Progress Report 2022 –

Scientific Annex

Program “Matter and the Universe”

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**Program “Matter and the Universe”**

Along with the Program Progress Report 2022, the program MU presents some scientific insights in its activities in 2022.

1 Introduction

The MU program is characterized by a particular breadth and depth of expertise in its coherent ap-proach 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.The program performs the research within three topics and two LK-II research infrastructures:

Program topic 1 - Fundamental Particles and Forces - investigates the most fundamental building blocks of the world and their interactions, addressing fundamental questions of 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 highlight of this topic in 2022 is the most up-to-date combination of results on the properties of the Higgs boson published by the experiments ATLAS and CMS in *Nature*. The measurements have advanced from discovery to precision mode, allowing researchers to harness the new particle for fundamentally new studies of the quantum world and the structure of the vacuum. Among the most striking summary results are the measurements of the couplings of the Higgs boson to other standard model (SM) particles as a function of particle mass. The measurements demonstrate how well the Higgs particle is described by the SM predictions.

Program topic 2 - Cosmic Matter in the Laboratory - 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 highlight of this topic in 2022 was achieved by an experiment at the Radioactive Ion Beam Factory RIBF at Riken by an international research team with leading participation of CML scientists from TU Darmstadt. An exotic 8He beam has been fragmented on a proton target to study events where the 8He nucleus emits an α-particle, thus a system of four neutrons is left behind. By measuring the energy of α-particle and the scattered proton, the missing energy could be attributed to the four neutrons.

Program topic 3 - Matter and Radiation from the Universe - has the largest structures of the universe and the properties of the fundamental building blocks as its research topic. Astroparticle physics in MU is carried out at observatories at extreme locations on Earth and at high-precision experiments in laboratories. The highlight of this topic in 2022 was a closer evaluation of data from the 2021 outburst of RS Ophiuchi, a recurrent nova, showing that the emission of the very-high-energy (VHE; ≳ 100 GeV) gamma rays lasted up to 1 month after the outburst. The temporal profile of VHE emission is similar to that of lower-energy GeV emission, indicating a common origin, with a 2-day delay in peak flux. These observations constrain models of time-dependent particle energization, favoring a hadronic emission scenario over the leptonic alternative.

LK-II Research Infrastructure – GridKa - as a WLCG Tier-1 center, is responsible for the processing, reprocessing, and archival of raw data from the LHC and future HL-LHC experiments as well as from specific MU astroparticle physics observatories. Other WLCG centers, in particular Tier-2 centers, rely on GridKa as their data source and data archive. In 2022, the compute and storage resources could be further expanded along the requirements of the experiments. Operations of the Batch Farm were smooth and security updates were done continuously. The usage of the GPU nodes is slowly but steadily picking up. A precise and detailed power monitoring has been installed.

LK-II Research Infrastructure – GSI-MU Ion Facilities – are operating large and worldwide unique heavy-ion accelerators which serve a multitude of scientific topics. It also includes the GSI Green IT Cube, the main facility for all computing activities on the campus. In 2022, the linear accelerator facility UNILAC, the heavy-ion synchrotron SIS18, and the fragment separator FRS have served a broad user community. Also the HADES and the WASA experiments have received beam time for studies of the electromagnetic decay of strange hyperons and the interaction of strange particles with nuclear matter. An application to the EU-REACT program for an extension of the Green-IT Cube has been approved and a Digital Open Lab within Green-IT Cube was founded.

However, 2022 was not throughout a year of progress and highlights. 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 has also led to the interruption of supply chains and rapidly rising energy costs. The situation is very volatile and the effects on science and, in particular, on the set goals of the Helmholtz program MU cannot be quantified at this time. In the case of the large particle physics experiments at CERN, for example, there is a backlog of unpublished research results, because there is still an agreement to be found on how to treat the authorships of Russian institutions in the collaborations. For other projects and large infrastructures (e.g. FAIR, XFEL, CERN), partnerships with Russian institutions have been suspended, resulting in a loss of know-how and a lack of technological and scientific contributions. The resulting energy crisis has led to unprecedented increases in the price of electricity, jeopardizing the operation of numerous infrastructures and experiments in planned operating cycles. How far this fundamental change in the situation in Europe and the world will affect the achievability of our scientific goals will only become clear in the years to come.

2 Topic 1 – Fundamental Particles and Forces

Topic 1 is structured into three subtopics: i) Higgs properties and fundamental interactions at high precision; ii) Searches for new particles and phenomena; iii) Cosmology and the dark sector of the universe. Significant work is also spent on technological aspects like detector and accelerator R&D, system integration, or scientific computing, software etc. Here, we will treat specific aspects of these efforts that are not part of the “Matter and Technologies” program under the heading of “Detector R&D and construction, accelerator R&D, system integration, computing” below.

In summer 2022, the **LHC** resumed operation (“Run 3”) after a long shutdown with many upgrades of the machine and detectors. The **ATLAS** and **CMS** teams are finalising the Run 2 data analysis and achieved first preliminary results from Run 3 at record proton beam energies of 6.8 TeV per beam. The HL-LHC upgrades planned for 2026-2028 were a central topic throughout 2022, with the preparations for production and integration at DESY of the tracker endcaps for both ATLAS and CMS progressing well. In contrast, the **Belle II** data taking period stopped earlier than planned in 2022 because of strongly increased electricity costs. Nevertheless, an integrated luminosity of 428 fb-1 could be recorded by the end of June 2022. The SuperKEKB accelerator experts succeeded in further increasing the instantaneous luminosity to 4.7·1034 cm-2s-1, but is still much below the design value. The ongoing long shutdown will be used to implement a number of hardware modifications to improve beam injection, beam lifetime and stability, and to reduce/mitigate the sudden beam loss events. The assembly of the two half-shells of the new two-layered PXD2 was finished in August, and both half-shells are currently being pre-commissioned before installation at KEK, hopefully in spring 2023.

A lot of progress was made for the DESY on-site experiments: In 2022, **ALPS II** has come very close to start a first science run. The experiment achieved an “interferometer world-record” [1], reaching a light-storage time in-between two mirrors of 6.75 ms. All components of the experiment are installed and operational; the collaboration plans to use a stray light search (to demonstrate the light-tightness of the “wall”) in early 2023 already for first axion searches. **BabyIAXO** is facing delays due to the Russian attack on the Ukraine: at present there is no supplier for the Al-stabilised Rutherford cable required for the magnet outside Russia. Counter-measures are pursued together with CERN. Significant progress of all other BabyIAXO components has been made. The collaboration is investigating the potential of a first set-up without the magnet to search for solar hidden photons and to study the system performance. **MADMAX** has progressed very significantly with the first prototype measurements with the MORPURGO magnet at CERN. Most prominently, the environment was found to be sufficiently “RF-quiet” and hence suitable for axion searches, and a detector calibration procedure based on reflection and black-body radiation measurements could be verified. The **LUXE** experiment has presented a complete technical design in early 2022 and the DESY directorate has included the project in its roadmap. Five new institutes joined, including partners from KIT, bringing the total now to 19 European institutions. With the Russian war on the Ukraine, a significant part of the foreseen funding has broken away, and currently ways to circumvent this problem while staying in time are being investigated.

**Theoretical physics** at DESY is pursuing its efforts in many sub-disciplines, closely interlinked with the experimental program, and DESY theorists play a key role in the Quantum Universe cluster of excellence between Hamburg University and DESY. The group still hopes to further strengthen its word-leading position with a dedicated building for the multi-disciplinary Wolfgang Pauli Centre (WPC) that will serve as a world-leading centre of theoretical physics. The DESY Theory workshop in September 2022 and the WPC symposium in connection with the award ceremony of the Hamburg Prize for Theoretical Physics funded by the J. Herz Foundation gathered a large international community in Hamburg.

Studies for **future international collider projects** are progressing, in particular for a Higgs factory as recommended by the European strategy for particle physics. DESY is involved in physics studies and generic technical developments for such facilities, and is represented in various bodies relevant for developing the future of the field (ICFA, ECFA, LDG, KET in Germany, etc.).

Concerning the subtopic “**Higgs properties and fundamental interactions at high precision**”, ten years after the Higgs (H) discovery in 2012, ATLAS and CMS have both published papers in *Nature* [2,3] containing the most up-to-date combination of results on the properties of the Higgs boson, including the most stringent limit on the cross section for the production of a pair of Higgs bosons. Numerous other important Higgs results were achieved. With the increasing size of the LHC datasets, measurements probing the structure of the Higgs particle and of fundamental interactions can be performed with higher precision and more differentially.

With the increasing size of the LHC datasets, measurements of standard model parameters can be performed with even higher precision. Lead by DESY scientists, the CMS group has measured the top quark pole mass using top-antitop quark events in the dilepton final states [4]; and the ATLAS collaboration with strong contributions from DESY physicists has provided the most precise measurement of the pp elastic and inelastic cross sections, allowing to separate different models [5].

Numerous theory results about Higgs and standard model physics have been obtained. The widely used tools *HiggsBounds* and *HiggsSignals* that compare model predictions of “Physics beyond the Standard Model” to searches for additional scalars and to measurements of the observed Higgs boson have been updated [6]. Theoretical [7] and phenomenological [8] characterisations of the violation of the CP symmetry have been pursed in parallel to the experimental analyses conducted by ATLAS and CMS. The prospects for the sensitivity of the Higgs coupling determination at different future Higgs factories have been updated [9], and the Next-to-Leading-Order electroweak corrections to multiple massive boson production processes at a future muon collider have been computed [10]. The impact of interactions between hidden sectors and the discovered Higgs boson was scrutinised to set stringent bounds on various dark matter models from the limit on the invisible decay width of the Higgs boson [11]. At KIT, precision calculations for observables to be measured at ATLAS, CMS, LHCb, and Belle II as well as at future colliders were pursued, with a focus on Higgs physics inside the standard model [12-14] and on low-energy observables [15-18] as well as single top [19] and dilepton production [20] at the LHC.

Efforts are underway atBelle II to update the search for the rare B-meson decay  with the full Belle II dataset, which will greatly improve on the existing results. The world’s best measurement of D0 and D+ meson lifetimes was performed [21]. This and a new world-best lifetime measurement of a charmed baryon produced at Belle II, the Λ+c [22], and a Ωc lifetime measurement [23] again demonstrated the excellent performance of the installed PXD, which has only two ladders out of 12 intended installed in its second layer. Nevertheless, the preparations for the fully instrumented PXD2, to be installed in 2023, are of very high importance for future data taking periods and for additional precision.

The second subtopic concentrates on “**Searches for new particles and phenomena**“; it is motivated by various shortcomings of the standard model. These searches can be carried out directly, looking for new particles or new processes to occur, or indirectly via high-precision measurements that probe the theory at the quantum level. In both cases, a close interplay between experiment and theory is crucial. The LHC collaborations have e.g. searched for long-lived particles with flight distances between less than a millimeter and meters that might be expected from several models of physics beyond the standard model. ATLAS could exclude models with dark photons in that range [24]. In another analysis searching for hadronic decays in the active volume of the detector, long-lived supersymmetric particles with masses below around 1.5 TeV could be excluded in the lifetime range [25]. ATLAS has also searched for promptly decaying supersymmetric partners of leptons and weak gauge bosons. The analysis is sensitive to relatively small mass differences between the lightest and the next-to-lightest super-symmetric particles [26]. This analysis especially covers regions in the supersymmetric parameter space that could explain the observed anomaly in the magnetic moment of the muon. In searches for additional Higgs bosons, CMS has recently discovered several excesses in top quark and tau lepton final states, e.g. at around 100 GeV, 400 GeV, and 1.2 TeV [27]. Together with a previously observed excess around 96 GeV in the di-photon channel and hints at the same mass region from b quark pair final states at LEP, this created a lot of discussion and efforts at interpretation among theorists [28,29]. At the same time, theorists are proposing new channels to search for extended Higgs sectors and confront bounds from Higgs searches with various model predictions [30-34]. Vacuum instabilities, scenarios of electroweak symmetry non-restoration, vacuum trapping and first-order phase transitions were studied in extensions of the standard model [35-37]. Precision calculations for Higgs physics in theories of new physics beyond the standard model [38,39] and for further signatures of new particles at the LHC [40] were also performed. Finally, signatures of monopoles in fixed-target experiments [41] and in unified gauge theories were studied [42].

Searches for axions and axion-like particles (ALP) are becoming an increasingly hot topic. New theoretical studies [43,44] show that some new kinematic effects can actually open up significantly the viable parameter space for ALP dark matter, giving extra motivations for the experimental searches: For ALPS II, the physics case has been inspired by predictions of QCD axions in reach of ALPS II [45] and the observations of TeV photons from GRB 221009A [46]. Additionally, new insights on the axion-nucleon coupling corroborate the BabyIAXO physics case [47]. DESY scientists have searched for ALP at Belle II [48], by using LHC data e.g. in diboson channels [49], and developed ideas for searches at LUXE [50].

The third subtopic “**Cosmology and the dark sector**” concentrates on the open questions of dark energy and dark matter. Besides searches e.g. at the LHC [51,52], the topic is much driven by theoretical studies of dark matter and energy [53-57], by string theory [58-63], and by the physics of gravitational waves (GW). The latter field, in particular GWs of cosmological origin, is a focus topic in the DESY theory group [64]. A large number of results have been achieved in the past year, see e.g. [65-72]. It has also been realised that the on-site axion experiments can be used to search for high-frequency GW, since a GW that travels through a magnet will result in photons being produced that could be detected. At these high frequencies, there are no known astrophysical processes expected such that it is ideal to look for low-signal anomalous sources, e.g. from primordial black holes. Several experimental approaches are being considered at DESY.

**Detector R&D and construction, accelerator R&D, system integration, and computing** are key for current and future experiments in particle physics. Much of the relevant work is organised within the Helmholtz Program “Matter and Technologies”. Here, only the more applied aspects of the work are reported, although the boundary is not always sharp. Tools like the Key4Hep framework are developed at DESY, being a key development necessary for physics studies towards future colliders and also useful for other experiments that are being planned. Detector developments are focussed on 65um CMOS technology for silicon tracking detectors and on high-granularity calorimeters. More details are given in the MT DTS topic.

The preparations for the construction of the two end-caps for the new tracking detectors for the HL-LHC phase of the ATLAS and CMS experiments have made significant progress in 2022. Both DESY teams around the large silicon detectors are in the final phase of developments and are setting up the production. In ATLAS, a system test of the detector is being prepared and will also be carried out at DESY. In this test, a prototype segment of the full detector will be loaded with up to 12 petals and then tested under real experimental conditions, such as running at very cold temperatures [73]. A cold chamber, the frame for mounting the petals, and a large part of the infrastructure were built for this purpose and installed in the clean room. The system test will be carried out in 2023 as soon as the petals start to arrive. In addition, the silicon module production at both DESY sites has been prepared to start production at the beginning of 2023. CMS has completed the design of the detector modules and the DESY CMS group has made major contributions to the development of the test systems [74] in preparation of the module pre-series production, which will start in the first quarter of 2023. The design of the local support structures for the CMS end-caps was finalized. The first support structure of the pre-series production is currently being manufactured.

Axion search and gravitational wave experiments pose new challenges for low-noise detection methods. For ALPS II, superconducting transition edge sensors for low photon flux counting were qualified. The development of the alternative heterodyne detection system is progressing [75], as is a project to investigate membrane-based pressure sensors for low pressures at cryogenic temperatures. For laser interferometers for gravitational wave detectors, a new mirror cooling concept based on gaseous Helium was developed [76]. For the MADMAX experiment, key technologies regarding the drive system and the dielectric-disc handling could be demonstrated.

The KIT Computing group is developing new IT technologies for the HL-LHC. The focus is on increasing the efficient use of computing resources and the performance of data analyses. In 2022, KIT led the design and prototyping of a dynamic distributed heterogeneous computing infrastructure for PUNCH4NFDI. A main component is the compute resource manager COBalD/TARDIS. Improvements of the system and the user support of COBalD/TARDIS led to many more user in the context of the joint research project FIDIUM. For the High-Throughput-Analysis-Cluster at GridKa, the integration of GPU resources into WLCG computing and the use of these by official workflows of the CMS experiment succeeded for the first time, as well as the prototypical implementation of a parallel dask analysis cluster with considerable potential for increasing the performance in data analysis.

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3 Topic 2 – Cosmic Matter in the Laboratory

In 2022, the topic CML completed successfully various milestones and achieved impactful physics results. The FAIR civil construction is progressing and the roof of the SIS100 experimental hall, the home of CBM and HADES, has already been poured. At the same time a unique and exciting FAIR Phase-0 science program exploits the upgraded GSI accelerator chain and fully or partly available FAIR experimental instrumentation. This is supplemented by the participation in the ALICE physics analysis and upgrade of the ALICE detector in preparation for the upcoming high-luminosity LHC runs. Scientists involved in MU-CML have performed 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.

**Understanding the properties of hadrons and their excitation spectrum:** In February and March 2022, HADES collected data during 4 weeks on hyperon production in proton-proton collisions using a T = 4.5 GeV beam impinging on a 5 cm liquid hydrogen target. The goal of this experiment is the investigation of the electromagnetic decays of hyperon resonances. Dalitz decays of hyperons are a yet unexplored process and can be studied using the excellent capabilities of HADES. Such measurements will provide complementary information on hyperon structure and the role of strange quarks in baryons [1].

The preparation of the measurement of the pion transition from factor in virtual Primakoff kinematics, which yields input for the hadronic radiative corrections for anomalous magnetic moment of the muon, is further progressing. During several tests with prototypes at the MAMI accelerator, data have been taken measure background rates and to commission the front-end electronics. It is a PANDA FAIR Phase-0 project, where the backward endcap of the electromagnetic calorimeter of the PANDA detector will be used at the MAMI accelerator in Mainz.

**Establishing the QCD phase structure and understanding the microscopic properties of QCD matter at vanishing and high net baryon densities:** The HADES collaboration presents the first measurement of an electromagnetic transition form factor of an excited nucleon de-exciting in its ground state. In such decays, baryonic resonances release their excitation energy by emitting a virtual photon. The emitted photon is detected as a pair of an electron and a positron with HADES. Such data constitute a crucial test for Vector Meson Dominance (VMD) inspired models. A VMD amplitude vanishing at small e+e− invariant masses supplemented coherently by a direct photon amplitude provide a good agreement with a data. A good description is also obtained using a calculation of electromagnetic timelike baryon transition form factors in a covariant spectator-quark model, demonstrating the dominance of meson cloud effects [2].

The mCBM set-up at SIS18 is the precursor of the CBM experiment at FAIR, where detector prototypes are tested and data acquisition concepts are tested. In 2022, it was possible to reconstruct 500 lambda hyperon candidates from data taken for Ni+Ni collisions at 1.91 AGeV during a 2 hours run, which is an important step towards online reconstruction of lambdas [CML milestone 9 “High-speed online reconstruction with mCBM@SIS18 demonstrated“].

A substantial fraction of light nuclei such as d, t, 3He and 4He (and their anti-particles eventually) are produced in heavy ion collision even at the highest energies at LHC. Elucidating their production mechanisms is of prime importance not only for the fundamental understanding of the strong interaction, but also for space-born cosmic-ray measurements that investigate the nature of the mysterious dark component supposed to account for a large fraction of matter in our universe. Therefore, nuclei production is an important field of research from both experiment and theory. The ALICE collaboration reported measurements of yield ratios of deuterons and 3He to protons for different collision systems and energies, which show an increase as a function of multiplicity and eventually saturation at high multiplicity, which can be interpreted as interplay between evolution of the yields and system size with multiplicity [3]. From the side of theory, the production of clusters and hypernuclei has been studied employing the PHQMD approach, a microscopic n-body transport model based on the QMD propagation of the baryonic degrees of freedom with density dependent 2-body potential interactions [4]. In PHQMD the cluster formation occurs dynamically, caused by the interactions, and they are recognized by a Minimum Spanning Tree (MST) algorithm. Good agreement between data and theory was reached.

On July 5, 2022, the LHC Run 3 started officially with proton beams colliding at a center of mass energy of 13.6 TeV, the highest energy ever reached. ALICE recorded proton-proton (pp) collision data, usually at an interaction rate of 500 kHz, but has been ramping up the interaction rate with goal of running with up to 50 kHz in Pb+Pb collisions. Tests at various collision rates, as high as 5 MHz, were performed to investigate the detector occupancy and response. In November 2022, the ALICE collaboration could validate the new detectors and data acquisition systems in a test run with Pb-Pb collisions ahead of Pb-Pb physics run in 2023 [CML milestone 1 “Operation of the upgraded ALICE detector at the upgraded LHC at full Pb–Pb interaction rate“].

**Understanding nuclear structure, nuclear reactions, and superheavy elements as well as their relevance for nuclear astrophysics**: The laser spectroscopy studies of super-heavy elements were extended to the nobelium isotope 251No. Living shorter than one second, it is the shortest-lived nuclide that has been studied with this technique despite its very low yield. In addition, we measured isotope shifts in the fermium isotopes 245,246Fm extending the studies to eight Fm isotopes on either side of the deformed neutron shell closure at N=152. After having identified Z=114 to be the most volatile metal in the periodic table [5], the investigations of the chemical properties of superheavy elements are continued beyond Z=114. Strong relativistic effects as they occur in superheavy elements will ultimately change the chemical properties.

The WASA detector, a large acceptance detector for charged and neutral particles, has been installed in the middle focal plane of the Fragment Separator FRS in such a way, that the downstream part of the FRS can be used as high-resolution spectrometer. Two experiments have been performed using this set-up. One was aiming to investigate the characteristics of light hypernuclei [6], the other one to establish bound states of η’ in nuclear matter.

Image-guidance is one of the major obstacles in particle therapy. An extensively used method is positron emission tomography PET. PET in particle therapy exploits β+ emitting nuclei, which are produced by the particle beam in the patient by nuclear fragmentation. However, the peak in the activity from the isotopic projectile fragments deviate from the position of the Bragg peak of the primary nuclei. Most of these problems are automatically overcome if β+-radioactive ion beams (RIB) are directly used for both treatment and imaging. Proof of principle experiments have been performed at FRS in a collaboration with colleagues from MML. Bragg curve measurements of 10,11,12C show that an accurate range determination can be achieved rather quickly with radioactive carbon ions (e.g. after several spills), which is necessary for tumor-conform treatment [7].

During the last years, the R3B set-up has been substantially upgraded to study measure quasi-free reactions in inverse kinematics, thus allowing to investigate the properties of exotic nuclei produced via the FRS by scattering off a hydrogen target. In 2022, this new scientific program started with measurement of short-range correlations (SRC) in radioactive neutron-rich nuclei (such experiments have been performed only with stable 12C beam [8]) and the investigation of 2n and 4n thresholds at the drip-line. Other objectives are the production of unbound states at and beyond the drip line, like the multi-neutron resonances mentioned above, as well as reactions to investigate clustering, fission dynamics and barriers, single particle structure of exotic nuclei, as well as the measurement of total neutron-removal cross sections to extract neutron-skin thicknesses.

Several theoretical studies have been dealing with the nucleosynthesis via the rapid neutron capture process (r-process) in neutron star mergers and a special type of core-collapse supernovae, so-called collapsars, which form a massive accretion torus around a central black hole. Similar black hole-torus systems can form in the aftermath of a NS merger and yield massive outflows producing heavy elements through the r-process. In [9] an extensive survey of the microphysical properties of such black hole tori and their outflows revealing a number on important dependencies on physical parameters but also on model ingredients are presented.

**Understanding the origin of the matter–antimatter asymmetry and testing fundamental symmetries:** TheJEDI collaboration performed experiments with polarized protons and deuterons as precursor experiments for the search of the electric dipole moment (EDM) of deuterons. First results have been published: Axions/ALPs introduce an oscillating electric dipole moment (EDM) causing a spin rotation around a radial axis in the storage ring. The so-called axion wind effect causes a pseudomagnetic field resulting in a rotation around the longitudinal axis. Both effects were studied at COSY for the first time. Storage ring experiments are specifically sensitive to the second effect mentioned above (axion wind). No axion/ALP signal was found [10].

In preparation of the JUNO experiment [11], a sensitivity study for 7Be, pep, and CNO solar neutrinos was completed.

A search for new particles, based on the nonlinearity of the so-called “King plot” describing isotope shifts in different atomic transitions, was completed and published [12]. The method was proposed by a collaboration in 2018, and many experimental groups are working on this now.

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4 Topic 3 – Matter and Radiation from the Universe

The topic aims to fully exploit the potential of cosmic messengers. Neutrinos play a central role, and activities in neutrino physics pave the way for decisive experiments for dark matter searches. By combining the information from gamma rays, high-energy neutrinos, cosmic rays, and gravitational waves, and by precisely determining the properties of neutrinos and performing dark matter searches, all complemented by theoretical studies, the topic is developing a new picture of the high-energy universe.

**High-energy neutrinos**

In September 2022, the NSF approved thenew baseline of the **IceCube Upgrade** project, which is the first step to the overall **IceCube-Gen2**. NSF approved the prolongation of the project by three years, including the addition of US-$15M (incl. contingency) for the corresponding labor cost. The entire scientific program for the planned extension to IceCube-Gen2 is outlined in a white paper [1], where the subsequent Technical Design Report is currently being prepared. The final design review of the new multi-PMT digital optical modules (mDOMs) [2], that were developed by DESY and KIT together with other groups, was held in April 2022 and series production started. KIT postdoc H. Dujmovic is monitoring the operation of the IceCube Neutrino Observatory on site as one of the two IceCube winterovers during the dark season until November 2023. Furthermore, the analyses of 10 years of data from IceCube as well as with the surface array IceTop are progressing. For the first time, it has found evidence of high-energy neutrino emissions from NGC 1068 [3]. With the IceCube detector, looking inside active galaxies is possible for the first time by detecting neutrinos, gaining knowledge about the physical processes. Related to cosmic ray measurements, the IceCube collaboration could publish a thorough study of the density of GeV muons in air showers using data recorded by the IceTop array. The measured muon densities have also been compared to simulations using various hadronic interaction models yielding to some tensions, which have to be further investigated [4].

After the successful association of a radio-emitting tidal disruption event (TDE) with a high-energy neutrino in the AT2019dsg event [5], studies show that the event AT2019fdr is coincident with another high-energy neutrino. Observations, including a bright dust echo and soft late-time X-ray emission, further support a TDE origin of this flare [6]. The probability of finding two such bright events by chance is just 0.034%. Several models for neutrino production are evaluated and show that AT2019fdr is capable of producing the observed high-energy neutrino, reinforcing the case for TDEs as neutrino sources. RNO-G went through a successful installation season with four new stations installed [7]. Two stations have been equipped with wind-turbines, which will allow data-taking during the polar night.

**Direct Dark Matter search**

In 2022, the **XENONnT** experiment continued data taking. The data of 2021 were analysed, and with the lowest electron recoil background ever achieved in dual-phase xenon detectors, XENONnT could exclude physics beyond the standard model as origin of the XENON1T excess of low energy electron recoils [8]. Activities towards a Next-Generation Liquid Xenon Experiment were further consolidated by a White Paper [9] signed by more than 600 authors including many from the XENON, DARWIN and LZ collaborations. Along this line, a major milestone was the first joint meeting of these collaborations which took place at KIT in June 2022 where joint working groups reported on technical challenges and scientific goals of a next-generation experiment. As a result of this meeting, the **XLZD** consortium was founded. The KIT group pursues R&D on large-scale high-voltage electrodes for **XENON** and **DARWIN** and on the DARWIN detector design (e.g. concept study of cryostat vessel, high-voltage feed-through into the cryostat, simulation of cosmogenic and radiogenic backgrounds). Based on the **EDELWEISS** infrastructure at LSM Modane, new limits on sub-GeV DM could be set [10] and final results of the search for the neutrinoless double-beta decay of 100Mo were published [11].

**Neutrino physics with KATRIN**

The KArlsruhe TRItium Neutrino experiment (KATRIN) at KIT continued its measurement program in 2022. Analysis of data collected until summer 2021 is in an advanced stage and being prepared for release. Now encompassing a total of five measurement campaigns (280 days), this data set yields almost a factor of 6 in statistics increase, improved systematics, and a reduced background compared to previous results. Moreover, KATRIN has successfully pursued a broad scientific program beyond the neutrino-mass search: Based on its first two science runs, KATRIN provides the most stringent direct bound on local overdensities of the cosmic relic neutrino background [12]. The remarkable factor of 100 in improvement with respect to previous laboratory-based measurements earned this result a mention as „APS Highlight“ in June 2022 [13]. The search for light sterile neutrinos at the eV scale was further refined [14] and a first investigation of keV-scale sterile neutrinos covers new parameter space previously not yet addressed in direct searches [15]. KATRIN has set either first or improved limits on several oscillation-free Lorentz-violating parameters [16] which are predicted in effective field theories as extensions of the standard model. Further investigations into physics beyond the standard model, regarding deeper sensitivity to light sterile neutrinos or General Neutrino Interactions (GNI) as exotic forms of the weak interaction, are under way. With an outreach webinar presenting the breakthrough result of the first sub-eV direct neutrino-mass measurement [17,18] to the general public on February 14, 2022, the KATRIN collaboration has attracted around 500 online participants during the livestream event and since then gathered a large number of viewers of the recorded event [19].

**Gamma-Ray Astronomy**

The ERIC founding documents for the **CTA** **observatory** (CTAO) were submitted to the European Commission and its establishment will mark the official start of the Construction and Operation Phase of the CTAO. Preparations of the in-kind contributions are ongoing in the four areas, i) Array Control And Data Acquisition system (ACADA), ii) Medium-Sized Telescopes (MST), iii) Small-Sized Telescopes (SST) cameras, iv) Monte Carlo (MC) simulation pipelines. For MST construction activities DESY has procured an assembly hall, which will host pre-assembly activities of MST and an IceCube upgrade production line. So-called pathfinder telescopes for the MST, which allow for lessons learnt for the actual telescope production and installation activities, will reduce cost and schedule risks significantly. The MC simulation software package passed the prototype stage and the first review is foreseen for early 2023.

The **HESS collaboration** celebrated the 20th anniversary of its inauguration and operations have now entered their second extension phase. The HESS group at DESY continues to operate and maintain four of the five HESS cameras and the DAQ cluster of the telescope system in low maintenance mode. The experiment achieved excellent data taking uptime in 2022 (>1300 hours, ~90% five-telescope availability) and the group played an important role in the publication of a detailed description of the HESS transient follow up system [20]. The observation of a recurring nova confirmed gamma-ray emission up to TeV energies from a galactic transient source for the first time and at the same time resolved the evolution of the particle acceleration over a time frame of four weeks. This discovery breaks the record on nova energetics and offers new insights into cosmic-ray acceleration at the theoretical limit [21,22]. The HESS team was also involved in the observation of very-high-energy emission in the bright GRB 180720B deep in the GRB afterglow, hours after the end of the prompt emission phase, when the X-ray flux has already decayed. Two possible explanations exist for the observed radiation: i) inverse Compton emission and ii) synchrotron emission of ultrarelativistic electrons. Observations show that the energy fluxes in the X-ray and γ-ray range and their photon indices remain comparable to each other throughout the afterglow. This places distinct constraints on the GRB environment for both emission mechanisms, with the inverse Compton explanation alleviating the particle energy requirements for the emission observed at late times [23,24]. DESY will deliver the UV camera of the **ULTRASAT** project and lead the multi-messenger science of astrophysical transients. The project is transiting into the production phase and qualification and performance tests as the critical design review was successfully passed [25,26].

**Ultra-high energy Cosmic Rays**

The **Pierre Auger Observatory** has equipped all accessible positions of the water-Cherenkov stations with scintillation detectors as part of the AugerPrime extension, and almost half have already been equipped with improved electronics that will only enable the readout of the additional extension with radio antennas per detector station. With the migration to measuring with the AugerPrime extension, the collaboration will enter a new phase marked by enhanced data quality and it will be feasible to re-analyse the previously measured air shower events with refined methods. Recent searches for angular correlations between cosmic rays of extragalactic origin and their sources at the highest energies have confirmed the previously published evidence for source regions of cosmic rays [27]. A multitude of hypotheses on the origin of cosmic rays are becoming increasingly constrained. The upcoming publication of the top 100 events registered with the water-Cherenkov and fluorescence detectors proves the high performance of the observatory. Fundamental particle physics aspects also play an increasing role in analyses, such as the search for Lorentz invariance violation [28]. The established multi-messenger analyses through collaboration with the ANTARES, IceCube and TA collaborations expand the field of vision beyond the own measurement data and allow the combination of the different particle types in a synopsis [29]. The Auger Collaboration is shaping the future of the field through its prominent participation in the drawing up of roadmaps, e.g. the Snowmass process [30].

**Multimessenger Astroparticle Physics**

DESY and KIT are continuing to work together on the implementation of an analysis and data centre for multi-messenger astroparticle physics. Significant progress was made in, e.g., the data broker service AMPEL as well as by dedicated multi-messenger studies. The work is supported both by the NFDI consortium PUNCH4NFDI and by the ADC-MAPP project, which is funded by the so-called Innovation Pool for 2021-23. The aim 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.

**Gravitational Waves**

The **Einstein Telescope** (ET) as a third-generation gravitational wave interferometer is currently receiving special attention in Europe. ET was accepted in the ESFRI Roadmap and is included in the Helmholtz Roadmap of Future Research Infrastructures. The ET collaboration was officially founded at the '12th Einstein Telescope Symposium' in Budapest in June 2022. KIT is a founding member and contributes to the technological challenges in the fields of cryogenics and vacuum technology, seismology, computing, and monitoring of environmental variables. DESY together with partners from astronomy and astroparticle physics in Germany was strongly involved in the competition for two large-scale research centres with its proposal to establish the German Centre for Astrophysics (DZA). In September 2022, it was announced that the DZA is coming to Lusatia with a yearly budget of 170 M€ (total volume of the application 1.4 B€). In 2023 the three-year preparatory phase will start. This will strengthen gravitational wave astronomy in Germany, as DESY will be responsible for the preparation of the Low Seismic Lab, a shallow underground lab with unique seismic properties, and the study of Lusatia as a potential site of the Einstein Telescope. Moreover, DESY is preparing the application to soon join the ET collaboration to investigate Lusatia as a potential site in the context of the European selection process.

**Theoretical Astroparticle Physics**

In the group of theoretical astroparticle physics at KIT, various aspects of neutrino phenomenology as well as dark matter physics were investigated in 2022, see Refs [31-42]. For the latter, the focus was on axions and axion-like particles, see Refs [33,34]. In Ref. [34], a formalism to calculate the survival probability of axion-minicluster within the dark matter halo of our galaxy was developed. This question is of importance for direct searches for axion dark matter. In neutrino physics, implications of cosmological neutrino mass bounds were investigated [31,35,38]. For instance in Ref. [31] a specific model was studied, which allows to relax cosmological neutrino mass bounds, such that neutrino masses within the sensitivity range for the KATRIN experiment are allowed. Furthermore, in Refs. [32,39,40,42] various phenomenological implications of sterile neutrinos at differenct mass scales and in different experiments were studied, including also xenon dark matter experiments [36,40].

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5 LK-II Facility GridKa

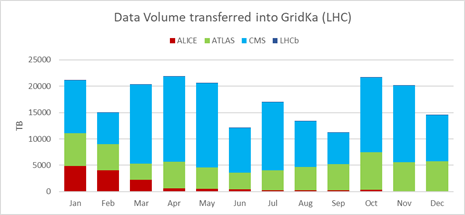
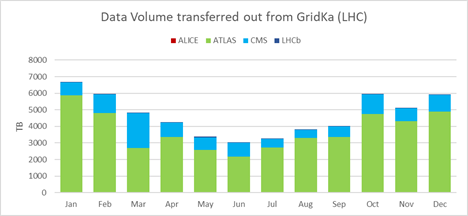
In 2022, GridKa provided the computing and storage resources with its usual high reliability. The LHC experiments, Belle II, and IceCube were provided with a total of 573 million core hours of computing time for 22 million computing jobs. The total resources of GridKa in 2022 comprised about 60,000 CPU-cores, 56 NVIDIA V100S and A100 GPU-cards, about 46 PB scalable online disk storage (in which about 120 PB were written and more than 450 PB were read) and more than 82 PB reliable offline data storage for data archival. During the reporting period all services were provided smoothly to the experiments. This was important as the Run3 data taking started in July; a high demand in particular for the tape and online storage systems could be seen.

The GridKa batch farm was enhanced in capacity and computing power according to the requirements and older, no-longer energy-efficient worker nodes were decommissioned. The regional resource pool, managed via the COBalD/TARDIS software developed inhouse at KIT, was continuously added and operates smoothly as well. Fortunately, no longer delays occurred here due to well-known supply chain problems worldwide. The GPUs in the GridKa farm are meanwhile more and more in use, primarily by ATLAS, CMS, and Belle II.

Preparations have started to further improve the energy usage monitoring of the GridKa resources as well as to prepare the whole computing center for more likely weather extremes during summer, i.e., longer periods of very hot (> 40 °C) outside temperatures.

The migration of the data on tape from the TSM to the HPSS technology and to a new library technology is successfully continuing with meanwhile most of the data being migrated. CMS and LHCb are using the HPSS tape since March 2022. To improve the efficiency of tape operations a new software stack was deployed, which improves the drive efficiency for recalls and the average read/write rates and which was developed in-house at GridKa. A new 300 Terabyte flash buffer to further increase the tape performance was added to the tape infrastructure and will be taken into operation in 2023. As part of the LHC Run3, the largest ever single raw dataset was successfully transferred to GridKa by ATLAS (over 1 PB instead of the expected 200 Terabyte maximum in Run3).

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 the opportunistic usage of computing resources in LHC computing was successfully continued. The open-source software enables the dynamic, transparent and on-demand integration of a large variety of resource types (e.g., HPCs, Clouds, …) providing community-overarching unified entry points to these. COBalD/TARDIS is used as a central building block for the Compute4PUNCH infrastructure within the BMBF-funded PUNCH4NFDI project as well as in the FIDIUM project together with the universities of Wuppertal and Göttingen. Furthermore, usage scenarios of opportunistic resources for astroparticle physics are being evaluated.

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. A new joint activity in the domain of Quantum Machine Learning was added in particular towards applicability in high-energy physics.

6 LK-II Facility GSI-MU Ion Facilities

The FAIR Phase-0 beamtime 2022 was successfully executed from February until end of June 2022. The uptime of the accelerator facility was 88% of the scheduled hours. The availability for users was 75% with beam on target. These values are within the typical range of the last years and confirm stable operation conditions. In average 2.6 experiments were served in parallel. Only in 2021 an even larger level of parallel operation was demanded. The GSI facilities were operated for 145 days in total (including testing and starting operation), the MU Ion facilities delivered 2674 h (of 3808 h scheduled) for main user experiments and additional 370 h for experiments performed in parallel to main user experiments.

*Accelerators:* A combined operation with three ion species was maintained throughout the entire remaining beam time block, in which all available ion source terminals continuously delivered beams for experiments. The operation mode became increasingly challenging over the beam time and up to six experiments were operated simultaneously. The MUCIS (MUlti Cusp Ion Source) ion source provided intense molecular CH3+ beams from methane during more than 50 days. The molecules were fragmented in a stripper gas target and high intensity proton (up to 5.5E11 particles/100 μs) and carbon beams (up to 1.1E11 particles/100 μs) were obtained. The proton beams were delivered to the WASA and HADES experiments. A prerequisite for the parallel operation of many experiments was the installation of the new FAIR control system. In preparation of the beam-time 2022, a wide range of improvements across all system layers were done, new operation features were added, and the performance and stability of the control system has been significantly improved for regular operation. During the SIS18 machine time in May 2022, the fast-cycling booster operation has been demonstrated for the first time. In the high repetition booster operation, a special concept used for requesting beam from UNILAC was developed for multi-multiturn injection.

A new pulsed gas stripper prototype was tested to strip low charge state beams from the High Current Injector (HSI), e.g. U4+ → U28+. It is a prerequisite for reaching highest intensities of intermediate charged ion beams. During the machine run, the operating parameters of the pulsed gas stripper were confirmed. Focus of the UNILAC post-stripper upgrade was the procurement of series components and the preparation of the in-house copper coating of the large accelerator tanks.

*Experimental facilities:* The TASISpec+ detector system was upgraded with a new set of customized cubic Ge-detectors equipped with a digital data acquisition system. These detectors form a key part of the novel Lundium detector setup that is optimized for particle-photon spectroscopy of superheavy nuclei. In an experiment searching for neutron-deficient plutonium isotopes near the proton dripline, a very good performance was demonstrated in a five-day beamtime irradiating two different Pt targets.

The R3B setup has been further upgraded by new detection systems. Beside the addition of four double planes in NeuLAND to improve the multi-neutron detection efficiency, two new systems have been introduced and put into operation. These are a large-area Restive-Plate Chamber RPC to detect recoil protons behind the dipole magnet GLAD, and a new target vertex tracker based on 10x10 cm2 FOOT [1] silicon micro-strip detectors for tracking protons emitted at large angles around 45°.

*IT:* The Green-IT Cube is an essential part of the GSI-MU Ion facilities. It provides advanced resources for high-performance and high-throughput computing, online computing and data storage and management. A fully virtualized system has been installed, in which all jobs are running as containers, enabling better support for various scientific use cases. In 2022, it was possible to acquire 5.5 Mio. EUR of additional funding to expand the Green-IT Cube installations with the goal to strengthen in-house research activities and collaborations with industry and other research institutions. The preparatory works started in December 2021 and completion of the project is planned for February 2023. This will increase the number of racks to 384 and essentially double the overall capacity of the Green-IT Cube. The Datacenter Strategy Award for Innovation, presented for the first time in 2022, was awarded to the Green IT Cube high-performance data center, at the Datacenter Strategy Summit 2022.

*[1] G. Silvestre et al., NIM A 936 (2019) 36-38, https://doi.org/10.1016/j.nima.2018.10.190.*