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The $\overline{\text{P}}$ANDA physics program

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Abstract. The understanding of the QCD in the non-perturbative regime, is one of the key issues to have a complete picture of strong interactions. Recent findings of new and unexpected resonances, with unresolved properties, show that the hadron spectrum is not yet completely understood. This is also underlined by the ongoing discussion on multi-quark states, and on other exotic states with gluonic degrees of freedom. The $\overline{\text{P}}$ANDA experiment, one of the biggest enterprises at the FAIR facility, aims at exploring this field thanks to the gluon rich environment offered by the annihilation of antiprotons. A general overview of the $\overline{\text{P}}$ANDA physics program is given in this paper.

1 Introduction

To have a complete picture of strong interactions, a better understanding of Quantum Chromo Dynamics (QCD) in the non-perturbative regime is necessary. To understand how quarks and gluonic degrees of freedom lead to hadronic states, and how hadrons get mass and all the properties we observe, still deserve a deeper study. These are the most burning questions of fundamental research, strongly linked to the issue about the existence of other forms of matter different from mesons and baryons (*i.e.* glueballs, hybrids, etc..). These unusual states have been theoretically predicted by QCD since its formulation, but experimentally their existence has been established only recently. Some of the so-called X, Y, Z states, that have been found by currently ongoing experiments, cannot be "conventional" antiquark-quark or three quark combinations. In order to understand their precise nature a campaign of dedicated measurements is desirable.

Antiproton-proton annihilation proceeds via two- or three-gluon processes, and this gluon-rich environment is perfect to investigate the nature of all kind of hadronic states. $\overline{\text{P}}$ANDA is a next generation hadron physics experiment whose name stands for antiProton ($\bar{p}$) ANnihilations in DArmstadt, and it will be located at the High Energy Storage Ring (HESR) of the Facility for Antiproton and Ion Research (FAIR) in Darmstadt (Germany) [1]. A state of the art, almost 4π fixed target detector (see Fig. 1), will be combined with a high intensity and high momentum resolution antiproton beam, in the momentum range from 1.5 to 15 GeV/c. $\overline{\text{P}}$ANDA will address at best many open and burning questions in the energy domain where QCD sees the transition from the perturbative to the non-perturbative regime.

The field of hadron physics is often subdivided into the following branches:

- hadron spectroscopy;

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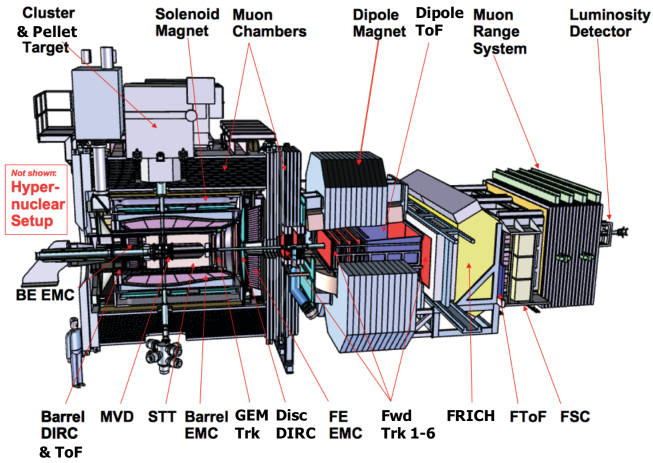

Figure 1. Schematic layout of the $\overline{\rm P}$ANDA detector; a dedicated setup (not shown in the picture) will be added in the central region for hypernuclear physics measurements. More details about detector sub-components can be found in Ref. [2]

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- hadron structure;
- interaction of hadrons.

The $\overline{\rm P}$ANDA detector [2] has been especially designed, together with the HESR accelerator, to be a perfect instrument to shed new light on the complete list of items above mentioned. This multi-task approach is new in the study of strong interactions and promises to deliver world class results.

In the following sections, more details on some topics of the $\overline{\rm P}$ANDA physics program are given. A complete overview of the scientific program of the $\overline{\rm P}$ANDA experiment, with detailed simulation results obtained with a realistic layout of the detector, can be found in Ref. [3].

2 Understanding QCD by means of antiprotons

$\overline{\rm P}$ANDA aims to perform a vast program of hadron spectroscopy of strange and charmed states to firmly identify exotics. Experimentally, the search for exotics in the light quark sector is a challenging task due to their mixing with nearby ordinary states having the same quantum numbers. In this respect, the charmonium energy region is favorable because the density of states is lower and also their widths are narrower. This is probably the reason why the first unambiguous exotic candidates have been detected in this energy region. To draw definitive conclusions, it is important to map out the entire spectrum of states and to study many different decay channels and different production processes. $\overline{\rm P}$ANDA will complement the efforts at facilities like JLab, BESIII, COMPASS and J-PARC by utilizing the environment of the antiproton-proton annihilation.

In the spectroscopy sector, antiproton-proton annihilations enable two modes to investigate final states (see Fig. 2):

- **Formation:** a single resonance is directly produced in the annihilation process, in this case the J^{PC} quantum numbers accessible to a fermion-antifermion pair can be obtained;

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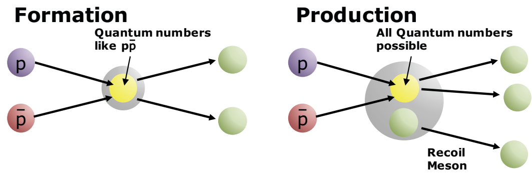

Figure 2. The cartoon is showing the two different production mechanisms by which a certain final state (yellow ball) can be studied via $\bar{p}p$ annihilation: **Formation** and **Production** (see the text for more details).

- **Production:** at least one additional particle is produced together with the one under study. Here restrictions on J^{PC} do not apply.

The comparison of the two production mechanisms helps to classify resonances and to identify those with an exotic nature. Furthermore, the high momentum resolution of the antiprotons achievable in the HESR ($\Delta p/p$ up to 2×10^{-5}), will allow mass resolutions better than $\Delta m/m < 10^{-4}$ that cannot be obtained in the production via the decay chain of heavier particles, where the detector resolution becomes a limiting factor. This feature will allow to measure precisely the widths and the line shapes of all poorly known conventional and exotic states in the centre of mass (c.m.) range from 2.2 to 5.5 GeV/c^2.

To give an example of the possibilities of the $\overline{\text{P}}$ANDA experiment, let's consider the $X(3872)$ resonance. This is the first of the new resonances in the series of unresolved states in the charmonium energy domain discovered by the Belle collaboration in 2003 [4] and then confirmed by many other experiments. Assuming a cross section of 100 nb for the channel $\bar{p}p \to X(3872)$, $\overline{\text{P}}$ANDA could produce about 860.000 events/day when the HESR will reach the top luminosity, but already at the initial luminosity of $\mathcal{L} = 10^{31}\text{cm}^{-2}\text{s}^{-1}$, foreseen for the FAIR starting phase (MSV0-3), the number of produced $X(3872)$ per day will still be about 43.000. No other running or planned experiment could have such a rate.

Another peculiar aspect of the hadronic studies performed via $\bar{p}p$ annihilations, resides in the unique possibility to measure precisely the resonance parameters, namely the mass M, the width Γ, and the line shape. These can be extracted by measuring the formation rate for that resonance as a function of the c.m. energy [3]. As an illustration of this technique, Fig. 3 shows a scan of the χ_{c1} resonance carried out at the Fermilab antiproton accumulator by the E835 experiment [5] using the process $\bar{p}p \to \chi_{c1} \to J/\psi\gamma$. The value obtained for the resonance width $\Gamma = 0.881 \pm 0.052 \pm 0.026$ MeV is still the best ever reached.

The beam energy distribution available at the HESR will be a factor from two to ten times better than that available at Fermilab, allowing to measure widths down to tens of keV. Again, in the case of the $X(3872)$ where there is only an upper limit for the width ($\Gamma < 1.2$ MeV/c^2 [6]), $\overline{\text{P}}$ANDA will be the only experiment able to perform a precise determination of this important parameter. The vicinity of the $X(3872)$ to the value of the sum of the masses $M_{D^0} + M_{D^{*0}}$ as well as the relative decay magnitudes to charmonium and open charm channels has inspired several models interpreting the state either as a loosely bound $D^0 - D^{*0}$ molecule or a virtual scattering state effectively created by threshold dynamics. The line shape of the state differs dramatically depending on the hypothesis, therefore a precise determination of the resonance line shape, will allow to disentangle between the two possibilities.

Complementary information on QCD dynamics can also be obtained from the measurement of the excitation spectrum of strange and charmed baryons. Baryons with strangeness extend the study

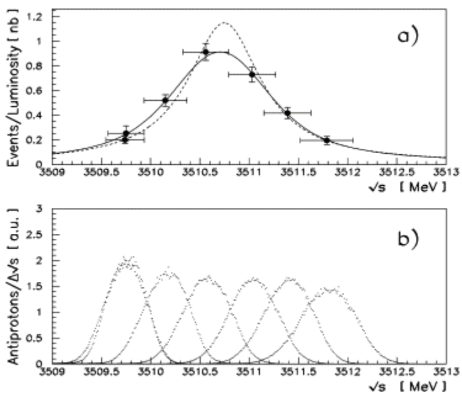

Figure 3. Resonance scan at the χ_{c1} carried out at Fermilab (a) and the beam energy distribution in each data point (from Ref. [5]).

of the nucleon structure to the three-flavor sector and via their self-analyzing weak decays one can access to spin properties of baryons. $\overline{\text{P}}$ANDA has unique opportunities in this field since the cross section for baryon-antibaryon final states, both ground state and excited, is large. Therefore, already in the starting phase of the experiment it would be possible to study the excitation spectrum of Ξ and Ω baryons.

The high production rate of hyperon pairs in antiproton annihilations will also allow to carry on a novel program at the border with nuclear physics: that of doubly-strange nuclear systems. The goal is to expand the nuclear chart in the strangeness dimension, thereby providing data that would help to study two- and many-body baryon-baryon forces that have astrophysical implications *i.e.* in the modelling of neutron stars. $\overline{\text{P}}$ANDA focuses on systems with strangeness $S = -2$: $\Xi-$atoms and $\Lambda - \Lambda$ hypernuclei, for which high resolution gamma spectroscopy will be performed for the first time. Details and plans for this research field can be found in Ref. [7].

3 Hadron's structure functions

Nucleon structure investigations have been performed since long time using electron beams. Electron scattering allows to access nucleon structure matrix elements in the region of negative momentum transfer of the intermediate virtual photon (space-like region) for many processes like elastic scattering or deep inelastic exclusive or inclusive scattering. The availability of a high intense antiproton beam annihilating on a proton target in combination with the $\overline{\text{P}}$ANDA detector offers the unique opportunity to extend these investigations to the region of positive momentum transfer of the photon (time-like region). Due to its analyticity, space-like and time-like observables are intimately connected by the application of dispersion relations. Perturbative QCD makes predictions for the large q^2 behavior of the connection between space-like and time-like regions that would be worth testing. Furthermore, recent measurements performed at JLab [8] using the polarization transfer and target asymmetry method, have shown that the ratio of the electric (G_E) and the magnetic (G_M) components of the proton form factors $R = |G_E|/|G_M|$ deviates from unity. This is inconsistent with the results derived from the use of the Rosenbluth separation technique. This surprising result has reopened the question on the determination of G_E and G_M, which in the time-like domain are complex functions. It is important to check whether the behaviour of G_E and G_M in the two domains are coherent.

The extension of the form factor measurements to the time-like region and the separate measurement of G_M and G_E can be improved almost of one order of magnitude compared to existing world data by using the antiproton beam at HESR. Figure 4 shows the statistical precision on the form factor ratio obtained using a detailed Monte Carlo simulation compared to the world database. $\overline{\text{P}}$ANDA will improve the precision on this ratio at lower q^2 in comparison to other experiments, and will provide additional measurements in a higher energy region [9]. Furthermore, the $\overline{\text{P}}$ANDA experiment offers

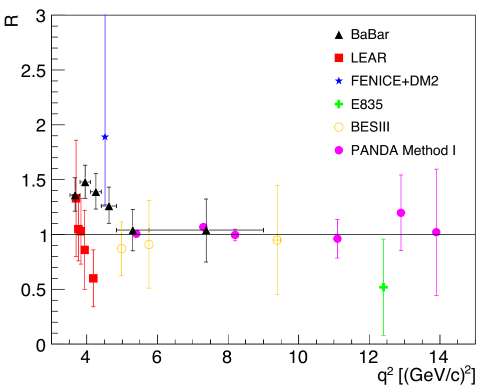

Figure 4. World data set of measurements of the ratio $R = |G_E|/|G_M|$ performed in the time-like region. Monte Carlo simulations of expected $\overline{\text{P}}$ANDA results are also shown (Details can be found in Ref. [9]).

a unique chance to determine the moduli of the complex form factors in the time-like domain, by measuring the angular distribution of the process $\bar{p}p \rightarrow e^+e^-$ in a q^2 range from about 5 (GeV/c)^2 up to 14 (GeV/c)^2. The $\overline{\text{P}}$ANDA detector will provide unprecedented luminosity and rich particle identification capabilities, which are necessary in order to discriminate against the very large hadronic background which is of the order of 10^6 times higher in cross section. Any possible two-photon exchange contribution in the time-like domain, which is regarded to be one of the radiative correction processes responsible for the discrepancy between the Rosenbluth and the polarization transfer methods in the space-like regime, can be detected in the same measurement. This effect will introduce a forward-backward asymmetry in the angular distribution which otherwise is symmetric if only one-photon exchange holds. Moreover, $\overline{\text{P}}$ANDA could access for the first time proton form factors in the muonic channel $\bar{p}p \rightarrow \mu^+\mu^-$, and make measurements in the unphysical region below the threshold through the reaction $\bar{p}p \rightarrow e^+e^-\pi^0$ at low beam energies, where the cross section is high.

Not only form factors, but also a wide set of electromagnetic observables which have been only studied in space-like momentum-transfer range can be addressed at $\overline{\text{P}}$ANDA: Transition Distribution Amplitudes via lepton pair production with an associated meson; Generalized Distribution Amplitudes with hard exclusive processes like Wide Angle Compton Scattering; Transverse Momentum Parton Distribution Functions via the measurement of final state asymmetries in Drell-Yan Production are in the plans of the experiment. For all the cases mentioned above, a $10^5 - 10^6$ times larger hadronic background is expected. Therefore feasibility studies of all signal channels are ongoing. The results are extremely promising thanks to the large solid angle and the PID-capabilities of the $\overline{\text{P}}$ANDA detector that helps to suppress this hadronic background.

4 Data acquisition strategy

$\overline{\text{P}}$ANDA will be a fixed target experiment to measure $\bar{p}p$ and $\bar{p}A$ collisions up to rate of $2 \cdot 10^7$ events/s. To achieve this goal, it will need a data acquisition concept matching the complexity of the experiment and the diversity of physics objectives. Every sub-detector unit will be a self-triggering entity. Signals will be detected autonomously by each sub-systems and pre-processed in order to transmit only the physically relevant information. The final event selection will occur in computing nodes which first isolate events, and then filter physical signatures of interest. This new concept will provide a high degree of flexibility in the development of trigger algorithms, and it will allow trigger conditions which are outside the capabilities of the standard approaches.

5 Summary

The $\overline{\text{P}}$ANDA research program at FAIR will explore a wide range of important questions for the understanding of strong interactions.

The $\overline{\text{P}}$ANDA collaboration aims to connect the perturbative and the non-perturbative QCD regions by means of high precision measurements that cannot be obtained elsewhere. The international collaboration (~ 400 scientists from all over the world) combines researchers from the nuclear and the particle physics communities that come together with the intention to have the most open-minded approach to the unsettled questions of subatomic physics. The examples given in the above sections represent only some highlights of the physics program that will be exploited. In fact, thanks to the completeness and versatility of the $\overline{\text{P}}$ANDA detector under construction, a wider spectrum of measurements would be possible. To accomplish at best this task, even the data acquisition system will be flexible and as much as possible unbiased, to allow for many measurements to be done in parallel. All these elements make $\overline{\text{P}}$ANDA to be more than a single experiment but rather as a universal facility for QCD physics.

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