4.1. WG 1 Hadron Physics

4.1.1. Introduction

Among the most challenging and fascinating goals of modern physics are the endeavours to understand how the spectrum and structure of hadrons emerge from the forces among their fundamental constituents and to find out whether there are new forms of matter. This requires a fully quantitative understanding of the strong interaction, especially in the non-perturbative (i.e. low-energy) regime, which is the subject of hadron physics. The modern theory of strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non-Abelian gauge group SU(3). It is one of the pillars of the Standard Model (SM) of particle physics. While QCD is well tested at high energies, where the strong coupling constant α_s is sufficiently small for perturbation theory to apply, it becomes a strongly coupled theory in the low energy regime where many aspects await a better understanding. Significant progress has been made over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated intense theoretical activity and a refinement of the theoretical tools. In spite of these developments, many fundamental questions concerning the structure and spectroscopy of hadrons remain unanswered. Furthermore, key issues such as the confinement of quarks or the existence of glueballs and hybrids are long-standing puzzles and present an intellectual challenge in our attempt to understand the nature of the strong interaction and of hadronic matter.

The theoretical description of the strong interaction has given rise to some of the most influential ideas in quantum field theory. QCD has been instrumental for establishing the Standard Model and provides accurate descriptions of many experimental observations. The importance of QCD can be highlighted by the fundamental role it plays in many apparently unrelated fields. First and foremost it gives rise to the mass of visible matter in the universe. QCD contains eight out of 19 parameters of the SM (the strong coupling, the six quark masses and the strong CP-violating parameter) and plays a central role in the determination of another four SM parameters, i.e. the parameters of the quark mixing matrix. QCD is essential for investigations at the energy frontier (since it describes the SM background to non-SM physics) as well as at the intensity frontier (since in the low-energy regime QCD is often the limiting factor in indirect searches for physics beyond the SM). Finally the QCD phase diagram plays a crucial role in cosmology and astrophysics.

Experiments that test QCD use various probes to investigate different aspects of hadron spectroscopy, hadron structure and hadron dynamics. These experiments explore both the non-perturbative and perturbative regimes. High-momentum processes, such as Deep Inelastic Scattering probe the perturbative regime, in which the observables are directly related to the quark and gluon degrees of freedom of the QCD Lagrangian. In these processes the soft (non-perturbative) part of the amplitude gives access to key aspects of hadron structure, such as the spatial distribution of quarks in the proton, or the connection between the quark spin and orbital angular momentum and the spin of the proton.

On the other hand, low-momentum processes explore QCD in the non-perturbative regime. These processes have largely resisted a treatment in terms of the quarks and gluons of the QCD lagrangian. Theoretical calculations can be carried out by means of computer simulations on a discretised space-time lattice (Lattice QCD) or using effective field theories based on hadronic degrees of freedom that respect the symmetries of QCD. Other possible theoretical approaches to non-perturbative QCD are functional methods as well as phenomenological models. A significant amount of additional experimental data is required to identify the relevant degrees of freedom. This is one of the main goals of hadron spectroscopy.

Understanding the physics of hadrons requires a large variety of complementary experiments and theoretical tools. In experiments, electromagnetic and hadronic probes can be used to study various aspects of hadron structure, spectroscopy and dynamics at different energy scales. These different experimental techniques provide complementary information, and it is of vital importance that all be pursued in order to obtain a complete picture and reach a full understanding of the field. In this respect a central role will be played by the antiproton programme at the FAIR facility under construction in Germany. FAIR is expected to produce groundbreaking results in all fields of nuclear physics and will, in particular, provide a unique research environment for all aspects of hadron physics coming from experiments with antiprotons. Tremendous theoretical progress has been achieved by lattice QCD and effective field theories, leading to *ab-initio* calculations of many hadronic properties. Of fundamental importance to the progress in hadron physics is the interplay between theory and experiment, which must continue in the future.

This chapter is organised as follows: after an introduction to the basic properties of QCD and the most important theoretical and experimental techniques, the three areas of hadron physics (spectroscopy, structure, dynamics) will be reviewed, highlighting, for each field, the state of the art and future perspective. The particular role of lattice QCD will be described before we formulate our recommendations for the future development of the field of hadron physics.

4.1.2. Theoretical Framework

The challenge for theoretical hadron physics is to obtain a quantitative description of the properties and the dynamics of hadrons in the low-energy regime. QCD is a non-Abelian gauge theory that describes the strongly interacting sector of the Standard Model in terms of the fundamental constituents of hadronic and nuclear matter, i.e. the quarks and gluons. Quarks are massive spin-$1/2$ matter fields. They carry fractional electric charges and come in six “flavours”, while the interactions are mediated by eight massless gauge bosons, the gluons. Quarks and gluons are also charged under the gauge group $\mathrm{SU(3)}_{\mathrm{colour}}$. The strength of the interaction is determined by the dimensionless parameter, α_s, called the strong coupling constant. As in any quantum field theory, this coupling depends on an energy scale. At the quantum level, QCD generates a fundamental dimensionful scale Λ_{QCD}, which controls the variation of α_s with energy. Unlike electromagnetism one finds that α_s decreases with increasing energy. This property is called asymptotic freedom, which has been spectacularly confirmed, for example, by the kinematic variation of cross-section measurements in high-precision deep-inelastic electron-proton scattering. Asymptotic freedom ensures that processes involving the strong interaction at high energies can be computed reliably in perturbation theory in α_s. However, by the same token one finds that α_s becomes large at low energies, i.e. in the region relevant for hadron physics. Since the dynamics of quarks and gluons is strongly coupled in this regime one has to resort to non-perturbative techniques, such as Lattice QCD, effective field theories (EFTs) and functional methods based on Dyson-Schwinger and functional renormalisation group (FRG) equations. More details on these formalisms can be found in the “boxes”.

Another unique feature of QCD is confinement, i.e. the fact that quarks and gluons are not observed as free particles but only occur as bound constituents within hadrons. The quarks and gluons, which form the fundamental degrees of freedom of QCD reveal themselves only at large energies but remain hidden inside hadrons in the low-energy regime. In mathematical terms this means that the only strongly interacting particles observed in nature are “colourless” and transform as singlets under the gauge group $\mathrm{SU(3)}_{\mathrm{colour}}$. While there is overwhelming experimental evidence for confinement, the theoretical understanding of this phenomenon continues to be an active field of research. In pure gluodynamics, i.e. in the absence of quarks, lattice QCD calculations of the static quark-antiquark potential display a linearly rising behaviour when the separation between quark and antiquark is increased, which implies that an infinite amount of energy is required to isolate free colour charges. This effect cannot be explained in perturbation theory. In the presence of dynamical quarks the linear rise of the potential is eventually stopped, due to hadronisation, the detailed nature of which is studied in connection with heavy ion collisions and is also of great importance for the design of event generators in collider physics.

The description of the strong interaction in terms of the non-Abelian gauge theory of QCD has important consequences for the observed hadron spectrum. In particular, QCD permits the existence of states that cannot be accommodated in the simple quark model, such as glueballs, which are composed of gluonic degrees of freedom only. While the formal mathematical proof for the existence of a state with non-vanishing mass in pure gluodynamics is one of the still unsolved Millenium Problems, the spectrum of glueballs has been determined in lattice QCD. Reliable predictions for glueball masses are, however, difficult to obtain, due to the complicated mixing patterns with mesons.

Quark masses vary over more than three orders of magnitude. The light quarks (up, down) have masses at the level of a few MeV, with the strange quark being somewhat heavier. Therefore, these quarks can be considered nearly massless at typical hadronic scales. As a consequence, QCD possesses a chiral symmetry which becomes exact when all quark masses are taken to vanish. One finds that chiral symmetry is spontaneously broken due to the formation of a chiral condensate, as is apparent from the observation of an octet of light pseudoscalar mesons in accordance with Goldstone's theorem. In the opposite limit of infinitely heavy quarks QCD has an exact spin-flavour symmetry. The charm and bottom quarks have masses in excess of 1 GeV, which is well above the intrinsic energy scale Λ_{QCD}. Indeed one finds that hadrons containing these quark flavours exhibit many of the features implied by the spin-flavour symmetry, such as the suppression of fine and hyperfine mass splittings.

The symmetries of QCD are not only important for the interpretation of the hadron spectrum but also form the basis for so-called effective field theories (EFTs). Chiral Perturbation Theory (ChPT) allows for the treatment of processes involving the up, down and strange quarks in terms of hadron fields, which are the relevant degrees of freedom at low energy scales. Spin-flavour symmetry is the basis for the Heavy Quark Effective Theory (HQET), which leads to a simplified description of the spectrum and decays of hadrons containing one or several of the charm or bottom quarks.

QCD is the prototype of a strongly coupled theory – the only one realised in experimental data up to now – and inspires new theoretical descriptions for strongly interacting systems with many possibilities for cross-fertilisation with fields like condensed-matter physics. The theory toolkit to study hadrons from QCD is quite diverse, as befits the rich set of phenomena it describes. It includes semi-classical gauge theory, functional methods and Schwinger-Dyson equations, techniques using limits in large number of colours, as well as tools derived from string theory. In addition, models at different levels of sophistication allow for new ideas that describe the structure and dynamics of hadrons to be confronted with experimental data.

During the past decade there has been enormous progress in applying QCD in the low-energy regime, thanks to advances in lattice QCD, effective field theories and functional methods. Moreover, data-driven approaches based on dispersion theory and phenomenological models continue to play an important role. Thus, a range of calculational tools is available with complementary strengths and weaknesses. Considering the wealth of precise experimental data that can be analysed using this variety of theoretical methods, one can rightly claim that hadron physics is entering the precision era. During the coming decade one can therefore expect significant progress in many areas, including accurate determinations of hadronic uncertainties in precision observables (such as hadronic contributions to the muon anomaly), calculations of nucleon form factors relevant for the determination of the proton radius and other structural properties, as well as the interpretation of the spectrum of heavy quarkonia and hadronic states in the charm sector.

4.1.3. Experimental Methods

In order to answer the open questions in hadron physics, dedicated experiments that test QCD in the non-perturbative regime are crucial to improve our limited understanding of these aspects of QCD. These measurements include the study of QCD bound states, the search of new forms of hadronic matter (hadron spectroscopy) and the study of hadron structure and of hadron dynamics. These investigations can be performed with different probes such as electrons, photons, pions, kaons, protons or antiprotons.

Many complementary approaches contribute to the knowledge of hadronic structure and dynamics. Historically lepto-production of hadrons has been the main tool to study the internal structure of the nucleon and its modification in nuclear matter as the probe interacts electromagnetically. It covers a large range of photon virtualities starting from real photons, allowing for elastic, inclusive, semi-inclusive and exclusive reactions with which one can access form factors, parton distributions up to transverse momentum distributions (TMDs) and generalised parton distributions (GPDs) which encode the information describing the 3D-structure of the nucleon. A complementary path for accessing TMDs is offered by Drell-Yan reactions in meson-nucleon, proton-proton (pp) and $\bar{p}p$ processes. An important characteristic of both lepto-production and Drell-Yan is the proven factorisation of the cross-sections into soft, non-perturbative terms and the hard process, while proton-proton collisions have the advantage of large cross sections, which is important for our ability to probe the gluon content of the nucleon.

For the field of hadron spectroscopy the main environments in which these studies have been carried out are e^+e^- and $\bar{p}p$ annihilation, pion-nucleon scattering, as well as photo- and electro-production.

In e^+e^- annihilation direct formation proceeds through an intermediate virtual photon and is therefore limited to the vector states ($J^{PC} = 1^{--}$). Other production mechanisms include photon-photon fusion, initial state radiation (ISR) and B-meson decay. e^+e^- annihilation is characterised by the low hadronic background and the high discovery potential. The main disadvantage is that, as mentioned earlier, direct formation is limited to vector states and this implies a limited mass and width resolution for all other states.

In $\bar{p}p$ annihilation it is possible to form directly states with any (non-exotic) quantum number combination, via intermediate states with the appropriate number of gluons. For all these states the mass and width resolution is excellent. States with exotic quantum numbers can be reached in production mode. $\bar{p}p$ is a gluon-rich environment, particularly favourable for the discovery of hybrids and glueballs. All three pillars of hadron physics (spectroscopy, structure, dynamics) can be studied in $\bar{p}p$, provided that a universal detector is employed. The main disadvantage of $\bar{p}p$ is the high hadronic background. However previous experiments at CERN and Fermilab have shown that the selection of exclusive final states allows to reduce backgrounds significantly.

With photon beams, hadronic excitations can be readily identified via their decay products, since the initial (QED) interaction is well understood. Electroproduction allows for the study of transition form factors. The ability to polarise photon and electron beams as well as the respective targets opens up the possibility of measuring observables that can help distinguish between overlapping resonances through amplitude analyses. As with $\bar{p}p$ annihilation, electromagnetic probes can be used to investigate all three pillars of hadron physics.

4.1.4. Hadron Spectroscopy

In any physical system, the manner in which it is excited is a fundamental manifestation of the underlying mechanisms that govern its behaviour. For instance, precise details of atomic spectra were instrumental in being able to deduce the properties of the electromagnetic interaction through the development of Quantum Electrodynamics (QED). Similarly, hadron spectra beautifully encode the complex properties of the theory of fundamental interactions: Quantum Chromodynamics (QCD).

The key idea in QCD is that hadronic states are colour-neutral, and this leads to the concept of mesons as bound quark-antiquark pairs, whilst baryons are systems that contain three quarks. “Exotic” hadrons can be loosely defined as states that are not explained in terms of these configurations, but that nonetheless retain the colour-neutrality demanded by QCD. Possible exotic configurations include multiquark states (e.g. tetraquarks, pentaquarks) and gluonic hadrons (hybrids and glueballs) in which excited gluons act as hadron components and determine their quantum numbers.

Hadron spectroscopy is the study of the meson and baryon spectrum (including the pattern of decays and transitions between states) and the search for exotics. Mesons are the simplest quark bound systems and are the ideal place to study quark-quark interaction. Baryons have a special role in spectroscopy since not only they are the building blocks of ordinary matter, but also because their three-quark structure is most obviously related to colour degrees of freedom. Exotic states, with quark configurations other than three quarks or quark-antiquark, can reveal new or hidden aspects of the dynamics of the strong interaction.

Why is hadron spectroscopy a prime tool to study the details of the underlying QCD interaction? At large momenta, the QCD coupling strength is weak and the interactions between quarks and gluons as well as the gluon self-interactions are precisely known. In bound states and resonances, however, the interactions occur at low momenta, where the QCD coupling becomes strong. As a consequence, the forces between the elementary particles become much more complicated to describe. They give rise to fascinating effects like dynamical mass generation, which accounts for 99% of the hadron mass and therefore of the visible mass in the universe. They also give rise to the intricate pattern of the spectra of mesons, baryons and the newly discovered exotic states. Extensive and precise spectroscopy, particularly of exotic states, combined with a thorough theoretical analysis of the data, will add substantially to our knowledge of the underlying strong interaction.

Recent Achievements and Hot Topics

There is more to spectroscopy than just bump hunting. In fact we need to understand the details of line shapes and information at the amplitude level in order to be able to study the nature of these states and their dynamics related to the underlying QCD forces. This involves experiments that require some combination of beam, target or recoil polarisation, which are technically very challenging.

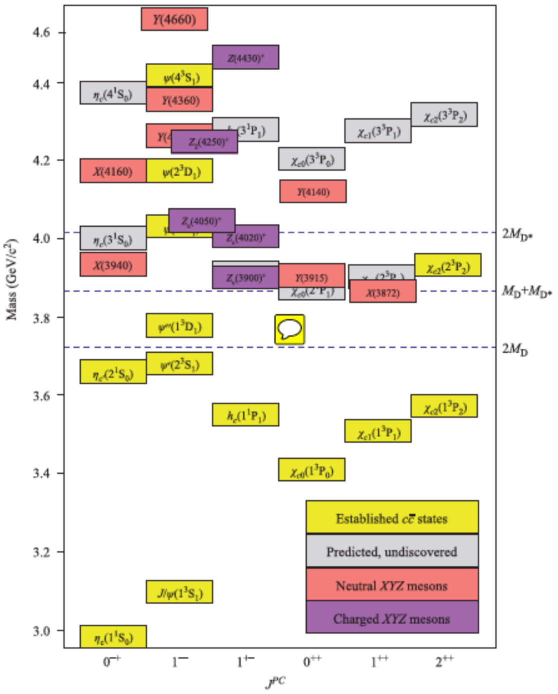


Figure 1: The spectrum of the X, Y and Z states.

In the energy region of the heavy quark sector (charm and bottom quarks) a plethora of new states has been discovered recently (Fig. 1). Experimentally, this energy region is easier to deal with than the light quark sector since many of the observed states are narrow. Furthermore, the energy scale provided by the heavy quark mass facilitates the theoretical treatment of heavy quark systems in terms of effective field theories. As a consequence, exotic states are easier to identify. In particular the X, Y and Z states in the charmonium sector have shown strong evidence for novel configurations. However, more work is required to understand what sort of resonances they really are. Interestingly, these new states have shown up in experiments that were designed to perform precision measurements on conventional hadrons.

In the light quark sector (up, down and strange quarks), some of the most intriguing states are scalar mesons. In the ground state multiplet, there is still speculation about whether the f_0 and a_0 are regular meson states, tetraquarks or hadronic molecules. For higher masses, more f_0 states have been observed than can be accommodated in a quark model multiplet, leading to discussions about whether some of these states might be glueballs (see below). COMPASS has also observed a new meson, the a_1(1420), but its interpretation is still unclear. The study of these states is extremely complicated because of the large widths that make them difficult to identify against a large background. Therefore, it is crucial that investigations with different probes and via different decay modes be carried out.

Another critical and poorly studied sector is strangeonium and strange-rich states; here the number of experimentally determined states is much smaller than expected, mostly because of limitations in the statistics and detector capabilities of previous experiments. Current and future experiments present a real opportunity for a dramatic improvement in our knowledge of the spectrum.

Evidence for the observation of states with explicitly exotic quantum numbers, for instance the $\pi_1(1400)$ and $\pi_1(1600)$, has been reported by several experiments. However, even after many years definitive conclusions have still to be reached.

The light quark sector is definitely more complicated than that of heavy quarks, but an understanding of light quark systems is an absolute necessity to claim that we understand hadrons. In the past, theoretical predictions were limited and quite model dependent but in the last decade, lattice QCD has made incredible progress in giving robust predictions for the light meson spectrum. Recent calculations reproduce the main features of the meson spectrum and provide indications for multiplets with exotic quantum numbers.

The self-interacting nature of gluons remains one of the most fascinating predictions of QCD. A direct observation of glueball states – states made prominently of gluons – will be the ultimate check of this prediction. While lattice simulations can make clear predictions for the glueball spectrum in the pure gauge theory without quarks, the mixing of states in the presence of light quarks is a challenge.

For several decades our knowledge of the light, non-strange baryon excitation spectrum stemmed essentially from data on elastic pion-nucleon scattering. Initially, the observed spectrum contained far fewer states than expected from the quark model or lattice calculations. A dramatic improvement occurred after performing partial wave analyses of new high-precision photoproduction data from MAMI, ELSA and JLab, including polarisation degrees of freedom. This has lead to the discovery of several new states while other previously discovered states have been established more firmly. This is illustrated by the following table, which lists the entries of several baryon states in the Review of Particle Properties (RPP) in 2010 and 2012 along with their star ratings assigned by the Particle Data Group.

	RPP 2010	**RPP 2012**
$N(1860)5/2^+$		**
$N(1875)3/2^-$		***
$N(1880)1/2^+$		**
$N(1895)1/2^-$		**
$N(1900)3/2^+$	**	***
$N(2060)5/2^-$		**
$N(2120)3/2^-$		**
$\Delta(1940)3/2^-$	*	**

In addition, our understanding of the properties of the observed states has greatly improved in the light of the new data. In the future, new data – for instance from double-polarised photo-production of protons and neutrons, electro-production or ψ-

decays – will provide a better understanding of the spectrum. Baryon spectroscopy would also benefit from new precise data from pion-induced processes. While the HADES experiment has already started to use the GSI pion beam, future projects involving meson beams are pursued at J-PARC. Pion production of baryonic resonances can be studied at HADES via the measurement of two-pion and dilepton final states, which provides a complementary perspective on baryonic resonances compared to photo- and electro-production. On the basis of the new data one hopes to answer questions such as: Why are certain baryon multiplets completely empty? Are specific sets of quantum numbers indeed not realised as observable states in nature? And if this is the case: Why?

New data obtained from existing (JLab, BES, LHCb, BELLE) or future facilities (Belle2, PANDA) will extend our knowledge into the strange and heavy quark sector, answering the question whether the same dynamics is at work in the single- and multi-strange sector or whether this might change for baryons including heavy quarks. This common effort will provide us with an answer to the question of how the strong interaction produces its bound states. One of the most spectacular results is the recent discovery of a heavy pentaquark state at LHCb. While further, more refined analyses of the present data have confirmed its existence, new data from the next LHC run will be needed to understand the exact nature of these states thus corroborating the evidence that quarks can aggregate in groups of five.

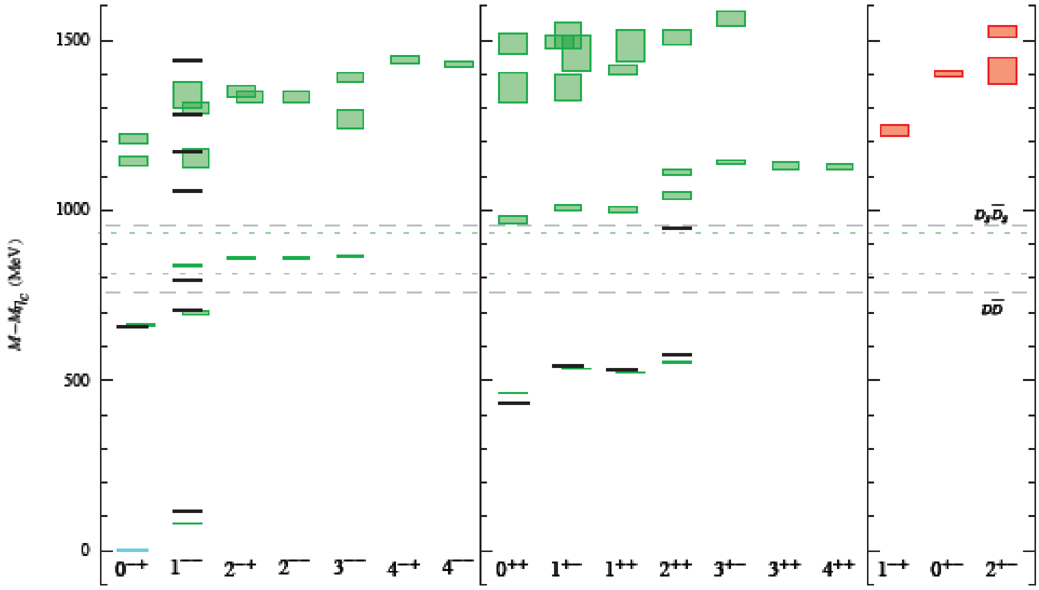


Figure 2: Charmonium spectrum as determined in Lattice QCD (from Liu et al., JHEP 1207 (2012) 126.)

Recent theoretical studies of hadrons have focused largely on lattice QCD and Effective Field Theories. In the baryon sector lattice simulations have achieved significant progress in computing the masses of the ground-state and the excited-state octet and decuplet baryons from first principles. In the meson sector the most significant progress came from the development and application of new techniques to study excited states and resonances (Fig. 2) and to address bound states close to the strong decay threshold. An important ingredient is the ability to perform simulations at the physical pion mass, which largely eliminates the systematic effects associated with chiral extrapolations.

Much progress has also been made in describing the spectrum and dynamics of excited baryonic states through coupled-channel studies based on effective hadronic Lagrangians constrained by QCD symmetries. These approaches, as well as tools like partial wave analysis are still the main tools for interpreting the tremendous amount of new data generated at JLab, ELSA and MAMI.

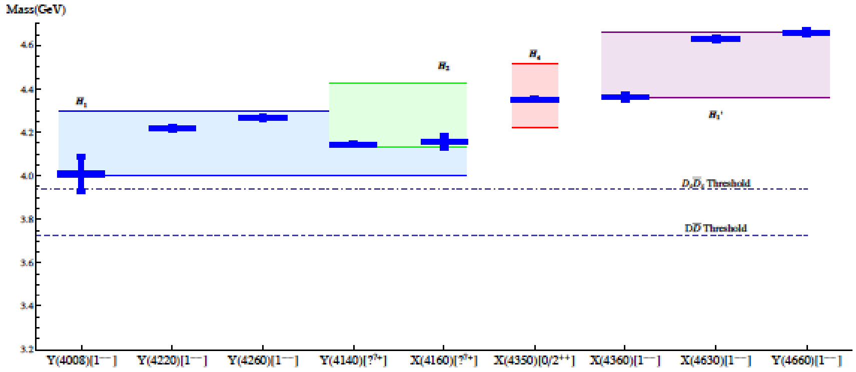


Figure 3: Mass spectrum of experimentally observed neutral mesons (solid blue points) compared to EFT predictions for heavy hybrid states (coloured bands) as determined in Berwein et al., Phys Rev D92 (2015) 114019.

Significant progress has been achieved in calculating higher-order perturbative corrections in EFT descriptions of heavy quark systems. This allows for precise determinations of mass spectra and transitions, as well as the strong coupling constant and the heavy quark masses. EFTs are also being formulated for the description of exotic states (Fig. 3).

Within the framework of Dyson-Schwinger/Bethe-Salpeter equations substantial progress has been made in the solution of the three-body Faddeev equation which replaces the previously employed quark-diquark models. The treatment of excited states is now possible, and the exploration of the baryon spectrum in this framework has begun. Other approaches include the string-theory-motivated AdS/QCD model, describing strong interactions in terms of a dual gravitational theory.

Future Prospects

The next generation of experiments should move from serendipitous discoveries of individual new states to the systematic study of spectral properties and patterns. More work is required to understand the underlying dynamics of resonances. This will involve the use of a wide range of experimental facilities, including photon, electron and meson beams, e^+e^- colliders and antiproton-proton annihilations.

Experiments will need to continue to improve on the statistical accuracy of measurements (higher luminosity and/or larger acceptance). In addition, the requirement to access spin degrees of freedom is crucial, so beam and target polarisation, as well as the determination of the polarisation of outgoing particles in a reaction, will be vital. An improvement in detector performance will open up other possibilities, such as the investigation of poorly known sectors such as strange-rich states (Λ's, Σ's and cascades).

As experiments get more complex, it will be necessary to develop more advanced statistical methods and sophisticated analysis tools that can be used to identify new resonant states and infer their properties. Experiments are also generating larger data sets, which creates new challenges for data handling and processing. A key component of this work will be the close cooperation between experimentalists and theorists in activities such as partial wave analysis. A joint venture, called JPAC, has already started.

4.1.5. Hadron Structure

It is the main purpose of hadron and nuclear physics to obtain an understanding of the properties of strongly interacting matter in terms of the basic constituents. A cornerstone in this enterprise is the description of the internal structure of the nucleon, which is one of the most intensely studied composite particles. Despite the large amount of available data and significant progress in the development of theoretical descriptions, unravelling the inner structure of the nucleon still presents enormous challenges.

Despite the fact that investigations of hadron structure have a long history the field continues to produce surprises that call for new and dedicated experiments and theoretical studies. Perhaps the most spectacular recent example is the “proton radius puzzle”, i.e. the observed inconsistency between the proton radius determined via the Lamb shift in muonic hydrogen and the corresponding measurement in ordinary hydrogen. The latter is consistent with the estimate derived from the proton's electromagnetic form factor measured in electron-proton scattering.

While the momentum of a fast moving proton is very precisely understood in terms of the momentum fraction of its constituents, the same cannot be said of our understanding of the proton spin. The most recent data from the COMPASS experiment at CERN have demonstrated that valence quarks account for only one third of the proton's spin. It is still unclear whether the remaining fraction can be firmly attributed to the contributions from the spin of gluons and virtual quarks, as well as those related to the angular motion of all the proton's constituents. This so-called “proton spin puzzle” has triggered a worldwide experimental research programme at the major laboratories. Its long-term goal is the generation of a comprehensive database on a number of key quantities, such as form factors, structure functions, generalised parton distributions (GPDs) and transverse momentum distributions (TMDs) all of which a crucial in order to obtain a quantitative understanding of the proton's spin, magnetic moment and three-dimensional internal structure in terms of quarks and gluons.

A detailed understanding of hadron structure is not only interesting in its own right but also indispensable for exploring the limits of the Standard Model. For instance, the overall precision of measurements performed at the LHC and other hadron colliders depends on the precise knowledge of parton distribution functions. Another example is the strangeness form factor of the proton which probes its sea quark structure. This quantity currently limits the accuracy of precision measurements of the electroweak mixing angle at low energies, which serves of a probe for physics beyond the SM.

A major experimental programme is under way to determine form factors, polarisabilities, parton distribution functions, GPDs and TMDs. This will provide the experimental data for detailed analyses based on the theoretical concepts that have been developed for many years. A powerful tool for the theoretical description of structural properties is QCD factorisation, which allows for the separation of energy scales characterising the hard and soft contributions to the relevant scattering amplitudes. While the former can be treated in QCD perturbation theory, the soft part is intrinsically non-perturbative and must be evaluated using phenomenological models. There has also been a major effort to determine structural properties from first principles using lattice QCD, with the main activities focussed on determinations of electromagnetic form factors, quark momentum fractions and the axial charge of the nucleon.

Recent achievements and state of the art

Electromagnetic form factors and the proton radius puzzle

The slope of the proton's electric form factor at zero momentum transfer as measured in electron-proton scattering (see Figure 4), as well as measurements of the energy levels in the hydrogen atom are well known methods to measure R_E, the charge radius of the proton. Estimates for R_E extracted either from electron-proton (ep) scattering data or from precision spectroscopy of ordinary, electronic hydrogen agree well with each other, which is reflected in the CODATA recommended value of $R_E = 0.877551$ fm. The situation changed dramatically when first results for the Lamb shift in muonic hydrogen were reported, which allowed for an extremely precise extraction of R_E in strong disagreement with the previous determinations. It has been shown that hadronic corrections from two-photon exchange, which are related to the magnetic polarisability of the proton, are too small to explain the proton radius puzzle. The experimental situation concerning the determination of R_E from atomic spectroscopy is discussed in detail in WG 5.

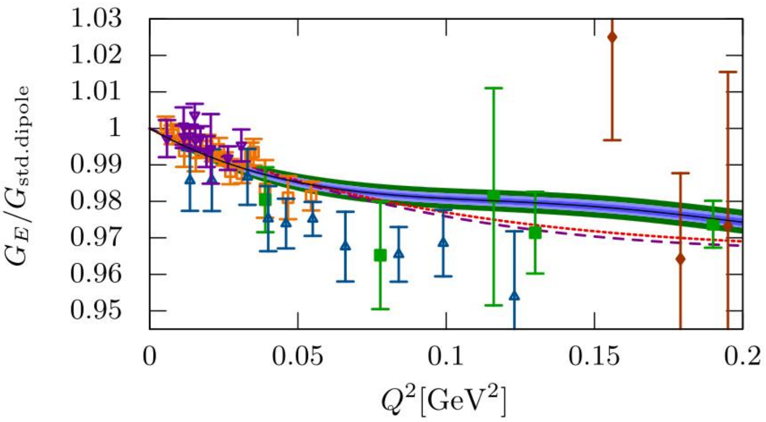


Figure 4: Compilation of data for the proton electric form factor G_E (see Bernauer et al., Phys Rev C90 (2014) 015206 and references therein). The charge radius is extracted from the slope at $Q^2 = 0$.

Among the possible origins of the puzzle are systematic effects in the experimental determinations that are unaccounted for. This concerns both the extrapolation of ep scattering data to zero recoil, as well as the determination of hydrogen spectra. An alternative explanation is based on missing or unknown hadronic effects in the ep scattering process. Finally, the observed discrepancy could be due to physics beyond the Standard Model, in the form of light scalar or vector particles in the MeV mass range, or large extra dimensions.

The current state of affairs calls for a dedicated, cross-disciplinary programme involving experimental hadron and atomic physics, supported by renewed efforts in hadron and particle theory, as well as lattice QCD. PSI has embarked on a rich programme to measure the charge radii of a range of light nuclei in muonic systems. This is complemented by new and improved measurements of atomic transitions in electronic hydrogen. Furthermore, a new generation of precision measurements of electromagnetic form factors at very low momentum transfers will be performed, using the ISR method at MAMI, PRad at JLAB, and the new MAGIX spectrometer at MESA. The proton radius puzzle will also be addressed by the MUSE experiment at PSI, which will determine electromagnetic form factors in μp scattering. These experimental activities will accompanied by new theoretical investigations as well as calculations of nucleon form factors in lattice QCD.

Nucleon form factors

The electromagnetic form factors (FFs) of hadrons, most prominently of nucleons, have been studied with ever increasing accuracy over the last 50 years. The main tool has been elastic lepton scattering, which probes spacelike momentum transfers. Timelike momentum transfers are accessible in annihilation processes. Due to their analyticity in the 4-momentum transfer Q^2, spacelike and timelike FFs can be connected through dispersion relations. In the spacelike region, they allow for a spatial imaging of quarks in a hadron, whereas in the timelike region they encode the excitation spectrum of spin-1 (vector) mesons. These two complementary aspects of hadron structure demand a determination of the electromagnetic FFs over the full kinematical range of Q^2.

On the theory side, a wide variety of models based on effective degrees of freedom have been used to estimate nucleon FFs. Form factor data also provide benchmarks for lattice gauge theory. Furthermore, spacelike FFs yield the first moment of GPDs (see below). Dispersion relations are used to analyse the structure of the FFs in the spacelike and timelike regions simultaneously.

For electric and magnetic FFs of the proton and neutron at spacelike momentum transfers, there are active experimental programmes at MAMI (at lower momenta) and at JLab (with higher momenta). The availability of CW electron beams at high current and high polarisation allows measurements with unprecedented accuracy up to high energies due to the large available luminosities and – for experiments with polarisation – large figures of merit.

There is continued interest in nucleon FFs, both in experiment and theory, because of the unresolved issue regarding the determination of FFs via the polarisation transfer method which shows that the ratio of electric and magnetic FFs, G_E/G_M, for the proton deviates from unity, in contrast to the results derived from the Rosenbluth separation technique. While it is still debated whether or not this discrepancy is connected with two-photon exchange amplitudes, it has been shown that the polarisation transfer method is much less sensitive to those effects and therefore yields clean FF extractions. The question of the importance of the two-photon exchange amplitude in elastic scattering has triggered a whole new field of research. Several dedicated programmes, comparing elastic scattering of electrons with elastic scattering of positrons from protons are underway at JLab, at the Novosibirsk e^+e^- collider VEPP2000, and at the Doris ring at DESY.

In the timelike region, where the FFs are complex functions of Q^2, the most precise experimental data have come from the BaBar experiment at the SLAC B-factory, via the process $e^+e^- \rightarrow p\bar{p}$, and from antiproton annihilation experiments at LEAR. The limited statistics of current data does not allow for an independent extraction of the timelike electric and magnetic FFs. Moreover, the present error on the ratio of electric over magnetic FF in the timelike domain is larger by almost two orders of magnitude compared to the spacelike region.

While the BESIII experiment at the BEPCII e^+e^- collider (IHEP, Beijing) devotes a significant part of its data taking to electromagnetic form factor measurements, the PANDA experiment at GSI/FAIR will make a real difference in the study of electromagnetic FFs in the time-like region. PANDA offers a unique opportunity to determine the moduli of the complex FFs in the time-like domain over a wide range of momentum transfers from antiproton annihilation reactions, with expected statistical errors 20 to 50 times smaller than those on present data.

Baryonic transition form factors

Extracting the electromagnetic amplitudes for the transitions between ground and excited nucleon states, over a broad range of Q^2 gives insight into the evolution of meson-cloud effects and how dynamically-generated masses emerge from the asymptotically-free, nearly massless quarks of QCD. Just like the elastic form factors mentioned above, transition form factors are expected to be analytical functions of Q^2, connected in spacelike and timelike regions by dispersion relations. The space-like region has been intensively explored using meson electro-production experiments for Q^2 up to about 5 GeV^2. In recent years, the CLAS detector at JLab has measured transition form factors for many baryon resonances (up to N(1720) and Δ(1700)). Furthermore, following the 12 GeV upgrade of JLab the new CLAS12 detector will soon extend these form factor measurements to 10 GeV^2. To explore the basically unknown timelike region, the HADES collaboration at GSI/FAIR, investigates electromagnetic baryonic transitions at low positive Q^2 by studying the Dalitz decay of baryonic resonances. Since vector meson poles play a prominent role in electromagnetic interactions in this regime, their study also provides constraints for the interpretation of dilepton spectra measured in heavy-ion experiments in terms of in-medium distortion of the ρ-meson spectral function which is one of the very few possibilities to experimentally study chiral symmetry restoration in hot and dense matter (see section WG 2 “Phases of Strongly Interacting Matter“).

Polarisabilities

While form factors provide the static distributions of charge of a particle, polarisabilities describe the deformation of the distribution by an external electromagnetic field. The proton and the neutron, each with spin-$1/2$, possess two scalar and four spin polarisabilities. While the scalar electric polarisability of the proton has been already relatively well determined, the magnetic and spin polarisabilities have been measured recently with a good precision at MAMI in real Compton scattering, using linearly and circularly polarised photons on transversely and longitudinally polarised proton targets. The neutron polarisability will also be studied at MAMI through a comparison of Compton scattering from high-pressure ^{3}He and ^{4}He targets and from a deuterated butanol target. An extensive programme to study generalised proton polarisabilities in virtual Compton scattering has been performed at MAMI, which completes earlier measurements performed at MIT/Bates and JLab. In contrast, for charged pions the experimental situation is more difficult since they are not available as fixed targets. Although different techniques exist, measurements are affected by large experimental and theoretical uncertainties. The most precise result has been obtained recently at COMPASS at CERN using a pion beam and the Primakoff technique. The result is in tension with previous measurements, but in agreement with the expectation from chiral perturbation theory. Another method using the reaction $\gamma\gamma \rightarrow \pi\pi$ will be investigated at BESIII and at JLab.

A feasibility study to measure kaon polarisabilities is being performed at CERN, using the radiofrequency separated high-intensity antiproton/kaon beam, which allows for an increase of the beam intensity by one to two orders of magnitude compared to the current COMPASS experiment. This will provide unique opportunities to accurately determine kaon polarisabilities.

Parton Distribution Functions

In the non-perturbative regime of QCD, the internal quark-gluon structure of hadrons is described in terms of a well-defined hierarchy of correlation functions as the unpolarised and polarised parton distribution functions (PDFs). These functions specify the number density of quarks q and gluons g carrying a momentum fraction x of the total hadron momentum and having a certain spin orientation inside the hadron. While QCD does currently not allow for a first-principles calculation of the quark and gluon distributions, they can be determined via evolution equations in terms of x and the energy transfer Q^2, respectively. The successful prediction of the dependence of PDFs on x and Q^2 has been one of the great triumphs of QCD.

In recent years also LHC pp data have been used in global analyses. Since the discovery of the Higgs boson, the LHC physics programme is mostly driven by the search for new physics. Precise theoretical predictions of background processes are needed for a discovery, whereas accurate predictions of new phenomena are needed for the interpretation of exotic physics signals or for verification of Higgs boson properties. This is why the precise knowledge of PDFs and their uncertainties is essential at the LHC.

Measurements of the total and differential cross sections of W and Z production, differential Drell-Yan cross-sections, W-charged lepton asymmetry, inclusive jet cross sections, as well as reactions related to top production are used successfully to validate NNLO predictions for PDFs and further constrain their uncertainties. In particular, the valence distribution of the d quark and the distribution of the s quark are better constrained with LHC data than from DIS measurements only. The latest data at $\sqrt{s} = 13$ TeV, as well as precise measurements of M_W and $\sin^2 \theta_W$ will be important to increase the precision further.

Two long-standing puzzles are of particular interest for the present experiments and for the planning of the future ones:

The first concerns the proton wave-function at small x, which is dominated by gluons and referred to as the Colour Glass Condensate (CGC). The question arises whether the gluon and quark densities can grow indefinitely at small x or whether a saturation regime is encountered. There are indications from HERA, RHIC and LHC that gluons will start to recombine, thereby reaching the saturation regime, but an independent confirmation is still missing. The main difficulty comes from the fact that the kinematical regime is difficult to realise experimentally: smaller values of x can be either reached by the expensive option of increasing the centre-of-mass energy or by using heavier nuclei. Therefore, the best short-term option to pin down the CGC is by performing DIS experiments on nuclei at a future Electron-Ion Collider (EIC), a project currently under consideration in the US.

The second is the “proton spin puzzle”, i.e. the question how the spin of the proton can be decomposed in terms of its constituents. Semi-inclusive Deep-inelastic Scattering (SIDIS) experiments at CERN, DESY and JLab cannot fix the gluon contribution Δg due to the limited kinematic range, but have accessed Δg directly through the process of photon-gluon fusion. COMPASS has measured a small value of Δg in the accessible range of x. The best prospects for measuring Δg directly are provided by polarised proton-proton collisions at BNL’s Relativistic Heavy Ion Collider (RHIC) using processes that receive substantial contributions from gluon-induced hard scattering. Recent global analysis using data from the PHENIX and STAR experiments have shown a substantial integrated gluon contribution in the covered x-region. Furthermore, measurements from PHENIX on longitudinal single-spin asymmetries in $W^{\pm}$ and Z^0 boson production have provided better constraints on the polarisation of sea quarks and anti-quarks. Recently, the COMPASS collaboration at CERN presented results for the proton longitudinal spin structure functions g_1^p and the double spin asymmetry A_1^p, increasing the coverage to lower values of x, while increasing the statistical precision by a factor of two. In order to address the proton spin puzzle the accuracy in the determination of polarised PDFs must be increased further. This can be achieved by extending to kinematic coverage to even smaller values of x, preferably at the EIC.

Generalised Parton Distributions

Our knowledge of nucleon structure has drastically improved in the last few years thanks to the vigorous activity revolving around Generalised Parton Distributions

(GPDs). These new functions combine the information from form factors and parton distributions into a more complete, three-dimensional description of the internal structure of hadrons. GPDs correlate the transverse position of partons with their longitudinal momentum, which opens the exciting possibility of determining the spatial distribution of quarks and gluons in the nucleon as a function of the parton wavelength. Two main processes have been identified as giving the best access to GPDs: Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). GPDs are process-independent universal quantities. A factorisation theorem has been proven for DVCS and for longitudinally polarised photons in DVMP, providing a solid theoretical basis for GPD measurements through hard exclusive reactions. GPDs can also be used to compute the total angular momentum from quarks and gluons, using the so-called Ji sum rule.

The large information content of GPDs implies a high level of complexity which translates into the necessity to perform many different measurements with polarised beams and polarised targets, in a wide range of kinematics and at increasing values of momentum transfer Q^2. This is an ambitious and challenging programme that requires the close collaboration between experiment and theory.

DVCS and DVMP have been explored in recent years at several experiments: HERMES used a 27 GeV electron and positron beam, H1 and ZEUS analyzed collisions of 820 GeV protons and 27 GeV electrons or positrons, while JLab has increased the energy of its electron beam from 6 to 12 GeV. Accurate cross-section measurements have shown indications of leading-twist dominance in the accessible kinematic regions. The high precision of the data has stimulated further theoretical analyses to understand the fine details. A variety of beam and target spin asymmetries have been used to constrain models and build GPD parameterisations that have delivered the first 3D images of nucleon structure.

In the next few years the most important data will come from the JLab 12 GeV upgrade and the GPD programme at COMPASS. The new kinematic regime accessible at JLab (see Fig. 5) and the extremely high luminosity will allow for a systematic and multi-dimensional exploration of GPDs, reaching values of the momentum transfer much higher than before. A dedicated experimental programme is planned in Hall A with existing equipment, in Hall B with the new CLAS12 spectrometer and in Hall C with the addition of a Neutral Particle Spectrometer (NPS). The COMPASS experiment will study DVCS and DVMP with polarised muon beams at 160 GeV and explore the region of intermediate x between H1/ZEUS and HERMES/JLab. The increased luminosity of upcoming experiments will make it possible to study GPDs through complementary channels such as timelike Compton scattering, the crossed reaction of DVCS, as well as Double DVCS, where both the initial and final photons are virtual. The large amount and precision of the data from all these different experiments will revolutionise our current understanding of hadron structure.

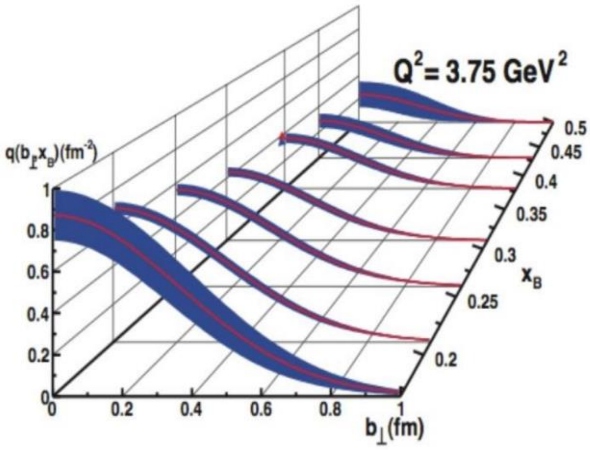


Figure 5: Nucleon transverse profile at different values of x. The bands show the projected uncertainties from the JLab experiments at 12 GeV.

Transverse spin and momentum-dependent distribution and fragmentation functions (TMDs)

TMDs describe hadron structure in terms of transverse degrees of freedom. They provide the motivation for upgrades of several existing facilities (JLab, COMPASS and RHIC) and have an important role in the design and construction of new facilities worldwide (EIC, FAIR, NICA and JPARC). Since TMDs are complex objects they must be accessed through global analyses of complementary processes (such as SIDIS, Drell-Yan, e^+e^- annihilation into hadrons and hard polarised pp-scattering) in order to disentangle their flavour and kinematic dependences.

Two striking effects have been demonstrated recently. One is the Collins mechanism that correlates the spin of the fragmenting quark with the azimuthal angle of hadrons produced in processes like SIDIS, $e^+e^- \to \mathrm{hadrons}$. The other is the correlation between the spin of a transversely polarised nucleon and the intrinsic transverse momentum of the quarks, giving rise to the so-called Sivers asymmetry. These measurements performed by the HERMES and COMPASS collaborations, as well as the JLab experiments have shown pronounced spin-orbit and quark-gluon correlations in kinematic regions where the valence quark contributions are significant. One of the most striking predictions of the TMD approach is the sign change of the Sivers and Boer-Mulders TMDs between SIDIS and Drell-Yan reactions, which represents a test of QCD factorisation. An experimental verification that the leading-order TMD formalism is correct is still missing, which is one of the most urgent goals of the present experimental activity. The non-trivial universality of the Sivers TMD will be verified by comparing the Sivers asymmetry from SIDIS with the one from Drell-Yan at COMPASS and planned experiments in Europe (PANDA at FAIR, AFTER at CERN, SPD at NICA) and the US, but also by studying *W*-boson production at RHIC.

A precise study of the distribution of transverse quark momenta is another pressing issue for investigations of TMDs. Such a programme has started only recently with the availability of multi-dimensional results on hadron multiplicities and their azimuthal dependences by HERMES and COMPASS. These analyses must be extended to e^+e^- colliders to fully disentangle the contributions of transverse hadron and quark momenta in hadron lepto-production. Precise information on the fragmentation process is expected in the near future thanks to the ongoing BELLE-II and BESIII upgrades, complementing SIDIS measurements that constrain the fragmentation functions at different centre-of-mass energy with specific flavour sensitivity.

Combining the multi-dimensional results from HERMES and COMPASS with the proposed experiments using the 12 GeV electron beam at JLab, as well as the forthcoming measurements at COMPASS will probe the kinematic dependence of azimuthal asymmetries for pion and kaon lepto-production. A combined analysis of all three data sets will constrain different TMDs and provide important input for global analyses of PDFs. This will constitute a significant step towards the full tomography of the nucleon. Combining the measurements at different energies allows for a comprehensive study of the Q^2-dependence of TMDs. The coverage in x and Q^2 will be significantly extended with the realisation of the EIC.

An overview of experiments to study TMDs and GPDs is presented in Table 1.

Experiment/Lab	**Running Time**	**Reactions for TMDs**	**Reactions for GPDs**	$\boldsymbol{\mathcal{L}}$ $(\boldsymbol{cm^{-2}s^{-1}})$	$\boldsymbol{\sqrt{s}}$ **GeV**
Completed					
Hermes/ DESY	1996-2007	$e^-\big[p^\uparrow,(p,d)_{\text{unp.}}\big]$	$(e^\pm)^\rightarrow\big[(p,d)^{\uparrow\rightarrow},(p,d)_{\text{unp.}}$	$> 10^{31}$	7
H1, ZEUS/ DESY	1996-2007		$(e^\pm)^\rightarrow p$		
BaBar/ SLAC	1999-2008	e^+e^-		$> 10^{33}$	10
Belle/ KEK	1999-2010	e^+e^-		10^{34}	10
Hall ABC/JLab	2005-2014	$e^-\big[(p,n)^\uparrow,(p,d)_{\text{unp.}}\big]$	$(e^-)^\rightarrow\big[(p,d)^{\uparrow\rightarrow},(p,d)_{\text{unp.}}$	10^{38}	3
Running					
COMPASS/ CERN	2002→	$\mu^+\big[(p,d)^\uparrow,(p,d)_{\text{unp.}}\big]$ $\pi^-[p^\uparrow]$	$(\mu^\pm)^\rightarrow\big[p_{\text{unp.}}\big]$	$> 10^{31}$	17-19
BesIII/ BEPC	2009→	e^+e^-			4
Hall ABC/ JLab12	2016→	$e^-\big[(p,n)^\uparrow,(p,d)_{\text{unp.}}\big]$	$(e^-)^\rightarrow\big[(p,d)^{\uparrow\rightarrow},(p,d)_{\text{unp.}}$	10^{38}	5
Star, Phenix/ RHIC	2001→	$p^\uparrow p^\uparrow$		10^{32}	200-500
Foreseen					
Belle2/ KEK	>2016	e^+e^-		10^{36}	10
SeaQuest/FLab	>2018	$pp^\uparrow$		$> 10^{35}$	15-30
COMPASS/ CERN	>2020	$\mu^+d^\uparrow$ $(\bar{p},K)\big[(p,d)^\uparrow\big]$	$(\mu^\pm)^\rightarrow\big[(p,d)^{\uparrow\rightarrow}\big]$	$> 10^{31}$	17-19
PANDA/ FAIR	>2022	$\bar{p}^{(\uparrow)}\big[p^\uparrow\big]$			5
EIC	>2025	$e^-(p,n,d)^\uparrow$	$(e^-)^\rightarrow(p,n,d)^{\uparrow\rightarrow}$ $(e^-)^\rightarrow(p,n,d)_{\text{unp)).}}$	$> 10^{34}$	25-145
SPD/NICA/JINR	>2020	$p\big[(p,d)^\uparrow\big]$			12-27
AFTER/CERN	>2017	$p\big[(p,d)^\uparrow\big]$		$> 10^{33}$	115

Table 1: A compilation of previous, running and planned experiments accessing TMDs and GPDs. Targets for fixed target experiments are in square brackets. Only reactions with lepton beams are reported here for GPD determinations.

Future Prospects

While the measurement campaign for form factors and polarisabilities of the nucleon will continue at the Mainz Microtron (MAMI) there are plans at Mainz for a dedicated new experiment (MAGIX) which is aimed at penetrating the very low-Q^2 regime for the determination of the electromagnetic form factors of the proton. This will allow for a much more precise determinations of the proton radius in ep scattering. Furthermore, planned measurements of the weak charge of the proton will complement the efforts at JLab.

At CERN the upgraded COMPASS experiment has started data taking and will produce new results for GPDs, TMDs, as well as pion and kaon polarisabilities. Parton distribution functions, GPDs and TMDs will also be measured at JLab. In addition, low-energy precision tests of the Standard Model will be performed via parity-violating processes. The 12 GeV upgrade of the JLab accelerator will be a major milestone. The long-term perspective (i.e. beyond 2025) for GPDs and TMDs includes plans to study the gluon and sea quark sectors at the EIC, which will greatly increase the kinematical range and complement the valence quark region probed with fixed-target experiments at JLab and CERN.

The generalisation of collinear QCD factorisation to other channels could give access to new hadronic matrix elements called transition distribution amplitudes (TDAs). If factorisation for these channels can be proven, these non-perturbative functions could be probed at antiproton-proton annihilation facilities such as FAIR.

4.1.6. Hadronic Interactions

A profound knowledge of hadron-hadron interactions is required for high-precision SM predictions and for our understanding of the structure of matter at the femtometer scale. This concerns both the emergence of hadrons from fundamental constituents and the formation of more composite structures like atomic nuclei. In particular, the longest-range forces are mediated by the lightest hadrons, the pions. Their special role is intimately linked to QCD by chiral symmetry.

The exploration of the intrinsic structure of hadrons cannot be disentangled from hadron-hadron interactions, as the effects of creating additional virtual particles become significant. Thus the study of the structure of a specific hadron by a specific probe involves the interplay between a target-independent, universal coupling of the probe to the lightest virtual particles, and the coupling of the latter to the target of interest. A model-independent tool to link the universal to the target-specific aspects is provided by dispersion theory, which in turn requires the experimental determination of various reaction amplitudes with high precision.

Strange quarks are light enough so that the replacement of a light (up or down) by a strange quark does not radically alter a hadronic system. On the other hand, strange quarks are heavy enough that techniques designed to analyse light-quark systems reach their edge of applicability. Kaon, hyperon and hypernuclear physics provide a highly attractive and challenging research field, offering the opportunity to develop appropriate and precise methods for studying strongly interacting systems.

Recent Achievements, Hot Topics and Future Prospects

Improving the precision of SM predictions and understanding the structure of hadrons, nuclei and hyper-nuclei calls for a thorough experimental and theoretical investigation of pion-pion and pion-kaon, pion-nucleon and kaon-nucleon interactions together with nucleon-nucleon, hyperon-nucleon and nucleon-antinucleon interactions.

A combination of high-quality experimental data, dispersion relations, chiral perturbation theory and lattice QCD has made pion-pion scattering one of the theoretically most rigorously understood examples of hadron-hadron interactions. The leading partial waves are known very accurately up to invariant masses of at least 1.1 GeV. The pion-pion system is also a test bed for hadron spectroscopy, as a dispersive representation allows for the extraction of the masses and widths of the lightest resonances in QCD, the f_0(500) and the ρ(770), with excellent precision from their respective pole positions in the complex energy plane. The current state of the art is to turn the knowledge of pion-pion scattering into a tool for many other applications, using the universality of final-state interactions: This includes the determination of light quark mass ratios from $\eta \rightarrow 3\pi$, the analysis of chiral low-energy constants in K_{e4} decays, as well as the study of various form factors that are highly relevant for determining the hadronic contributions to the muon's anomalous magnetic moment, or for describing more complicated scattering processes involving pions, such as pion-kaon or pion-nucleon scattering.

The situation for the simplest meson-meson scattering process including strangeness, pion-kaon scattering, is far less satisfactory. Chiral perturbation theory with the heavier strange quarks is not as well behaved, and the experimental data is much less precise. Modern tau-charm factories offer opportunities for improvement: τ decays into $\pi K \nu_\tau$ already offer precision information on the vector channel, and the decay $D \to \pi K \ell \nu_\ell$ might allow for a model-independent extraction of pion-kaon phase shift information. Such progress would be highly desirable, not least due to the large number of mixed pion and kaon final states in many heavy-flavour decays that are important for precision studies of CP violation. Both systems, $\pi\pi$ and πK, are closely related, as the crossed channel of πK scattering describes the dominant inelasticity for the $\pi\pi$ s-wave, and therefore is an important ingredient for a better understanding of the spectrum of scalar-isoscalar resonances with its glueball candidates.

Pion-nucleon scattering, which has seen a remarkable revival recently, has a profound impact on nuclear physics, since it determines the two-pion-exchange contributions to nucleon-nucleon potentials, as well as the leading long-range three-nucleon force. The t-channel amplitude ($N\bar{N} \to \pi\pi$) is highly relevant for nucleon electromagnetic form factors. Furthermore, the πN amplitude is closely related to the pion-nucleon sigma term via a low-energy theorem due to Cheng and Dashen. The latter quantifies the light-quark contribution to the nucleon mass and is directly linked to the scalar couplings of the nucleon, whose precise determination is crucial for the interpretation of direct dark matter searches. The dispersive framework of Roy-Steiner equations has led to a remarkably accurate determination of the so-called sigma term of 59.1 ± 3.5 MeV. This value is directly correlated with the pion-nucleon scattering lengths that are determined with high precision from pionic atom spectroscopy at PSI. However, it is in conflict with the most accurate calculations of the sigma term in lattice QCD, which seem to agree on a value closer to 40 MeV. A resolution of this conflict is urgently called for.

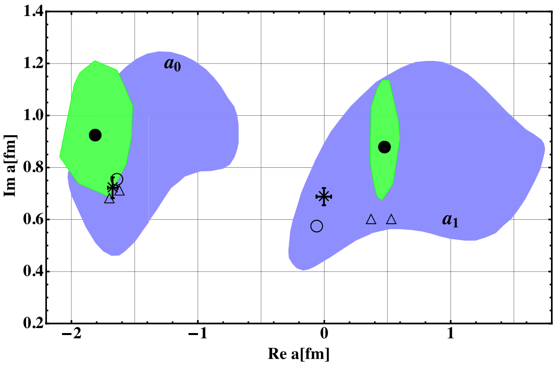


Figure 6: Illustration of the improved determination of antikaon-nucleon scattering lengths, based on unitarised chiral perturbation theory and the high-precision measurements of SIDDHARTA. The blue and green areas denote the 1 σ uncertainties (from Mai and Meißner, Nucl. Phys. A900 (2013) 51).

A lot of progress has been achieved for antikaon-nucleon scattering over the last few years, thanks partly to the new, much improved determination of ground state energy level shift and width of kaonic hydrogen by the SIDDHARTA collaboration (Fig. 6). Unitarised chiral perturbation theory can now describe the resulting antikaon-nucleon scattering lengths consistently with scattering data. The antikaon-nucleon interactions are highly relevant for investigations of the two-pole structure of the Λ(1405) resonance. While the scattering lengths alone do not constrain the pole positions well enough, recent precise photoproduction data from CLAS have led to a clear preference for certain classes of solutions for the scattering amplitudes. Better data, as well as analyses using higher-order theoretical amplitudes are still desirable.

Chiral EFT for nuclear forces is advancing rapidly. While there is an ongoing debate about the renormalisation of these forces and the resulting expansion scheme, enormous progress has been achieved within Weinberg's original approach. In particular, fifth-order corrections to the two-nucleon force have been worked out and implemented. The resulting potentials demonstrate a good convergence of the chiral expansion and allow for an accurate description of low-energy NN scattering data. They also provide clear evidence of the corresponding two-pion exchange contributions with all low-energy constants being determined from pion-nucleon scattering. This consistency between the πN and NN sectors shows that the theory has reached a remarkable level of maturity. Chiral EFT also offers a consistent framework for the construction of three- and four-body forces that appear at third and fourth orders in Weinberg's scheme, respectively. The existing *ab initio* nuclear structure and reaction calculations utilizing the leading chiral three-nucleon forces provide a clear indication of their importance for an accurate description of light nuclei. These studies are now extended to include higher-order corrections to the three-nucleon force. If supplemented by a quantitative uncertainty analysis, this will allow one to test the theory beyond the two-nucleon system. In particular, it remains to be seen whether the long-standing discrepancies in the three-body continuum can be resolved by the inclusion of the three-nucleon force.

Few-nucleon reactions with electroweak and pionic probes offer another exciting testing ground of chiral EFT. The corresponding two-nucleon electromagnetic and weak current operators are presently known to one-loop accuracy and have already been shown to provide a good description of the isoscalar and isovector charge and magnetic structure of light nuclei. The measurement of muon capture on the deuteron by the MuSun experiment at PSI will enable a precise determination of the short-range NN axial current, which plays an important role in the description of fundamental reactions of astrophysical interest.

Hypernuclei, i.e. nuclear systems with one or more bound hyperons, offer a unique opportunity to probe inner regions of nuclei and to study non-mesonic weak decays such as $\Lambda N \rightarrow NN$ since hyperons are free from Pauli blocking by other nucleons. Hyperons and their interactions with nucleons may also play an important role for the understanding of the interior of neutron stars. Hyperon-nucleon and hyperon-hyperon interactions have been studied at next-to-leading order using an SU(3) version of chiral EFT. An excellent description of the available hyperon-nucleon scattering data could be achieved. Also the leading three-baryon forces have been worked out, and the strength of the corresponding low-energy constants has been estimated. In the long term, a larger and better database for hyperon-nucleon scattering and light hypernuclei is needed in order to reliably pin down the values of the corresponding low-energy constants.

Significant progress has also been made in calculating the properties of light nuclei and hypernuclei from first principles within the framework of lattice QCD. While the results await further confirmation, most of the available lattice QCD studies indicate that the nuclear force becomes considerably more attractive for unphysically large values of the light-quark masses. In the regime with sufficiently heavy pions, pionless EFT has been demonstrated to provide an efficient approach for extrapolating the lattice QCD results to heavier systems beyond $A = 2 - 4$. For pion masses closer to the physical point, the results of lattice QCD should eventually be matched to an appropriately tailored chiral EFT. In addition, one can use low-energy theorems for NN scattering to reconstruct the energy dependence of the amplitude at unphysical pion masses from the lattice-QCD results for the binding energy.

Chiral EFT methods are increasingly used to study $N\bar{N}$ interactions, whose elastic part is related to NN interactions by G-parity. There is a wealth of new experimental information on $p\bar{p}$ systems, in particular from J/ψ decays, often in connection with the quest for new resonances. However, many of the near-threshold enhancements can potentially be explained by conventional strong final-state interactions. A sound theoretical understanding of $N\bar{N}$ scattering is a prerequisite for the interpretation of timelike nucleon form factor data that will be obtained from PANDA. Hyperon-antihyperon systems will be investigated at PANDA as well, with high relevance for exotic spectroscopy with strangeness. Due to their self-analysing weak decays hyperon-antihyperon systems provide straightforward access to their spin properties without explicit polarisation. In the long run the successive weak decays of multi-strange hyperons have the potential to reveal CP violation in baryons, which may have implications for the baryon asymmetry of the universe.

As discussed in the section on hadron spectroscopy, a plethora of new states has been discovered over the last years, mainly in the area of heavy quarkonia. While some of them are manifestly exotic in the sense that they cannot be thought of as having simple $q\bar{q}$ or qqq quark structures (e.g., the Z_b states in the bottomonium sector, or the pentaquark candidates seen by LHCb), others seem to be at odds with the quark model as far as their properties are concerned (e.g. the X(3872)). A common feature of many of these states is their proximity to certain thresholds. The X(3872) lies very close to the sum of the D^{0*} and the $\bar{D}^0$ masses, while the two Z_b states are within a couple of MeV of the BB^* and the B^*B^* thresholds, respectively. Such situations are well known from EFTs in nuclear physics: systems with bound or virtual states very close to threshold have a scattering length much larger than all other scales of the problem, and hence display several universal properties independent of the details of the short-distance interaction. The resulting large spatial extent makes the interpretation in terms of a significant molecular component unavoidable. The explanation of other “dynamically generated” states, also in the light-quark sector, relies on coupled-channel effects or even anomalous thresholds and triangle singularities. To fully explain the spectroscopy of these new, exotic states, an improved understanding of the interaction dynamics of the supposed constituents is mandatory.

4.1.7 Lattice QCD

Lattice QCD calculations are instrumental for a quantitative description of hadronic properties in terms of fundamental interactions. Below we summarise the current status and provide an outlook for future work.

Hadron Spectroscopy: While there has been tremendous progress in determining the spectrum of baryons and mesons in lattice QCD, both in the light and heavy quark sectors (see Fig. 2), additional efforts must be made in order to obtain more precise results on the excitation spectrum and perform more refined investigations of resonances and their decay properties. The use of a large basis of interpolating operators in conjunction with finite-volume techniques allows for detailed studies of mixing patterns among different states, as well as the determination of scattering phase shifts. Such calculations are becoming increasingly demanding since the numerical effort is largely driven by the complexity of the observable and its statistical noise, which is particularly severe for baryonic channels. Despite the development of efficient noise-reduction techniques, precise lattice calculations in hadron spectroscopy still require huge statistics.

The computational effort associated with the actual observables arises in addition to the generation of the gauge field ensembles, which has also become more expensive as realistic values of the dynamical quark masses – including the charm sector – are now used on a routine basis in lattice QCD. The requirement to control all sources of systematic error associated with the lattice formulation and the inclusion of electromagnetic effects makes a strong case for the development of supercomputers with exascale capabilities.

Hadron Structure: QCD factorisation is a key theoretical tool for the description of the scattering processes that probe the internal structure of the nucleon. It implies that scattering amplitudes can be separated into a “hard” and “soft” contribution. A non-perturbative approach such as lattice QCD must be applied in order to avoid any model dependence in the treatment of the soft part. One long-term goal of lattice QCD is to provide a comprehensive set of results for quantities such as form factors, structure functions and GPDs with controlled systematic uncertainties. This task is made more difficult due to a number of technical issues that arise in calculations in the baryonic sector, which have to be addressed and resolved. One important issue is the large intrinsic statistical noise of baryonic correlation functions that serve to extract the relevant physical information, such as masses and matrix elements. The large statistical errors impede the reliable isolation of the ground state, and thus the results extracted from baryonic correlation functions are prone to unwanted “contamination” from excited states in the same channel. The application of suitable noise reduction techniques that make it much cheaper to accumulate large statistics is a key development for achieving the long-term goal of lattice calculations. The statistical accuracy of iso-scalar quantities and observables that quantify the contributions from virtual quarks is also limited by the ability to compute so-called quark-disconnected diagrams efficiently. Significant progress has been achieved in the last few years, which, for instance, has lead to first results for the strangeness electromagnetic form factors of the nucleon.

Recent calculations have mostly focussed on a number of benchmark quantities that involve simple (forward) kinematics such as the quark momentum fraction $\langle x\rangle_{u-d}$ or the axial charge g_A of the nucleon, which are both important observables to describe the proton spin. While there are some discrepancies between lattice estimates and the experimental determinations of these quantities, it is likely that these are due to residual systematic effects related to unsuppressed excited state contributions.

Electromagnetic form factors of the nucleon have been another focus of recent lattice calculations. Thanks to the ability to control excited state contamination and to perform calculations near the physical pion mass the dependence of the form factors on the momentum transfer Q^2 can be reproduced. However, the current overall accuracy is not yet sufficient to clarify the proton radius puzzle or the discrepancy observed when using different methods to determine the ratio G_E/G_M. There are also efforts to predict the scalar and tensor charges of the nucleon, which are important quantities to constrain models for new physics based on additional scalar and tensor interactions. In addition, there have been exploratory calculations of GPDs in lattice QCD.

Among the main tasks in the years ahead is the increase in the overall precision of lattice calculations for form factors, quark momentum fractions and static charges of the nucleon. It is also the right time to tackle more complex observables such as GPDs and TMDs as new experimental data are awaited.

Hadronic Interactions: Lattice calculations are increasingly important for investigations of the dynamics of hadronic systems. A powerful technique (the so-called Lüscher formalism) has been developed, which allows for the determination of scattering phase shifts and scattering lengths, by computing the energy levels of multi-particle states in a finite volume. A number of results have been reported for meson-meson interactions, while the extension to meson-baryon and baryon-baryon systems is technically more involved, not least because of the noise problem inherent in baryonic correlation functions. An alternative formalism is based on the determination of the baryon-baryon potential via the Bethe-Salpeter amplitude which can be accessed in lattice simulations. There have been detailed studies on nucleon-nucleon interactions, including the determination of binding energies and scattering lengths. Several calculations have also focussed on hypernuclei and the possible existence of a stable H-dibaryon.

Another example that illustrates the impact of lattice QCD on hadronic interactions is the calculation of the πN sigma term, which is currently in conflict with the value extracted from the πN scattering length. Furthermore, lattice QCD becomes increasingly important for the determination of the hadronic contributions to the muon’s anomalous magnetic moment, particularly the hadronic light-by-light (HLbL) scattering contribution. While *ab initio* calculations of the HLbL scattering part are still in an exploratory phase, it is also possible to use lattice QCD to test phenomenological models based on dominant sub-processes that are linked to meson-photon interactions.

4.1.8. Physics Perspectives

European Perspectives

Over the past few years Europe has been playing a leading role in hadron physics thanks to dedicated experiments and facilities, like COMPASS, ELSA and MAMI. Furthermore, experiments whose primary goal is not the study of hadron physics, like LHCb, ATLAS and CMS at LHC, have been able to make significant contributions mainly to the field of hadron spectroscopy. In addition, the e^+e^- meson factory DAΦNE, at 1020 MeV centre-of-mass energy will continue operation with the KLOE 2 and SIDARTHA II detectors with a broad physics programme ranging from the study of CP and T violation in kaon decays to hypernuclei and kaonic atoms. HADES at GSI offers unique opportunities to determine baryon transition form factors in NN and πN reactions and to study hyperon resonances and pion-induced processes. HADES will be continued at SIS18 and later at FAIR. The next major step forward will require the HESR antiproton facility at FAIR and the PANDA experiment to be completed and become operational without further delay. With the operation of FAIR the leading role of Europe in the field of hadron physics will be established even more firmly. The main players in the field, present and future, are listed below.

COMPASS @ CERN
COMPASS is a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN in Geneva, Switzerland. The purpose of this experiment is the study of hadron structure and hadron spectroscopy using high intensity muon and hadron beams.

ELSA @ Bonn
The Electron Stretcher Accelerator ELSA at Bonn University provides a beam of polarised and unpolarised electrons with a tunable energy of up to 3.5 GeV. Its hadron physics programme using the large acceptance CBELSA/TAPS and BGO-OD detectors is devoted to baryon spectroscopy via meson photoproduction using polarised beams and polarised targets. The CBELSA/TAPS experiment, which combines the Crystal Barrel and TAPS electromagnetic calorimeters, is ideally suited to investigate the photoproduction of neutral mesons decaying into photons. BGO-OD is a newly commissioned experiment at ELSA, consisting of a central BGO calorimeter and a large aperture forward magnetic spectrometer. This setup allow detection of complex final states with neutral and charged particles and is particularly suited for the study of vector meson and associated strangeness photoproduction.

MAMI @ Mainz
The Mainzer Mikrotron (MAMI) is an electron accelerator delivering beams of electrons and photons up to a maximum energy of 1.5 GeV. Many high-precision measurements of meson photoproduction near threshold have been performed and are planned for the future. In addition to being able to produce polarised beams, cryogenic target technology has allowed for the deployment of polarised targets, and recoil polarisation techniques have been developed. Results from MAMI nicely complement those from Bonn and JLab. MAMI is also a unique meson factory with world-class photoproduction rates for η, η' and ω-mesons. Furthermore, precision

measurements of the kaon-nucleon interactions and of light hypernuclei are carried out at the A1 experiment.

HADES @ GSI and FAIR

HADES is operated at the SIS18 and was designed to investigate microscopic properties of resonance matter formed in heavy-ion collision in the 1–2 AGeV energy regime via e^+e^- and strangeness production. Also, the underlying processes are studied using beams of pions, protons and deuterons, providing a wealth of hadron physics measurements in the field of strange and non-strange baryon spectroscopy, as well as hadronic interactions and electromagnetic baryon transitions in the time-like region. HADES will soon be equipped by an electromagnetic Calorimeter and will be operated in future at FAIR with proton beams up to 30 GeV and ion beams up to 8 AGeV.

PANDA @ FAIR

The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. Antiprotons produced by a primary proton beam will then be stored into the High Energy Storage Ring (HESR) and collide with the fixed target inside the PANDA Detector. PANDA will study antiproton-proton interactions in the centre of mass energy range between 2.0 and 5.5 GeV and will be unique in the world in terms of beam momentum resolution and luminosity. The use of a general-purpose detector with excellent performance in terms of resolution and sensitivity will enable PANDA to carry out a comprehensive and far-reaching experimental programme from hadron spectroscopy to hadron structure and hadronic interactions, thus exercising a huge impact on the field. Given the recent positive developments of the FAIR project, PANDA can be expected to become operational in the first few years of the next decade.

LHC @ CERN

The Large Hadron Collider beauty (LHCb) experiment was designed to study matter-antimatter asymmetries through b-quark decays. After the reported discovery of a charmed pentaquark state, it has an important role to play in hadron spectroscopy. There are plans by the AFTER collaboration to run the LHC in fixed target more with and without polarisation. This will allow for probing rare proton fluctuations at large x, studies of vector boson production near threshold and studies of TMDs and the gluonic structure of the nucleon via Drell-Yan reactions.

NICA @ JINR

The Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research in Dubna, Russia, will provide important new opportunities for investigations of the nucleon spin via Drell-Yan processes. Longitudinally polarised proton and deuteron beams will become available, as well as a dedicated detector for spin physics.

Global perspectives

The most important experimental contributions to hadron physics outside Europe come from facilities in the United States (JLab), China (BESIII) and Japan (Belle2). They are briefly discussed in the following. Other significant contributions to hadron physics will come from the VEPP-2000 e^+e^- collider (Novosibirsk, Russia), as well as from the Japan Proton Accelerator Research Complex (J-PARC) at Tokai and other Japanese facilities such as LEPS @ SPring-8 and ELPH @ Tohoku. Furthermore, hadron structure investigations will profit enormously from an Electron-Ion Collider, which is under consideration in the US.

JLab, Newport News, VA, United States

In the USA, Jefferson Lab is completing a major upgrade that involves doubling the accelerator energy to 12 GeV, upgrading the equipment of the existing experimental Halls and building the new Hall D. The latter hosts the GlueX experiment, which is designed to study meson spectroscopy in the light quark sector, making use of a high-intensity tagged photon beam and of a hermetic large acceptance detector. This will be complemented by the hadron spectroscopy programme carried out in Hall B with the CLAS12 detector that will use both quasi-real and virtual photon production to carry out an extensive programme in light quark meson and baryon spectroscopy. The new kinematic domain accessible by the increased beam energy will also allow for the multidimensional exploration of nucleon structure at increased values of momentum transfer. With its extremely high luminosity, JLab at 12 GeV will become a leading facility for accurate measurements of TMDs and GPDs in the coming years.

BESIII, Beijing, China

The Beijing Spectrometer (BES) is a general-purpose detector located in the interaction region at the BEPC storage ring, where the electron and positron beams collide with centre-of-mass energies ranging from 2 GeV to 4.6 GeV. The e^+e^- collider is part of the Institute of High Energy Physics, Beijing. BESIII features a very rich experimental programme with a very prominent series of hadron physics measurements, from hadron spectroscopy (light hadrons, charm and charmonium, both conventional and exotic) to hadron structure (electromagnetic form factors, fragmentation functions). The experiment is currently in the process of upgrading its central tracker and is expected to run into the first years of the next decade.

BELLE2, Tsukuba, Japan

Designed as a B factory, the BELLE detector has had an important impact in the discovery of new mesonic states. The KEKB e^+e^- collider which delivered beams to BELLE will soon be upgraded to the Super-KEKB accelerator, and a commensurate upgrade to the detector (BELLE 2) will be complete. There is a good chance that this facility will continue to yield important hadron spectroscopy results, in addition to its main objective of studying CP-violation.

4.1.9. Recommendations

Since the publication of the last Long Range Plan in 2010 enormous progress has been achieved, which presents clear evidence that Hadron Physics is a thriving field that has significantly extended our knowledge about the properties and interaction processes of hadrons. The availability of new experimental facilities, as well as progress in the theoretical treatment of hadronic systems has been of crucial importance. Some of the most important milestones concerning the experimental infrastructure include the successful upgrade of COMPASS and the completion of the 12 GeV upgrade at JLab. They are complemented by several accelerator facilities operated by universities, such as ELSA (Bonn) and MAMI (Mainz), with the MESA accelerator being on track for commissioning in 2020. GSI also contributes to the European research effort in hadron physics via the HADES experimental programme, which will continue to operate at FAIR.

The COMPASS experiment at CERN has made important contributions to hadron structure and spectroscopy, and data taking for the GPD run has started. At ELSA new baryonic states have been discovered while existing ones could be established more firmly. The spectroscopy programme of ELSA will continue performing polarisation experiments. A broad experimental programme on form factor measurements and spectroscopy is in place at MAMI. This will be extended further to allow for precision measurements of electromagnetic form factors, as well as parity-violating processes in ep scattering in the years after 2020. This also impacts on other fields such as atomic physics and tests of fundamental interactions.

Several important recent discoveries have firmly established that QCD predicts a much richer hadronic spectrum as would be expected from the quark model. The most spectacular examples include the observation of the Z_c particles at BESIII and the pentaquark at LHC-b.

Although the completion of the FAIR facility and the PANDA experiment have been delayed, they are eagerly awaited by the international community. It is important to note that the political decisions have now been taken which will secure the construction of FAIR and PANDA and the start of the physics programme within the next five years.

Against this backdrop we make the following recommendations:

First recommendation: **Completion of the PANDA experiment at FAIR without further delays.**

The strategic importance of PANDA for hadron physics cannot be underestimated. It provides a unique opportunity for a comprehensive research programme in hadron spectroscopy, hadron structure and hadronic interactions. The combination of PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world. Despite the delays in its construction, PANDA continues to be viewed as a major flagship experiment, which attracts a large international community.

One of the key features of PANDA and the entire FAIR accelerator complex is the availability of an antiproton beam. Therefore, the completion and continued operation of the High Energy Storage Ring (HESR) is vital to sustain this unique research environment.

Second recommendation: Support for a research programme in precision physics at existing facilities

The currently operating facilities offer high-quality research programmes. Very significant new results can be expected not only from the big laboratories (such as CERN, JLab and IHEP), but also from smaller scale facilities, such as ELSA, HADES, MAMI and, in the near future, MESA, where high-precision experiments can be performed. They will not only greatly advance our knowledge about hadrons and their underlying structures, but also explore the limits of the Standard Model. A quantitative understanding of hadronic effects with sufficient precision is necessary to detect signatures for physics beyond the SM. These facilities, whose scientific potential is complementary to FAIR, provide an ideal training environment for future generations of scientists and a highly qualified workforce.

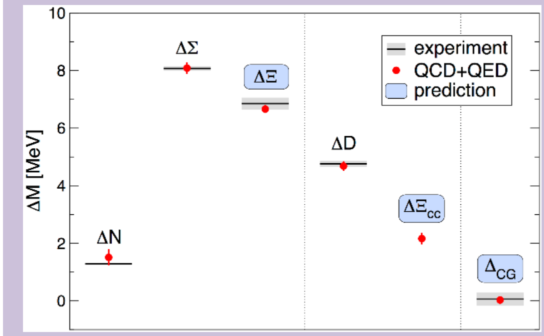
Third recommendation: Support for theory and computing

Many of the major insights of recent years have been gained by confronting increasingly sophisticated theoretical tools with experimental data. The interplay between complementary theoretical approaches such as lattice QCD, effective field theories and functional methods has been a great asset for obtaining a deep understanding of hadronic properties in terms of fundamental interactions. Further progress depends crucially on the availability of large-scale computing facilities. We recommend that European computing laboratories receive the support that is necessary to provide an environment for internationally competitive calculations in lattice QCD.

Lattice Box

Lattice Methods for Nuclear Science - A Grand Challenge for Computational Science

Numerical simulations of Quantum Chromodynamics formulated on a discrete space-time lattice have become an essential tool in strong interaction physics. Lattice QCD aims at providing quantitative information on nuclear and hadronic properties in terms of the fundamental constituents of matter and their interactions.



Baryonic mass splittings computed in Lattice QCD by the BMW collaboration. *ΔN* denotes the proton neutron mass difference including electromagnetic effects.

Thanks to the significant increase in the capabilities of large-scale supercomputers in conjunction with the enormous progress made in developing efficient simulation algorithms, calculations can now be performed at the physical value of the pion mass on a routine basis. The overall accuracy has even been pushed to a level at which it is possible to resolve isospin-breaking effects induced by electromagnetism, as well as the mass splittings between the up and down quarks. These recent refinements have, for instance, allowed for an accurate determination of the mass difference between proton and neutron from first principles. Lattice QCD is also an essential ingredient for the interpretation of experimental data collected in heavy-ion collisions, in order to explore the phase diagram of strongly interacting matter. Furthermore, lattice methods are applied to study properties of nuclear matter. Here the numerical simulation of effective theories for light nuclei has proved very successful and enabled, for instance, the *ab initio* study of the scattering of alpha particles.

These examples show that numerical simulations of theories describing strongly interacting systems have become an indispensable tool for a great variety of problems in nuclear science. Further progress in this field relies not only on further theoretical and algorithmic developments but also on the availability of sufficient computer power. At the dawn of the era of Exascale computing, nuclear science has an important strategic role in supporting European leadership in computing.

EFT Box

Effective Field Theories

Effective field theories (EFTs) are a standard method for analysing physical systems with different energy scales. Crucial for the construction of an EFT is the notion of factorisation, whereby the effects in a physical system can be separated into short-distance and long-distance (low-energy) contributions, with each factor amenable to calculation by different techniques. The short-distance factor is typically calculated using analytic techniques, such as weak-coupling perturbation theory and the renormalisation group, while the low-energy contribution may be determined in lattice QCD or phenomenological methods. Low-energy EFTs such as Chiral Perturbation Theory retain as dynamical variables the relevant hadronic degrees of freedom, while the short-distance contribution is absorbed into effective coupling constants. The underlying scale separation is largely based on symmetries that emerge from QCD in some limit.

The approximate chiral symmetry among the up, down and strange quarks forms the basis for Chiral Perturbation Theory (ChPT) which is formulated in terms of the Goldstone boson fields describing the pions, kaons and η-mesons. ChPT is instrumental for our understanding of many of the properties of light mesons and baryons, in studies of pion and kaon interactions and in the construction of nuclear forces from QCD. It also plays an important role in lattice QCD calculations, by providing theoretical constraints for the chiral extrapolation to the physical pion mass.

The properties of hadrons that contain heavy quarks (charm and bottom) whose masses are bigger than Λ_{QCD} depend only weakly on the spin and the flavour of the heavy quarks. This approximate spin-flavour symmetry forms the basis for the Heavy Quark Effective Theory, which has been instrumental for studying the properties of D and B mesons. For hadrons containing two or more heavy quarks additional symmetries allow for the construction of other EFTs such as potential non-relativistic QCD. In this way a QCD-derived description of the properties of heavy quarkonia and of baryons with two heavy quarks could be achieved, which is important for our understanding of the X, Y and Z resonances discovered in the charm sector.

FM Box

Functional Methods

Functional approaches to QCD, including Dyson-Schwinger and Exact Renormalisation Group equations, are formulated at the level of the Green's functions of the theory, which contain all information on the physical content of QCD. Applications include determinations of the hadron spectrum, form factors and observables describing decays, and other processes involving hadrons such as Compton scattering or pion-nucleon interactions. Functional equations come in the form of an infinite tower of relations that couple Green's functions to one another in a hierarchical fashion. These exact equations need to be approximated ('truncated') in practice to allow for a numerical treatment. Truncation schemes at very different levels of sophistication have been developed: very simple approximations allow for making contact with quark model calculations; highly sophisticated and numerically demanding schemes admit a direct comparison with lattice QCD.

Phenomena of QCD in the strongly interacting regime like confinement and dynamical chiral symmetry breaking have been and are still being studied using these methods. Bound state equations are derived which allow for the determination of the spectrum and the wave functions of mesons and baryons including also 'exotic' objects like glueballs and tetraquarks. The gauge-invariant coupling of external currents allows for the extraction of form factors and production processes. One of the benefits of functional methods is the possibility to maintain Poincaré covariance. Thus they can be used in the light and heavy quark region alike, allowing for fruitful interactions with chiral perturbation theory and heavy quark effective theory, respectively. Systematic comparisons with other approaches including lattice QCD offer a very high potential for the identification of the physical mechanisms behind the observable phenomena.

g-2 Box

Meson form factors and the muon anomalous magnetic moment

The muon anomaly $a_\mu = (g-2)_\mu/2$ is a low-energy observable, which can be both measured and computed within the Standard Model with extremely high precision (see the discussion in WG 5). The present experimental value stems from the BNL E821 experiment and corresponds to an uncertainty of 0.54 ppm. It deviates from the SM prediction, whose accuracy is even slightly better, by more than three standard deviations. While the discrepancy is not sufficient to claim the observation of "new physics", it calls for a concerted international effort to increase the accuracy of both the direct measurement and the SM prediction. New direct measurements of $(g-2)_\mu$ are being prepared at Fermilab and JPARC and are scheduled to start taking data in 2017 and 2019, respectively. The goal is to reduce the uncertainty on the direct measurement by a factor of four. In order to allow for an interpretation of the improved direct measurements, improvements in the overall accuracy of the SM prediction are mandatory.

The SM prediction is limited by hadron-induced quantum corrections that cannot be estimated in perturbation theory. While the hadronic vacuum polarisation (HVP) contribution can be related to hadronic cross section measurements via a dispersion relation, one has had to rely mostly on model estimates to quantify the hadronic light-by-light scattering (HLbL) contribution. Recently, phenomenology-driven approaches were suggested for HLbL, relying on meson transition form factor data. Therefore, meson form factors not only provide insights into the structure of hadrons, but are also of utmost importance to increase the precision of the SM estimate for the HVP and HLbL contributions to $(g-2)_\mu$. The exclusive channel $e^+e^- \to \pi^+\pi^-$, which is determined by the pion vector form factor, contributes almost 75% to the dispersion relation for HVP. The importance of this channel and other channels with higher multiplicities has led to detailed experimental studies of the hadronic cross section at electron-positron colliders.

For the HLbL contribution, a dispersion-theory-based strategy was only recently suggested. In this approach, the relation to experimental data is much more subtle, and so is the diversity of the required data input. The most relevant contribution comes from pseudoscalar pole terms, which are linked to meson transition form factors, describing the coupling of the neutral mesons π^0, η and η' to two photons. A new campaign of precision measurements of these form factors is currently ongoing at various hadron facilities worldwide. Finally, also large-scale efforts using lattice QCD as well as Dyson-Schwinger equations are currently ongoing to determine the HVP and HLbL contributions.

Boxes with overlap among different WGs:

WG1: Hadron Physics

Lattice simulations of QCD allow for ab initio calculations of hadronic properties. Significant progress has been made in controlling the systematic uncertainties associated with discretisation artefacts, finite-volume effects and the variation with the quark mass to the precent level. Lattice QCD provides important information on the hadron spectrum, as well as on structural properties encoded in form factors and structure functions. A particular challenge for the next decade is the complete characterisation of a variety of hadronic resonances in terms of their masses and widths. This includes the newly discovered states in the charm sector, as well as glueballs, tetra- and pentaquarks. Finite-volume techniques, based on the Lüscher formalism, provide an elegant but computationally costly methodology for this purpose. Lattice studies of properties of the nucleon and other baryons have to overcome the large noise-to-signal ratio inherent in baryonic correlation function. This is a particular challenge for accurate determinations of form factors and other structural quantities of the nucleon.

WG2: Strongly interacting matter

Lattice QCD calculations are essential theoretical tools to study the phase diagram of QCD. At LHC energies the inclusion of dynamical charm quarks is particularly important. Increased computational power and further conceptual developments are required in order to tackle real-time processes and determine transport properties and spectral functions. The region of the phase diagram at low temperature and high baryon density is still inaccessible due to the severity of the sign problem. However, additional computational resources will allow one to push the boundary of the red region in the figure towards larger densities μ, possibly encompassing the region of the critical endpoint.

WG3: Nuclear Structure

Understanding the stability of nuclear matter is a major challenge for experimental and theoretical physics. Lattice methods have successfully captured the properties of nuclei up to $A \approx 6$, above which other many-body methods may be applied. The interplay between different theoretical formalisms, which provide complementary information, is crucial for further progress. Electromagnetism plays a major role, and lattice simulations of both QCD and QED have produced first promising results for small systems.