Input of the German Nuclear and Hadron Physics Community to the ESPPU 2026 Regarding the Programs at CERN, at FAIR, and Related Activities

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Abstract

This document summarizes the contributions of the German nuclear and hadron physics community, represented by the elected KHuK committee, to the ESPPU 2026 and complements the input from the German particle physics community submitted by KET[1]. Our statements and recommendations are based on both our established priorities and those outlined in the European community's NuPECC Long-Range Plan (LRP) 2024[2]. We focus primarily on areas of overlap with the particle physics community, including fixed-target experiments at the SPS at CERN, QCD studies in hadron and heavy-ion physics at the FAIR facility, comprising key activities within the CBM and PANDA collaborations. We also address complementary dark matter searches, precision measurements at low energies to explore beyond-standard-model physics at various facilities, and low-energy antiproton experiments at the CERN AD. We emphasize the importance of maintaining a diverse and compelling scientific program at CERN, extending beyond the development of future colliders. Such a program offers attractive opportunities for early-career scientists to engage in cutting-edge research, while fostering related technological and methodological advancements. Furthermore, projects that deliver high-impact results in shorter time frames, while retaining flexibility to adapt to emerging developments, remain essential.

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[1] https://www.ketweb.de/stellungnahmen/

[2] https://nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf

1 Driving scientific questions

Research in hadron and nuclear physics has made significant contributions to our understanding of the structure of matter and the evolution of the universe. However, many critical questions remain unresolved.
↪ How does the strong force generate the confinement of quarks and gluons?
↪ How do the complex structures of hadrons and nuclei arise?
↪ What are the properties of dense and hot (deconfined) strong-interaction matter?
↪ How are the heavy elements formed in the universe and where are the limits of stability?
↪ How can fundamental symmetries be tested?
↪ Is there physics beyond the Standard Model?

Answering these fundamental science questions requires a comprehensive approach integrating both experimental and theoretical research in nuclear and hadron physics to enhance our understanding of the underlying phenomena. This approach involves advancing current large-scale facilities and developing a new generation of accelerators and experimental tools.

Europe is home to some of the world's leading research facilities, such as CERN's LHC, SPS, ISOLDE, and the GSI/FAIR facility, all dedicated to addressing these unresolved scientific challenges. The European community has recently published its recommendations for the strategy in nuclear and hadron physics in the NuPECC Long-Range Plan 2024. This plan is aligned with the KHuK recommendations and strongly advocates the timely initiation of the physics program at the international Facility for Antiproton and Ion Research (FAIR) with its scientific pillars APPA, CBM, NUSTAR, and PANDA in a staged approach, alongside the full utilization of CERN's scientific potential. This includes advancing experiments like ALICE at the LHC, AMBER at the SPS, and COLLAPS, IDS, ISOLTRAP, MINIBALL, RILIS, and PUMA at ISOLDE, while continuing their development. Furthermore, we emphasize the importance of completing the full FAIR facility with all next-generation storage rings and essential accelerator upgrades such as SIS 400. Similar activities are also ongoing at other international facilities in the US, Japan, and China with involvement of part of the German community in the field Hadrons and Nuclei (HuK).

2 Scientific program at CERN

The German HuK community is actively involved in nearly all accelerator facilities at CERN, including the Booster, the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), and the Large Hadron Collider (LHC) as well as the Antiproton Decelerator (AD) and its low-energy storage ring ELENA. The research is highly visibly and has produced numerous impactful results in recent years and provides excellent opportunities for the decades to come. The science conducted spans more than 20 orders of magnitude in energy. This diversity significantly enhances the education of the next generation of scientists and engineers. The experiments undertaken often have much shorter time scales from design to realization compared to typical high-energy physics projects, providing young researchers with excellent hands-on experience in key areas related to particle physics: design, simulations, R&D, detector construction, commissioning, operation, and data analysis. The HuK community emphasizes the critical importance of continued CERN support for this broad range of activities, both from a scientific and educational perspective.

2.1 ALICE

The ALICE experiment at the LHC is dedicated to the characterization of the Quark-Gluon Plasma (QGP) and to the study of a broad range of QCD phenomena in proton-proton, proton-nucleus, and nucleus-nucleus collisions. The ALICE Collaboration has recently completed a major detector upgrade achieving substantially improved pointing precision in continuous data readout mode, with collision rates up to 50 kHz in Pb-Pb collisions. A further significant upgrade is in preparation for the Long Shutdown 3 (LS3, 2026-2030) at the LHC, when a new inner barrel of CMOS Monolithic Active Pixel Sensors (MAPS), realized with curved large-area sensors, and a Forward Electromagnetic and Hadronic Calorimeter will be installed. The data recorded until the end of Run 4 (2033) will allow precision measurements for a broad range of observables, including charmed mesons and baryons, hadron-hadron interactions through femtoscopic correlations, and first-time measurements of low-transverse momentum beauty hadrons as well as thermal radiation through dielectrons. The German

ALICE community has long been responsible for three key subsystems of ALICE: the Time Projection Chamber, the Transition Radiation Detector, and the Event-Processing Nodes compute farm utilizing GPUs. It remains fully dedicated to maintaining its significant contribution to the full exploitation of ALICE.

To utilize the high-luminosity LHC (HL LHC) over its complete running time (until 2041), a new detector optimized for QGP physics is currently under design, ALICE 3. A technologically-innovative concept based on tracking over a large rapidity range via CMOS MAPS detectors with an ultra-precise vertex detector located inside the beam pipe and excellent particle identification through RICH and time-of-flight methods, ALICE 3 will enable precision measurements with discovery potential of: i) rare multiply-charmed baryons and light nuclei carrying a charmed hyperon (super nuclei); ii) comprehensive measurements in the beauty sector, including production rates and collective flow at low momentum; iii) hadron-hadron interactions in the charmed sector; iv) the QGP temperature and its evolution through real and virtual photons (dileptons); iv) collective effects in small collisions systems (proton-proton, proton-nucleus); and searches for axion-like particles in ultra-peripheral Pb-Pb collisions, amongst others. This detector design together with several descoping options is currently under review by the LHC Committee.

The German community is a major player in the international group which has expressed interest in actively preparing for the construction of the Outer Tracker (OT) of ALICE 3. Covering a total area of about 60 m^2, the OT requires extensive R&D efforts to optimize the CMOS sensors using 65 nm technology, with a particular focus on achieving low power consumption below 30 mW/cm^2. Building such a complex large-scale tracking device demands close collaboration with external companies, particularly in the development of sensors, sensor modules, readout electronics, and computing components for both data processing and storage. Equally critical are mechanical supports, cooling systems, power distribution, and data links. In all these areas, the expertise of the German community will be a decisive factor ensuring the project's success.

In summary, the German QGP community is an integral part of the international effort that strongly supports the physics and technology case for ALICE 3. As formulated in the NuPECC LRP 2024, ALICE 3 is regarded as its flagship experiment for the coming decades. The programme is built on innovative R&D that will also benefit related fields in nuclear and particle physics. To ensure the possibility of installing ALICE 3 for Run 5 at the LHC, strong support for R&D is essential. The unique capability of the LHC as the only accelerator producing deconfined QCD matter with the highest energy density in the laboratory calls for its full exploitation in this research field.

2.2 AMBER

AMBER (NA66) is a recently approved fixed-target experiment at the M2 beam of the CERN SPS that will perform globally unique measurements in the field of hadron structure and spectroscopy. It is the successor experiment to COMPASS and uses much of the existing magnetic spectrometer, improved by upgrades and augmented by new detector components to meet the requirements of the new physics program. AMBER's physics program will go substantially beyond the previous COMPASS program. It has been extensively reviewed within the Physics-Beyond-Colliders Initiative of CERN, which was started in the framework of the 2017 Update of the European Particle Physics Strategy.

The AMBER physics program is divided into two phases. Phase-1 was approved by the CERN governing bodies in December 2020 and covers three main physics questions: (i) the measurement of the production cross section of antiprotons on helium over a wide energy range; (ii) the precise measurement of the proton form factor at small momentum transfers with a high-energy muon beam; (iii) the determination of the pion and kaon PDFs by Drell-Yan and charmonium production measurements with negative and positive meson beams. New detector components for Phase-1 include a high-pressure TPC acting as active target and telescopes of Monolithic Active Pixel Sensors (ALPIDE) for high spatial resolution, combined with scintillating-fiber hodoscopes for time resolution; for the Drell-Yan program, a segmented target interlined with Si-strip trackers will reduce systematic effects due to energy loss and multiple scattering of the produced muons when crossing the target. A novel, free-streaming DAQ will act as the backbone of the experiment, allowing for high-level event selection including detectors with very different latencies. The measurements of Phase-1 began in 2023 and will extend beyond LS 3 of the CERN accelerators (2027 - 2029). Phase-2, currently planned to start in 2031, will focus on measurements with an intense kaon beam provided by the upgraded M2 beam line. This will include the spectroscopy of strange mesons, measurements of the quark and gluon structure of kaons via kaon-induced production of prompt photons, the determination of low-energy parameters of the kaon in ultra-soft collisions with nuclei, and measurements of meson charge radii in inverse kinematics. Particle identification both upstream and downstream of the target will be an essential ingredient for the physics program of Phase-2. The full physics program of AMBER is expected to also cover Run 5 and 6 of the CERN accelerators.

2.3 ISOLDE/AD

ISOLDE is a unique and world-leading facility for radioactive beam science, using GeV protons delivered by the PS Booster to produce a wide range of isotopes used in a diverse science program including ground-state properties of nuclei, radioactive decay, nuclear reactions with post-accelerated beams, and the use of radioisotopes as probes for condensed matter physics and in medicine. The German ISOLDE community is particularly involved in the precise determination of ground state properties using mass and laser spectroscopy at ISOLTRAP and COLLAPS, studies of nuclear reactions and deformation using γ-ray spectroscopy at the MINIBALL spectrometer and C-REX/ T-REX detectors installed at HIE-ISOLDE, and exploiting the post-accelerated beams with energies of up to 10 MeV/u available since 2015. These experiments provide complementary information to GSI/FAIR experiments to understand nuclear reactions and structure since they use ion beams with lower energies and corresponding methodically adapted detectors. A new initiative has been recently started with the PUMA project. Here, stored cold anti-protons will be transferred from the Antiproton Decelerator (AD) and merged with the radioactive isotopes supplied by ISOLDE to obtain information about the nucleon distribution at the nuclear surface, a region inaccessible by other methods. Finally, several German groups are involved in the n_TOF experiment at CERN that is important for nuclear astrophysics and other fields.

During CERN LS3, the facility will be upgraded to allow the use of protons of higher energy and intensity, improving the production yields of exotic nuclei, which, together with other infrastructure improvements, will enhance the facility's capability and capacity. The opportunities offered by these improvements will be exploited in subsequent running periods. The ISOLDE collaboration is developing a plan for further facility improvements during LS4 and new instruments to enable novel measurements. In the longer term, the ISOLDE users have proposed ambitious plans for an additional experiment hall and new target stations. The development of the facility's infrastructure and the associated instrumentation will ensure a leading position for ISOLDE in the future. As the roadmap for the post-LHC future is developed, a strategy will be required to secure the long-term opportunities for continuing world-leading nuclear physics programs at ISOLDE, together with the other facilities using the proton injector chain unique to CERN.

The experimental program on nuclear structure and nuclear astrophysics at FAIR and ISOLDE is directly supported by theory to enable a comprehensive interpretation of the results obtained. Conversely, the experimental findings form the basis for the further development of the theory leading to more accurate extrapolations and predictions in areas of the nuclear chart that are not accessible to direct experiments.

3 Scientific program at FAIR

FAIR (https://fair-center.eu), an ESFRI landmark for nuclear and hadron physics, is currently under construction next to GSI in Darmstadt, Germany. It will provide European scientist with world-class research opportunities for decades. The first stage of FAIR is expected to become operational by 2028, facilitating experiments with SIS 100 using the High-Energy Branch of the Superconducting Fragment Separator (Super-FRS), the Compressed Baryonic Matter (CBM) cave, and the existing GSI facilities. The remaining parts will be implemented in stages , ultimately supporting all four FAIR scientific pillars.

To fully utilize FAIR's scientific potential and effectively serve its large international user community, the construction of an additional synchrotron would be highly beneficial. Increased parallel operation — successfully demonstrated at GSI for decades — would significantly enhance the facility's capabilities. Notably, the existing SIS 100 tunnel provides the necessary infrastructure to accommodate such an upgrade.

We emphasize that completing the FAIR Modularized Start Version (MSV) remains the declared goal of all present FAIR shareholders. However, driven by scientific needs, discussions are ongoing regarding projects that extend beyond the MSV as originally proposed. These include accelerator upgrades such as the construction of SIS450 and the expansion of storage ring facilities. A SIS 400(450) would overlap with the SPS energy range for heavy-ion experiments, enabling a connection in the investigation of the QCD phase diagram.

3.1 Compressed Baryonic Matter (CBM)

Heavy-ion programs at RHIC and LHC provide unprecedented insights into the properties of QCD matter at high temperature and small to vanishing baryon chemical potential (μ_B). The detailed understanding of the properties and microscopic structure of QCD matter in the region from moderate to high μ_B and lower temperatures is of utmost importance. Effective theories or models inspired by lattice QCD predict a rich structure in this region of the QCD phase diagram. Among such landmarks are a first-order phase transition between hadronic and partonic matter, which terminates in a second-order QCD critical end point. CBM will play a unique role in studying QCD matter and its phase diagram at the highest net-baryon densities and moderate temperatures. The experimental strategy of CBM is to perform systematic measurements, both integral and differential, of particles produced in nuclear collisions with unprecedented precision and statistics with particular focus on rare and penetrating probes. According to the current schedule, the start of operation of the SIS100 synchrotron and the CBM experiment is envisaged for late 2028.

Significant information of the QCD phase structure, its microscopic properties, and its equation-of-state requires systematic measurements of excitation functions, system size dependencies and multi-differential phase-space distributions of various observables will be extracted, the most promising being: i) event-by-event fluctuations, ii) thermal radiation (photons and dileptons), iii) (multi-)strangeness, iv) hypernuclei and v) charm production. These measurements will be performed at different beam energies and with different collision systems from nucleus-nucleus to proton-nucleus and proton-proton collisions for baseline determination. The availability of SIS100 proton or deuteron beams will significantly extend our exploration of the field of hadron physics. The maximum center-of-mass energy in proton-proton collisions will reach about 7.6 GeV, thereby, sufficient energy to produce baryons with open strangeness $|S| = 1, 2, 3$, open-charm $|C| = 1$, and mesons with hidden strangeness and charm. The CBM detector will provide an excellent basis to reconstruct the complete reaction topologies via exclusive coincidence measurements of momenta and particle types of final-state reaction products. The physics program of HADES at the CBM cave is complementing the beam energy scan program of the CBM. Prior moving to the CBM cave HADES will carry out the unique physics program with secondary pion beams, which is only possible at the current location of HADES at SIS18. The German community plays a leading role in the construction of detector components, data acquisition combined with fast real-time event selection, as well as in quantifying the overall detector performance in preparation for physics with first beams from SIS100. While the construction of the CBM detector is ongoing, R&D activities are being pursued by the collaboration, in particular on CMOS Monolithic Active Pixel Sensors (MAPS) and low-gain avalanche diode (LGAD) sensors.

To investigate strong-interaction matter at high baryonic density, the timely completion of SIS100 at FAIR and the completion of the CBM experiment are of utmost importance. Efforts should continue to support R&D activities related to advanced CBM silicon vertexing and tracking devices, as well as for photon detection.

3.2 NUclear STructure, Astrophysics and Reaction (NUSTAR)

NUSTAR makes use of a versatile suite of experimental set-ups for NUclear STructure, Astrophysics and Reaction studies of exotic nuclei produced by the Super FRS. The low-energy stable-beam programme will use the UNILAC and later the future HELIAC heavy-ion accelerator. In this way NUSTAR can access exotic nuclei across the full nuclear chart probing the limits of nuclear existence up to superheavy nuclei. This will enable unique opportunities for studying reactions of exotic nuclei, for the extension of the nuclear chart towards the driplines, to idnetify new decay modes, and to provide accurate data of several nuclear properties relevant for the understanding the element formation in the universe. The high energy provided by FAIR enables unique experiments providing insights into nuclear structure and reaction dynamics as well as enable studies of hypernuclei and delta resonances in exotic nuclei. The completion of the FAIR facility including the Low-Energy-Branch of the Super-FRS, where mass spectrometry, laser spectroscopy, and γ spectroscopy experiments are foreseen, is urgent to fully exploit the science potential.

3.3 antiProton ANihilation at DArmstadt (PANDA)

PANDA will consist of a versatile, large-acceptance detector and will make use of stored anti-proton beam in the range between 1.5 to 15 GeV/c, which corresponds to the production of strange and charm hadrons. The PANDA physics program will probe a broad range of aspects of QCD at the scale where quarks and gluons form hadrons. As noted in a recent review of the FAIR facility [3], the very small spread of the anti-proton beam energy will provide highly significant experimental constraints benchmarking LQCD calculations for especially two highly relevant areas of hadron spectroscopy:

1. The search for *glueballs*, which are the only particles predicted in the SM with mass generated entirely through the strong interaction. PANDA will not only produce many different types of glueballs with different masses and quantum numbers for the first time, but will also produce them in abundance, which will allow for measuring their mass spectra with high precision.
2. The measurement of decay properties of *exotic* hadronic particles containing charm quarks at PANDA will be essential to determine whether they have compact or a molecular nature. The extremely high energy resolution of PANDA will be crucial in this context.

In addition, PANDA has a broad program including studies of baryons containing more than one strange quark (strange hyperons). The study of excited and exotic hyperons remains a principal goal of PANDA, where $\bar{p}p$ annihilations hold the distinct advantage that all excited multi-strange hyperons and antihyperons can be produced in simple, parameterisable two-body reactions. These studies incorporate tests of CP violation that conceivably might explain the matter-antimatter asymmetry in the Universe, one of the most fundamental questions in physics today. Double-strange hypernuclei, in particular their excitation spectra, probe three-body $\Lambda\Lambda N$ interaction as well as $\Lambda\Lambda - \Sigma\Sigma - \Xi N$ mixing. PANDA is the only planned experiment where the excitation spectrum of light double-strange hypernuclei can be measured in the future. Regarding the measurement of nucleon form factors, which incorporate basic information on nucleon structure, PANDA will probe the high-q^2 region in the time-like domain through $\bar{p}p \to e^+e^-$ and $\bar{p}p \to \mu^+\mu^-$ processes.

3.4 Atomic, Plasma Physics and Applications (APPA)

APPA is devoted to precision studies on fundamental interactions and symmetries with highly charged ions, high-density plasmas, atomic and material science, radio-biological investigations and other applications. An important aspect with respect to standard model and particle physics are tests of quantum electrodynamics (QED) in extremely strong electric and magnetic fields near the Schwinger limit in heavy highly charged ions as they are currently only available in sufficient amounts at GSI/FAIR. High-precision tests of QED require a cross-disciplinary approach of atomic and nuclear physics since nuclear structure effects often limit the precision of QED predictions. Complementary approaches are carried out at lower Z at smaller facilities and universities as discussed below. The future CR and HESR at FAIR would provide unique opportunities by extending the storage ring programmes with highly charged ions to high energies and, therefore, their completion should be vigorously pursued.

4 Scientific program at smaller German facilities

4.1 MAMI and MESA

The Mainz Microtron electron accelerator(MAMI), operated by the Institute of Nuclear Physics of the University Mainz, delivers continuous-wave electron beams with energies from 180 MeV to 1.6 GeV. It features unpolarized and polarized electron sources, an injection linac, three race-track microtrons, and a harmonic double-sided microtron. MAMI stands out with its 100 μA beam intensity, up to 85% polarization, and an absolute energy resolution of (10^{-4}). Major experiments include the A1 high-resolution spectrometer setup and the large-acceptance A2 experiment, which is located at the tagged-photon beamline of MAMI and which consists of the the Crystal Ball and TAPS calorimeters. The combination of a high-intensity electron beam with its outstanding beam conditions together with the experimental facilities A1 and A2 make MAMI to premier facility for low-energy particle, hadron, and nuclear physics research. Highlights of the recent past include searches for dark photons, world-class measurements of form factors, electric and magnetic charge radii and polarizabilities of protons and neutrons as well as the measurement of single-spin asymmetries of nuclei.

Over the past decade, the institute has been preparing the Mainz Energy-Recovering Superconducting Accelerator (MESA), a high-intensity electron accelerator set to begin operation in 2025. Running in parallel to MAMI, MESA's three experiments will support a long-term research program in subatomic physics. A new underground hall has been built to house MESA and its experimental facilities, requiring a major cryogenics system for its superconducting accelerator cavities. MESA will operate in two modes: an extracted-beam mode, delivering up to 155 MeV polarized electrons at 150 μA to thick

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[3] cite Heuer-Tribble report

targets in the P2 spectrometer, achieving luminosities above 10^{39} cm^{-2}s^{-1}, and an energy-recovery (ERL) mode, providing up to 105 MeV at $>$1 mA. At the MAGIX experiment, for the first time in accelerator physics a high-intensity ERL beam will be operated in conjunction with a thin gas jet target for physics experiments, thereby reaching luminosities of at least 10^{35} cm^{-2}s^{-1}. After passing the gas jet target, the beam is decelerated back to injection energy via cryostat re-injection, enabling exceptionally clean conditions for precision experiments, from astrophysical cross-section measurements to nucleon form factor studies and new particle searches. In the extracted-beam mode, the 155 MeV polarized electron beam will interact with hydrogen targets for the P2 experiment, measuring the proton's weak charge with unprecedented precision and probing new physics scales by a precision determination of the weak mixing angle of up to 50 TeV. Parity-violating asymmetry studies with nuclear targets will furthermore allow to determine the neutron-skin thickness of nuclei, constraining the equation of state, and thus improving our understanding of neutron stars. The P2 Collaboration is also considering a determination of the weak charge of ^{12}C, which is highly complementary to the hydrogen measurement, both in terms of sensitivity to BSM physics (where it is closer to that of atomic parity violation) and in terms of experimental systematics. The P2 beam dump can finally be used as a target for the hypothetical production of dark sector particles. A dedicated calorimeter, the DarkMESA experiment, will be placed behind the beam dump, providing world-leading sensitivity for light dark-matter particles.

4.2 ELSA

The Electron Stretcher Accelerator (ELSA) (http://www-elsa.physik.uni-bonn.de/) is operated by the Institute of Physics of the University of Bonn. It comprises two electron LINACs, a booster synchrotron, and an electron stretcher ring. Electron beams, either polarised or unpolarised, are injected into the synchrotron at approximately 20 MeV via either LINAC, accelerated to 1.2 GeV, and then transferred to the stretcher ring. The stretcher ring operates in three modes: booster, stretcher, and storage. In booster mode, which is primarily used for hadron physics experiments, multiple pulses from the synchrotron are accumulated, reaching an internal current of typically 20 mA. The electrons are then further accelerated to a maximum of 3.5 GeV, extracted slowly via resonance extraction, and delivered to experiments with a typical spill time of 4–9 seconds. A recently added beamline connected to the stretcher ring provides electron beams for detector testing and characterization with energies up to the full 3.5 GeV, and beam currents ranging from 1 fA to 100 pA and a duty factor of 80%. ELSA's primary research areas include hadron physics and irradiation studies for medical and other applications. The hadron-physics program focuses on baryon spectroscopy via meson photoproduction, with an emphasis on polarization experiments. ELSA will continue to supply beams for existing hadron-physics experiments to maximize utilizing their scientific potential. ELSA serves two experimental areas, each equipped with photon tagging systems including diamond radiators to provide polarized photon beams. The BGOOD experiment (https://www.pi.uni-bonn.de/bgood/en) combines a central almost 4π acceptance BGO crystal calorimeter with a large aperture forward magnetic spectrometer providing excellent detection of both neutral and charged particles. Measurements are performed of non-strange and strange meson photoproduction reactions, in particular t-channel processes at low momentum transfer. The CBELSA/TAPS experiment (https://www.cb.uni-bonn.de/) integrates the Crystal Barrel and the TAPS electromagnetic calorimeters, making it ideal for studying neutral mesons decaying into photons with a nearly complete solid-angle coverage. Together with the polarized frozen-spin target and a circularly or linearly polarized photon beam, single and double polarization experiments have been successfully performed. A significant upgrade to trigger on final states including neutrons has been completed. For the future, a new experiment called INSIGHT is planned that extends the Crystal Barrel calorimeter with a new forward spectrometer for charged and neutral particles to access final states exhibiting strangeness. The forward spectrometer will feature a dipole magnet with gaseous tracking detectors, a time-of-flight wall, and a segmented high-resolution electromagnetic calorimeter. Detector tests are pursued at LINAC I, with a pulsed high-current 20-MeV beam for material irradiation, and with the test beamline providing beams for detector development. Both areas serve as a facility for the Centre for Detector Physics FTD at the University of Bonn campus which recently went into operation (https://www.ftd.uni-bonn.de/).

4.3 Low-Energy Tests of the Standard Model

Test the standard model of particle physics at low energy are complementary to accelerator-based high-energy approaches and are often conducted at small-scale facilities or even in university laboratories. They often use methods from hadron, nuclear, atomic, molecular, optical physics, and quantum technologies and drive the development of these techniques to extreme efficiency and accuracy. Examples are tests of QED in strong fields, the search for CPT violation by comparing the properties of matter and antimatter, investigations of parity non-conservation in atoms (APV), and the search for permanent electric dipole moments (EDM) of leptons or quarks either directly on neutrons or protons or in atoms and molecules. Beyond-Standard-Model (BSM) physics would manifest as a difference between a precise measurement and the SM prediction. Lacking quantitative understanding of strong interactions and nuclear properties often limits the required SM/BSM description. The study of these effects not only extends the frontiers of precision physics, but also provides new diagnostic tools for understanding the strong interaction. APV experiments, for example, can be used to search for new physics such as a dark Z boson, but are also sensitive to nuclear anapole moments and neutron distributions. This requires high precision atomic physics calculations and a good understanding of the nuclear structure and its influence on the atomic spectrum. Another relatively young field in this respect is the search for nonlinearities in King plots, i.e. in the isotopic shifts of atomic or ionic transitions, which are expected to be highly linear in the first order. Nonlinearities may herald new long and intermediate range interactions between the nucleus and electrons that are not proportional to the nuclear charge, but may also be caused by nuclear deformations or higher order mass-dependent contributions from atomic physics. These examples highlight the need for interdisciplinary approaches involving particle, nuclear and atomic physics. Since such experiments are often located at universities, they play an important role in the training of young scientists and allow students to participate in and contribute to research at the frontier of our knowledge. Nuclear physics also plays a central role in the search for dark matter and the study of neutrino properties that are discussed in the contributions from the astroparticle physics community.

5 Theory

Theorists, constituting roughly a quarter of the European Nuclear physics community, explore the physics of the strong interaction, from quarks to hadrons, nuclei, and stars. They play an essential role in interpreting experimental results and in providing input and predictions for new experiments. To match experimental progress, sophisticated approaches need to be developed. Theory groups should be strongly supported throughout Europe to ensure their fundamental contributions to nuclear and particle physics.

Collaboration should be encouraged and nurtured to strengthen the relation between nuclear physics and neighbouring fields, including astrophysics and particle physics. It should be ensured that theoretical centres continue to play a strategic role in the development of nuclear and particle physics in Europe. Here a very important role is played by the European Centre for Theoretical Studies (ECT*, Trento, Italy) dedicated to theoretical nuclear physics and related areas.

Theoretical work in hadron and heavy-ion physics, nuclear physics and nuclear astrophysics should be guaranteed continuous support, both in its phenomenological aspects (theoretical support needed to interpret the results and to provide guidance to the experimental programme) and from first principles (studies of quantum chromodynamics using effective field theories, dispersion relations, functional methods and lattice gauge theory). To achieve a better understanding of the element synthesis and chemical evolution in the Cosmos, microscopic theories for nuclear structure, decay and reactions as well as the equation of state of dense matter are needed. Initiatives to develop an inclusive theoretical framework fostering sustainable connections between nuclear theory, quantum chemistry, atomic and molecular physics and particle physics should be encouraged. For example, recent years have seen an increase in interest in the systematic and model-independent framework of Standard Model Effective Field Theory (SMEFT), in which the complementarity of proton and neutron weak charges in BSM searches becomes particularly transparent. To solidify our knowledge of Standard Model physics and to enhance the discovery potential of BSM experiments (important examples include neutrino physics and dark matter searches), a precise theoretical description of different nuclei is essential.

Support for theoretical groups in terms of positions and career prospects is essential for progress in nuclear and particle physics. Excellence programmes to train, attract, and keep talent within the field should be pursued.

6 Cross-sectional topics

6.1 R&D-Detectors

The development of detector technologies for future experiments at large-scale research facilities is a central prerequisite for the optimal use of existing and new infrastructures and thus for long-term progress in the field. This requires resources beyond those for the construction and operation of detectors for current experiments. Together with KET and KAT, strategic developments beyond individual experiment collaborations have been identified and corresponding alliances have been established. European particle physics organizes its strategic detector developments within the framework of the ECFA Detector R&D Roadmap[4] in so-called Detector Research & Development (DRD) collaborations, which are based at CERN. For nuclear and hadron physics, priority projects have been identified in the NuPECC Long Range Plan 2024. The GSI detector laboratory will be established as a central hub for developments in the KHuK community, similar to the DESY detector laboratory for the KET community. This guarantees a strong German network of activities, also via the HGF Distributed Detector Laboratory (DDL).

There is a large overlap between the communities for some technologies, while some are more strongly anchored in one field or another. Here we focus on those aspects of the R&D in the field of particle detectors, where members of KHuK are leading the technology development.

Heavy ion experiments place high demands on spatial resolution and at the same time require a low material budget for their silicon detectors. This makes them technology drivers for MAPS-based systems. Their suitability for large-scale experiments was first demonstrated with the STAR-HFT and the ALICE ITS2. MAPS will play a major role in ITS3 of ALICE and in ALICE 3 as well as in CBM and its envisaged upgrade. In recent years, the rate capability of MAPS was improved by several orders of magnitude, with outstandingly light material budget (50 μm thickness), low power dissipation (less than 100 mW/cm^2) and spatial resolution of about 5 μm, while prototypes of MAPS with precision timing are being currently investigated. Common development goals are to improve the time resolution and reduce the power consumption of MAPS. Flexible, wafer-sized sensors for particularly lightweight vertex detectors employing stitching are currently under evaluation. Cost-efficient, more conventional integration solutions should enable the construction of ultra-lightweight tracking detectors several 10 m^2 in size and give small collaborations access to a standardized version of the sophisticated technology. Silicon sensors with the highest time precision based on LGAD technologies has the potential to complement the position resolution of MAPS thanks to their excellent timing precision of 20–30 ps and potentially a spatial resolution down to 20 μm. They are already in use in primary beams as start time and beam-monitoring detectors. Broad interest in these technologies created room for synergies in all fields of detector R&D, design and construction.

Micropattern Gaseous Detectors (MPGD) are of great importance for the reconstruction of charged particle tracks at high rates over large areas, both in fixed target (AMBER, CBM, PANDA, etc.) and collider experiments (CMS, ATLAS, EIC, ILC, etc.). The most widely used technologies nowadays, GEMs and micromegas, were pioneered by the COMPASS experiment at CERN SPS. The focus of developments is on further reducing material occupancy, using sustainable gas mixtures, and on improving time resolution, rate capability and radiation hardness of large-size detectors. New, promising structures are being developed using advanced microstructuring techniques, such as μRWELL and InGrid. Multi-gap Resistive Plate Chambers (MRPC) provide fast signals for triggering or time-of-flight measurements over very large areas at affordable cost. The technology was driven by FOPI at GSI, ALICE at CERN, and has been further developed for CBM at FAIR, reaching a rate capability of up to $30\,\mathrm{kHz/cm^2}$. R&D for future applications aims at reaching significantly higher rates up to $150\,\mathrm{kHz/cm^2}$. New types of resistive glass and readout geometries are promising approaches to reach this goal.

In the detection of electromagnetic probes, nuclear and hadron physics covers six orders of magnitude from keV to GeV energies and regularly demands highest resolution in energy as well as position information. Hence, detector research in electromagnetic calorimetry that is able to meet these demands is deeply rooted in the community. Large crystal spectrometers based on high-density crystalline scintillators with 4π coverage such as Crystal Barrel, the planned PANDA EMC and many others set the standard for the reconstruction of neutral mesons from their electromagnetic decay products. Novel approaches based on newly developed scintillators and detector techniques are under development. At lower energies down to the photons from $\mathrm{e^+e-}$ annihilation, nuclear spectroscopy and applications

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[4] https://indico.cern.ch/event/957057/

such as positron emission spectroscopy are also driving the detector development.

The technology high-resolution gamma spectrometer based on segmented germanium crystals and their signal processing is being driven by the nuclear physics community. It enables gamma-ray tracking in the European gamma-ray spectrometer AGATA, which in turn will be the main detector for the HISPEC experiment at FAIR. Improvements to the spatial and energy resolution of the interaction points of the gamma radiation in the detector through improved electronics and analysis algorithms increase the sensitivity and efficiency of the experiments.

The development of quantum & cryogenic detectors has been pushed forward particularly for atomic-physics investigations but has recently found applications in nuclear physics and fundamental symmetry research. For example superconducting or magnetic microcalorimeters have reached very high resolution in the determination of X-ray and γ-ray photons that exceeds those of the detectors mentioned above. The Penning-trap technology, used for decades for precise mass measurements of stable and short-lived isotopes, has recently been improved in precision by orders of magnitudes and extended towards nuclear charge radii determinations via nuclear and bound-electron magnetic moment measurements with a strong impact in nuclear structure physics and searches for BSM physics. The combination of Penning traps with quantum technologies like laser cooling or the application of quantum logic spectroscopy for SM tests will provide a further boost for particle-physics-relevant applications of these techniques.

6.2 R&D-Computing and Software Developments

The exponential growth in data rates from modern and next-generation experiments, coupled with the imperative for sustainable resource utilization, demands cutting-edge software algorithms and advanced computing infrastructures designed and implemented by specialized experts within the community, ensuring the field can meet the challenges of scale, performance, and sustainability.

Strong collaborations are necessary which exist since a long time with the field of particle physics and between the different research centers and experiments. Good examples are the common software stack used by ALICE at CERN and the future FAIR experiments in Darmstadt or the Green-IT-Cube at GSI which serves as a role model for the future computing infrastructure at CERN.

In addition more institutionalized collaborations exist at the national level through PUNCH4NFDI and DIG-UM, and at the international level through JENA, EOSC, and EuCAIF, involving particle physics and other fields facing similar challenges.

We recommend to facilitate and strengthen access by nuclear and particle physics researchers to large HPC centres, to address computing needs for both theory (such as performing microscopic QCD and nuclear physics calculations as well as multidimensional astrophysics simulations) and experiment, and to allocate funding for enhanced GPU clusters (in particular for AI and ML) within established HPC centres across Europe. In lattice QCD, the rapid evolution of computational techniques and hardware calls for new algorithms and software. Similarly, quantum computing requires appropriate algorithms and tests on quantum hardware.

6.3 R&D-Accelerators

Cutting-edge advances in the field of accelerator technologies are also in the focus of KHuK's interest. Developments in continuous-wave particle accelerators are underway worldwide for electrons (S-DALINAC/TU Darmstadt, MAMI, MESA/Univ. Mainz), protons (PSI/Switzerland), and heavy ions (FRIB/U.S.A., SPIRAL/France, HELIAC/GSI). These efforts comprise accelerator development, prototype design, and "first-of-series" construction. The corresponding development of key technologies should be further advanced, including the development of versatile ion sources, high-performance radio frequency quadrupole accelerators, highly efficient compact drift-tube linear accelerators, superconducting high-frequency cavities, and the processes required for their optimization and preparation. State-of-the-art infrastructure, such as clean rooms, high-performance test stations, and independent beam experiment caves for cryomodule testing, support these efforts. Facilities at universities in Mainz and Frankfurt, as well as at prominent German accelerator institutions like GSI Darmstadt, KIT Karlsruhe, and DESY Hamburg, contribute to this research.

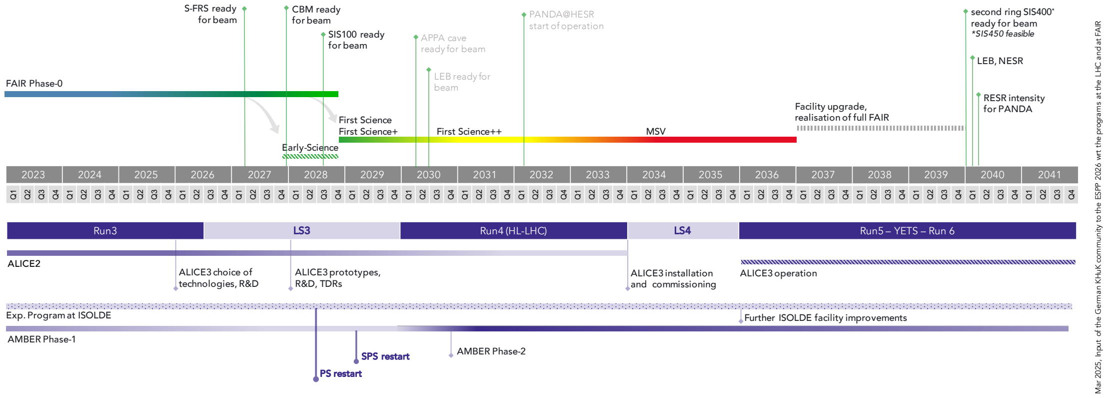
The operation of recirculating ERL beams is a promising and cost-effective path towards high-intensity electron beams as for instance proposed for the LHeC project at CERN. The recent results achieved at the S-DALINAC at TU Darmstadt and the future operation of MESA at JGU Mainz with mA-beam intensities allow for a detailed investigation of all aspects related to this innovative technique and are of utmost importance for future large-scale projects.

For the development of future lepton and hadron facilities, further R&D work in the field of laser plasma acceleration is essential.

R&D in beam diagnostics is of crucial importance in optimizing the performance of large accelerator systems. Examples include reconstruction methods based on advanced algorithms or AI, the development of broadband systems in the multi-GHz range, and highly sensitive systems such as cryogenic current comparators. Ensuring the availability and continued development of these technologies is essential for their widespread application at future accelerators, for example at FAIR or at CERN.

7 Timelines

Fig. 1 shows the anticipated timelines of the CERN operation and upgrade schedule until 2041 as well as the planned stages of the FAIR project. Regarding GSI/FAIR, the facilities currently in operation are expected to continue serving experiments during the future phases of the FAIR project. Steps beyond First Science (FS) require additional funding.



Mar 2025, Input of the German KHuK community to the ESPP 2026 wrt the programs at the LHC and at FAIR

Anticipated timeline for the operation of the FAIR and the CERN accelerator facilities. For some projects (FAIR beyond FS and ALICE3 at CERN) the funding has not been approved yet.

8 Recommendations

We recommend the full utilization of HL-LHC until the end of its present runtime schedule end of 2041. We strongly support the timely realization of the ALICE 3 experiment, a top priority of the European community identified in the NuPECC LRP 2024. We recommend the completion of phase-1 of the AMBER experiment and the timely realization of its phase-2 including necessary upgrades of the beam line for higher beam intensities. We recommend continuing the successful programs at ISOLDE, n-ToF, and at the AD including planned upgrades at ISOLDE to higher energy and intensity of the PSB beams in the shutdowns LS3/LS4.

Fundamental physics problems such as low-energy searches for physics beyond the standard model and neutrino physics complementary to a direct search at a future collider must be targeted from a diverse perspective. Ensuring a rich and diverse physics programme beyond the HL-LHC era is crucial to pursue world-leading science with radioactive ion beams, complementing and diversifying CERN's scientific program focused on collider physics.

We recommend increasing the cooperation and collaboration of the particle physics community with the HuK community on detector developments, in particular related to detector technologies addressed in section 6.

We recommend the timely exploitation of FAIR to enable cutting-edge experiments in hadron, heavy-ion, and nuclear physics for QCD studies at different energy scales with the SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave, and the current GSI facilities. Completing the full FAIR facility will provide European science with world-class and often unique opportunities in nuclear and hadron physics for decades and is highly recommended.