HELMHOLTZ

Research for grand challenges.

Progress Report 2023

Program “Matter and the Universe”

Spokesperson of the Program:
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Contents

0 Preamble Program “Matter and the Universe”

As we reach the mid-term point of the fourth program period, this progress report will present highlights and special events in 2023 as well as a brief interim resume of the achievement of the research policy objectives.

The research policy objectives formed the starting point and the framework for the design of the three programs of the Research Field Matter for the Helmholtz Association's fourth program period. Overarching goals in the research field Matter and their implementation are presented in the progress report of the coordinator of the research field.

Chapter 1 of the following program report describes the global research objectives, the embedding in the research field and the program structure. Structural developments and changes in the framework conditions compared to the original research policy objectives and program goals are outlined.

Chapter 2 presents scientific highlights for the year 2023.

Chapter 3 presents the status of implementation of the Senate's recommendations on cross-program activities, followed by an interim resume of the implementation status of the specific research policy objectives at topic level.

Chapter 4 describes overarching activities and the strategic topics (which the Senate of the Helmholtz Association considers to be of paramount importance). Both chapters directly address the research policy objectives on structural goals and joint initiatives of the research field on cross-divisional activities, for example on talent management, networking, transfer to industry and society, acquisition of third-party funding and research infrastructures. With regard to the latter, the specific research policy objectives are also mentioned, an interim resume of the implementation status is provided.

Chapter 5 shows the key performance parameters that quantify progress based on standardized scales.

This is followed by a report on the status of the large-scale research infrastructures associated with the program also with regard to the original research policy objectives.

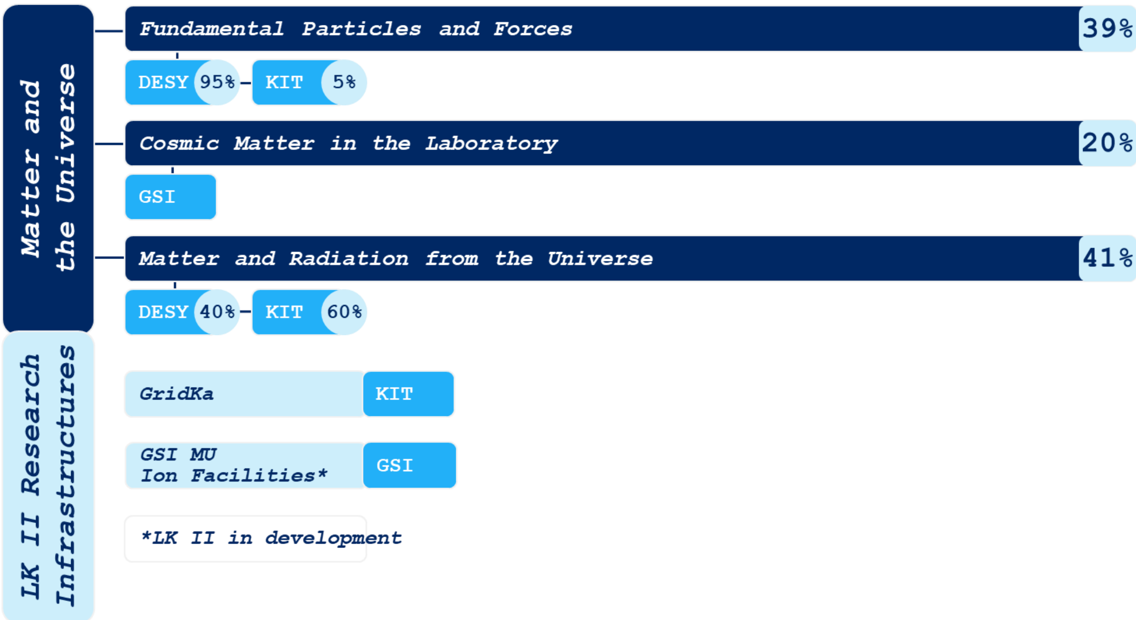
1 Program "Matter and the Universe"

1.1 Goals and Embedding into the Research Field

Goals of the program are the identification and characterization of fundamental particles and their interactions as well as their role for the history and evolution of the universe; an exact understanding of the structure of the vacuum; strengthening the understanding of the structure and dynamics of hadrons, nuclei and nuclear matter and their role in the astrophysical formation of chemical elements; revealing the nature of dark matter and neutrinos; and exploring the universe at high energies.

The MU program is characterized by a particular breadth and depth of expertise in its coherent approach to advancing understanding in elementary particle physics, astroparticle physics, and the physics of hadrons and nuclei. The joint research is carried out by experimental and theoretical methods, by modeling and observations, by technological developments, and by operating of and measurements on large research infrastructures. The research in MU is particularly characterized by international cooperation of different research institutions, which are organized in (partly very large) collaborations. This work is made possible by globally unique research infrastructures at our Helmholtz centers and at other international research centers and facilities.

1.2 Structure



The program Matter and Universe is led by Ralph Engel (spokesperson, KIT) and Beate Heinemann (co-speaker, DESY). It is organized into three major topics and two so-called LK-II infrastructures, which will be presented in chapter "Associated Research Infrastructures (LK II)". The program MU is structured as follows:

Topic 1: Fundamental Particles and their Interactions (FPF)

(Spokesperson: Isabell Melzer-Pellmann (DESY), Co-spokesperson: Kai Schmidt-Hohberg (DESY))

The program Topic 1 investigates the most fundamental building blocks of the world and their interactions and their influence on structure and evolution of the universe, addressing fundamental questions about nature such as the origin of mass, the structure of the vacuum, the imbalance between matter and antimatter in the universe, or the nature of dark matter. The participating research groups are involved in large-scale international multi-purpose projects such as the LHC experiments ATLAS and CMS at CERN or Belle II at SuperKEKB in Japan, and they pursue a rich program of smaller experiments focusing e.g. on dark matter searches at the DESY Hamburg site with international participation. These experimental activities are accompanied and guided by a broad and internationally leading portfolio of theory activities. The Topic is supported by infrastructures close to the experiments, such as the GridKa (Tier 1) at KIT or the Interdisciplinary Analysis Facility (IDAF, used partly as Tier 2 for LHC), the Test Beam Facility or the Detector Assembly Facility (DAF) at DESY, and by the Wolfgang Pauli Centre for Theoretical Physics.

Topic 2: Cosmic Matter in the Laboratory (CML)

(Spokesperson: Frank Maas (HIM), Co-spokesperson: Tetyana Galatyuk (GSI))

Program Topic 2 explores the formation of matter from the elementary building blocks and the various aspects and role of the strong interaction in these processes. Extreme forms of matter are created in the laboratory to recreate the formation of primordial matter and to understand extreme astrophysical objects such as neutron stars. The focus is on understanding the origin of complex phenomena in strong-interaction matter in non-perturbative regime of QCD. The objective is to unravel the properties of hadrons, access and understand the QCD spectrum, explore strong-interaction systems under extreme conditions of temperature, density, and isospin. GSI and FAIR in the future, with its high-intensity, high-energy, stored and cooled ion and antiproton beams, is the central infrastructure for addressing the questions in this Topic. This is supplemented by the participation in the physics analysis and upgrade of the ALICE detector in preparation for the upcoming high-luminosity LHC runs. The study of the strong interaction also aims at physics beyond the Standard Model, and includes the search for dark matter, the exploration of matter-antimatter asymmetry, and further tests of fundamental symmetries. Scientists involved in CML have actively pursued a proof-of-principle experiment to search for an electric dipole moment (EDM) of charged particles by using storage rings and to detect axion-like particles in the ultralight mass range and were engaged in experiments studying neutrino characteristics.

Topic 3: Matter and Radiation from the Universe (MRU)

(Spokesperson: Christian Stegmann (DESY), Co-spokesperson: Kathrin Valerius (KIT))

The program Topic 3 has the largest structures of the universe and the properties of the fundamental building blocks as its research topic. Astroparticle physics in MU is performed at observatories at extreme locations on Earth and at high-precision experiments in laboratories. The participating research groups play a major role in shaping neutrino astronomy at IceCube, the investigation of high-energy gamma rays at CTA, and the study of ultra-high-energy cosmic rays at the Pierre Auger Observatory. The properties of neutrinos are determined with the unique infrastructure KATRIN and the expertise gained is continued for the investigation of dark matter in DARWIN. The research provides insights to draw a new and coherent picture of the high-energy universe, combining the different information channels such as high-energy radiation, neutrinos, cosmic particles, gravitational waves as well as dark matter searches. With the development of new and improved research infrastructures, a research landscape covering the full range of cosmic particle and radiation investigations will be created.

Theoretical studies and developing new technologies for detectors, accelerators, and data processing complement the experimental program of each Topic and form a common basis for thematic advancement across all three program Topics.

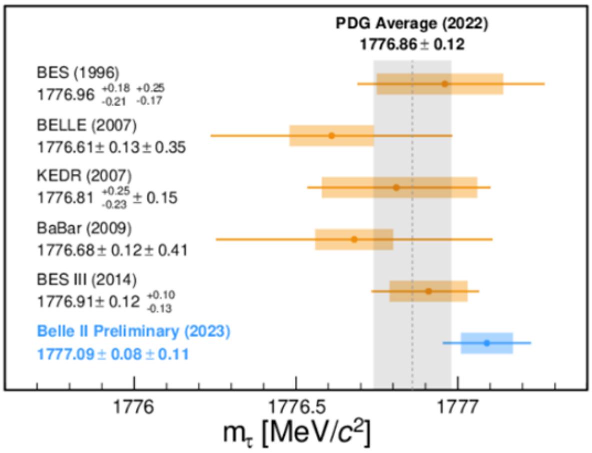
1.3 New structural Developments and Changes of Framework

Russia's invasion of Ukraine has severely changed the international environment and is strongly condemned by the German and international scientific community. Many long-standing and productive collaborations are suspended. The prolonged war also influences economics. In the case of the large international particle physics experiments at CERN, the CERN Council has decided in December 2023 that CERN's cooperation with both countries, Russia and Belarus, will conclude in 2024 upon the expiry of the respective International Cooperation Agreements (ICAs). Cooperation will thus come to an end on 27 June 2024 for the Republic of Belarus, and on 30 November 2024 for the Russian Federation. All relations between CERN and Russian and Belarusian institutions will cease as of these dates. However, relations continue with scientists of Russian or Belarusian nationality otherwise affiliated with CERN.

After the termination of the ICAs, the authorship situation of scientists with Russian and Belarussian affiliations at CERN will have to be rediscussed – they currently appear without their institutional affiliation in scientific publications. Further large infrastructures and experiments (e.g. FAIR, EU, XFEL) are also bound by international treaties and solutions are found case by case.

2 Scientific Highlights

Highlight 1: The Belle II experiment has started to obtain results based on the full luminosity integrated thus far. DESY's physics analysis contribution is – among other things – focusing on the physics of the tau lepton, both in the field of precision measurements of standard model (SM) parameters and in searches for "new" physics not predicted by the SM.



The tau lepton mass measurement of ref. [1] compared to previous measurements and the world average.

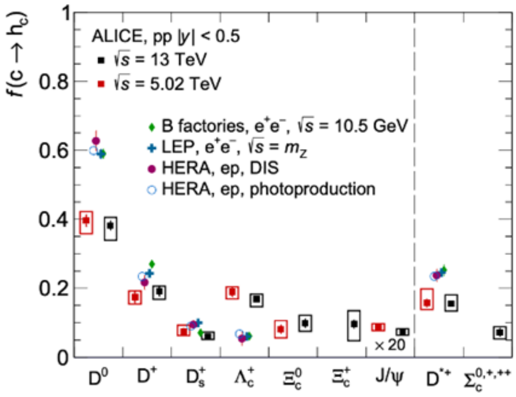
Belle II has published the world's most precise measurement of the tau-lepton mass [1]. The analysis uses the kinematic edge in the decay of tau leptons (originally developed at ARGUS) to three pions and a tau neutrino and arrives at a value of the tau mass of 1777.09 ± 0.08 ± 0.11 MeV/c^2, which is in good agreement with previous determinations. Tau leptons also allow for stringent tests of lepton flavor universality (LFU), a strong prediction of the SM. Belle II recently presented a new result on LFU in tau lepton decays [2], comparing the ratio of electron and muon couplings – which according to the SM should be exactly 1. Belle II could improve the precision of existing results considerably, leading to a world average of the coupling ratio of 1.0005 ± 0.0013 and thus hinting to LFU at least at this level of precision. And, in a preliminary analysis, the LFU-violating decay – suppressed by very many orders of magnitude in the SM – of tau leptons into three muons, $\tau \rightarrow \mu\mu\mu$, has been investigated [3]. The Belle II analysis leads to the world's most stringent limit on the branching fraction this process of 9×10^{-8}.

[1] Belle II Collaboration, Phys. Rev. D 108 (2023) 032006.

[2] P. Feichtinger for the Belle and Belle II Collaborations, preliminary result shown at TAU2023, University of Louisville, USA, 4-8 December 2023, https://indico.cern.ch/event/1303630/contributions/5571690/.

[3] A. Martini for the Belle and Belle II Collaborations, preliminary result shown at TAU2023, University of Louisville, USA, 4-8 December 2023, https://indico.cern.ch/event/1303630/contributions/5571692/.

Highlight 2: Heavy quarks, such as the charm quark, are produced almost exclusively in the initial interactions taking place in electron-positron, electron-proton, proton-proton, or nucleus-nucleus collisions. The subsequent hadronization is a non-perturbative process taking place on long space-time scales and, therefore, originally was considered to be independent of the colliding particles species. Measurements from ALICE question this long-standing paradigm. The large data samples collected during Run-2 of the LHC allowed ALICE to count the vast majority of charm quarks produced in the proton-proton collisions by reconstructing the decays of all charm ground-state meson species and the most abundant baryons [1–4]. Scientists from GSI measured for the first time at the LHC in proton-proton collisions the charm fragmentation fractions, $f(c \rightarrow H_c)$, which represent the probability for a charm quark to hadronize into a given charm hadron [3,4]. Charm quarks were found to form baryons almost 40% of the time, which is four times more often than what was expected from previous measurements at colliders with electron beams.

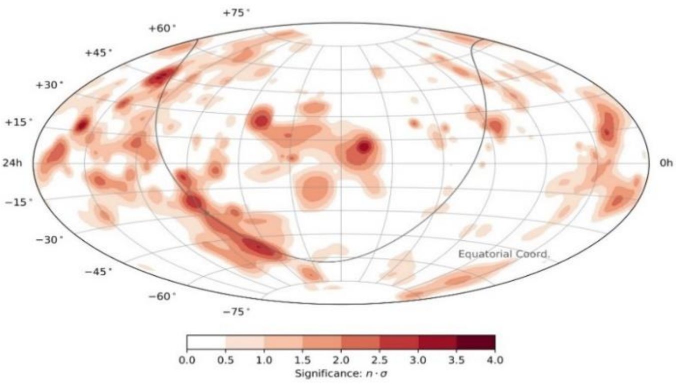


Charm–quark fragmentation fractions into charm hadrons measured in proton-proton collisions at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 13 TeV, in electron-positron collisions, and in electron-proton collisions.

These recent heavy-flavour baryon measurements in hadronic collisions challenge the assumption that heavy-quark hadronisation is a universal process across different colliding systems. These measurements demonstrate that the process of colour-charge confinement and hadron formation is still a poorly understood aspect of the strong interaction. Current theoretical efforts trying to explain the increased baryon production include the combination of quarks from multiple initial scattering processes as well as new mechanisms in the neutralisation of the colour charge.

[1] ALICE Collaboration, Phys.Rev.C 107 (2023) 6, 064901, DOI:10.1103/PhysRevC.107.064901.
[2] ALICE Collaboration, Phys.Lett.B 846 (2023) 137625, DOI:10.1016/j.physletb.2022.137625.
[3] ALICE Collaboration, Phys.Rev.D 105 (2022) 1, L011103, DOI:10.1103/PhysRevD.105.L011103.
[4] ALICE Collaboration, JHEP 12 (2023) 086, DOI: 10.1007/JHEP12(2023)086.

Highlight 3: The IceCube collaboration has provided proof of the existence of high-energy neutrinos from the Milky Way. The view of the Milky Way with its many billions of stars and the central black hole was examined and visualised in many wavelength ranges of electromagnetic radiation. The IceCube Neutrino Observatory has now succeeded for the first time in creating an image of the Milky Way with neutrinos. Neutrinos are traces of the high-energy cosmic radiation that is generated and accelerated in the Milky Way. Due to deflection by interstellar magnetic fields, these cosmic rays arrive on Earth from random directions. However, the cosmic rays interact with matter near their sources and as they propagate, create the high-energy neutrinos. IceCube searched for neutrino emissions using machine learning techniques developed within the German IceCube network and applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models with a background-only hypothesis, we were able to identify neutrino emissions from the Galactic plane at a significance level of 4.5σ [1]. The signal is consistent with the diffuse emission of neutrinos from the Milky Way, but could also originate from a population of unresolved point sources.



Best-fit pre-trial significance as a function of direction in equatorial coordinates for the total sky scan. The galactic plane is represented by a grey curve, the galactic center by a dot.

[1] IceCube Collaboration, Science, 2023, 380, 6652, p.1338; DOI: 10.1126/science.adc9818.

3 Implementation of the program

3.1 Implementation of the Senate recommendations

The Senate of the Helmholtz Association provides the following specific recommendations at the level of the Research Program at LK I:

- *The strong leadership position of Helmholtz in the global field should be fully supported.*

  Members of the Program MU are in leading positions at all levels (national, EU, international) and work in relevant strategy boards and roadmap processes (national: KET, KAT, KHuK, ErUM-Data, NFDI; Europe: ECFA Detector Roadmap, Future Colliders Forum, APPEC, NuPPEC; international: ICFA, IUPAP-C4, P5). Central management and consulting positions are staffed by MU members at all main international, current and future collider projects, e.g. at the LHC experiments or studies towards prospective Higgs facilities. Alongside members of MU are (co-)spokespersons (e.g. Auger Observatory, KATRIN, CBM, or ALICE) or hold other key positions in many international collaborations of those experiments and observatories we are participating in. Based on these positions and the impact of the scientific contributions of Helmholtz, the constitutive influence of Helmholtz is ensured.

- *Retain some degree of flexibility for adjustments over the period of PoF IV.*

  The Program MU is dominated by many long-standing remits and projects which can only be mastered with endurance. Nevertheless, the fields of interest offer many new developments, new sprouting questions or technological innovations which open up new approaches to our research. These possible opportunities are pondered and taken where appropriate and integrated in our continuous formation of our program-oriented research.

  In the field of elementary particle and astroparticle physics, important strategy processes are recently concluded or ongoing (European Strategy, US "Decadal Survey on Astronomy and Astrophysics" and "Snowmass" and "P5" processes) which address, e.g., the questions about next international collider projects and future observatories for neutrinos, ultra-high energy cosmic rays, gamma-rays, and gravitational waves.

  The idea of a "Higgs factory" for high-precision measurements of this particle is pursued, but also studies and technological R&D for even more advanced projects which could enable particle collisions at even higher energies are investigated. Helmholtz and in particular DESY as a national lab and hub are of central importance for German contributions to international projects in this field. Complementary ideas extend further the DESY axion program to also include searches for high-frequency gravitational waves.

  Furthermore, in the 2020-years the course for observatories in multi-messenger astroparticle physics of the next 30 to 40 years are set. The plans of the proposals Einstein Telescope, IceCube-Gen2, GCOS and DARWIN are important contributions and Germany can shape the R&D and the design of these infrastructures. It is therefore all the more important that the Einstein Telescope, IceCube-Gen2, and DARWIN are part of the Helmholtz Roadmap for large infrastructures. Accompanying work for new experimental approaches take place at KIT within the Tritium Laboratory Karlsruhe (e.g. for KATRIN++) and at DESY in Zeuthen within the framework of UltraSat.

- *Nurture the novel idea for EDM determination in COSY.*

  The unique global feature of COSY is its ability to accelerate, store and manipulate polarized proton and deuteron beams. The results of the proof-of-principle experiment have been published in Phys.Rev.X 13 (2023) 3, 031004 describing in detail the first search for axion like particles (ALPs) using a storage ring. With the end of operation at COSY this project, the search for Electric Dipole Moment of protons and deuterons, will be phased out. Part of the gained knowledge will be used for experiments at ESR and CRYRING at GSI, e.g. by constructing a polarized beam source. A W3 position at the University of Cologne on the topic “Precision experiments with rings” has been filled and will serve as a new hub to restart this activity.

- *Continue to clarify the TransFAIR (FZJ/GSI) evolution.*

  The transfer of IKP/Jülich to GSI together with surrounding universities in the process TransFAIR is progressing very well: Two people have been selected for joint professorships (Livia Ludhova with University of Mainz, and Yuri Litvinov with University of Cologne), the cooperation with Ruhr-Uni-Bochum has been strengthen, including the approval to proceed with a new joint W2 professorship, and the new NRW-FAIR network is now in full operation.

- *Consider participation in future global initiatives in gravitational wave observations e.g. the Einstein Telescope.*

  Topic 1 is intensely discussing the aspects of gravitational wave physics that are relevant to the mission of particle physics. Concepts are being developed that are particularly suited for investigations of gravitational waves of cosmological origin at high frequencies (> 1 MHz) using existing expertise and infrastructures on the DESY campus. These studies are driven by both experimentalists and theorists and are focusing specifically on lessons to be learned about the early universe (e.g. inflatons, Higgs potential etc.).

  In Topic 2, nuclear physics aspects of gravitational wave research are investigated theoretically. This important project intertwines with the GSI/FAIR research activities. The GSI theory group is leading at studies of dynamics of mergers of binary neutron stars, applying highly advanced numerical simulations of the general relativity theory for precise predictions. The expected signal of gravitational waves and its associated signal in the electromagnetic spectrum as the fingerprint of the nucleosynthesis of heavy elements has been predicted in large detail and enables the formulation of state equations of matter at high densities. This project opens up new possibilities for cross-topic and –program activities in theory, for analysis of big data and for new detector technologies.

  DESY and KIT have advanced their leading roles in the field of multi-messenger astronomy with their activities in Topic 3, strengthened Germany’s contribution to the Einstein Telescope (ET) project, and prepared a possible participation of the Helmholtz Association in the project. The activities of the two Helmholtz centers range from direct experimental participation, particularly in the development of innovative and sustainable cryogenic and vacuum technology, and implementing the project in the Helmholtz Association to coordinating the German ET community and supporting the consolidation of gravitational wave astronomy in Germany. Both centers could successfully implement ET in the Helmholtz Roadmap for future large infrastructures together with HZDR. Both groups at DESY and at KIT are “Research Units” of the Einstein Telescope Collaboration with seats in the Collaboration Board. DESY together with partners from astronomy and astroparticle physics in Germany is strongly involved in the German Centre for Astrophysics (DZA), which is responsible for the preparation of the Low Seismic Lab, a shallow underground laboratory of the DZA with unique seismic properties, and for the investigation of Lusatia as a site for the Einstein telescope. DESY scientists are active in the Observational Science Board to prepare the physics program of ET and in the Site Preparation Board to carry out studies at the Lusatia site. The KIT group is heavily involved in the Site Preparation Board with seismic measurements at all possible sites as well as in the Instrument Science Board leading the Vacuum & Cryogenics Division, the E-Infrastructure Board, and in activities at the Einstein Telescope Pathfinder facility in Maastricht. In addition, KIT scientists also contribute to the scientific portfolio of the DZA.

- *Enhance coordination of theoretical and experimental approaches across the program.*

  In all Topics of the program MU, a close cooperation between experimental and theoretical research is essential. At all centers and in all subjects, cooperations are stengthened, which yields for instance many common publications of more theoretically and more experimentally working groups.

In Topic 1, the close cooperation between theory and experiment is well established; both activities fertilize each other and address common research questions. This regularly results in joint publications and new ideas for experimental analyses or activities (e.g. LUXE, axion experiments).

Theoretical nuclear, hadron and nuclear-astrophysics has the important task of working out the essential questions of the field as well as accompanying the experiments and interpreting their results. The Research Cluster "ELEMENTS" between Goethe University of Frankfurt, TU Darmstadt, JLU Gießen, and the GSI Helmholtzzentrum für Schwerionenforschung, as well as Helmholtz Research Academy Hesse for FAIR (HFHF) provide important support by bringing together world-leading scientists from distinct fields of research – the physics of particles and nuclei, the gravitational physics of neutron stars, and the nucleosynthesis of heavy elements.

Also in astroparticle physics, fundamental scientific results can only be validated in conjunction of experiment and theory. Many publications in 2023 of collaborations like IceCube, Auger Observatory, or H.E.S.S. testify these successful interactions. Several phenomenological studies, e.g., in neutrino physics or multi-messenger astroparticle physics, provide an important link between theory and the experimental astroparticle program and offer interpretation of results within the broad physics landscape.

- *Execute the FAIR Phase-0 program with a continuous management of the work force. With the use of FAIR Phase-0, accomplish smooth transition from old to new facilities at GSI.*

  Rising costs for energy and materials in addition to extended construction works in the building of the UNILAC accelerator forced the GSI management to shift the planned user beam time for 2023. Instead of user operation an extended engineering run for accelerator tests and optimization. Hence, no beam time for scientific experiments on MU topics have been offered. The user beam time will start in February 2024 and will be continued in 2025 with an extension which will partially compensate the loss in 2023. All experiments rated with "A" by the Program Advisory Committees in 2022 could be scheduled during those beam times in 2024 and 2025. An additional four weeks were allocated and will be distributed in an extraordinary PAC meeting. Planning of the commissioning phase of FAIR and its synchronisation of user operation during FAIR Phase-0 was started. Schedules integrating the commissioning of the FAIR accelerators, the first beam times at FAIR and the continuation of user operation at the GSI facilities for 2024 to 2029 have been developed during 2023 and are constantly adapted to changing conditions. According to the current planning, operation of the Super-FRS with SIS18 beam will start in 2027 and SIS100 will operate end of 2028.

3.2 Implementation of specific research policy objectives

The following section lists the specific research policy objectives at the level of the Topics and provides an interim resume on the implementation:

3.2.1 Topic 1

Core statements of the research policy target agreements:

- *Accurate measurements of the properties of the Higgs boson will be carried out at LHC/HL-LHC, as well as high-precision investigations of the electroweak and strong interaction at LHC/HL-LHC and at Belle II. Search with these experiment for new particles and phenomena, either by direct observation or by deviations between theory and precision measurements.*

  DESY is involved in the experimental and theoretical program, and KIT is involved in the theoretical research.

The LHC experiments ATLAS and CMS are progressing with the execution of their physics program while at the same time preparing for the upgrade towards the HL-LHC era. The goal of an integrated luminosity of 300 fb^{-1} per experiment has not yet been achieved due to LHC machine problems, which caused several weeks of downtime, resulting in a total of about 200 fb^{-1}. With the extension of Run 3 by one year, however, it is expected to reach 400 fb^{-1} by the end of 2025.

After seminal publications in *Nature,* summarizing the status of Higgs physics 10 years after the particle's discovery published in 2022, analyses are being refined in order to profit from the ever-increasing LHC data sets from the ongoing Run 3. The goals laid out for the theory and experimental precision on the Higgs couplings, the Higgs mass and on the Higgs cross sections have largely been reached; the framework for global fits of LHC and other data are in use and are being constantly refined. The potential of the LHC for direct discoveries of new particles at high mass and energy scales is being fully exploited with a whole slew of dedicated analyses that cover more and more corners of the accessible phase space, for example long-lived particle searches.

The Belle II experiment – besides providing precision measurements of standard model parameters – is complementing the LHC searches for "new physics". The year 2023 brought first measurements with the full luminosity collected before the currently concluding first long shutdown. An example is given above as the 2023 highlight of Topic 1 and more physics results are outlined in the Scientific Annex of the report. The Belle II results cover decay processes in the B flavor and the tau lepton sectors, with measurements of e.g. the tau lepton mass. The large integrated luminosity also allows for unprecedented precision for rare decays (publications in 2023 on $B^+ \rightarrow K^+\nu\bar{\nu}$ and on $\tau \rightarrow \mu\mu\mu$) with unique discovery potential. The experiment is aiming at increasing the luminosity by a factor of 10 until the end of the PoF IV period, including the data from the new pixel-vertex detector PXD2, installed and commissioned in 2023. The findings and insights from measurements of yet undiscovered and even rarer channels will throw light e.g. on the matter-antimatter asymmetry in the universe and – potentially – on its dark sector.

With the studies for the LUXE experiment to study strong-field QED, another avenue towards high-precision investigations of fundamental forces, but also towards alternative approaches on new physics is being pursued. LUXE cannot be realized during the PoF IV period; the experiment is instead aiming for PoF V.

- *Search for axions and similar hypothetical particles with the ALPS II experiment at DESY. In addition, the technical and financial feasibility of the possible follow-up projects, MADMAX and IAXO, will be worked out and possibly lead to first demonstrators.*

In May 2023, data taking with the ALPS II started after 11 years of preparation, with only a mild delay with respect to the original PoF IV planning, caused mostly by the Covid-19 pandemic. In two long runs in 2023, the entire setup of the experiment and its operation was scrutinized, primarily with the aim of excluding stray light sources, but already with a significant physics potential beyond previous experiments (the sensitivity is roughly increased by a factor 100 with respect to former experiments). A first physics publication will be derived from the obtained data. The experiment will now upgrade its optics, further enhancing its sensitivity for axions and ALPs by a factor 10. The foreseen ALPS II physics program will last until 2027 and cover also e.g. measurements of vacuum magnetic birefringence. The suitability of the ALPS II infrastructure for even more diverse physics purposes in the PoF V period – for example measurements of high-frequency gravitational waves – is currently being investigated.

BabyIAXO – a precursor experiment for the International Axion Observatory IAXO that could be realized at DESY on the timescale of PoF V – and the MADMAX experiment are in the preparatory phase and currently try to secure the funding for the realization in PoF V. BabyIAXO is ready for the production of a conceptual design report and could successfully address important technical and procurement issues concerning its magnet in 2023. The experiment has also received a significant boost by an ERC Synergy grant for DESY and several collaborating institutes, among them is a leading scientists from KIT in the Research Field Information. The schedule for the magnet construction is not yet clear due to various uncertainties; it is unlikely to start before 2027/2028. MADMAX has successfully tested prototypes of its dielectric discs and other important components, not least at the CERN MORPURGO magnet, and recently, in late 2023, the Max Planck Association has granted significant funding for coils of a large magnet prototype. A formal time scale for MADMAX does not yet exist.

- *Advance the understanding of cosmology, illuminate the so-to-speak “dark side” of the universe, and are complementary to astroparticle physics activities in the Topic 3.*

  For the first time compelling evidence for the existence of a stochastic gravitational wave background (GWB) has been established by a variety of pulsar timing arrays. Andrea Mitridate from DESY in Hamburg and a member of the NANOGrav collaboration were centrally involved in one of the main research articles and additional work has been done within the DESY theory group to pin down possible sources of this tentative GWB, including cosmological phase transitions or primordial black holes from the dawn of time.

3.2.2 Topic 2

Core statements of the research policy target agreements:

- *Investigate the phase diagram of hot and dense nuclear matter with their effect on the equation of state of astrophysical objects such as supernovae, neutron stars, and merging neutron stars. This may also lead to new insights into gravitational wave signals.*

  The phase diagram of strong-interaction matter is being investigated in experiments studying heavy-ion collisions at various net-baryon densities. At vanishing net-baryon densities, i.e. LHC beam energies, the smooth crossover from quark and gluon phase to hadronic matter is investigated with the ALICE experiment with a particular emphasis on the production of particles with heavy flavor. Complementary to the investigations at LHC, the HADES experimental campaign concentrated on the region of high net-baryon densities, which is most relevant for the understanding of the characteristics of neutron stars and neutron star mergers. By comparing results from heavy-ion collisions to predictions from theoretical models yield constraints to the equation-of-state (EoS) of nuclear matter which are compared to results astrophysical observations. In general, a consistent description of both heavy-ion data and astrophysical observations is achievable. However, the high quality, high statistics data obtained in the novel experiments at GSI and later with the CBM/HADES experiments at FAIR compared to state-of-the-art theoretical models will allow to provide better constraints for the EoS up to several times of the nuclear matter ground state density.

- *Investigate the nuclear structure and the reaction phenomena far away from the so-called valley of stability. In particular, a better understanding of the element formation in the universe in supernovae and neutron star fusions should follow from the study of the r-process, e.g., the element abundances of the elements gold, platinum, and beyond.*

  Neutron merger events have been identified as a dominant site of nucleosynthesis of heavy elements via the r-process. Extensive calculations of GSI theoreticians could reproduce measured spectra of the neutron star merger event observed in 2017 (GW170817). In parallel, the understanding of the characteristics of exotic nuclei is continuously progressing. The discovery of the tetra neutron and the discovery and investigation of the ^{28}O nucleus are decisive in the understanding of very neutron rich systems. For the discovery of neutron rich heavy very exotic nuclei at the N=126 shell closure, higher beam intensities are required which will be available with the Super-FRS at FAIR. The exploitation of advanced instrumentation built for FAIR has opened the possibility to study the (decay) characteristics of moderately neutron rich nuclei in this region (N~126), e.g. lifetimes and isomeric and β-decays in the framework of FAIR Phase-0. Data analysis of such experiments is ongoing.

- *Test QCD predictions for exotic particle states via precision measurements of proton-antiproton collisions.*

  Large experimental efforts employing different experimental approaches at CERN (AMBER, COMPASS, LHCb), Japan (Belle II), China (BESIII) and the U.S. (CLASS12, GLUEX) are being put to understand the nature of the strong interaction in the 'non-perturbative' lower-energy regime. A new facility at the horizon is the Electron Ion Collider (EIC) in the US. Stored anti-proton beams at FAIR in combination with the PANDA-experiment is unique and can clarify the nature of the new, 'exotic', forms of hadronic matter. The PANDA-experiment has a unique discovery potential for the complete glueball spectrum. This will provide a critical test of predictions of strong interaction theory that predicts bound states of pure glue only. We aim in PoF V for the realisation of this unique program that requires execution of the full FAIR-MSV. In POF IV, the PANDA collaboration prepares this program by conducting world-leading research at various international facilities, the PANDA Phase-0.

3.2.3 Topic 3

Core statements of the research policy target agreements:

- *Gain a comprehensive understanding of the structure of the universe as a whole, derived from the observations of the various complementary messengers (gamma radiation, neutrinos, particles and nuclei, and gravitational waves). The Research Field will strengthen this so-called multi-messenger approach significantly during the PoF IV period.*

  The data from the Pierre Auger Observatory have fundamentally expanded our understanding of ultra-high-energy cosmic rays (UHECR) through many unexpected observations. Besides a large-scale dipole anisotropy, whose characteristics are indicative of extragalactic sources, an excess of cosmic rays could be observed on smaller angular scales from the direction of the Centaurus region, an area of the most prominent active and star-forming galaxies, together with a strong directional correlation with starburst galaxies in our cosmological neighbourhood. Analysing the data from the IceCube has now led to a move from the discovery of astrophysical neutrinos to neutrino astronomy. With the discovery of our own galaxy as a source of high-energy neutrinos, the Milky Way is now also an object of the combination of electromagnetic radiation and particle components as messengers of a better understanding of processes in the universe, in addition to the extragalactic multi-messenger physics. Gamma-ray measurements with the H.E.S.S. observatory in Namibia have detected the highest energy gamma rays ever from the Vela pulsar. The discovery opens a new observation window for detection of pulsars as a high-energy population with current and in particular upcoming more sensitive gamma-ray telescopes like CTA. Pulsars are a key observation for a better understanding of the extreme acceleration processes in highly magnetised astrophysical objects. The observation of the universe with another messenger, gravitational waves, will be dominated by the Einstein Telescope in the future. DESY and KIT are visibly involved in the preparation of this observatory with innovative technology studies in the field of vacuum, cryogenics and computing, as well as with the course of the installation of the German Centre for Astrophysics, DZA. An important aspect for efficient multi-messenger astroparticle physics is the provision of services in the areas of data management, software, and computing. The Topic's activities in this area are extensive, including cross-community collaboration in projects like NFDI4PUNCH, ADC-MAPP, CORSIKA, AMPEL or Gammapy.

- *Integrate existing and future observatory data into a data and analysis center for high-energy astroparticle physics.*

The research field of astroparticle physics requires a cross-experiment computing and data centre for the efficient use of the resulting data. The ADC-MAPP, which was initiated in the innovation pool process, aims to enable a broad user community to perform multi-messenger analyses using state-of-the-art methods. This requires not only FAIR access to the data of the large research infrastructures, but also the creation and validation of the necessary (software) tools and (analysis) methods. The project aims to develop the software required for a FAIR (Findable - Accessible - Interoperable - Reusable) data cycle with a focus on analysing the data streamed in real-time from the various infrastructures and on integrating operating and future gravitational wave detectors into the system. The work in ADC-MAPP concerns all four carriers of multi-messenger physics, in particular with respect to their respective flagship observatories CTA, Pierre Auger Observatory, IceCube-Gen2, and Einstein Telescope. Successes have been achieved so far in the area of analysis tools (CORSIKA, Gammapy, AMPEL, etc) including the application machine learning methods and in data management (KCDC, AMPEL, Gammapy, etc) for open data and efficient real-time data flows.

- *Measure the mass or the most stringent limitation of the mass of the electron neutrinos with the KATRIN experiment by the end of the PoF IV period. Investigate the feasibility of a corresponding campaign to search for Dark Matter with KATRIN.*

  The KATRIN experiment is on schedule to deliver by the end of the PoF IV period the most stringent limits on the neutrino mass. Data taking runs smoothly and efficiently, with roughly 60% of the anticipated full data set already on disk. The beamline and the tritium processing at Tritium Laboratory Karlsruhe show stable operation benchmarks, and by the end of 2025 a unique data set for maximal sensitivity is anticipated to be available. Results from the first few months of KATRIN data already improved the neutrino-mass upper limit from 2 eV to the currently leading direct bound of 0.8 eV. The same data set is used to search for light sterile neutrinos at the eV scale, again yielding leading direct exclusion limits. The next intermediate releases, both for the neutrino mass (employing ~20% of the total expected data for a sensitivity of ~0.5 eV) and for the light sterile neutrino search, are targeted at the summer conferences 2024. Analysis of the final neutrino-mass data sets will be continued throughout the concluding phase of PoF IV.

  For the search of keV-mass sterile neutrinos as a potential contribution to Dark Matter, the KATRIN collaboration has consolidated its plans to run a dedicated campaign in 2026 and 2027. The required detector upgrade (TRISTAN) is fully on schedule for integration into the beamline starting 2026. Analysis preparations – in particular, detailed predictions of systematic effects – have been intensified. A short exploratory measurement campaign with the current beamline, i.e. with a detector not yet optimized for this search, has already been performed. From this pilot run, KATRIN produced the most stringent lab-based constraints to date on parts of the keV neutrino parameter space. These results underscore the potential of KATRIN to search for heavy sterile neutrinos as Dark Matter candidates.

4 Strategic Topics

For the strategic advancement of interconnecting activities in the Research Program and the Research Field, three innovative projects in MU are currently supported by the so-called Innovation Pool: „LUXE-QED - LUXE-Quantum-computing and advanced Experimental Detectors“ - (DESY, HZDR, GSI (HI Jena)); „ADC-MAPP - Analysis and Data Centre for Multi-Messenger Astroparticle Physics“ - (KIT, DESY); „VQCS - Variational Quantum Computer Simulations for complex quantum systems and optimization problems“ - (DESY).

The LUXE experiment has been proposed to investigate quantum electrodynamics (QED) in a yet unexplored regime of field strength at and above the Schwinger limit, to be achieved via the collision of electron bunches from the European XFEL with strong laser pulses. The experiment is designed to measure electron-photon scattering as well as the formation of electron-positron pairs in pure light scattering processes with percent-level precision and thereby shed light on the transition from perturbative to non-perturbative QED. Following the inclusion of LUXE in the roadmap of the DESY directorate in November 2022, the LUXE collaboration completed the Technical Design Report [1] in August 2023, including the design of the laser system and its diagnostics, which was the first goal of the innovation pool project LUXE-QED. The second part of the project, the development of a quantum computing method for reconstructing charged particle candidates from energy depositions in the LUXE tracking detector, has also achieved major milestones: First results comparing quantum computing and classical methods on a simplified simulation of the tracking detector were published [2,3] (see below). In parallel, the quantum computing based method was also successfully applied to a more realistic simulation, and is being ported to collider-type of detectors.

[1] H. Abramowicz et al., Technical Design Report for the LUXE Experiment, arXiv:2308.00515.

[2] L. Funcke et al., J.Phys.Conf.Ser. 2438 (2023) 1, 012127.

[3] A. Crippa et al., Comput. Softw. Big Sci. 7 (2023) no.1, 14; doi:10.1007/s41781-023-00109-6, [arXiv:2304.01690 [quant-ph]].

The aim of ADC-MAPP is to extend the existing approaches such as the KASCADE Cosmic-ray Data Center (KCDC), the Alert Management, Photometry and Evaluation of Lightcurves (AMPEL), or the analysis tool Gammapy into a coherent concept of a user facility. In addition, the application of artificial intelligence and deep learning for the optimization of data processing and data analysis is advanced within ADC-MAPP. The activities serve the digitization of this data-intensive research field and focus on specific tasks of research data management, big-data and multi-messenger analyses, services for a broad user community, as well as networks and training. In 2023, we had further progress in accelerating air-shower simulations by Deep Learning Methods using a sequential model of generating cosmic ray showers. In addition, the application of Graph Neural networks to determine cosmic-ray elemental composition in the PeV to EeV energy range from the IceCube/IceTop data have been presented [1]. ADC-MAPP develops procedures and tools for FAIR data management for astroparticle telescopes, efficiently utilizing long-term collected data. VERITAS and H.E.S.S. data archives including all available observations of the two instruments are generated adopting an open and standardized format compatible with Gammapy for wider accessibility. ADC-MAPP emphasizes preparing archives for publication, ensuring sustained availability to the scientific community. The development of a unified strategy for transient alert generation is the second important activity, including telescopes like ZTF, Vera Rubin, IceCube, and CTA and the open AMPEL software project connecting these instruments. This approach promotes collaboration and data integration, advancing the study of multi-messenger astroparticle phenomena. The working groups in ADC-MAPP collaborate closely with other initiatives such as the NFDI (PUNCH4NFDI), ErUM-Data, or EOSC in the field of digitization of astroparticle physics, research data management and sustainable publication of scientific data.

[1] Paras Koundal et al.; PoS(ICRC2023)334; doi:10.22323/1.444.0334.

The project VQCS has progressed excellently also in 2023. Investigations of the phase diagram of the 1+1-dimensional Schwinger model have been performed, confirming the first order nature of the proposed CP violating phase transition in an external electric field [1]. A first quantum simulation of a real time scattering process has been taken out and the entanglement properties after the collision and their dependence on the couplings of the model has been carried out [2]. Most remarkably, both tasks were also run on real quantum hardware at IBM with very good results [1,2]. This is an important milestone of the VQCS project. The members of VQCS have been very active in the writing of the white paper for quantum computing for problems in high-energy physics [3]. This paper's analyses use cases and applications in both, theoretical and experimental high energy-physics, which can already run now on existing quantum hardware. The white paper is also a first step towards the 100x100 challenge of IBM, meaning to use 100 qubits and a quantum circuit depth of O(100).

Using symmetries of physical models, an imaginary time evolution has been quantum simulated, demonstrating that employing symmetries in a variational quantum eigensolver allows for a better computation of ground state properties of physical models [4]. Members of VQCS have also been actively involved in the quantum computing part of the LUXE experiment [5,6] (see above) where they could provide important input with their algorithmic knowledge in quantum computing and also covered the quantum machine learning part. As outreach activities, members of VQCS have developed strategies for generating quantum music which have been described in a publication [7]. VQCS took also part in the organization of the very successful workshop for quantum computing in October 2023 in Cyprus and the quantum music symposium in Berlin, also in October 2023.

[1] T. Angelides et al., arxiv:2312.12831.
[2] Y. Chai et al., arxiv:2312.02272.
[3] A. Di Meglio et al., arxiv:2307.03236.
[4] X. Wang et al., arxiv:2307.13598.
[5] A. Crippa et al., Comput.Softw.Big Sci. 7 (2023) 1, 1; doi:10.1007/s41781-023-00109-6, [arXiv:2304.01690 [quant-ph]].
[6] A. Crippa et al., arxiv:2210.13021.
[7] P. Vitor Itaborai et al., arxiv2309.12254.

4.1 Talent Management

In 2023, the Hertha Sponer prize was awarded to two researchers of the MU program at the DPG annual meeting in Dresden. The former DESY postdoc Adinda de Wit, now U Zurich, received the prize for her contributions to the determination of the Yukawa coupling of the Higgs boson to b quarks, and Belina von Krosigk from KIT received the prize for her fundamental contributions to the understanding of dark matter through the further development of interaction models and the analysis of their expected signals in terrestrial detectors. Since March 2023, Belina von Krosigk is also professor for experimental physics at the Kirchhoff Institute for Physics of U Heidelberg. Also at the DPG meeting in Dresden, former DESY PhD student Robert Stein, now at Caltech, was awarded the dissertation prize of the *Fachverbände SMuK* for his PhD thesis "Search for multi-messenger transients with IceCube and ZTF" he finished in 2021 at DESY in Zeuthen.

Annika Rudolph, DESY, now at Niels Bohr Institute at Copenhagen, was awarded the 2023 dissertation prize of the German Astronomical Society for her PhD thesis „Emission of Multiple Messengers from Gamma-Ray Bursts".

DESY theorist Johannes Braathen was awarded a new Emmy Noether Research Group on Higgs precision physics with the title "Cornering new physics with generic precision calculations". Braathen receives altogether 1.59 million Euros for a period of 6 years.

In the 2023 decisions for ERC Grants, the following researchers in MU were awarded a Starting Grant: Anna Nelles, DESY (Discovering neutrinos of extreme energies with the Radio Neutrino Observatory Greenland), Andrea Caputo, DESY (Astro Dark Large & Small), Priscilla Pani, DESY (Searches at ATLAS for low mass resonance in di-bjet final state (mass < 150 GeV)); and a Consolidator Grant: Elisa Pueschel, DESY, now at U Bochum (Probing the Finely-resolved 100 TeV Gamma-ray Sky for Ultra-heavy Dark Matter).

Carl A. Lindstrøm, formerly at DESY, now at U Oslo, has been awarded the Simon van der Meer Early Career Award in Novel Accelerators. The award is for "numerous outstanding experimental and theoretical contributions to the field of beam-driven plasma accelerators, including the demonstration of beam quality preservation and efficient acceleration, the investigation of advanced beam transport concepts, and the invention of self-stabilizing multistage acceleration", work that was performed partially during Lindstrøm's time at the FLASHForward project.

DESY scientists Kerstin Tackmann has been selected for a Visiting Millner Research Professorship at Berkeley. Tackmann spent half a year at Berkely, starting in mid-March 2023 to work on Higgs physics and B physics, and on improving the understanding of the new ATLAS tracking detector.

The Helmholtz Association has awarded DESY Ph.D. student Peera Simakachorn the Ph.D. Prize for Mission-Oriented Research in the Research Field Matter. Simakachorn is one of two awardees in the Helmholtz Research Field Matter.

Members of the program MU have received numerous awards from their respective collaborations and institutions in 2023, for example the ATLAS thesis award (E. Thompson), the ATLAS outstanding achievement award (T. Novak), the DESY exceptional achievement award (F. Poblotzki), several CMS achievement awards (J. Rübenach, F. Blekman, Y. Otarid, S. Consuegra Rodriguez, M. Reineke), or the IceCube impact award (C. Lagunas Gualda).

In 2023, Andreas Haungs from KIT was elected speaker of the PUNCH4NFDI consortium according to the Articles of Association of the NFDI and thus represents PUNCH in the NFDI Consortia Assembly.

Almudena Arcones has been appointed Max-Planck fellow at Max Planck Institute for Nuclear Physics.

Michael Block has been elected as the Chair of the Committee for Hadron and Nuclear Physics (KHuK) in Germany.

Tetyana Galatyuk has been re-elected by community to the DFG Review Panel 3.24-01 Nuclear and Elementary Particle Physics, Quantum Mechanics, Relativity, Fields.

Yuri Litvinov, GSI Darmstadt / University of Heidelberg, has been appointed to the W3 professorship for Experimental Nuclear Physics (based on the Jülich model with GSI Darmstadt) at the University of Cologne.

At several conferences, workshops or schools, young investigators of MU were honored with poster/presentation prizes during 2023: N. Feigl, DESY, working at the IceCube experiment, best Flash Talk at the NuTel 2023 conference in Venice; L. Hasselmann, KIT, working on tritium handling for KATRIN and beyond, poster prize at KSETA annual retreat in Durbach; S. Mohanty, KIT, working on dark matter searches, poster prize at ISAPP school in Varenna; C. Fengler, KIT, working at the KATRIN experiment, poster prize at EPS HEP conference in Hamburg.

In 2023, almost 70 doctoral researchers of the KIT Graduate School KSETA – "Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology" worked on their thesis on topics of MU. The school offered 14 lecture courses, covering scientific specialization as well as addresses wider professional education and key competences. Special highlights in 2023 were the large Plenary Workshop and the "Wess lecture" by the Julius Wess awardee of 2022 Elena Aprile from Columbia University, NY, USA. An internship program with IIT Bombay in Mumbai, India, offered the opportunity for three doctoral researchers of MU, Topic 3, to gather early experience in supervising international master students. With more than 30% female researchers and 50% international researchers with more than different 15 nationalities, the group of MU-related PhD resarchers in KSETA offers a multi-cultural working environment.

The KSETA school is intertwined with the Helmholtz International Research School for Astroparticle Physics and Enabling Technologies (HIRSAP) which offers two special Double Doctoral Degree paths between KIT and UNSAM in Buenos Aires, Argentina, the Double Doctoral degree in Astrophysics (DDAp) and the Double Doctoral degree in Electrical engineering and Information Technology (DDEIT). In 2023, 12 doctoral students of HIRSAP were pursuing their work in topics of the two Research Programs MU and MT. During 2023, 12 long-term exchanges took place and the annual meeting was held in Buenos Aires with presentations by the PhD students themselves and two lectures given by invited speakers, one expert on exoplanets and machine learning from UNSAM and the second speaker was HIRSAP alumni Ana M. Botti, now pursuing dark matter searches at FNAL and KICP, Chicago, USA.

The international exchange program of the Helmholtz Alliance for Astroparticle Physics (HAP) could grant one iPROGRESS - Internship Program for Young Research Scientists – research visit for a doctoral researcher in MU to work together with partners in the USA. The project of the 2023 internship was related to dark matter searches within the XENONnT collaboration.

In 2023, four new doctoral students were accepted at the International Helmholtz-Weizmann Research School on Multimessenger Astronomy. The graduate school has a total of 33 doctoral students from 15 countries. In addition, five students successfully completed their doctorates. In June, the annual school meeting took place at the Weizmann Institute of Science (Israel). In addition to numerous presentations by doctoral students and invited scientists, the program also included events about careers and gender equality. The research stays abroad included a 3-month project at the Weizmann Institute to work on the observation strategy for the ULTRASAT space mission.

HGS-HIRe the graduate school of GSI/FAIR had a total of 336 students from all four research pillars of FAIR in 2023, of which 224 doctoral students are working on research projects of the Topic "Cosmic Matter in the Laboratory". A total of 23 theses on CML topics were successfully completed.

DESY scientist Karl Jansen has been awarded an ERA Chair, given by the European Research Executive Agency. The QUantum Computing for Excellence in Science and Technology (QUEST) project is to establish a new centre for quantum computing at the Cyprus Institute. The centre will work closely with the Centre for Quantum Technologies and Applications (CQTA) at DESY in Zeuthen. The QUEST project aims to enable Cyprus to harness the unprecedented potential of quantum computing through the establishment of an excellence hub at the Computation-based Science and Technology Research Centre (CaSToRC) of the Cyprus Institute, led by Karl Jansen. The work is in close cooperation with Constantia Alexandrou of the Cyprus Institute, who has received a Helmholtz International Fellow Award and conducted research at DESY.

KIT scientist Joachim Wolf was elected to the managing board of the German Vacuum Society (DVG) for the election period 2023-2026. He was also unanimously elected as one of two Vice Presidents.

4.2 Networking and Cooperation

The PUNCH4NFDI consortium integrates the German communities of particle physics, astroparticle physics, astronomy, and hadron & nuclear physics firmly into the National Research Data Infrastructure (NFDI e.V.). In 2023 the consortium, with DESY as its coordinator and KIT scientist Andreas Haungs as spokesperson according to the statutes, could demonstrate large steps towards achieving its main goals of a science data platform, the definition of a digital research product for its communities, and conclusive discussions on metadata schemata. More and more use cases can now be implemented, opening the consortium for an ever-wider fraction of scientists working in the field, and also connecting the activities firmly to the European level via ESCAPE. With the Base4NFDI initiative a tool has been established in 2023 to support concrete activities and services that benefit all parts of the NFDI, providing cross-links between more and more fields of research. A prominent example is the IAM4NFDI proposal, in which an authentication and authorisation infrastructure for the entire NFDI and ultimately for the entire German science system is proposed; also in this proposal DESY and KIT scientists were significantly involved. This AAI infrastructure is complemented by a federated Compute4PUNCH infrastructure, largely developed at KIT, which provides seamless and federated access to the huge variety of compute systems available in the participating communities, covering their very diverse needs and comprising state-of-the-art technologies. This goes together with the DESY-driven Strorage4PUNCH initiative, which ensures access to federated storage systems.

With the first edition of the Conference on Research Data Infrastructure from 12 to 14 September 2023 at KIT, the Association German National Research Data Infrastructure (NFDI) has initiated a conference that will focus on establishing interdisciplinary research data management (RDM). Under the theme Connecting Communities, national and international stakeholders from all research fields as well as from the infrastructure sector presented their contributions to an excellent RDM of the future and to exchange information about the latest developments.

The Helmholtz Alliance “Physics at the Terascale” – connecting all German universities and research centres working in elementary particle physics – has again conducted numerous education and training events in 2023, among them the 15th Terascale Detector Workshop and an annual meeting in December 2023. The meetings were organized as in-person, hybrid, or pure online events.

The Dark Matter Laboratory (DMLab), an International Research Lab of the French IN2P3, has started in early 2023. The lab will bring closer together IN2P3 activities on dark matter searches with related ones in the Helmholtz Association within its centers DESY, GSI, and KIT. The scientific topics explored by DMLab include the direct search for dark matter, the study of gravitational waves and astrophysical messenger particles, the development of new techniques for particle acceleration and detection, theoretical physics, and the management and processing of the data generated by the experiments. Examples for the cooperation are developments for the MADMAX experiment, phenomenological studies, and the DARWIN experiment.

DESY's participation in the excellence cluster "The Quantum Universe" (QU) is crucial: it fosters scientific exchanges and networking, enriches the research portfolio, complements our competences and underlines the attractiveness of the research field, e.g. for the recruitment of talented young scientists. Closely connected to the excellence cluster is the recently granted DFG collaborative research center "Höhere Strukturen, Moduläume und Integrabilität" under the leadership of Jörg Teschner (DESY/ U Hamburg) from which DESY, in the course of the coming years, will receive around 1.25 MEUR.

The NRW-FAIR initiative is being provided with 16.5 Mio Euro over four years by the state NRW. This has enabled the participating research groups so far to hire 45 PhD students, 15 PostDocs and one W2 Professor, who are all now actively strengthening the NRW groups' theory and experimental activities for the CBM and PANDA pillars of FAIR.

In May 2023, the 30th anniversary of the TLK – Tritium Laboratory Karlsruhe – was celebrated. This facility for processing tritium is a world-wide unique infrastructure with a significant license to handle the radioactive hydrogen isotope. TLK is indispensable for the KATRIN experiment and also essential for fusion research. Along with a ceremony act, an international symposium about tritium science and technology was held for two days. The meeting was used for interdisciplinary discussions, covering topics starting from scientific questions about the neutrino mass and an atomic tritium source, to R&D on fuel cycles and tritium material interactions, tritium processing, analytics, and applications, and even to tritium based industry.

In October 2023, the COST action COMETA – "Comprehensive Multiboson Experiment-Theory Action" started for four years. COMETA brings together theorists, experimentalists and machine learning experts, with the goal of creating a tightly interconnected community that can boost the development of innovative approaches to multi-boson measurements. The network currently includes more than 150 researchers distributed over 28 countries within and outside Europe.

In November 2023, the annual IRN Neutrino meeting took place at KIT. The IRN Neutrino meetings provide an occasion to exchange on the latest results in neutrino physics, give the opportunity to PhD students and young postdocs to present their work and make themselves known in the French and European community, and consolidate the relationship between experimental and theoretical neutrino physicists. This International Research Network is an international network bringing together physicists from the French IN2P3 and CEA and from four European institutes: the University of Milano-Bicocca (Italy), IFIC (Instituto de Física Corpuscular, Valencia, Spain), UCL (University College London, UK) and KIT (Karlsruher Institut für Technologie, Germany).

A joint project on "High-fidelity time-resolved 3D imaging of radio emission from cosmic-ray air showers with LOFAR and the SKA" was granted by the DFG for the three research groups of T. Huege, KIT, T. Enßlin, Garching, and A. Nelles, DESY and Erlangen.

4.3 Transfer in Economy and Society

With its knowledge transfer activities, the Research Field Matter pursues the goal of making socially relevant scientific topics and findings available through non-monetary channels and bringing them into application. This enables societal stakeholders to make robust and evidence-based decisions, to participate in scientific dialogues, or to pursue scientific careers themselves. In addition, the Research Field Matter also pursues knowledge transfer as an enrichment for society to satisfy curiosity about fundamental knowledge - the interest in "what holds the world … together." During 2023, the Research Field

Matter has launched a webportal matter.helmholtz.de to invite everybody to experience our science and the infrastructures virtually. The webportal offers many insights in the research of the program MU which is characterized by its particular diversity of international collaborations resulting in a general "open access" availability of publications, research data, media and software. The webportal is the starting point to visit several of the research infrastructures virtually in 360° views, to participate and apply public data of international experiments together with analyses and software tools, or to find dedicated events and hands-on experiences for students and school classes. Researchers of the program MU are very much engaged in many knowledge transfer and outreach activities and some examples during 2023 are given below.

On 21. November 2023, DESY and KIT offered highschool students at the International Cosmic Day to become a researcher on cosmic rays for one day. The students learnt many facts all around high-energy cosmic rays and neutrinos, made hands-on experiences with analysing real experiment data in Master-classes, and at the end of the day, the groups met internationally with other participating groups in video meetings to exchange the results and experiences. At DESY, a particular participation with Ukrainian students was provided this year, and the student group at KIT exchanged their results with further groups in Germany, China, and the UK.

Due to its immense success, the ”Wie alles begann” exhibition (“How everything started”) that started already in 2022 in the Museum der Arbeit had been prolonged until May 2023. Altogether, the exhibition attracted 26.500 people, and almost 300 guided tours and events were organised around it.

Regular labs for highschool students and Masterclasses are offered at DESY and KIT throughout each year. MU scientists regularly present their work at schools or outreach events. In 2023, KIT could look back to a 10-year long, close cooperation with a local Gymnasium, which was celebrated at the school and in local media. Furthermore, GSI, DESY, and KIT are participating each year in the Girls’ Day to promote young girls in pursuing STEM subjects, e.g. with lab visits, hand-on experiences of data analyses, or with live talks with international female researchers at our research infrastructures all around the world. Also with resp ect to STEM subjects at high schools, KIT is performing regularly advanced trainings for teachers in topics around particle and astroparticle physics, so in May 2023.

Several science events during 2023 were dedicated to the “Wissenschaftsjahr – Unser Universum”, e.g. MU scientists from KIT presented long-lasting questions and most recent results about the topics Dark Matter, Cosmic Rays, neutrino properties, and research at the LHC during three evenings at the *Naturkundemuseum Karlsruhe*. During the summer months, KIT opened its gates to the area of the research center for an open day, attracting about 25.000 visitors, and enthralled the public audience at EFFEKTE all around the Karlsruhe castle or at a KCETA evening at the Triangel science and culture meeting place. The interested public listened to MU scientists talking about particle and astroparticle physics, as well as about big data science. At DESY, the “Wissenschaftsjahr – Unser Universum” was celebrated with an open-air exhibition „Beam me up, Potsdam. Einmal Milchstraße und zurück!" in Potsdam. The exhibition was complemented with podcasts, events and student academies to convey the fascination about our Milky Way. In August, Science / AstroCamps for young people were offered for the first time from KIT and DESY during the summer holidays at schools. DESY researchers hold the AstroCamp at a nearby lake where e.g. a stratospheric weather balloon was launched, and at KIT many hands-on experiments and data analyses were combined with lab visits at the large experimental infrastructures at the Helmholtz research center area.

The aim of the European research project artEmis, in which GSI is involved together with twelve other institutes, is to improve earthquake prediction. The project is funded with two million euros. The aim is to lay the foundations for a reliable early warning system for earthquakes. A network of sensors that measure the radon content and other parameters in selected water sources in Europe should be able to detect earthquakes several days in advance. GSI plays a key role here in sensor technology and analytics, and contributes knowledge based on particle and radiation detectors, signal processing electronics and data processing systems for nuclear physics experiments and AI methods.

At the Green IT Cube of GSI, the establishment of the AI innovation laboratory "GSI/FAIR Digital Open Labs" in partnership with the Hessian Center for Artificial Intelligence "hessian.AI" was completed in 2023, which serves as a contact point in this field for more than 70 companies, start-ups and scientific institutions to share the unique IT infrastructure. The Digital Open Lab is now one of the flagship projects of intensive development cooperation between industry and academia.

4.4 Third-Party Funding

The Collaborative Research Center SFB 1245 on "Nuclei: From Fundamental Interactions to Structure and Stars" at the Technical University of Darmstadt with participation of GSI scientists, investigates the strong and electroweak interaction physics from nuclei to stars and has entered its third funding period with a funding volume of 13 million Euros.

In 2023, the second funding period of the collaborative research center TRR 257 "Phänomenologische Elementarteilchenphysik nach der Higgs-Entdeckung" was started, in which KIT is the applicant institution. For the second period, 4.5 million EUR budget was granted.

DFG has approved the funding for the first phase of 5 years from October 2023 to September 2028 of the International Research Training Group IRTG 2891 "Nuclear Photonics". Funds are provided by the German Research Council (DFG), by the Romanian Institute of Atomic Physics (IFA), and by the Universities in Darmstadt and Bucharest. The IRTG aims at qualification and training of Early-Career Researchers on photon-induced phenomena on a nuclear energy scale and corresponding instrumentation and methods. MU-CML scientists participate as Project Leaders.

As mentioned already above, the DFG collaborative research center led by J. Teschner is granted with a budget of 1.25 million EUR.

The European Research Council (ERC) has bestowed a prestigious Synergy grant that will develop novel quantum sensors for experiments searching for dark matter. The DarkQuantum project, which is coordinated by the University of Zaragosa in Spain, has been funded with almost 13 million euros. The aim of which 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 experiments benefitting from this effort is the experiment BabyIAXO, a dark matter observatory under construction at DESY. The funding foreseen for DESY in the framework of DarkQuantum might make a real difference in dark matter searches and in addition will help very much further enlarging quantum sensing expertise at DESY in general. KIT is participating in this project with a leading scientists from the Research Field Information.

Also mentioned already above, each of the four ERC grants for A. Nelles, A. Caputo, P. Pani, and E. Pueschel comes along with a budget of about 1.5 to 2.0 million EUR.

4.5 Research Infrastructure

Finally, the specific research policy objectives on the research infrastructures at topic level are mentioned and an interim resume of the status of implementation is drawn up, in detail:

- *Provide large-scale research facilities for users at GSI/FAIR affiliated with the MU program including the UNILAC, SIS18, and FSR accelerator facilities as well as the FAIR Green IT Cube.*

  GSI accelerator facilities UNILAC, SIS18 and FRS, are operated regularly for user experiments. Since main focus of GSI's activities is on the construction of the FAIR accelerator and experiment facilities, user beam time at GSI is limited to 100 days per year only. All GSI accelerator facilities were subject of extensive upgrade measures, i.e. the complete exchange of the accelerator control system, renewal of the SIS18 vacuum system and development of a pulsed gas stripper. During the current POF-IV period, the Green IT cube was constantly upgraded – partially by third-party funds - and offers compute capacities for all users of the experimental facilities as well as theoreticians. Compute resources are provided for the ALICE experiment at LHC in addition.

- *Operate the German Tier data centers for the LHC experiments, for Belle, and other consortia in particle and astroparticle physics (see the program MT).*

  The three German Tier data centers operated by Helmholtz are all LK-II facilities - at DESY (IDAF, Tier-2 for ATLAS, CMS, LHCb) associated to the program MT, at GSI (Green-IT Cube, Tier-2 for ALICE) and KIT (GridKa, Tier-1 for ALICE, ATLAS, CMS, LHCb) associated to this program MU. All Tier data centers are serving the four LHC experiments, Belle-II and further experiments in the particle and astroparticle physics domain such as Pierre-Auger Observatory and IceCube. The operational budget (in particular personnel and consumables including electricity) come from the LK-II budgets.

- *In particular, develop GridKa to be able to cope with the significantly higher data flows from the HL-LHC.*

  All three Helmholtz centers DESY, GSI, and KIT that are operating Tier data centers for HL-LHC have joined forces to position an entry in the Roadmap Research Infrastructures of the Helmholtz Association named "Upgrade TIER-Centers for HL-LHC" with a planned start of the financing for new hardware in 2027. GridKa as the German Tier-1 center serves all four LHC experiments, ATLAS, CMS, LHCb and ALICE, and is thereby one of the largest Tier-1s worldwide and is the major part of this joint infrastructure upgrade. KIT requires the financing from the research infrastructures roadmap entry to enable GridKa to cope with the significantly higher data flows from the experiments of the HL-LHC. In addition, the GridKa is being prepared in terms of operational readiness and flexibility as well as in particular in terms of energy-efficiency, e.g. through an advanced energy monitoring system, through seamless integration of opportunistic computing resources, through more energy-efficient computing hardware (ARM CPUs) and increased data handling capacities between the online/offline storage systems and computing cores.

- *Address additional challenges for the large-scale research infrastructures used within the program, e.g. the high luminosity upgrade of the LHC, novel sensors and detector systems, the Gamma Observatory CTA, the IAXO experiment, the IceCube-Gen2 interdisciplinary neutrino observatory, the GCOS Global Cosmic Ray Observatory, the AugerPrime upgrade, and the DARWIN project.*

  In the recent three years, the two **LHC groups ATLAS and CMS** made significant progress towards the assembly of each on end-cap for the new tracking systems for the HL-LHC phase of the experiments. The detector assembly facility is in full swing and used by the DESY groups for the many different tasks towards the construction of these complex detectors. Both groups finalized the developments for the module production and are ready to start the production. In addition, CMS has shown at DESY in a test with international partners that modules can integrate into a full Dee. ATLAS set up the system test in which fully loaded petals will be tested under realistic conditions including running at -30°C.

  Most activities towards developing novel sensors and detector systems are part of the program Matter and Technologies (MT), and are addressed in the corresponding report. Within MU, the new pixel vertex detector for the **Belle II** experiment has been developed, built and commissioned at DESY in the past years, with the help of numerous German university groups. The new detector will be instrumental for high-precision measurements of rare processes at Belle II. The massive steps towards realizing the upgraded tracker endcaps for the LHC experiments ATLAS and CMS have been addressed above.

  DESY has taken on a lead role in the organisation of the German community contributions, in the communication with the German ministry in the context of **CTAO**, and as a shareholder of the current legal entity (CTAO gGmbH). Observatory contributions in the areas of telescopes (Medium-Sized Telescopes, cameras for Small-Sized Telescopes) and software and computing (off-site data centre, control and simulation software, computing services) are now in full swing at DESY. The end of construction of the Science Data Management Center (SDMC), one of four CTAO locations, at DESY in Zeuthen is foreseen for the second half of 2024, while DESY is already hosting 15 CTAO SDMC staff members on its own premises.

The **BabyIAXO** experiment, a prototype for the larger **IAXO** with own unique discovery potential, was essentially ready to start construction in spring 2022, when the Russian invasion into the Ukraine ripped the collaboration apart. Among others, essential components of the large dipole magnet were planned to be contributed by Russian institutes. Since then, the collaboration has re-organized itself also involving industrial companies and recovered from the shock. All components for BabyIAXO are ready to be built with the exception of the magnet, where a Conceptual Design Report will be evaluated in April 2024. Assuming a positive outcome, a Technical Design Report will be worked out by the end of 2024 as a basis for financial discussions and call for tenders.

There is continuous progress in the realization of the expansion of the IceCube Observatory at the South Pole to **IceCube-Gen2** despite the additional challenges caused by the COVID-19 pandemic (during which the South Pole station was effectively closed) and the resulting logistical problems of the NSF. As a result, the original planning for the financing and construction of the IceCube-Gen2 Interdisciplinary Observatory will be delayed by a few years. Nevertheless, the course for Gen2 must still be set in PoF-IV. The technical design report with its three parts (science, detector, logistics) has already been partially published and will be completed and submitted to the NSF in 2024. The two groups of the Helmholtz program MU in IceCube at KIT and DESY are significantly involved in the TDR and are together the largest partner in the project after the NSF. In addition, IceCube-Gen2 is part of the Helmholtz Roadmap for large infrastructures. Detector prototypes are developed and the IceCube-Upgrade as test environment has made significant progress. As a further achievement, the IceCube Neutrino Observatory has now been included in GridKa as a supported experiment.

AugerPrime as a comprehensive extension of existing detector systems of the Pierre Auger Observatory, of which all planned systems except the radio extension have already gone into operation during Phase I of the observatory until the end of 2023, will lay the foundations for the next generation experiment **GCOS**. There are already scientific results from Phase I that support the realization of a next-generation experiment, the relevance of which will be demonstrated by more detailed investigations performed using AugerPrime. This view is also reinforced by an international science advisory committee, established by the Finance Board of the Pierre Auger Observatory, that has recommended a prolongation of the operation of the observatory until at least 2035. Furthermore, the observatory has become an important testbed for new detector developments in order to explore and establish promising detection methods, notably including work on GCOS but also from other experiments. The successful implementation of the AugerPrime upgrade was largely undisturbed despite the coronavirus pandemic, as comprehensive measures were implemented very quickly, particularly on site in Argentina, to minimize delays. After early discussions in a kind of orientation phase, first actions towards a future GCOS experiment will be carried out during the next PoF period.

A first-stage proposal for **DARWIN** to the Roadmap Research Infrastructures of the Helmholtz Association as an international infrastructure (category C) was put forward to Helmholtz in summer 2022. The project was positively evaluated by the Research Infrastructure Committee and endorsed by the Helmholtz senate in 2023. As a result, the next-generation xenon-based observatory is now included in the Helmholtz Research Infrastructure Roadmap. In 2021, the DARWIN, XENON and LZ collaborations formed the XLZD Consortium, with the goal of building a next-generation xenon detector together. Consortium members published a White Paper detailing the broad physics reach of the next-generation xenon-based and convened for a first in-person consortium meeting at KIT in summer 2022. Meanwhile, DARWIN/XLZD has entered multiple international roadmaps and funding schemes in recent years (e.g. SERI Roadmap 2025-28 in Switzerland, the „Future Academic Advancement Plan (update 2023)" of the Science Council of Japan, the APPEC Roadmap Update 2023, among others). A large-scale funding initiative for XLZD was launched in the UK, and the next-generation dark matter observatory was supported by the P5 recommendations in the US in December 2023. A shortlist of hosting lab options is actively investigated, and a detailed siting report is expected to be released in spring 2024 alongside a preliminary "Design Book". During 2023, a computing framework for the DARWIN Observatory was included in GridKa at KIT as a supported experiment, and also R&D efforts addressing technological and physics challenges are under way throughout the collaboration, with a current focus on the development of large-scale high-voltage electrodes for the detector with the Helmholtz program MU at KIT.

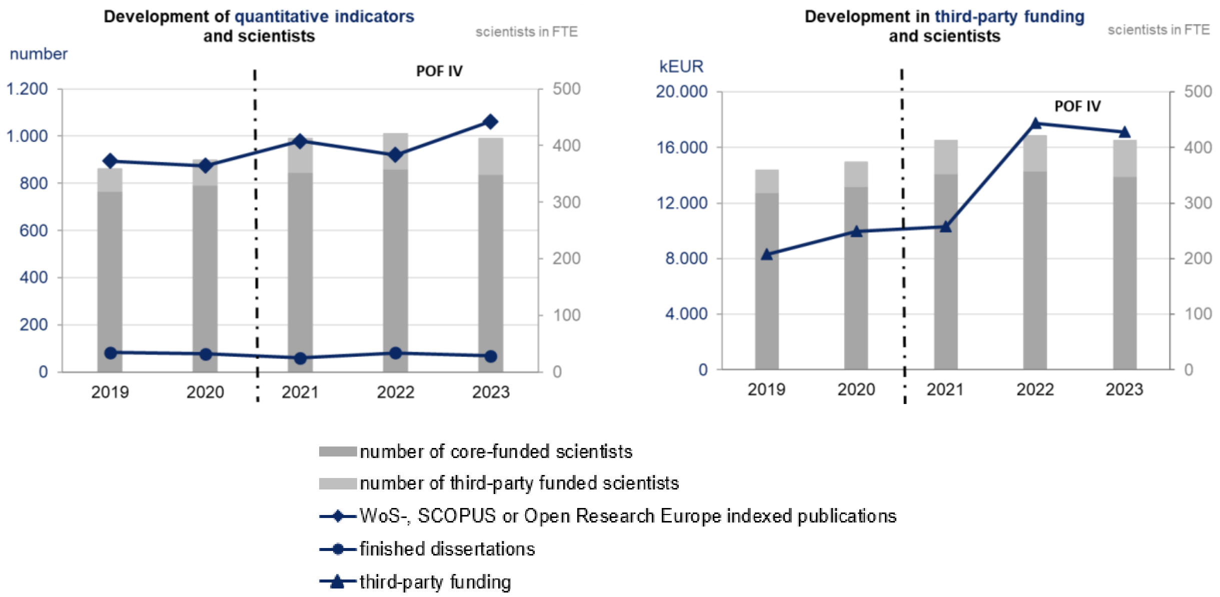
5 Indicators and Resources

5.1 Quantitative Indicators

	unit	2019	2020	2021	2022	2023	development 2023 vs. 2022 absolute	development 2023 vs. 2022 percentage
WoS-, SCOPUS or Open Research Europe indexed publications	no.	894	874	979	920	1.062	142	15%
… thereof open access publications	no.	802	767	842	813			
Other peer-reviewed publications	no.	116	21	156	103	127	24	23%
Third-party funding	kEUR	8.319	9.985	10.312	17.765	17.112	-653	-4%
Finished dissertations	no.	83	78	61	82	69	-13	-16%
Postdocs	no.	205	217	248	239	217	-22	-9%
Junior research group leaders	no.	17	12	13	12	14	2	17%
Selected coordinated national and international third-party funded research programs	no.	27	27	35	43	44	1	2%
Cooperations with the industry and external non-scientific institutions, publicly or privately financed	no.	23	28	23	23	37	14	61%
Spin-offs and competence-based foundations (start-ups)	no.	0	0	0	0	0	0	-
knowledge transfer activities in FTE	FTE	11	11	10	18	17	-1	-6%
Number of core-funded scientists	FTE	320	330	353	358	349	-10	-3%
Number of third-party funded scientists	FTE	40	44	60	62	64	1	2%
Scientists in total	FTE	341	356	412	421	412	-8	-2%

for information:

Citable published research data publications	no.	0	0	3	31	64	33	106%
Citable published research software publications	no.	0	3	1	2	10	8	400%



Comments:

Publications: The number of publications has increased a bit, but can be considered as a typical annual fluctation. Furthermore, the numbers of publications for 2022 have been adjusted by all contributing centers because of delayed updates of the corresponding databases, so that the value for 2022 has increased by 56, compared to the reported value in the 2022 program report.

The rate of open access publications for 2022 lies at the good level of previous years. For 2022, the program MU has published more than 88% of its publications in an open access format. With this open access rate, the program MU is reaching the target of the Helmholtz open access policy which aims for an open access rate of at least 60% for 2021, steadily increasing by 10% each year, and having full open access coverage in 2025. However, also a kind of different culture can be seen within the different communities. While the particle and astroparticle physics communities have open access rate between 92% and 99.5% over the reported years, with maxima for 2022 publications of those centers participating in these communities of 97.6% and 99.5%, the open access rate in the community of physics of hadrons and nuclei lays between 62% and 72%.

Please note that the numbers of publications for the PoF-IV, so the data since the year 2021, are corrected for double reporting in case of participation of more than one center. In the program MU, there are between 40 and 85 publications in each of the years, which list authors of two of our contributing Helmholtz centers. In the sum reported here, these publications appear only once.

In addition to the classical paper publications, it has been started to evaluate also the numbers of open access scientific data and software publications. For being countable in this indicator, the data and software has to be citable published provided with a persistent identifier (esp. DOI) and must be stored in a repository with metadata (e.g. as listed in re3data.org). The numbers for MU are given in the grey rows in the upper table. It has to be mentioned that this is a new test monitoring, and the given numbers are incomplete as only KIT has set up a procedure for monitoring these numbers backwards since 2018. GSI started this monitoring in 2022 and DESY in 2023. The given numbers for open access software publications from KIT do include publications from the LK-II facility GridKa. The high and increasing rate of open access scientific data is dominated by publications of the community of physics of hadrons and nuclei.

Third-party funding: The amount of third-party funds is at a compatible level to the previous year, even though there are smaller variations at some participating centers. For multi-annual projects, the funding provision is typically not flat, so that for some years larger amounts of third-party funding are recorded. Furthermore, the contributing centers serve as primary recipients for several multi-partner consortia.

Finished dissertations: The number of finished dissertations is in the range of typical year-to-year fluctuations, where the last years showed somewhat larger fluctuations because of the COVID-19 pandemic.

Core-funded scientists: The number of core-funded personnel is slightly lower than in previous years during this PoF-period. This is a first sign of significantly increasing energy and personnel costs for the program while the budget remains constant.

Third-party funded scientists: The number of third-party funded personnel is almost constant and should be interpreted only as typical annual fluctuations.

5.2 Development of Costs

strategic recommendations of the Senate [in kEUR]	plan 2021	plan 2022	plan 2023	plan 2024	plan 2025	plan 2026	plan 2027	total 2021-2027
program costs incl. non program bound (20 %)	**88.427**	**89.922**	**91.448**	**93.006**	**94.595**	**96.216**	**97.871**	**651.485**
DESY	49.138	50.251	51.389	52.552	53.740	54.954	56.194	368.218
GSI	15.044	15.044	15.044	15.044	15.044	15.044	15.044	105.310
KIT	24.244	24.626	25.015	25.410	25.811	26.218	26.632	177.957

actual costs update: February 2024 [in kEUR]	actual 2021	actual 2022	plan 2023	prel. actual 2023	plan 2024
program costs	**101.762**	**104.248**	**91.448**	**107.632**	**93.005**
DESY	53.368	55.080	51.389	52.211	52.552
GSI	19.376	18.459	15.044	25.381	15.044
KIT	29.018	30.709	25.015	30.040	25.410

deviation actual costs vs. strategic recommendations of the Senate [in %]	15%	16%	0%	18%	0%
DESY	9%	10%	0%	2%	0%
GSI	29%	23%	0%	69%	0%
KIT	20%	25%	0%	20%	0%

Comments:

GSI: The higher preliminary ACTUAL costs of the GSI program share is explained by the overall higher costs of the GSI compared to the Senate recommendations, which lead to a higher allocation than planned. In addition, depreciation (from third-party funds) is higher than originally assumed.

KIT: The preliminary cost deviation of approximately 5.0 Mio. € (20 %) is partially based on the extrapolations still included in the costs as of the reporting date, e.g. from the areas of internal cost allocation, apportionment allocations, calculation of depreciation, etc. From today's perspective, KIT cannot exclude that the 20% overrun existing on the reporting date will persist as an unplanned deviation from the financing recommendations after completion of the internal cost allocation for 2023. Exceeding costs are financed with non-program-related funds from other programs. Based on the current resource planning for 2024, KIT does not expect any relevant deviations from the existing funding recommendations for this program.

Associated Research Infrastructures (LK II)

1 Research Infrastructure GridKa

In the reporting period the GridKa compute and storage services were provided smoothly to the experiments. All technical developements are done in close coordination with the GridKa Overview Board. The batch farm was upgraded in terms of security software to replace the aging X.509 access mechanisms with modern token-based authentication/authorization methods. Due to foreseeable higher energy costs per kWh for 2023, a discussion and decision took place in the GridKa Overview Board in November 2022 to switch off more energy-consuming compute nodes for 2023 to stay within budget – this had absolutely no influence on fulfilling the pledges of GridKa resources to the international user community. Towards the end of the year a procurement was initiated for a few ARM based compute nodes, which will provide a ~20% higher computing performance per Watt.

In the tape-based offline storage system the migration activities from TSM to the HPSS technology dominated 2023. After CMS and LHCb in 2022, ATLAS is also finished, and the ALICE data are now being migrated. The new flash-based buffer in front of the tape system has been put into production and has significantly increased the overall performance.

The volume of data transferred to and from GridKa to other centers has remained at a very high level. The joint development of the COBalD/TARDIS software for opportunistic computing was successfully continued. In addition, the close cooperation with the Helmholtz program "Engineering Digital Futures" (EDF) in the Research Field Information is successfully continued regarding the development of COBalD/TARDIS, European projects in the context of the European Open Science Cloud (EOSC), in the context of the National Research Data Infrastructure (NFDI) as well as in the context of ErUM-Data and related development projects. COBalD/TARDIS was used to build up the federated compute & data infrastructure in PUNCH4NFDI.

1.1 Recommendations of the Senate

The Senate of the Helmholtz Association provides the following specific recommendation:

- *The Senate agrees with the very positive evaluation of the LK II infrastructure Tier-1 data and computing center GridKa and approves its funding with an according increase of 2% adjusted full-cost accounting planning.*

  GridKa LK II is extremely grateful for this recommendation as it provides an important basis for operating the GridKa compute and data resources for the LHC Run3 as well as for the HL-LHC phase for the international user community. However, price increases, especially for electricity in the year 2023, have shown that the 2 % increase will not be sufficient. Additionally, moving to more green energy will further increase prices per kWh. Therefore several measures are taken within GridKa in fulfilling the future resource pledges, while at the same time become more energy-efficient, consume less energy and potentially utilize locally produced energy from renewable sources.

1.2 Indicators and Resources

1.2.1 Quantitative Indicators

		unit	2019	2020	2021	2022	2023	development 2023 vs. 2022 absolute	development 2023 vs. 2022 percentage
total annual runtime		h	8.760	8.784	8.760	8.760	8.760	0	0%
planned runtime for users		h	8.740	8.736	8.737	8.700	8.725	25	0%
reliability of the large scale facility during user operation		%	99	99	99	99	99	0	0%
booking factor Helmholtz-intern		%	< 5	< 5	< 5	< 5	< 5	-	-
booking factor Helmholtz-extern		%	> 95	> 95	> 95	> 95	> 95	-	-
external users: universities	national	no.	> 100	> 100	> 100	> 100	>100	-	-
	international	no.	> 2000	> 2000	> 2000	> 2000	> 2000	-	-
external users: research Institutes	national	no.	> 50	> 50	> 50	> 50	>50	-	-
	international	no.	> 1000	> 1000	> 1000	> 1000	>1000	-	-
publications	total number	no.	k.A.	k.A.	k.A.	k.A.	k.A.	-	-
	thereof LK I	no.	4	6	1	0	4	4	-
	thereof also noted in *Matter and Technology:*	no.	0	0	0	0	0	0	-
average utilization of CPU		%	100	99	99	97	97	0	0%
average utilization of online storage		%	80	90	85	85	85	0	0%
number of core-funded scientists		FTE	14	18	19	17	17	0	2%

Comments:

Availability and Utilization: GridKa's availability and utilization are at a consistently high level. Part of the online storage is used for temporary storage of data for high-throughput computing and as temporary intermediate storage for transfers to and from offline storage. Therefore, utilization close to 100% is not possible in principle for the online storage. The actual utilization depends on the way the storage is used by the experiments in the form of the combination of analysis, simulation and reprocessing jobs and therefore fluctuates from year to year.

Publications: For GridKa, the number of publications is determined as for the research of the LK-I part of MU. These numbers are within typical variations, and the low level is caused by the systematics of counting. Some publications with participation of GridKa are primarily assigned to LK-I research activities in MU and thus counted in the LK-I statistics.

Core-funded scientists: The number of core-funded scientists is quite stable and lies within typical personnel turnover.

1.2.2 Resources

strategic recommendations of the Senate [in kEUR]	plan 2021	plan 2022	plan 2023	plan 2024	plan 2025	plan 2026	plan 2027	total 2021-2027
costs of research infrastructure GridKa (KIT)	7.442	7.591	7.743	7.897	8.055	8.217	8.381	55.326

actual costs update: February 2024 [in kEUR]	actual 2021	actual 2022	plan 2023	prel. actual 2023	plan 2024
research infrastructure costs	7.612	6.396	7.743	6.339	7.897
deviation actual costs vs. strategic recommendations of the Senate [in %]	2%	-16%	0%	-18%	0%

Comment:

The preliminary cost deviation of approximately -1,4 Mio. € (-18 %) is partially based on the extrapolations still included in the costs as of the reporting date, e.g. from the areas of internal cost allocation, apportionment allocations, calculation of depreciation, etc. In the case that funds are not utilized, they are being used to finance cost overruns in other programs. Based on the current resource planning for 2024, KIT does not expect any relevant deviations from the existing funding recommendations for this program.

2 Research Infrastructure GSI-MU Ion Facilities

The linear accelerator facility UNILAC, the heavy-ion synchrotron SIS18, and the fragment separator FRS for the production and identification of exotic nuclei were operated during an extended engineering run in 2023. The user beam time originally planned in 2023 was shifted to 2024 because of rising energy and materials costs, in addition to extensive construction works. Several experimental facilities have been served for detector testing, with the major goal to facilitate an early start of user beamtime in 2024.

Within six weeks in autumn, an extremely ambitiously planned engineering run was carried out. The accelerator crew performed over 50 machine experiments and intensity campaigns. New machine modes were established, such as the world’s first dual-beam mode, in which two types of ions are accelerated simultaneously. New methods, devices and systems were tested. A particular highlight is the new world intensity record for the FAIR design beam Uranium 28^{+} of more than 5×10^{10} particles per spill.

The experimental facilities of CML have been upgraded for the FAIR Phase-0 campaign in 2024. One decisive measure took place at the separator for super-heavy element production studies, SHIP. New power supplies for the quadrupole magnets were delivered and installed. The functionality of the new power supplies was tested at the engineering run in November 2023. Here, one day of ^{40}Ar beam was used with ^{169}Tm and ^{208}Pb targets. The obtained results of the fusion products in rate and spatial distribution match the expectations and thus SHIP is again ready for the upcoming physics beamtime 2024.

GSI is currently installing an extensive measuring network to record energy data (electrical & thermal data) and is planning to introduce an extended energy management system that meets the requirements of ISO 50.001. Since 01.01.2023, GSI has only purchased electricity from renewable energy sources.

2.1 Recommendations of the Senate

- *The funding of the Research Field associated User Facility at GSI (UNILAC, SIS18, FRS, ESR etc.), which is in reduced operating mode, is organized by a dedicated agreement of the Helmholtz Association and GSI, and can be assigned in total or parts as a LK II facility in PoF IV, given fulfilled criteria for that.*

  In 2022, it was requested and supported by Management Board Matter that the GSI ion facilities will be classified as LK II user infrastructures in the current PoF period, as they meet the relevant requirements and are already listed as such in the documents. This does not have any effective financial consequences until 2025, and the GSI-MU Ion Facilities do not profit from the increase in funding of LK II infrastructures.

2.2 Indicators and Resources

2.2.1 Quantitative Indicators

		unit	2019	2020	2021	2022	2023	development 2023 vs. 2022 absolute	development 2023 vs. 2022 percentage
total annual runtime		days			161	145	77	-68	-47%
planned runtime for users		hours			95	95	95	0	0%
reliability of the large-scale facility during user operation		%			1	1	-	-	-
number of experimental stations	used simultaneously or not	no.			10	10	-	-	-
	only used simultaneously	no.			10	10	-	-	-
actually used beamtime		hours			124	118	0	-118	-100%
overbooking factor					-	3	-	-	-
booking factor Helmholtz-intern		%			52%	14%	-	-	-
booking factor Helmholtz-extern		%			48%	86%	-	-	-
external users: universities	national	no.			104	113	-	-	-
	international	no.			226	274	-	-	-
external users: research institutes	national	no.			92	25	-	-	-
	international	no.			228	228	-	-	-
external users: industry	national	no.			0	0	-	-	-
	international	no.			0	0	-	-	-
publications	total	no.			30	3	24	21	700%
	thereof LK I	no.			29	0	23	23	-
number of core-funded scientists		FTE			0	48	45	-3	-6%

Comments:

During PoF III, GSI's campus Darmstadt was excluded from the PoF procedure, i.e. the facilities did not operate as LK II facilities. In PoF IV they will be listed as LK II facilities again.even if GSI does not participate in the regular LK II procedure of the Helmholtz Association until 2025.

While the main focus at GSI currently and in the coming years will continue to be on the design and construction of FAIR, a limited user operation of the experimental and accelerator facilities will continue as part of the so-called "FAIR Phase-0". With experimental operation at the UNILAC/SIS18 accelerators, which are being improved in preparation for FAIR, and the FAIR instruments already available, such as CRYRING, R3B etc., FAIR Phase-0 offers the national and international user community of GSI and FAIR unique opportunities as a user facility.

Due to increased energy costs and technical work, no regular user beam time was offered at the GSI accelerators in 2023. However, experiments could be carried out at the FAIR CRYRING ring in standalone operation (program MML). Additionally, various user groups used the opportunity to test beam conditions on their experimental setups during the engineering run at the end of 2023, during which numerous improvements could be made to the accelerators. However, longer experiment times were not possible during this time.

(1) The actual value given here for the total operating time of the ion facilities refers to the days on which they were running in the reporting year (in the engineering run) (77 days).

(2) During FAIR Phase-0, "Calls for Proposals" are only opened approximately every two years due to the limited amount of beam time available. While no applications could be submitted for MU research in 2021 and 2023 (i.e. no overbooking), beam time applications were submitted to the General Advisory Committee (G-PAC) in 2022. Depending on the facility, the overbooking was between 1.8 and 4.0.

2.2.2 Resources

strategic recommendations of the Senate [in kEUR]	plan 2021	plan 2022	plan 2023	plan 2024	plan 2025	plan 2026	plan 2027	total 2021-2027
costs of research infrastructure GSI MU Ion Facilities (GSI)	23.579	23.579	23.579	23.579	23.579	23.579	23.579	165.053

actual costs update: February 2024 [in kEUR]	actual 2021	actual 2022	plan 2023	prel. actual 2023	plan 2024
research infrastructure costs	32.070	27.658	23.579	17.192	23.579
deviation actual costs vs. strategic recommendations of the Senate [in %]	36%	17%	0%	-27%	0%

Comment:

There was no beam time at GSI in 2023, so the costs were lower than originally planned.