

The \bar{P} ANDA Experiment at FAIR - Subatomic Physics with Antiprotons

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The non-perturbative nature of the strong interaction leads to spectacular phenomena, such as the formation of hadronic matter, color confinement, and the generation of the mass of visible matter. To get deeper insight into the underlying mechanisms remains one of the most challenging tasks within the field of subatomic physics. The antiProton ANnihilations at DArmstadt (\bar{P} ANDA) collaboration has the ambition to address key questions in this field by exploiting a cooled beam of antiprotons at the High Energy Storage Ring (HESR) at the future Facility for Antiproton and Ion Research (FAIR) combined with a state-of-the-art and versatile detector. This contribution will address some of the unique features of \bar{P} ANDA that give rise to a promising physics program together with state-of-the-art technological developments.

KEYWORDS: antiprotons, hadrons, new facilities

1. Introduction

The physics of strong interactions is undoubtedly one of the most challenging areas of modern science. Our present elegant and “simple” underlying fundamentals of the strong interaction, Quantum Chromodynamics (QCD), is reproducing the physics phenomena only at distances much shorter than the size of the nucleon, where perturbation theory can be used yielding results of high precision and predictive power. At larger distance scales, however, perturbative methods cannot be applied anymore, although spectacular phenomena - such as the generation of hadron masses, the formation of hadronic matter, and color confinement - occur. It remains puzzling to identify the relevant degrees of freedom that connect the perturbative regime, driven by quarks and gluons, to the strong regime, which eventually leads to the formation of nuclei in which colorless pions and nucleons are the fundamental building blocks (see Fig. 1).

The \bar{P} ANDA (antiProton ANnihilation at DArmstadt) collaboration will address various questions related to the strong interactions by employing a multi-purpose detector system [1] at the High Energy Storage Ring for antiprotons (HESR) of the upcoming Facility for Antiproton and Ion Research (FAIR). The \bar{P} ANDA collaboration aims to connect the perturbative and the non-perturbative QCD regions, thereby providing insight in the mechanisms of mass generation and confinement. The collaboration is composed of an international spectrum of researchers from the nuclear, hadron, and particle physics communities, hence, covering the complete field of subatomic physics.

The key ingredient for the \bar{P} ANDA physics program is a high-intensity and a high-resolution beam of antiprotons in the momentum range of 1.5 to 15 GeV/c. Such a beam gives access to a center-of-mass energy range from 2.2 to 5.5 GeV in $\bar{p}p$ annihilations. In this range, a rich spectrum of hadrons with various quark configurations can be studied. In particular, hadronic states which contain charmed or strange quarks and gluon-rich matter are expected to be abundantly produced in $\bar{p}p$ annihilations.

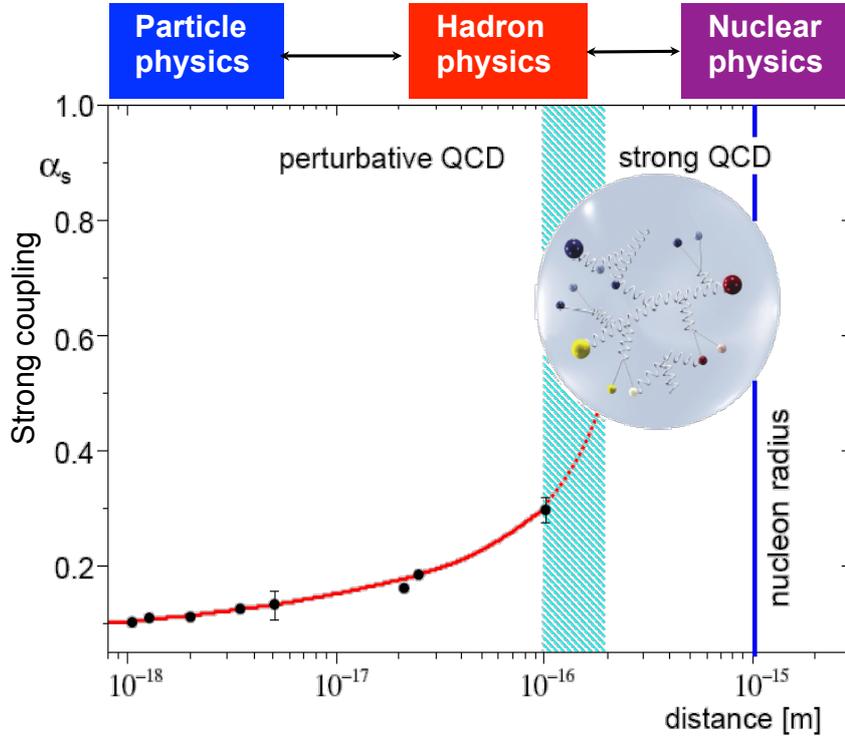


Fig. 1. The strong coupling constant as a function of distance scale. The ambition of $\bar{\text{P}}\text{ANDA}$ is to provide data that helps to bridge our understanding of QCD from short distance scales (quarks and gluons) to the scale of (hyper)nuclei (baryons and mesons).

The $\bar{\text{P}}\text{ANDA}$ detector will be installed at the HESR at the future FAIR facility. Antiprotons will be transferred to the HESR where internal-target experiments can be performed using beams with unprecedented quality and intensity. Stochastic phase space cooling (and possibly electron cooling) will be available to allow for experiments with a momentum resolution in the range from $0.4\text{--}2 \times 10^{-4}$ at luminosities up to $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to about 10^{11} stored antiprotons in the ring. We note that the maximum number of stored antiprotons will be in the order of 10^{10} in the modularized start version of FAIR.

The usage of high-intense and cooled antiprotons covering a large center-of-mass range makes $\bar{\text{P}}\text{ANDA}$ unique in the sense that it enables a *strange* and a *charm* “factory” providing a rich database for precision and exploratory studies. Such versatility also poses challenges in the development of the detector and its data processing. In the following, a more thorough discussion on these aspects will be given, highlighting the magical aspects of antiprotons in terms of addressing forefront physics questions and contributing to the next generation technology.

2. Versatility of antiprotons

The antiprotons that will be used by $\bar{\text{P}}\text{ANDA}$ will enable a diverse physics program with unique capabilities that cannot be found at other facilities. The following aspects are at the basis of this uniqueness:

- **Large mass-scale coverage.** Center-of-mass energies from 2 to 5.5 GeV/c^2 are accessible with the antiproton-momentum range covered at HESR. This will give access to hadronic states made

from light, strange, and charm quarks. The various quark-mass scales covered by $\bar{\text{P}}\text{ANDA}$ give a remarkable opportunity to systematically study the underlying degrees of freedoms in hadrons. Moreover, unconventional hadronic states with a gluon-rich nature, or composed from more than three quarks, are expected to be present in this energy regime. The recent discoveries of X, Y, Z states clearly demonstrate that this regime is rich in unconventional states. But also the large momentum range gives access to the associated production of pairs of hadrons and antihadrons with open strange- or/and charmness, such as $\Lambda\bar{\Lambda}$ and $D_s\bar{D}_s$ pairs.

- **High hadronic production rates.** In contrast to experimental facilities that make use of electromagnetic probes (such as e^+e^- colliders, e/μ -scattering facilities, and tagged-photon beams), $\bar{\text{P}}\text{ANDA}$ exploits hadronic interactions in the initial state, thereby taking advantage of large production cross sections and a high sensitivity to gluon-rich matter. In essence, $\bar{\text{P}}\text{ANDA}$ will be a charm and strange factory providing high statistics data.
- **Access to large spectrum of J^{PC} states.** The direct formation of meson-like states is feasible in $\bar{p}p$ annihilation, similar to, for example, the abundant charmonium production in e^+e^- . This aspect is attractive since it allows to study the basic properties, such as the natural width of very narrow states via the resonance scanning technique. Antiproton-proton annihilation has the advantage that it can form states with all conventional J^{PC} spin parities, whereas in e^+e^- annihilation vector spin-parity states in formation, $J^{PC} = 1^{--}$, are produced. In the latter case, other spin-parity states can be produced only indirectly via the decay of a vector state. Even in the indirect case, higher spin states remain unreachable as a consequence of the angular-momentum barrier. Antiproton-proton annihilations would, however, be sensitive to high spin states as well.

Driven by the above-mentioned features, $\bar{\text{P}}\text{ANDA}$ has formulated an extensive physics program addressing the “hot spots” in hadron physics using spectroscopical techniques and reaction dynamics. Details, including the results of feasibility studies using Monte Carlo (MC) simulations, have been reported in Ref. [1]. These physics goals are supported by theorist and representatives of currently running and planned experiments in the field [2]. To summarize, the following items have been identified (with a large mutual overlap):

- **Hadron spectroscopy and dynamics.** Spectroscopy of hadronic states has been extremely successful in the past and has led to the development of QCD and the quark model for baryons and mesons. QCD also predicts new forms of hadronic matter such as multi-quark states, glueballs, and hybrids. The existence of these non-conventional forms of matter has been recently discovered experimentally by the observation of the so-called X, Y, Z states. Their internal structure, e.g. the relevant degrees of freedom that lead to their formation, remains a mystery. The annihilation of antiprotons with protons or neutrons will be a complementary approach to systematically study their behavior. In particular, the sensitivity of probing high spin states and the possibility to form directly unconventional states with conventional quantum numbers are of great advantage that cannot be done elsewhere. With $\bar{\text{P}}\text{ANDA}$ it would, therefore, be possible to determine precisely basic properties such as the line shape of some of the very narrow states and expand our spectroscopical knowledge. One also expects that with antiprotons it would be possible to abundantly produce unconventional hadronic states, in particularly gluon-rich matter.
- **Nucleon structure.** Since in the case of $\bar{\text{P}}\text{ANDA}$, the initial state is composed of a proton and an antiproton, it is feasible to study the structure of the nucleon as well, and in a way that is complementary to the traditional electron-scattering technique. $\bar{\text{P}}\text{ANDA}$ will exploit the electromagnetic probe, the exchange of a virtual photon, in the time-like region, a regime that is not well explored yet but theoretically as important as the space-like region. $\bar{\text{P}}\text{ANDA}$ will access time-like electromagnetic form factors with unprecedented accuracy via the annihilation of the antiproton with the proton and an electron-positron or negative-positive muon pair in

the final state [3]. In addition, transition distribution amplitudes (TDA) via meson production, generalized distributed amplitudes (GDA) via hard exclusive processes and Compton scattering, and transverse parton distribution functions (TPD) via Drell-Yan production are foreseen to be studied by PANDA.

- **Hyperons and hypernuclei.** Baryons with strangeness extend the study of nucleon structure to the SU(3) domain. The additional strange quark probes a different QCD scale and, thereby, helps to systematically study the dynamics of three-quark systems. The self-analyzing property of their weak decays provides a new rich of observables from which one gains more insight in the spin properties of baryons. Moreover, a good understanding of the interaction among baryons with strangeness, e.g. on the level SU(3), is of crucial importance in view of understanding the properties of astrophysical objects such as neutron stars. At present, our incomplete understanding of the underlying meson-baryon, baryon-baryon and multi-body interactions in baryonic systems limits probably our knowledge of the flavor composition of neutron stars. PANDA will be able to produce copiously hyperon pairs in antiproton-proton annihilations, acting as a strangeness factory. This will provide the basis to carry out an extensive baryon structure program. In a dedicated setup with a secondary target in combination with an additional array of Germanium gamma-ray detectors, it is foreseen to study the radiative level scheme of hypernuclei. The available antiproton momentum will, furthermore, allow to produce pairs of open-charm baryons and mesons. This will extend the baryon and meson spectroscopy and production dynamics with the much heavier charm quark as scale.
- **Hadrons in nuclear medium.** PANDA plans to use heavy nuclear targets as well, thereby, giving access to the study of antiproton-nucleus collisions. One of the physics interests lies in studying the properties of hadrons, produced in the antiproton interaction, inside the nuclear environment. At finite nuclear density one expects that chiral symmetry is partially restored leading to a modification of the masses of hadrons. This would provide the opportunity to study systematically the mass-generation mechanism. Another aspect that is on the PANDA physics with nuclear targets is the usage of the nucleus as a laboratory to determine the distance and time scale of hard QCD reactions. This relates to the phenomenon known as “Color Transparency (CT)”. Last, not least, is to study the short-distance structure of the nucleus itself. Hard collisions of antiprotons inside the nucleus can be used as a probe to study “Short Range Correlations (SRC)”, e.g. correlation effects of high momentum nucleons and non-nucleonic components of the nuclear wave function.

In the following sections, a few physics topics will be discussed of the above list that serve as key examples illustrating the uniqueness and competitiveness of PANDA. Note that the choice is partly driven by personal interest. Moreover, topics that are potentially suited for a “day one” program with a somewhat limited intensity will be highlighted.

3. Discovery by precision and exploration

PANDA will cover center-of-mass energies up to $5.5 \text{ GeV}/c^2$ in $\bar{p}p$ collisions, sufficiently high to extensively cover open- and hidden-charm states. The level scheme of lower-lying bound $\bar{c}c$ states, charmonium, is very similar to that of positronium. These charmonium states can be described fairly well in terms of heavy-quark potential models. Precision measurements of the mass and width of the charmonium spectrum give, therefore, access to the confinement potential in QCD. Extensive measurements of the masses and widths of the $1^{--} \Psi$ states have been performed at e^+e^- machines where they can be formed directly via a virtual-photon exchange. Other states, which do not carry the same quantum number as the photon, cannot be populated directly, but only via indirect production mechanisms. This is in contrast to the $\bar{p}p$ reaction, which can form directly excited charmonium states of all conventional quantum numbers. As a result, the resolution in the mass and width, or

more generally the line shape, of charmonium states can be determined by the precision of the phase-space cooled beam momentum distribution and not by the (significantly poorer) detector resolution. Moreover, in $\bar{p}p$ annihilation, charmonium states with high spin contents can be populated directly, which cannot be done in e^+e^- annihilation or in decays of higher-lying states. Hence, PANDA will be able to expand the existing and near-future experimental activities in charmonium(-like) research performed by BESIII, LHCb, BelleII, etc.. The need for such a tool becomes evident by reviewing the many open questions in the charmonium sector. For example, our understanding of the states above the $D\bar{D}$ threshold is very poor and needs to be explored in more detail. There are various charmonium states predicted, but yet to be discovered. Even more strikingly, there are many states experimentally found that cannot be assigned to a conventional charmonium state. These so-called X, Y, Z states got recently lots of attention. In particular, the charged Z states gave rise to an excitement in the field, since their first-time confirmed discovery proofs unambiguously that hadronic states composed of at least four quarks do exist. Even more recently, and in the same energy interval, signals that strongly hints towards pentaquarks were found. Both discoveries of Z-states and pentaquarks were labeled as physics highlights by the American Physical Society (APS) in 2013 and 2015, respectively, demonstrating the high impact of this type of research. Refs. [1, 4, 5] describe the feasibilities of PANDA for this physics topic in more detail.

To illustrate the potential of PANDA in the field of X, Y, Z spectroscopy, consider the X(3872). This state, discovered more than 10 years ago by Belle and confirmed by many other experiments, has a natural width of less than 1.2 MeV (90% confidence level), lies suspiciously close to the DD^* threshold, has a large isospin breaking, and has a spin-parity of 1^{++} . Based on these properties, it is expected that it is not a conventional $c\bar{c}$ configuration but a candidate for a four-quark state, a DD^* molecule, cusp effect, or any other exotic combination involving charm-anticharm quarks. It is an experimental challenge to provide observables that would shed light on its true nature. One of the most sensitive parameters that would depend strongly on its nature, would be the actual lineshape or natural width of the state [6]. The resonance scanning technique offered by using cooled antiprotons would be ideal to study the lineshape of this very narrow state. Detailed MC simulations were carried out to demonstrate the feasibility to use the observation of the channel $\bar{p}p \rightarrow X(3872) \rightarrow J/\psi\pi^+\pi^-$ with a resonance scan to study the lineshape. The simulation was based on a full detector model [7] with realistic background conditions, based on the Dual Parton Model [8] with a total $\bar{p}p$ cross section of 46 mb and a non-resonant $\bar{p}p \rightarrow J/\psi\pi^+\pi^-$ contribution of 1.2 nb [9], a presumed production cross section for $\bar{p}p \rightarrow X(3872)$ of 100 nb, and a branching fraction of 5% for the decay $X(3872) \rightarrow J/\psi\pi^+\pi^-$. With the HESR “day one” condition of a luminosity of $1170 \text{ (nb-day)}^{-1}$ and a center-of-mass energy resolution of 84 keV, a natural width for a Breit-Wigner response of 100 keV can be measured with a precision of about 20% in about 40 days. Such a sensitivity would only be possible with an experiment like PANDA.

In the discussion above, an example was given on how PANDA can make an impact by exploiting the excellent resolution of the antiproton beam. Another advantage of PANDA is its high hadronic interaction rates which provide the basis to carry out precision and exploration studies by statistics. PANDA will be in essence a factory of strange and charm hadrons. The hyperon sector is one of the topics that illustrate nicely the advantages of PANDA in this respect. These studies are largely motivated by extending our knowledge in the SU(2) sector to SU(3), e.g. what happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)? Moreover, the dynamics in which hyperons are produced in hadronic interactions are of great interest, since it helps to shed light on the degrees of freedom that are relevant at different mass scales. Already past experiments using antiprotons at LEAR gave a rich database in the associate production $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near its production threshold. The database above a beam momentum of 4 GeV/c remains scarce. Furthermore, only a few bubble chamber events have been observed for $\bar{p}p \rightarrow \bar{\Xi}\Xi$, and no data exists for systems with an absolute strangeness of three ($|S|=3$), e.g. $\bar{p}p \rightarrow \bar{\Omega}\Omega$, nor in charmed hyperons, $\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$. With PANDA it would become possible to produce strange hyperon pairs with typical observed rates,

exclusively measured using favorable decay modes, ranging from a few per hour ($\Omega^+\Omega^-$) to tens per second ($\bar{\Lambda}\Lambda$, $\bar{\Lambda}\Xi^0$) at a “day-one” luminosity of 10^{31} cm⁻²s⁻¹. With these high rates, it would even become possible to obtain for the first time a rich set of polarisation observables by making use of the self-analyzing feature of weak decays.

The high production rate of hyperon pairs in antiproton collisions is the basis for the novel hypernuclear program of \bar{P} ANDA. Details of the plans and feasibility of the hypernuclei program can be found in Refs. [10, 11]. The goal is to expand the nuclear chart in the dimension of strangeness, thereby providing data that would help us studying two- and many-body baryon-baryon forces with the inclusion of strangeness. \bar{P} ANDA focusses on strangeness $S = -2$ systems, Ξ -atoms and $\Lambda\Lambda$ hypernuclei. The hypernuclei program of \bar{P} ANDA complements the research that is ongoing or planned at facilities like J-PARC [12], STAR [13], ALICE [14], CBM and NUSTAR [15], by providing the environment that allows to study γ -unstable excited states of double-hypernuclei. To produce these hypernuclei, a primary diamond filament target will be bombarded by the antiproton beam, producing Ξ^- baryons in $\bar{p}N \rightarrow \Xi^-\bar{E}$. The Ξ^- particles will be decelerated in a secondary target, for example a boron absorber with active silicon layers. The Ξ^- hyperons might be captured in an electron shell of an atom, forming hyperatoms. An excited $\Lambda\Lambda$ -nucleus can be formed via the conversion reaction $\Xi^-p \rightarrow \Lambda\Lambda$. It will decay to its groundstate by the emission of γ -rays, which are detected by an array of Germanium detectors. The pionic decays of the Λ hyperons can be exploited to provide a clean signal. Already at an antiproton interaction rate of 2×10^6 s⁻¹, \bar{P} ANDA will be able to reach a rate of stopped Ξ^- which is comparable to the maximum rate expected at [12].

The formation of Ξ^- atoms will be the first step towards a forefront game changer, namely a study of the spectroscopic quadrupole moment of the Ω^- via the hyperfine splittings in Ω^- -atoms. The long lifetime and its spin of 3/2 makes the Ω^- the only candidate to obtain direct experimental information on the shape of an individual baryon. Such a measurement would complement the world-wide studies of the shape of the proton, with the interesting feature of addressing a $|S| = 3$ system in which meson cloud corrections to the valence quark core are expected to be small. The quadrupole moment of the Ω^- would also serve as an ideal benchmark for lattice QCD calculations since the contributions from light quarks are small. Unfortunately, it is yet unknown what the production rates of Ω hyperons are in antiproton collisions.

4. Technological innovation

The physics ambitions of \bar{P} ANDA go hand-in-hand with technological detector developments. The $\bar{p}p$ cross section with the momentum range covered by \bar{P} ANDA, range from 50-100 mb. Such large cross sections together with an intense antiproton beam result in enormous interaction rates going up to 2×10^7 s⁻¹. In contrast, the \bar{P} ANDA detector will be able to identify reactions with cross sections of only a few nb, i.e. needle-in-a-haystack capabilities. To cope with the high rates, a highly granular detector will be used with components that are capable of coping with high count rates. To address the different physics topics, the detector needs to cope with a variety of final states and a large range of particle momenta and emission angles. A 4π detection system is foreseen which is necessary in order to unambiguously carry out a partial-wave decomposition. The broad physics program, that asks for hadronic, electromagnetic and weak probes, requires, furthermore, a detector that has excellent particle identification capabilities and a high momentum resolution to be able to identify and measure the momentum of photons, electrons/positrons, muons, pions, kaons, and (anti)protons. The lead-tungstate photon calorimeter of \bar{P} ANDA will have a huge dynamic-range capability to detect photons from a few MeV to a few GeV in energy. To identify weakly decaying open-strangeness/charmness hadrons, \bar{P} ANDA will be equipped with the capability to identify displaced vertices. The experiment will use internal targets. It is conceived to use either pellets of frozen H₂ or cluster jet targets for the $\bar{p}p$ reactions, and wire targets for the $\bar{p}A$ reactions. Moreover, the

setup has been designed in a modular way, that would allow to easily replace the micro vertex detector and the backward part of the electromagnetic calorimeter by the hypernuclear setup with its dedicated targets and gamma-ray detectors. A sketch of the PANDA setup is depicted in Fig. 2 indicating the various components that are foreseen to reach all the previously mentioned requirements. More details can be found in various technical design reports [16].

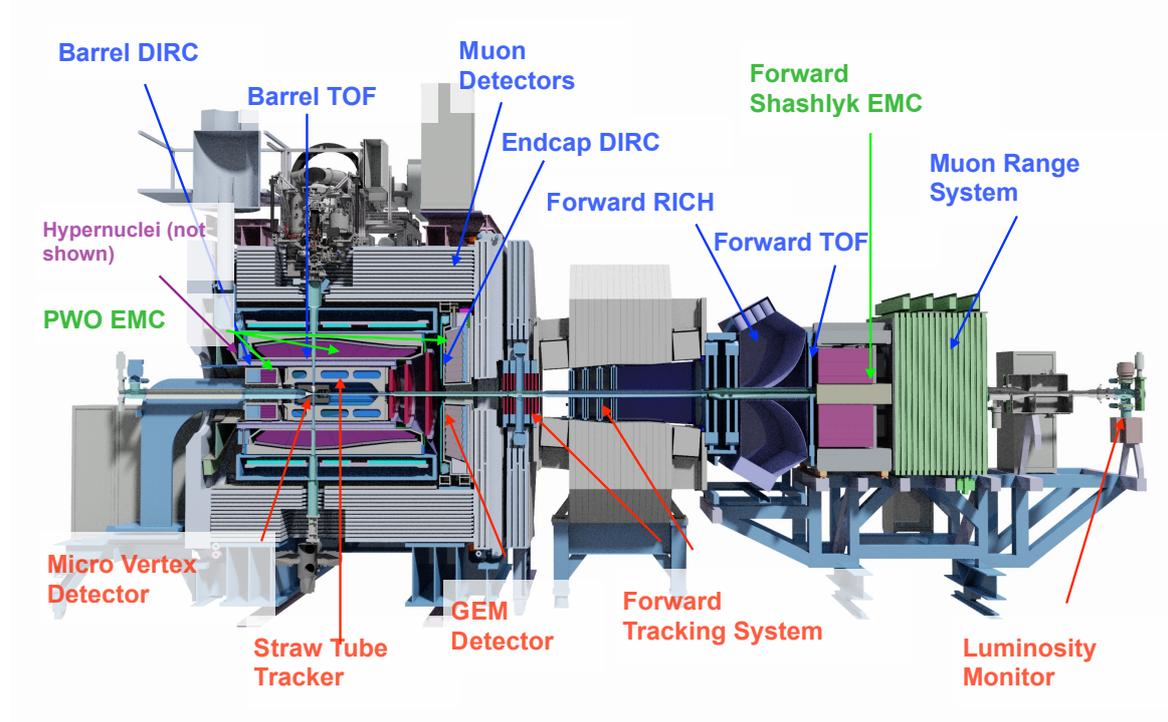


Fig. 2. A sketch and cross section of the full PANDA setup. The various vertex, tracking, particle identification, and photon calorimeter components are indicated. More details can be found in Refs. [1, 16].

For the full design of the detector as shown in Fig. 2, an interaction rate of $2 \times 10^7 \text{ s}^{-1}$ would translate in a raw data rate of the order 200 GBytes/s. It would be impossible and unpractical to simply store all data on disk or tape. Since a conventional hardware trigger will not be possible, a new paradigm in data processing is being developed. The aim is to deploy a free-streaming data-processing scheme, whereby the challenge lies in reconstructing *in-situ* the complete event topology for each $\bar{p}p$ interaction under high-coutrate conditions and using massive parallization hardware architectures. Feasibility studies show promising results [17–21].

5. Summary

The PANDA experiment at FAIR will address a wide range of topics in the field of QCD, of which only a small part could be highlighted in this paper. The physics program will be conducted by using beams of antiprotons together with a multi-purpose detection system, which enables experiments with high luminosities and precision resolution. PANDA has the ambition to provide valuable and new insights in the field of hadron physics which would bridge our present knowledge obtained in

the field of perturbative QCD with that of non-perturbative QCD and nuclear structure. It offers a long-term program for the next generation (nuclear, hadron, and particle) physicists. Already at the starting phase of HESR, with a reduced luminosity, various key experiments can be carried out, such as a resonance scan of the X(3872), a search for high-spin states in charmonium-like systems, a high-statistics study of hyperons and their production in $\bar{p}p$ annihilation, and many more.

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References

- [1] PANDA Collaboration, W. Erni *et al.*, arXiv:0903.3905 (2009).
- [2] M. Lutz *et al.*, Nucl. Phys. **A948**, 93 (2016).
- [3] PANDA Collaboration, B. Singh *et al.*, arXiv:1606.01118 (2016).
- [4] S. Lange *et al.*, proceedings of CHARM 2013, arXiv:1311.7597 (2013).
- [5] E. Prencipe, proceedings of ICHEP 2014, arXiv:1410.5201 (2014).
- [6] C. Hanhart *et al.*, Phys. Rev. **D76**, 034007 (2007).
- [7] S. Spataro, proceedings of CHEP2010, J. Phys.: Conf. Ser. **331**, 032031 (2011).
- [8] A. Capella *et al.*, Phys. Rep. **236**, 225 (1994).
- [9] G.Y. Chen *et al.*, Phys. Rev. **D77**, 097501 (2008).
- [10] A. Sanchez Lorente, Hyperfine Interact **213**, 41 (2012).
- [11] PANDA Collaboration, B. Singh *et al.*, Nucl. Phys. **A954**, 323 (2016).
- [12] K. Tanida (spokesperson) *et al.*, J-PARC P03 proposal, http://j-parc.jp/researcher/Hadron/en/Proposal_e.html.
- [13] STAR Collaboration, B.I. Abelev *et al.*, Science **328**, 58 (2010).
- [14] ALICE Collaboration, J. Adam *et al.*, Phys. Lett. **B754**, 360 (2016).
- [15] A.S. Botvina *et al.*, Phys. Lett. **B742**, 7 (2015).
- [16] PANDA Collaboration, Technical Design Reports; Magnets, FAIR TDR 4.02, arXiv:0907.0169 (2009); Targets, FAIR TDR 4.05 (2012); Micro Vertex Detector, FAIR TDR 4.03, arXiv:1207.6581 (2012); Straw Tube Tracker, FAIR TDR 4.04, arXiv:1205.5441 (2012), Eur. Phys. J. **A49**, 25 (2013); Electromagnetic Calorimeter, FAIR TDR 4.01, arXiv:0810.1216 (2008); Forward Spectrometer Calorimeter, FAIR TDR 4.08 (2015); Muon System, FAIR TDR 4.06 (2013).
- [17] M. Kavatsyuk *et al.*, Conference Records of 2012 IEEE Nuclear Science Symposium, DOI10.1109/NSSMIC.2012.6551420 (2012).
- [18] M.J. Galuska *et al.*, Proceedings of Science, Bormio 2013, 23 (2013).
- [19] A. Adinets *et al.*, Procedia Computer Science **29**, 113 (2014).
- [20] T. Stockmanns, proceedings of CHEP2015, J. Phys.: Conf. Ser. **664**, 072046 (2015).
- [21] M. Babai *et al.*, Mathematical Morphology and Its Applications to Signal and Image Processing Volume 9082 of the series of Lecture Notes in Computer Science, 86 (2015).