-03854, arXiv:2301.08096. CMS-SUS-21-003. CERN-EP-2022-254.
doi: 10.1007/JHEP06(2023)060.

CMS Collaboration.
Search for Z′ bosons decaying to pairs of heavy Majorana neutrinos in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 11(11):181, and PUBDB-2023-07751, arXiv:2307.06959. CMS-EXO-20-006. CERN-EP-2023-115.
doi: 10.1007/JHEP11(2023)181.

CMS Collaboration.
Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):073, and PUBDB-2023-04367, arXiv:2208.02717. CMS-HIG-21-001. CERN-EP-2022-137.
doi: 10.1007/JHEP07(2023)073.

CMS Collaboration.
Strange hadron collectivity in pPb and PbPb collisions.
Journal of high energy physics, 05(5):007, and PUBDB-2023-03255, arXiv:2205.00080. CMS-HIN-19-004. CERN-EP-2022-036.
doi: 10.1007/JHEP05(2023)007.

CMS Collaboration.
Test beam performance of a CBC3-based mini-module for the Phase-2 CMS Outer Tracker before and after neutron irradiation.
Journal of Instrumentation, 18(04):P04001, and PUBDB-2023-07956, arXiv:2205.00961.
doi: 10.1088/1748-0221/18/04/P04001.

CMS Collaboration.
Two-particle azimuthal correlations in γp interactions using pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV.
Physics letters / B, 844:137905, and PUBDB-2023-05216, arXiv:2204.13486. CMS-HIN-18-008. CERN-EP-2021-100.
doi: 10.1016/j.physletb.2023.137905.

CMS Collaboration and TOTEM Collaboration.
Proton reconstruction with the CMS-TOTEM Precision Proton Spectrometer.
Journal of Instrumentation, 18(09):P09009, and PUBDB-2023-06315, arXiv:2210.05854. CMS-PRO-21-001. TOTEM-2022-001. CERN-EP-2022-139.
doi: 10.1088/1748-0221/18/09/P09009.

CMS Collaboration and TOTEM Collaboration.
Search for high-mass exclusive $\gamma\gamma \to$ WW and $\gamma\gamma \to$ ZZ production in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):229, and PUBDB-2023-05337, arXiv:2211.16320. CMS-SMP-21-014. TOTEM-2022-002. CERN-EP-2022-177.
doi: 10.1007/JHEP07(2023)229.

CMS HGCAL Collaboration.
Neutron irradiation and electrical characterisation of the first 8" silicon pad sensor prototypes for the CMS calorimeter endcap upgrade.
Journal of Instrumentation, 18(08):P08024, and PUBDB-2023-07913, arXiv:2209.10159.
doi: 10.1088/1748-0221/18/08/P08024.

J. C. Criado, R. Kogler and M. Spannowsky.
Quantum fitting framework applied to effective field theories.
Physical review / D, 107(1):015023, and PUBDB-2022-03922, DESY-22-126. arXiv:2207.10088. IPPP/22/51.
doi: 10.1103/PhysRevD.107.015023.

Group, CMS Tracker.
Beam test studies with silicon sensor module prototypes for the CMS Phase-2 Outer Tracker.
Journal of Instrumentation, 18(01):C01005, and PUBDB-2023-00446.
doi: 10.1088/1748-0221/18/01/C01005.

I. M. Macías Labrada et al.
Carbon nanotubes with point defects produced by ionizing radiation: a study using DFTB.
The European physical journal / D, 77(8):153, and PUBDB-2023-07788.
doi: 10.1140/epjd/s10053-023-00735-0.

T. Maekelae et al.
Investigation of the scale dependence in the MSR and $\overline{\text{MS}}$ top quark mass schemes for the $t\bar{t}$ invariant mass differential cross section using LHC data.
Journal of high energy physics, 09(9):037, and PUBDB-2023-00006, DESY-23-001. arXiv:2301.03546. UWThPh-2023-1.
doi: 10.1007/JHEP09(2023)037.

I. Mateos Domínguez et al.
Software tools for hybrid quality control for the CMS Outer Tracker Phase-2 Upgrade.
Journal of Instrumentation, 18(01):C01048, and PUBDB-

2023-00654.
doi: 10.1088/1748-0221/18/01/C01048.

M. N. Mazziotta et al.
The EXTRA-BL4S experiment for the measurement of the energy and angular distributions of transition radiation X-rays.
Journal of Instrumentation, 18(4):P04017, and PUBDB-2023-00919, arXiv:2301.11247.
doi: 10.1088/1748-0221/18/04/P04017.

D. Perez Adan et al.
A new LHC search for dark matter produced via heavy Higgs bosons using simplified models.
Journal of high energy physics, 08:151, and PUBDB-2023-00548, EFI-22-10. DESY-23-014. arXiv:2302.04892.
doi: 10.1007/JHEP08(2023)151.

F. Lorkowski.
Measurement and QCD Analysis of Inclusive Jet Production in Deep Inelastic Scattering at HERA.
5. Diffraction and Low-x 2022, Corigliano Calabro (Italy), 24 Sep 2022 - 30 Sep 2022.
Acta physica Polonica / B / Proceedings supplement, vol. 165:A35, and PUBDB-2023-03715.
Inst. of Physics, Jagellonian Univ., Cracow.
doi: 10.5506/APhysPolBSupp.16.5-A35.

ZEUS Collaboration.
Measurement of jet production in deep inelastic scattering and NNLO determination of the strong coupling at ZEUS.
The European physical journal / C, 83(11):1082, and PUBDB-2023-07645, arXiv:2309.02889. DESY-23-129.
doi: 10.1140/epjc/s10052-023-12180-9.

Master Thesis

K. de Ligt.
Effects of model parameter variations forthe bbH→Za→ll$_{\chi\chi}$ process in theperformance of multivariate classifiers.
University of Hamburg, 2023.

L. Sommer.
Qualification of Silicon Detectors for the Phase 2 Upgrade of the CMS Outer Tracker.
Universität Wuppertal, Hamburg, 2023.

Ph.D. Thesis

O. Filatov.
Tau identification algorithms and study of the CP structure of the Yukawa coupling between the Higgs boson and tau leptons in CMS.
Universität Hamburg, Hamburg, 2023.

A. Giraldi.
Measurement of the $t\bar{t}H(b\bar{b})$ process in the dilepton final state with machine learning techniques at the CMS experiment.
Universität Hamburg, Hamburg, 2023.

F. Lorkowski.
Measurement and NNLO QCD analysis of jet production in deep inelastic scattering at ZEUS.
Universität Hamburg, Hamburg, 2023.

M. Mendizabal Morentin.
Z boson production in association with jets: measurement and phenomenology.
Universität Hamburg, Hamburg, 2024.

Y. Otarid.
Pixel-Strip Modules for the CMS Tracker Phase-2 Upgrade:From DAQ test system development to module assembly and qualification.
Universität Hamburg, Hamburg, 2023.

B. Ribeiro Lopes.
Differential ratio measurements of $t\bar{t}/t\bar{t}$ and a search for exclusive $t\bar{t}$ with the CMS experiment.
Universität Hamburg, Hamburg, 2023.

J. Ruebenach.
Search for heavy Higgs bosons in conjunction with neural-network-driven reconstruction and upgrade of the Fast Beam Condition Monitor at the CMS experiment.
Universität Hamburg, Hamburg, 2023.

A. R. Sahasransu.
Triggering and Data Scouting on compressed dark matter models at the CMS experiment.
Vrije Universiteit Brussel, 2023.

V. Scheurer.
First measurement of the $t\bar{t}$ production cross section in association with a Z boson decaying into a quark pair at the CMS Experiment.
Universität Hamburg, Hamburg, 2023.

N. Stylianou.
Search for the four top quark production process at the CMS experiment via the single lepton channel.
University of Bristol / University of Brussels, 2023.

V. Wachirapusitanand.
Search for Standard Model Production of Four Top Quarks in Compact Muon Solenoid Detector and Designing Neural Networks for Top Quark Yukawa Coupling Measurement from Four Top Quark Production.
Chulalongkorn University, 2023.

S. Wuchterl.
Top quark pole mass from $t\bar{t}$+jet using a machine learning based reconstruction for $t\bar{t}$ kinematics.
Universität Hamburg, Hamburg, 2023.

H. Yang.
Measurement and phenomenology of azimuthal correlations in Z+jet events in CMS at the center of mass energy of 13 TeV.
University of Beijing, Hamburg, 2023.

Electronics Development

Published

A. Boebel et al.
Current status of the end-of-substructure (EoS) card project for the ATLAS strip tracker upgrade using final ASICs.
03. Topical Workshop On Electronics For Particle Physics , Bergen (Norway), 19 Sep 2022 - 23 Sep 2022.
Journal of Instrumentation, vol. 1803:C03016, and PUBDB-2022-05224.
Inst. of Physics, London.
doi: 10.1088/1748-0221/18/03/C03016.

A. Castoldi et al.
Qualification of the X-ray spectral performance of the DEPFET pixels of the DSSC imager.
Nuclear instruments & methods in physics research / Section A, 1057:168686, and PUBDB-2023-06285.
doi: 10.1016/j.nima.2023.168686.

A. Costa et al.
A Study of the Latest Updates of the DAQ Firmware for the DSSC Camera at the European XFEL.
IEEE access, 11:84323, and PUBDB-2023-06284.
doi: 10.1109/ACCESS.2023.3302400.

T. Lojewski et al.
The interplay of local electron correlations and ultrafast spin dynamics in fcc Ni.
Materials Research Letters, 11(8):655, and PUBDB-2022-06731, arXiv:2210.13162.
doi: 10.1080/21663831.2023.2210606.

S. Maffessanti et al.
A 64k pixel CMOS-DEPFET module for the soft X-rays DSSC imager operating at MHz-frame rates.
Scientific reports, 13(1):11799, and PUBDB-2022-04665.
doi: 10.1038/s41598-023-38508-9.

T. Muscheid et al.
DTS-100G — a versatile heterogeneous MPSoC board for cryogenic sensor readout.
Journal of Instrumentation, 18(02):C02067, and PUBDB-2023-07868, arXiv:2301.10706.
doi: 10.1088/1748-0221/18/02/C02067.

FTX

Published

A. Boebel et al.
Current status of the end-of-substructure (EoS) card project for the ATLAS strip tracker upgrade using final ASICs.
03. Topical Workshop On Electronics For Particle Physics , Bergen (Norway), 19 Sep 2022 - 23 Sep 2022.
Journal of Instrumentation, vol. 1803:C03016, and PUBDB-2022-05224.
Inst. of Physics, London.
doi: 10.1088/1748-0221/18/03/C03016.

E. Buhmann et al.
CaloClouds: fast geometry-independent highly-granular calorimeter simulation.
Journal of Instrumentation, 18(11):P11025, and PUBDB-2024-00454, arXiv:2305.04847. DESY-23-061.
doi: 10.1088/1748-0221/18/11/P11025.

D. Heuchel.
Commissioning, characterisation and temperature stabilisation of a 22000 channel SiPM-on-tile hadron calorimeter system.
Conference on New Developments in Photon Detection, Troyes (France), 4 Jul 2022 - 8 Jul 2022.
Nuclear instruments & methods in physics research / A, vol. 1045:167536, and PUBDB-2022-06701, arXiv:2211.04418.
North-Holland Publ. Co., Amsterdam.
doi: 10.1016/j.nima.2022.167536.

CALICE Collaboration.
Description and stability of a RPC-based calorimeter in electromagnetic and hadronic shower environments.
Journal of Instrumentation, 18(03):P03035, and PUBDB-2023-07902, arXiv:2207.06291. CALICE-PUB-2023-02.
doi: 10.1088/1748-0221/18/03/P03035.

CALICE Collaboration.
Design, construction and commissioning of a technological prototype of a highly granular SiPM-on-tile scintillator-steel hadronic calorimeter.
Journal of Instrumentation, 18(11):P11018, and PUBDB-2023-07837, arXiv:2209.15327. CALICE-PUB-2022-003.
doi: 10.1088/1748-0221/18/11/P11018.

CMS Collaboration and CALICE Collaboration.
Performance of the CMS High Granularity Calorimeter prototype to charged pion beams of 20–300 GeV/c.
Journal of Instrumentation, 18(08):P08014, and PUBDB-2023-07915, arXiv:2211.04740.
doi: 10.1088/1748-0221/18/08/P08014.

CMS HGCAL Collaboration.
Neutron irradiation and electrical characterisation of the first 8” silicon pad sensor prototypes for the CMS calorimeter endcap upgrade.
Journal of Instrumentation, 18(08):P08024, and PUBDB-2023-07913, arXiv:2209.10159.
doi: 10.1088/1748-0221/18/08/P08024.

A. Crippa et al.
Quantum Algorithms for Charged Particle Track Reconstruction in the LUXE Experiment.
Computing and software for big science, 7(1):14, and PUBDB-2023-07901, arXiv:2304.01690. DESY-23-045. MIT-CTP/5481.
doi: 10.1007/s41781-023-00109-6.

S. Diefenbacher et al.
New angles on fast calorimeter shower simulation.
Machine learning: science and technology, 4(3):035044, and PUBDB-2023-07637.
doi: 10.1088/2632-2153/acefa9.

L. Helary.
LUXE: A new experiment to study non-perturbative QED.
Il nuovo cimento / C, 46(1):24, and PUBDB-2023-07795.
doi: 10.1393/ncc/i2023-23024-y.

J. Slim et al.
Quantum mechanical derivation of radio-frequency-driven coherent beam oscillations in storage rings.
Physical review accelerators and beams, 26(1):014201, and PUBDB-2023-06272, arXiv:2111.08444.
doi: 10.1103/PhysRevAccelBeams.26.014201.

Master Thesis

R. Löwenberg.
Revisiting Gravitational Wave Detection with SCRF Cavities at DESY.
University of Hamburg, 2023.

Ph.D. Thesis

J. Beyer.
Achieving electroweak precision at future electron-positron colliders.
Universität Hamburg, 2023.

S. M. Jaster-Merz.
High-dimensional and ultra-sensitive diagnostics for electron beams.
Universität Hamburg, Hamburg, 2023.

C. Li.
Phenomenology of extended Two-Higgs-Doublets models.
University of Hamburg, 2023.

H1

Published

DPHEP Collaboration.
Data preservation in high energy physics.
The European physical journal / C, 83(9):795, and PUBDB-2023-07863, arXiv:2302.03583. DPHEP-2023-01.
doi: 10.1140/epjc/s10052-023-11885-1.

H1 Collaboration.
Unbinned Deep Learning Jet Substructure Measurement in High Q^2 ep collisions at HERA.
Physics letters / B, 844:138101, and PUBDB-2023-07051, arXiv:2303.13620. DESY-23-034.
doi: 10.1016/j.physletb.2023.138101.

HERMES

Published

V. D. Burkert et al.
Precision studies of QCD in the low energy domain of the EIC.
Progress in particle and nuclear physics, 131:104032, and PUBDB-2023-07670, arXiv:2211.15746.
doi: 10.1016/j.ppnp.2023.104032.

IT

Published

E. Buhmann et al.
CaloClouds: fast geometry-independent highly-granular calorimeter simulation.
Journal of Instrumentation, 18(11):P11025, and PUBDB-2024-00454, arXiv:2305.04847. DESY-23-061.
doi: 10.1088/1748-0221/18/11/P11025.

S. Diefenbacher et al.
New angles on fast calorimeter shower simulation.
Machine learning: science and technology, 4(3):035044, and PUBDB-2023-07637.
doi: 10.1088/2632-2153/acefa9.

E. Genthe et al.
PickYOLO: Fast deep learning particle detector for annotation of cryo electron tomograms.
Journal of structural biology, 215(3):107990, and PUBDB-2023-06092.
doi: 10.1016/j.jsb.2023.107990.

A. Götz et al.
LEAPS data strategy.
The European physical journal / Plus, 138(7):617, and PUBDB-2023-07784.
doi: 10.1140/epjp/s13360-023-04189-6.

Theory

Published

J. Aalbers et al.
A next-generation liquid xenon observatory for dark matter and neutrino physics.
Journal of physics / G, 50(1):013001, and PUBDB-2023-07113, arXiv:2203.02309. INT-PUB-22-003. FERMILAB-PUB-22-112-PPD-QIS-T.
doi: 10.1088/1361-6471/ac841a.

I. Akal.
Exact instantons via worldline deformations.
Classical and quantum gravity, 40(2):025014, and PUBDB-2023-00075, DESY-18-145. arXiv:1808.06868.
doi: 10.1088/1361-6382/acadcc.

C. Alexandrou et al.
Moments of the nucleon transverse quark spin densities using lattice QCD.
Physical review / D, 107(5):054504, and PUBDB-2023-03146, arXiv:2202.09871.
doi: 10.1103/PhysRevD.107.054504.

A. Ali, A. Parkhomenko and P. Irina.
Branching fraction of the decay $B^+ \to \pi^+\tau^+\tau^-$ and lepton flavor universality test via the ratio $R_\pi(\tau/\mu)$.
Physics letters / B, 842:137961, and PUBDB-2023-01451, DESY-23-036. arXiv:2303.15384.
doi: 10.1016/j.physletb.2023.137961.

S. Ali et al.
Baryonic states in $\mathcal{N}=1$ supersymmetric SU(2) Yang–Mills theory on the lattice.
The European physical journal / C, 83(7):558, and PUBDB-2023-07639, arXiv:2303.02137. MS-TP-23-05.
doi: 10.1140/epjc/s10052-023-11730-5.

S. Alioli et al.
Double Higgs production at NNLO interfaced to parton showers in GENEVA.
Journal of high energy physics, 06(6):205, and PUBDB-2023-01835, DESY-22-204. arXiv:2212.10489.
doi: 10.1007/JHEP06(2023)205.

S. Alioli et al.
Refining the GENEVA method for Higgs boson production via gluon fusion.
Journal of high energy physics, 05(5):128, and PUBDB-2023-00387, DESY-23-009. arXiv:2301.11875. UWThPh-2023-2.
doi: 10.1007/JHEP05(2023)128.

J. R. Andersen, A. M. Maier and D. Maître.
Efficient negative-weight elimination in large high-multiplicity Monte Carlo event samples.
The European physical journal / C, 83(9):835, and PUBDB-2023-06613, arXiv:2303.15246. IPPP/23/15. DCPT/23/30. DESY-23-037.
doi: 10.1140/epjc/s10052-023-11905-0.

J. R. Andersen et al.
High energy resummed predictions for the production of a Higgs boson with at least one jet.
Journal of high energy physics, 03(3):001, and PUBDB-2023-07054, arXiv:2210.10671. IPPP/22/71. DCPT/22/142. DESY-22-164.
doi: 10.1007/JHEP03(2023)001.

E. Andriolo et al.
Covariantly constant anomalies on conformal manifolds.
Physical review / D, 107(2):025006, and PUBDB-2023-07797, arXiv:2210.10891.
doi: 10.1103/PhysRevD.107.025006.

T. Angelides et al.
Computing the mass shift of Wilson and staggered fermions in the lattice Schwinger model with matrix product states.
Physical review / D, 108(1):014516, and PUBDB-2023-04852, arXiv:2303.11016. MIT-CTP/5483.
doi: 10.1103/PhysRevD.108.014516.

Anisha et al.
Higgs Footprints of Hefty ALPs.
Physical review / D, 108(9):095032, and PUBDB-2023-04097, DESY-23-082. arXiv:2306.11808.
doi: 10.1103/PhysRevD.108.095032.

Anisha et al.
On the BSM reach of four top production at the LHC.
Physical review / D, 108(3):035001, and PUBDB-2023-00965, DESY-23-025. arXiv:2302.08281.
doi: 10.1103/PhysRevD.108.035001.

F. Arco et al.
Sensitivity to triple Higgs couplings via di-Higgs production in the 2HDM at the (HL-)LHC.
The European physical journal / C, 83(11):1019, and PUBDB-2024-00480, arXiv:2212.11242. DESY-22-203. IFT-UAM/CSIC-22-073. KA-TP-30-2022.
doi: 10.1140/epjc/s10052-023-12193-4.

N. Asmussen et al.
Hadronic light-by-light scattering contribution to the muon $g-2$ from lattice QCD: semi-analytical calculation of the QED kernel.
Journal of high energy physics, 2023(4):040, and PUBDB-2022-05302, DESY-22-163. arXiv:2210.12263. MITP-22-083.
doi: 10.1007/JHEP04(2023)040.

S. Bacchio et al.
Learning trivializing gradient flows for lattice gauge theories.
Physical review / D, 107(5):L051504, and PUBDB-2023-03144, arXiv:2212.08469.
doi: 10.1103/PhysRevD.107.L051504.

H. Bahl, J. Braathen and G. Weiglein.
Theoretical concepts and measurement prospects for BSM trilinear couplings: a case study for scalar top quarks.
The European physical journal / C, 83:685, and PUBDB-2022-07865, DESY-22-208. arXiv:2212.11213.
doi: 10.1140/epjc/s10052-023-11839-7.

H. Bahl et al.
`anyH3`: precise predictions for the trilinear Higgs coupling in the Standard Model and beyond.
The European physical journal / C, 83(12):1156, and PUBDB-2024-00143, arXiv:2305.03015. DESY-23-042.
doi: 10.1140/epjc/s10052-023-12173-8.

H. Bahl et al.
HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals.
Computer physics communications, 291:108803, and PUBDB-2023-07954, arXiv:2210.09332. DESY-22-130. IFT–UAM/CSIC–22-123. EFI-22-9. KA-TP-25-2022.
doi: 10.1016/j.cpc.2023.108803.

M. C. Banuls et al.
Quantum information perspective on meson melting.
Physical review / D, 108(7):076016, and PUBDB-2024-00179, arXiv:2206.10528.
doi: 10.1103/PhysRevD.108.076016.

O. Bar, A. Broll and R. Sommer.
$B\pi$ excited-state contamination in lattice calculations of B-meson correlation functions.
The European physical journal / C, 83(8):757, and PUBDB-2023-06226, arXiv:2306.02703. HU-EP-23/12-RTG.
doi: 10.1140/epjc/s10052-023-11906-z.

T. Bargheer, T. Fleury and V. Gonçalves.
Higher-Point Integrands in $\mathcal{N}=4$ super Yang-Mills Theory.
SciPost physics, 15:059, and PUBDB-2023-04878, arXiv:2212.03773. DESY-22-195.
doi: 10.21468/SciPostPhys.15.2.059.

J. Barrat, A. Gimenez Grau and P. Liendo.
A dispersion relation for defect CFT.
Journal of high energy physics, 02(2):255, and PUBDB-2023-07858, arXiv:2205.09765. HU-EP-22/18-RTG.
doi: 10.1007/JHEP02(2023)255.

J. Barrat, P. Liendo and G. Peveri.
Multipoint correlators on the supersymmetric Wilson line defect CFT. Part II. Unprotected operators.
Journal of high energy physics, 08(8):198, and PUBDB-2023-07642, arXiv:2210.14916.
doi: 10.1007/JHEP08(2023)198.

B. Basso et al.
All-Orders Quadratic-Logarithmic Behavior for Amplitudes.
Physical review letters, 130(11):111602, and PUBDB-2022-07820.
doi: 10.1103/PhysRevLett.130.111602.

F. Baume, J. J. Heckman and C. Lawrie.
Super-spin chains for 6D SCFTs.
Nuclear physics, 992:116250, and PUBDB-2023-04866, arXiv:2208.02272. DESY-22-132.
doi: 10.1016/j.nuclphysb.2023.116250.

B. Bécsy et al.
How to Detect an Astrophysical Nanohertz Gravitational Wave Background.
The astrophysical journal / Part 1, 959(1):9, and PUBDB-2024-00416, arXiv:2309.04443.
doi: 10.3847/1538-4357/ad09e4.

A. Behring, J. Blümlein and K. Schönwald.
The inverse Mellin transform via analytic continuation.
Journal of high energy physics, 2023(6):062, and PUBDB-2023-00950, DESY-20-053. arXiv:2303.05943. DO-TH 23/01. CERN-TH-2023-020. ZU-TH 13/23.
doi: 10.1007/JHEP06(2023)062.

B. Bellazzini, G. Isabella and M. M. Riva.
Classical vs quantum eikonal scattering and its causal structure.
Journal of high energy physics, 04(4):023, and PUBDB-2023-03394, arXiv:2211.00085. DESY-23-011.
doi: 10.1007/JHEP04(2023)023.

J. M. Berryman et al.
Neutrino Self-Interactions: A White Paper.
Physics of the Dark Universe, 42:101267, and PUBDB-2023-00730, DESY-22-035. arXiv:2203.01955. CERN-TH-2022-024. FERMILAB-PUB-22-099-T.
doi: 10.1016/j.dark.2023.101267.

T. Biekötter, S. Heinemeyer and G. Weiglein.
Excesses in the low-mass Higgs-boson search and the W-boson mass measurement.
The European physical journal / C, 83(5):450, and PUBDB-2023-04865, arXiv:2204.05975. DESY-22-067. IFT-UAM/CSIC-22-043.
doi: 10.1140/epjc/s10052-023-11635-3.

T. Biekötter, S. Heinemeyer and G. Weiglein.
The CMS di-photon excess at 95 GeV in view of the LHC Run 2 results.
Physics letters / B, 846:138217, and PUBDB-2023-06434, arXiv:2303.12018. KA-TP-03-2023. DESY-23-033. IFT-UAM/CSIC-23-028.
doi: 10.1016/j.physletb.2023.138217.

T. Biekötter et al.
The trap in the early Universe: impact on the interplay between gravitational waves and LHC physics in the 2HDM.
Journal of cosmology and astroparticle physics, 03(03):031, and PUBDB-2023-01874, arXiv:2208.14466. DESY-22-127. IFT-UAM/CSIC-22-015.
doi: 10.1088/1475-7516/2023/03/031.

I. Bierenbaum et al.
$O(\alpha_s^2)$ Polarized Heavy Flavor Corrections to Deep-Inelastic Scattering at $Q^2 \gg m^2$.
Nuclear physics / B, 988:116114, and PUBDB-2023-00946, DESY-15-004. DO-TH 15/01. TTP 22-023. SAGEX-20-11. arXiv:2211.15337. ZU-TH 57/22.
doi: 10.1016/j.nuclphysb.2023.116114.

F. Bishara and M. Montull.
Machine learning amplitudes for faster event generation.
Physical review / D, 107(7):L071901, and PUBDB-2023-07947, arXiv:1912.11055. DESY-19-232.
doi: 10.1103/PhysRevD.107.L071901.

F. Bishara et al.
Revisiting $Vh(\to b\bar{b})$ at the LHC and FCC-hh.
Journal of high energy physics, 06(6):077, and PUBDB-2023-07860, arXiv:2208.11134. DESY-22-136. HU-EP-22/27.
doi: 10.1007/JHEP06(2023)077.

S. Blasi et al.
Gravitational waves from defect-driven phase transitions: domain walls.
Journal of cosmology and astroparticle physics, 2023(10):051, and PUBDB-2023-06207.
doi: 10.1088/1475-7516/2023/10/051.

J. Blümlein, N. Fadeev and C. Schneider.
Computing Mellin Representations and Asymptotics of Nested Binomial Sums in a Symbolic Way: The RICA Package.
ACM communications in computer algebra, 57(2):31, and PUBDB-2023-06888, arXiv:2308.06042. RISC Report Series 23-11.
doi: 10.1145/3614408.3614410.

J. Blümlein, M. Saragnese and C. Schneider.
Hypergeometric Structures in Feynman Integrals.
Annals of mathematics and artificial intelligence, 91(5):591, and PUBDB-2023-07057, arXiv:2111.15501. DESY-21-071. DO-TH 21/16. RISC Report Series 21-17. SAGEX-21-10-E.
doi: 10.1007/s10472-023-09831-8.

Q. Bonnefoy, C. Grojean and J. Kley.
Shift-Invariant Orders of an Axionlike Particle.
Physical review letters, 130(11):111803, and PUBDB-2023-01408, arXiv:2206.04182. DESY-22-096. HU-EP-22/22.
doi: 10.1103/PhysRevLett.130.111803.

Q. Bonnefoy et al.
Opportunistic CP violation.
Journal of high energy physics, 06(6):141, and PUBDB-2023-06432, arXiv:2302.07288. DESY-23-018. HU-EP-22/39. TUM-HEP-1453/23.
doi: 10.1007/JHEP06(2023)141.

M. Borinsky, H. J. Munch and F. Tellander.
Tropical Feynman integration in the Minkowski regime.
Computer physics communications, 292:108874, and PUBDB-2023-06430, arXiv:2302.08955. DESY-23-026.
doi: 10.1016/j.cpc.2023.108874.

C. Borschensky et al.
The trilinear Higgs self-couplings at $\mathcal{O}(\alpha_t^2)$ in the CP-violating NMSSM.
The European physical journal / C, 83(2):118, and PUBDB-2023-01101, arXiv:2210.02104. DESY-22-141.
doi: 10.1140/epjc/s10052-023-11215-5.

T. Bringmann et al.
Does NANOGrav observe a dark sector phase transition?
Journal of cosmology and astroparticle physics, 11(11):053, and PUBDB-2024-00147, arXiv:2306.09411. DESY-23-077.
doi: 10.1088/1475-7516/2023/11/053.

T. Bringmann et al.
Minimal sterile neutrino dark matter.
Physical review / D, 107(7):L071702, and PUBDB-2023-03385, arXiv:2206.10630. CERN-TH-2022-099. DESY-22-102. ULB-TH/22-09.
doi: 10.1103/PhysRevD.107.L071702.

S. Bruggisser et al.
Dilaton at the LHC: complementary probe of composite Higgs.
Journal of high energy physics, 05:080, and PUBDB-2023-03389, arXiv:2212.00056. DESY-22-190.
doi: 10.1007/JHEP05(2023)080.

S. Bruggisser et al.
Status of electroweak baryogenesis in minimal composite Higgs.
Journal of high energy physics, 08(8):012, and PUBDB-2023-04883, arXiv:2212.11953. DESY-22-209.
doi: 10.1007/JHEP08(2023)012.

M. Bruno et al.
Exploiting stochastic locality in lattice QCD: hadronic observables and their uncertainties.
Journal of high energy physics, 11:167, and PUBDB-2023-05127, DESY-23-105. arXiv:2307.15674.
doi: 10.1007/JHEP11(2023)167.

W. Buchmuller, V. Domcke and K. Schmitz.
Metastable cosmic strings.
Journal of cosmology and astroparticle physics, 11(11):020, and PUBDB-2023-05315, CERN-TH-2023-118. DESY-23-117.
doi: 10.1088/1475-7516/2023/11/020.

I. Buric and V. Schomerus.
Universal spinning Casimir equations and their solutions.
Journal of high energy physics, 03:133, and PUBDB-2023-03392, arXiv:2211.14340.
doi: 10.1007/JHEP03(2023)133.

A. Butter et al.
Machine learning and LHC event generation.
SciPost physics, 14(4):079, and PUBDB-2023-07799.
doi: 10.21468/SciPostPhys.14.4.079.

F. Caceffo and G. Clemente.
Spectral analysis of causal dynamical triangulations via finite element method.
Physical review / D, 107(7):074501, and PUBDB-2023-06885, arXiv:2010.07179.
doi: 10.1103/PhysRevD.107.074501.

D. Carney et al.
Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter.
SciPost Physics Core, 6(4):075, and PUBDB-2024-00167, arXiv:2203.06508. FERMILAB-PUB-22-160-T.
doi: 10.21468/SciPostPhysCore.6.4.075.

A. Chatrchyan and G. Servant.
Relaxion dark matter from stochastic misalignment.
Journal of cosmology and astroparticle physics, 06(06):036, and PUBDB-2023-04871, arXiv:2211.15694. DESY-22-177.
doi: 10.1088/1475-7516/2023/06/036.

A. Chatrchyan and G. Servant.
The stochastic relaxion.
Journal of high energy physics, 06(6):107, and PUBDB-2023-04870, arXiv:2210.01148. DESY-22-149.
doi: 10.1007/JHEP06(2023)107.

A. Chatrchyan et al.
ALP dark matter with non-periodic potentials: parametric resonance, halo formation and gravitational signatures.
Journal of cosmology and astroparticle physics, 10(10):068, and PUBDB-2024-00453, arXiv:2305.03756. DESY-23-060.
doi: 10.1088/1475-7516/2023/10/068.

P.-T. Chen, G.-J. Ding and C. Y. Yao.
Systematic study of one-loop realizations of $d = 7$ long-range $0\nu\beta\beta$ decay operators.
Journal of high energy physics, 03(3):138, and PUBDB-2023-01992, arXiv:2301.02503. DESY-22-211.
doi: 10.1007/JHEP03(2023)138.

G. Choi and J. Leedom.
Implications of protecting the QCD axion in the dual description.
Journal of high energy physics, 09(9):175, and PUBDB-2023-07667, arXiv:2307.08733. CERN-TH-2023-117. DESY-23-095.
doi: 10.1007/JHEP09(2023)175.

K. Choi et al.
Axion dark matter with thermal friction.
Journal of high energy physics, 02(2):180, and PUBDB-2023-07507, arXiv:2206.01462. CTPU-PTC-22-12.
doi: 10.1007/JHEP02(2023)180.

M. Cicoli et al.
On the choice of entropy variables in multifield inflation.
Classical and quantum gravity, 40(2):025008, and PUBDB-2023-07949, arXiv:2107.03391. DESY-21-106.
doi: 10.1088/1361-6382/acabf7.

M. Ciuchini et al.
Charming penguins and lepton universality violation in $b \to s\ell^+\ell^-$ decays.
The European physical journal / C, 83(1):64, and PUBDB-2023-07856, arXiv:2110.10126. DESY 21-168. HU-EP-21/42. TTP21-040. P3H-21-077. YITP-SB-2021-20.
doi: 10.1140/epjc/s10052-023-11191-w.

T. Cridge and L. Matthew.
Constraining the top-quark mass within the global MSHT PDF fit.
The European physical journal / C, 83(9):805, and PUBDB-2023-04071, DESY-23-087. arXiv:2306.14885.
doi: 10.1140/epjc/s10052-023-11961-6.

A. Crippa et al.
Quantum Algorithms for Charged Particle Track Reconstruction in the LUXE Experiment.
Computing and software for big science, 7(1):14, and PUBDB-2023-07901, arXiv:2304.01690. DESY-23-045. MIT-CTP/5481.
doi: 10.1007/s41781-023-00109-6.

T. N. Dao, M. Gabelmann and M. Mühlleitner.
The $\mathcal{O}(\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$ correction to the ρ parameter and its effect on the W boson mass calculation in the complex NMSSM.
The European physical journal / C, 83(11):1079, and PUBDB-2024-00154, arXiv:2308.04059. KA-TP-17-2023. DESY-23-112.
doi: 10.1140/epjc/s10052-023-12236-w.

L. Darmé et al.
UFO 2.0: the 'Universal Feynman Output' format.
The European physical journal / C, 83(7):631, and PUBDB-2023-06573, arXiv:2304.09883. BONN-TH-2023-03. DESY-23-051. FERMILAB-PUB-23-138-T. KA-TP-06-2023. MCNET-23-06. P3H-23-023. TIF-UNIMI-2023-11.
doi: 10.1140/epjc/s10052-023-11780-9.

K. De Bruyn et al.
New physics in $B_q{}^0$– mixing: present challenges, prospects, and implications for.
Journal of physics / G, 50(4):045003, and PUBDB-2023-07948, arXiv:2208.14910. Nikhef-2022-012.
doi: 10.1088/1361-6471/acab1d.

B. Dehnadi et al.
Top quark mass calibration for Monte Carlo event generators — an update.
Journal of high energy physics, 12(12):065, and PUBDB-2023-05424, arXiv:2309.00547. UWThPh-2023-16. DESY-23-127.
doi: 10.1007/JHEP12(2023)065.

M. Diehl, F. Fabry and V. Alexey.
Two-loop evolution kernels for colour dependent double parton distributions.
Journal of high energy physics, 05:067, and PUBDB-2023-00617, DESY-22-206. arXiv:2212.11843.
doi: 10.1007/JHEP05(2023)067.

M. Diehl, R. Nagar and P. J. Ploessl.
Quark mass effects in double parton distributions.
Journal of high energy physics, 09(9):100, and PUBDB-2023-00112, DESY-22-197. arXiv:2212.07736.
doi: 10.1007/JHEP09(2023)100.

M. Diehl et al.
Evolution and interpolation of double parton distributions using Chebyshev grids.
The European physical journal / C, 83:536, and PUBDB-2023-03019, arXiv:2305.04845. DESY-23-062.
doi: 10.1140/epjc/s10052-023-11692-8.

G.-J. Ding, X.-G. Liu and C. Y. Yao.
A minimal modular invariant neutrino model.
Journal of high energy physics, 01(1):125, and PUBDB-2023-01106, arXiv:2211.04546. UCI-TR-2022-24. DESY-22-171.
doi: 10.1007/JHEP01(2023)125.

J. Distler et al.
Isomorphisms of 4d $\mathcal{N} = 2$ SCFTs from 6d.
Physical review / D, 107(10):106005, and PUBDB-2023-03177, DESY-22-201. arXiv:2212.11983. CALT-TH-2022-044. UTWI 17-2022.
doi: 10.1103/PhysRevD.107.106005.

C. Dlapa et al.
Symbol alphabets from the Landau singular locus.
Journal of high energy physics, 10(10):161, and PUBDB-2023-06571, arXiv:2304.02629. DESY-23-048.
doi: 10.1007/JHEP10(2023)161.

H. K. Dreiner et al.
Lepton PDFs and multipurpose single-lepton searches at the LHC.
Physical review / D, 107(3):035011, and PUBDB-2023-01097, arXiv:2112.12755. BONN-TH-2021-13. DESY-21-210.
doi: 10.1103/PhysRevD.107.035011.

J. A. Dror et al.
Sensitivity of Spin-Precession Axion Experiments.
Physical review letters, 130(18):181801, and PUBDB-2023-02151, DESY-22-155. arXiv:2210.06481. CERN-TH-2022-163.
doi: 10.1103/PhysRevLett.130.181801.

V. D. Duca et al.
Tree-level soft emission of a quark pair in association with a gluon.
Journal of high energy physics, 01:040, and PUBDB-2023-07632, DESY-22-073. arXiv:2206.01584.
doi: 10.1007/JHEP01(2023)040.

C. Eröncel and G. Servant.
ALP dark matter mini-clusters from kinetic fragmentation.
Journal of cosmology and astroparticle physics, 01(01):009, and PUBDB-2023-00516, arXiv:2207.10111. DESY-22-115.
doi: 10.1088/1475-7516/2023/01/009.

J. R. Espinosa, R. Jinno and T. Konstandin.
Tunneling potential actions from canonical transformations.
Journal of cosmology and astroparticle physics, 02(02):021, and PUBDB-2023-01102, arXiv:2209.03293. DESY-22-147. IFT-UAM/CSIC-22-99.
doi: 10.1088/1475-7516/2023/02/021.

Extended Twisted Mass Collaboration.
Pion transition form factor from twisted-mass lattice QCD and the hadronic light-by-light π^0-pole contribution to the muon $g-2$.
Physical review / D, 108(9):094514, and PUBDB-2024-00185, arXiv:2308.12458.
doi: 10.1103/PhysRevD.108.094514.

Extended Twisted Mass Collaboration.
Probing the Energy-Smeared R Ratio Using Lattice QCD.
Physical review letters, 130(24):241901, and PUBDB-2023-03985, arXiv:2212.08467.
doi: 10.1103/PhysRevLett.130.241901.

FASER Collaboration.
First Direct Observation of Collider Neutrinos with FASER at the LHC.
Physical review letters, 131(3):031801, and PUBDB-2023-07627, arXiv:2303.14185. CERN-EP-2023-056.
doi: 10.1103/PhysRevLett.131.031801.

B. Filoche et al.
Anomalies from an effective field theory perspective.
Physical review / D, 107(2):025017, and PUBDB-2023-07658, arXiv:2205.02248.
doi: 10.1103/PhysRevD.107.025017.

J. Frerick, F. Kahlhoefer and K. Schmidt-Hoberg.
A' view of the sunrise: boosting helioscopes with angular information.
Journal of cosmology and astroparticle physics, 03(3):001, and PUBDB-2023-01211, arXiv:2211.00022. DESY-22-165. TTP22-065.
doi: 10.1088/1475-7516/2023/03/001.

L. Funcke, K. Jansen and S. Kühn.
Exploring the CP-violating Dashen phase in the Schwinger model with tensor networks.
Physical review / D, 108(1):014504, and PUBDB-2023-04591, arXiv:2303.03799. MIT-CTP/5485.
doi: 10.1103/PhysRevD.108.014504.

X. Gan and D. Liu.
Cosmologically varying kinetic mixing.
Journal of high energy physics, 11(11):031, and PUBDB-2023-07093, arXiv:2302.03056. DESY-23-013. LAPTH-003/23.
doi: 10.1007/JHEP11(2023)031.

M. A. G. Garcia and M. Pierre.
Reheating after inflaton fragmentation.
Journal of cosmology and astroparticle physics, 11(11):004, and PUBDB-2023-07100, arXiv:2306.08038. DESY-23-075.
doi: 10.1088/1475-7516/2023/11/004.

M. A. G. Garcia, M. Pierre and S. Verner.
Isocurvature constraints on scalar dark matter production from the inflaton.
Physical review / D, 107(12):123508, and PUBDB-2023-06433, arXiv:2303.07359. DESY-23-027.
doi: 10.1103/PhysRevD.107.123508.

M. A. G. Garcia, M. Pierre and S. Verner.
New window into gravitationally produced scalar dark matter.
Physical review / D, 108(11):115024, and PUBDB-2024-00145, arXiv:2305.14446. DESY-23-065.
doi: 10.1103/PhysRevD.108.115024.

M. A. G. Garcia, M. Pierre and S. Verner.
Scalar dark matter production from preheating and structure formation constraints.
Physical review / D, 107(4):043530, and PUBDB-2023-00904, arXiv:2206.08940. DESY-22-104.
doi: 10.1103/PhysRevD.107.043530.

M. A. G. Garcia et al.
Effects of fragmentation on post-inflationary reheating.
Journal of cosmology and astroparticle physics, 12(12):028, and PUBDB-2024-00106, arXiv:2308.16231. DESY-23-122. UMN-TH-4223/23. FTPI-MINN-23/15.
doi: 10.1088/1475-7516/2023/12/028.

C. Grojean, J. Kley and C.-Y. Yao.
Hilbert series for ALP EFTs.
Journal of high energy physics, 11(11):196, and PUBDB-2024-00151, arXiv:2307.08563. DESY-23-098. HU-EP-23/39.
doi: 10.1007/JHEP11(2023)196.

V. Guidetti et al.
Axionic Festina Lente.
Journal of high energy physics, 01(1):114, and PUBDB-2023-00505, arXiv:2206.03494. DESY-22-098.
doi: 10.1007/JHEP01(2023)114.

E. Hall et al.
Asymmetric matter from a dark first-order phase transition.
Physical review / D, 107(5):055011, and PUBDB-2023-03251, arXiv:1911.12342. IPMU19-0171. DESY-19-209.
doi: 10.1103/PhysRevD.107.055011.

H. S. Hannesdottir et al.
Prospects for strong coupling measurement at hadron colliders using soft-drop jet mass.
Journal of high energy physics, 04(4):087, and PUBDB-2023-03386, DESY-22-156. arXiv:2210.04901. MIT-CTP-5461. UWThPh 2022-15.
doi: 10.1007/JHEP04(2023)087.

B. von Harling, O. Matsedonskyi and G. Servant.
High-temperature electroweak baryogenesis with composite Higgs.
Journal of high energy physics, 12(12):138, and PUBDB-2024-00152, arXiv:2307.14426. DESY-23-103.
doi: 10.1007/JHEP12(2023)138.

N. A. Husung.
Erratum to: Logarithmic corrections to O(a) and O(a^2) effects in lattice QCD with Wilson or Ginsparg–Wilson quarks.
The European physical journal / C, 83(4):276, and PUBDB-2023-07319, arXiv:2206.03536.
doi: 10.1140/epjc/s10052-023-11392-3.

N. A. Husung.
Logarithmic corrections to O(a) and O(a^2) effects in lattice QCD with Wilson or Ginsparg–Wilson quarks.
The European physical journal / C, 83(2):142, and PUBDB-2023-00863, arXiv:2206.03536.
doi: 10.1140/epjc/s10052-023-11258-8.

T. Jakobs et al.
Canonical momenta in digitized Su(2) lattice gauge theory: definition and free theory.
The European physical journal / C, 83(7):669, and PUBDB-2023-04846, arXiv:2304.02322.
doi: 10.1140/epjc/s10052-023-11829-9.

X. Jing et al.
Quantifying the interplay of experimental constraints in analyses of parton distributions.
Physical review / D, 108(3):034029, and PUBDB-2023-07097, arXiv:2306.03918. ANL-182798. DESY-23-068. FERMILAB-PUB-23-276-T. MSUHEP-23-016. PITT-PACC-2315. SMU-HEP-23-02.
doi: 10.1103/PhysRevD.108.034029.

R. Jinno et al.
Higgsless simulations of cosmological phase transitions and gravitational waves.
Journal of cosmology and astroparticle physics, 02(02):011, and PUBDB-2023-01103, arXiv:2209.04369. DESY 22-148. IFT-UAM/CSIC-22-100. TUM-HEP-1416/22.
doi: 10.1088/1475-7516/2023/02/011.

M. J. Kang et al.
Emergent $\mathcal{N} = 4$ supersymmetry from $\mathcal{N} = 1$.
Physical review letters, 130(23):231601, and PUBDB-2023-03712, DESY-23-021. arXiv:2302.06622. CALT-TH-2023-005.
doi: 10.1103/PhysRevLett.130.231601.

A. Kaviraj et al.
Multipoint lightcone bootstrap from differential equations.
Journal of high energy physics, 08(8):011, and PUBDB-2023-04884, arXiv:2212.10578. ZMP-HH/22-21.
doi: 10.1007/JHEP08(2023)011.

H. Kim.
Gravitational interaction of ultralight dark matter with interferometers.
Journal of cosmology and astroparticle physics, 12(12):018, and PUBDB-2024-00149, arXiv:2306.13348. DESY-23-085.
doi: 10.1088/1475-7516/2023/12/018.

H. Kim et al.
Adiabatically compressed wave dark matter halo and intermediate-mass-ratio inspirals.
Physical review / D, 107(8):083005, and PUBDB-2023-01877, arXiv:2212.07528. DESY-22-200.
doi: 10.1103/PhysRevD.107.083005.

F. Kling, T. Mäkelä and S. Trojanowski.
Investigating the fluxes and physics potential of LHC neutrino experiments.
Physical review / D, 108(9):095020, and PUBDB-2024-00481, arXiv:2309.10417. DESY-23-131.
doi: 10.1103/PhysRevD.108.095020.

F. Kling et al.
FLArE up dark sectors with EM form factors at the LHC forward physics facility.
Nuclear physics, 987:116103, and PUBDB-2023-00820, arXiv:2205.09137. DESY-22-084. UCI-HEP-TR-2022-06. FERMILAB-PUB-22-975-V.
doi: 10.1016/j.nuclphysb.2023.116103.

F. Kling et al.
Light Scalars at FASER.
Journal of high energy physics, 08(8):001, and PUBDB-2023-07953, arXiv:2212.06186.
doi: 10.1007/JHEP08(2023)001.

S. Kuehn et al.
Quantum spin helices more stable than the ground state: Onset of helical protection.
Physical review / B, 107(21):214422, and PUBDB-2023-07083, arXiv:2302.02603. MIT-CTP/5478.
doi: 10.1103/PhysRevB.107.214422.

R. von Kuk, J. K. L. Michel and Z. Sun.
Transverse momentum distributions of heavy hadrons and polarized heavy quarks.
Journal of high energy physics, 09(9):205, and PUBDB-2023-06696, arXiv:2305.15461. MIT-CTP 5537. DESY-23-032.
doi: 10.1007/JHEP09(2023)205.

C. Lawrie et al.
Operator spectroscopy for 4d SCFTs with a=c.
Physical review / D, 107(6):066018, and PUBDB-2023-03176, arXiv:2210.06497. CALT-TH-2022-035. DESY-22-152.
doi: 10.1103/PhysRevD.107.066018.

J. M. Leedom, N. Righi and A. Westphal.
Heterotic de Sitter beyond modular symmetry.
Journal of high energy physics, 02(2):209, and PUBDB-2023-01107, arXiv:2212.03876. DESY 22-173. KCL-PH-TH/2022-54.
doi: 10.1007/JHEP02(2023)209.

A. Leite Antunes and C. Behan.
Coupled Minimal Conformal Field Theory Models Revisited.
Physical review letters, 130(7):071602, and PUBDB-2022-07212, DESY-22-191. arXiv:2211.16503.
doi: 10.1103/PhysRevLett.130.071602.

A. Leite Antunes, M. Costa and J. Pereira.
Exploring Inelasticity in the S-Matrix Bootstrap.
Physics letters / B, 846:138225, and PUBDB-2023-00674, DESY-23-015. arXiv:2301.13219.
doi: 10.1016/j.physletb.2023.138225.

M. Lencsés et al.
$\mathcal{PT}$ breaking and RG flows between multicritical Yang-Lee fixed points.
Journal of high energy physics, 09(9):052, and PUBDB-2023-07094, arXiv:2304.08522. DESY-23-035.
doi: 10.1007/JHEP09(2023)052.

M. Lencsés et al.
Multicriticality in Yang-Lee edge singularity.
Journal of high energy physics, 02(2):46, and PUBDB-2023-01105, DESY-22-162. arXiv:2211.01123.
doi: 10.1007/JHEP02(2023)046.

T. Li, C. Y. Yao and M. Yuan.
Searching for heavy neutral lepton and lepton number violation through VBS at high-energy muon colliders.
Journal of high energy physics, 09(9):131, and PUBDB-2023-07745, arXiv:2306.17368. DESY-23-092.
doi: 10.1007/JHEP09(2023)131.

T. Li, C.-Y. Yao and M. Yuan.
Revealing the origin of neutrino masses through the Type II Seesaw mechanism at high-energy muon colliders.
Journal of high energy physics, 03(3):137, and PUBDB-2023-01696, arXiv:2301.07274. DESY-23-006.
doi: 10.1007/JHEP03(2023)137.

P. Liendo, J. Rong and H. Zhang.
Spontaneous breaking of finite group symmetries at all temperatures.
SciPost physics, 14(6):168, and PUBDB-2023-07628.
doi: 10.21468/SciPostPhys.14.6.168.

LISA Cosmology Working Group Collaboration.
Cosmology with the Laser Interferometer Space Antenna.
Living reviews in relativity, 26(1):5, and PUBDB-2024-00355, arXiv:2204.05434. LISA CosWG-22-03. FERMILAB-PUB-22-349-SCD.
doi: 10.1007/s41114-023-00045-2.

S. Ma et al.
The application of encoder–decoder neural networks in high accuracy and efficiency slit-scan emittance measurements.
Nuclear instruments & methods in physics research / Section A, 1050:168125, and PUBDB-2023-07657, arXiv:2207.09144.
doi: 10.1016/j.nima.2023.168125.

C. S. Machado, S. Renner and D. Sutherland.
Building blocks of the flavourful SMEFT RG.
Journal of high energy physics, 03(3):226, and PUBDB-2023-01876, arXiv:2210.09316. DESY-22-161.
doi: 10.1007/JHEP03(2023)226.

A. J. Macleod et al.
Strong-field vacuum polarisation with high energy lasers.
New journal of physics, 25(9):093002, and PUBDB-2023-07782, arXiv:2304.02114.
doi: 10.1088/1367-2630/acf1c0.

E. Marchetto, A. Miscioscia and E. Pomoni.
Broken (super) conformal Ward identities at finite temperature.
Journal of high energy physics, 12(12):186, and PUBDB-2024-00148, arXiv:2306.12417. DESY-23-083.
doi: 10.1007/JHEP12(2023)186.

V. Martin Lozano, R. M. Sanda Seoane and J. Zurita.
Z'-explorer 2.0: reconnoitering the dark matter landscape.
Computer physics communications, 288:108729, and PUBDB-2023-07482, DESY-21-146. arXiv:2109.13194. ICAS 066/21. IFIC/21-33.
doi: 10.1016/j.cpc.2023.108729.

Mass, Extended Twisted.
$\eta \to \gamma^*\gamma^*$ transition form factor and the hadronic light-by-light η-pole contribution to the muon $g-2$ from lattice QCD.
Physical review / D, 108(5):054509, and PUBDB-2023-06038.
doi: 10.1103/PhysRevD.108.054509.

Mass, Extended Twisted.
Lattice calculation of the short and intermediate time-distance hadronic vacuum polarization contributions to the muon magnetic moment using twisted-mass fermions.
Physical review / D, 107(7):074506, and PUBDB-2023-03145, arXiv:2206.15084.
doi: 10.1103/PhysRevD.107.074506.

K. Mękała, J. Reuter and A. F. Żarnecki.
Optimal search reach for heavy neutral leptons at a muon collider.
Physics letters / B, 841:137945, and PUBDB-2023-03393, arXiv:2301.02602. DESY-23-002.
doi: 10.1016/j.physletb.2023.137945.

A. Mitridate et al.
Energetic long-lived particles in the CMS muon chambers.
Physical review / D, 108(5):055040, and PUBDB-2023-07095, arXiv:2304.06109. CALT-TH-2023-001. DESY-23-054. FERMILAB-PUB-23-204-PPD.
doi: 10.1103/PhysRevD.108.055040.

A. Mitridate et al.
Snowmass white paper: Light dark matter direct detection at the interface with condensed matter physics.
Physics of the Dark Universe, 40:101221, and PUBDB-2023-07629, arXiv:2203.07492. FERMILAB-PUB-23-551-T.
doi: 10.1016/j.dark.2023.101221.

Z. Nagy and D. E. Soper.
Gauge choice for organizing infrared singularities in QCD.
Physical review / D, 108(7):074008, and PUBDB-2023-06204, DESY-23-052. arXiv:2304.11736.
doi: 10.1103/PhysRevD.108.074008.

Y. Nakamura and G. Schierholz.
The strong CP problem solved by itself due to long-distance vacuum effects.
Nuclear physics, 986:116063, and PUBDB-2023-07497, arXiv:2106.11369. DESY-21-078.
doi: 10.1016/j.nuclphysb.2022.116063.

K. Nakayama and K. Suzuki.
Dirac/Weyl-node-induced oscillating Casimir effect.
Physics letters / B, 843:138017, and PUBDB-2023-07325, arXiv:2207.14078.
doi: 10.1016/j.physletb.2023.138017.

K. Nakayama and K. Suzuki.
Remnants of the nonrelativistic Casimir effect on the lattice.
Physical review research, 5(2):L022054, and PUBDB-2023-03987, arXiv:2204.12032.
doi: 10.1103/PhysRevResearch.5.L022054.

NANOGrav Collaboration.
The NANOGrav 15 yr Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries.
The astrophysical journal / Part 2, 951(2):L50, and PUBDB-2023-07502.
doi: 10.3847/2041-8213/ace18a.

NANOGrav Collaboration.
The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background.
The astrophysical journal / Part 2, 952(2):L37, and PUBDB-2023-07501.
doi: 10.3847/2041-8213/ace18b.

NANOGrav Collaboration.
The NANOGrav 15 yr Data Set: Detector Characterization and Noise Budget.
The astrophysical journal / Part 2, 951(1):L10, and PUBDB-2023-07491.
doi: 10.3847/2041-8213/acda88.

NANOGrav Collaboration.
The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background.
The astrophysical journal / Part 2, 951(1):L8, and PUBDB-2023-07622, arXiv:2306.16213.
doi: 10.3847/2041-8213/acdac6.

NANOGrav Collaboration.
The NANOGrav 15 yr Data Set: Observations and Timing of 68 Millisecond Pulsars.
The astrophysical journal / Part 2, 951(1):L9, and PUBDB-2023-07636, arXiv:2306.16217.
doi: 10.3847/2041-8213/acda9a.

NANOGrav Collaboration.
The NANOGrav 15-year Data Set: Search for Signals from New Physics.
The astrophysical journal / 2, 951(1):L11, and PUBDB-2023-04004, arXiv:2306.16219.
doi: 10.3847/2041-8213/acdc91.

D. Neill, A. Pathak and I. Stewart.
Small-x Factorization from Effective Field Theory.
Journal of high energy physics, 09(9):089, and PUBDB-2023-03465, DESY-23-024. arXiv:2303.13710. MIT-CTP/5529. UWThPh 2023-3.
doi: 10.1007/JHEP09(2023)089.

A. Papageorgiou, P. Quilez Lasanta and K. Schmitz.
Axion dark matter from frictional misalignment.
Journal of high energy physics, 01(1):169, and PUBDB-2023-01100, arXiv:2206.01129. CTPU-PTC-22-11. DESY-22-094. MS-TP-22-17. CERN-TH-2022-091.
doi: 10.1007/JHEP01(2023)169.

A. Pathak.
The Catchment Area of Groomed Jets at NNLL.
Journal of high energy physics, 08(8):054, and PUBDB-2023-03464, DESY-23-003. arXiv:2301.05714.
doi: 10.1007/JHEP08(2023)054.

D. Perez Adan et al.
A new LHC search for dark matter produced via heavy Higgs bosons using simplified models.
Journal of high energy physics, 08:151, and PUBDB-2023-00548, EFI-22-10. DESY-23-014. arXiv:2302.04892.
doi: 10.1007/JHEP08(2023)151.

E. Pomoni, W. Yan and X. Zhang.
Probing M-theory with tetrahedron instantons.
Journal of high energy physics, 11(11):177, and PUBDB-2024-00146, arXiv:2306.06005. DESY-23-073.
doi: 10.1007/JHEP11(2023)177.

QCDSF-UKQCD-CSSM Collaboration.
Feynman-Hellmann approach to transition matrix elements and quasidegenerate energy states.
Physical review / D, 108(3):034507, and PUBDB-2023-05309, arXiv:2305.05491. ADP-23-12/T1221. DESY-23-059. Liverpool LTH 1340.
doi: 10.1103/PhysRevD.108.034507.

QCDSF/UKQCD/CSSM Collaboration.
Constraining beyond the standard model nucleon isovector charges.
Physical review / D, 108(9):094511, and PUBDB-2024-00144, arXiv:2304.02866. ADP-23-10/T1219. DESY-23-047. LTH 1336. MIT-CTP/5581.
doi: 10.1103/PhysRevD.108.094511.

QCDSF/UKQCD/CSSM Collaboration and CSSM Collaboration and UKQCD Collaboration and QCDSF Collaboration.
Moments and power corrections of longitudinal and transverse proton structure functions from lattice QCD.
Physical review / D, 107(5):054503, and PUBDB-2023-01875, arXiv:2209.04141. ADP-22-27/T1198. DESY-22-145. LTH 1307.
doi: 10.1103/PhysRevD.107.054503.

RCstar Collaboration.
First results on QCD+QED with C^* boundary conditions.
Journal of high energy physics, 03(3):012, and PUBDB-2023-01337, arXiv:2209.13183. HU-EP-22/29-RTG.
doi: 10.1007/JHEP03(2023)012.

M. M. Riva, F. Vernizzi and L. K. Wong.
Angular momentum balance in gravitational two-body scattering: Flux, memory, and supertranslation invariance.
Physical review / D, 108(10):104052, and PUBDB-2024-00142, arXiv:2302.09065. DESY-23-019.
doi: 10.1103/PhysRevD.108.104052.

G. Servant and P. Simakachorn.
Constraining postinflationary axions with pulsar timing arrays.
Physical review / D, 108(12):123516, and PUBDB-2024-00150, arXiv:2307.03121. DESY-23-094.
doi: 10.1103/PhysRevD.108.123516.

A. V. Sokolov and A. Ringwald.
Generic Axion Maxwell Equations: Path Integral Approach.
Annalen der Physik, 536(1):2300112, and PUBDB-2023-01308, DESY-23-031. arXiv:2303.10170v2.
doi: 10.1002/andp.202300112.

R. Sommer and M. Bruno.
On fits to correlated and auto-correlated data.
Computer physics communications, 285:108643, and PUBDB-2022-04925, DESY-22-154. arXiv:2209.14188.
doi: 10.1016/j.cpc.2022.108643.

P. Stornati et al.
Crystalline phases at finite winding densities in a quantum link ladder.
Physical review / D, 107(3):L031504, and PUBDB-2023-01184, arXiv:2208.01964.
doi: 10.1103/PhysRevD.107.L031504.

S. Syritsyn et al.
Nucleon Electromagnetic Form Factors at Large Momentum Transfer from Lattice QCD.
Few-body systems, 64(3):72, and PUBDB-2023-05306.
doi: 10.1007/s00601-023-01839-4.

S. Tang and B. King.
Locally monochromatic two-step nonlinear trident process in a plane wave.
Physical review / D, 107(9):096004, and PUBDB-2023-07662, arXiv:2211.13299.
doi: 10.1103/PhysRevD.107.096004.

F. Tellander and M. Helmer.
Cohen-Macaulay Property of Feynman Integrals.
Communications in mathematical physics, 399(2):1021, and PUBDB-2023-00321, arXiv:2108.01410.
doi: 10.1007/s00220-022-04569-6.

M. E. Tobar et al.
Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics.
Annalen der Physik, 536(1):2200594, and PUBDB-2023-03388, arXiv:2211.09637. DESY-22-185.
doi: 10.1002/andp.202200594.

M. Tobar et al.
Searching for GUT-scale QCD Axions and Monopoles with a High Voltage Capacitor.
Physical review / D, 108(3):035024, and PUBDB-2023-03900, DESY-23-084. arXiv:2306.13320.
doi: 10.1103/PhysRevD.108.035024.

C. Tueysuez et al.
Classical Splitting of Parametrized Quantum Circuits.
Quantum machine intelligence, 5(2):34, and PUBDB-2023-04070, arXiv:2206.09641.
doi: 10.1007/s42484-023-00118-z.

V. E. Vileta et al.
Discrete Goldstone bosons.
Physical review / D, 107(3):035009, and PUBDB-2023-01099, arXiv:2205.09131. DESY-22-082. IFT-UAM/CSIC-20-144. FTUAM-20-21. IPPP/22/31.
doi: 10.1103/PhysRevD.107.035009.

X. Wang et al.
Critical behavior of the Ising model by preparing the thermal state on a quantum computer.
Physical review / A, 108(2):022612, and PUBDB-2023-06218, arXiv:2302.14279.
doi: 10.1103/PhysRevA.108.022612.

Ph.D. Thesis

P. Englert.
New Physics Probes at Present / Future Hadron Colliders via Vh Production.
Humboldt-Universität zu Berlin, 2023.

F. Fabry.
Double parton scattering: parton correlations and their scale evolution.
Universität Hamburg, Hamburg, 2023.

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Gravitational Signatures of Wave Dark Matter.
University of Hamburg, 2023.

J. A. Mann.
Multipoint Lightcone Bootstrap from Conformal Block Integrability.
University of Hamburg, 2023.

I. Novikov.
Precision theory predictions and interpretation of differential distributions in inclusive decays at Belle II.
University of Hamburg, 2023.

P. J. v. Vliet.
A Modern Study of Extended Objects in Conformal Field Theory.
University of Hamburg, 2023.

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Published

DPHEP Collaboration.
Data preservation in high energy physics.
The European physical journal / C, 83(9):795, and PUBDB-2023-07863, arXiv:2302.03583. DPHEP-2023-01.
doi: 10.1140/epjc/s10052-023-11885-1.

F. Lorkowski.
Measurement and QCD Analysis of Inclusive Jet Production in Deep Inelastic Scattering at HERA.
5. Diffraction and Low-x 2022, Corigliano Calabro (Italy), 24 Sep 2022 - 30 Sep 2022.
Acta physica Polonica / B / Proceedings supplement, vol. 165:A35, and PUBDB-2023-03715.
Inst. of Physics, Jagellonian Univ., Cracow.
doi: 10.5506/APhysPolBSupp.16.5-A35.

ZEUS Collaboration.
Measurement of jet production in deep inelastic scattering and NNLO determination of the strong coupling at ZEUS.
The European physical journal / C, 83(11):1082, and PUBDB-2023-07645, arXiv:2309.02889. DESY-23-129.
doi: 10.1140/epjc/s10052-023-12180-9.

ZEUS Collaboration.
Search for effective Lorentz and CPT violation using ZEUS data.
Physical review / D, 107(9):092008, and PUBDB-2023-03659, arXiv:2212.12750. DESY-22-210.
doi: 10.1103/PhysRevD.107.092008.

Ph.D. Thesis

F. Lorkowski.
Measurement and NNLO QCD analysis of jet production in deep inelastic scattering at ZEUS.
Universität Hamburg, Hamburg, 2023.

Photographs and graphics

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Karl Jansen

Marta Mayer
Géraldine Servant
Georg Wendt

ATLAS
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Imprint

Publishing and contact
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A Research Centre of the Helmholtz Association

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www.desy.de
ISBN 978-3-945931-50-9
DOI 10.3204/PUBDB-2024-01463

Editing
Ilka Flegel, Manfred Fleischer, Thomas Konstandin

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

Production
Cristina Lopez Gonzalez

Printing
EHS Druck GmbH, Schenefeld

Editorial deadline
2 March 2024

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

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

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