Update on the Physics Perspectives of $\overline{\text{P}}$ANDA

The long-range plan of NUPECC for the European hadron physics community of the year 2010 identifies three major areas in hadron physics as prime goals for the future. Those are 'Hadron Spectroscopy', 'Hadron Structure' and 'Hadronic Interactions'. The $\overline{\text{P}}$ANDA experiment by design can contribute to all of these. The reason why these areas have been identified as prime targets for research by NUPECC is that they are rapidly developing in terms of new interesting experimental results and in terms of theoretical understanding. Therefore it is obvious that the physics case for $\overline{\text{P}}$ANDA has been strengthened and gained additional perspectives. The scope of this paper is to demonstrate this on a few examples in each of the areas.

Spectroscopy of X, Y and Z states

The initial discovery of the charm quark in the 1970s was followed by the discovery of a quick succession of charmonium states with relatively narrow widths. The narrow widths indicate a long lifetime of the states, which results from the fact that charmonium states below the open-charm decay threshold of 3.73 GeV (i.e., twice the mass of the D-mesons) must decay through the annihilation of the $c\bar{c}$ pair. The spectroscopic investigation of these experimentally clean charmonium states deserves major credit in the development of Quantum Chromodynamics (QCD), the theory of the strong interaction.

The total widths in these charmonium decays have traditionally been described in terms of annihilation into gluons, using the corresponding formulas for positronium annihilation into photons, but with α_s vertices and combinatorial color factors. It was the spectrum of particles consisting of the fourth generation of quarks (charm) and later the fifth generation (bottom) that lent strong support to the viewpoint that mesons could be understood in a way analogous to positronium in the electroweak interactions. In its simplest form, the resulting potential contains a Coulomb-like part based on a one-gluon exchange (OGE) and—special to the strong interaction—a part describing the observed confinement:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

The narrow width of the charmonium states and the fact that they are well separated without interfering amongst each other allowed for precise theoretical calculations to be made. Even the simple-minded OGE complemented with a spin-dependent Breit-Fermi Hamiltonian and a spin-orbit term gave a very good description of the charmonium spectrum as it was known before 2003. Thus the case of charmonium physics seemed to be closed.

From the theoretical side, however, it is questionable whether the concept of "free" gluons is valid in QCD. It seems much more reasonable to describe the binding of the quark-antiquark pair by a flux of multiple gluons confined to a tube due to the gluon self-interaction, as already mentioned earlier.

Interest in charmonium physics got a big boost again in 2003, when the Belle collaboration found an unexpected, very narrow state in the $J/\psi\pi^+\pi^-$ invariant mass spectrum, called X(3872). The latest spectrum from Belle is shown in figure 1 [1].

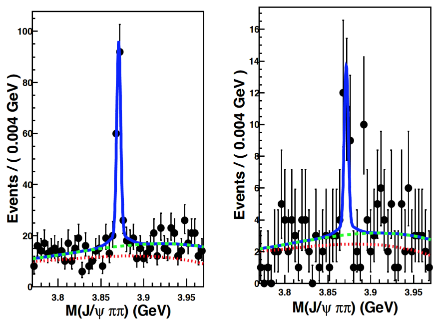

Figure 1: The $J/\psi\pi^+\pi^-$ invariant mass distribution for charged (left) and neutral (right) B decays.

The properties of this state according to the Particle Data Group [2] are

$$M = 3871.68 \pm 0.17 \text{ MeV}$$
$$\Gamma < 1.2 \text{ MeV}$$

The Belle collaboration gives as a likely J^{PC} assignment 1^{++} or 2^{-+}. In particular this assignment makes it, together with the narrow width that is so far known only as an upper limit, unlikely to be a conventional charmonium state. What else could it be? It is interesting to recognize that it lies within 0.5 MeV of the $D^{*0}\overline{D}^0$ threshold, and nowadays we know that it decays into $J/\psi\pi^+\pi^-$ and $J/\psi\pi^+\pi^-\pi^0$ with similar rates. The proximity to a threshold makes it a prime candidate for a hadronic molecule. Molecules are weakly bound states of at least two hadrons and nuclei. Here hypernuclei could be considered as well-known examples.

If such hadronic molecules indeed exist, they should appear in the vicinity of a two-particle threshold or between two close-by thresholds, where attractive S-wave interactions can bind a pair of mesons or where a meson and a baryon form this type of resonance. Given this rich set of possibilities, it is one of the mysteries of QCD that so far only quark-antiquark and three-quark states have been firmly established.

Obviously the characteristics for a molecule should be that its mass is slightly less than the mass of the free constituents, due to the binding energy. The interpretation of the state depends critically on the measured values of the state's properties. Various calculations show that depending on what kind of object the X(3872) is, different dispersive effects would result in different line shapes [3, 4].

The additional measurement of B decays from BaBar is significantly worse and does not help the situation. How about hadron colliders? The CDF collaboration studied the X(3872) in $J/\psi\pi^+\pi^-$ decays. They observed approximately 6000 X(3872) events in antiproton-proton collisions at $\sqrt{s}$ = 1.96 TeV [5] (see figure 2), showing a remarkably strong coupling of this state to $\overline{p}p$. The D0 collaboration confirms the result of CDF [6]. The newest results from LHCb [7] still have a slightly bigger error, but are compatible with the other results.

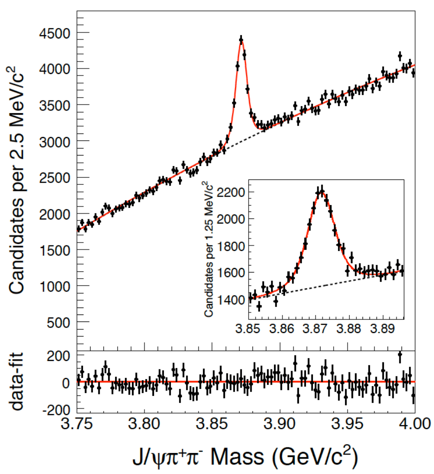

Figure 2: Invariant mass distribution of the X(3872) candidates. The points show the data distribution, the full line is the projection of the unbinned maximum-likelihood fit, and the dashed line corresponds to the background part of the fit. The inset shows an enlargement of the region around the X(3872) peak. Residuals of the data with respect to the fit are displayed below the mass plot.

The mass value of $M = 3871.68 \pm 0.17$ MeV brings the world average of the X(3872) mass within a mass difference of -0.05 ± 0.27 MeV to the sum of masses of the D^0 and D^{*0} [2]. Unfortunately the value for the width given by Belle is just an upper limit and has little chance of being improved upon in the immediate future because it is given by the detector resolution; thus a precise determination of the line shape is unthinkable at present.

$\overline{\text{P}}$ANDA will change the data situation dramatically. It will scan the parameters of the resonances in formation mode, making use of the excellent momentum resolution $\Delta p/p=10^{-4}$-10^{-5} of the HESR beam. This technique has proven to be very successful in the Fermilab experiment E835 inside the Fermilab accumulator [8]. Since the parameters of a resonance show up as a formation rate as a function of the center-of-mass energy, the quality of the measurement depends not on the energy resolution of the detector but on the quality of the beam, which is much easier to control. A simulation and the reconstructed line-shape spectrum is shown in figure 3 for three different assumed widths of the X(3872).

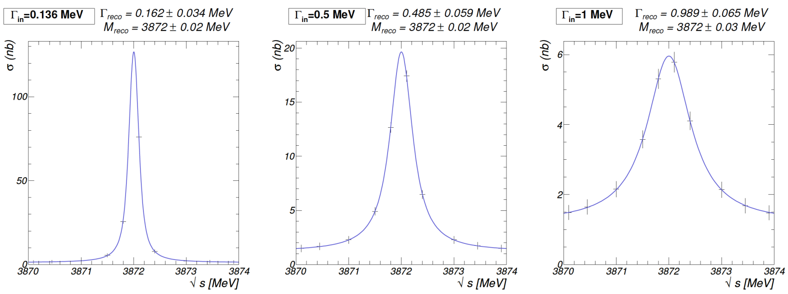

Figure 3: Reconstructed cross section distributions corresponding to the three assumed input widths for the X(3872) of 0.136 MeV, 0.5 MeV and 1 MeV. The blue curve corresponds to a specific fit function.

One particle that is definitely not a charmonium state or a traditional meson is the $Z^+(4430)$. This was discovered by Belle in the $K\pi^\pm\psi'$ channel (see fig. 4) [9]. This state carries electric charge and thus cannot be a charmonium state even though it must contain a $c\bar{c}$ pair due to its decay into $\psi'\pi^+$. It is an obvious candidate for a multiquark state. Two more things are remarkable about the $Z^+(4430)$: its decay into $J/\psi\pi^+$ is not observed, which might be indicative of a certain selection rule, and the width is again rather narrow. It is exactly this narrow width that allowed Belle to rebuke the claim made by the BaBar collaboration that the signal is caused not by a resonance but by interference effects in the Kπ channel. However, the presence of possible interference effects in the Dalitz plot cannot be excluded in B decays, where the K* are naturally present. To finally resolve the issue, one has to go to different channels.

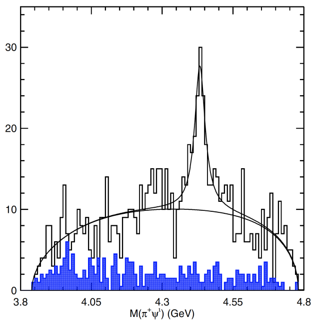

Fig. 4: The $\pi^\pm\psi'$ invariant mass spectrum for $B \to K\,\pi^\pm\psi'$ decays. The fit shows a Breit-Wigner and a phasespace-like background. The blue area shows the estimated background.

$\overline{\mathrm{P}}$ANDA can study the $Z^+(4430)$ in both production and formation experiments. In the production experiment, the $Z^+(4430)$ would be produced, e.g., in the reaction $\bar{p}p \rightarrow Z^+(4430) + \pi^-$. The subsequent decay chain is then:

$$Z^+(4430) \rightarrow \psi(2S)\pi^+ \rightarrow J/\psi\pi^+\,\pi^-\,\pi^+ \rightarrow e^+e^-\,\pi^+\,\pi^-\,\pi^+$$

The reconstruction efficiency for this channel with the $\overline{\mathrm{P}}$ANDA detector has been studied in Monte Carlo calculations and is 24%.

Furthermore, the Monte Carlo study shows that the Dalitz plot for the above-mentioned channel is clean and almost background-free (figure 5) due to the presence and effective detection of the J/ψ in the decay chain. Two high-energy electrons can be clearly identified and distinguished from pions by their shower in the EMC, and together the electrons must have a very narrow invariant mass; both conditions are extremely hard to mimic in any background reaction.

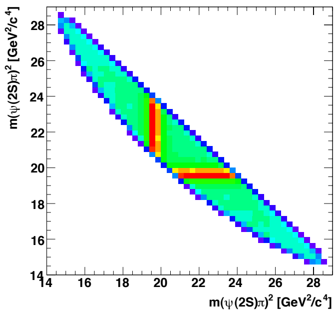

Figure 5: The ψ(2S)π Dalitz plot for the reaction $\bar{p}p \rightarrow Z^{\pm}(4430)+\pi^{\mp}$ with the Z decaying into ψ(2S)π.

The invariant ψ(2S)π mass is shown in figure 6. Since the Z is produced together with an associated pion and there are additional pions from the decay $\psi(2S) \rightarrow J/\psi\ \pi^+\ \pi^-$, the possibility of a combinatorial background exists. However it turns out that for an incoming antiproton momentum of 15 GeV/c, the “incorrect” combination of pions has a completely different invariant mass distribution.

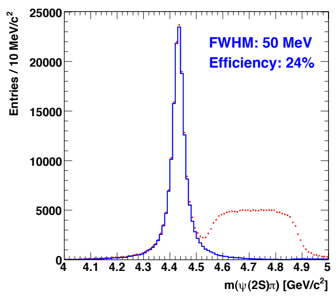

Figure 6: The ψ(2S)π invariant mass spectrum is shown by the blue curve. Combinatorial background from the wrong association of the 3 pions of the final state leads to the distribution in red.

$\bar{\text{P}}$ANDA can investigate the $Z^+(4430)$ even further by switching to studies of the $Z^+(4430)$ in formation mode. Due to the charge of the Z, this is only possible by annihilating the antiprotons on a neutron in a deuterium target. Experimentally it is no problem to replace the hydrogen gas, for example in a pellet target, with deuterium. The reaction to look for in $\bar{\text{P}}$ANDA would then be:

$$\bar{p}d \rightarrow Z^-(4430) + p_{spectator}$$
$$\downarrow$$
$$\psi(2S)\pi^- \rightarrow J/\psi\ \pi^+\pi^-\pi^-$$

The reconstruction efficiency for this channel studied in Monte Carlo reactions is 35% and both the invariant mass of the $Z^-(4430)$ and of the ψ(2S) can be reconstructed cleanly, as shown in figure 7.

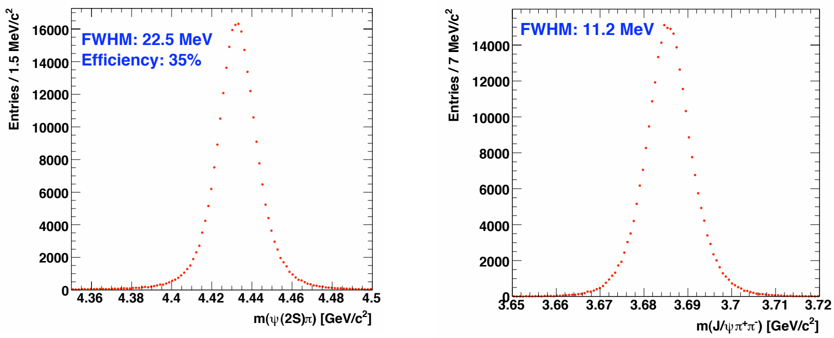

Figure 7: The reconstructed invariant masses of the $Z^-(4430)$ and the ψ(2S) in $\bar{\text{P}}$ANDA Monte Carlo simulations of an antiproton annihilation on the neutron of a deuterium target.

Two more charged states like the $Z^+(4430)$ were observed by Belle but not by other experiments—the $Z^+(4050)$ and the $Z^+(4250)$, both decaying into $\pi^+\chi_{c1}$ [10]. Needless to say, $\overline{\mathrm{P}}$ANDA will be able to study both states in a way similar to that described for the $Z^+(4430)$. Additionally two charged bottomonium-like states have been found by BELLE [11] in various decay modes, adding to the evidence that the hadronic spectrum is much richer than originally thought.

Many more states, most of them above the open-charm threshold, have since been found by several experiments. (For a review of this topic, refer, e.g., to [12].) Many of the new states do not fit into the expected charmonium spectrum due to their unusual properties or decay patterns. Figure 8 gives an overview of these states in relation to the conventional charmonium spectrum.

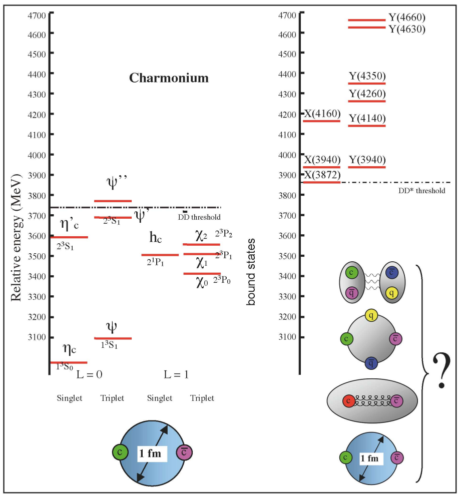

Figure 8: The established charmonium spectrum is plotted on the left side. The right side shows newly discovered X and Y states with unusual properties, whose nature is yet unknown.

Decay patterns that result in a charmonium state and a light meson instead of resulting into open-charm particles raise the question as to whether one or more of the charmonium states could actually be charmonium hybrids. As mentioned earlier, hybrids are quark-antiquark states in which the gluonic degrees of freedom have been excited and contribute to the overall quantum numbers. It seems very plausible that such a gluonic excitation could decay into a light meson, while the relatively heavy charm quarks stay in place and form a charmonium state. A good candidate for a charmonium hybrid is the Y(4260), a state found by BaBar (and subsequently confirmed by Cleo-c and Belle). The Y(4260) decays into $J/\psi\pi^+\pi^-$. The quantum numbers are known from the production mechanism and must be $J^{PC} = 1^{--}$. The 1^{--} states in this mass region are well-known from previous e^+e^- studies, and the Y(4260) seems supernumerary. Such overpopulation could also be a further indication for charmonium hybrids.

In order to classify all these new particles and to unveil their nature, their quantum numbers need to be determined and their decay branching fractions—into the different charmonia and possibly open charm—need to be established. For most of these particles, however, the available statistics are insufficient for this (see, e.g., Figure 12), and even less so for measuring the line shape of the resonances to get more insight.

It is therefore worthwhile to turn to the question of how progress could be made in the foreseeable future. In e^+e^- annihilations, direct charmonium formation is possible only for states with the quantum numbers $J^{PC} = 1^{--}$ of the photon, namely the J/ψ , ψ' and $\psi(3770)$ resonances. Precise measurements of the masses and widths of these states can be obtained easily by knowing the exact energies of the electron and positron beams. Charmonium states with different quantum numbers can be reached via the decay of these resonances or, at higher energies, by means of other production mechanisms, such as photon-photon fusion, initial state radiation and B-meson decays.

In comparison, antiproton-proton annihilations can access any quantum number and thus all charmonium states, thanks to the multiple gluons present in the process. This was demonstrated by the Fermilab E835 experiment in scanning experiments. The scanning technique became available thanks to the development of stochastic beam cooling. By scanning a resonance in antiproton-proton annihilations, the masses and widths of all charmonium states can be measured with excellent accuracy, since they can be determined through the very precise knowledge of the initial antiproton and proton beams and are therefore not limited by the resolution of the detector. As outlined above, such precision data are necessary to progress further in understanding the conventional charmonium system and the underlying forces. Compared to previous experiments and in order to ensure success, such an antiproton facility should have:

- up to ten times higher instantaneous luminosity ($L = 2\times10^{32}\ cm^{-2}s^{-1}$ in high-luminosity mode, compared to $2\times10^{31}\ cm^{-2}s^{-1}$ at Fermilab);
- better beam momentum resolution ($\Delta p/p = 10^{-5}$ in high-resolution mode, compared with 10^{-4} at Fermilab);
- a better detector (higher angular coverage, the presence of a magnetic field, the ability to detect the hadronic decay modes and to do particle identification).

$\overline{\text{P}}$ANDA and the FAIR antiproton facility were designed keeping these numbers in mind.

What are the cross sections we can expect in $\overline{\text{P}}$ANDA? Very little is known in particular for the production cross sections of charmonia, where the charmonium state is associated with an additional meson in the $\bar{p}p$ annihilation process. Therefore we tried to estimate charmonium production cross sections by using the decay $\psi \rightarrow m\,\bar{p}p$ (where m represents any meson measured), where the results are known and related to the annihilation process by crossing symmetry [13]. This method was refined in a second paper in a hadron pole model [14]. The predicted cross sections vary between 100 pb and 20 nb. Given an integrated luminosity of

$$\int \mathcal{L}\, dt = 8\, pb^{-1} / day$$

for the $\overline{\text{P}}$ANDA experiment, we can expect between 100 and several thousand charmonia per day in production. The formation cross section is then usually 2-3 orders of magnitude bigger for narrow states. This estimate should also apply to QCD exotics, since we know from previous LEAR experiments and high-energy antiproton collider experiments at Fermilab that exotics are produced with cross sections similar to those of normal mesons.

Nucleon Structure from electromagnetic processes in PANDA

The absorption and radiation of real or virtual photons by the electromagnetic charges inside a strongly interacting system reveals the structure of quark currents in the space like regime. Since momentum and space are conjugate variables, one finds in many cases that the Fourier transform of momentum dependent observables measured in lepton scattering yield distributions in space. With the relatively weak coupling strength of the electromagnetic interaction of $\alpha \sim 1/137$, resulting in a dominating one photon exchange, a clean factorisation of the probe and the system under investigation is possible after some small radiative corrections. This is true for processes with photons or charged leptons in the initial or in the final state. Typical examples being electron scattering or observation of lepton pairs from decays or Drell-Yan type processes.

Absorption and emission of real photons has been studied extensively in elastic and inelastic processes and has contributed significantly to our current understanding of hadrons, which is available as form factors and structure functions. While virtual photons in lepton scattering access only momentum transfer values of the probing photon which are negative (space-like) or equal to zero (real photons), the interval of positive momentum transfer (time-like) accessible in antiproton annihilation processes is basically unexplored. The available antiproton rates at CERN and Fermilab for example have limited the available relative accuracy for the separation of the electromagnetic form factors in the time like domain to about 50% while present accuracy in the space like domain ranges from 1% to 3%.

The upcoming FAIR facility with its high energy storage ring HESR and the high luminosity stored antiproton beam opens here a new window into electromagnetic hadron structure which is intimately connected to the space-like region due to the fact that the matrix element for the accessible observables is the same. The extension of form factor measurements to the so called time-like region separating the magnetic and electric components can be performed with an order of magnitude improvement compared to existing world data by using the antiproton beam at FAIR. Moreover, form factors are observables that can probe our understanding of the nucleon structure in the regime of nonperturbative QCD as well as at higher energies where regime of perturbative QCD sets in.

The matrix elements are analytic functions of the four-momentum transfer q^2. In the Breit frame, space-like FFs have concrete interpretations, since they are the Fourier transforms of the spatial charge and the magnetization distribution of the proton. Their slope at $q^2 = 0$ $(GeV/c)^2$ directly yields the charge and magnetization radius of the proton. In time-like region, their Fourier transform corresponds to the response of the nucleon in the time domain. That way two complementary aspects of nucleon structure can be studied and ask for a full and complete description of the electromagnetic form factors over the full kinematical range of q^2.

The experimental determination of the electromagnetic form factors of the nucleon has triggered large experimental programs at all major facilities since they have long served as one of the testing grounds for our understanding of nucleon structure ranging from the low q^2 regime of QCD up to the high energy perturbative regime. Basically, all models of nonperturbative QCD, which are using effective degrees of freedom, have been used to estimate the nucleon form factors. For example, different constituent quark models, skyrmion type of models, bag models and more recently a framework like chiral perturbation theory and lattice gauge theory have been applied. Due to its analyticity space-like and time-like form factors are intimately connected by the application of dispersion relations, which are an application of Cauchy's integral formula. Perturbative QCD makes predictions for the large q^2 behaviour of the connection between space-like region and time-like region. Space-like form factors are connected to recent developments using nonperturbative generalized parton distributions.

The interest in the time-like form factors of the nucleon has been renewed by recent measurements at JLAB using the polarization transfer and target asymmetry method, showing that the ratio of $R = \mu G_E/G_M$ deviates from unity and is in contrast to the results derived from Rosenbluth separation technique. While this discrepancy is most probably connected with radiative corrections, it has been shown, that the polarization transfer method is much less sensitive to those effects. It seems that G_E is approaching zero around a q^2 of 8 $(GeV/c)^2$ while G_M follows a dipole form factor indicating that the charge distribution has a hard surface in contrast to the magnetization distribution.

This surprising result has reopened the question on the determination of G_E and G_M in the time-like domain, which are complex functions. Almost all experiments so far have determined $|G_E|/|G_M|$ in the time-like domain with very low statistics. They have been forced to use the hypothesis of equality between G_E and G_M in time like domain, which is largely questioned now due to the JLAB results in space like domain. Only two experiments had enough statistics to determine the ratio of $|G_E|/|G_M|$ independently from any hypothesis and which have so far reached contradicting results with large experimental uncertainties. The determination of the electromagnetic form factors in the time-like domain at low to intermediate momentum transfer is therefore regarded to be an open question. Fig. 1 shows the world data for an effective electromagnetic form factor together with the expected accuracy from the $\overline{\text{P}}$ANDA experiment [15]. Data have been analyzed under the assumption that $G_E = G_M$ due to lack of statistics (left). The ratio $R = G_E/G_M$ has been extracted from experiments at LEAR and more recently by the BABAR experiment. Fig 1 (right) shows the result of simulations for the $\overline{\text{P}}$ANDA experiment together with the world data.

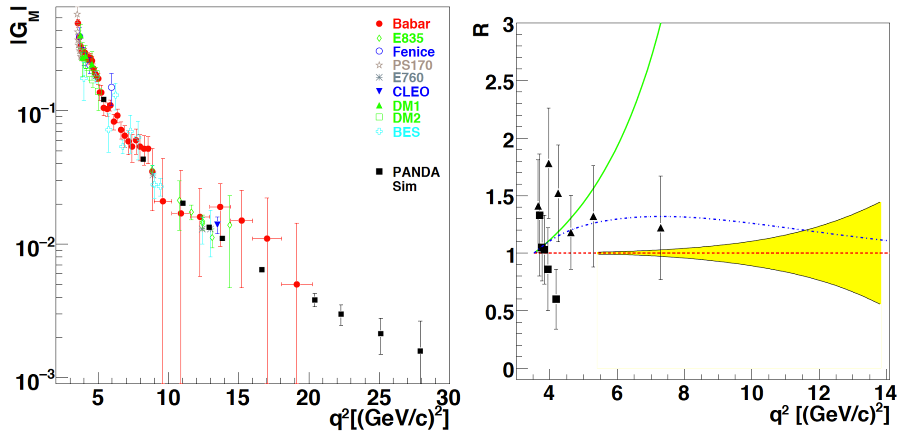

Figure 9: Left: q^2 dependence of the world data on the effective proton form factors in the time like regime, $|G_M|$, as extracted from the annihilation cross section assuming $|G_E| = |G_M|$: Simulations for the PANDA detector (full black squares) correspond to an integrated luminosity of 2 fb^{-1}, errors are statistical only. Right: Expected statistical precision on the determination of the ratio R, (yellow band) for R = 1, as a function of q^2, compared with the existing data from Refs. [16] (triangles) and [17] (squares). Curves are theoretical predictions (see text).

The $\overline{\text{P}}$ANDA experiment at GSI/FAIR offers a unique opportunity to determine the moduli of the complex form factors in the time-like domain, by measuring the angular distribution of the process pbar-p -> e^+e^- in a q^2 range from about 5 $(GeV/c)^2$ up to 22 $(GeV/c)^2$. The $\overline{\text{P}}$ANDA experiment is planned to have unprecedented luminosity and rich particle identification capabilities, which are necessary in order to discriminate against the very large background of pbar p -> $\pi^+ \pi^-$ which is about 10^6 times higher in cross section. In the framework of the $\overline{\text{P}}$ANDA physics performance report, we just have shown, that a clean measurement of the time like electromagnetic form factors is possible with unprecedented accuracy.

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 Rosenbluth and polarization transfer method in the space-like regime, can be detected in the same measurement since it introduces a forward-backward asymmetry in the angular distribution which otherwise is symmetric in one-photon exchange.

We have recently shown in extended simulations, that the e^+e^--pair from the virtual, time-like photon can be very well separated from the hadronic background using the particle identification capabilities of the $\overline{\text{P}}$ANDA detector. This can be applied to a wide variety of time-like electromagnetic structure observables with a virtual photon in the final state, decaying to a lepton pair. It opens a window to a rich variety of time-like electromagnetic processes in antiproton annihilation, which complements the lepton scattering observables. Apart from form factors a wide field of electromagnetic observables that have successfully been studied in space like momentum transfer range can be studied. The study of these processes for measurements at the GSI/FAIR facility with high energy antiproton annihilation reactions in $\overline{\text{P}}$ANDA is one of the goals of this research area.

Polarization degrees of freedom, either on the target side or with a transversely polarized pbar-beam would allow to access the imaginary part of the complex form factors. For example, with a transversely polarized target only one could already determine the phase difference of the two form factors. Other parts of the $\overline{\text{P}}$ANDA scientific program would benefit largely from this. In the investigation of baryon-antibaryon production the helicity amplitudes to be measured can be reduced to the half. Part of the hadron transverse helicity structure functions could be measured already at the HESR with unpolarized antiproton beam and a transversely polarized hydrogen target. A feasibility study with the production of a prototype superconducting thin counter solenoid is one of the work packages of this research area.

A large experimental activity is coming from B-factory e^+e^- colliders where the energy is fixed to a bbar-b-resonance. The process of initial state radiation (ISR), where the variable energy γ from an initial state electron is used in order to "scan" the q^2 of the virtual photon probing the form factors, is used at those B-factories. The BABAR experiment has recently published results for the ratio $R=|G_E|/|G_M|$, but is penalized by the fact, that the luminosity for the ISR-process is suppressed by factors of 10^5 to 10^6 as compared to the direct e^+e^--luminosity and cannot so far compete with the proposed measurement at $\overline{\text{P}}$ANDA.

An analog process to ISR would be the emission of a π by one of the hadrons (pbar or p) in the initial state which would lower the q^2 of the virtual photon at the annihilation vertex. That way, one could reach the otherwise inaccessible range below the threshold and measure the form factors down to lower q^2 below threshold. Vector meson dominance and hypothetical baryonium states could be accessed that way. Another possible extension of the program could be a possibility to access the axial form factor in time-like domain, by using a neutron (deuteron) target. In analogy to electro-pion production, the chiral ward-identities could be used here to extract the axial form factor in the time-like domain, for which no data exists at all. We have performed first estimates of cross sections for both, subthreshold electromagnetic form factors and axial form factor measurement, but more theoretical work and simulations is necessary.

There are a number of nucleon structure observables, which have been developed in recent years only and which are accessible in antiproton annihilation reactions. The transition distribution amplitudes (TDA) [18] are new universal nonperturbative objects describing the transition between two different particles. They are an extension of the concept of general parton distributions (GPD) [19], which contain information about nucleon structure. The proton-to-meson TDA are defined from the Fourier transform of a matrix element of a three-quark light-cone local operator [20]. The TDA can be used to calculate the cross section of hard exclusive processes. Leading-twist amplitudes can be factorized in a perturbatively calculable process at quark level convoluted with the nonperturbative object, which are the TDA. Due to this non-perturbative character, the TDA can not yet be calculated ab initio. Therefore models had to be constructed. There exist models that describe baryonic TDA in terms of spectral functions known as quadruple distributions, using chiral symmetry and the extension of soft pion theorems for pN TDA as a boundary condition. One may also construct a simple resonance exchange model for pN TDA considering N and D(1232) exchange contributions. A reasonable two-component model [21] contains both a factorized ansatz for quadruple distributions with input from the soft pion theorem and a contribution from the nucleon exchange in the u-channel of the reaction. The experimental way of testing the validity of the TDA approach is to measure the cross section for hard exclusive processes and compare the experimental results with the values given by the calculations done using the TDA model.

The validity of this approach and its s-dependence can be investigated in $\overline{\text{P}}$ANDA by measuring the cross section of pbar p -> $e^+ e^- pi^0$ and comparing the results with the theory values. Dedicated simulations have been done based on the $\overline{\text{P}}$ANDA simulation framework and the $\overline{\text{P}}$ANDA detector to study the feasibility of measuring this cross section. The main background channel was taken into account. For the simulation of the signal, the event generator was based on the cross section calculation available using the TDA approach. This calculation is done for zero transverse momentum of the pion. Very good background suppression has been reached based on the particle identification capabilities of the $\overline{\text{P}}$ANDA detector and kinematical constraints. The background to signal cross section ratio was chosen to be 10^6 following the average value taken for the study of the electromagnetic form factors. The results showed that the signal cross section can be measured with a relative error of about 8% in the worst case, sufficient precision for a first comparison to the predictions given in the TDA approach [22].

$\overline{\text{P}}$ANDA is an ideal tool to study nucleon structure observables with high precision. The key point is the clean separation of a dilepton signal from hadronic background with very high efficiency. One can expect that this clean identification of dileptons can be used to measure a whole series of other electromagnetic processes like for example Drell-Yan in order to get access to the transverse spin structure functions.

Physics of doubly strange systems

Precision spectroscopy of ΛΛ Hypernuclei

The recent precision observation of a two-solar mass neutron star [23] significantly constrains the hadronic equation of state at high densities. The J1614-2230 pulsar mass of (1.97±0.04) M_{λ} excludes several soft equations of states, many of which contain exotic constituents like quarks or hyperons at high densities (see e.g. [24] and references therein). However, our limited knowledge of the hyperon-nucleon, the hyperon-hyperon and the three-body YNN or YYN interactions and possible charge symmetry breaking in these interactions [25] still does not exclude the appearance of hyperons in the inner core of neutron stars [26-30].

The presence of hyperons may not only show up in the neutron star mass but can also play a crucial role in the dynamics of the core-collapse supernovae or in neutron star mergers [31]. Non-mesonic weak decays of hyperons may control the bulk viscosity of neutron star matter [32], thus regulating the e.g. r-modes instability [33] of pulsars and may leave fingerprints in the emission of gravitational waves [34].

Nuclei containing one or more strange baryons are unique in their potential of improving our knowledge on the strange particle-nucleus interaction in a many-body environment. Combined with modern ab initio nuclear structure calculations (see e.g. [35] and references therein) or in the not too far future even Lattice QCD calculations [36], this knowledge is essential to derive eventually a more general and self-consistent description of the multi-baryon-baryon interaction. It must be remarked that the ΛΛ hypernuclei are the only systems, which allow studying the ΛΛ interaction since e.g. the final state interaction of two lambda hyperons produced in energetic heavy ion reactions suffers from the ambiguity of the spatial dimension of the emission zone. Since a simultaneous implantation of two Λ hyperons is not possible, a ΛΛ hypernucleus, also called Double Hypernucleus (DH), is created by the reaction $\Xi^- + p \rightarrow \Lambda + \Lambda$ inside a nucleus. Other creation mechanisms, involving two-step processes, are possible but their cross sections are small [37]. By measuring the binding energy of the DH the ΛΛ interaction energy can be obtained. Measurements of several hypernuclei are needed in order to obtain a satisfying knowledge about the core of the ΛΛ interaction. Nowadays, the set of available data is scarce: since the discovery in the 60's, the most recent contribution came from the KEK-E373 experiment [38-40]. Nevertheless, the total data collection includes less than ten individual double hypernuclei.

Particularly in heavier nuclei the Pauli principle suppresses the pionic decay of the Λ hyperon inside the nucleus. In this situation ΛN → NN and ΛΛ→ Λn are allowed, opening a unique window for the four-baryon, strangeness non-conserving weak interaction. In double hypernuclei the non-mesonic decay mode can shed light on the ΛΛ weak interaction e.g. the ΛΛK vertex [41-43]. The hyperons and nucleons are emitted with quite high momenta and should be easily detectable [44].

Hyperonic atoms

The Ξ^- exotic atoms belong to the class of the hadronic atoms. They are formed by capture of the hyperon nearly at rest into an atomic orbit, in general in a highly excited level. After capture, they cascade emitting Auger electrons or X-rays. When the lowest levels are reached, the hadronic wave function overlaps the low density region of the nuclear matter. The lowest levels are shifted and broadened by this strong interaction, which adds to the Coulomb potential. The detection of X-rays emitted during the transitions permits measuring these shift and width allowing to determine the nuclear potential in the peripheral region of the nucleus, where the nuclear density varies appreciably [45]. Data from different atoms are needed to have a deep insight into the nuclear potential.

Antihyperons in nuclei

Quantitative information on the antihyperon potentials relative to that of the corresponding hyperon may be obtained via exclusive antihyperon-hyperon pair production close to threshold in antiproton-nucleus interactions [46-48]. Once the hyperon as well as the coincident antihyperon leave the nucleus and are detected, their asymptotic momentum distributions will reflect the depth of the respective potentials. However, since in the antiproton-proton center-of-mass the distribution of the produced baryon-antibaryon pair will usually not be isotropic, the analysis can rely only on the transverse momenta of the outgoing baryons [46].

At the expected ΛΛbar detection rates at $\overline{\mathrm{P}}$ANDA , measurement periods of a few hours will be sufficient to reach a good statistical uncertainty of the potential difference [46]. Given the relative large cross section for pbarp → ΞΞ at 2.9 GeV/c of ~1μb the sensitivity of the transverse asymmetry is sufficiently large to explore the ΞΞ pair production at the future FAIR facility with a few days of data taking. The angular dependence of the momenta of the produced hyperons and antihyperons may allow studying directly the momentum dependence of their respective potential(s). Since most of the hyperons are created in the nuclear periphery at subsaturation density, a neutron skin of neutron rich target nuclei may help to explore different effective potentials.

These measurements need a complex nuclear target within the HESR. However they require only a limited luminosity and – compared to e.g. charmed particle reconstruction – the demands on vertex reconstruction are moderate. Therefore, such measurements may be ideally suited in an early stage of the $\overline{\mathrm{P}}$ANDA commissioning.

Hyperon-proton and antihyperon-proton scattering

The $\overline{\mathrm{P}}$ANDA experiment offers a high rate for pair production of charged hyperons like pbarp → $\Sigma^+\Sigma^-$ or pbarp → $\Xi^+\Xi^-$. Close to threshold, where no additional particles are produced, the momenta of the hyperon and the antihyperon as well as their polarization are correlated. Detecting one of the two particles in PANDA and determining it's momentum, one could search for antihyperon (or hyperon) scattering events of the associated particle of known momentum in a secondary $(CH_2)_n$ target. Since hyperon decays are self-analyzing, also polarization dependent scattering may be within reach.

The Quest for the H-particle

Another burning topic intimately related to the physics of double strange system is the so called H-particle, i.e. the spin and flavor singlet six quark state *uuddss*. Proposed more than 3 decades ago [49] and expected to be bound by many theoretical models [50]. This boson could even make its appearance in the center of a neutron star. The story of the H-dibaryon moved into the spotlight again, when recent high statistics lattice QCD studies of various hyperon-nucleon and hyperon-hyperon channels revealed exclusively in the ΛΛ channel a hint for an attractive interaction [51]. The H-dibaryon was finally revived by lattice QCD calculations of the NPLQCD [52] and the HAL QCD [53] collaborations, both providing evidence for a bound state, though at pion masses larger than the physical one. A chiral extrapolation of calculations to the physical mass suggested a H-dibaryon unbound by (13±14) MeV [54] while the NPLQCD collaboration could not (yet) discriminate between a bound H-dibaryon or a near-threshold scattering state [55]. The coupling of the ΛΛ, ΞN, and ΣΣ channels may introduce additional uncertainties to the extrapolation procedure [56].

A bound H-particle escaped experimental verification so far. A possible enhancement of the ΛΛ production near threshold [57] could suggest a weakly unbound H-dibaryon, but the statistics of this experiment is unfortunately still rather limited. At present the only solid limit on the binding energy of the H-particle comes from double ΛΛ hypernuclei. Their binding energies mark upper limits for that of the H-dibaryon. Since the mass of the H-particle might drop inside a nucleus [58-61] and due to the small mass difference between Λ−Λ and Ξ-N, it might be possible to observe traces of an H-dibaryon even if it is unbound in free space by a precise study of the energy levels in double hypernuclei.

Production of S=-2 systems at FAIR

The $\overline{\text{P}}$ANDA Collaboration will exploit HESR antiprotons to produce Ξ^- by means of the following reactions:

$$\bar{p} + p \rightarrow \Xi^- + \Xi^+ \text{ and } \bar{p} + n \rightarrow \Xi^- + \Xi^0$$

the momentum threshold of these processes is $p_{\bar{p}} \approx 2.6\,\text{GeV}/c$. This approach is alternative to the use of a K^- beam employed in the past and foreseen for the new J-PARC experiments [62].

A dedicated setup will be used for these measurements consisting of a primary target inside the storage ring, and an assembly of layered Si-μstrips and secondary targets, located all around the beam pipe.

The Ξ^-s are produced in the primary target, where they undergo a strong deceleration by scattering inside the primary target nucleus. After emission they are stopped in the secondary targets. The rate of stopped to produced hyperons depends on the geometry of the secondary target and a preliminary estimate for a homogeneous carbon target give results of the order of 10^{-3} [49]. After stopping, Ξ^- exotic atoms and ΛΛ hypernuclei can be formed. Several particles will be present in the final state of the this processes:

i) X-rays from the atomic cascade,
ii) γ-rays from the nuclear capture,
iii) γ-rays from the deexcitation of the ΛΛ hypernucleus
iv) pions and nucleons from the weak decay of double-hypernuclei.

Charged particles, produced in the Ξ^- interaction, will be detected by the Si-μstrips interleaved with the secondary target layers; anti-hyperon (Ξ^+, Ξ^0) annihilation products will be measured by the $\overline{\text{P}}$ANDA general tracking apparatus and will be used as a tag of the Ξ^- production. The X- and γ-ray spectroscopy will be performed using a set of HPGe detectors.

It must be noticed, that the present design of the secondary target foresees the possibility to have simultaneously different target's materials; in this way the goal of studying double strange systems in different nuclei is fulfilled using the same apparatus with the same efficiency and acceptance.

The Ξ^- hyperons are produced inside the internal target by the above-mentioned reactions. For a fixed geometry of the secondary target, the DSS production rate depends also on the antiproton beam intensity, and on the dimensions and materials of the internal target. In order to insert a solid target inside a storage ring, a number of constraints have to be satisfied, due to the beam lifetime and to the overwhelming background, which impinges on the detectors. In order to avoid that the background from the antiproton annihilation blinds the detectors, the technique of slowly steering the beam onto the target will be applied [63].

It is important to underline that the availability of the RESR could allow to recover the time of collection and preparation of the antiproton bunch inside the HESR, with a gain of at least a factor 2 in the antiproton's intensity.

Another facility in the world, J-PARC [65] (Japan Proton Accelerator Research Complex), plans to investigate the

S=-2 systems, using high intensity kaon beams. The first data acquisitions are foreseen after 2014, on the K1.8 beam line and some 10^4 stopped Ξ^- are expected [66]. The same goal can be reached in $\overline{\text{P}}$ANDA in few days of data taking, with the advantage of performing a systematic study of different nuclei. It should be stressed, however, that the activities at FAIR and JPARC are also widely complementary:

- With the emulsion-counter hybrid technique at JPARC only ground state properties of double hypernuclei can be studied. At $\overline{\text{P}}$ANDA, we will investigate the excited level structure of these nuclei with high precision. Furthermore, the detection of the pions from the weak decay will also provide information on the ground state masses at $\overline{\text{P}}$ANDA.
- The spectroscopy of Ξ-atoms complements the search for Ξ-hypernuclei in the missing mass studies at JPARC using the (K^-,K^+) reaction.
- At JPARC the scattering experiment with Σ^{-+} are planned. At $\overline{\text{P}}$ANDA Σ and Ξ hyperons as well as their antihyperons can be scattered on protons with defined momentum.
- Pair production with antiprotons at $\overline{\text{P}}$ANDA will be a unique method to obtain information on the potential of antihyperons, e.g. Ξ, in nuclei.

Operation of PANDA and HESR in the Modularized Start Version

At FAIR (Modularized Start Version 0-3) the antiprotons are collected in the CR at a rate of 10^7 $\bar{p}$/s up to a stack of 10^8. Then, they are cooled for 10 s and transferred to HESR. This operation is repeated until 10^{10} antiprotons are accumulated in the ring requiring 1000 s. This bunch is pre-cooled, accelerated/decelerated, steered and squeezed inside the HESR before the target is activated. Then the data acquisition starts and the bunch is consumed in a cycle of about 1000 s. Afterwards the collection and injection from CR is repeated. The achievable luminosity in this initial setup (without the RESR) will be 2-4 times 10^{31} cm^2/s.

Technical Progress of PANDA since 2009

Already in 2008 the first TDR of $\overline{\text{P}}$ANDA was completed for the electromagnetic calorimeter (EMC) followed by the TDR on the magnet systems in 2009. In the past three years since then the focus was on the technical design of the central detector systems to bring them to the completion of TDRs. The major paradigm for the $\overline{\text{P}}$ANDA systems is to operate at very high rates and perform event selection online in software without a hardware trigger. The reason for this lies in the broad physics program and the complex signatures of physics channels.

Large efforts in design work and prototyping lead to the completion of the TDR for the micro vertex detector (MVD) at the end of 2011. The design consists in state-of-the-art self-triggering hybrid pixel sensors with low material budget surrounded with doublesided silicon strip detectors. Readout ASICs for both are developed within the collaboration.

For the central tracker responsible for momentum determination in the solenoidal field two options were considered, a low mass straw tube tracker (STT) and a time projection chamber with GEM detectors as readout stage (GEM TPC). For both systems prototypes were built and gave promising results. Due to the complexity of the GEM TPC the collaboration in fall 2011 took the decision to employ the STT as baseline central tracker. This was shortly followed by the completion of the STT TDR in spring 2012. Some of the development work for the GEM TPC is however reused for the planar GEM tracker in the forward endcap of the target spectrometer. The same concept as for the STT but in planar arrangement is also used for the tracking stations in the forward spectrometer.

After conceptual work with the completion of the magnet TDR the basic concept of a range system for muon detection based on the usage of a highly segmented return yoke of the solenoid was fixed. In the following years the technical details of the muon system were worked out and led to the submission of the Muon System TDR in fall 2012. The main detection element are rather robust drift tubes with wire and cathode strip readout.

In parallel the development of the cluster jet target led to a break through reaching record densities for this type of target close to the values needed for the design luminosity of $\overline{\text{P}}$ANDA. This was documented in the Target System TDR. Concerning the pellet target needed for better IP definition and even higher rates more development work is needed and will be put in an addendum to the Target TDR.

For the very challenging DIRC detector design work continued with prototypes and testbeams to assess possible options comparing bar shaped and plate-like radiators. Simulation of various focusing concepts are being performed. For the endcap disc DIRC a more robust modular concept was worked out. The main issue remaining open is the choice of photon detectors which have to be insensitive to magnetic fields and have a long stable lifetime.

On the side of the magnet, detailed mechanical design and integration work was performed. For the EMC the mechanical engineering of the endcap was completed, a cooling concept with prototypes was worked out and realistic prototypes for both barrel and endcap EMC were constructed and tested at various testbeam campaigns. A complete readout chain with self triggering frontend electronics with feature extraction was set up and tested. Preparations for the construction of the detector system are ongoing.

Finally, for the data acquisition and trigger system much conceptual work was done. On the hardware benchmark platform, an FPGA based compute node, algorithms for online track reconstruction were developed. Simulation tools to study event overlap and the fully time based streaming of data were developed and are about to be employed in large scale simulations.

In summary, $\overline{\mathrm{P}}$ANDA is well under way with the TDRs of its subsystems and will commence construction once the memorandum of understanding has been signed. The procurement of essential components has partly started already. Nevertheless, some financial items remain to be resolved within the Resource Review Board meetings. To shorten the time to deploy $\overline{\mathrm{P}}$ANDA at FAIR systems will be pre-assembled and tested at various sites, mostly at FZ Jülich. This will ensure to have the experiment ready in a timely manner to take data once beam is available at FAIR.

REFERENCES

[1] S.-K. Choi, S.L. Olsen, K. Trabelsi et al. (Belle collaboration), PRD 84, 052004 (2011).
[2] J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012).
[3] C. Hanhart, Y. S. Kalashnikova, A. E. Kudryavtsev, and A. V. Nefediev, Phys. Rev. D76 (2007) 034007.
[4] E. Braaten and M. Lu, Phys. Rev. D77 (2008) 014029.
[5] T. Aaltonen et al.; [CDF collaboration], arXiv: 0906.5218v2.
[6] V.M. Abazov et al.; [D0 Collaboration], Phys. Rev. Lett. 93 (2004) i62002.
[7] R. AAji et al.; [LHCb Collaboration], EPJC 72 (2012) 1972.
[8] M. Andreotti et al.; Nuclear Physics B 717 (2005) 34–47.
[9] S.-K. Choi et al.; [Belle Collaboration], Phys. Rev. Lett. 100 (2008) 142001. S.-K. Choi et al.; [Belle Collaboration], arXiv: hep-ex/0708.1790v2
[10] R. Mizuk *et al.*; [Belle Collaboration], Phys. Rev. D78 (2008) 072004.
[11] A. Bondar et al.; [Belle Collaboration], Phys. Rev. Lett. (2012) 122001.
[12] S. Godfrey and S. L. Olsen, Ann. Rev. Nucl. Part. Sci. 58 (2008) 51.
[13] A. Lundborg, T. Barnes, and U. Wiedner, Phys. Rev. D73 (2006) 096003.
[14] T.Barnes and X.Li, hep-ph/0611340, Phys. Rev. D75 (2007) 054018.
[15] M. Sudol (Orsay, IPN), M.C. Mora Espi (Mainz U., Inst. Kernphys.), et al. *"Feasibility studies of the time-like proton electromagnetic form factor measurements with PANDA at FAIR."*, Eur.Phys.J. A44 (2010) 373-384.
[16] C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson, F.E.Maas *"Testing axial and electro-magnetic nucleon form factors in time-like regions in the processes anti-p + n ---> pi- + l- + l+ and anti-p + p ---> pi0 + l- + l+, l=e, mu."*, Phys.Rev. C75 (2007) 045205
[17] E.A. Kuraev, C. Adamuscin, E. Tomasi-Gustafsson, F. Maas "Study of resonant processes for multi-pion production in anti-p + p ---> l+ + l- + n(pi) pi annihilation." Phys.Lett. B649 (2007) 400-404.
[18] B. Pire and L. Szymanowski, *"Hadron annihilation into two photons and backward VCS in the scaling regime of QCD,"* Phys.Rev., vol. D71, p. 111501, 2005.
[19] L. Frankfurt et al., *"Hard exclusive pseudoscalar meson electroproduction and spin structure of a nucleon,"* Phys.Rev., vol. D60, p. 014010, 1999.
[20] B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, "pN transition distribution amplitudes: Their symmetries and constraints from chiral dynamics," Phys. Rev., vol. D84, p. 074014, 2011.
[21] B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, "*Cross section and single transverse target spin asymmetry for backward pion electroproduction*," arXiv:1201.0123 [hep-ph].

[22] M.-C. Mora Espí, *"Feasibility studies for accessing nucleon structure observables with the PANDA experiment at the future FAIR facility",* phd-Thesis.
[23] P.B. Demorest et al, Nature 467 (2010) 1081.
[24] W. Weise, Lectures at the Erice School 2011 "From Quarks and Gluons to Hadrons and Nuclei", arXiv:1201.0950 [nucl-th].
[25] Kota Masuda, Tetsuo Hatsuda, Tatsuyuki Takatsuka, arXiv:1205.3621 [nucl-th].
[26] Simon Weissenborn, Debarati Chatterjee, Juergen Schaffner-Bielich, Nuclear Physics A 881 (2012) 62-77, arXiv:1111.6049 [astro-ph.HE].
[27] R. Lastowiecki, D. Blaschke, H. Grigorian, S. Typel, Acta Phys. Pol. B Proc. Suppl. 5, 535 - 540 (2012), arXiv:1112.6430 [nucl-th].
[28] D.L. Whittenbury, J.D. Carroll, A.W. Thomas, K. Tsushima, J.R. Stone, arXiv:1204.2614 [nucl-th].
[29] Wei-Zhou Jiang, Bao-An Li, Lie-Wen Chen, The Astrophysical Journal, 756:56, 2012; arXiv:1207.1686 [astro-ph.SR].
[30] Tetsuya Katayama, Tsuyoshi Miyatsu, Koichi Saito, arXiv:1207.1554 [astro-ph.SR].
[31] Kenta Kiuchi, Yuichiro Sekiguchi, Koutarou Kyutoku, Masaru Shibata, Class. Quantum Grav. 29 (2012) 124003, arXiv:1206.0509 [astro-ph.HE].
[32] Lee Lindblom and Benjamin J. Owen, Phys. Rev. D, 65, 063006 (2002).
[33] N. Andersson, K.D. Kokkotas, Int.J.Mod.Phys. D10 (2001) 381-442, arXiv:gr-qc/0010102.
[34] Mark G. Alford, Simin Mahmoodifar and Kai Schwenzer, arXiv:1103.3521 [astro-ph.HE].
[35] H.-W. Hammer, A. Nogga, A. Schwenk, arXiv:1210.4273 [nucl-th].
[36] S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H. W. Lin, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Walker-Loud, arXiv:1206.5219 [hep-lat].
[37] M. May, Nucl. Phys. A 691 (2001) 226c.
[38] S. Aoki et al., Nucl. Phys. A828 (2009) 191-232, and references quoted therein.
[39] J.K. Ahn et al., Phys. Rev. Lett. 87 (2001) 132504.
[40] K. Nakazawa for KEK-E373 and J-PARC E07 collaborators, Nucl. Phys. A835 (2010) 207.
[41] K. Itonaga, T. Ueda, and T. Motoba, Nucl. Phys. A691 (2001) 197c.
[42] A. Parreno, A. Ramos and C. Bennhold, Phys. Rev. C65 (2001) 015205.
[43] K. Sasaki, T. Inoue, and M. Oka, Nucl. Phys. A726 (2003) 349.
[44] F. Iazzi et al., PoS(STORI11) 020.
[45] C. J. Batty, E. Friedman, and A. Gal, Phys. Rev. C 59, 295 (1999).
[46] Josef Pochodzalla, Physics Letters B 669 (2008) 306–310
[47] Josef Pochodzalla , Hyperfine Interact 194:255–261 (2009), DOI 10.1007/s10751-009-0083-9
[48] J. Pochodzalla and S. Pomp, World Scientific, ISBN-13 978-4277-60-0, p.358 (2010).
[49] R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977) [Erratum-ibid. 38, 617 (1977)].
[50] T. Sakai, K. Shimizu, and K. Yazaki, Prog. Theor. Phys. Suppl. 137, 121 (2000) and references therein, arXiv:nucl-th/9912063.
[51] Silas R. Beane et al., Phys. Rev. D 81, 054505 (2010).
[52] S. R. Beane *et al.* [NPLQCD Collaboration], Phys. Rev. Lett. 106, 162001 (2011).
[53] T. Inoue *et al.* [HAL QCD Collaboration], Phys. Rev. Lett. 106, 162002 (2011).
[54] P. E. Shanahan, A.W. Thomas, and R. D. Young, Phys. Rev. Lett 107. 092004 (2011)
[55] S. R. Beane *et al.*, Mod. Phys. Lett. A 26, 2587 (2011); arXiv:1103.2821 [hep-lat]
[56] J. Haidenbauer, Ulf-G. Meißner, arXiv:1109.3590 [hep-ph], arXiv:1111.4069 [nucl-th].
[57] C. J. Yoon et al., Phys. Rev. C 75, 022201 (2007).
[58] St. Mrowczynsk, Phys. Lett. 152B, 299 (1985)
[59] Ryozo Tamagaki, Prog. Theor. Phys. 85, 321 (1991)
[60] T. Sakai, K. Yazaki, K. Shimizu Nucl. Phys. A594, 247 (1995)
[61] T. Yamada, Nucl. Phys. A691 (2001) 250c.
[62] Mark G. Alford, Simin Mahmoodifar and Kai Schwenzer, arXiv:1103.3521 [astro-ph.HE].
[63] D. Prahsun, PANDA meeting Dec. 2010.
[64] S. Bleser et al., XI International Conference on Hypernuclear and Strange Particle Physics, Barcelona, October 1 - 5, 2012.
[65] http://j-parc.jp/en/jparc.html.
[66] T. Takahashi, XI International Conference on Hypernuclear and Strange Particle Physics, Barcelona, October 1 - 5, 2012.