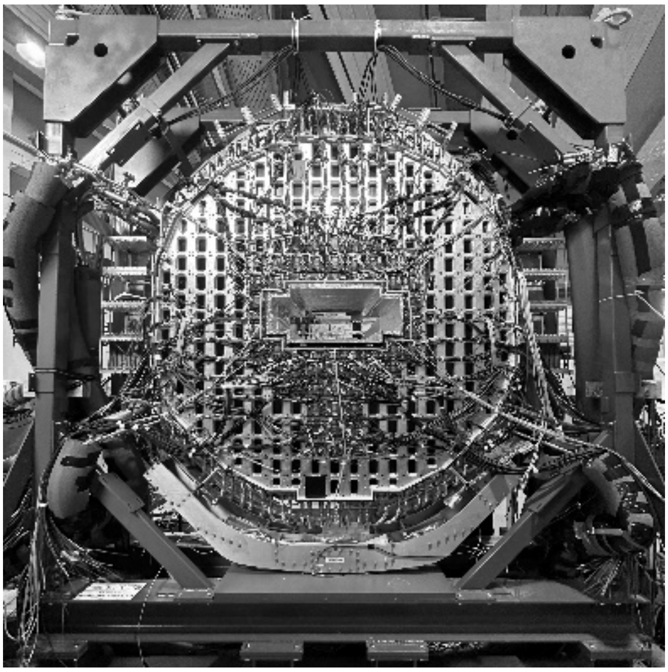
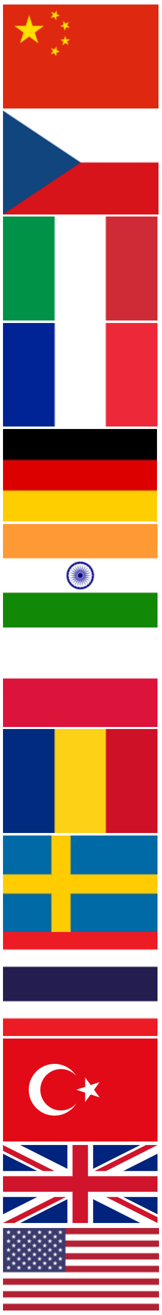
p̄anda

Annual Report

2023





51 Active Institutes

Università Politecnica delle Marche, Ancona
Institute of High Energy Physics (IHEP), Beijing
Ruhr University Bochum
Abant Izzet Baysal University Golkoy, Bolu
University of Bonn
Università degli Studi di Brescia
FAIR, Darmstadt
GSI Helmholtzcentre for Heavy Ion Research, Darmstadt
Friedrich-Alexander-Universität Erlangen-Nürnberg
Northwestern University, Evanston
Goethe-University Frankfurt
Laboratori Nazionali di Frascati (LNF)
University Genova
Justus Liebig-University Giessen
Giresun University
Glasgow University
Gauhati University, Guwahati
USTC Hefei
URZ Heidelberg
University of South China, Hengyang
Doğuş University, Istanbul
Okun University, Istanbul
Forschungszentrum Jülich
Institute of Modern Physics (IMP), Lanzhou
AGH University of Krakow
IFJ PAN, Krakow
Jagiellonian University, Krakow
Krakow University of Technology
Laboratori Nazionali di Legnaro (LNL)
Helmholtz-Institute Mainz (HIM)
Johannes Gutenberg University Mainz
Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Magurele
Universität Münster
Suranaree University of Technology (SUT), Nakhon Ratchisma
INP Orsay
University of Wisconsin, Oshkosh
University Pavia
West Bohemian University, Pilzen
Charles University, Prague
Czech Technical University, Prague
IRFU CEA-Saclay
KTH Stockholm
Stockholm University
Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat
Veer Narmad South Gujarat University, Surat
Florida State University Tallahassee
Nankai University, Tianjin
University & INFN Torino
Uppsala University
National Centre for Nuclear Research (NCBJ), Warsaw and
York University

from 13 Countries

Preface

The year 2023 was a phase of consolidation and reorientation for the PANDA Collaboration. Following the decisions by the FAIR Council to concentrate on Early Science and First Science at the FAIR complex and the suspension of the completion of the Modularized Start Version, PANDA started to investigate also alternative options and fostered R&D cooperations around the globe.

In these days education of the next generation and the preservation of expertise are important tasks and the PANDA Satellite activities have been strengthened to reach this ambitious goal. Apart from activities outside GSI/FAIR, also the study of a small setup, aka RedPANDA, in front of the CBM experiment using the ZEUS magnet was performed. This would be intended to do proton physics at SIS-100 energies. Although this technical solution will probably not be realized, together with activities in CBM, this led to certain workshops and a white-paper on proton physics at CBM which is being prepared now.

Looking more closely into options with alternative magnets goes along with investigating complementary setups of the PANDA hardware which would allow more resource-effective solutions for the detector systems which are not already under construction. This is an ongoing topic.

Two well attended PANDA Collaboration Meetings were held, one in Prag/Czech Republic in June and one at GSI/Germany in November with lively discussions to shape the future of PANDA.

PANDA Management Team since July 2023

Spokesperson	Klaus Peters/GSI & U Frankfurt/Germany
Deputy Spokesperson	Miriam Fritsch/U Bochum/Germany
Collaboration Board Chair	Kai-Thomas Brinkmann/U Giessen/Germany
Deputy Collaboration Board Chair	Frank Goldenbaum/FZ Jülich/Germany
Technical Coordinator	Lars Schmitt/FAIR
Deputy Technical Coordinator	Anastasios Belias/GSI/Germany
Finance Coordinator	Ralph Böhm/FAIR
Physics Coordinator	Karin Schönning/U Uppsala/Sweden
Deputy Physics Coordinator	Stefan Diehl/U Gießen/Germany
Computing Coordinator	Tobias Stockmanns/FZ Jülich/Germany
Deputy Computing Coordinator	Michael Papenbrock/U Uppsala/Sweden
Representative of the Young Scientists	Stephan Bökelmann/U Bochum/Germany

complemented by Alfons Khoukaz/U Münster/Germany as Advisor and

Peter Wintz/FZ Jülich/Germany and Udo Kurilla/GSI/Germany as representatives of the Speakers Committee and the Membership Committee of PANDA.

We also thank U. Wiedner/U Bochum/Germany, R. Kliemt/GSI/Germany, J. Messchendorpp/GSI/Germany, F. Nerling/GSI/Germany, and F. Maas/HI Mainz/Germany for their management service to the PANDA Collaboration until June 2023.

PANDA Introduction

PANDA Elevator Pitch

Do we understand the matter we are made of? Everything can be traced back to tiny atoms – each one made of a nucleus of protons and neutrons, surrounded by a cloud of electrons. But the story does not end here: protons and neutrons are composite systems of even smaller units: elementary quarks, glued together by the strong force. And here something astonishing happens: The quarks only make up about 1% of the proton mass, while the remaining 99% is created by the strong force! According to Einstein's famous formula $E=Mc^2$, the energy E of the strong force is transformed into the mass M of the proton. But how exactly does this happen given that the strong force carriers – the gluons – are massless?

The future PANDA experiment at FAIR will address this truly fundamental question by using a unique beam of antiprotons - the antimatter counterparts of protons. When the antiprotons collide with protons, they will annihilate each other and create many gluons. Theorists predict that these gluons bind together to form so-called glueballs – matter made of force. But do they really exist? PANDA will tell – and provide decisive information to solve the puzzle of how mass is created.

Another mystery of nature that PANDA will unravel is why our Universe consists of so much more matter than antimatter. In the Big Bang, equal amounts of matter and antimatter should have been created, and yet we only consist of matter. At PANDA, we will produce matter and antimatter particles in pairs and study their properties in detail. Revealing even tiny matter-antimatter differences can explain why matter prevailed in our Universe.

Together with the other experiments at FAIR, we bring the Universe to the laboratory.

PANDA Overview

The whole is more than the sum of its parts. This is sometimes said and for the proton, this expression is literally true. The sum of the masses of its valence quarks accounts for less than 2% of the proton's total mass, with the rest resulting from the kinetic and binding energies among quarks due to dynamics of the strong interaction. Quantum Chromodynamics (QCD) is the accepted theory of the strong interaction and describes the properties of quarks and their interactions through gluons, the force mediator of the strong interaction. Despite the success of QCD in predicting processes at high energies, at low energies, the theory becomes strongly coupled as α_s becomes large. In this non-perturbative regime, it is still hard to make predictions from first principles.

The complexity of the strongly coupled many-body system in non-perturbative QCD gives rise to many questions: What are the effective degrees of freedom which systematically describe resonances and bound states? Where are the exotic resonances and bound states predicted by QCD? How do bound quark systems interact? What is the residual structure of the hadronic systems? Thus, the central goal of the PANDA experiment is the elementary understanding of hadrons using the power of an antiproton beam on hydrogen or nuclear targets. This very process, the annihilation of nucleons, creates a rich variety of hadrons with respect to other experimental probes with the additional advantage of a well-defined and flavor-blind initial state. High precision mass scanning complements this and underlines the uniqueness of the project. All this has been proven in the past to be a universal tool for carrying out the necessary investigations and in order to utilize antiprotons for hadron physics the PANDA (anti**P**roton **AN**nihilation in **DA**rmstadt) collaboration has been formed and is today a cooperation of almost 500 scientists from 20 countries.

The experiment will be located at the Facility for Antiproton and Ion Research (FAIR), an accelerator facility leading the European research in nuclear and hadron physics in the coming decade. It builds on the experience and technological developments from the existing GSI facility, and incorporates new technological concepts, such as rapidly cycling super-conducting magnets. It will e.g. address a wide range of physics topics in the fields of nuclear structure, nuclear matter, atomic and plasma physics.

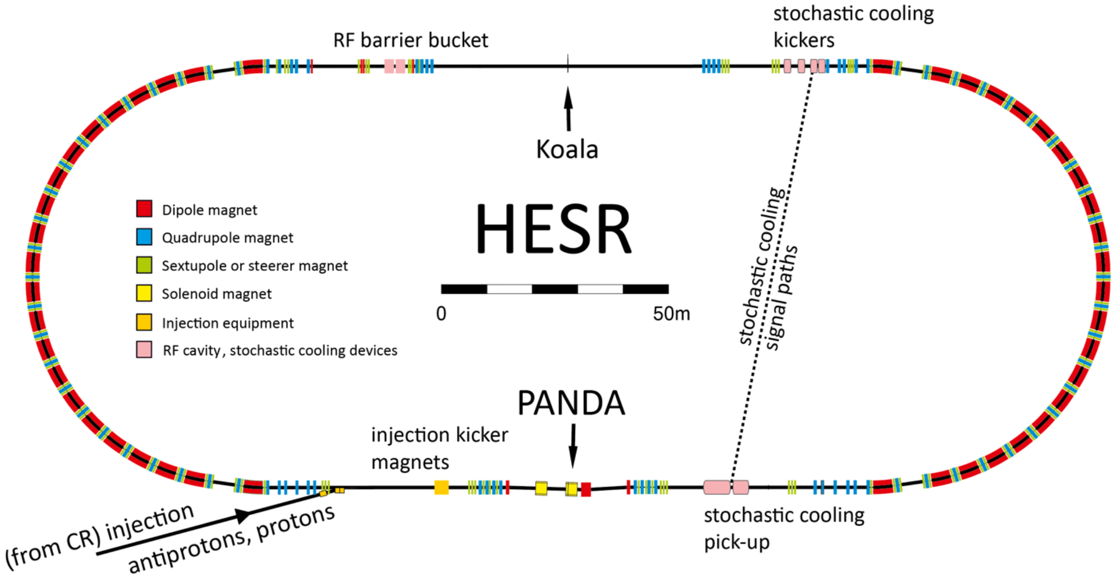


Figure 1: High Energy Storage Ring at FAIR. The PANDA detector is located in one of the straight sections where the antiproton beam interacts with a fixed target. Koala is a precision scattering experiment for systematic luminosity studies.

An important feature of the new antiproton facility is the combination of dense internal targets and phase-space cooled beams in the High Energy Storage Ring (HESR) which hosts PANDA as an in-beam experiment. It will allow two operation modes: A high-resolution mode with a momentum spread down to a few times 10^{-5} and beam intensities up to 10^{10} using a powerful stochastic cooling system, and a high-luminosity mode with beam intensities up to 10^{11} in a later stage. The HESR is filled by the Collector Ring (CR) which accumulates by stacking the antiprotons every 10 seconds from the collision of 2.5×10^{13} protons of 29 GeV in a 50 ns bunch on the production target.

The HESR lattice is designed as a racetrack shaped ring, consisting of two 180° arc sections connected by two long straight sections. One straight section will host the installation of the PANDA experiment with an internal target as well as RF cavities, injection kickers, and septa (see Fig. 1). The other section will mainly be occupied by an electron cooler at a later stage and will host smaller experiments for nuclear and atomic physics with ion beams. For stochastic cooling, pickup and kicker tanks are in the straight sections, opposite to each other. The momentum of the antiprotons ranges from 1.5 to 15 GeV/*c*, allowing for a wide variety of physics channels (see Fig. 2).

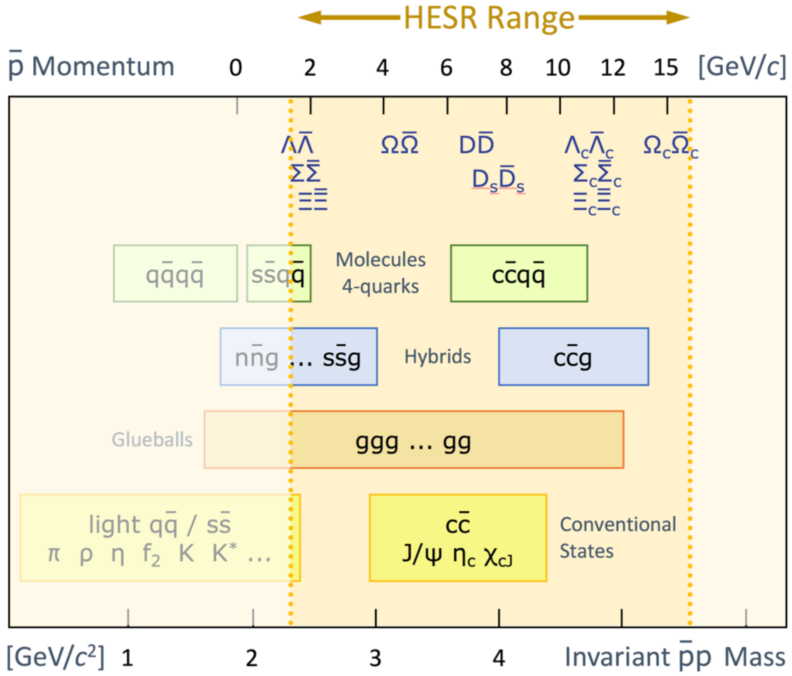


Figure 2: Some of the many accessible hadron species with PANDA and HESR.

The PANDA experiment belongs to a new generation of hadron physics experiments, hereby building on the experiences and successes of previous generations. It features a modern multipurpose detector (see Fig. 3). The combination of a high-quality antiproton beam at the HESR, an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test QCD in the non-perturbative regime. In the following, we will outline a few of the physics aspects that will be addressed using this facility (see Ref [1,2] for more details).

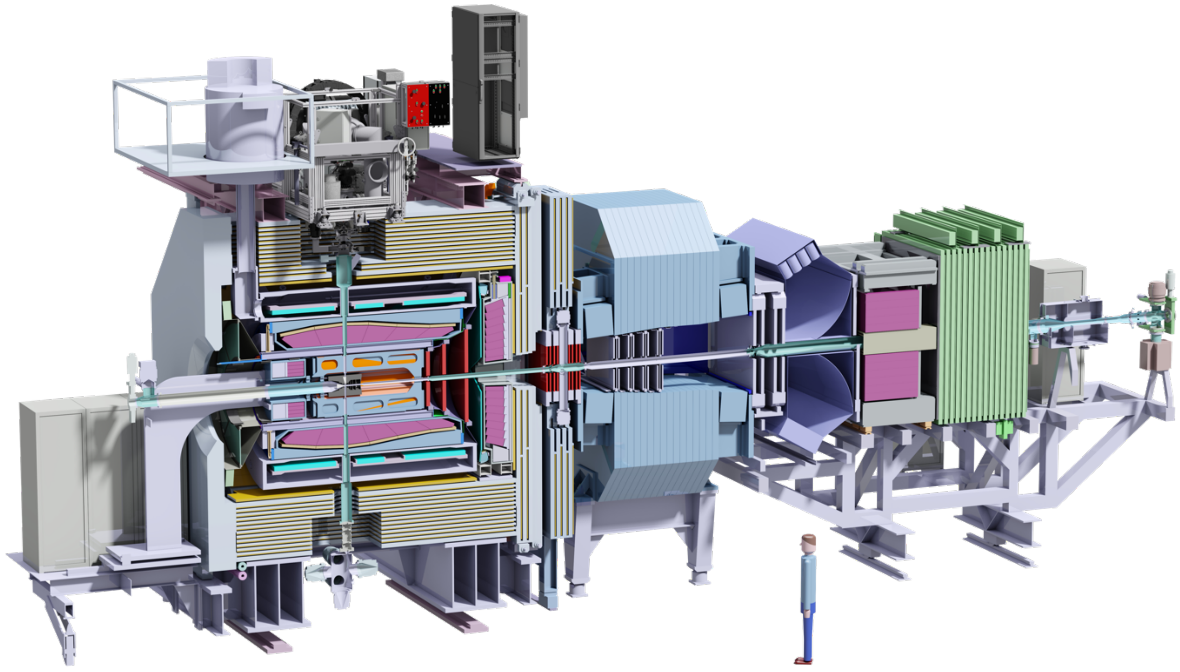


Figure 3: CAD drawing of the full PANDA Detector.

PANDA will copiously produce anti-hyperon-hyperon pairs through the reaction $\bar{p}p \rightarrow Y\bar{Y}$. The energy scale is given by the mass of the strange quark (m_s~100 MeV/c^2), which is below, but near the strong coupling scale Λ_{QCD}. This corresponds to the confinement domain, where our knowledge of the strong interaction is scarce. Therefore, the relevant degrees of freedom – quarks and gluons or hadrons – remain unclear. Spin observables have been proven to be very sensitive to the underlying degrees of freedom of the model describing the interaction. The high cross section for hyperon pair production using antiproton interactions will provide the necessary high statistics to access spin observables with sufficient precision. In addition, so far unmeasured multi-strange hyperons are accessible with PANDA. In particular, seven polarization parameters of the spin 3/2 Ω-hyperon can be extracted for the first time.

This large production cross section will also enable several innovative studies of systems containing two or even more units of (anti-)strangeness in antiproton-nucleus collisions at the PANDA experiment. The interaction of antibaryons in nuclei provides a unique opportunity to elucidate strong in-medium effects in baryonic systems. Quantitative information on the anti-hyperon potentials will be obtained for the first time via exclusive anti-hyperon-hyperon pair production close to its production threshold in antiproton-nucleus interactions. After pioneering studies of the Λ potential during the first phase of PANDA, the Ξ and even the Ω potential can be explored once the full luminosity is available. Baryons with strangeness embedded in the nuclear environment, hypernuclei or hyper-atoms, are the only available tool to approach the many-body aspect of the three-flavor strong interaction. A new key measurement will be high resolution γ-spectroscopy of excited states in several doubly strange ΛΛ-hypernuclei. Hypernuclear studies would result also in valuable insights to astrophysics as well, such as the Hyperon-puzzle of neutron stars and mechanisms of core-collapse supernovae.

The field of charmonium spectroscopy is an exciting field with many discoveries in the past 15 years. Many predicted states have not been observed and, on the other hand, masses, widths, and decay rates of many unexpected states (XYZ states) have been measured. Until today, a coherent picture cannot be drawn from what is available experimentally. PANDA will contribute to this field in two unique ways: a) in explorative studies in many-body experiments to search for high-spin and spin-exotic states and b) by a precision measurement of the mass and width (or more generally the line-shapes) of any neutral charmonium-like state. The very small momentum spread of the antiproton beam allows a determination of the width, for example of the X(3872), with an accuracy of 50 keV. Such an accuracy will provide a decisive measurement on the nature of the narrow X(3872). This technique can also be used to investigate excitation curves of open-charm final states, like e.g. $D_sD_{s0}^*(2317)$ to measure the width of the respective $D_{s0}^*(2317)$.

Furthermore, antiproton annihilations allow for the study of a rich variety of nucleon structure observables in large (partly) unexplored areas such as the kinematical regime that corresponds to the time-like (positive, s-channel) momentum transfer of the virtual photon. The electromagnetic form factors of the proton, Transition Distribution Amplitudes (TDA), Wide Angle Compton Scattering (WACS), and Drell-Yan processes for accessing Transition Momentum-Dependent Parton-Distribution Functions (TMD-PDF) are examples of those variables. Fig. 4 shows how crossing symmetry e.g. connects space- and time-like regions.

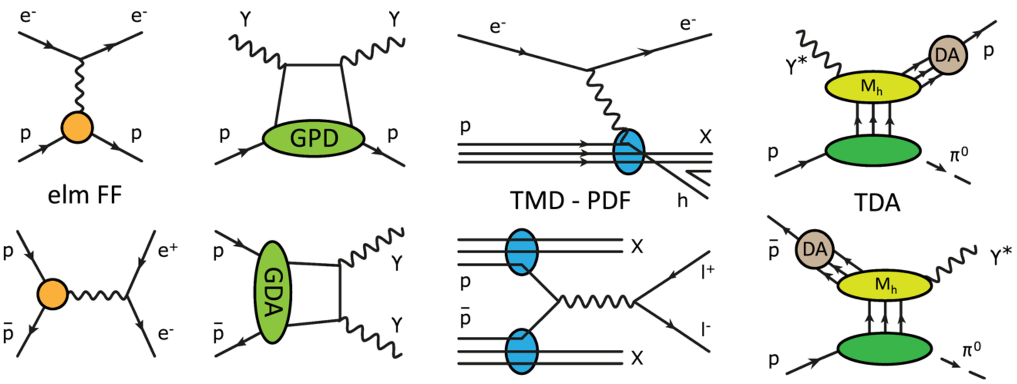


Figure 4: Crossed channel diagrams that relate electromagnetic scattering off the proton to lepton/photon pair production from antiproton-proton annihilations (elm FF=electromagnetic form-factor, GPD=Generalized Parton Distribution, GDA=Generalized Distribution Amplitudes, M_h=hard process amplitude, DA=Distribution Amplitude, see Ref [1,3] for more details).

Experiments accessing the region of positive momentum transfer squared complement the studies of the nucleon structure from the lepton scattering experiments (negative q^2). They provide experimental support to the non-perturbative approaches used to describe the high energy electromagnetic processes in different regimes. Fig. 4 shows crossed channel diagrams that allow to extract the same functions, like for the case of TDAs and TMD PDFs, or to extend their measurements like for the case of form factors and GDAs, in/to different kinematical regimes (space- and time-like regions).

The main objectives of the design of the PANDA experiment are to achieve almost 4π acceptance, high resolution for tracking, particle identification and calorimetry, high-rate capabilities and a versatile readout and event selection. To obtain a good momentum resolution, the detector will be composed of two magnetic spectrometers: The Target Spectrometer (TS), based on a superconducting solenoid magnet surrounding the interaction point, for particle tracks at large angles and the Forward Spectrometer (FS), based on a dipole magnet, for small angle tracks. In both spectrometer parts, tracking, charged-particle identification, electromagnetic calorimetry and muon identification will be available to allow to detect the complete spectrum of final states relevant for the PANDA physics objectives.

The TS has a typical onion-like structure, very much like the detectors used for the B-Factories Babar and Belle: A cluster jet or pellet target system will be used to provide either a cluster beam of a target gas or frozen hydrogen pellets. Thin foils or noble gasses will be used for antiproton-nucleus studies. The interaction point is surrounded by the Micro Vertex Detector (MVD) which has a vertex resolution of about 50 µm in transverse and 100 µm along the beam direction. Surrounding the MVD, the Straw Tube Tracker and Gas Electron Multiplier (GEM) stations will be used for tracking charged particles ($\Delta p_T/p_T = 1.2\%$) in the magnetic field. Photons and the energy of electrons will be reconstructed with the Electromagnetic Calorimeter (EMC). The EMC consists of a barrel (azimuthal angle 22° to 140°), a forward endcap (down to the opening for the FS) and backward endcap (145° to 170°) and consists of about 16,000 $PbWO_4$ crystals providing an energy resolution of $1.5\%/\sqrt{E}$, whereby E is given in units of GeV. Particle identification of pions, kaons and protons will utilize information from a Time-of-Flight system (ToF), a cylindrical DIRC (Detection of Internally Reflected Cherenkov light), and a forward Disc DIRC detector. The ToF will use scintillating tiles with Silicon Photomultiplier readout. The cylindrical DIRC is a bar-type DIRC with quartz-prisms, while the Disc DIRC uses large quartz plates. The solenoid magnet will provide a homogeneous magnetic field up to 2 T in the beam direction. The segmented yoke is instrumented with chambers for muon identification.

The FS covers polar angles below 10° horizontally and 5° vertically. Charged particles will be detected using the Forward Tracking System, which consists of multiple straw tube layers, in conjunction with a dipole magnet with variable field depending on the incident antiproton momentum. The momentum resolution for tracks above 1 GeV/c is better than 1%. A Forward Time-of-Flight and an aerogel-based Ring Imaging Cherenkov Counter detector will provide particle identification. A Shashlyk-type Calorimeter with an energy resolution of $3\%/\sqrt{E}$ is followed by the Muon Range System for muon detection. At the forward end, the Luminosity Detector uses elastic scattering of antiprotons on protons to determine the interaction rate measuring antiprotons deflected at low angles. A detailed description of the PANDA detector and its components can be found at [4].

As the detector response of background events is very similar to that of the decay of the exotic states, the use of a conventional triggered readout scheme, where a limited number of subdetectors generates a trigger signal that engages the readout of the complete detector, is not practical. Therefore, a new type of intelligent readout is being developed, where kinematical constraints are imposed online on reconstructed events. This technique is dubbed as “triggerless readout” and allows adjusting the data selection to numerous physics channels. A data reduction factor of up to $\sim 10^3$ is expected to be achieved by employing this technique for the whole detector, resulting in a data rate of $\sim 10^4$ events/s (or, equivalently, 200 MB/s) that will then be sent to storage for offline processing and analysis.

References and further reading

[1] M.F.M. Lutz et al., *Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons*, arXiv:0903.3905 (2009)

[2] M.F.M. Lutz et al., *Resonances in QCD*, Nucl.Phys. A948 (2016) 93, https://doi.org/10.1016/j.nuclphysa.2016.01.070

[3] R.A. Briceno et al., *Issues and Opportunities in Exotic Hadrons,* Chin.Phys. C40 (2016) no.4, 042001, see also INT-PUB-15-066, JLAB-THY-15-2174, FERMILAB-PUB-15-652-T

[4] U. Wiedner, *Future Prospects for Hadron Physics at PANDA*, Prog.Part.Nucl.Phys. 66 (2011) 477-518, 10.1016/j.ppnp.2011.04.001

[5] https://panda.gsi.de

Already in the first two phases of PANDA several different scientific topics within subatomic physics will be addressed. These two, referred to as *Phase-1* and *Phase-2*, both occur during the period without the RESR that comes with *Phase-3*. In the transition from Phase-1 to Phase-2 additional detector components will be installed to have the full setup of PANDA available, mainly for a better coverage for particle identification. Phase-3 corresponds to the full design luminosity, which is possible with the additional storage ring available beyond MSV0-3 ($\int L > 10\ \text{fb}^{-1}$). Thus for our considerations, the luminosity will be limited in Phase-1 and Phase-2 to $L = 2 \cdot 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$. During Phase-1 and -2, we aim to collect data corresponding to an integrated luminosity of about $\int L = 0.5\ \text{fb}^{-1}$ each, using the so-called *Start-setup* of PANDA described below. The period leading up to the very first antiproton runs of PANDA is referred to as *Day-1*. During this period, we will perform the first necessary steps towards the realization of Phase-1 and -2. In the text we quote how much of the program can be accomplished in these phases with the sum Phase-1 plus -2 defined as 100%. We have used the amount of required data to quantify the fraction of accomplishment.

Below, we briefly discuss the present goals of the physics pillars for the first two phases (including comments on the respective competition), followed by a discussion of the activities at Day-1 with quantitative statements. However, we are prepared that new discoveries may alter these plans.

Hadron spectroscopy

The first pillar is devoted to providing precision data for hadron spectroscopy with light to charm constituent quarks, and gluons. Concerning the light-quark and gluon sector, we plan to map out the glueball spectrum and to search for exotic forms of hybrids and meson-like or molecular states.

Final states best suited for that include one or multiple ϕ, ω, η, J/ψ as well as D and D_s mesons since their production is OZI suppressed due to the large flavor component, and thus those channels have reduced conventional matter content.

The data we foresee to harvest are complementary to studies conducted at BESIII, COMPASS, GlueX, and Clas12 due to various reasons like the probe, the analysis technique and the accessible quantum numbers. The LEAR facility has demonstrated the strong advantage of using antiprotons for gluon-rich matter such as various scalar states that were first discovered using antiproton annihilations including the candidate for the glueball ground state, *i.e.* the $f_0(1500)$. PANDA will extend these measurements by probing a sufficiently larger energy range (E_{cms} = 2-5.5 GeV) and with a detector capable to perform a fully exclusive study of practically all final states. As demonstrated by LEAR, the cross sections are spectacularly high in contrast to reactions with electromagnetic probes. Already with lower luminosities, this gives excellent prospects for the search for massive glueballs with $J^{PC} = 2^{++}$ and 0^{-+}, hybrid states with gluonic degrees of freedom and exotic quantum numbers as well as meson-like states with light and strange quarks. The analysis technique at PANDA is based on PWA of exclusive final states and constraints on the initial state for the ease of reliable quantum number assignments that are crucial for the interpretation of the data. This is superior to scattering experiment in terms of systematics and backgrounds and can systematically be extended to the hidden and open-charm sector. This will *e.g.* shed new light on the recently discovered charmonium-like *XYZ*-spectrum with precision line-shape scans (with a resolution of about 50 keV/c^2 per point). In particular, it will allow for searches in the high spin segment (up to J = 6) or at larger mass (up to 5.5 GeV/c^2) to complement the existing findings such as $X(3872)$, $Z_c(3900)$ and $Z_c(4020)$ (to name a few) for which most of the decay channels are not found yet and counter parts for an understanding of the spectrum are missing. In Phase-1, we expect to complete 75% and 25% of our light-(include strange-)quark-exotics and charm-exotics programs, respectively.

Hyperon physics

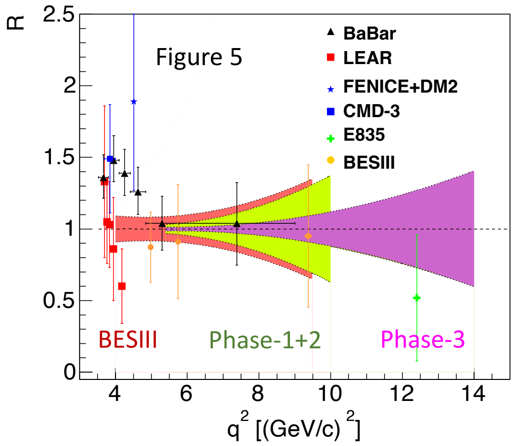
The second physics pillar of PANDA is the pairwise production of mesons and baryons with open-strangeness and charmness in $\bar{p}p$ annihilations. This is truly unique in the world and will provide insight in the underlying mechanisms that play a role in the creation of strange and charm quark pairs. For the Phase-1 and Phase-2 programs of PANDA, we foresee to exploit the pair production of |S|=1, 2, and 3 and |C|=1 baryons and mesons near their production thresholds. It delivers a rigorous test for the validity of few-body models at various mass and energy scales. The self-analyzing feature of weakly-decaying hyperons gives experimental access to spin observables such as polarization and spin correlations, which are sensitive to the production mechanism. A multidimensional analysis of the particle-antiparticle symmetric final state provides a model-independent test of CP violation in baryon decays. This has to be seen in the context of the long-standing puzzle of the matter-antimatter asymmetry of the Universe.

We expect to complete in Phase-1 100%, 90%, 10%, and 10% of the hyperon spin program for |S|=1, 2, 3, and |C|=1, respectively on the basis of 7M , 4M, 90k, and 100 reconstructed events per day for $\bar{p}p \rightarrow \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$ near threshold in Phase-1 respectively.

The associated production also will provide the opportunity to extensively investigate the spectrum of the charm and strange sector. This allows for a tagging method, an ideal tool for spectroscopy purposes near production thresholds where the missing-mass resolution is optimal and the background is small. Limitations in the luminosity are compensated by the huge cross sections (up to microbarns) that can be expected because of past experience, in particular for |S|=1, 2 hyperons. In general, the production cross sections of |S|=2 states with antiprotons are two- or three-orders in magnitude larger than that of photons. PANDA will be able to study the |S|=3 sector, where only very few experiments can contribute measurements. Furthermore, the antiproton probe makes PANDA sensitive to states that do not couple to photons or kaons. We expect to complete in Phase-1 70%, 40%, but 0% of our programs for |S|=2, 3, and |C|=1, respectively.

Proton structure

Proton structure experiments with electromagnetic final-states in antiproton-proton collisions are the third physics pillar of PANDA. In the first phases of PANDA, we want to measure the electric and magnetic form factors, $|G_E|$ and $|G_M|$, and their ratios at various q^2 values in $\bar{p}p \rightarrow l^+l^-$. These time-like electromagnetic form-factor studies are a necessary complement to the space-like counterpart in lepton-scattering experiments. The foreseen PANDA measurements will extend the time-like data of electron-positron annihilation experiments, such as the ones conducted at BESIII, substantially in terms of energy range as well as accuracy. PANDA will collect data that are sensitive to probe the unphysical regime, $4m_e^2 < q^2 < 4m_p^2$ by exploiting a final-state with an additional pion that brings the (anti)proton offshell. The present-day accuracy will be improved from 20% at low q^2 values to 3%. Combining data from BESIII (yet unpublished) and PANDA, the analytical nature of the form factors can be studied. Besides these unique measurements, PANDA will be the first experiment capable to measure the proton time-like form factors in both e^+e^- and $\mu^+\mu^-$ final states. It might offer new insights in the proton radius puzzle by testing the lepton universality in these reactions.



Recent Monte Carlo (MC) studies have been performed for the Phase-1 setup as well as for the full setup at Phase-3. They have demonstrated that the PANDA start setup has the capability of successfully suppressing the huge background from the di-pion channel provided that satisfactory knowledge is obtained on the background dynamics. PANDA can provide data for detailed studies of multi-pion production in antiproton-proton annihilations. These data will serve as input to QCD calculations. Fig. 5 shows a comparison of existing data on $R = |G_E|/|G_M|$, the size of the errors of the so-far unpublished BESIII measurement (red-shaded area for comparison) and the error forecast for PANDA Phase-1+Phase-2 (green-shaded area). 50% of this program will be completed during Phase-1. The pink-shaded area indicates the error that we will achieve at Phase-3 with a factor of ten higher beam intensity.

Strange hadrons in nuclei

The fourth pillar of the Phase-1/2 program is dedicated to study the properties of hadrons in a nuclear medium. Firstly, we propose studies of the antihyperon-nucleus potential, accessible via the associated production of hyperon pairs close to the production threshold, which cannot be studied at any other laboratory in the world. It offers essential information for the interpretation of data from heavy-ion collision experiments. Furthermore, the foreseen program includes measurements of the basic (mass, width) parameters of hidden-charm states at nuclear densities. This might give complementary information that helps to shed light on the formation of hadrons and measures signatures that could point to the (partial) restoration of chiral symmetry. Also, in the context of color transparency we can deliver significant contributions that exceed those of other experiments, *e.g.* access to other final states due to the $\bar{p}N$ entrance channel. We expect to complete 70% of this program in Phase-1.

Furthermore, antiprotons can be used to implant hyperon pairs into a nucleus as a Phase-2 program. PANDA offers also the unique possibility to search for X-ray transitions from very heavy hyperatoms as e.g. Ξ^{-208}Pb which is not possible at other labs. This will complement experiments at J-PARC which attempt to measure X-rays in medium-heavy nuclei. The measurement at PANDA will for the first time allow to constrain the interaction of Ξ^--hyperons in the neutron skin. In a later stage, PANDA will extend the studies on double hypernuclei by performing for the first-time high resolution γ-spectroscopy of these nuclei. Thus, PANDA complements measurements of ground state masses of double hypernuclei in emulsions at J-PARC by the E07 Collaboration or the production of excited resonant states in heavy ion reactions which may for example be performed in future by the CBM Collaboration. Both studies are unique and cannot be done elsewhere. In Phase-3 we are planning to study charm in nuclei as well.

Early Science

Under the assumption that the starting luminosity at Day-1 could be significantly below design, the goal is to primarily concentrate on channels with large cross sections (µb) and relatively simple event topologies. Also, the setup will be reduced due to fabrication schedules and available funds. We expect to collect in the order of 5 pb^{-1} of data, which will be roughly 1% of the total Phase-1 integrated luminosity. Thus, one must differentiate between two aspects. There is the Day-1 setup, which seamlessly evolves to the Phase-1 setup as more components get ready, and the initial Day-1 luminosity, which is expected to increase quickly to the desired Phase-1/2 beam intensity to eventually allow for the full MSV0-3 program. Given these preconditions of Day-1, we have identified i) flagship experiments with a guaranteed physics outcome, ii) feasibility studies with a high discovery potential, and iii) development activities to realize the full physics program. These three categories of experiments will provide data for all pillars of PANDA. The focus will be largely on studying the various production mechanisms of strange and partly charm-rich hadrons. In addition, we will map out the elastic $\bar{p}p$ cross section for the ease of luminosity calibration. Below, we briefly illustrate a few typical cases of each of the three categories as indicators of the Day-1 capabilities of PANDA.

Flagship studies

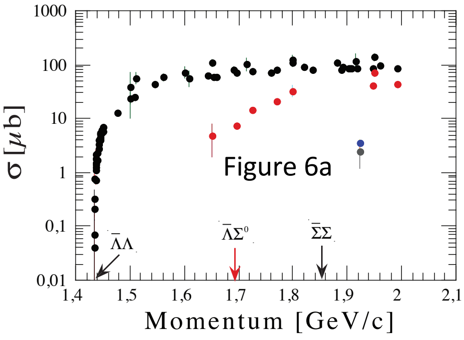
As a typical flagship study for Day-1 within the light-meson and gluonic matter spectroscopy program of PANDA, we consider relatively simple two-body final-state reactions that are easily identifiable and, preferably, are flavor-blind to be sensitive to gluon-rich matter (like massive glueballs). A key example is $\bar{p}p \rightarrow \phi\phi$ which has been first observed by Jetset in the late 1990's and which has a huge cross section in the order of a few μb at threshold, about 100 times larger than expected from the OZI rule. This has been interpreted as an indication of a strong tensor glueball contribution. We would be able to study this reaction at energies beyond what has been achieved at LEAR and being extendable with additional mesons, *e.g.* π^0. This would also be an excellent case to benchmark the partial-wave analysis tools[1].

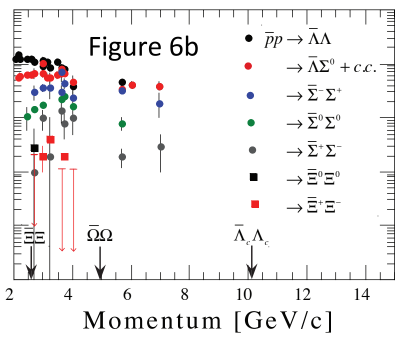
We expect to achieve a significant physics output by studying the production of antihyperon-hyperon pairs for both |S|=1 (i.e. $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$) and |S|=2 (i.e. $\bar{p}p \rightarrow \bar{\Xi}\Xi$) systems near their corresponding production thresholds at ~1.64 GeV/*c* and ~4 GeV/*c*, respectively. Differential cross sections and polarization observables can be measured within a few days, whereby the systematic uncertainty will be the limiting factor. The study of the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ channel at 1.64 GeV/*c* will be benchmarked using published data from LEAR as a reference. At 4 GeV/*c*, both |S|=1 and |S|=2 systems will be unique and new measurements.

The hyperon-antihyperon production studies at threshold energies can be extended using nuclear targets. We then would have access to the relative asymmetry between the transverse and longitudinal momentum of the two hyperons. These observables are of particular interest since they are sensitive to the antihyperon-nucleus potential. Their measurements can be conducted with sufficient data samples in only one week of data collection at a luminosity of about 10^{30} cm^{-2}s^{-1} and would not only be exclusive in the world, but also very valuable for the heavy-ion physics community.

Feasibility studies with discovery potential

The cross sections in the μb range (Fig. 6) and the promising perspective of associated hyperon production provides a basis for baryon spectroscopy measurements with strangeness degrees-of-freedom. Even with a limited setup at Day-1, excited baryons with strangeness contents can be studied using the missing-mass technique as a first step. In particular, the excited spectrum of |S|=2 baryons (Ξ) give information, *e.g.* mass and partial width, and are complementary to the baryon spectroscopy studies conducted at JLab.





The hidden-charm sector above the open-charm threshold is one of the mysteries since many unconventional charmonium states have been discovered in the past decades. For the Day-1 program, it is intriguing to open a new territory with the use of $\bar{p}p$ or $\bar{p}n$ reactions to search for yet unobserved charged Z-states. Such discoveries would be complementary to the spectrum of recently discovered $J^P = 1^+$ Z-states in e^+e^- collision experiments (BESIII, CLEO-c, BELLE2). The $\bar{p}n$ reaction can be used to produce these charged states without a recoil particle. These states are easily identifiable via their decay into a J/ψ. The final state will therefore be composed of a few charged pions and a lepton pair from the J/ψ, for which the Day-1 setup will have sufficient efficiency and acceptance. With the available energy at PANDA, we can study heavier Z-states than BESIII and/or states with a spin that exceeds $J^P = 1^+$.

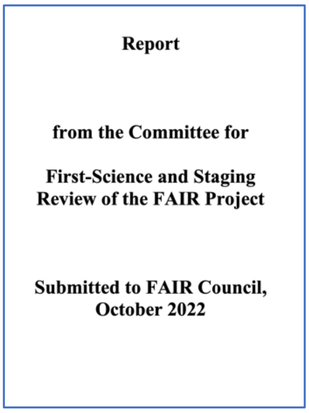
Development of novel techniques

One of the features of PANDA is the usage of stochastically cooled antiprotons with an excellent momentum resolution. Such a beam allows to perform an energy/mass scan of various narrow states with hidden-charm and a variety of spin and parity. One of the Phase-1 goals is a scan of the mysterious X(3872). The measurement of the width, or the line shape in general, of this very narrow resonance could conclude its nature. However, the prospects of this study at Day-1 are not very promising since the production cross section is less than 50 nb. Instead, we will develop and validate the line-scan method by applying it on one of the well-known conventional charmonium states below the open-charm threshold. The vector charmonium states would be the best candidates because of their relatively large coupling to $\bar{p}p$.

The electromagnetic form factor studies require good knowledge on the multi-pion background channels. We plan to measure extensively differential cross sections of these channels that will be used as input to QCD models to develop accurate event generators. Since the cross sections of these background channels are large and the event topology fairly simple, it will be ideally suited as a Day-1 development study. The goal would be to validate the simulation result with experimental data that the background can be suppressed sufficiently enough to be able to identify $\bar{p}p \rightarrow \mu^+\mu^-/(\pi^0)e^+e^-$.

Science Review in 2022

In 2022 a scientific review was conducted for all FAIR pillars. The final paragraphs of the PANDA section (after explaining the physics case) read



Report

from the Committee for

First-Science and Staging
Review of the FAIR Project

Submitted to FAIR Council,
October 2022

“The compelling case of PANDA’s high-precision science program justifies the execution of the full MSV, even if delayed by five years. In particular, it is recognized that many of the accelerator components for the full MSV are available and currently in storage. The team is encouraged to complete designs of the system using CERN’s Antiproton Accumulator (AA, currently in storage in Japan), for parts of the Collector Ring (CR) and recycling the COSY ring for the RESR Accumulator Ring. This would alleviate the problems caused by reduction of contributions from Russia.

PANDA’s high precision measurement program is unique. With no other competing experiments of comparable precision on the horizon, PANDA can afford to be delayed by five years. However, a clear schedule from the Council is necessary. It is important that the steps in a staged and well-developed plan, including the required civil construction and installation of accelerator components towards its completion, be carefully monitored and any updates are clearly communicated to the PANDA collaboration.”

PANDA 2023: Phase-0 at PANDA Satellites

The Phase-0 activities at GSI and other Laboratories and Universities have been continued and extended in 2023. They cover intellectual aspects like software and analysis development and teaching as well as common R&D and using PANDA hardware in other experimental environments, which we call Satellites. In this section we report the Phase-0 activities with PANDA equipment used at HADES at GSI, at A1 at MAMI in Mainz, at Crystal Barrel at ELSA in Bonn and Koala at COSY at FZ Jülich.

PANDA (Straw Tube Systems) @ HADES

The PANDA@HADES collaboration was working over improvements of the STS tracking. We were able to significantly improve the tracking resolution but optimizing and refactoring the tracking code. The tracking procedure consists of clustering fired straws into groups of related hits, tracking each STS1 and STS2 separately, finding matching pairs of tracks between both STS modules, and recalculating whole tracks from both stations. Then, second stage tracking is running where the whole tracks are matched against hits in the time-of-flight FRpc detector. If the match is found, the timing information from FRpc and each straw hit belonging to the track are used to calculate isochrones. The final tracking uses the isochrones for precise track calculation. The χ^2 of tracks residuals (distance between track and isochrones) assuming tracking resolution of 120 µm are shown in the figure below.

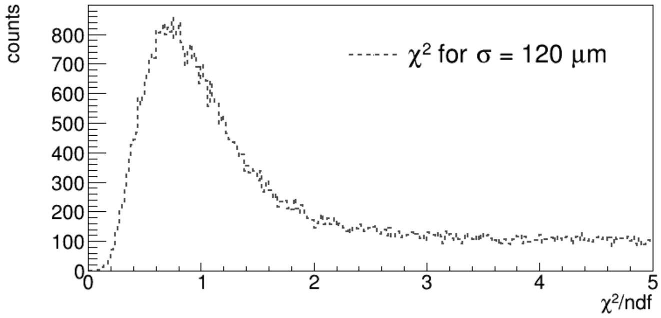


Figure 7: The χ2 distribution of tracks.

The tracking improvements, among others, include improvements of the isochrone calculations, track pattern matching and fakes rejection. With the new tracking code, we obtained 13% more accepted tracks and were able to reconstruct 5% more single track events. However, we are still identifying some problems with the straw isochrone modeling. We see systematic shift of the isochrone distribution towards the smaller values. Similar effects are seen in the simulations, but they have opposite effects, and isochrones seems to be overestimated. We identified those problems as related to the straw drift times modeling and the calibration parameters. Currently we are working on improving both for the next Hades DST production.

Ongoing is the alignment procedure. Current alignment allowed us to achieve satisfying resolution however further improvements are possible using the MilliPede alignment software developed at DESY and used in various experiments, including alignment of HADES detectors. MilliPede is however very sensitive to isochrones calculations and with current problems with isochrones, we are unable to achieve stable results of alignment procedure.

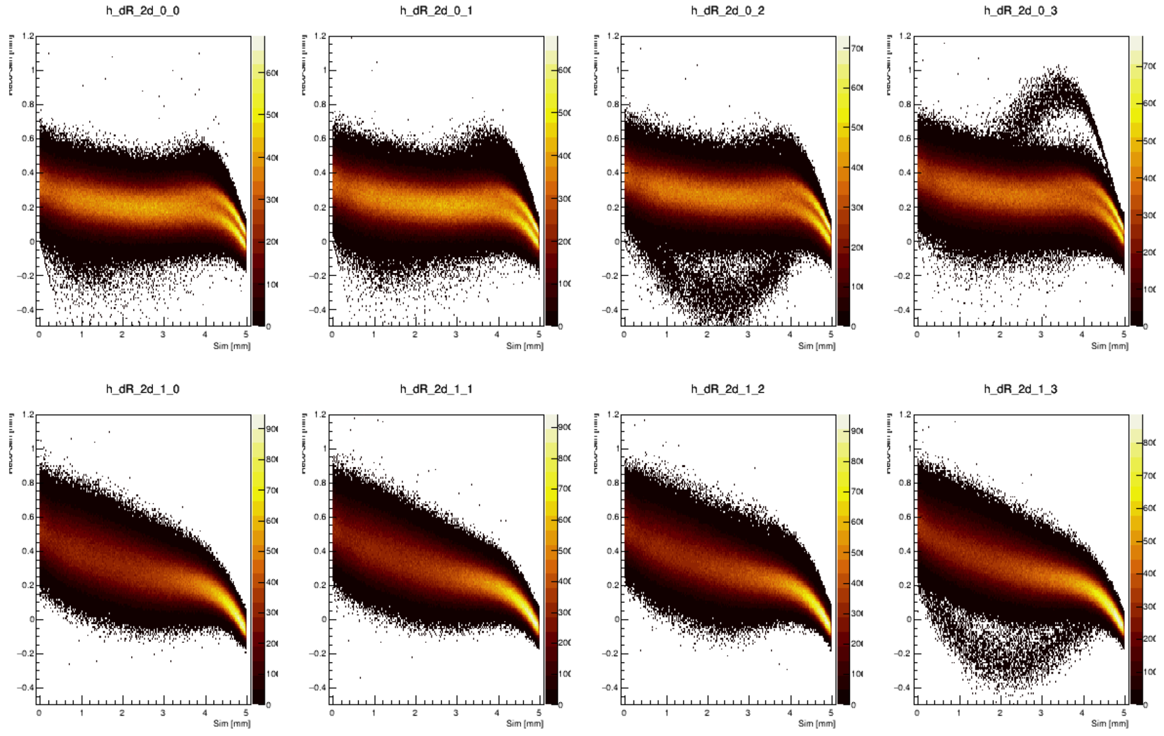


Figure 8: Reconstructed - simulated isochrones as a function of simulated value. Distributions clearly shows overestimation of reconstructed isochrones in almost whole range of values.

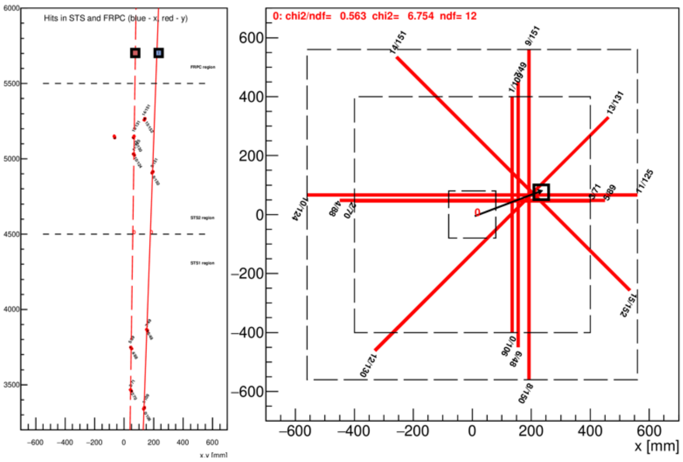
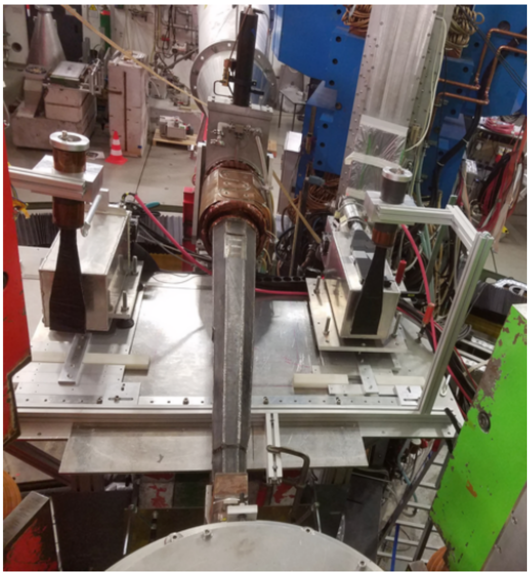


Fig. 9: The Forward Detector event viewer of a single track. The left panel shows the x or y vs z hits in the STS1 (y-axis range up to 4000), STS2 (4500–5500) and the FRpc hits (above 5500) respectively. The straight line is the x-z projection, and the dashed line is y-z projection. The red circles denote fired straws. The red and blue boxes are x and y coordinates of the FRpc hits. The right panel shows the x-y projection of the tracks. The red thick lines denote the fired straws. The black-framed box is the FRpc hit, and the track itself is shown by black arrow. The base of the track emerges from the target region. The tracking parameters of the track are given in the upper part of the panel.

PANDA (Backward Endcap) @ MAMI

The preparation of the Phase-0 experiment for measuring the π^0 transition form factor in single-pion electroproduction at Mainz is continuing.



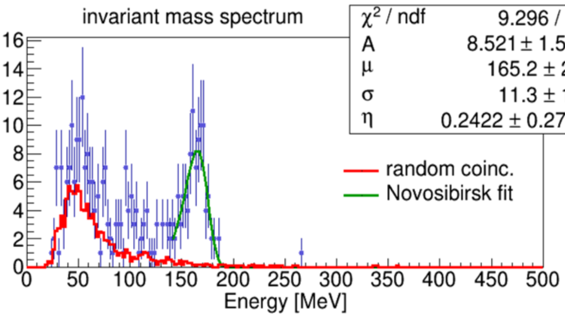


Figure 1. On the left: view of the test setup with two prototype calorimeters. On the right: invariant mass spectrum from events recorded in both prototypes in coincidence. The estimation of the random coincidences is obtained from events where the hit time difference between the two detectors lies outside the coincidence time window.

All the 48 detector submodules (32 with 16 crystals and 16 with 8 crystals) have been mounted, tested and calibrated with a dedicated setup in a climatic chamber. Every 4 crystals there is a home-made thin Pt100 temperature sensor which has been calibrated by setting different temperatures in the chamber and measuring the Pt100 resistances. The baseline of each analogue signal channel from the APFEL preamplifiers (2560 in total) has been acquired and studied, and the noise hit rates have been measured as a function of the hit detection threshold for every channel. The APD gain characteristics of all 1280 APDs was measured with pulsed light both at +20°C and -25°C. Cosmics data were then collected for each submodule for several hours at -25°C and two different APD gains. These data give a first approximate energy calibration of the detector.

All mechanical components for assembling the full detector, including holding the submodules, services and signal routing and shielding, insulation and cooling system have become available. All components for the arrangement in the hall have been designed and are being manufactured. These include the scattering chamber, the exit beam pipe and a support structure for the calorimeter.

Much progress was made in the readout system. The SADC firmware was updated to be able to send out time-sorted and conveniently bunched hits within the standard gigabit ethernet protocol. The TRB system with TRB3sc boards has been embedded in the system for distributing clock and real-time readout trigger signals through the optical links, and at the same time functioning as a gigabit ethernet switch for the data transport.

The control of the APFEL preamplifier, the light pulser, the temperature readout, the cooling system, was implemented in EPICS. A web-based user interface has been developed, giving access to all control parameters and to the readout system, and providing some online data visualization features.

The results of the beam test, performed in 2022 with two calorimeter prototypes have been further analyzed. Coincidence events from the two detectors could be reconstructed and invariant mass spectra were obtained, featuring a clear π^0 peak (Fig. 9). Although the energy calibration needs some improvement, the resolution is already satisfactory for this experiment.

In the second half of 2024 the A1 Hall at MAMI will become available and the experiment will be set up. There will be first a commissioning beam time for bringing the detector into operation and then one or two production runs, depending on the actual accumulated statistics. The beam schedule is to date not yet defined.

PANDA (Forward Endcap) @ ELSA

Due to the large delays at FAIR and especially for PANDA, the PANDA-FWEC will be scientifically at the electron accelerator ELSA in Bonn until antiprotons become available at the HESR at FAIR. This opens great physics opportunities. At ELSA, the FWEC, closed to ~1°, will be part of a new experiment, allowing not only for high resolution photon measurements over almost the entire 4π-solid angle, but also for precise charged particle detection and measurements with polarized target and beam. The experimental setup shown in Fig. 10 will also use the recently upgraded Crystal Barrel calorimeter. The new experiment and the ability to perform (double) polarization experiments will put us in an excellent position to investigate the spectrum of baryons containing up and down quarks or up, down and one strange quark.

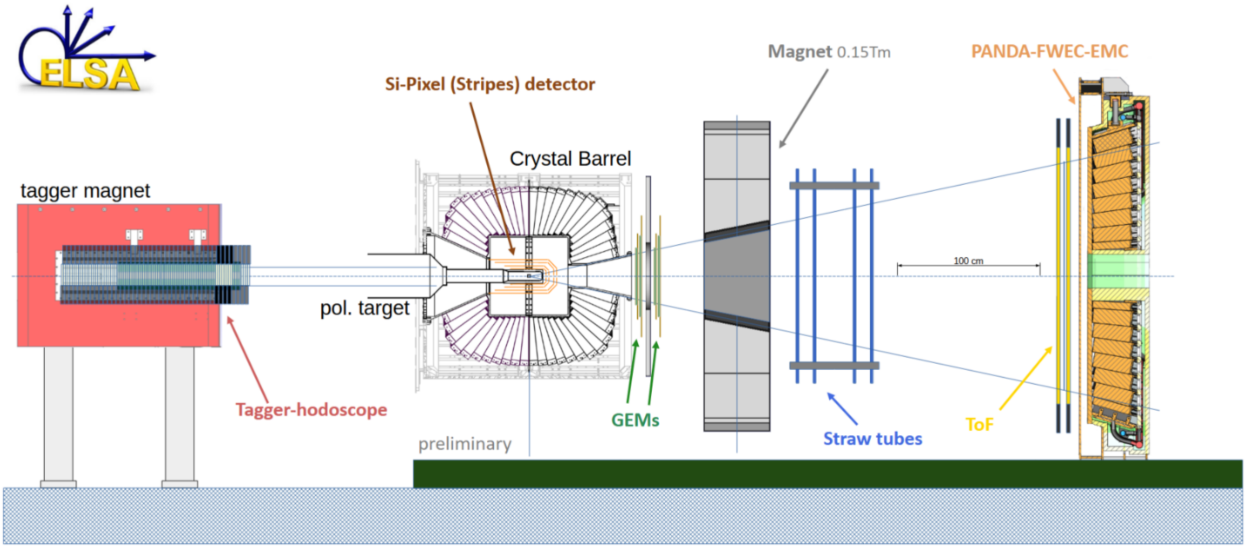


Figure 10: Sketch of the new experiment at ELSA (preliminary) using the PANDA-FWEC for high resolution photon detection in forward direction. The FWEC will be closed to ~1°.

Using the FWEC, the very successful photoproduction experiments off the proton at ELSA will be further extended to the neutron. Here, polarization data needed to perform an unambiguous partial wave analysis to extract the contributing resonances from the data, are scarce. This data will provide detailed information on the existing N^*- and Δ^*-resonances and their properties, including the interesting multi-mesons decays, where cascading decays via intermediate excited mesons and baryons were observed. Furthermore, in the interesting, strange quark sector, where progress was hampered for decades by the lack of data (with one exception: the famous $\Lambda(1405)$ with its observed two-pole structure), the new experiment will provide the data urgently needed. In this sector, even though more Λ^*- and Σ^*-states compared to the N^*- and Δ^*-resonances are expected to exist, much less were identified so far. Not even all states related to the first negative parity excitation band are known. In addition, the interesting question, whether pentaquark-states as observed by LHCb in the charm quark sector may also exist in the strange quark sector will be addressed.

Fast simulations of the new experiment to investigate its ability to detect and investigate strange baryon resonances have been performed with convincing results, one of which is shown in Fig. 11. The resonance signals can be clearly identified with a very convincing signal-to-background ratio.

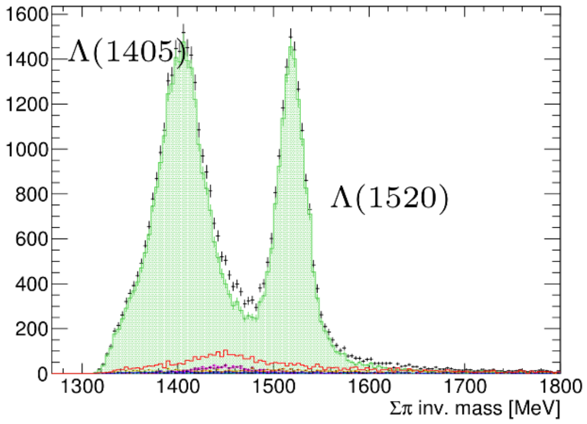


Figure 11: Result of fast simulations of the new experimental setup for the reaction $\gamma p \rightarrow K^+\Sigma^0\pi^0 \rightarrow K^+\Lambda\gamma\pi^0 \rightarrow K^+p\pi^-\gamma\pi^0$. *As signals, the* Λ^**-resonances,* $\Lambda(1405)$ *and* $\Lambda(1520)$, *were simulated with cross sections of 0.5* μb *and 0.7* μb *(green), respectively. The red curve shows the sum of the background channels simulated, which were:* $K^+\Sigma(1385)$ $(0.8\mu b)$, $K^0\Sigma^+$ $(0.6\mu b)$, $K^+\Sigma^0$ $(1.8\mu b)$, $p\pi^0\eta$ $(3.5\mu b)$, $p\pi^+\pi^-$ $(9\mu b)$, $K^+\Sigma(1385)\pi^0$ $(0.4\mu b)$, $K^+\Sigma^+\pi^-$ $(1\mu b)$, $K^+\Lambda\pi^0$ $(1\mu b)$.

After the very effective test beam times at COSY, where the FWEC equipped with 20% of its crystals, was very successfully run at its design temperature of -25°C and observed its first highly convincing π^0-peak, it will now be finally assembled for its use at ELSA by all the FWEC-groups. The engineering effort of installing the FWEC in the experimental hall at ELSA as a system movable on rails (needed for the measurements with polarized target) has started in an excellent cooperation between GSI/FAIR and Bonn.

More details on the test-beamtime results are given in the detector section of the report.

KOALA Experiment

The goal of this project is to provide the input necessary to achieve the desired precision for the absolute normalization of the luminosity measurements at PANDA. KOALA measures both the forward scattered particle and the backward recoil proton in coincidence to achieve a very high level of background suppression. KOALA was foreseen in two stages, first as KOALA@COSY to measure proton-proton elastic scattering and in the final version as KOALA@HESR to measure antiproton-proton scattering at very small scattering angles. The final setup at HESR will consist of the KOALA Cluster-Jet Target, the KOALA Recoil Detector to measure the recoil proton and the prototype of the PANDA Luminosity Detector to measure the forward scattered (anti)proton.

Due to the early shutdown of COSY in 2023, only first measurements were performed by using the ANKE Cluster-Jet Target, the KOALA Recoil Detector and some scintillating detectors for measuring the forward scattered protons. To finalize the setup, the experimental program will be continued and finalized at GSI using the SIS18 proton beam in the experimental area CaveC as KOALA@CaveC. All components will be tested there, and proton-proton data will be taken earliest end of 2026. An important aspect of KOALA@CaveC will be that also the use of the final PANDA Cluster-Jet Target and the final Luminosity Detector is possible. This allows to both make use of the high-intense target beam and to gain information about the realistic vacuum situation later at HESR. The measurements at CaveC will provide high precision data for the hadronic part of elastic proton-proton scattering to enable a comparison between pp to p̅p and to benchmark the respective hardware for FAIR.

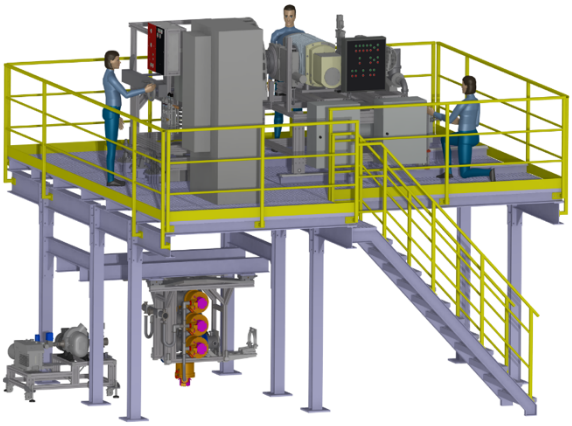


Figure 12: Koala@CaveC Setup.

A dedicated and powerful KOALA Cluster-Jet Target is required for the final KOALA experiment at HESR. Preparations for the design of the KOALA target have started as planned in 2023. In addition to the required performance parameters (e.g. density, width and vacuum at the IP), the final design will incorporate particularly the findings from KOALA@COSY and KOALA@. The KOALA Recoil Detector was commissioned at COSY and used in several measurements at KOALA@COSY. The prototype of the PANDA Luminosity Detector is under construction. Since issues with the MuPix8 sensors and also with TRBv3 DAQ system appeared unsolvable, the prototype will be built with MuPix11 sensors which became available in the meantime. The new DAQ system based on kintex7 FPGAs works with the old MuPix8 sensors and is on the way to be adapted to the MuPix11 sensors. As soon as the communication with the sensors works, the electronics will be adjusted and finalized. The mechanical part is ready.

In parallel, the analysis software development for the determination of the model parameters of the elastic scattering events is ongoing. Crucial information for event selection is the position of the interaction point. With having the scintillating detectors as forward detector this information is difficult to access. By using the prototype of the PANDA Luminosity Detector, the exact position and direction of the tracks is available which simplifies the IP position.

Outer Tracker of LHCb donated to PANDA

Upon completion of the OT donation process, with the signatures of all parties involved in the production and construction of the detector, including the directorates at CERN and GSI/FAIR, preparations for the transport intensified in Q1/2023.

At CERN the complete OT detector within its transport frame was covered with protective plastic foil by the LHCb colleagues ready for the transport. In cooperation with the CERN transport services, several offers from transport companies were received and evaluated with the best possible offer selected for the safe transport form CERN to GSI. Having the dimensions of 7.5 m length, 3.5 m wide and 5.2 m height, and a weight of 24 t the OT transport structure was declared “convoy exceptionell”. This over-wide and over-height load was to embark on a 5-day journey to GSI. Anticipating the arrival at GSI, all preparations were made months in advance with the professional help of GSI transport and logistics and FAIR site colleagues, with detail and foresight planning to receive the OT on the GSI campus, for storage in the BE42 hall.

The OT was loaded on a truck at LHCb/CERN on August 21 (the image below to the left). The trip carried on through the French countryside up to port Colmar, where it was placed on a boat and continued its transit on the river Rhine to port Gernsheim, where it was unloaded onto a truck for the final road trip, arriving at GSI on August 25. Prior to the departure from CERN two standalone sensors have been mounted on the detector frame within the enclosure, to record the temperature and rel. humidity at regular intervals, throughout the journey and during storage, to date. The CERN Public Relations office had a GoPro camera installed on the outer frame taking photos at regular intervals. A time laps video exists, until the moment when a tree branch hit the camera off the frame at the first day of the journey.

On GSI premises, the GSI/FAIR colleagues took over to safely guide the truck to the unloading section, in front of BE42, where an external crane was hired to unload the OT onto the heavy-duty roller system for the movement into the hall.

In anticipation to use some of the OT modules in PANDA, the development of an interface board for the readout of the original ASICs on the OT with electronics hardware, the DiRICH, has started including a test crate in cooperation with the GSI/EE. The tests continue in 2024 to read out multiple ASICs of several OT modules. During the GSI Summerschool 2023, a software description of the OT modules has been successfully implemented within the PANDA simulation framework. In addition, an automated remote monitoring system for multiple environmental sensors was developed, to be installed within the OT detector volume in 2024.

Figure 13: (Left) The CERN team with OT starting the journey to GSI (Right) The OT moving out of the boat at port Gernsheim (Photos: Courtesy CERN, and D. Lehman (GSI)).

Figure 14: (Left) The PANDA TC team with the OT at GSI (Right) OT "handover" Uli Uwer (DSP LHCb) and Klaus Peters (SP PANDA).

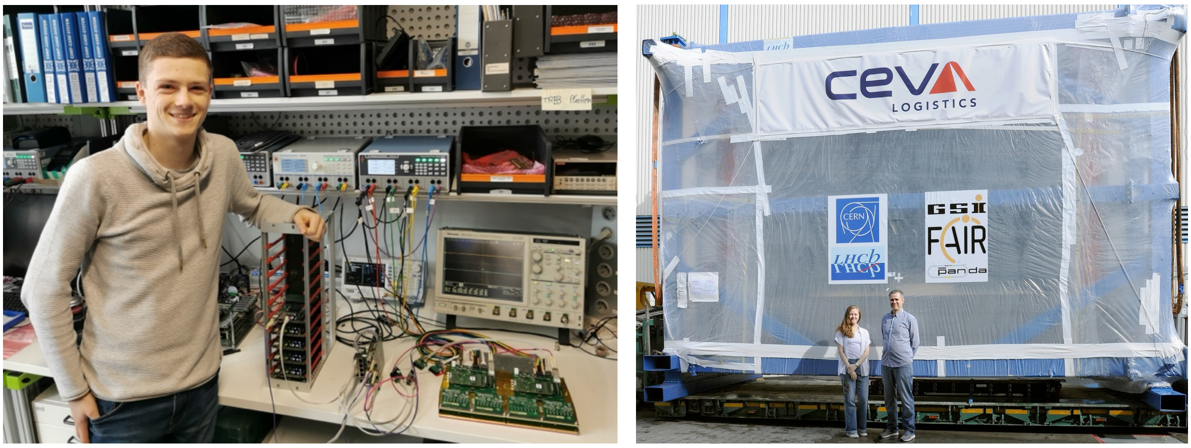


Figure 15: (Left) OT Readout crate system designed by Luca Schramm. (Right) GSI Summerstudent Nafija Ibrisimovic (Simulation Software for the OT) with tutor Radoslaw Karabowicz in front of OT at GSI.

Other Technical Highlights at PANDA

PANDA Interaction Region: In March 2023 a workshop was held at FZ Jülich to hand over the design of the PANDA beam-target pipe done until that point at ZEA1 of FZ Jülich. The design work, safety considerations, welding procedures and special devices like bayonet flanges and procedures for insertion and extraction were discussed. Prototypes of flanges and pipes were handed over to the GSI team (see Fig. 16).

Figure 16: (Left) Titanium cross prototype; (right) bayonet prototype.

In parallel to this activity the development of ultra-high vacuum pipes based on CFC was started, both as a general technology development and as alternative to the Titanium based beam-target pipe of PANDA. The development is supported by the GSI innovation fund, as a technological spin-off of a successful development may have multiple applications in vacuum industry and elsewhere.

Solenoid Magnet: Following the EU sanctions in response to the Russian attack on Ukraine the contract with BINP Novosibirsk for the superconducting solenoid of PANDA was cancelled in fall 2022. A potential procurement of the magnet from European companies would require having a superconducting cable available. As the magnet due to its size and field has a high energy content, an Aluminum stabilized conductor is the expert choice regarding safety and stability. However, currently there is no such conductor on the market. Developments for future magnets are anticipated at CERN and take place in China for CEPC, but both are for projects with longer time horizons. PANDA will observe both initiatives, but either way the construction of a new magnet will become the most time-critical element of PANDA. With the specification by the FAIR management of a completion of the modularized start version (MSV) by 2032 the risk of not having a magnet in time for PANDA was assessed.

Forward Endcap EMC Mechanics at ELSA: To assist with the implementation of the PANDA Forward Endcap EMC for an intermediate application at the CBELSA experiment at U Bonn the coordination group started the development of a mechanical structure for the insertion, alignment, and support of the detector at the location at ELSA in Bonn (see Fig. 17). The design incorporates elements required for a mounting device for the Forward Endcap at PANDA.

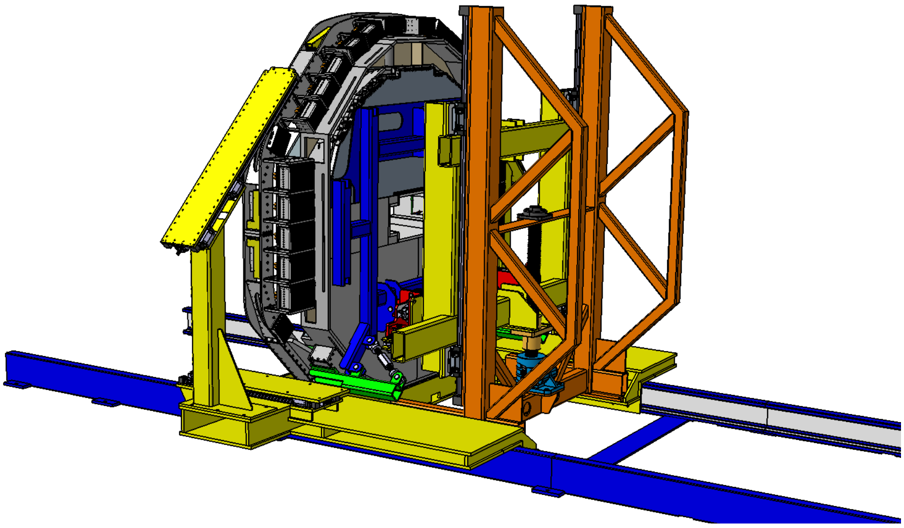


Figure 17: CAD of mounting device and support for Forward Endcap at ELSA.

Overview of PANDA Systems

Cluster Jet Target: The PANDA Cluster-Jet Target had its final beamtime for studies on the beam-target interaction at COSY in Q3 2023. A Micro Channel Plate (MCP) system was implemented to monitor the beam-target vertex region. The MCP system as important beam dump diagnostic system to investigate the beam-target vertex region as well as to monitor the cluster beam shape/intensity has been set into operation first at the Prototype Cluster-Jet Target at Münster U. Good results monitoring the beam-target vertex region with a Micro Channel Plate (MCP) system were achieved at COSY. A new beam dump system for the PANDA Cluster-Jet Target is currently in preparation at Münster U and the remaining vacuum components are being procured.

Micro Vertex Detector (MVD): The current start version of the MVD will consist of the barrel strip sensors located at the inside of the STT. To test the current prototype of ToASt, the frontend ASIC for the strip sensors in the MVD, with beam, two chips were set up with strip sensors at COSY. The beamtime in August 2023 successfully provided data with beam profiles and correlations between the two sensors. Data analysis shows proper responses. Next step is the attachment of a double-sided readout to wafers. The revised version of the ToASt ASIC will be submitted in spring 2024. The development of the Module Data Concentrator ASIC and the MVD Buffer Board progresses at KIT. Test kits for several institutes participating in the PANDA MVD were produced.

Straw Tube Tracker (STT): The STT will be the central tracking detector in the solenoid field of the PANDA Target Spectrometer. As part of the Polish in-kind contribution, both analog and digital first-of-series electronics to equip STT and FT were approved. The series production of 800 frontend boards with the PASTTREC ASIC was completed and series testing started. The design of a high voltage decoupling board is ongoing.

All straws were pre-assembled. Design work in 2023 focused on the cooling of electronics. In 2022 planar straw detectors were employed at the HADES experiment at GSI. This offered the opportunity for the development of calibration software and a testing ground for the optimization of electronics settings. A further pion beamtime with the PANDA-type straws is planned for 2025 at HADES in the frame of FAIR Phase-0.

Forward Tracker (FT): An in-kind contract with JU Krakow covers the production of 4 stations of straws for the forward tracking. The production of tracking stations FT1/2 has started, the first about 30 modules out of 184 were completed in 2023. The frames of station FT1 and FT2 were built, the ones for FT3 and FT4 are in production. A new clean gas system, composed of the mixing and the distribution systems has been built. A new automated testing system was assembled for series screening of straw modules. It comprises two radioactive sources, an XY movement system, gas system, high voltage and readout and a laser scanner. With the ^{55}Fe source straw and wire positions are scanned. The ^{90}Sr source serves to determine HV plateaus and drift times. The setup is controlled by a central computer.

Luminosity Detector (LMD): The luminosity detector will measure elastic scattering of antiprotons in a roman pot system at the downstream end of the PANDA setup. The design of the luminosity detector progressed significantly as the design of the cooling, vacuum and overall mechanics were approved. The final version of the vacuum vessel is in construction and will be completed in 2024. Tests at COSY were done in Q3 2023 with the prototype chip MuPix8 for which flex cables were delivered by LTU in Ukraine. Readout was provided by a Xilinx Kintex 7 development board. Further cables for the next chip version MuPix10 were produced as well. The final chip version for the LMD will be MuPix11. Measurement and alignment procedures with a coordinate measuring machines and a laser scanner were set up and tested reaching precision values down to few µm for the detector modules.

Barrel DIRC: The core detector for charged particle identification in PANDA is the Barrel DIRC which is based on internal reflection of Cherenkov light in fused silica quartz radiator bars. All required bars were delivered by the beginning of 2023 and are under test regarding reflectivity and geometry. A procedure for gluing the quartz bars was set up at HI Mainz. After the first-of-series production MCP-PMT deliveries are ramping up to complete by Q1 2025. QA tests of the delivered PMTs are regularly performed at U Erlangen. At GSI long-term tests of Carbon fibers material outgassing showed no deterioration of optical parameters of the reference quartz bar. The goal is to complete one bar box made of Carbon fibers by the end of 2025. Further work regards the integration of the DiRICH readout and the HV supply of the PMTs.

Target Spectrometer EMC

The high-resolution detection of photons and electrons in the Target Spectrometer of PANDA will be achieved with PWO crystals arranged in three subsystems, the barrel with

11,360 crystals, the backward endcap with 560 crystals and the forward endcap with 3,856 crystals.

Barrel EMC: The first slice of 16 of the full Barrel EMC was assembled and awaits a complete readout test. Cooling and thermal insulation were set up. A further work package in progress is the coupling of light fibres to the crystal to monitor detector performance.

Beam tests at MAMI to test the full readout electronics chain were performed. The involved stack of boards includes the HV-PCB from series production, Interface-PCBs with Firefly links for analog signals and flex cable for control and several variants of backplane-PCBs. In total 22 crystals with matched and glued LAAPDs were prepared.

The barrel mechanics contracted to IHEP in Russia is mostly delivered. The design of the support beam was updated, the production remains unclear and still has to be done. All HV-PCBs are produced, the final design iteration of the Interface-PCB will conclude in Q2 2024, the design of the backplane-PCB is complete. All essential functionalities of controls and monitoring are integrated in the EPICS DCS system.

To complete the 3rd slice 107 crystals are needed and 398 for the 4th slice. Further small-scale production orders funded by various collaborators aim at the completion of 4 slices by 2027. In total approx. 6,000 crystals are missing to complete all 16 slices of the Barrel EMC.

Backward Endcap EMC: At HIM all submodules of the subsystem were assembled and fully calibrated. All HV boards were assembled and are being calibrated. The light-pulser system is ready. The mechanical housing for the detector at MAMI is complete and cooling was tested. The assembly of the Backward Endcap will be completed in spring 2024 in a setup with 640 crystals. Measurements at MAMI for commissioning and physics will start in 2024.

Forward Endcap EMC: All modules of the Forward Endcap were assembled. A test beam at COSY of the partially equipped Forward Endcap was performed in three periods in July, August, and September 2023. In the final period cooling could be improved and the nominal -25°C were reached. Preliminary data analysis shows good performance and a π^0 signal with 5 MeV resolution. It is planned to complete the assembly of the Forward Endcap at Bonn University after the beam periods at COSY. The design of support structures and assembly tools started in December 2023 in a cooperation between U Bonn and GSI.

Setup Studies

An alternative option would be the use of the existing superconducting coil of ZEUS/HERA available at DESY. This however has some repercussions on the setup of PANDA which were extensively studied by the PANDA coordination group in the course of 2023. The first critical item in this regard is the need for a horizontal target pipe traversing the magnet at 30° as the ZEUS coil does not have an opening for a pipe perpendicular to the beam axis.

In addition, the diameter of the magnet’s warm bore is smaller by 180 mm. This leads to the necessity to arrange the PANDA Barrel EMC slices at a smaller radius. Keeping the original slice design some losses are expected for higher energies at the rear of the slices. Almost full coverage can be reached with 12 slices instead of 16. Later, the ZEUS coil could be replaced with a new coil with vertical bore to use the high-rate PANDA target requiring vertical operation. Then the remaining gap in the Barrel EMC can be closed with two smaller special slices.

The arrangement with the smaller radius Barrel EMC in turn points to a shift of the existing Forward Endcap EMC in downstream direction. With this the detector can be again fully covered and a collision with the horizontal target pipe and target dump can be avoided. A further consequence is a smaller acceptance in the forward spectrometer reduced to 6.5° horizontal, 3° vertical from originally 10° horizontal and 5° vertical. This leads to a smaller dipole magnet and a smaller detector array behind the dipole with possible cost reductions. See Fig. 18 for an artistic view.

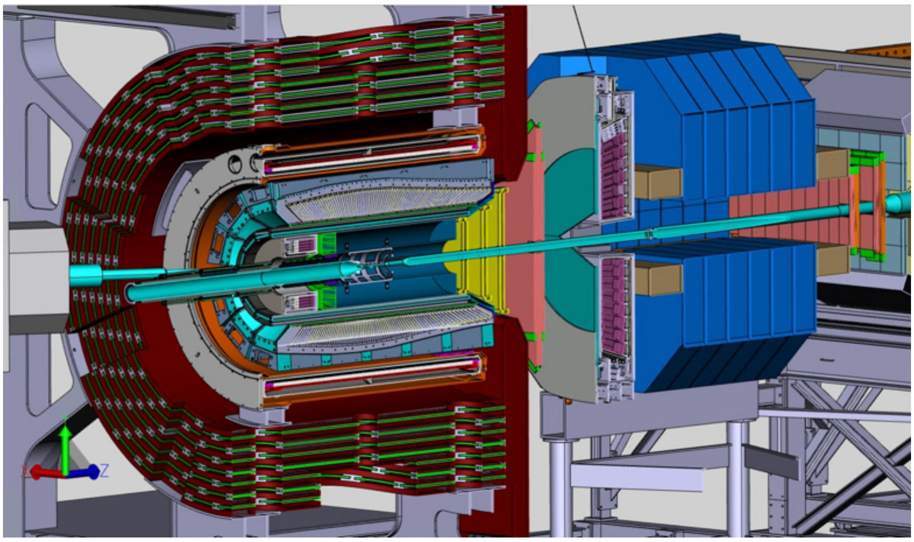


Figure 18: Setup study for PANDA based on ZEUS magnet.

Because of the smaller radius of the ZEUS coil the acceptance of the Forward Endcap EMC is not fully covered anymore at its nominal position within the solenoid yoke. A better position would be approx. 80 cm further downstream outside the solenoid yoke. This results in a smaller acceptance for the forward spectrometer, which however still matches the tracking coverage of the detectors already under construction. One can then employ a smaller, more cost-effective dipole magnet in the forward spectrometer and use smaller detectors for particle identification and calorimetry behind the dipole. PID detectors and dipole are as well missing as contributions from Russia. The discussed modifications need verification with simulations to evaluate their impact on the physics performance of the modified setup. First studies regarding the geometry of the Barrel EMC were started at U Bonn at the end of 2023 with input from the PANDA coordination group.

First π^0's in the PANDA-FWEC from the test-beamtime at COSY

The forward endcap of the PANDA detector's lead tungstate electromagnetic calorimeter was for the first time put into operation as common system under the conditions (-25°C) planned for its later usage in the experiment. For the test-beamtime at COSY about 20% of the crystals were installed including all the detector modules read out via VPTTs, which are in the innermost region of the FWEC plus six additional detector modules with APD-readout (Fig. 19). During the test-beamtimes a block of plastic, two meters in front of the detector was used as target, which corresponds to the nominal target-FWEC distance in the PANDA detector. In the resulting proton-nucleon collisions especially pions, neutral and charged ones, were produced and their characteristic signals in the detector were used in the data analysis discussed below.

The measurements started with two days of COSY-beam for final DAQ and hardware tests in July 2023 and were followed by two weeks of test-beamtime in August and September. During the second week of test-beamtime, the important goal of a stable operation of the detector system at the intended temperature of -25°C, was reached (see Fig. 20). The detector was flushed with nitrogen in addition to dry air in the insulation region. The data recorded during the first test-beamtime while cooling down the detector allowed for the interesting measurement of the temperature dependent light yield of $PbWO_4$ (see Fig. 21). The data showed the expected behavior and the analysis results, as expected, in a light yield dependence of about 3% per °C (preliminary).

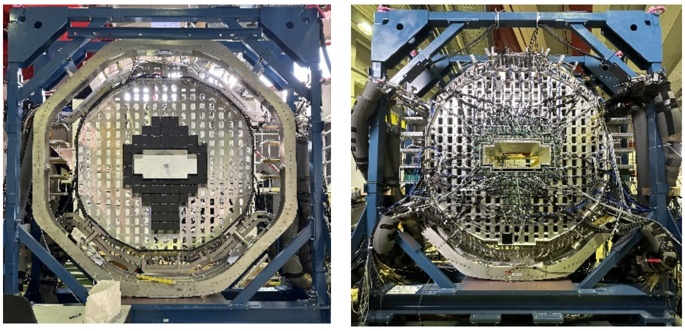


Figure 19: FWEC equipped with 20% of its detector modules, the lower six modules include crystals read out by 2 APDs, the others use VPTTs (pictures taken while setting up the FWEC for the test-beamtime at COSY). Left: front view, right: back view, visible are the electronic boards and the cabling.

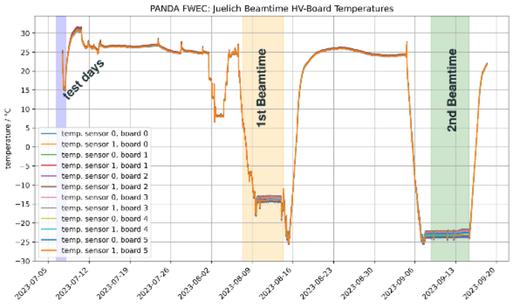


Figure 20: Temperatures of the FWEC measured during and in-between the test-beamtimes

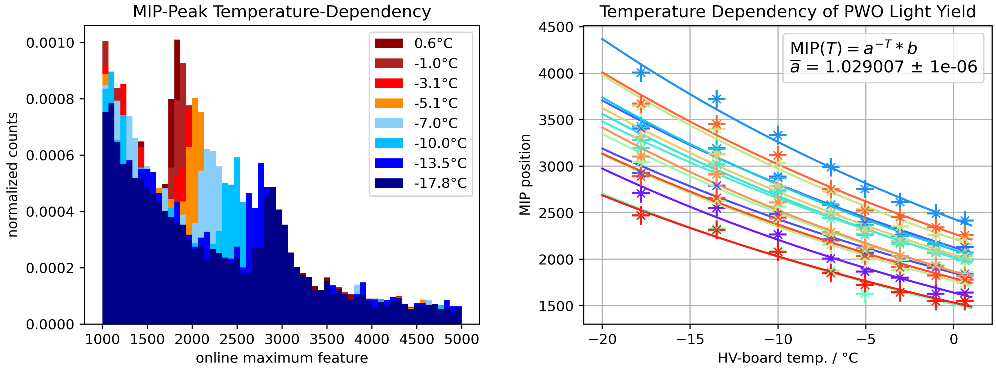


Figure 21: Temperature dependence of the $PbWO_4$ light yield, determined by investigating the position of the minimum ionizing peak ($\pi^{\pm}$) in the detector. Left: Measured single crystal energy for different temperatures, the minimum ionizing peak (MIP) is clearly visible. Right: Preliminary determination of the light yield dependence by fitting an exponential curve to the MIP-peak positions of several readout channels (crystals).

A further important goal reached during the test-beamtimes was the first observation of neutral pions decaying into two photons. The $\pi^0 \to \gamma\gamma$-signal will in future also be used for a precise calibration of the detector system. Based on so far only 10% of the statistics taken, events with two clusters in the FWEC were selected and were used to reconstruct the invariant mass of the π^0 (Fig. 22).

Based on the results obtained it can be stated that this low-temperature crystal calorimeter works excellently. Even though only a preliminary calibration and analysis was used and no energy correction function is implemented yet, resulting in a low π^0-mass of only 120 MeV, a clear π^0 peak with a mass resolution of as narrow as ≈5 MeV was observed (Fig. 6). This can be considered as first very convincing proof of the quality of the detector system as high-resolution electromagnetic calorimeter.

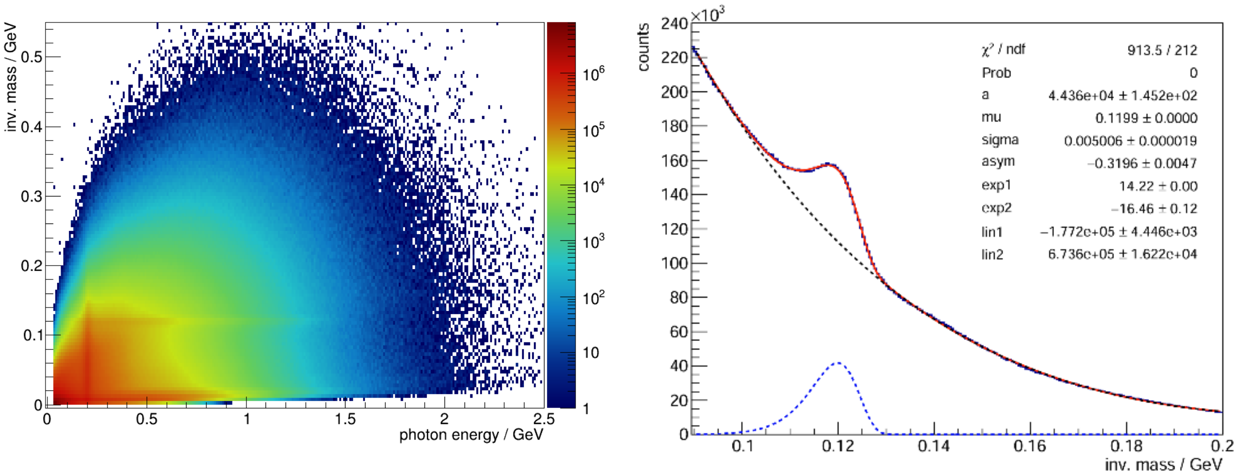


Figure 22: COSY test-beamtime results: Shown are events with two clusters in the FWEC (based on 10% of the statistics taken). Left: events as function of the cluster energy of one of the photons (x-axis) and the 2-photon invariant mass (y-axis). The horizontal band due to $\pi^0 \rightarrow \gamma\gamma$ events is clearly visible. In addition, a vertical band due to minimum ionizing particles can be clearly seen. Right: Projection of the left plot on the y-axis. The $\pi^0 \rightarrow \gamma\gamma$ peak is clearly visible. Even though only a preliminary calibration was used and no energy correction function is implemented yet, resulting in a low π^0-mass of only 120 MeV, the resulting mass resolution of only 5 MeV is already very convincing.

In total, 220 TB of data were recorded including full waveform information. This data will allow for a comprehensive data analysis and waveform studies, which are of importance to further study the detector's behavior and to improve the simulation and analysis software, as well as to develop a powerful online feature extraction for the future measurements with the detector.

PANDA 2023: Status Report on Computing and Software

The computing activities within the PANDA collaboration have made continuous progress throughout 2023 even though the number of software developers is continuously declining.

The main activities have been focused on the EMC restructuring and the charged particle tracking algorithms with additional improvements in other fields.

The original EMC code treated the different subdetectors as one system even though they are using different electronics or are even different type of calorimeters. This caused a lot of duplicated code in large files which made the code very difficult to understand and maintain. The new structure separates the monolithic code of the EMC subdetectors into individual detectors with their own implementations based on a common code basis for all calorimeters. This approach reduced the size of the individual classes, separated the different parameter sets and thus improved the maintainability of the code drastically. A very thorough comparison of the new and old implementation was performed showing that no substantial difference between the two could be found. The new implementation of the EMC serves as a blueprint for a future restructuring of other subdetectors within PandaRoot. Furthermore, the position reconstruction method for EMC clusters has been checked and the parameters for the offset parameters updated. It could be shown that the angular spatial resolution for the barrel part is about 0.3° depending on the particle momentum as it was required in the TDR.

Besides an excellent calorimetry, charged particle tracking is one key feature of the PANDA experiment. Several improvements have been made here. The first is in the forward tracking.

Here the reconstruction efficiency could be improved by a few percentage points for single tracks and up to 25 percentage points for up to 8 tracks in the Forward Tracking System (FTS). The overall tracking efficiency over the full momentum range is now well above 95 %. Furthermore, the momentum resolution for high momentum tracks (muons at 5.55 GeV/c) was significantly improved from a sigma value of 20 % down to 7 %. The FTS serves also as a test case for online reconstruction methods. Based on SYCL, a higher-level heterogeneous programming model, it is possible to use the same code and run it in a parallel way on CPUs, GPUs and even FPGAs. An implementation of the FTS reconstruction algorithms in SYCL showed a significant improvement of the processing speed up to 240,000 events per second on a single CPU and a comparable performance on a GPU. Further tests are planned for 2024 and an expansion of the usage of SYCL for other subdetectors is foreseen.

The second improvement is based in the barrel part of PANDA where the development of a track finder for particles displaced from the primary interaction point was finalized. This development is especially important for the reconstruction of hyperons, relatively long living particles with decay lengths of a couple of centimeters. The newly developed method combines an existing track finder for primary particles with a new, second algorithm looking in the STT for hits which do not come from the primary interaction point. In this way it was possible to improve the reconstruction efficiency for secondary particles from 45 % up to 79 %. It could be shown in a test case involving 4 hyperons that the reconstruction efficiency of the full event was improved by a factor 4.

An alternative approach uses machine learning techniques for particle tracking. Two networks have been trained to find tracks in the STT, a conventional deep learning network (DL) and a more complex geometric deep learning network (GDL). While both networks have been able to find tracks, the GDL network with a track finding efficiency of above 90 % outperformed the DL network with just 77 %. In a test example with a pair of lambda particles the GDL network was able to find also secondary tracks with a track finding efficiency above 90 % up to a distance to the primary vertex of 14 cm.

Outside from calorimetry and tracking further advancements have been made in various fields. The DecayTreeFitter, a fitter which takes a complete decay chain into account and assigns constraints to it, is now able to handle also pure neutral events without any charged tracks. Various problems in the PID correlator have been fixed. The PID correlator assigns the PID information to charged tracks and creates charged and neutral candidates. In the older version an EMC cluster could be assigned to different tracks which effectively increased the number of EMC cluster and made wrong correlations. In the new version the EMC cluster is only assigned to the best matching track. Also tracks in the barrel and forward part can now be matched together into one charged candidate if they are coming from the same particle.

The fast simulation framework PndFastSim which allows to perform feasibility studies of signal channels without the time-consuming simulation of the complete detector, is now a stand-alone package called HepFastSim which can run outside PandaRoot.

To improve the reliability of PandaRoot the test structure has been changed. The idea is to test every stage of the simulation chain individually to achieve a higher test coverage and a more detailed information at which point of the chain a problem arises. Furthermore, the many individual test macros have been replaced by common macros which are adopted via JSON text files for the individual needs of a test.

The physics potential of PANDA was praised in the scientific review in 2022 [6]:

> *With its use of a stored anti-proton beam, PANDA is unique and is the only experiment in the world that can definitely answer the question as to whether or not the states under study are new, 'exotic', forms of hadronic matter. PANDA's unique glueball-discovery program will provide the critical tests of strong interaction theory that predict masses of the only particles with mass generated entirely through the strong interaction. The compelling case of PANDA's high-precision science program justifies the execution of the full MSV, even if delayed by five years.*

Ideas for an intermediate physics program

Despite the positive review, it has become clear that the financial situation of FAIR will lead to a delay of the construction of the HESR tunnel and the PANDA cave. While waiting for antiprotons at FAIR, PANDA will need to find ways to stay together as a collaboration, preserve competence and train the next generation of hadron physicists. Short-term, this is achieved by the Phase 0 activities at GSI/FAIR and MAMI. Beyond this, a strategy for common intermediate-term physics activities is imperative. Since 2023, the following approaches are being discussed within PANDA:

Physics at FAIR without antiprotons: GSI and FAIR offers possibilities to conduct hadron physics with proton beams from SIS18 (up to 4.5 GeV/c) and in the future also from SIS100 (up to 30 GeV/c). In these experiments, the HADES and CBM detectors can be used, possibly in combination with systems from PANDA. A series of workshops on the opportunities for proton beam physics with the SIS100 has been initiated by the former PANDA PCs and the PANDA management are participating actively in these discussions.

Physics with antiprotons but not at FAIR: PANDA has been contacted by the antiproton community active in the AD/ELENA experiments at CERN about possible collaboration on an extended low-energy antiproton physics program. A working group has been formed and the topic will be discussed at a dedicated workshop in April as well as at the EXA/LEAP conference in August 2024. In addition, a new PANDA group leader in Japan has proposed a potential antiproton beam program at J-PARC with an external target and a beam of similar beam momentum as PANDA. Discussions have started on synergies and opportunities for collaboration between PANDA and J-PARC.

Physics at FAIR or elsewhere with PANDA detectors: The Forward Endcap of the PANDA calorimeter has been successfully tested at FZ Jülich and will be installed at the accelerator facility ELSA in Bonn where it can be thoroughly tested. However, the planned upgrade of ELSA also provides an opportunity to use the Forward Endcap in the foreseen baryon spectroscopy program.

The PANDA Theory Advisory Group (ThAG)

The collaboration between PANDA and its theory advisors has since long been immensely valuable – the most recent example is the extensive and profound input we received in the preparations for the scientific review of FAIR in 2022. The need for creative discussions with theoreticians will increase even more in the next few years, in the endeavor to find an intermediate physics program. We are therefore very happy to welcome twelve new members of the PANDA ThAG:

Constantia Alexandrou (Cyprus)
Sara Collins (Regensburg)
Michael Döring (Washington)
Gernot Eichmann (Graz)
Evgeni Epelbaum (Bochum)
Francesco Giacosa (Kielce)
Nimani Mathur (Mumbai)
Sasa Prelovsek (Ljubljana)
Laura Tolos (Barcelona)
Marc Wagner (Frankfurt)
Luigi del Debbio (Edinburgh)
Jeremy Green (DESY)

Together with the scientists who continue their membership in the ThAG

Reinhard Alkofer
Gunnar Bali
Nora Brambilla
Stan Brodsky
Umberto D'Alesio
Christian Fischer (chair)
Johann Haidenbauer
Christoph Hanhart
Alexei Larionov
Horst Lenske
Stefan Leupold
Matthias Lutz
Thomas Mannel
Ulf-G. Meissner
Simone Pacetti
Juan Miguel Nieves Pamplona
Anton Rebhan
Sinead Ryan
Andreas Schaefer
Kirill Semenov-Tian-Shansky
Mark I. Strikman
Eric Swanson
Lech Szymanowski
Rob Timmermann
Marc Vanderhagen

This makes our current ThAG diverse in terms of physics as well as geographically. Christian Fischer from Giessen continues as the chair of ThAG and we are grateful for his continuous engagement in our activities.

Career Development and Completed PhDs in 2023

PANDA PhD Prize 2023

The PANDA PhD Prize 2023 was awarded to Anna Alicke (FZ Jülich/Germany) for her thesis “Development of fast track finding algorithms for densely packed straw tube trackers and its application to Ξ hyperon reconstruction for the PANDA experiment". During her thesis, she developed two new tracking algorithms and combined these primary and secondary trackers to achieve the highest efficiency, which was tested on reactions with multiple secondary vertices. But the algorithm can also be used for other densely packed straw tube trackers. The certificate and the prize money of 200 € was presented by the spokesperson Klaus Peters during the PANDA Collaboration Dinner in Münster on March 6, 2024 at Münster.

Finished PhD Theses in 2023

- Adeel Akram, U Uppsala, “Towards Realistic Hyperon Reconstruction in PANDA: From Tracking with Machine Learning to Interactions with Residual Gas“
- Anna Alicke, FZ Jülich/RU Bochum, “Development of fast track finding algorithms for densely packed straw tube trackers and its application to Xi(1820) hyperon reconstruction for the PANDA experiment“
- Akshay Malige, JU Krakow, “Read-out and online processing for the Forward Tracker in HADES and PANDA”
- Gabriela Perez, FZ Jülich/RU Bochum, “Measurement of proton-proton elastic scattering to commission the STS tracking stations in the HADES spectrometer”
- Rene Hagdorn, RU Bochum, “Characterization of the MuPix8 Sensor for the Prototype of the PANDA Luminosity Detector”
- Aleksandra Molenda, AGH U Krakow, “CMOS Technologies in Detector Readout Systems of Modern Particle Physics Experiments”
- Áron Kripkó, U Gießen, “Studying the hadron structure with PANDA and CLAS using machine learning techniques”

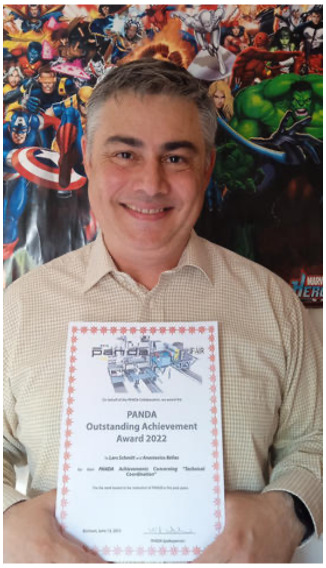
Outstanding Achievement Award 2022

Prizes for outstanding achievements in 2022 to the benefit of PANDA have been awarded to two groups:

Tobias Stockmanns and Anna Alicke for their development of a realistic and generalized tracking algorithm for the PANDA experiment.

Their development of a more generalized algorithm that is agnostic to the point of production is absolutely crucial for the foreseen hyperon physics program of PANDA and an important milestone for the PANDA software.

The second prize went to Lars Schmitt and Anastasios Belias for their tireless work to realize the PANDA detector at FAIR.



Their continuous persistence and creativity, which went far beyond what could have been expected, is not only an inspiration for the entire collaboration, but also a guarantee for the realization of our ambitious project eventually. Both are unparalleled in their commitment to the technical side of the project and are like a rock in the current storm

The awards were presented by the Spokesperson Ulrich Wiedner in Prag during the Collaboration Dinner on a boat tour on the Danube River.

Publications in 2023

- G. Mazza et al., “A 64 channels ASIC for the readout of the silicon strip detectors of the PANDA micro-vertex detector”, 2023 JINST 18 C01020 DOI 10.1088/1748-0221/18/01/C01020
- D. Miehling et al., "Lifetime and Performance of the very latest Microchannel-Plate Photomultipliers", Proceedings of NDIP20, NIM A1049 (2023) 168047; https://doi.org/10.1016/j.nima.2023.168047
- A. Lehmann, "Status and perspectives of vacuum-based photon detectors", Proceedings of RICH2022, NIM A1056 (2023) 168568; https://doi.org/10.1016/j.nima.2023.168568
- S. Krauss et al., "Performance of the most recent Microchannel-Plate PMTs for the PANDA DIRC detectors at FAIR", Proceedings of RICH2022, NIM A1057 (2023) 168659; https://doi.org/10.1016/j.nima.2023.168659
- M. Firlej et al., “Production tests of front-end electronics for Straw Tube Trackers in HADES and PANDA experiments at FAIR“, Journal of Instrumentation 2023 vol. 18 no. 5 art. no. P05008, s. [1–2], 1–17.
- T. Johansson, “The PANDA Experiment at FAIR”, Proceedings of INPC 2022, J. Phys: Conf. Ser. 2586 (2023) 012004, (Proc. INPC2022)
- P. Jiang, K. Götzen, R. Kliemt et al, “Deep Machine Learning for the PANDA Software Trigger”, Eur. Phys. J. C 83, 337 (2023), https://doi.org/10.1140/epjc/s10052-023-11494-y

Talks at Workshops and Conferences in 2023

- Karin Schönning, “Hyperon and hypernuclear physics with PANDA”, 3rd J-PARC HEF-ex Workshop, March 14-16, 2023
- Heinrich Leithoff, “Der PANDA-Luminositätsdetektor”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Niels Bölger, “Silicon Pixel Sensors for the PANDA Luminosity Detector”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Steffen Krauss, “New "escalation" effect observed in recent MCP-PMTs”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Ken Suzuki, “Implementation of the Acts tracking software into PandaRoot”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Katja Gumbert, “Performance of the first mass production MCP-PMTs for the PANDA Barrel DIRC and lifetime of the latest MCP-PMTs”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Orsich Pavel, “Systematic Studies of Radiation Damage and Stimulated Recovery of PWO”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Christopher Hahn, “Series calibration of the slow-control of the barrel part of the PANDA EMC front-end electronics”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Lukas Linzen, “Aufbau und Kalibration der Vorwärtsendkappe des elektromagnetischen Kalorimeters des PANDA-Experimentes am COSY in Jülich”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Anna Alicke, “Hyperon Reconstruction with Realistic Track Finding for PANDA”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023

- Jakapat Kannika, “A language model-based tracking algorithm for the Straw Tube Tracker of the PANDA experiment”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Philipp Brand, “A State-of-the-Art Cluster-Jet Target for the PANDA Experiment at FAIR”, DPG Spring Meeting 2023 - Hadronic and Nuclear Physics, March 20-24,2023
- Frank Nerling, “PANDA perspectives in exotics”, Hadron 2023, June 5-9, 2023
- Michael Papenbrock, “Antihyperons in Nuclei (with PANDA)”, EMMI Workshop: Bound states and particle interactions in the 21st century, July 3-6, 2023
- Francesca Lenta, “Characterization of ToASt ASIC for the readout of the PANDA MVD strip detector “, 16th Topical Seminar on Innovative Particle and Radiation Detectors, Sept 25-29, 2023
- Carsten Schwarz, “PID of the PANDA Experiment”, The 2023 international workshop on the high energy Circular Electron-Positron Collider (CEPC) / Oct 23-27, 2023

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Frontpage:

1) 3D rendered PANDA Hall

2) Delivery of the Outer Tracker from LHCb

3) Forward Electromagnetic Calorimeter Endcap at the test-beam at COSY

PANDA Annual Report 2023

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