Whitepaper From DNP Town Meeting On Hadronic Physics

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1 Executive Summary

1.A Background

This White Paper presents the recommendations and scientific conclusions from the Town Meeting on Hadronic Physics that was held January 12-14, 2007 at Rutgers University as part of the NSAC 2007 Long Range Planning process. The meeting was held in coordination with the Town Meeting on Phases of QCD and included a full day of joint plenary sessions of the two meetings. One hundred twelve physicists registered for the meeting and the agenda is included in the Appendix.

The goals of the meeting were to highlight the progress in hadronic physics since the last Long Range Plan in 2001, prioritize the outstanding physics opportunities in the field for both the short term (~ 5 years) and the long term ($\sim 10 - 15$ years), recommend facilities, personnel and other resources necessary to take advantage of these opportunities, and assess the role of hadronic physics in the American Competitiveness Initiative and its impact on society. The program was organized around the five major areas of hadron structure at short distances, hadron structure at long distances, nuclear structure at short distances, hadron spectroscopy, and hadron physics theory. The goal of the joint session was for the US QCD community to explore its common future interests and, in particular, the need and justification for an electron-ion collider.

This executive summary presents the recommendations of the Town Meeting and explains their rationale. Section 2 summarizes progress in hadron physics since the last Long Range Plan and Section 3 outlines the physics program for the immediate future, including the JLab 6 GeV program, RHIC spin physics, and opportunities at other domestic and international facilities. Finally, Section 4 describes outstanding long term opportunities

1.B Recommendations

Hadron physics is at the frontier of modern nuclear science, providing outstanding challenges and opportunities. The fundamental goal of hadron physics is to understand the structure and interactions of protons, neutrons, and other hadrons. The facility at Jefferson Lab has been playing a world-leading role in exploring the fundamental properties of the building blocks of atomic nuclei since it began research operations late in 1995. Much progress has also been made using other facilities, notably at DESY, Mainz, CERN, and, more recently, polarized proton-proton collisions at RHIC.

It is essential that the US continues to make significant investments in hadronic physics over the next 5-15 years if we are to further our basic knowledge about strongly-interacting nuclear matter and to maintain our world-leadership position in this field. To achieve this goal, we make the following five recommendations:

We are gratified that the 12 GeV Upgrade of CEBAF, a formal recommendation of the last Long Range Plan, is now well underway, with CD-2 expected this year. The associated science program has three major elements: the fundamental structure of hadrons, the physics of nuclei, and fundamental symmetry tests in nuclear physics. The planned research program in each of these areas has strengthened and solidified since the last Long Range Plan, underscoring the importance of constructing the Upgrade as quickly as possible. Hence, we recommend:

- **Recommendation 1: Our highest priority is the timely completion of the 12 GeV Upgrade of CEBAF and the start of its exciting research program.**

The research facilities currently in operation in the US are among the best in the world. To fully realize the potential of these facilities, it is crucial that adequate funds be provided for their efficient utilization. University-based research groups and laboratories are a key part of the infrastructure of the field and must be strengthened if we are to maintain our competitiveness. Therefore, we recommend:

- **Recommendation 2: It is imperative that funding be provided to make effective use of our major research facilities, including the operation of CEBAF, RHIC-SPIN, and TUNL-HIγS. We recommend increased federal investment in both people and equipment at our universities.**

Nuclear theorists play an essential role in the development of future research directions, the interpretation of experiments, and the articulation of the impact of these experiments to the broader physics community. In many cases, significant contributions originate from our young scholars. In addition to the importance of sustaining this effort to ensure its continuing success, a number of key theoretical challenges remain. Meeting these challenges through targeted new investments is critical to realizing the full impact of the scientific program outlined here. Therefore, we recommend:

- **Recommendation 3: We strongly recommend new investments in the next generation of nuclear theorists who are critical to the future of the field, and targeted support for initiatives to solve the key scientific problems identified in the Long Range Plan.**

The communities at the Hadronic Physics and Phases of QCD Town Meetings have jointly concluded that the next-generation facility for studies of hadron structure and QCD matter at high-energy should be an electron-ion collider with the center-of-mass energy in range of 30 to 100 GeV and a luminosity of at least 10^{33}/A cm^{-2}s^{-1}. This collider will address compelling physics questions essential for understanding the fundamental structure of matter, including precision mapping of the sea-quarks and gluons to determine the full spin and flavor structure of the nucleon, and definitive study of the universal nature of strong gluon fields manifest in nuclei. Hence the following joint recommendation is made by the whole US QCD community:

- **Recommendation 4: A high luminosity Electron-Ion Collider (EIC) facility is the highest priority of the QCD community for new construction after the JLab 12 GeV Upgrade and the RHIC II luminosity upgrade.**

  This goal requires that R&D resources be allocated for expeditious development of collider and detector design.

Recently, a workshop on Education and Outreach has examined the role of education and outreach in the US nuclear science community. The White Paper *"A Vision for Nuclear Science*

Education and Outreach for the Next Long Range Plan" makes the following two key recommendations:

1) The nuclear science community should increase its involvement and visibility in undergraduate education and research, so as to increase the number of nuclear science PhDs and the number of scientists, engineers and physics teachers exposed to nuclear science; and

2) The nuclear science community should develop and disseminate materials and hands-on activities that illustrate and demonstrate core nuclear science principles to a broad array of audiences, so as to enhance public understanding and appreciation of nuclear science and its value to society. These recommendations are endorsed by the hadron physics Town Meeting, and therefore:

Recommendation 5: We strongly support the recommendations of the White Paper on Education and Public Outreach.

1.C Physics Rationale for the Recommendations

Fundamental questions driving the theoretical and experimental exploration of hadronic phyiscs include:

- What is the role of gluons in nucleons and nuclei?
- What is the internal spin and flavor landscape of the hadrons?
- How do hadron final states emerge from quarks and gluons in high-energy scattering?
- What are the effective degrees of freedom governing hadron spectroscopy and their low-energy properties?
- What role does the approximate chiral symmetry of QCD play in determining hadron properties?
- What happens when two nucleons in the nucleus get very close?

Answering these questions requires sophisticated experimental facilities, creative theoretical advances, and a talented and superbly educated scientific work force.

Gluons are ubiquitous components of hadrons, producing confinement, contributing as much as 50% of the momentum of the nucleon, most of its mass and a large fraction of its angular momentum. Yet, thus far, their signature has been hard to observe in low-energy spectroscopy. Hence, a major goal of the JLab 12 GeV Upgrade is to seek evidence of gluon degrees of freedom in spectroscopy, possibly through gluonic flux tube excitations in hadrons and the observation of hadrons with exotic quantum numbers. Since gluons can be probed directly through a variety of perturbative QCD processes at high energy, an electron-ion collider is an ideal tool to study the gluonic degrees of freedom of QCD in higher energy processes.

The spin and flavor physics of hadrons reveals detailed information about their structure. Two decades of dedicated deep-inelastic scattering experiments have shown that about 40% of the nucleon's spin is carried by the helicity of u and d quarks, and the RHIC spin program, together with semi-inclusive DIS experiments from HERMES, COMPASS, and JLab, will continue to probe the contribution of quark and gluon helicities to the nucleon spin. Generalized parton distributions

(GPD's) probed through deeply virtual Compton scattering and similar processes will provide complementary information on the contribution of quark orbital angular momentum to the nucleon spin. The contributions of different quark flavors to physical observables probes the flavor structure of the nucleon wave function, and strange quarks are particularly interesting because they uniquely display the role of sea quarks.

Generalized parton distributions connect the spatial distributions of quarks (determined from elastic electron scattering) with their longitudinal momentum distributions (determined from deep inelastic scattering) and quantify the correlations between them. They provide a framework for developing a three-dimensional picture of the nucleon and have led the way to the development of a new class of experiments, deep exclusive scattering, which provide direct access to the structure of the quark and gluon correlations in the nucleon.

In high-energy processes, although the hard scattering of quarks and gluons is well understood perturbatively, there is presently no quantitative understanding of the hadronization process that produces the observed hadronic final states. Hence, at this stage, thorough high-precision studies of hadron final states are necessary components of future DIS and hadron-hadron experiments, and comprehensive phenomenological analyses are essential to determine hadronization and fragmentation probabilities.

In terms of nucleon degrees of freedom, when two nucleons get close to each other in a nucleus, strong short-range interactions generate strong correlations. The resulting depletion of nucleon occupation in low-lying states and the generation of high-momentum nucleons can be probed through single nucleon knock-out experiments. In terms of quark degrees of freedom, when two nucleons get close together, one might expect the quarks from the nucleons to overlap, leading to short range correlations that could be probed through DIS in the $x > 1$ region. The study of such correlations could be valuable in understanding the role of quarks in nuclei.

Hadronic physics has advanced significantly since the last Long Range Plan. In parton physics, the neutron spin asymmetry in the DIS region has been measured accurately for the first time at large x at JLab; the spin asymmetries measured at HERMES, COMPASS, and RHIC provide our first glimpse at the polarized gluon distribution; and large transverse single-spin asymmetries were found both in polarized DIS at HERMES and proton-proton collisions at RHIC. The first data on a new class of hard scattering processes, Deeply-Virtual Compton Scattering (DVCS), has been taken, and results from JLab indicate the feasibility of these experiments to carry out nucleon "tomography". In elastic nucleon scattering, the electric form factor of the proton was found to be significantly different from the values that had been extracted using the Rosenbluth approach; the neutron electric form factor has been measured with much better precision over a much larger range of momentum transfers; and the strange form factor of the proton has been probed by several dedicated experiments. Our understanding of nucleon-nucleon short range correlations has been advanced by high-precision measurements of single- and two-nucleon knockout reactions and by inclusive electron scattering over a broad range of kinematics. Data has been accumulated on the excited state spectrum of hadrons and its analysis and interpretation are underway.

In theoretical hadronic physics, understanding the physical content of generalized parton distributions and the range of ways to measure them has opened up a whole new area of research. Effective field theory has provided a precise tool for quantitatively separating physical processes at different energy scales. Lattice QCD has developed to the point of calculating nucleon form factors, moments of structure functions, and generalized form factors from first principles and in agreement with experiment.

Precise experimental knowledge of hadron structure and spectroscopy is a major driving force in our understanding of hadronic physics. Much of our new experimental data has come from JLab, which has operated throughout the period since the last Long Range Plan and had its scientific reach extended significantly through developments in polarized electron technology, a steady increase in its maximum energy, and the construction of a variety of dedicated experimental equipment. Major contributions have also come from operations of the LEGS facility at BNL and our use of important international facilities such as DESY and CERN. Development of high polarization and luminosity for proton beams at RHIC has been crucial to the realization of the RHIC spin physics program.

The 12 GeV Upgrade at Jefferson Lab will offer electron beams with a unique combination of high intensity, duty factor, polarization, and kinematic reach, opening new opportunities for discovery in our field. For the first 5 years of its operation, it will support a comprehensive physics program including: (1) searching for exotic mesons and thereby exploring the mechanism of quark confinement, (2) expanding our knowledge of the charge and current distributions in the nucleon, (3) deepening our knowledge of the spin, flavor, and transverse momentum dependence of valence parton distribution functions (4) providing a new, tomographic view of hadron structure through GPD's, (5) exploring the spin and flavor dependence of the EMC effect and studying the propagation of quarks through nuclear matter, and (6) searching for new physics beyond the Standard Model through precision tests of its predictions.

In the near future, the HIγS facility at Duke will make accurate measurements of the nucleon polarizabilities, providing precision tests of chiral dynamics. The new Drell-Yan experiment at FNAL allows accurate measurements of antiquark distributions at large x.

The next exciting step in exploring the quark and gluon structure of hadrons is to build an electron-ion collider with a center-of-mass energy in the 30 to 100 GeV range and a luminosity of at least 10^{33}/A cm^{-2}s^{-1}. The EIC will complement our present understanding and the detailed explorations of the valence regime, which will be completed by the JLab 12 GeV Upgrade, by enabling precise and detailed studies of the nucleon in the regime where its structure is dominated by gluons and sea quarks. Scientific highlights would include: (1) measurement of the contributions of gluons, sea quarks, and quark orbital angular momentum to the nucleon spin, (2) determination of the three-dimensional spatial quark and gluon structure of the proton, (3) precision study of the proton's gluon distribution over a wide range of momentum fraction, and (4) mapping new spin-dependent features of the quark fragmentation process.

Education and outreach are essential to the QCD and Hadronic physics community, to the nuclear physics community, and to the nation. Education is crucial both for attracting and training future generations of nuclear physicists in our field and those who will make important contributions to medicine, energy, and national security. More broadly, it is important to expand our education and outreach at all levels, including public schools and public media to improve scientific literacy in a world increasingly affected by the science policies of our elected leaders.

2 Progress Since Last Long Range Plan

Hadron physics has witnessed significant advances since the last Long Range Plan. In parton physics, the nucleon spin asymmetry in the DIS region has been accurately measured for the first time at large x at JLab; the spin asymmetries measured at HERMES, COMPASS, and RHIC provide the first hint about the polarized gluon distribution; large transverse single-spin asymmetries are found both in polarized DIS at HERMES and proton-proton collisions at RHIC; and first data on a new class of hard scattering process, deeply-virtual Compton scattering, has been accumulated. In elastic nucleon scattering, the electric form factor of the proton is found to be significantly different from what has been extracted from the Rosenbluth approach; the neutron electric and magnetic form factors are now measured to much better precision and to much smaller distance scales; the strange form factor of the proton has been probed by several dedicated experiments. Understanding of nucleon-nucleon short range correlation has been advanced by high-precision measurement of single- and two-nucleon knock out reactions. Much data have been accumulated that contain useful information on the excited spectrum of hadrons. Finally, hadron physics theory, and lattice QCD calculations in particular, have helped us understand the physics of strong interactions quantitatively. Some highlights of these achievements are described in this section. We regret that limitations of both time and space do not permit a more complete survey of the exciting developments in the field.

2.A Hadron Physics at Short Distances

Measurements of parton distribution functions (PDFs) are central to understanding the structure of hadrons and to making quantitative QCD calculations in high-energy scattering. Despite many years of dedicated efforts, many key pieces of information about the parton distributions are still missing. Spin plays a fundamental role in many physical processes and in understanding the dynamics of fundamental interactions. While the low-energy nucleon spin structure can be described well by simple quark models, these models failed to describe high energy experiments involving nucleon spin. The fact that the helicity of quarks and anti-quarks barely contributes to the nucleon's spin was the surprising observation of the EMC collaboration [As88] in 1989. Despite experiments through 1990s (E142-E155 at SLAC, SMC at CERN and HERMES at DESY), where remarkable progress was made in technology and computing and where new theoretical tools were developed [Ba05b] to handle the precision data sets obtained, we remain a long way away from understanding fully the helicity/spin structure of the nucleon. In another surprise, large *transverse* spin asymmetries have been measured in polarized proton-proton scattering and in DIS experiments [Ai05].

In the past five years the two premier experimental facilities in the US: the CEBAF facility at the Thomas Jefferson National Accelerator Facility (JLab) and the Relativistic Heavy Ion Collider (RHIC) at BNL, in the polarized collider mode, have come of age and contributed spectacularly in furthering our knowledge of QCD and the nucleon's structure by producing precise data, that have provided stringent tests for existing theories and models. With the complementary techniques that they (RHIC and CEBAF) employ, these facilities are exceptionally well suited to address unanswered questions about the nucleon's spin structure, now and into the next decade. CEBAF, coupled with the experimental spectrometers in Halls A, B, and C, has made measurements with unprecedented precision. The focus has been on the regime of distance and energy scales where non-perturbative QCD applies and on the transition region, where QCD changes from non-perturbative to perturbative. Understanding the transition region is essential for understanding how QCD "works" in the non-perturbative regime, where we find most nuclear matter. Quite omplementarily, the RHIC spin program at BNL has evolved into a powerful new tool for the exploration and understanding the nucleon's spin at high energy, firmly in the perturbative QCD regime. International collaborations, such as HERMES at DESY and COMPASS at CERN, have made significant contributions to spin physics through lepton-nucleon DIS. Motivated by the precise data that are now available and by the theoretical tools now available to analyze them, physicists are *beginning* to develop a coherent picture of both the longitudinal and the transverse spin structure of the nucleon. The new data and their impact on our current understanding of hadron/nucleon structure was reviewed in three talks at the Town Meeting: hadron structure at short distance and high energies [Ch07a]; hadron structure at high-x [Ch07b]; and the transverse structure of the nucleon [Ma07]. A brief summary of the progress in these areas is presented in this section.

2.A.1 The longitudinal spin structure of the nucleon

Parton distributions: The behavior of parton distributions at high x is of great importance and interest primarily because in the high x region the nucleon can be described by valence quark dominance. Valence quark dominance allows direct comparisons of the high-x data with relativistic constituent quark models (RCQM) [Is99] and pQCD [Br95], providing direct tests of concepts such as SU(6) symmetry and hadron helicity conservation and probing the role of quark orbital angular momentum (OAM). Precise knowledge of parton distributions in the valence region also provides crucial input for high energy accelerator searches for physics beyond the Standard Model.

Despite the paramount importance of the valence quark distributions, no precise measurements were available in that region for the nucleon's spin structure before JLab. Now, the virtual photon asymmetry A_1 for the proton and the deuteron have been measured to intermediate x, using polarized NH_3 and ND_3 targets respectively [Dh06], for a wide kinematic range covering both the resonance and the DIS regions. Results for the neutron A_1^n obtained from a polarized ^{3}He target have improved the precision on this quantity, to $x = 0.6$, by an order of magnitude [Zh03a]. The extracted $\Delta d/d$ distribution contradicts the pQCD prediction based on helicity conservation. Contrary to our naive expectation, the quark OAM (which is related to its transverse motion) plays an important role in the region explored so far. The extracted $\Delta q/q$ are shown in Fig. 1a.

It has been recently demonstrated that the data from JLab experiments provide crucial input for global QCD analyses [Le06b, So05, Ac05] on many fronts: they improve the quark distributions, and also provide a sufficient Q^2 lever arm, when added to available data, to allow a better extraction of the gluon distribution from the QCD evolution equations [Le06b]. Furthermore, the JLab data have also been used [Le05] to extract higher-twist effects in the spin structure, allowing new data sets in this kinematic region to be included in global DIS fits. These data have also demonstrated the transition from partonic to hadronic degrees of freedom, for instance from the Bjorken Sum Rule at large Q^2 to the GDH sum rule at the photon point, and delineate the kinematic region over which spin structure functions in the resonance region are dual to those in the DIS regime.

Sum Rules and Moments of Nucleon Spin Structure Nucleon spin structure studies have yielded many exciting and surprising results. Moments of the spin structure functions and the associated spin sum rules provide one of the cleanest means for studying nucleon structure and

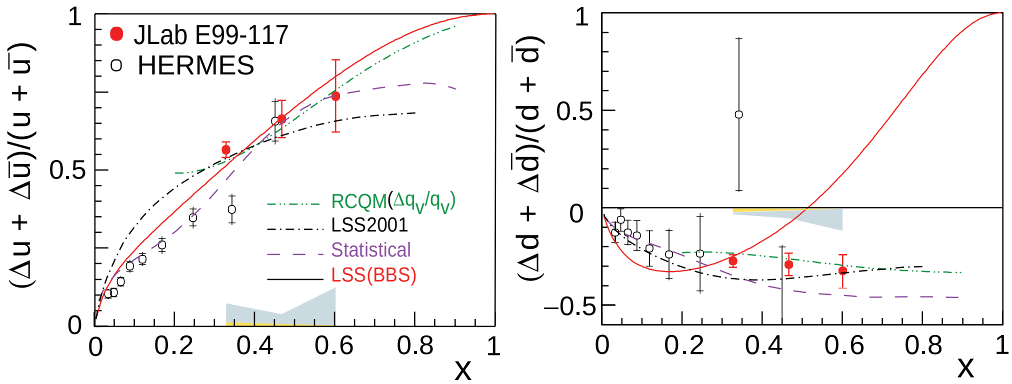


Figure 1: **a)** JLab (6 GeV) results for polarized quark distributions derived from the neutron virtual photon asymmetry A_1^n. The LSS(BBS) curves are pQCD predictions assuming hadron helicity conservation.

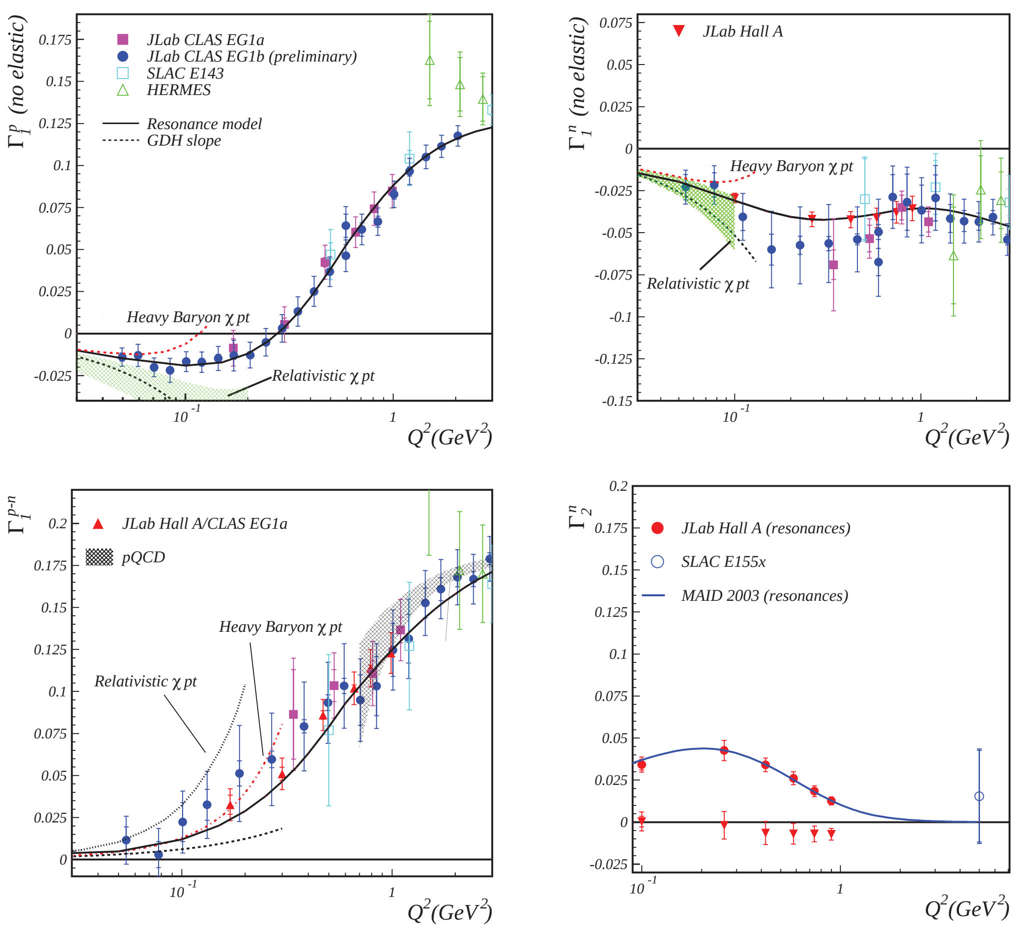


Figure 1: **b)** JLab results on Γ_1^p, Γ_1^n, Γ_1^{p-n} and Γ_2^n, together with world data and comparisons with theoretical calculations.

Quantum Chromodynamics (QCD). They are among the few experimental quantities that can be compared directly with theoretical calculations over a broad range of momentum-transfer (Q^2. Early spin moment results provided one of the cleanest tests of QCD via measurement of the Bjorken sum rule at high Q^2 where QCD can be solved perturbatively due to the property of "asymptotic freedom". Recent activities have focused on the low to intermediate Q^2 region, where QCD can not be solved analytically and other means, such as Lattice QCD or effective field theories, are needed. In the low Q^2 region, Chiral Perturbation Theory (χPT), an effective field theory that takes into account the chiral symmetry property of QCD, can make predictions for the spin moments. At intermediate Q^2, where the transition from the perturbative region to the confinement region occurs, Lattice QCD is expected to provide predictions in the near future.

The recent precision results from JLab on the proton and the neutron provide, for the first time, a comprehensive landscape of the nucleon spin structure functions at low to intermediate Q^2. Figure 1b shows $\Gamma_1^p(Q^2) = \int_0^1 g_1^p(x, Q^2)dx$, the first moment of the g_1 spin structure function (the generalized Gerasimov-Drell-Hearn sum) for the proton; also shown are the moments for the neutron and the proton-neutron difference (the Bjorken sum). The data show a smooth transition from high Q^2 to low Q^2, with the transition to values consistent with pQCD ocurring at a much lower Q^2 than was expected. At the lowest Q^2 of the data set (0.05 - 0.1 GeV^2), where χPT is expected to become valid, the data agree reasonably well with two state-of-the-art χPT calculations. To provide a pecision benchmark test, new data have been taken to extend the results to very low Q^2 (down to 0.02 GeV^2). Also shown are values of the moment of g_2 for the neutron. The Burkhardt-Cottingham sum rule predicts this moment to be zero for all Q^2 values. These data show that the B-C sum rule is satisfied within the experimental uncertainties.

Gluons and the spin of the nucleon: Experiments with polarized protons colliding at RHIC probe the proton spin in profound new ways that are complementary to DIS. Understanding nucleon structure and the nature of confinement of quarks and gluons inside the nucleons is a major goal of nuclear physics and the primary objective of the RHIC spin program. One emphasis is the measurement of the gluon contribution to the proton spin. A second will be a clean, elegant measurement of the quark and anti-quark polarizations, sorted by quark flavor, via parity-violating W boson production. RHIC is also probing the structure of transversely polarized protons, which may be related to the orbital angular momentum of the quarks and gluons in the proton.

The key tool for this work is polarized RHIC. Achievements of the past five years include: 60% average beam polarization and average luminosity $L = 2 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ (achieved in 2006 at $\sqrt{s}$ = 200 GeV); results for unpolarized cross sections for π^0, jet, and direct-photon production that are described well by next-to-leading order perturbative QCD [Rh07], providing the basis for extracting the gluon and anti-quark polarizations from spin asymmetries; and published results for helicity asymmetries for π^0 and jet production that rule out early theoretical predictions of a gluon contribution two or three times the proton spin [Ad06, Ad06b]. A sensitivity at the level of distinguishing between whether the gluons contribute 70% or little of the proton spin is expected from the 2006 data (see Fig. 2) and future runs. For more details of the recent achievement the reader is referred to the RHIC Spin White Paper prepared for the 2007 NSAC Long Range Plan and the references within [Rh07].

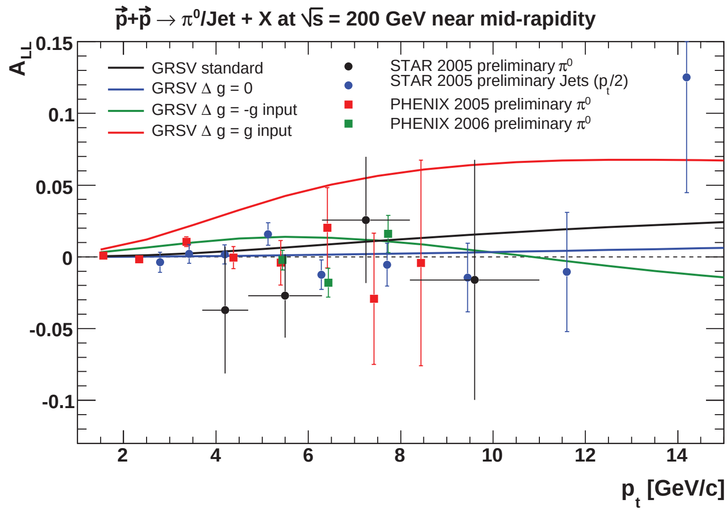


Figure 2: PHENIX and STAR preliminary data on the double spin asymmetry in inclusive π^0 and jet production at RHIC, respectively, at $\sqrt{s} = 200$ GeV. Also shown are theoretical curves which were pQCD fit to the deep inelastic fixed-target data and some models with additional assumptions of polarized gluon distribution [Gl96]

2.A.2 The transverse spin structure of the nucleon

Within the leading-twist collinear formalism of QCD, vanishingly small transverse single spin asymmetries (SSA) are expected. The large asymmetries observed experimentally have stimulated theoretical developments aimed at understanding the transverse spin structure of the proton. One important objective is to elucidate the role of parton orbital angular momentum. The Sivers effect [Si06], which involves a correlation between the parton intrinsic transverse momentum k_T and the proton spin in the initial state, may provide this opportunity. A further key objective is to access the transversity distributions through the Collins-Heppelmann effect [Co93], where the Collins function correlates transverse momentum of hadrons relative to the thrust axis with the transverse spin of the parton in the fragmentation process.

The precise knowledge of the transversely polarized quark distributions is essential to a full understanding of the nucleon structure. The difference between the transversely and longitudinally polarized quark distributions is a measure of the relativistic nature of the motion of quarks in the nucleon [Ba01]. The quark transversity distributions are intimately related to the chiral property of QCD, being entirely due to chorally odd (helicity-flipping) effective interactions induced by the spontaneous breaking of chiral symmetry in QCD. Due to their chiral-odd property, they are decoupled from the gluons and are essentially valence-dominated.

The Sivers effect has witnessed particularly interesting theoretical developments recently. It was realized that the Sivers functions contribute with opposite signs to the single-spin asymmetries for DIS and Drell-Yang processes [Br02, Co02, Ji02, Be03b, Bo03]. This remarkable prediction of “non-universality” of the Sivers functions really tests all concepts for analyzing hard-scattering reactions that we know of, and awaits experimental scrutiny. The process-dependence of the Sivers functions will also manifest itself in more complicated QCD hard-scattering. An example is the

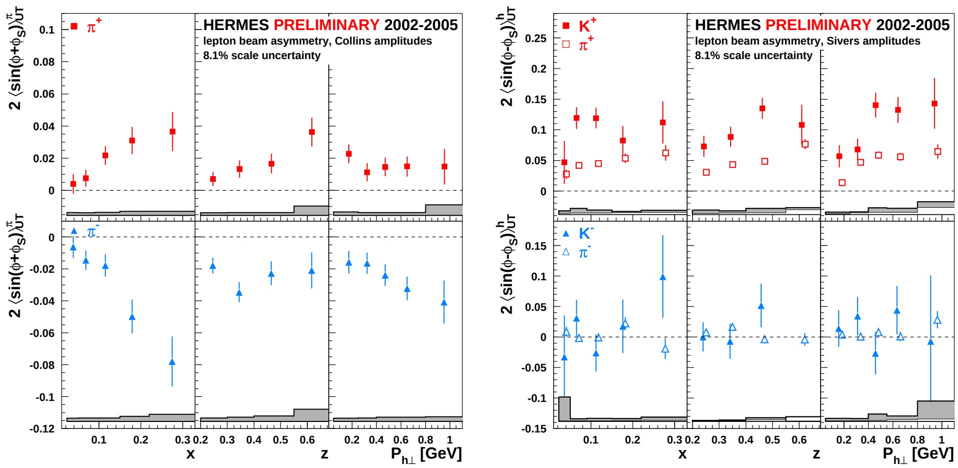


Figure 3: Collins (left) and Sivers (right) asymmetries from HERMES for positive and negative pions and kaons.

single-spin asymmetry in di-jet angular correlations [Bo04b, Vo05], which is now under investigation at RHIC.

Experimental work on transverse spin physics is a world-wide effort. Recent experimental progress includes direct observation of the Collins function in e^+e^- collisions by the Belle collaboration [Se06]. Both Collins and Sivers type asymmetries have been clearly observed by the HERMES collaboration in semi-inclusive deep inelastic scattering (SIDIS) from a transversely polarized hydrogen target [Ha06]. No transverse spin asymmetries have been observed by the COMPASS collaboration in SIDIS from a polarized deuterium target, consistent with theoretical expectations of cancelations between up quark and down quark contributions, which are averaged in their measurement. RHIC has begun such measurements, already with a confirmation of the earlier measurements of Fermilab E704 [Kr98], and is poised for more complete studies in future runs. Complementary experiments to explore and understand the intricacies and richness of the transverse momentum distribution PDFs (TMD PDFs) are ongoing at Jefferson Laboratory by the CLAS collaboration [Av05a].

When single spin-momentum correlation is associated with a fragmenting quark (Collins fragmentation function, CFF) through its coupling to the chiral odd transversity distribution function, h_1, knowing one of these quantities permits the other to be determined. Therefore, the recent measurement of the fragmentation function by the BELLE collaboration [Se06], taken together with the known SIDIS asymmetries from HERMES [Ha06], should allow the first extraction of the transversity distribution h_1.

In Hall A [Ji06] at Jefferson Laboratory, using a polarized ^{3}H target, the Collins and Sivers asymmetries will be measured on the neutron [Af07] soon. These measurements are setting the groundwork for the next round of high-precision measurements at future facilities, such as the JLab 12 GeV Upgrade, enabling a model-independent determination of the transversity distributions, the Collins functions and the Sivers functions, including the moment of the transversity distribution known as the tensor charge, a fundamental property of the nucleon.

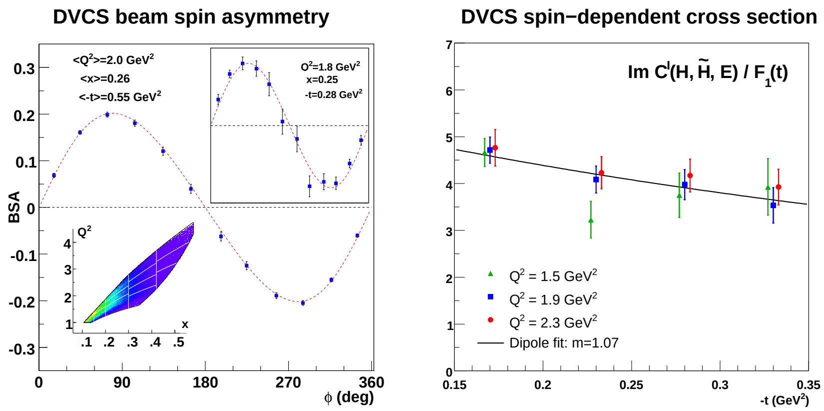


Figure 4: DVCS results from JLab with 6 GeV beam energy. *Left:* The beam spin asymmetry A_{LU} from CLAS experiment E01-113 (preliminary) vs. the azimuthal angle ϕ. The plot shows the data integrated over the entire kinematic range, while the insets show the kinematic coverage in x and Q^2 and the statistics achieved in a typical (x, Q^2, t) bin. *Right:* The first measurement of the DVCS cross section by the Hall A experiment [Mu06, Ro06]. Shown is the dimensionless coefficient of the spin–dependent Bethe-Heitler/DVCS interference cross section at $x = 0.36$ as a function of t for different values of Q^2. The observed Q^2–independence is consistent with the scaling behavior predicted by QCD. The coefficient is proportional to a linear combination of GPD's, which can be disentangled through target spin–dependent measurements.

2.A.3 Toward a three–dimensional picture of the nucleon

Over the last 10 years a comprehensive framework has been developed for describing the quark and gluon structure of the nucleon based on the concept of generalized parton distributions (GPDs). GPDs unify the momentum–space parton densities measured in inclusive deep-inelastic electron scattering with the spatial densities (form factors) measured in elastic scattering. They describe correlations between the momentum and spatial distributions of quarks, which are revealed in exclusive processes in electron scattering at large momentum transfers, such as Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). GPDs are the basis for fundamentally new ways of representing the nucleon as an extended object and promise to provide access to fundamental static properties such as the quark orbital angular momentum. A White Paper [WP1] summarizes the status of this exciting field and outlines the prospects for future GPD measurements with the 12 GeV Upgrade of Jefferson Lab and a future EIC.

Extending earlier exploratory measurements [Ai01, St01], experiments during the last 5 years have clearly demonstrated the feasibility of DVCS measurements at momentum transfers $Q^2 \sim$ few GeV^2 and have provided crucial first tests of the GPD–based description of these processes. These experiments aim to access the GPD's through the interference between the DVCS and the Bethe–Heitler processes in the $eN \to e'N\gamma$ cross section, using measurements of spin–dependent and independent cross sections and relative asymmetries. Detailed measurements of the beam spin asymmetry by CLAS at JLab ($0.15 < x < 0.55$, see Fig. 4) and the target spin asymmetry [Ch06b] show the potential for fully differential measurements of DVCS observables; the data are consistent with the predictions of some of the present GPD models.

The JLab Hall A experiment recently reported first measurements of absolute DVCS cross sections in the valence quark region, see Fig. 4 [Mu06, Ro06]. The results indicate that the scaling behavior of the cross section with Q^2 predicted by QCD factorization already appears to be satisfied at $Q^2 \sim 1 - 2\,\mathrm{GeV}^2$, supporting our expectations that information about GPDs can be extracted from DVCS measurements at such momentum transfers. The first model-dependent extraction of the quark angular momentum was attempted [El06] using the HERMES DVCS data.

GPDs and exclusive processes are also the subject of intensive on-going theoretical studies. Recent investigations have further explored the idea of spatial quark/gluon imaging of the nucleon, and developed essential tools for the GPD analysis of exclusive reactions (GPD parameterizations and higher–order QCD calculations; see Ref. [Be05] for a review). Progress was also made in lattice QCD simulations of the lowest moments of the GPD's and their t–dependence [WP2].

New measurements of exclusive processes at high energies (DVCS, J/ψ production) have also been made with the HERA collider ($10^{-4} < x < 10^{-2}$) [Ak05, Ak05a]. These reactions probe the gluon GPD and reveal the transverse spatial distribution of gluons in the proton — information that is essential for modeling QCD dynamics in high–energy $pp/\bar{p}p$ collisions at RHIC, the Tevatron and the LHC ("small–x physics") [Fr05].

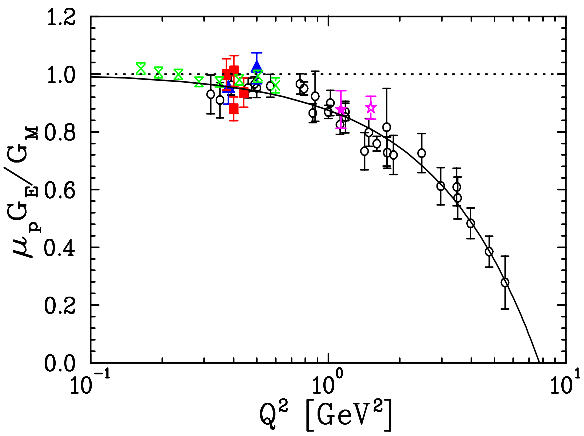
2.B Hadron Physics at Long Distance

Elastic scattering provides crucial information on the charge and current distributions in the nucleon. By combining these data with precise studies of parity violation arising from the neutral weak current, we have a unique opportunity to separate the individual quark flavor contributions to the charge and current distributions — including, in particular, the strange quark contribution. Considerable experience in the study of long distance hadronic physics has taught us that it is vital to incorporate the physical effects of spontaneous symmetry breaking.

2.B.1 Electromagnetic structure of the nucleons and the pion

The electromagnetic form factors of the nucleons are fundamental quantities describing their charge and magnetization distributions. They provide vital information on the characteristics of the interactions that bind the constituents of the nucleon together. Historically, the determination of the nucleon elastic electromagnetic form factors came predominantly from unpolarized electron scattering experiments using the Rosenbluth separation technique. In the past decade, advances in high-intensity polarized beam, high polarization targets, and polarimetry have led to a new class of precision measurements of all four nucleon form factors (G_E^p, G_M^p, G_E^n, and G_M^n) using spin-dependent observables [Ga03, Hy04, Ar06]. Measurements of these form factors have been performed up to $Q^2 \sim 3.5\,\mathrm{GeV}^2$, allowing detailed comparison of the data with the nucleon structure models over a broad range of Q^2.

New, accurate nucleon form factor measurements have led to new insights on the role of quark orbital angular momentum, the Q^2 scale for the onset of perturbative QCD effects, the strangeness content of the nucleon, meson-cloud effects at low Q^2, and the connection between the nucleon form factors and the generalized parton distributions. Moreover, the comparison between the proton and neutron form factors provides information on the flavor structure of the nucleon and on the isovector



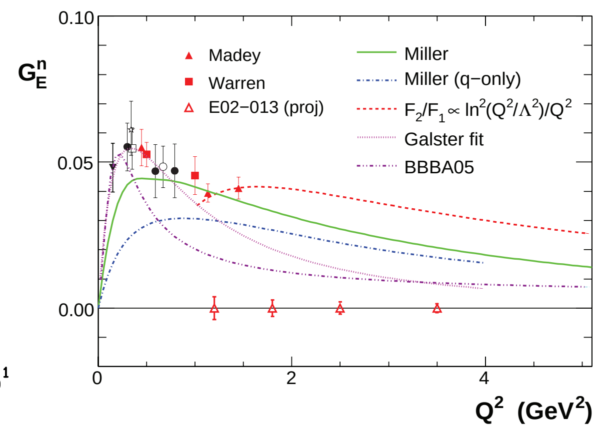


Figure 5: *Left:* recent results from polarization transfer measurements of $\mu_p G_E^p / G_M^P$ [Ar06]. The solid line is a linear fit to the JLab data, $\mu_p G_E^p / G_M^P = 1 - 0.13(Q^2 - 0.04)$. *Right:* Available G^n data compared to calculations and the Galster parametrization [Ga71]. Projected sensitivities of a recently completed JLab Hall A measurement are also shown.

form factors that can be compared with lattice calculations. These data have also taught us about the importance of the two-photon-exchange process in high-precision electron scattering.

Figure 5 shows the recent results from the polarization transfer measurements of $\mu_p G_E^p / G_M^p$ covering the 0.15 GeV$^2 < Q^2 < 5.5$ GeV^2 range. These results include the recoil polarimeter measurements at JLab [Ga01, Ga02, Pu05, Ma06] and MAMI [Po01], and the polarized beam-target asymmetry measurements at JLab [Jo06] and BLAST [Cr07]. Figure 5 shows a significant decrease in the ratio of $\mu_p G_E^p / G_M^p$ at large Q^2 that differs greatly from the results obtained from the Rosenbluth separation measurements indicating that $\mu_p G_E^p / G_M^p$ was consistent with unity up to $Q^2 \sim$ 6 GeV^2. A recent high-precision Rosenbluth measurement detecting the recoil proton instead of the scattered electron [Qa05] confirmed the discrepancy between the Rosenbluth technique and the polarization transfer measurements. This discrepancy is attributed to the effects of two-photon exchange (TPE) contributions to the electron scattering cross sections [Gu03, Ko05], and the polarization transfer data are viewed as a much more accurate measurement of the G_M^p / G_M^p ratio. Extensive theoretical efforts to calculate the TPE [Ko05, Af05, Bo06] are underway, and dedicated future experiments to measure the TPE effects by comparing the electron and positron scattering cross sections have been proposed at JLab and VEPP-3 [Br04, Ar05, Af07a].

The precise recent polarization transfer measurements of $\mu_p G_E^p / G_M^p$ shown in Fig. 5 clearly establish differences between the electric and magnetic form factors in the proton for Q^2 up to 6 GeV^2. Dimensional counting rules for perturbative QCD predict a constant value of G_E^p / G_M^p at $Q^2 > \zeta_{pQCD}^2$ [Br75], where ζ_{pQCD} is the scale for perturbative QCD. The recent data on $\mu_p G_E^p / G_M^p$ strongly suggest that $\zeta_{pQCD}^2 > 6$ GeV^2. The decrease of $\mu_p G_E^p / G_M^p$ with increasing Q^2 has been reproduced in recent analyses using vector meson dominance [Lo01, Bi04] and dispersion relations [Be06]. Figure 5 also suggests the possibility of a vanishing $G_E^p(Q^2)$ at $Q^2 \approx 7.8$ GeV^2. A forthcoming experiment at JLab [Br04a] will test this zero-crossing of G_E^p with polarization transfer data up to $Q^2 = 8.5$ GeV^2.

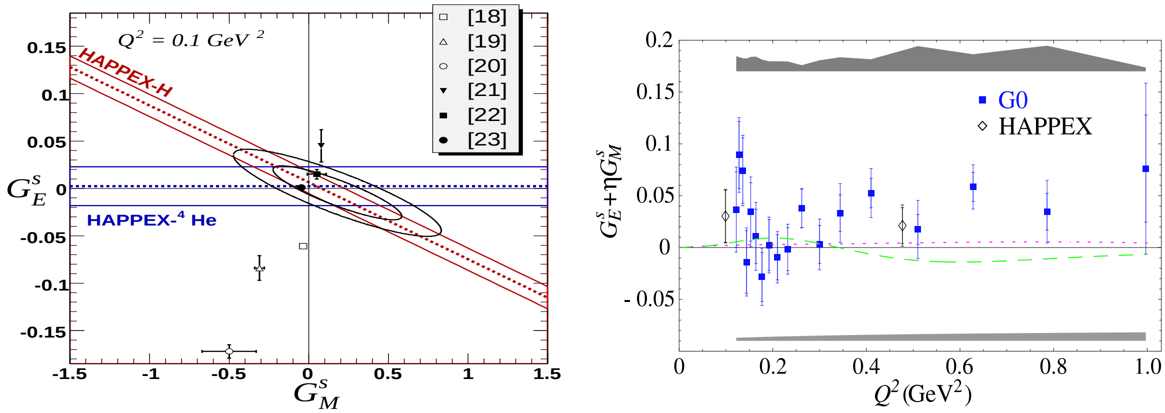


Figure 6: *Left:* 68 and 95% confidence limit constraints in the $G_E^s - G_M^s$ plane from the recent HAPPEX data [Ac07]. Various theoretical predictions are also shown. *Right:* the combination $G_E^s + \eta G_M^s$ as a function of Q^2 from the G0 experiment [Ar05a]

Accurate measurements of the neutron form factors are challenging due to the lack of a free neutron target and the reduced sensitivity of unpolarized electron scattering to G_E^n at high Q^2. Recent progress in the extraction of G_M^n includes the comparison of $d(e, e'n)$ to $d(e, e'p)$ at CLAS [La05], polarization transfer measurements on polarized ^3He at JLab [Xu03, An06], and measurements of the $\vec{d}(\vec{e}, e)$ spin-dependent asymmetry at BLAST [Ga06]. The difficulty of extracting G_E^n using the Rosenbluth separation technique has led to the use of polarization transfer or beam-target asymmetry techniques to determine G_E^n/G_M^n. Recent experiments include quasi elastic scattering from polarized deuterium [Pa99, Wa04] and polarized ^{3}He targets [Be03, Ca02], and measurements of recoil polarization from an unpolarized deuterium target [Ma03, Gl05]. The results for G_E^n are shown in Fig. 5. Also shown in the figure are the projected uncertainties of a recently completed JLab Hall-A experiment [Ca02].

Real Compton Scattering (RCS) on the proton was measured recently in the hard scattering regime [Ha05, Da07]. Both the cross section data and the polarization transfer parameter K_{LL} were in fair agreement with calculations using the handbag mechanism, but in strong disagreement with the predictions of perturbative QCD.

The role of strange quarks in nucleon structure at long-distance scales has been a subject of intense theoretical and experimental interest. Since the nucleon contains no net strangeness, any contribution of strange quarks to the nucleon structure observables is clearly a sea-quark effect. The scalar strangeness density of the nucleon, $\langle N|\bar{s}s|N\rangle$, extracted from the πN sigma term from new πN scattering data, is found to be $\sim$ 11-23% percent of the up and down quark scalar density, $\langle N|\bar{u}u + \bar{d}d|N\rangle$ [Pa02]. Polarized deep-inelastic scattering data also suggest that the strangeness axial charge $\langle N|\bar{s}\gamma_\mu\gamma^5 s|N\rangle$, which corresponds to the strangeness contribution to the nucleon spin, is large [Le03]. It is quite plausible that strange quark can also make a significant contribution to the vector current in the nucleon. Parity-violating polarized electron scattering off nucleons provides a direct access to the strange-quark vector current in the nucleon $\langle|\bar{s}\gamma_\mu s|\rangle$, or equivalently, G_E^s and G_M^s, the electric and magnetic strange-quark form factors [Ka88, Mc89, Be89].

Tremendous progress has been made on the measurement of G_E^s and G_M^s since the last Long Range Plan, as several parity-violating electron scattering experiments have reported their results. The SAMPLE experiment reported a new determination of $G_M^s(Q^2 = 0.1\text{GeV}^2) = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$ [Sp04]. The A4 experiment at MAMI obtained $G_E^s + 0.106 G_M^s = 0.071 \pm 0.036$ at $Q^2 = 0.108$ GeV^2, showing a two-σ effect for non-zero strangeness form factors [Ma05a]. In a series of recent experiments, the HAPPEX Collaboration at JLab measured parity-violating asymmetry (A_{PV}) for 3 GeV electrons scattering off hydrogen [An01, An06a, An04, Ac07] and ^{4}He targets [An06b, Ac07] at $Q^2 \sim 0.11$ GeV^2. Since A_{PV} for hydrogen is sensitive to a linear combination of G_E^s and G_M^s while A_{PV} for ^{4}He is sensitive only to G_E^s, the HAPPEX data allowed a precise determination of both G_E^s and G_M^s at $Q^2 \sim 0.1$ GeV^2. The HAPPEX results, $G_E^s = -0.005 \pm 0.019$ and $G_M^s = 0.18 \pm 0.27$, are shown in Fig. 6. Also shown in Fig. 6 are the various theoretical predictions based on Lattice QCD, chiral perturbation theory, and hadron models. Models that predict small values of G_E^s and G_M^s are clearly favored by the data [Le03, Le06]. A recent global fit [Yo06] to all A_{PV} data with $Q^2 \leq 0.3$ GeV^2 showed that the strange form factors and the anapole contributions to the nucleon axial form factors are consistent with zero. However, there is only a small possibility that these form factors all vanish simultaneously [Yo06].

The G0 Collaboration at JLab recently reported [Ar05a] measurements of A_{PV} for forward-angle $e-p$ scattering over the range $0.12 \leq Q^2 \leq 1.0$ GeV^2. As shown in Fig. 6, the G0 $G_E^s + \eta G_M^s$ (where $\eta \sim 0.94\ Q^2$) data exhibit an intriguing Q^2 dependence. Since η increases linearly with Q^2, the drop of $G_E^s + \eta G_M^s$ in the region up to $Q^2 \sim 0.3$ GeV^2 indicates a negative G_E^s in this Q^2 range [Ar05a]. The data also show that $G_E^s + \eta G_M^s$ have positive values at higher Q^2. The G0 data exclude the hypothesis $G_E^s + \eta G_M^s = 0$ with an 89% confidence level. Additional parity-violating asymmetry experiments, including back-angle measurements by G0 and A4, will allow accurate separations of G_E^s and G_M^s over a wide range of Q^2. A very accurate forward-angle measurement at $Q^2 = 0.6$ GeV^2 will also be performed by the HAPPEX Collaboration soon [Pa05].

The electromagnetic structure of the spinless pion is characterized by a single form factor F_π, which is calculated in perturbative QCD to be $F_\pi(Q^2) = 8\pi\alpha_s f_\pi^2/Q^2$ as $Q^2 \to \infty$. Various hadron models involving Vector Meson Dominance, QCD sum-rule, Dyson - Schwinger, light-front quark model, and dispersion relation have been used to calculate $F_\pi(Q^2)$ at low Q^2. Recently, new data on $F_\pi(Q^2)$ have been obtained at JLab for $0.6 \leq Q^2 \leq 2.45$ GeV^2 using L/T separated longitudinal $p(e, e'\pi^+)n$ cross sections (σ_L) [Ho06, Ta06]. At small values of t, σ_L is dominated by the quasi-elastic scattering of the electron from a virtual pion in the nucleon and is proportional to F_π^2. The recent JLab data show that F_π is slightly lower (by 1σ) than the monopole form constrained by the pion charge radius, but far above the prediction of perturbative QCD. With the JLab 12 GeV Upgrade and the proposed forward-angle SHMS spectrometer, F_π could be measured up to $Q^2 = 6$ GeV^2, providing sensitive comparisons with the predictions of perturbative QCD [Ba04].

2.B.2 Chiral Dynamics

Chiral perturbation theory (χPT) [We79, Ga83, Be06b] is the effective theory of QCD for the kinematic domain where energies and momenta are comparable to the pion mass. It encodes the consequences of chiral symmetry and chiral-symmetry breaking for low-energy hadron dynamics. It therefore provides a unified framework for hadron phenomenology in this regime, and facilitates the connection of laboratory data to the underlying theory of strong interactions, QCD. χPT can predict a broad range of observables in low-energy hadron physics including the properties and interactions of Goldstone bosons, pion-nucleon interactions, and nucleon electromagnetic structre. More recently it has been successfully applied to improve understanding of the NN interaction, and to develop consistent three- and four-nucleon forces.

Properties of Goldstone bosons: The $\pi^0 \to \gamma\gamma$ decay rate predicted in the chiral limit by the QCD axial anomaly is consistent with the current experimental value within 10%. Chiral corrections to this decay rate has been calculated to next-to-leading order [Go02]. The predicted chiral correction of $4 \pm 1\%$ involves $\pi - \eta$ isospin-breaking mixing and is sensitive to $m_d - m_u$. The Primex Collaboration at JLab has recently completed a measurement of $\pi \to \gamma\gamma$ decay width aiming at a 1.5% accuracy using the Primakoff effect and a tagged photon beam. Results from this experiment were presented at the April 2007 APS meeting, and are consistent with Standard Model predictions, with the preliminary error a factor of two smaller than that given by the Particle Data Group. An extension of this experiment proposed for 12 GeV JLab is a measurement of $\eta \to \gamma\gamma$.

The polarizability of pions has been measured in $e^+e^- \to \gamma\gamma \to \pi\pi$, $\gamma p \to \gamma\pi^+ n$, and $\pi^- Z \to \gamma\pi^- Z$ experiments [Fi06]. A recent one-loop χPT calculation to order $O(p^6)$ using new Low Energy Constraints (LECs) obtained $(\alpha + \beta)_{\pi^+} = (0.16 \pm 0.1) \times 10^{-4}$ fm^3 and $(\alpha - \beta)_{\pi^+} = (5.7 \pm 1.0) \times 10^{-4}$ fm^3 [Ga06a], but a recent Mainz extraction of $(\alpha - \beta)_{\pi^+}$ from $\gamma p \to \gamma\pi^+ n$ [Ah05], shows a significant difference from the χPT prediction. More accurate $e^+e^- \to \gamma\gamma \to \pi\pi$ and Primakoff experiments could aid in understanding this apparent discrepancy.

Interactions between Goldstone bosons: Pion-pion scattering is an ideal place to explore chiral dynamics. At low energies, it is specified by the $I = 0$ and 2 s-wave scattering lengths a_0^0 and a_0^2. The BNL-E865 Collaboration obtained a constraint on a_0^0 and a_0^2 from the $K^\pm \to \pi^+\pi^- e\nu$ K_{e4} decay [Pi01], while the NA48/2 Collaboration at CERN followed Cabibbo's suggestion [Ca04] and determined $a_0^0 - a_0^2$ from the cusp structure in the $K^\pm \to \pi^\pm\pi^0\pi^0$ decay [Ba06]. The DIRAC Collaboration at CERN has recently measured the lifetime of $\pi^+\pi^-$ bound state (pionium) [Ad05], providing further constraints on $\pi\pi$ scattering lengths. These data go hand-in-hand with advances in lattice QCD compuatations of $\pi\pi$ scattering lengths discussed elsewhere in this document [Be06c].

πN interaction and photo- and electro-pion production: χPT's predictions for πN s-wave interactions have been tested in a series of experiments on pionic hydrogen and deuterium at PSI [Go05]. Meanwhile, χPT's predictions for threshold pion photo- and electro-production were examined in great detail in a number of experiments at the Mainz Microtron [Me04]. Recent theoretical developments allow the extension of chiral effective field theories (EFTs) like χPT to the kinematic regime where the photon energy is sufficient to excite the Delta resonance [He97, Pa03]. This has led to the development of chiral EFT analyses of experiments designed to probe the nucleon-to-Delta transition at low Q^2. For instance, the MIT-Bates measurement of the transverse-longitudinal interference cross section, σ_{LT}, from the $ep \to e'\pi^0 p$ reaction [Sp05] is well described by a recent EFT calculation [Pa05a].

Nucleon polarizabilities: Data from Compton scattering on proton targets at energies below the Delta resonance can be used to extract the electromagnetic polarizabilities of the proton. A χPT fit to data obtained with tagged photons of energy < 180 MeV at Illinois [Fe91], Saskatoon [Ma95], and Mainz [Ol01] yields proton electric and magnetic polarizabilities of $\alpha_p = (12.1 \pm 1.1 \pm 0.5) \times 10^{-4}$ fm^3 and $\beta_p = (3.4 \pm 1.1 \pm 0.1) \times 10^{-4}$ fm^3 [Be03d]. This is consistent with other EFT extractions that employ a dynamical Delta [Hi04]. Neutron polarizabilities have been extracted from both quasi-free scattering [Ko00, Ko02] and coherent elastic scattering [Lu94, Ho99, Lu03] data off deuterium targets. The elastic data gives isoscalar polarizabilities $\alpha_N = (11.3 \pm 0.7 \pm 0.6 \pm 1.0) \times 10^{-4}$ fm^3 and $\beta_N = (3.2 \pm 0.7 \mp 0.6 \pm 1.0) \times 10^{-4}$ fm^3 [Hi05]. This data set will be vastly improved and expanded by an ongoing experiment at MAX-Lab in Lund, Sweden [Fi06a]. Meanwhile, a major upcoming program at the HIγS facility will measure proton and neutron polarizabilities using polarized beam and polarized hydrogen, deuterium, and ^{3}He targets.

Generalized polarizabilities of the proton have been measured recently at Mainz [Ro00], MIT-Bates [Bo06a], and JLab [La04] using virtual Compton scattering. The measurements from Mainz and JLab established that $\alpha(Q^2)$ falls off at large Q^2, but with a form inconsistent with a dipole shape. The MIT-Bates measurement at $Q^2 = 0.057$ GeV^2 showed that the proton's electric polarizability radius is dominated by pion-cloud effects, and in consequence is much larger than its charge radius. The Bates results for $\alpha(Q^2)$ and $\beta(Q^2)$ are in good agreement with the one-loop χPT prediction. They provide no evidence for curvature in $\beta(Q^2)$, which is consistent with cancellations between paramagnetic and diamagnetic effects in the magnetic polarizability.

Nuclear forces from χPT Following the suggestion of Weinberg [We90], NN and NNN potentials based on χPT have been systematically developed over the past ten years [vK94, Or96, En03a, Ep04, Ep05]. This is now a sophisticated enterprise: the N^{3}LO χPT potential describes NN phase shifts below $E_{\rm lab} = 200$ MeV with a comparable precision to that obtained using 'high-quality' phenomenological potentials. χPT's ability to provide three- and four-nucleon forces and electromagnetic currents which are conistent with the NN potential facilitates EFT calculations with a well-defined theoretical error bar. These calculations should be particularly useful as we strive to understand neutron structure at $Q^2 \leq 1$ GeV^2, since they will allow rigorous estimates of the theoretical uncertainties associated with the 'nuclear' corrections that must be accounted for when light nuclei are used as effective neutron targets.

2.C Nuclear Physics at Short Distance

While we have not yet answered the key quesiton: *what does QCD predict for the properties of nuclear matter?*, we have made significant progress in addressing it. While progress at Jefferson Lab, building on the past extensive experiments at high-energy facilities such as SLAC, FNAL and DESY is impressive, the short distance behavior of nuclei remains a mystery. Short distances involve the poorly understood short-range components of the nucleon-nucleon (NN) interaction as well as a possibly modified quark structure of the nucleon. The nucleus contains more than just mean-field behavior and long range correlations. Experimentally, addressing short distances requires high momentum transfer.

Remarkable progress has been made in hadronic descriptions of nuclei over the past two decades, with *ab initio* calculations using bare nucleon form factors and meson exchange currents successfully reproducing energy spectra and form factor measurements. The translation of this to a pure QCD description requires an understanding of the clusters of quarks in a nucleus. These clusters are approximately nucleons, but are not necessarily the same as free nucleons. There has been considerable theoretical progress in this approach, with phenomenologically successful density dependent forces of the Skyrme type being derived from an underlying quark description [Gu06].

Medium Modifications of Nucleon Properties: JLab has taught us that the structure and interactions of baryons do not change drastically within the precision we can determine today at normal nuclear matter densities. Nuclear structure function moments, related to the momentum sum rule, have been found to agree with moments simply constructed from protons and neutrons, indicating nuclear effects cause a redistribution of quark momentum without changes due to the nuclear environment beyond those already present in the deuteron. Remarkably, quark-hadron duality has been observed in nuclei, indicating that the medium modifications to nucleon resonances are the same as those observed in deep inelastic scattering (DIS). However, the somewhat controversial polarization transfer results [Di01, St01] do suggest that the ratio of electric to magnetic form factors of a proton in helium is different than that of a free proton. Using quark-hadron duality [Me05], this would rule out large bound structure function modifications, and instead points to a small medium modification of the intrinsic nucleon structure function, which is complemented by standard many-body nuclear effects.

Results from DIS experiments incontrovertibly demonstrate that the parton distribution functions (PDFs) change in the nuclear medium. The current knowledge of nuclear corrections is not sufficient to permit data taken on heavy targets being utilized to constrain *nucleon* PDFs. Rather, CTEQ and others have recently concluded that global PDF extraction fits should be limited to data taken on proton and, perhaps, deuteron targets. The resulting nucleon PDFs may then be used to model *nuclear* PDFs using data from heavy targets. Here, the question remains whether the nuclear corrections in neutrino DIS will significantly differ from the corrections in charged lepton DIS due to the axial coupling.

It should be noted that our ability to use QCD to describe even the bare proton may not yet be adequate to permit us to calculate nuclear effects. Indeed, what has been learned from the beautiful JLab measurements of nucleon form factors and other new data, such as the Drell-Yan measurements of the nucleon anti-quark sea, is that QCD calculations are still missing major parts of the physics of the nucleon.

Short Range Correlations: The long-range attraction between nucleons would lead to a collapse of a heavy nucleus into an object the size of a hadron if there were no short-range repulsion. This highly repulsive nature of the nucleon-nucleon interaction at short distances manifests itself in a variety of nuclear properties. For instance, only $\sim 60\%$ of the expected number of protons is observed in proton knock-out experiments. Nucleons with high internal momenta in a nucleus are a clean signature for violent nucleon-nucleon collisions (short-range correlations) not described by the standard mean field theory.

Using the CLAS detector, the cross section for inclusive electron scattering with large momentum transfer off medium and light nuclei was measured in the kinematic region that is forbidden for scattering off low-momentum nucleons. Steps in the value of this ratio (see Fig. 7) appear to be the first direct observation of the short-range correlations (SRCs) of two and three nucleons in nuclei, with local densities comparable to those in the cores of neutron stars [Eg06]. The measured probability of finding 3-nucleon SRCs in these nuclei ranges from about 0.2% to 0.8% compared to the 8% to 23% probability for 2-nucleon SRCs. The nucleon-nucleon correlation effects have also been studied extensively in Halls A and C through single- and two-nucleon knock-out reactions, mostly off light nuclei where theoretical descriptions are reliable.

A systematic study of the $(e, e'p)$ reaction on ^{12}C [Ro04] directly measured the contribution from short-range correlations at large values of the missing energy E_m and momentum p_m. The quasi-elastic ^{3}He$(e, e'p)$ reaction was studied up to a very high p_m value of 1 GeV/c. At p_m-values

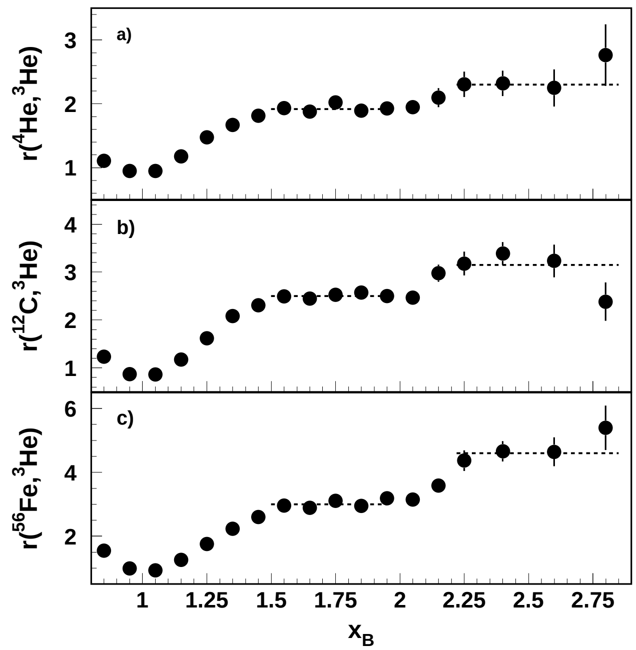


Figure 7: Weighted cross section ratios of (a) ^{4}He, (b) ^{12}C, and (c) ^{56}Fe to ^4He as a function of x_B. The horizontal dashed lines indicate 2N and 3N scaling regions used to calculate the per-nucleon probabilities for 2- and 3N SRCs in nucleus A relative to ^{3}He.

larger than 750 MeV/c the cross section was observed [Rv05] to be up to an order of magnitude larger than predicted by any available theory; this is interpreted as a strong indication of NN correlations. In the same experiment the three-body break-up channel [Be05a] was shown to provide a clear signature of NN correlations. A study of the $^3\text{He}(e, e'pp)n$ reaction over a wide kinematic range [Ni04] measured the momentum distribution of NN pairs by detecting the correlated nucleon pair after striking the third nucleon. In a recent experiment [Sh07, Wa07] the number of (pn)-pairs knocked out from ^{12}C was observed to be nearly twenty times as large as the number of (pp)-pairs (see Fig. 8). This observation was attributed by a recent calculation [Sc07] to the dominance of tensor correlations in the high p_m range studied in the experiment.

Strangeness in Nuclei: Introducing strangeness into the nuclear medium provides selective information about the hadronic many-body system because one-pion exchange between a Λ and a nucleon is excluded due to isospin conservation. The Λ also probes the nuclear medium down to deeply-lying shells, since it is not subject to Pauli blocking. Nuclear matter containing strangeness is also predicted to play an important role in stellar objects such as neutron stars. Thus, a detailed knowledge of the Λ-N interaction, which at present can only be extracted accurately from hypernuclei, is a necessary ingredient for a complete understanding of the evolution of nuclear matter in the universe.

Traditionally, hypernuclei have been produced with secondary beams of kaons or pions. Kaon electro-production from nuclei has the advantage of a large angular momentum transfer, strong spin-flip contributions and a significantly improved energy resolution. A high energy resolution (to separate the individual states in the hypernuclear system) and a high beam intensity (to com-

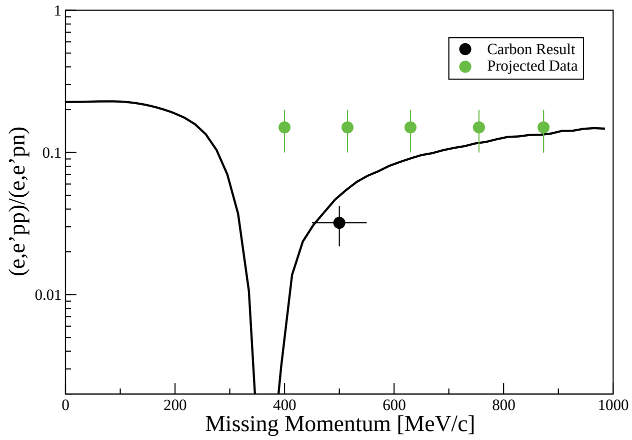


Figure 8: Comparison between the yield of correlated np and pp pairs in ^{12}C obtained recently at JLab. The ratio of approximately 20:1 strongly supports the idea that tensor correlations play a major dynamical role at short distances.

pensate for the small cross section) are essential requirements for such studies. A pioneering experiment [Yu06] in Hall C at JLab has proven the feasibility of such studies by obtaining spectra of the $^{12}_{\Lambda}$B and $^{7}_{\Lambda}$He hypernuclei with an energy resolution of better than 1 MeV. In a follow-up experiment in Hall A [Io07] an energy resolution of close to 600 keV was obtained, which allowed the extraction of quantitative information on core-excited states in the $^{12}_{\Lambda}$B hypernucleus for the first time. A second generation facility has been constructed in Hall C and demonstrated both higher production rates and improved resolution, and a program of measurements is planned for the long term.

Space-time characteristics of fundamental processes in QCD: While often discussed, these processes remain poorly understood experimentally. This frontier has, however, recently begun to yield new insights with the advent of precise measurements in experiments on nuclei. New experimental results are now emerging for color transparency, quark propagation, and hadron formation that hold the promise of developing a self-consistent picture of the space-time evolution of de-confined quarks, $q\bar{q}$ dipoles, and the formation of a hadron's color field.

Color transparency, the reduced interaction of small-sized hadrons, is broadly acknowledged to have been clearly observed in the A-dependence of diffractive di-jet production from nuclear targets using 500 GeV/c pions, and in other experiments at high energies. However, searches at lower energies have historically not observed the effect. From a series of precise electroproduction measurements over the past decade [quasifree $A(e,e'p)$, final state interactions in $^2H(e,e'p)$], color transparency has not been observed for $Q^2 < 10$ GeV^2 in three-quark systems. However, the onset of the phenomenon is expected to occur at lower Q^2 for two-quark systems, and recent experimental results have consistently shown tantalizing hints of color transparency. Pion photoproduction off neutrons in ^{3}He, and pion and rho electroproduction from larger nuclei, have all exhibited evidence of reduced interactions that are consistent with color transparency for $Q^2 \approx 1 - 2$ GeV^2. In particular, the rho measurements offer an effect of many standard deviations in a channel with a well-understood reaction mechanism and minimal theoretical bias. Further theoretical work and experiments with higher beam energies will clarify the point of onset of color transparency and will permit interpretation of this phenomenon in terms of the rate of expansion of small $q\bar{q}$ systems.

The confinement of quarks into hadrons is the most important manifestation of the nonabelian character of QCD. Achieving a quantitative understanding of confinement is one of the highest priority endeavors of nuclear and hadronic physics and ranks as one of the great quests of modern science. The effort to understand confinement is multi-pronged, typically involving hadron spectroscopy interpreted through the use of models and lattice calculations, which aim to characterize the effective potential between quarks. In addition to the effective potential, another important piece of confinement is the process of color neutralization, wherein a de-confined colored quark finds colored partners such that the resulting system is a color singlet; this requires a time τ_p ("production time"). An experimental observable sensitive to this physics is the broadening of the transverse momentum of hadrons produced off nuclei in kinematics that isolate the propagation of the struck quark within the nuclear medium, rather than a propagating hadron. The emission of medium-stimulated gluons from the quark is associated with the broadening of the transverse momentum due to medium interactions; once the quark color is neutralized, the broadening ceases. Thus a measure of the lifetime of the de-confined quark can be obtained by systematically comparing broadening in nuclei of varying size and by changing the propagating quark energy ν to see the effect of time dilation.

The process in which the color field of a hadron develops can be studied as a companion analysis to that described above. The experimental observable sensitive to this process is the observed attenuation of hadrons in larger nuclei compared to smaller nuclei in DIS kinematics. The hadron attenuation is dominated by the interaction of a forming color-singlet hadron or 'prehadron' with the nuclear medium. Varying the size of the nuclear target as well as ν, Q^2 and $z_h(= E_{hadron}/\nu)$ for a variety of hadron final states provides new, direct access to hadron formation times. Experiments of this type at HERMES and Jefferson Lab are stimulating a significant wave of theoretical interest and activity to test the physical picture and begin to extract less ambiguous physics results from the data.

In summary, major progress has been made in mapping out two-nucleon correlations in nuclei in a regime that is unique compared to all other correlated many body systems, and information on three body correlations as well as nucleon-hyperon interactions are beginning to accrue. The quest to understand the quark structure of the nucleon in the nuclear medium has progressed. The space-time characteristics of hadron formation is now being investigated in the nuclear environment.

2.D Hadron Spectroscopy

The central questions in hadron spectroscopy are: how does confinement work in valence-quark systems? what are the effective degrees of freedom that define the spectrum of hadrons? and what is the role of glue in the spectrum? In order to answer these questions, there is a three-fold approach to understanding the spectrum and, in the case of baryons, the form factors for transitions between the nucleon and its excited states. The first is to experimentally identify the states, the second is to obtain fundamental predictions from Lattice QCD (LQCD) for the masses and structure of these states, and the third is the development of the needed phenomenology and models to enable the physical and lattice spectra and transition form factors to be connected to experimental data. Significant progress is being made in all three of these areas.

For baryons, understanding the internal structure of nucleons has been at the center of nuclear and particle physics for decades. Measurements of the properties of nucleon excited states (N^*s),

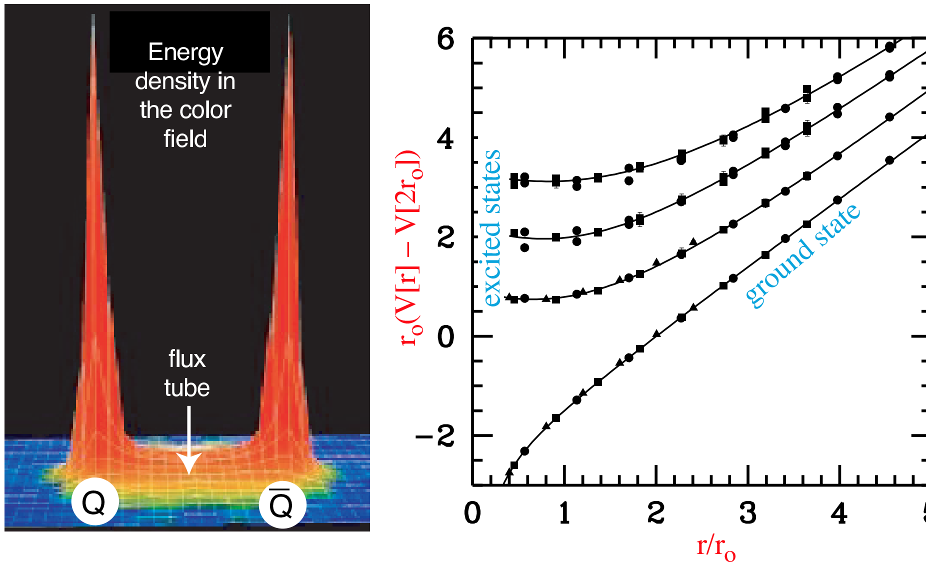


Figure 9: *Left:* A lattice QCD calculation of the action density in the color field between a quark and an anti-quark. The density peaks at the positions of the quarks and is confined to a tube between the quarks. This calculation is for heavy quarks in the quenched approximation. *Right:* The corresponding potential between the quarks. The ground state potential has a $1/r$ dependence at small distances and is linear for large distances.

through meson photo- and electro-production reactions, probes the systematics of the spectrum and the internal structure of baryons, yielding information on the nature of the effective degrees of freedom and how quarks are confined. In the area of mesons, lattice QCD indicates that the gluonic fields, which bind the quark and the antiquark, are confined to the regions near and in between the quarks [La97]. It is also believed that these fields can be excited. Two new types of meson are predicted to exist: states only containing the gluonic fields (glueballs) and states in which the field itself carries angular momentum (hybrid mesons). Only the hybrid mesons are expected to have an unambiguous experimental signature: non quark-antiquark (*exotic*) quantum numbers.

Finally, in the charm-quark sector where significant new data has become available from the B-factory experiments, several new states have been discovered. While some of these are states that fit well into the expected charmonium spectra, two may need more exotic explanations.

2.D.1 Meson Spectroscopy: Data and Phenomenology

Over the last decade, experimental information on hybrids and glueballs has come from several experimental sources. The largest volume of data is new information in the scalar meson sector. There, a combination of results from several different production mechanisms, coupled with detailed decay information, has shown that while the lightest glueball exists, it is quantum-mechanically mixed with two nearby meson states with the same quantum numbers. Unfortunately, there is currently no clear answer as to whether predicted higher-mass glueballs exist. Also, while the mixing is not unexpected, it does make an unambiguous discovery of a single state difficult.

In the hybrid sector, exotic-quantum-number states have the advantage that they cannot mix with normal mesons. However, while there is a clear signal, the experimental evidence only hints at these states. In particular, there are reports of three isospin 1 states with the same quantum numbers. Unfortunately, only one of these would be expected in a nonet of hybrids. The best signature – more than one state in a given nonet – has not been seen.

Until recently, one of the three observed states appeared to be a very solid candidate for the first hybrid, the $\pi_1(1600)$. However, recent analysis of a higher statistics data requires that the community look carefully at the phenomenology needed to extract the signal from the data [Dz06]. Phenomenology is a crucial element in the understanding of gluonic excitations, serving several important roles. First is its ability to use models to predict observed behavior. While the lattice may ultimately be able to provide answers, it is good modeling that reproduces known experimental and lattice results that is crucial for our understanding of physical phenomena. In addition, the size and quality of recent and expected data sets on mesons have reached the point where the assumptions that go into extracting information from the data limit our ability to find states. The best experimental signature for a resonance is a pole in the T-matrix. This is often simplified to be phase motion going through 90° in a partial wave. However, what can be measured is the differences in phase between two partial waves. In order to be able to extract resonance information, the motion of the background, or non-resonant phases need to be understood. Recent phenomenological work is providing a handle on this, but in order to fully utilize it, it needs to be incorporated into the data analysis in the least biased way possible. This generally implies it should be incorporated as an input to a partial wave analysis. Collaborations to implement these procedures have been formed and are just starting to analyze data this way.

With the advent of high statistics data sets on the decay of B mesons into charmonium states, several surprises have been found recently. In particular, five new states have been discovered with widths ranging from about 2 MeV up to about 90 MeV: the X(3872) [Ch03], X(3940) [Ab07], Y(3940) [Ch05a], Z(3930) [Ab07a], Y(4260) [Au07]. While some of these states are likely to simply be expected but to-date unseen charmonium states, several are difficult to explain. In particular, the 2 MeV wide X(2872) is quite difficult to explain. Models have been put forth for to explain it as everything from a glueball to a molecular state. Similarly, some of the observed decay modes of the Y(3940) have led to speculation that it is a charmed hybrid state. In order to fully understand the nature of these states, more data will be needed as well as lattice calculations and phenomenology. However, it is clear that when significant data sets from previously unstudied production mechanisms become available, surprises can still occur.

2.D.2 Excited Baryons

The US excited baryon program has two main components. The first is to establish the systematics of the baryon spectrum, which provides information on the nature of the effective degrees of freedom of strong QCD. The second is to probe the internal structure of excited baryon states and provide information about the nature of confinement by measuring the transition form factors from the nucleon ground state to excited baryon states. At Jefferson Laboratory (JLab), extensive data on photo- and electro-production of pseudo-scalar mesons $(\pi, 2\pi, \eta, K)$ and vector mesons (ρ, ω, ϕ) have been accumulated using the CEBAF Large Acceptance Spectrometer (CLAS). Pion electro-production data from JLab up to $W = 2.5$ GeV and $Q^2 = 6$ GeV^2 makes up 75% of the current world database. A full set of $2\pi N$ final state observables has been obtained for the first time.

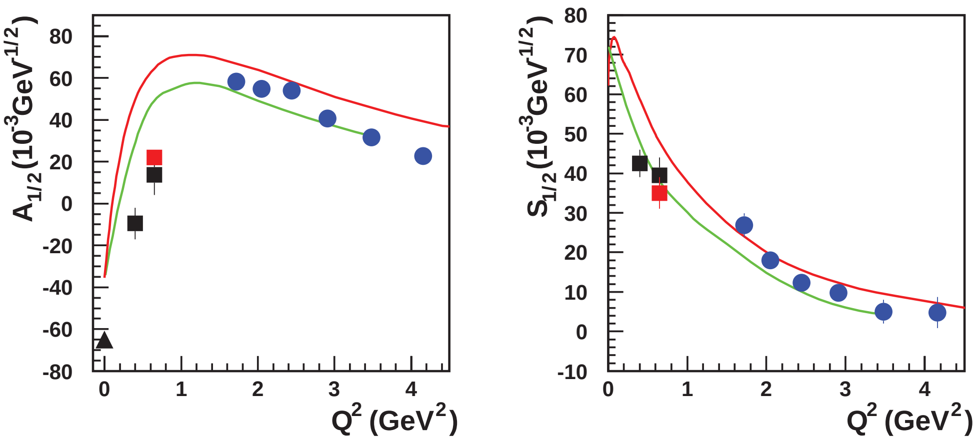


Figure 10: The extracted $\gamma N \rightarrow N^*(1440)$ transverse (left) and scalar (right) form factors compared with the results from relativistic quark model calculations (Ref. [Ca95], red curves, and Ref. [Az07], green curves).

Complementary data have been collected with the involvement of US scientists on photo-production of neutral final states ($\pi^0\pi^0$, $\pi^0\eta$) using CB-ELSA at Bonn and the Crystal Ball at Mainz in Germany, and on threshold production of strange mesons using the far-forward detection capability of LEPS at Spring-8 in Hyogo, Japan.

With a concerted effort to analyze the very extensive data from JLab and other electron facilities such as Mainz, significant progress has been made in the past few years. The extracted N-Δ (1232) transition form factors are now considered, along with the nucleon form factors, as benchmark data challenging the theoretical community. Moreover, accurate results for the transition form factors for several higher mass N^*s have been extracted from data in the past two years. The comparison of the transition form factor for the Roper resonance with relativistic quark models, shown in Fig. 10, shows that this state has a quark substructure at small distances, eliminating hybrid-baryon or meson-baryon-molecule models for its structure. In addition, candidates for new baryon states have been found in various channels, requiring confirmation with the planned experiments using polarized targets in CLAS and experiments at other facilities. These developments mark a major advance in our understanding of baryon structure.

The forthcoming data, together with available unpolarized cross sections, will form the basis for a significantly more efficient and less ambiguous search for new baryon states than has been possible to date. These data will allow the much more accurate extraction, using a coupled-channel analysis, of the resonance parameters of N^*s, including well established states. Methods for performing empirical amplitude analysis of the extensive data sets available and anticipated have been developed by several groups, and they are being improved continuously. To strengthen this effort and to interpret the extracted resonance parameters, the Excited Baryon Analysis Center (EBAC) was established at Jefferson Laboratory in January, 2006. A dynamical coupled-channel analysis of the data for photo- and electro-production of π, η, ω, K and $\pi\pi$ is underway at EBAC. A primary goal of EBAC is the development of techniques for confronting the extracted N^* parameters directly with QCD calculations. This work is beginning with a reanalysis of data on the Δ (1232) resonance. EBAC will work with lattice-QCD groups and more the QCD community to explore connections between dynamical reaction models and the theory underlying strong interaction physics.

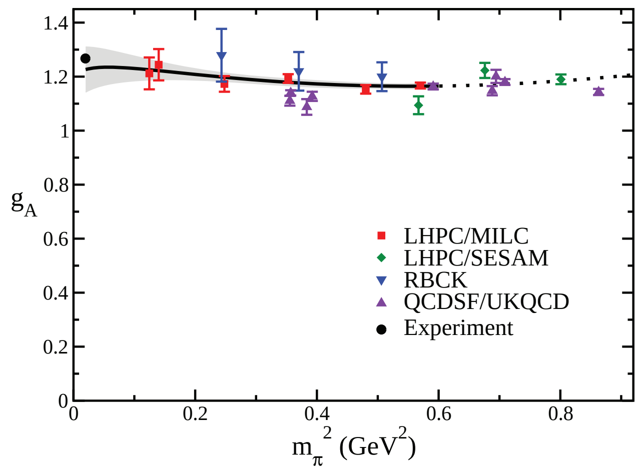


Figure 11: Calculation of the nucleon axial charge, g_A, from full QCD lattice calculations in the chrial regime. The solid line and error band denote the infinite volume chiral perturbation theory fit to the LHPC/MILC lattice results shown in red and agree with experiment denoted by the black circle, which is well within the 6.8% theoretical errors.

2.E Theoretical Advances

The overarching theoretical goal is a fundamental understanding of hadronic physics from QCD. Numerical solution of lattice QCD now enables solution of some problems from first principles. For other problems, controlled expansions are obtained using effective field theory, in which the physics at different scales can be systematically separated and solved one scale at a time. For processes at short distances, perturbative QCD provides essential results. For yet other problems, such as quark fragmentation and, to a large extent, excited states of hadrons, phenomenological methods and modeling are indispensable. In this subsection, we discuss recent advances in these areas.

2.E.1 Lattice QCD

Numerical solution of lattice field theory is the only known way to solve, rather than model, non-perturbative QCD. The combination of advances in lattice field theory, developments in computer technology, and the investment by the DOE in Terascale facilities for lattice QCD have given rise to dramatic progress in understanding the structure, spectrum and iteractions of hadrons from first principles. For the first time, full QCD calculations in the chiral regime of light quark masses and extrapolation via chiral perturbation theory have yielded a variety of calculations of observables directly comparable with exepriment. Highlights include the following advances.

Nucleon axial charge: The nucleon axial charge, governing neutron β decay, has been calculated for pion masses as light as 350 MeV using a hybrid combination of domain wall valence quarks, which have chiral symmetry on the lattice, and computationally economical improved staggered sea quarks. Using chiral perturbation theory, analytic expressions for the mass and volume dependence were used to extrapolate to the physical pion mass and infinite volume, obtaining the axial charge to a precision of 6.8% and in agreement with experiment as shown in Fig. 11 [Ed05].

Isovector nucleon form factors: Full QCD calculations with domain wall valence quarks on a staggered sea[Ed06] dramatically display the the growth of the nucleon pion cloud as the pion mass decreases into the chiral regime. The F_1 form factor monotonically decreases toward the experimental result as the pion mass decreases and a chiral perturbation theory fit to the slope extrapolates to the experimental value. Similarly, as the pion mass decreases, these calculations also approach the experimental result for the ratio F_1/F_2 measured by polarization transfer experiments at JLab.

Quark helicity and orbital angular momentum contribution to the nucleon spin: Recent lattice calculations provide the first glimpse of the origin of the nucleon spin in the chiral regime. The contribution of the spin of the up and down quarks to the total spin of the nucleon is given by the zeroth moment of the spin dependent structure function $\frac{1}{2}\Delta\Sigma = \frac{1}{2}\langle 1\rangle_{\Delta u+\Delta d}$ and by the Ji sum rule [Ji97], the contribution of the quark orbital angular momentum is given by $L_q = \frac{1}{2}\left(A_{20}^{u+d}(0) + B_{20}^{u+d}(0)\right) - \frac{1}{2}\Delta\Sigma$. The dominant connected diagram contributions to these matrix elements have been calculated down to the chiral regime using domain wall valence quarks on a staggered sea[Ed06] with the result that the fraction of the nucleon spin arising from the up and down quark helicity decreases from around 70% at $m_\pi = 900$ MeV to approximately 50% at 350 MeV, and chiral extrapolation yields a result consistent with the Hermes measurement of 42%[Ai08]. Although the magnitudes of the up and down quark orbital angular momentum contributions are separately approximately 30% of the nucleon spin, they cancel yielding a negligible combined contribution to the spin.

Spectra of glueballs and quenched nucleons: A powerful demonstration of the use of correlation matrix techniques to determine the excitations of a theory was the calculation, within the pure-gauge Yang-Mills theory, of the spectrum of glueballs, pure gluonic states characteristic of the non-Abelian nature of the theory[Ch06a]. More recently, a basis of operators for baryon states has been developed [Ba05, Ba05c], and the spectrum calculated in quenched QCD shows qualitative similiarity to the experimental spectrum.

Nature of Roper resonance: The Roper resonance, the lowest-lying radial excitation of the nucleon with a mass below that of the lightest negative-parity state, the $S_{11}(1535)$, is difficult to reconcile with phenomenological models of QCD. Employing the overlap-fermion formulation to reach unprecedentedly low pion masses, and using Bayesian analysis techniques, the mass of the Roper in the quenched approximation to QCD has been shown to approach that of the S_{11} as the pion mass decreases[Ma05b].

Radiative transition form factors and two-photon decays in charmonium: The first calculation of the transition form factors between the lowest-lying charmonium states was performed, showing good agreement with experimental measurements as well as QCD-inspired models[Du06]. This work lays the ground work for future computations of photocouplings both to hybrid states, and in the light-quark sector. In a novel extension, the two-photon decay rate was computed[Du06a].

Meson-meson scattering: Meson-meson scattering lengths were calculated with domain-wall fermions on a staggered sea with pion masses down to $m_\pi \sim 290$ MeV [Be06c]. The first prediction of the $K\pi$ scattering lengths in both isospin channels was made possible by combining the lattice QCD calculation in the $I = 3/2$ channel with chiral perturbation theory. This work computes the energy-eigenstates of the two particle system at finite volume to extract the scattering amplitude [Lu86].

Nucleon-nucleon scattering: The first studies of nucleon-nucleon scattering with fully-dynamical lattice QCD were performed [Be06d]. Although the pion masses used in the calculation $m_\pi \sim$ 350 MeV were too large to uniquely match to low-energy effective theory, including the physical scattering lengths demonstrated the power of the method for future calculations. In addition, the first calculations of hyperon-nucleon interactions were performed [Be06e], in which it was shown that the scattering phase-shifts for elastic processes such as $n\Sigma^-$, of importance for the nuclear equation of state at high densities, can be extracted.

2.E.2 Effective Field Theory

Effective field theory is a powerful framework based on controlled expansions for problems with a natural separation of distance scales. Effective theories are a particularly important tool for QCD, where the relevant degrees of freedom include both quarks and gluons as well as the bound hadrons and nuclei that we observe. For nuclear physics, important examples include chiral perturbation theory and few-nucleon effective theories at low energy, and the soft-collinear effective theory (SCET) for processes with energetic hadrons, which describes nuclear properties exposed by hard interactions. Effective theories are also an important tool for the extrapolation of lattice QCD results to the continuum limit. Conversely, lattice QCD is an important tool for the determination of couplings in low energy effective theories, as well as determining the hadronic matrix elements which appear in results derived from factorization and SCET.

Chiral perturbation theory: At low energies the dynamics of pions and nucleons can be systematically described by chiral perturbation theory in a manner consistent with the symmetries of QCD and the pattern of symmetry breaking. In the meson sector much of the recent progress involves results to $\mathcal{O}(p^6)$ in the chiral expansion, which require two-loop computations [Bi06]. Notable examples are the pion and kaon electromagnetic form factors, and $K \to \pi\ell\bar{\nu}$ decays relevant for determining $|V_{us}|$. Other examples include predictions for the near threshold cusp in $K^+ \to \pi^+\pi^0\pi^0$ decays, and high precision determinations of the mass and width of the σ resonance [Le06a]. Recent lattice computations by the MILC and NPLQCD collaborations give theoretical computations of meson decay constants and the $\mathcal{O}(p^4)$ Gasser-Leutwyler coefficients which agree well with the experimental results. In the single nucleon sector examples include precise, controlled extrapolation of the nucleon mass and the discovery that once chiral corrections are implemented, quenched QCD no longer appears to be an uncontrolled approximation to QCD (at least for the lowest octet and decuplet baryons) [Le03a]. Further examples include the theoretical advances on Compton scattering using chiral EFTs, both inside and outside the Δ region, and analyses of N-Δ form factors and Δ decays.

Few-nucleon effective theory: Few-nucleon effective field theory describes problems with two or more nucleons. Recent progress includes the computation of neutron-proton phase shifts at $\mathrm{N}^3\mathrm{LO}$ in the expansion, as well as high precision analysis of deuteron form factors, and the computation of Compton scattering on nuclei. At thermal energies, a recent high precision effective theory computation of $nd \to {}^3H\gamma$ has yielded uncertainties that are a factor of five smaller than currently available from experiment. Exploiting the connection to the effective theory, lattice computations have explored the m_π dependence of NN scattering lengths. Finally, the exploration of hypernuclei includes computations of cross-sections and the binding energy of ${}^3_\Lambda H$ which agree well with experiment results.

Hard scattering: For reactions involving energetic hadrons, nuclear dynamics is encoded in objects like the proton and meson light-cone distribution functions, and parton distribution functions. The soft-collinear effective theory [Ba00, Ba01a, Ba01b] provides a general framework for deriving predictions (known as factorization theorems) in terms of these and other hadronic distributions. Here the expansion parameter is Λ/Q where Λ is hadronic scale and Q the hard momentum transfer. The basic building blocks of this effective theory are parton fields, which carry gauge invariant momentum fractions and can be derived directly from QCD. The formalism can be used to compute hadronic form factors and also describes the properties of jets and their accompanying soft hadronic radiation. This framework has been well tested using B-decays, where the energy release $Q^2 = m_b^2 \simeq 22\,\mathrm{GeV}^2$ provides a clean source of energetic hadrons. Factorization theorems at leading and subleading order in the power expansion have been derived for decays like $B \to D\pi$, $B \to \pi\pi$, $B \to X_s\gamma$, and agree well with experiment. Recently the SCET has also been used to study jet event shapes and to provide a framework to systematically improve algorithms for parton showering. On a different front, by combining SCET with non-relativistic QCD, results have been derived for quarkonia processes including $e^+e^- \to J/\Psi X$, $\gamma p \to J/\Psi X$, and Υ-decays. With the large Q^2 available from the 12 GeV JLab Upgrade, it will be interesting to use these techniques to derive factorization theorems for the Q^2 dependence of pion and proton form factors to subleading order in the power expansion. Finally, for deep-inelastic scattering at large Bjorken x, SCET and factorization techniques have been used to address threshold resummation up to NNLO. The region of x where this resummation becomes important may well be probed by the JLab Upgrade.

2.E.3 Perturbative QCD

The asymptotic freedom of QCD makes it possible to use perturbation theory to treat interactions of quarks and gluons at short distances. Indeed, this is the regime where QCD has been subjected to the most stringent tests, and where it was established as the theory of the strong interactions. To date, essentially all of our endeavors in high-energy nuclear physics rely in one way or another on the use of perturbative QCD (pQCD). QCD observables at large momentum transfer, short-distance and long-distance phenomena may be separated to leading power in the momentum transfer. This is known as *factorization.* Of particular importance for the field of hadronic physics is the factorization discussed in the previous section in which for hard processes, short-distance and long-distance phenomena may be separated to leading power in the momentum transfer. Typical examples are *ep* or *pp* cross sections at large momentum transfer, which become products of parton (quark and gluon) distribution functions in the proton, and partonic hard-scattering cross sections. The former contain long-distance information on the structure of the proton, while the latter only depend on the large momentum transfer and are hence amenable to QCD perturbation theory. Measurements of the cross sections, when combined with pQCD calculations of the partonic hard-scattering cross sections, will therefore give insight into the structure of the proton. Much of what we know today about the proton is based on this approach, which is a cornerstone for the ongoing and future programs at JLab and RHIC. The following developments indicate the significant progress in this area since the last Long Range Plan.

Factorization and universality in single-transverse-spin observables: As discussed earlier in Section 2.A.2, the last few years have seen a renaissance in the experimental studies of single-spin asymmetries. After the discovery of very large asymmetries in fixed-target *pp* scattering in the late 1970s, measurements have now been made in semi-inclusive deep-inelastic scattering as well as at RHIC, and substantial asymmetries were also observed. The value of these asymmetries lies in what they might tell us about QCD and the structure of the proton, which has been an area of much recent theoretical activity. They may probe parton orbital angular momenta and spatial distributions,transversity, correlations of quarks and gluons inside the nucleon, and the color Lorentz force inside a polarized nucleon that is experienced by a struck parton [Qi99]. The latter aspect has witnessed particularly important theoretical developments recently. Some single-spin observables may have their origin in novel parton distributions, known as "Sivers functions" [Si06]that express a correlation between the parton's transverse momentum and the proton spin vector. It was realized that for the Sivers function to exist, final- or initial-state interactions are required. In the absence of these, the Sivers function would vanish by time-reversal invariance of QCD. As was shown in [Br02, Co02, Ji02, Be03b, Bo03], the interactions are represented in a natural way by the gauge link that is required for a gauge-invariant definition of a transverse-momentum-dependent parton distribution. In physical terms, this gauge-link may be viewed as a rescattering of the parton in the color field of the nucleon remnant. Depending on the process, the associated color Lorentz forces will act in different ways on the parton. In DIS, the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it is repulsive. Therefore, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes [Br02, Co02, Ji02, Be03b, Bo03]. This remarkable physical prediction of "non-universality" of the Sivers functions really tests all the concepts for analyzing hard-scattering reactions that we know, and awaits experimental testing. It has become a driving force for many of the ongoing activities in transverse-spin physics at JLab and RHIC (see Sections 3.B.3 and 4.A.4).

Generalized parton distributions: Measurements of GPDs are a crucial part of the current and planned programs in lepton-nucleon scattering (see Sections 2.A.3 and 4.A.5). Much of the theoretical groundwork that motivates these studies was laid over the past few years, in particular the realization that GPDs provide insights into the spatial distributions of partons in the nucleon and hence open the door to "proton tomography".We also note that the next-to-leading order QCD corrections for many of the observables that are sensitive to GPDs are now known, and that detailed studies of higher-twist effects have been performed [Be02]. These developments significantly strengthen the theoretical framework underlying experimental studies of GPD's.

Polarized p-p scattering: Knowledge of higher-order corrections in the perturbative expansion of the partonic cross sections is important, particularly in the case of hadronic scattering, where they can be sizable. There has been a large effort over the past few years to determine the next-to-leading order (NLO) corrections for the processes relevant for the RHIC Spin program. At RHIC, the spin asymmetries for the abundant channels $pp \to \pi X$ and $pp \to \mathrm{jet}X$ are now being used to learn about the polarization of gluons in the proton (see Section 3.B.1), and the NLO corrections relevant for these reactions have been presented in [Ja03]. We note that comparisons of the NLO calculations for the spin-averaged cross section with RHIC data have been very successful, which gives confidence that the NLO framework is appropriate for analyzing the RHIC spin asymmetry data in terms of Δg. Eventually, when data from RHIC become available for a variety of processes, a "global" analysis of the data, along with information from lepton scattering, will be performed to determine $\Delta q, \Delta\bar{q}$, and Δg. Efforts toward global analyses are now underway [St01a].

2.E.4 The Roles of Phenomenology and Model Building

Models have historically played an important role in the development of nuclear and hadronic physics. The spin-orbit interaction discovered by Guppert-Mayer was the underpinning for the nuclear shell model. The Veneziano model for hadron-hadron scattering amplitudes spearheaded development of string theory and development of a possible bridge between strong interactions and weakly interacting strings. The nonrelativistic quark model and the bag model embody salient qualitative features of hadron spectra and structure. Model building is a valuable tool for development of intuition about complex systems and for connecting results of *ab initio* computations and experimental data.

Hadron spectroscopy: Recent advances in the phenomenology of hadron dynamics have been stimulated both by growing efforts in the application of lattice gauge techniques in computations of hadron properties and studies of the nature of quark confinement and by the growing demands to provide understanding of the high quality data emerging from JLab and RHIC. Interplay of lattice and model studies resulted in description of the confining force between color charges. The confining mechanism leads to a linear static potential that for source separation less than approximately 1.5 fm depends on the source's color charge, much like the electrostatic potential on the electric charge, while for large separation the gluonic string develops and builds a chromo-electric flux tube. The spectrum of excitations of the Wilson line that represents the chromoelectric flux between quark-antiquark pairs leads to predictions for hybrid meson spectra, understanding of the ordering of hyperfine splittings and predictions for strong decays of hybrid mesons. Exploration of the hybrid meson spectrum, in particular states with exotic quantum numbers whose internal structure is expected to be dominated by excitations of gluon degrees of freedom, is at the center of the 12 GeV Jlab physics program. In addition, there is now evidence that confinement may be related to non-trivial topological configurations and boundaries in the domain allowed for the gluon field variables. These find support in novel analyses of QCD in the continuum based on the set of many-body Dyson-Schwinger equations where one finds a set of universal relations between low energy behavior of QCD Green's functions. Models and applications to hadron structure based on these observations have just started to emerge.

Strange nucleon form factors: In our quest to understand hadron structure from QCD, the investigation of the strange form factors of the nucleon play a crucial role in revealing the role of sea quarks. Such contributions are purely "disconnected" terms in the sense that they involve quark loops disconnected from the valence quarks other than through gluon exchange. Since these contributions cannot yet be calculated adequately directly from lattice QCD, they provide an excellent example of the synergy between creative phenomenology and lattice calculations. The combination of using experimental data for the magnetic moments and charge radii of the octet baryons, together with charge symmetry (which is also required in order to analyze the data) and a sophisticated chiral extrapolation of lattice QCD data for the valence quark contributions to the electric and magnetic form factors [Le99], has proven highly successful. The reported values for the strangeness magnetic moment [Le04], $G^s_M = -0.046 \pm 0.019 \mu_N$, and the strange charge radius squared [Le06c], $\langle r^2 \rangle_s = 0.001 \pm 0.004 \pm 0.004$ fm^2, are in excellent agreement with the values extracted from world data [Yo06] but almost an order of magnitude more accurate. This is a unique example in strong interaction physics of a case where theory is so much more precise than the experimental data.

Quark model insight into $\Delta g(x)$ The polarized gluon distribution $\Delta g(x)$ is crucial to our understanding of the origin of the nucleon spin, and is a central focus of current RHIC spin experiments and experiments envisioned for an electron-ion collider. Even qualitative features, such as whether it changes sign, are important in understanding and analyzing current experiments. Hence, since it cannot yet be calculated from first principles, a recent calculation from the quark color currents found in simple quark models is quite valuable [Ch06c]. The first result from the MIT bag model as well as the non-relativistic quark model shows that $\Delta g(x)$ is positive at all x, and the total gluon helicity ΔG from the bag model is about $0.3\hbar$ at the scale of 1 GeV, considerably smaller than previous theoretical expectations.

Phenomenolgy from string theory correspondence: A new phenomenology has also emerged as a result of the correspondence between conformal theories and string theory. QCD approaches a conformal theory at short distances and the correspondence provides new classes of models that relate QCD observables to string observables in weak coupling gravity. The mapping has been utilized, for example, to reproduce high energy scaling of the parton scattering amplitudes from "soft string" amplitudes. The approach was also used to make predictions for meson wave functions and the resulting light meson spectrum compares favorably with the data. As described in the companion white paper on the Phases of QCD, related ideas are also exploited to calculate the properties of supersymmetric gauge theories at finite temperature and relate this phenomenology to the physical quark gluon plasma.

Generalized parton distributions: The generalized parton distributions discussed in the previous section map out quark distributions in both longitudinal and transverse directions, providing a bridge between structure functions and form factors, and encode information about hadron structure that is common to a variety of reactions including wide angle Compton scattering, exclusive electro-production, and photon-photon annihilation. Thus, a theoretically motivated phenomenology incorporating constraints from Regge behavior and fitting relevant form factor and structure function data[Di04] is an essential tool for the analysis of emerging experiments.

Dispersion relations: The combination of dispersion relations, effective field theory, and high-energy reaction phenomenology has recently led to a high precision determination of the mass and width of the lightest scalar resonance, the σ meson. Further analysis of the dependence of effective interactions on the underlying number of quark colors gave insights into the dynamical origins of this resonance and others seen in the scattering of ground state pseudo-scalar meson pairs. In a similar vein, dispersion analysis of nucleon form factors has recently provided an excellent framework for parameterizing experimentally measured form factors subject to rigorous theoretical constraints and knowledge of the relevant spectral functions from other existing data[Me07].

3 Physics Program for the Immediate Future

An exciting program for hadron physics is planned for the next 5 years. At JLab, the full exploration of 6 GeV physics is yet to be done. At RHIC, the polarized proton-proton collisions will generate much more accurate data on gluon and sea-quark polarizations. At HIγS facility, Compton scattering on proton and He targets will measure various polarizabilities of the nucleon. In this section, we outline what is expected in hadronic physics at these facilities.

3.A JLab 6 GeV Program

Over its first ten years of operation, the capabilities of CEBAF for world leading, high precision studies of hadrons and nuclei have improved dramatically. As one measure, the product of polarization squared times the current (of relevance for parity violation experiments) has increased by a factor of six, and the product of polarization squared times energy squared times current (of relevance for recoil polarization measurements) has increased by over an order of magnitude. Studies of parity violating effects at the part per million level will never be routine but JLab's capabilities are nearer to that goal than previously achieved anywhere. As a result of these impressive technical developments, the experimental program planned for the remaining years of the 6 GeV era are among the most important to be performed at JLab. In many ways the best is still to come.

In this section we describe the major elements of the experimental program that will be performed in the 6 GeV era. The research program at 12 GeV, which is both a natural development of the present achievements and a dramatic increase in potential for new science, is discussed in Section 4 below. JLab currently has a backlog of more than 40 highly rated experiments with exciting new ideas being presented at each PAC. At the funding levels anticipated for FY08 the backlog alone would take approximately five years to execute.

The JLab 6 GeV research program can be separated into three broad areas of investigation: the structure of the nuclear building blocks; the structure of nuclei; and symmetry tests in nuclear physics. A number of the experiments planned (such as the measurement of the neutron radius in ^{208}Pb) have an impact in more than one of these areas and their placement is somewhat arbitrary. A large fraction of the planned program is focused on addressing the issues of high scientific priority that motivated the choice of the NSAC-recommended OMB milestones for Hadronic Physics; these are identified with the phrase "(OMB milestone)" following the subject. Completing this portion of the program is essential if we are to gather the data required to achieve these milestones. A substantial fraction of these experiments build on the successes of the recent past, completing programs of measurements that have been underway for years. Some of this research also lays essential foundations for the research program that motivates the CEBAF 12 GeV Upgrade. In what follows we provide a brief summary of the programs in each of these three areas.

3.A.1 The Structure of the Nuclear Building Blocks

Measure precisely the nucleons' charge and magnetization distribution, and determine their decomposition into the contributions from the different quark flavors. Determining the electromagnetic form factors of the nucleon up to high momentum transfer gives precise information on the nucleons charge and magnetization distribution down to small distance scales. The series of experiments recently completed and planned for the near term at JLab will complete this effort. Final results are expected shortly for the CLAS G_M^n measurements [La05], and new data on G_M^n have also been taken at JLab in the BONUS experiment using a deuterium target and tagging the low-momentum spectator proton to provide a nearly-free neutron target [Fe03]. A planned experiment will extend our knowledge of the proton's electric form factor to significantly smaller distance scales through a polarization transfer measurement [Br04] of G_E^p/G_M^p to $Q^2 = 8.5$ GeV^2. The surprising feature of the available proton data, showing the charge form factor falling rapidly relative to the magnetic form factor, will be pushed to the regime where it may even change sign. This regime is very sensitive to the features of different descriptions of the quark structure of the nucleon, especially the orbital angular momentum carried by the valence quarks. A second, recently-completed G_E^n experiment in Hall A [Ca02] that is now under analysis, extended our knowledge of the neutron's electric form factor by a factor of two as well. The role of two-photon exchange processes in these experiments will be clarified by a series of high-precision Rosenbluth extractions of G_E^p and G_M^p [Ar05b] and by the comparison of e^+ and e^- elastic scattering cross section [Br04].

Parity-violating electron scattering provides a powerful tool for accessing the strange quark component of the nucleon's 'sea' of quark-antiquark pairs through the interference between the weak and electromagnetic interaction amplitudes. A series of experiments at JLab have focused on this program. The forward angle data from the G0 experiment has been published [Ar05], and data-taking at backward angles on both hydrogen and deuterium (necessary to separate the electric and magnetic contributions to the form factors and to determine the axial contribution) has just been completed. One more high-precision measurement of forward scattering from ^{4}He at 0.6 GeV^2 will complete this program. By combining the traditional electromagnetic form factors with the parity violating electron scattering results, it will be possible to separate the contributions from the quark flavors (u, d, and s) to a Q^2 of $\sim$1 GeV^2, meeting the goal of the 2010 OMB milestone.

Determine the degrees-of-freedom governing the excitation spectra of the hadrons and reveal the structure of these excitations by measuring their transition form factors. We are addressing one of the most fundamental open questions in nucleon structure: understanding whether the nucleon's excitation spectrum is governed by its three valence quarks all contributing, or whether di-quarks reduce the degrees-of-freedom, leading to a smaller number of states.

The current challenge of the excited baryon program is to measure some of the higher lying baryon states with masses of 1.7 to 2.5 GeV to test the predictions of several competing hadron structure models and Lattice QCD. The identification of these states requires precise measurements of polarization observables to supplement available data on pseudo-scalar and vector meson production. Thus the next generation CLAS experiments will use polarized targets to investigate double polarization observables on both hydrogen and deuterium. The polarized FROzen Spin Target (FROST) is in the final testing phase at JLab and will be used to measure all beam-target double polarization observables for a large number of final states. In the case of hyperon production, additional triple polarization observables are accessible that will allow for the first time the measurement of all observables needed for an unambiguous model-independent determination of the reaction amplitudes. The FROST experiments are scheduled to begin in 2007, and will provide the first measurements ever of many of these observables.

Measurements off polarized protons provided by FROST will be complemented with data on polarized neutrons provided by an HD polarized target to permit the isospin decomposition of the resonance amplitudes. It is planned to transfer the HD target, developed for the LEGS program at BNL, to JLab for data taking in 2009/2010. These data, together with the available unpolarized cross sections, will form the basis for a much more efficient and much less ambiguous search for new baryon states than has been possible to date. A coupled channel analysis these data will allow extraction of N^* resonance parameters of even well known states with much improved accuracy.

Although the focus of the current program is on strangeness $S = 0$ baryons, hyperon states with $S = -1$, and cascade states with $S = -2$ can also be accessed with the CLAS detector using single and double kaon photo-production reactions. Cascade baryons are of special interest, as they are predicted to have narrow widths and therefore it will be easier to separate their excitation from underlying non-resonant production cross sections. The results of an exploratory experiment performed recently shows the high potential of CLAS to study strange baryon spectroscopy. An experimental program along these lines is being prepared.

Methods for performing empirical amplitude analysis of both the extensive data in hand and the even larger data set that will be forthcoming are under development by several groups. To strengthen this effort, and to interpret the extracted resonance parameters, the Excited Baryon Analysis Center (EBAC) was established at Jefferson Laboratory in January, 2006. A dynamical coupled-channel analysis of the data on photo- and electro-production of π, η, ω, K and $\pi\pi$ is now underway at EBAC. A primary goal for EBAC is the development of a method to compare the extracted N^* parameters directly with QCD calculations. Progress is being made with the Δ (1232) resonance. EBAC is planning to work with lattice-QCD groups and more broadly with the QCD community to explore connections between dynamical reaction models and the theory underlying strong interaction physics.

There is a complementary program in meson spectroscopy, and, in particular, the search for exotic hybrid mesons. This is a key goal of the JLab 12 GeV Upgrade as described in Section 4. In the near-term future, searches for low-lying hybrid mesons will be carried out using CLAS. These searches will use the highest energy tagged photon beams currently available (about 5.5 GeV versus the eventual 9 GeV planned in GlueX). They are targeted at a limited number of final states, and have as their primary goal the observation of some of the already identified states and the measurement of their properties in photoproduction. While the combination of the lower energy beams now available and the CLAS detector do not provide the optimum facility for carrying out a broad search, the fact that there is virtually no data on the photoproduction of hybrids could lead to exciting results. These searches will, as a minimum, experimentally establish the photoproduction cross sections and provide a logical stepping stone in the broad effort to map out the hybrid spectrum.

Determine the internal structure of the nucleon in the valence region via measurements at intermediate-x of the lowest moments of their structure functions. Inclusive electron scattering from a nucleon (unpolarized and polarized) provides integral information on the structure of the nucleon free from uncertainties caused by the interactions of outgoing hadrons. Unpolarized structure functions have been measured in a wide range of kinematics, providing the best information on the parton distributions and one of the best tests of QCD. Polarized structure functions have already revealed surprises in nucleon spin structure. The near-term JLab 6 GeV physics program on structure functions and parton distributions covers unpolarized, longitudinally polarized and transversely polarized nucleon structure functions, and includes studies of quark-gluon correlations and transverse-momentum dependent distributions (TMDs).

An on-going study of unpolarized structure functions focuses on the determination of the d-quark distribution at intermediate-x. This study uses a novel setup: a low momentum recoil detector using a radial geometry Time Projection Chamber (TPC) tags scattering from the neutron in a deuterium target [Fe03] by detecting the recoil proton at low, backwards momentum. This technique will determine the structure of the neutron nearly free of the ambiguities associated with the large nuclear corrections in the intermediate-x region.

The structure of the polarized proton, deuteron and neutron will be studied with unprecedented precision by using polarized proton [Ch07], deuteron [Bo07] and ^{3}He [Ch02] targets in combination with large-acceptance specialized electron detectors. The proton spin asymmetry $A_1(x, Q^2)$ will be extracted [Ch07] in a model-independent way in the intermediate-x region, allowing precise comparison with theoretical models that predict the behavior of A_1 as $x \to 1$. The Q^2 coverage and precision of the resulting deuteron structure function g_1^d [Bo07] will provide a significant improvement over available data in the determination of the polarized gluon distribution from DIS data through the use of the QCD evolution equations.

The second spin structure function, g_2, and its 3rd moment, d_2, will be determined with high precision. At large Q^2, the moment, $d_2 = \int_0^1 \bar{g}_2 \, dx = \int_0^1 x^2(2g_1+3g_2) \, dx$, is a twist-3 matrix element in the operator product expansion of QCD. d_2 is directly related to the quark-gluon correlations inside the nucleon. In particular, it reflects the response of the *color* electric and magnetic fields to the nucleon's polarization. d_2 has been studied extensively using Lattice QCD, and is one of the cleanest observables with which to test these calculations. Nucleon models, such as bag and chiral quark models, and QCD sum rules also predict d_2. New measurements will significantly reduce the experimental uncertainty on both d_2^p and d_2^n, shedding new light on the current situation where d_2^n has a two sigma discrepancy with the Lattice QCD calculation.

Study the contribution of the orbital motion of the different quark flavors to the nucleon's spin. Semi-inclusive DIS is becoming increasingly important thanks to the recent progress in the theoretical study of factorization [Ji05] and its experimental verification [En00]. It provides a powerful tool to access information not only on the longitudinal spin and momentum structure of the nucleon but also on its transverse structure.

The neutron transversity experiment [Ch06] will be the first to study the neutron's transverse spin structure. This experiment will use the Hall A High Resolution Spectrometer (for pion and kaon detection) and the BigBite spectrometer (for electron detection) together with a transversely polarized ^{3}He target. The measurement will extract and separate the Collins and Sivers asymmetries for a range of x from 0.1 to 0.4, where the asymmetries are expected to be significantly non-zero. The measurement will have a strong impact on our understanding of transverse spin. When combined with available data, the results of this experiment will permit a reliable extraction of the transversity, the Collins function and Sivers function for the valence quarks.

A semi-inclusive experiment [Av05] using CLAS with a longitudinally polarized proton target will be the first to study the transversely polarized quarks in the longitudinally polarized proton through measurements of the $\sin(2\phi)$ moment of the single target spin asymmetry. It will also be the first to study the Collins fragmentation function with longitudinally polarized protons. In addition, precision measurements of the p_T-dependence of the double spin asymmetry and its azimuthal moments will provide the first measurement of the differences in the longitudinal and transverse momentum distributions of different quark flavors due to their orbital motion.

A longitudinally polarized semi-inclusive experiment [Bo04] aims at separating the polarized quark distributions by flavor. In particular, it will provide the first precise determination of the polarized sea asymmetry. Finally, an unpolarized SIDIS experiment [Ch04] on both the proton and the deuteron will provide a precision measurement of the sea asymmetry, i.e. the asymmetry between $\bar{u}$ and $\bar{d}$ quarks, which was observed at Fermilab using the Drell-Yan reaction [Ga01] .

Develop the experimental and theoretical methods for performing tomography on the nucleon. This will take the study of the nucleon to a new level by determing the correlated quark distributions in both momentum and coordinate space via the measurement of Generalized Parton Distributions (GPDs). This sub-femtometer tomography is crucial for a more complete understanding of the complex internal structure and quark-gluon dynamics of the nucleon. Initial measurements have already provided important insight into the feasibility of this program through the measurement of the exclusive process $ep \to ep\gamma$ in deep inelastic kinematics (Deeply Virtual Compton Scattering, DVCS). DVCS has been identified as the cleanest reaction to access GPDs at the relatively low energies available at JLab, while Deeply Virtual Meson Production (DVMP) will likely play a complementary, important role at higher energies. The first accurate measurements with high statistics and broad kinematic coverage have been carried out in dedicated measurements in Hall A and with CLAS in Hall B. New experiments to obtain further insights into the GPDs are planned for the next several years.

In Hall A helicity-dependent and helicity-independent cross sections have been measured with high precision in a limited kinematics range. By measuring the Q^2 dependence with high precision this experiment demonstrated the dominance of the so-called "handbag" mechanism, a prerequisite for using DVCS to probe the soft physics in the proton that is parameterized by the GPDs. A surprising result of this measurement was the observation of a substantial increase in the number of high energy photons produced at large azimuthal angles relative to the predictions of available models. This suggests that the DVCS contributions to the production of high energy photons are considerable higher than current GPD parameterizations predict, unless one assumes other sources of single photons. A clarification of the source of these contributions is important for the extraction of GPDs from the DVCS data as current analyses have used the assumption that at JLab energies the dominant contributions to the cross section are from the Bethe-Heitler process modulated by the interference of DVCS and Bethe-Heitler. A planned experiment in Hall A will explore this observation further by measuring the deeply virtual photon production at different beam energies and performing a L/T separation of the cross section. This will allow a separation of the various contributions to the spin-dependent and spin-independent cross sections.

Beam spin asymmetries and DVCS cross sections have been measured using CLAS in Hall B. Beam asymmetries largely reflect the interference of the DVCS process with the Bethe-Heitler process. Cross section measurements have also been performed for a broad range of kinematics: $x_B = 0.15 - 0.5$, $Q^2 = 1.5 - 4$ GeV^2, and $-t = 0.17 - 1.5$ GeV^2. The CLAS measurements cover the full deep inelastic kinematics at reduced statistical accuracy for individual kinematics bin. A first comparision of beam spin asymmetries with GPD parametrizations shows qualitative agreement for the leading twist components. The full statistics of the experiment (only about 1/3 of the data has been taken to date) will be collected in 2008-2009. Improvements to the experimental setup should allow higher luminosity, providing high statistics data even for rather high values of Q^2. A second DVCS experiment with CLAS will use a longitudinally polarized NH_3 target to measure the single target spin asymmetry A_{UL}, which contains a combination of GPDs that is different from the combination in the beam helicity dependent measurements. While A_{LU} on protons is dominated by the vector GPD H, the target asymmetry A_{UL} is more sensitive to the axial GPD $\tilde{H}$. The combination of the two measurements will allow a separation of the GPDs H and $\tilde{H}$. The two complementary programs combined, high precision measurements in the limited kinematics in Hall A and the broad kinematics coverage with CLAS at lower statistics, will pave the way for the much extended GPD program using the DVCS process with polarized beams and polarized targets at the 12 GeV Upgrade.

Both Hall A and CLAS experiments will also measure deeply virtual π^0 and η production, testing the applicability of the handbag mechanism for the more complex DVMP processes that are needed for a flavor separation of the GPDs at the energies available with the 12 GeV Upgrade.

3.A.2 The Structure of Nuclei

In nuclear physics it is known that nucleons at long range strongly attract each other through the exchange of pions, whereas at short range the nuclear force changes sign and the nucleons repel each other. However, it is not yet understood under what conditions the $N - N$ force can be described through the exchange of pions and when it is more efficient to resort to the underlying gluon exchanges. In the near future aspects of this puzzle will be resolved through a number of experiments that will be carried out with the 6 GeV beam at Jefferson Lab.

Probe the nuclear interior with a controlled impurity to learn about deeply-lying shell structure and to help unravel the QCD basis for the $N - N$ force. Information about the deeply-lying shell structure of the nuclear interior is difficult to obtain since the nucleon levels are filled and the addition of a nucleon to a low-lying shell is blocked by the Pauli principle. Strange particles, like the Λ, are not subject to this limitation because they are not identical to the protons and neutrons, so they can be used to probe the nuclear interior. The "impurity approach has been broadly successful in many areas, such as μSR (for condensed matter studies) and muonic atoms (for atomic structure). Nuclear matter containing strangeness is also predicted to play an important role in stellar objects such as neutron stars, so a detailed knowledge of the $\Lambda - N$ interaction is a necessary ingredient for a complete understanding of the evolution of nuclear matter in the universe.

Kaon electro-production from nuclei makes it possible to deposit a tagged Λ deep inside the nucleus, and to observe its interaction with the nuclear system. A high energy resolution (to separate the individual states in the hypernuclear system) and a high beam intensity (to compensate for the small cross section) are essential requirements for such studies. Pioneering experiments in this area have been carried out in both Halls A and C at JLab in which for the first time quantitative information could be extracted for core-excited states in the hypernuclear systems thanks to an energy resolution of close to 600 keV. A specialized system, which aims at an overall energy resolution of 300 keV and compatibility with a broader range of incident electron energies, is under construction for use in Hall C. It will support a broad program of hypernuclear studies and be compatible with the beam energies available after the 12 GeV energy upgrade. The first of these experiments is included in the presently approved program.

Clarify the short-range nature of nucleon-nucleon interactions in nuclei and compare the properties of bound nucleons with those of free nucleons. The existence of short-range $N - N$ (and $3N$) correlations has been quantitatively established through the scaling behavior as a function of x_{Bj} of inclusive electron scattering [Eg06]. Nucleons with high internal momenta in a nucleus are also a clean signature for violent nucleon-nucleon collisions (short-range correlations) not described by the standard mean field theory. These nucleon-nucleon correlation effects are being studied in single- and two-nucleon knock-out reactions, mostly off light nuclei where the theoretical description is reliable. They will be extended to heavier nuclei, such as ^{208}Pb, to explore systems with properties close to those of nuclear matter. In a recent experiment [Be01] the number of (pn)-pairs knocked out from ^{12}C was observed to be nearly twenty times as large as the number of (pp)-pairs. This observation was attributed by a recent calculation [Sc06] to the dominance of tensor correlations in the high missing-momentum range studied in the experiment. In a future experiment [Pi07] the ratio of (pn)-pairs to (pp)-pairs knocked out from ^{4}He will be studied over a large range of missing momentum to investigate the validity of the tensor-correlation dominance. In a planned precision experiment [Ch05] the longitudinal response for quasi-elastic scattering in a range of nuclei will be determined accurately through a Rosenbluth separation. By integrating this response function one extracts the Coulomb Sum, that will provide sensitive information on $N-N$ short-range correlations and in-medium modifications.

Measure the neutron radius of ^{208}Pb *to provide vitally needed information for physics ranging from the modeling of neutron stars to the interpretation of atomic parity violation experiments.* While we have detailed information on the charge distribution of nuclei, the existing information on the neutron distribution, even of its mean-squared radius, is severely limited by systematic uncertainties due to the poorly understood interaction of the probe used. A precise determination of the neutron distributions mean-squared radius in a heavy nucleus is important for our understanding of neutron stars and for the interpretation of atomic parity experiments. Parity-violating electron scattering is directly sensitive to the neutron radius. An experiment to measure the neutron radius of ^{208}Pb via parity violating electron scattering at small momentum transfer is under preparation; obtaining the necessary precision requires the superb characteristics of the CEBAF polarized electron beam and the Hall A High Resolution Spectrometers.

Extend our knowledge of the elastic form factors of light nuclei to momentum transfers where the underlying quark-gluon structure of the nucleus may become evident. Measurements of both the photodisintegration of deuterium and elastic scattering from it have revealed clearly the limitations of the conventional picture of nuclear structure, which is based on nucleons interacting via meson exchange. It is clear that at distance scales of order 0.1 fm quark models offer a much more economical description of the experimental data. These experiments have also revealed the applicability of the nucleon-meson picture down to distance scales of order half the nucleon size (much smaller than expected). Planned extensions of elastic scattering to higher Q^2 for the slightly more complex but still exactly calculable nuclei (^{3}He and ^{4}He) [Ka04] will provide important information for our exploration of the transition between these two regimes and our understanding of its nature.

Investigate the modification of the quark-gluon structure of nucleons and mesons by the nuclear environment. Possible modifications of the properties of a bound proton in the nuclear medium have been studied via a precision measurement of the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction (data have been taken [En03] and analysis is in progress). This will allow a precise comparison of the ratio of electric and magnetic form factors for free and bound protons. Such changes would support novel theoretical approaches to nuclear structure starting from the level of quarks and gluons, within which such changes are a natural precursor to the transition to a quark-gluon phase at higher densities.

Explore the space-time characteristics of fundamental QCD processes. The space-time characteristics of fundamental processes in QCD, while often discussed, remain poorly understood experimentally. This frontier has recently begun to yield new insights, thanks to precise measurements on nuclei investigating color transparency, quark propagation, and hadron formation. These experiments hold the promise of yielding a self-consistent picture of the space-time evolution of de-confined quarks, $q\bar{q}$ dipoles, and the formation of a hadron's color field.

To augment the color transparency analysis of available data on the rho meson, exploratory studies of this phenomenon will be undertaken for the phi and omega mesons. Theoretical model efforts will focus on fully characterizing the rate of expansion of the $q\bar{q}$ dipole within the medium, which is the essential space-time information accessible at few-GeV energies. In addition, a broader range of theoretical approaches can be tested against all of the available data and it will become clearer whether the effects from the 6 GeV experiments can be unambiguously characterised as demonstrating color transparency.

In the study of quark propagation through nuclei, new investigations of p_T broadening will be carried out for the negative pion and for neutral kaons. Exploratory investigations of p_T broadening for neutral pions and eta mesons will be performed. In parallel, theoretical work continues with the aim of understanding the connections of these observables to quark energy loss and to determine the sensitivity of the measurements to the gluon density of the medium.

Studies of hadron formation in the near term will focus on lower-energy data and will include determination of hadronic multiplicity ratios for negative and neutral pions, neutral kaons, eta mesons, and an exploratory look at phi and omega mesons as well as lambda baryons. Correlations between the leading hadron and the next-to-leading hadron, initially derived from HERMES experiments, can be extended with Jefferson Lab measurements to multi-dimensional binning with several species of identified hadrons. Correlations between the leading particle and low-energy protons and pions will also be examined to better characterize the target fragmentation region and the energy loss process. Photons correlated with the leading particle have been observed and these may also lead to insights on the microscopic processes involved. Theoretical work to understand the essential ingredients needed to describe these observables will be ongoing on many fronts, with the short-term aim of identifying specific observables that discriminate between models. As a part of this work, theoretical frameworks capable of extracting hadron formation lengths will begin development.

3.A.3 Symmetry Tests in Nuclear Physics

Determine the weak charge of the proton to test Standard Model predictions for the running of the electro-weak coupling constant and to begin an important search for physics beyond the Standard Model. The Electro-weak Standard Model (SM) has been enormously successful although it is known to be incomplete. The search for a fundamental description of nature beyond the SM is driven by two complementary experimental strategies. The first is to build increasingly energetic colliders, such as the Large Hadron Collider (LHC) at CERN, to excite matter into a new form. The second approach is to perform high precision measurements where an observed discrepancy with the SM would reveal the signature of new forms of matter.

Parity violating electron scattering off the proton at small momentum transfer is largely free of hadronic interaction uncertainties, and its measurement will allow us to determine directly for the first time the weak charge of the proton; this quantity is predicted by the Standard Model (based on the running of the weak mixing angle Θ_W from the Z^0 pole down to low energies). This experiment offers the unique opportunity to test the predictions of the Standard Model far away from the Z^0 pole, and to search for physics beyond the Standard Model. The Q_{Weak} experiment [Bo05], which is under construction, will measure the A_{PV} asymmetry at $Q^2 = 0.03$ GeV^2, where the asymmetry is dominated by the weak charge of the proton with negligible contribution from the hadronic form factors. It builds on previous technical advances that have been made in JLab's world-leading parity violation program.

Figure 12 illustrates the level of precision with which the weak charges of the quarks will be determined when the Q_{Weak} data is combined with earlier data, notably the PVES results from G0 and HAPPEX at JLab and data from atomic parity. The result shown assumes that the Q_{Weak} result is consistent with the Standard Model. In that case, one finds a substantial improvement in the limit on possible new Z' bosons, with the relevant mass scalle pushed beyond 2 TeV. On the

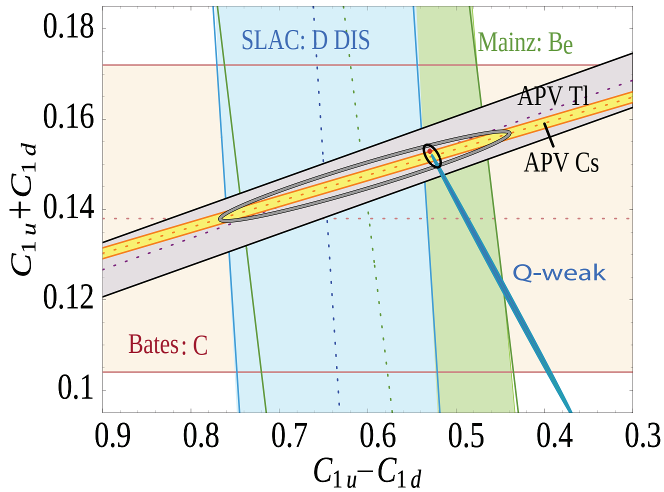


Figure 12: The anticipated knowledge of the weak charges associated with an axial coupling to the electron and a vector coupling to the up and down quarks after the Q_{Weak} measurement . The large grey contour displays the previous experimental limits (95% confidence level, CL) reported by the Particle Data Group, together with the prediction of the Standard Model (small red dot). The solid teal ellipse denotes the anticipated constraint provided by the upcoming Q-weak measurement on the proton, (at 1 standard deviation) while the small black contour (95% CL) indicates the full constraint obtained by combining all results. All other experimental limits shown are displayed at 1 standard deviation [Yo06].

other hand, if there is a Z' below that mass scale Q_{Weak} has the potential not only to discover it but to pin down the flavor dependence of its couplings. That would be important even if the LHC were to find it first, as the flavor dependence is a crucial factor for differentiating between possible extensions of the Standard Model.

3.B RHIC Spin Physics

At RHIC, 60% average beam polarization and average luminosity $L = 2 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ were achieved in 2006, at $\sqrt{s} = 200$ GeV. In the next few years, the polarized collider will produce a large body of data which contain key information on the spin structure of the nucleon. Here are some highlights.

3.B.1 Gluon helicity distribution

The goal is to measure the gluon polarization versus the gluon momentum fraction in the proton, x_g. The single-inclusive measurements have the great virtue of large cross sections and significant sensitivity to the gluon polarization through their subprocesses. However, these measurements do not provide an x_g distribution directly. One major complication is that at lower p_T and mid-rapidity, gluon-gluon scattering is most important, and for this subprocess the asymmetry A_{LL} is roughly "quadratic" in the gluon density. These probes cannot distinguish well the sign of the gluon polarization unless one accesses transverse momenta in excess of about 10 GeV or measures at forward rapidities.

Direct-photon production is dominated by the gluon-Compton contribution, $q\,g \to \gamma\,q$. Its spin asymmetry is therefore linear in gluon polarization. Further, due to the electromagnetic vertex for the photon, the quark polarization contribution enters A_{LL} weighted by the quark charge squared and, to lowest order, is directly related to the already measured DIS asymmetry A_1^p, which is large at large quark momentum fraction x_q. Therefore, a direct-photon measurement directly measures the sign and size of the gluon polarization with excellent sensitivity. However, the figure of merit is low due to the small cross section. As shown in the Spin Plan [Ai07], the expected sensitivity for the gluon polarization from direct-photon production distinguishes the sign of the gluon polarization.

An important part of the RHIC spin program will be two-particle, jet-jet (or hadron-hadron) and photon-jet correlations, basing on the feature of the large aperture STAR experiment and the PHENIX upgrade plan with vertex and nose cone calorimeter detectors. At leading order approximation, the hard-scattering subprocess kinematics can be calculated directly for these correlations on an event-by-event basis, giving an estimate of x_g for each measurement. This idea is presented in the Spin Plan [Ai07]. Theoretical work is in progress that will provide all relevant cross sections and spin asymmetries to next-to-leading order accuracy, so that spin asymmetries for two-particle correlations will provide results on gluon polarization at much better constrained values of x_g than all single-inclusive measurement done so far.

As mentioned before, it is important to measure the gluon polarization over the widest possible range in x_g, in order to reduce the uncertainty to the gluon contribution to the proton spin from unmeasured regions. The RHIC program will use three approaches to extend gluon polarization measurements to lower x_g. The first is to collide at higher energy, $\sqrt{s}$=500 GeV, the energy that is planned for 2009-12 to measure the parity-violation for W boson production. Running at 500 GeV extends the x_g range to lower values by the factor 2.5 for fixed minimum p_T, compared to 200 GeV running. The second approach is to measure A_{LL} for heavy quark production, using the vertex detectors being built. The heavy quark mass sets the hard scale so that pQCD applies, and heavy-quark production at lower p_T is mainly described by gluon-gluon fusion. These measurements will then access lower x_g. However, like for other single-particle inclusive processes, no information about the sign of the gluon polarization can be obtained from measurements at small p_T. The photon-jet (or photon-pion) two-particle correlation at large rapidity is dominated by quark-gluon scattering. These measurements, using existing and new forward electromagnetic calorimeters that will be in place for 2007 for both STAR and PHENIX, offer access to low x_g and large x_q, with large subprocess analyzing power. The process has a large quark polarization due to the large x_q. Indeed, STAR will have electromagnetic calorimeter coverage from η from $+4$ to -1, including the new FMS and the existing end cap and barrel calorimeters.

Finally, the determination of the gluon polarization requires consideration of all existing data through a "global analysis" by making use of results from all probes, from RHIC and from DIS. Examples of early work on this are Ref. [Hi06]. An important advantage of a global analysis is to consider each measurement directly in its experimental variables, rather than attempting to use derived or unmeasurable variables such as x_g. Also, the global analysis can be consistently carried out at next-to-leading order accuracy.

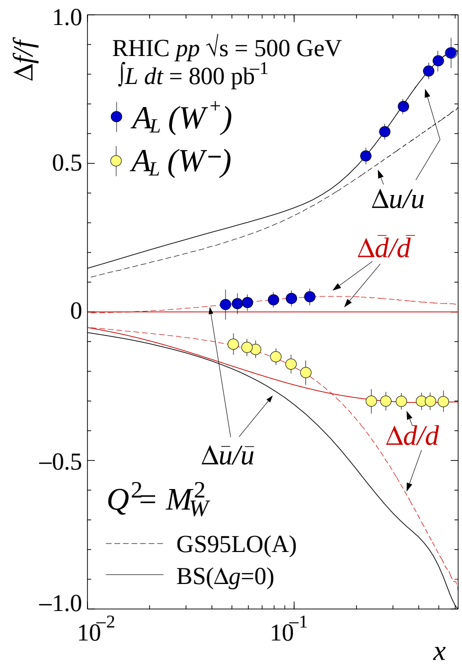


Figure 13: Expected asymmetries and error bars for W-boson production at polarized RHIC with center-of-mass energy 500 GeV. They are sensitive to polarized quark and antiquark distributions

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To summarize, we anticipate measurements of the gluon polarization using many probes at RHIC, and also with two collision energies, and that these measurements will, together, produce a robust understanding of the gluon contribution to the proton's spin.

3.B.2 Polarized quark densities

The polarized RHIC uses the parity-violating production of W bosons to measure the anti-quark and quark polarizations identified by flavor. This will be a clean, elegant, direct measurement which is a central focus of the RHIC spin program. This program requires $\sqrt{s} = 500$ GeV. W-bosons are identified as high p_T leptons, typically requiring $p_T > 20$ GeV/c. They are produced at RHIC with both beams longitudinally polarized. Single-helicity parity violating asymmetries are obtained for each polarized beam by summing over the spins of the other beam:

$$A_L = \frac{1}{P} \times \frac{(N/L)_- - (N/L)_+}{(N/L)_- + (N/L)_+} \tag{1}$$

with P the measured polarization of the polarized beam, and $(N/L)_-$ the number of observed W bosons, normalized by the relative luminosity, for collisions with beam helicity $-$.

Drell-Yan production of, for example W^+, $\vec{p} + p \to u + \bar{d} \to W^+ \to l^+ + \nu$, can be considered for three kinematic regions: W produced forward, central, and backward from the polarized beam. Forward W^+ production is dominated by a contribution with the u-quark from the polarized proton, and the $\bar{d}$ anti-quark from the unpolarized proton, due to the much larger quark density vs. anti-quark density at large momentum fraction. In this case, A_L(forward W^+) $\approx \Delta u/u$. That is, the parity violation signal, due to the maximal violation of parity in the production of the W, directly measures the u-quark polarization at that momentum fraction in the polarized proton. Similarly, A_L(backward W^+) $\approx \Delta\bar{d}/\bar{d}$. For centrally produced W, the parity violating asymmetry combines contributions from both the u and $\bar{d}$ polarizations, as discussed in the Spin Plan [Ai07]. Our expected sensitivity can be found in Fig. 13 where the PHENIX muon data sensitivity is shown; STAR electron data will be similarly very sensitive to the quark and anti-quark polarizations.

3.B.3 Single transverse-spin asymmetries

As described in the previous section, the Run-6 transverse spin results are striking. Results [Le06e] for A_N for forward $\pi^{\pm}$ production in polarized proton collisions at $\sqrt{s}$=62 GeV show flavor-dependent mirror asymmetries that increase with x_F, for positive values of x_F. At the highest π^+ x_F probed the ratio of spin dependent cross sections, $\sigma(\uparrow)/\sigma(\downarrow)$, is greater than a factor of two, comparable to analogously large spin effects observed at lower collision energy. Similarly, both K^+ and K^- are produced with large (positive) asymmetries. This striking spin dependence, even at collision energies that permit production of hundreds of particles, demands a simple explanation. Precise results for SSA in forward neutral pion production were obtained by STAR.

Dijet production near midrapidity in polarized proton collisions at $\sqrt{s}$=200 GeV was expected to be sensitive to Sivers type asymmetries through spin dependence of the jet-pair momentum imbalance, responsible for the observed azimuthal angle difference distribution [Bo04b, Vo05, Ba05a]. The large SSA expected in dijet production near midrapidity are in contrast to observations by STAR [Ba06a] that find the dijet SSA to be consistent with zero. This discrepancy may reflect delicate subprocess-dependent cancellations in the theory [Ba05a].

Future prospects for understanding the origin of these striking transverse phenomena at RHIC are bright. Both STAR and PHENIX have implemented large-acceptance forward electromagnetic calorimeters. These devices will permit the measurement of transverse SSA in multi-photon (jet-like) final states, near-side π^0-π^0 correlations and direct photon production. Such measurements can isolate contributions from the Sivers and Collins effects, and can elucidate the dynamical origin of the forward pion transverse SSA.

3.C Other Facilities

Fermilab Drell-Yan experiment:

A new Drell-Yan experiment (FNAL E906) aiming at a precise measurement of the antiquark distributions in nucleons and nuclei was recently approved by the FNAL PAC. An intriguing x-dependence in the $\bar{d}/\bar{u}$ flavor asymmetry was previously observed in the FNAL E866 experiment. For $x < 0.2$, $\bar{d}/\bar{u}$ was found to increase roughly linearly with x, reaching a value of ~ 1.75 at $x = 0.2$. The enhancement of $\bar{d}$ over $\bar{u}$ in this x region is well described by theoretical models taking into account of the meson-baryon configurations of the nucleon. However, the E866 data showed that the $\bar{d}$, $\bar{u}$ sea became more symmetric as x increases further, suggesting the onset of a new mechanism for generating the nucleon sea at large x. The goal of the FNAL E906 experiment is to carry out a high statistics measurement of $\bar{d}/\bar{u}$ over the kinematic region $0.1 < x < 0.45$ using 120 GeV proton beam at the FNAL Main Injector. E906 also proposes a definitive measurement of the antiquark distributions in a heavy nucleus, which should provide valuable new insight for understanding the EMC effect.

HIγS Facility and Nucleon Polarizabilities:

Nucleon electric and magnetic polarizabilities are fundamental quantities which describe the response of protons and neutrons to external electromagnetic fields. Hence they encode information about the nucleon's internal structure. Further information about that structure is provided by another set of fundamental quantities known as the spin polarizabilities. There are four of these for the proton and four for the neutron, and they describe the stiffness of the nucleon spin when subjected to external electric and magnetic fields. In consequence they provide complementary information on the origin of the nucleon's spin. All these quantities can be accessed through low-energy Compton scattering experiments—with neutron polarizabilities being extracted from experiments employing few-body nuclear targets.

The High Intensity γ-ray Source (HIγS) uses intra-cavity back-scattering of Free-Electron-Laser light to produce intense γ-ray beams. Over the next few years HIγS' intense, 100%-polarized, nearly mono-energetic beams will provide forefront information on nucleon polarizabilities—including the first direct measurement of individual proton and neutron spin polarizabilities. HIγS' unique beam will be combined with polarized p, d and ^{3}He targets in a Compton scattering program which will use an array of high-resolution, efficient detectors to measure polarizabilities for the neutron and the proton. This is made possible by a HIγS upgrade allowing the production of γ-rays up to energies of about 160 MeV with total intensities greater than 10^8 /sec which is about to be completed. The primary component of the upgrade is a 1.2 GeV booster-injector which makes it possible to replace lost electrons at full energy. In addition, an upgrade of the present linear undulator to a helical system is underway which will provide essentially 100% linear and circularly polarized beams. The full system will be ready for use at beam energies up to 85 MeV in early 2007. Additional upgrades are needed to extend the maximum energy to 160 MeV.

This experimental opportunity coincides with the vigorous application of effective field theory (EFT) methods to Compton scattering from proton and light nuclear targets. Chiral perturbation theory calculations to next-to-next-to-leading order provide a good description of the existing (unpolarized) Compton scattering data on both the proton and the deuteron in this energy range [Be03d]. The polarizabilities are dominated by the physics of the nucleon's pion cloud, and, in consequence, are predominantly isoscalar. However, EFT corrections to the pion-cloud picture reveal the role that physics at distances $\ll 1/m_\pi$ plays in the electromagnetic response of the nucleon. Meanwhile, the technology to compute this short-distance physics directly using lattice QCD is developing rapidly [Ch05b, Le06d, De06]. Future advances in theoretical methods and computing power will yield more accurate predictions of all of the polarizabilities. Therefore we envision precision nucleon polarizability data being compared with rigorous theoretical predictions based on lattice QCD and EFT methods, thereby testing our understanding of the manner in which the nucleon's low-energy electromagnetic structure emerges from QCD.

However, the magnetic polarizability of the proton is at present $\pm 50\%$ uncertain. A $\sim$280 hour HIγS experiment using 100% linearly-polarized γ-rays can reduce this to $\sim$5%. A precision measurement of the differential cross section for elastic scattering of γ-rays from the deuteron at energies of 50–80 MeV is also planned. Chiral perturbation theory calculations of the γd cross section will then be used to extract the neutron electric and magnetic polarizabilities to better than ∼20%. In the case of β_n the statistical uncertainty alone is presently 65%.

Even less is known about the nucleon spin polarizabilities (γ_1–γ_4). They have never been measured individually in a low-energy Compton scattering experiment, although some constraints on combinations of the γ's from other data do exist. A frozen-spin (butanol) polarized target and a detector array consisting of eight large high-resolution NaI detectors surrounded by 3-inch thick segmented NaI shields will be used in a double-polarization experiment at photon energies above 100 MeV that will yield new information on proton spin polarizabilities. Compton scattering experiments in which circularly polarized photons impinge on a polarized ^{3}He target [Ga06b] are also planned. A polarized ^{3}He target that is based on the principle of spin exchange between optically pumped alkali-metal vapor and noble-gas ^{3}He nuclei [Bo60] has already been built for the HIγS program at TUNL. The first calculations [Ch07c] of elastic γ^3He scattering show that asymmetries from this reaction will be largely free of 'nuclear' corrections. The results for these asymmetries are therefore expected to be very similar to what would (hypothetically) be obtained with a free-neutron target. (These asymmetries can also be obtained more directly via quasi-free neutron Compton scattering on a ^{3}He target.) The use of well-established polarized ^{3}He target technology at the upgraded HIγS with upgraded detectors should enable measurement of neutron spin polarizabilities with a precision comparable to that attainable for the proton.

This is particularly interesting because recent calculations of spin polarizabilities in chiral perturbation theory show that significant pieces of the spin polarizabilities are isovector [Vi00, Ge00]. For instance, in γ_1 a difference between proton and neutron values of about a factor of 3 is predicted. With an expected experimental accuracy of better than ± 10%, this should be readily observed, providing new insight into the way that degrees of freedom other than pions impact nucleon polarizabilities.

Once HIγS achieves its full upgraded energy of 160 MeV, expected in 2009, its unique polarization and intensity capabilities facilitate a suite of novel experiments in the pion-threshold regime. Prominent among these are measurements of the violation of isospin symmetry in πN scattering via rescattering effects in the final state of pion photoproduction. The first experiment in this domain will measure the polarized target analyzing power of the p(γ, π^0)p reaction at $E_\gamma = 158$ MeV. Simulations show that a 200-hour measurement will determine the charge-exchange scattering length $a_{\rm cex}$ $(\pi^+ + n \to \pi^0 + p)$ to ∼4%. A comparison of this result to the value of $a_{\rm cex}(\pi^- + p \to \pi^0 + n)$, well known from the width of pionic hydrogen, will be a sensitive probe of isospin violation.

4 Outstanding Opportunities in Future

4.A JLab 12 GeV Upgrade

The 12 GeV Upgrade at Jefferson Lab will offer electron beams with a unique combination of high intensity, duty factor, polarization, and kinematic reach, opening new opportunities for discovery in our field. The combination of these beams with greatly enhanced detector and electronics technology will support orders of magnitude improvement in data rates, providing critically needed data for the investigation of a broad range of QCD phenomena that have simply not been experimentally accessible. Exploiting these features will make it possible to explore the valence structure of nucleons and nuclei in new ways. Crucial questions concerning the existence and properties of possible new states of matter, the exotic mesons, will be answered definitively. It will be possible to probe nuclear structure at the most fundamental level, namely in terms of the underlying quarks and gluons. Using the exceptionally high quality beams for which Jefferson Lab has become famous and which have enabled a series of high precision studies of parity violation, one will seek the subtle signals of new physics beyond the current Standard Model of nuclear and particle physics.

There is a remarkable synergy between the experimental capabilities offered by the Upgrade and two major recent developments in theory: the feasibility of experimentally-relevant calculations in Lattice QCD (LQCD); and the development of the unified framework of the generalized parton distributions (GPD's) for understanding the parton distributions in hadrons and unraveling the quark-gluon correlations.

QCD has been thoroughly investigated in the high energy or perturbative regime. However, in the non-perturbative, low energy limit only lattice QCD offers the possibility of unambiguously calculating its predictions. While that capability has been mainly promise so far, over the next decade the advances in high performance computing and algorithm development, as well as the application of chiral perturbation theory, mean that it will be possible to directly confront the predictions of non-perturbative QCD with the results of the carefully chosen experiments made possible by the Upgrade.

The GPDs connect the transverse distributions of the quarks (as inferred from elastic electron scattering) with the longitudinal momentum distributions of the quark-antiquark pairs (as inferred from deep inelastic scattering). They provide a framework for organizing and interpreting many other experiments investigating nucleon structure, and have lead the way to the development of a new class of experiments, deep exclusive scattering, which provide direct access to the structure of the quark and gluon correlations in the nucleon. The character of the beams and apparatus planned for the Upgrade are essential for the experimental development of this exciting new tool.

In this brief summary it is impossible to offer a comprehensive summary of the science that will be enabled by the Upgrade. Instead we concentrate on a selection of the highlights of the first five years of operation. The main physics aims of those first five years are:

- To explore QCD in the non-perturbative regime, establishing the existence and properties of exotic mesons and hence exploring the mechanism of quark confinement.
- To vastly expand our knowledge of the charge and current distributions in the nucleon

- To revolutionize our knowledge of the spin, flavor, and transverse momentum dependence of valence parton distribution functions (PDFs)
- To provide a totally new, tomographic view of hadron (and nuclear) structure through the Generalized Parton Distributions (GPDs).
- To establish a new paradigm for nuclear physics through the quest to understand nuclear structure in terms of QCD. In particular, the unique features of this new facility will enable us to explore the spin and flavor dependence of the famous EMC effect and to study the propagation of quarks through nuclear matter.
- To search for new physics beyond the Standard Model through precision tests of its predictions.

We now present a brief description of each of these topics. For an extended presentation of the program envisaged so far, we refer to the pre-CDR document [pCDR].

4.A.1 Exotic mesons and the origin of confinement

Unlike any area of physics hitherto explored, QCD has the property that the force carriers, the gluons, can by themselves form new structures. In combination with quark-anti-quark pairs, gluons can also give rise to new particles whose quantum numbers cannot be made from a quark-anti-quark pair alone. The former are known as glueballs and the challenge to find them has been the lack of any distinct quantum numbers, at least in the low mass regime and the fact that they almost certainly mix strongly with normal mesons. Exotic mesons, on the other hand, are expected to occur at low mass and, precisely because of the unique signature of their quantum numbers, be readily identifiable. Indeed, the best available theory suggests that there are as many as three nonets of these "exotic mesons" in the mass range 1.5 to 2.5 GeV. The maximum energy of 12 GeV was chosen for the Upgrade in order to make this mass region accessible with a proton target.

The GlueX detector was designed to have extremely high efficiency for detecting the multi-meson final states expected from the decay of these exotic mesons. Sophisticated techniques for making the partial wave analysis (PWA) needed to recognize an exotic meson signal have been underway at Indiana University for some years, with recent support at Jefferson Lab. The physics interest in these states arises because the unique quantum numbers have their origin in excitations of the flux tube or string joining the quark-anti-quark pair. This flux tube is intimately connected with the nature of the QCD vacuum and the origin of confinement itself. Establishing the existence and properties of these exotics is a crucial step along the path to understanding whether QCD really is the complete theory of the strong interaction.

According to the flux tube model and LQCD calculations, one expects the lightest $J^{PC} = 1^{-+}$ exotic hybrid to have a mass of order 1.7 to 1.9 GeV, with the $J^{PC} = 2^{+-}$ exotic hybrid lying 0.2 to 0.5 GeV higher. Lattice studies recently commenced at JLab aim not only to improve the accuracy with which these masses are determined but also to estimate the photo-couplings, both to improve estimates of production rates and to guide decay studies. A common feature of the models describing hybrid decays is the selection rule (though not absolute) that the hybrid meson cannot transfer its angular momentum to the final state meson pairs as relative angular momentum, but instead to the internal angular momentum of the $q\bar{q}$ pairs. In the flux tube model, low-lying hybrids are expected to decay into one ground-state S-wave meson and one excited P-wave meson, thus favoring decay modes such as $b_1(1235)\pi$ or $a_2(1320)\pi$ and suppressing decay to $\pi\eta$ or $\pi\rho$. If this selection rule holds, it may explain the failure to uncover hybrid mesons to date, since the favored decays involve complicated multi-pion final states.

The GlueX experiment will initially focus on exotic J^{PC} hybrid mesons since they cannot mix with conventional $q\bar{q}$ mesons. The identification of these states requires a partial wave analysis (PWA) of exclusive reactions. For a given reaction, *e.g.* $\gamma p \rightarrow Xp$, where X refers to a specific set of detected mesons $(\pi^{\pm}, \pi^0, K^{\pm}, \eta, \dots)$, the decay angular distribution of final state particles is fitted to a finite set of partial waves that characterize the production of X and its decay. The fitting procedure is carried out in bins of X mass, and the net result is the mass dependence of individual partial waves and their relative phases. Thus states are identified by their Breit-Wigner line shapes and interferences with each other and with well-established meson resonances.

Linearly polarized photons are required to extract maximum information from the PWA by adding information on selecting production mechanisms and filtering quantum numbers of produced states. Linearly polarized photons will be produced by coherent bremsstrahlung from thin diamond crystal radiators. Recent developments make possible production of thin wafers of sufficient quality to permit tight collimation of the photon beam to produce the polarization enhancement needed for GlueX. The technique also requires the superb beam characteristics of the CEBAF electron beam (spot size and emittance) and a minimum energy of 12 GeV to achieve the requisite degree of linearly polarization for 9 GeV photons.

Advances in science are often enabled by advances in technology, and GlueX can now address the experimental challenge of mapping exotic mesons because of developments in electronics (to achieve data-taking rates), significant increases in computational power (needed to analyze large data sets), and recent developments in producing thin diamond crystals (necessary for producing photon beams of requisite polarization). With the energy upgrade of the CEBAF accelerator, the final requirement to do this fundamental physics will have been met. In parallel, increased computational power will also enable LQCD calculations to yield the detailed prediction of the spectrum of exotic hybrid mesons whose validation will lie in the experimental information from the GlueX experiment. As a result JLab at 12 GeV will be uniquely positioned to exploit the discovery potential needed to address an important and fundamental question in physics – the nature of confinement in QCD.

4.A.2 Charge and current distributions of the nucleon

Measurements of the nucleon elastic form factors map the charge and current distributions. In spite of a long history of such experiments, of the four form factors for elastic eN scattering (electric and magnetic, proton and neutron) only the magnetic form factor of the proton, G_M^p, has been measured up to high $Q^2(\sim 30\,\mathrm{GeV}^2)$ with relatively good accuracy. Recent JLab results show the potential for discovery with increasing Q^2 – see Fig. 14. Contrary to long-held beliefs, the ratio F_2^p/F_1^p is still far from the $1/Q^2$ behavior implied by perturbative QCD for momentum transfers as high as $Q^2 \approx 6\,\mathrm{GeV}^2$. This demonstrates that the charge and current distributions in the proton are quite different, and points to the importance of orbital angular momentum in the proton wavefunction. With the 12 GeV Upgrade, the ratio F_2^p/F_1^p will be measured up to $14\,\mathrm{GeV}^2$, probing the proton's structure at distances as small as 0.1 fm.

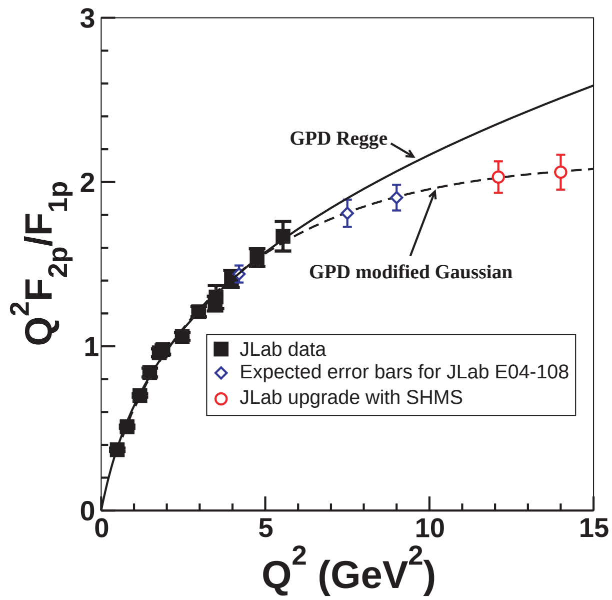

Figure 14: The JLab 6 GeV data on the ratio of proton form factors, F_2^p/F_1^p, and the projected measurements at 12 GeV. Perturbative QCD implies that $F_2^p/F_1^p \sim 1/Q^2$ for $Q^2 \to \infty$. The graph illustrates the potential of form factor measurements at 12 GeV to discriminate between GPD models. Shown are the predictions of a Regge–based GPD model [Gu04] and a model based on soft Gaussian nucleon wavefunctions modified by a short–range interaction [St03b].

Knowledge of neutron form factors at high Q^2 is equally important. With the 12 GeV Upgrade, the neutron magnetic form factor will be measured up to about $14\,\mathrm{GeV}^2$, and its electric form factor up to $8\,\mathrm{GeV}^2$. These form factor measurements will provide crucial constraints on the first moments of the GPDs and their t–dependence. Figure 14 demonstrates the power of form factor measurements to discriminate between GPD models. An equally important consideration is that form factors can be measured up to high $|t|$ ($= Q^2$ for elastic scattering), while direct measurements of the GPDs in exclusive processes are restricted to $|t| \leq 1\,\mathrm{GeV}^2$. Thus, form factor measurements will continue to provide our only source of information about the quark distributions at small transverse distance scales. Finally, we note that once again modern lattice QCD promises to complement these measurements with precise calculations of the predictions of QCD itself.

4.A.3 Revolutionize our knowledge of spin and flavor dependence of valence PDFs

One of the most fundamental properties of the nucleon is the structure of its valence quark distributions. Valence quarks are the irreducible kernel of each hadron, responsible for its net charge, baryon number and other macroscopic quantum numbers. In deep–inelastic scattering at average values of x, the valence quarks are "dressed" by quark-antiquark pairs produced by non-perturbative effects at large distance scales ($\sim$ 1 fm), as well as by gluon bremsstrahlung at short distances. At higher x values these $q\bar{q}$ contributions drop away, and the physics of the valence quarks is cleanly exposed [Is99]. Previous deep inelastic scattering and other experiments have provided a detailed map of the nucleon's quark momentum distributions at average ($\sim$ 0.3) and small values of x, but only with the 6 GeV beams of CEBAF could we begin to access the "deep valence region"

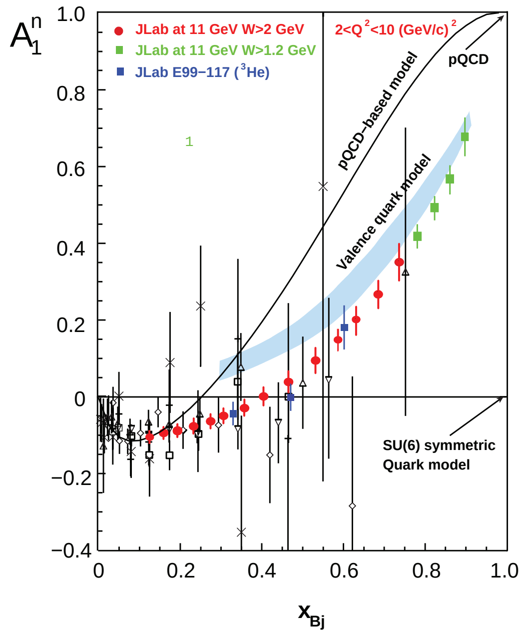

Figure 15: Projected measurement of the neutron polarization asymmetry, A_1^n, with the 12 GeV Upgrade. The shaded band represents the range of predictions of valence quark models; the solid line is the prediction of a pQCD–based quark model.

($x > 0.5$), where the three basic valence quarks of the proton and neutron dominate the wave-function. The lack of data in the deep valence region represents a glaring gap in our knowledge of nucleon structure, especially since there are qualitatively different predictions for the quark spin and flavor distributions in the $x \to 1$ limit.

The 12 GeV Upgrade will provide for the first time the necessary combination of high beam intensity and reach in Q^2 to allow us to map out the valence quark distributions throughout the deep valence region with high precision. These measurements will have a profound impact on our understanding of the structure of the proton and neutron. They will also provide crucial input for calculating cross sections for hard processes that will be used at high-energy hadron-hadron colliders such as the LHC in searches for the Higgs boson or for physics beyond the Standard Model. The 12 GeV Upgrade will allow measurements of inclusive spin structure functions at large x with unprecedented precision. As an example, Fig. 15 shows the neutron spin asymmetry, A_1^n, which is determined by a ratio of spin-dependent to spin-averaged quark distributions. Most dynamical models predict that in the limit where a single valence up or down quark carries all of the nucleon's momentum ($x \to 1$), it will also carry all of the spin polarization (*i.e.*, $A_1^n \to 1$ as $x \to 1$). Previously available data on A_1^n have poor accuracy at large x, and end before reaching the region of valence quark dominance. Only the recent data from the JLab Hall A experiment E99-117 [Zh03a, Zh04] show the first hint of the predicted dramatic transition $A_1^n \to 1$ at the largest x value reached.

The proton spin asymmetry A_1^p can also be measured to high precision in the high x region, and combined with data on A_1^n to separate the polarized valence parton distribution functions, $\Delta u/u$ and $\Delta d/d$, in the framework of naive parton models. The results can be compared directly to relativistic constituent quark models and pQCD-based models, allowing a conclusive test of

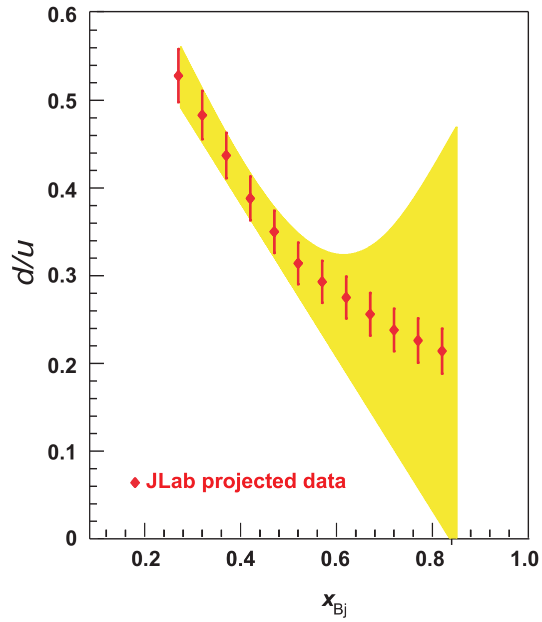

Figure 16: Projected measurement of the ratio of d– and u–quark momentum distributions, $d(x)/u(x)$, at large x, made possible by the 12 GeV Upgrade. The shaded band represents the uncertainty in existing measurements arising from nuclear Fermi motion effects.

hadron helicity conservation and probing the of role of quark orbital angular momentum in a deep valence quark region. The A_1^p and A_1^n data will provide crucial input to global QCD analyses and significantly improve our knowledge of the polarized quark and gluon distributions.

Polarized parton distributions will also be studied with Semi-Inclusive DIS. The 12 GeV Upgrade will provide a unique opportunity for semi-inclusive measurements with high precision over a wide kinematic range, allowing a mapping of the flavor dependence of the polarized valence and sea quark distributions and significantly improving the extraction of the polarized gluon distribution.

Even in unpolarized deep inelastic scattering, where the available data are best, there are long-standing unresolved issues. One example is the ratio of down to up quarks in the proton, $d(x)/u(x)$, whose large–x behavior is intimately related to the fact that the proton and neutron, and not the Δ, are the stable building blocks of nuclei [Cl88]. Determining this ratio requires measurement of both the neutron and the proton structure functions. Information about the neutron must be extracted from deuterium data, and is difficult to disentangle from nuclear effects (binding of p and n) at large x [Wh92, Me96]. Figure 16 shows the precision with which this fundamental ratio can be measured with the 12 GeV Upgrade. The proposed experiment will utilize a novel technique, recently pioneered at JLab: detection of the slowly recoiling proton spectator will "tag" scattering events on a nearly on-shell neutron in a deuteron target [Fr88, Me97]. An independent measurement of $d(x)/u(x)$ can be made by exploiting the mirror symmetry of $A = 3$ nuclei in simultaneous measurements with ^{3}He and ^{3}H targets [Af00, Pa01, Sa01, Af03]. Both methods are designed to largely eliminate the nuclear corrections, thereby permitting the d/u ratio to be extracted with unprecedented precision.

4.A.4 Studies of Spin-orbit correlations with semi-inclusive DIS

The knowledge of correlations of transverse momentum of partons and spin is crucial for the understanding of the spin structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD. Azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering provide access to the orbital motion of quarks and play an important role in the study of transverse momentum distributions of quarks in the nucleon.

Significant progress has been made recently in understanding the role of partonic initial and final state interactions [Br02, Co02, Ji02, Be03, Be03b]. The account of the interaction between the active parton in the hadron, and the spectators leads to gauge-invariant transverse momentum dependent (TMD) parton distributions [Co02, Ji02, Be03b, Bo03]. Furthermore, QCD factorization for semi-inclusive deep inelastic scattering at low transverse momentum in the current-fragmentation region has been established in Ref. [Ji05]. This new framework provides a rigorous basis to study the TMD parton distributions from SIDIS data using different spin-dependent and independent observables. TMD distributions describe transitions of a nucleon with one polarization in the initial state to a quark with another polarization in the final state.

The TMDs known as the Sivers and Boer-Mulders (BM) functions [Si90, An98, Bo98] parameterize the correlations between the transverse momentum of quarks and the spin of a transversely polarized target or the transverse spin of the quark respectively. They require both orbital angular momentum as well as non-trivial phases from the final state interactions. Experimental results on the Sivers functions for up and down quarks, so far, are consistent with a heuristic model of up and down quarks orbiting the nucleon in opposite directions [Bu02, Bu04].

The transverse flavor dipole moment for transversely polarized quarks in an unpolarized nucleon, recently calculated for the first time in lattice QCD [Go06], suggests the Boer-Mulders functions that are significantly larger than Sivers functions. Moreover, consistent with large N_C predictions [Bu06], the displacement of transversely polarized u and d quarks was found to be in the same direction, indicating the same sign for the BM functions for u and d quarks. In combination with a final state interaction that is on average attractive, a measurement of the sign of the BM function would thus already reveal the correlation between orbital angular momentum and spin of the quarks [Bu05].

Similar correlations of spin and orbital motion arise also in the hadronization process. One particular case is the Collins T-odd fragmentation function $H_1^\perp$ [Co93] describing fragmentation of transversely polarized quarks into unpolarized hadrons. A significant asymmetry was measured recently by Belle [Ab06] indicating that the Collins function is indeed large.

For transversely polarized targets, several azimuthal asymmetries already arise at leading order, providing access to the transversity distribution h_1 [Ra79, Ja92] as well as first moments of Sivers distribution function and Collins fragmentation functions. The transversity distribution and its first moment, the tensor charge (calculable in lattice QCD), are as fundamental for understanding of the spin structure of the nucleon as are the helicity distribution g_1 and the axial vector charge. The transversity distribution h_1 is charge conjugation odd. It does not mix with gluons and for non-relativistic quarks it is equal to the helicity distribution g_1. Thus, it probes the relativistic nature of quarks and it has a very different from g_1 Q^2 evolution.

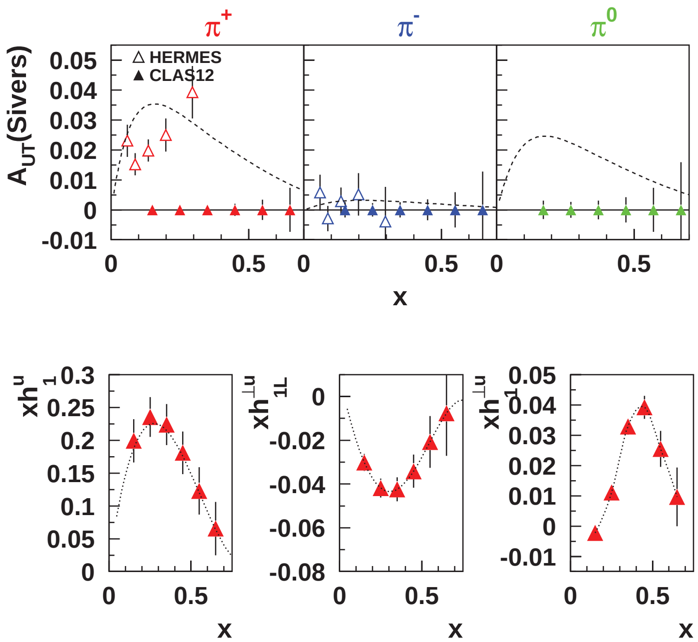

Figure 17: Projected transverse spin asymmetry from the Sivers effects ($A_{UT}^{\sin(\phi-\phi_S)} P_T/M$) in single π production with CLAS at 11 GeV (top) and transverse spin distributions extracted from transversely polarized, longitudinally polarized and unpolarized target measurements (bottom). Curves are predictions for transversity, h_1, [An07], Mulders, $h_{1L}^{\perp}$ [Ef05] and Boer-Mulders, $h_1^{\perp}$ [Ba04] distributions for u-quarks.

The study of transverse structure has gathered increasingly large interest after the first evidence of non-zero transversity was observed in the HERMES experiment [Ai05] (Fig.17). Recent explorations of the Collins and Sivers effects from the HERMES [Ai05], COMPASS [Al05] and BELLE [Ab06] experiments have set the groundwork for the next phase at performing high-precision measurements. The first extraction of the transversity distribution has been carried out recently [An07], combining e+e- and semi-inclusive DIS data from HERMES and COMPASS. Few projections for TMD measurements with JLab at 11 GeV are plotted in Fig. 17.

Spin-orbit correlations due to fragmentation of transversely polarized quarks are also accessible in SIDIS at JLab with unpolarized and longitudinally polarized targets, where at leading order they are observable as $\cos 2\phi$ and $\sin 2\phi$ moments of the cross section, respectively. These contributions, known as Boer-Mulders [Bo98] and Kotzinian-Mulders [Ko96] asymmetries, involve the Collins fragmentation function $H_1^{\perp}$ [Co93] coupled to distribution functions describing transversely polarized quarks in unpolarized ($h_1^{\perp}$) and longitudinally polarized ($h_{1L}^{\perp}$) nucleons. Studies of Collins fragmentation, with unpolarized and longitudinally polarized targets, thus will provide complimentary information on Collins function and provide access to BM and Mulders distribution functions (see Fig.17). Independent information on both distribution functions can be obtained from the study of the $\cos 2\phi$ azimuthal asymmetry in unpolarized and polarized Drell-Yan processes [Ta95], where the BM and Sivers functions were predicted to have opposite to SIDIS sign [Co02].

Measured single and double spin asymmetries for all pions in a large range of kinematic variables (x_B, Q^2, z, $P_{\perp}$ and ϕ) combined with measurements with unpolarized target will provide detailed information on flavor and polarization dependence of transverse momentum distributions of quarks in valence region. Measurements of semi-inclusive processes combined with inclusive and exclusive measurements with upgraded JLab will allow to study the quark structure of nucleon with unprecedented detail. Understanding of spin-orbit correlations, together with independent measurements related to the spin and orbital angular momentum of the quarks will help construct a more complete picture of the nucleon in terms of elementary quarks and gluons going beyond the simple collinear partonic representation.

4.A.5 Quark imaging of the nucleon through generalized parton distributions

It has recently been realized that the elastic form factors and PDFs, which are so important to our understanding of nucleon structure, may be viewed as special cases of a more general and potentially more powerful way to characterize that structure — the generalized parton distributions (GPDs) [Ji97, Ra97]. The GPDs describe the quantum–mechanical amplitude for "taking out" a quark (or antiquark/gluon) of a fast–moving nucleon and "putting it back" with different longitudinal and transverse momentum. They provide a unified description of the response of the nucleon to scattering processes in which a short–distance probe interacts with a single quark in the nucleon; see Refs. [Di03, Be05] for recent reviews. In addition to the spatial densities (form factors) and longitudinal momentum densities (parton distributions), these functions describe the correlation of the spatial and momentum distributions, *i.e.*, how the spatial shape of the nucleon changes when probing quarks of different wavelengths.

The correlations are most simply revealed by the Fourier transform of the GPDs with respect to the transverse momentum transfer to the nucleon ("impact parameter–dependent parton densities"). These functions describe the transverse spatial distribution of quarks with given longitudinal momentum fraction x and amount to a set of 2–dimensional tomographic quark images of the nucleon, see Fig. 18 [Bu03, Di02]. This new representation offers unprecedented possibilities for visualizing the nucleon as an extended object and for testing dynamical models of its structure. Traditional concepts of hadronic physics such as the nucleon's quark core and the pion cloud can be rigorously formulated within this new representation. The spatial representation naturally lends itself to the discussion of polarization phenomena. For example, transverse polarization of the nucleon leads to a distortion of the longitudinal motion of the quarks, which can be related to the observed spin asymmetry in polarized semi-inclusive eN scattering (Sivers effect) [Bu02]. The transverse spatial distribution of partons is also a crucial ingredient in modeling high–energy proton–(anti)proton collisions with hard QCD processes, which are studied at the Fermilab Tevatron and the CERN LHC [Fr05, Fr07]. More generally, the GPDs can be related to the Wigner quantum phase–space distributions of quarks in the nucleon, which describe the simultaneous distribution of particles with respect to both position and momentum and provide genuine 3–dimensional spatial quark images of the nucleon [Be03].

Moments of the GPD's — weighted integrals over the quark momentum fraction, x — give access to fundamental static properties of the nucleon which are very difficult to measure otherwise. The second moments of the Dirac and Pauli form–factor type GPDs give the total (spin plus orbital angular momentum) quark contribution to the nucleon spin, $J^q = \frac{1}{2}\Delta\Sigma + L^q$ [Ji97]. A measurement of this quantity, combined with existing data on $\Delta\Sigma$ from inclusive deep–inelastic scattering, will make it possible to determine the quark orbital angular momentum, L^q. The GPD moments also contain information about the forces acting on the quarks inside the nucleon [Po03]. In parallel with the measurements described below, from which one aims to extract these moments, the LQCD

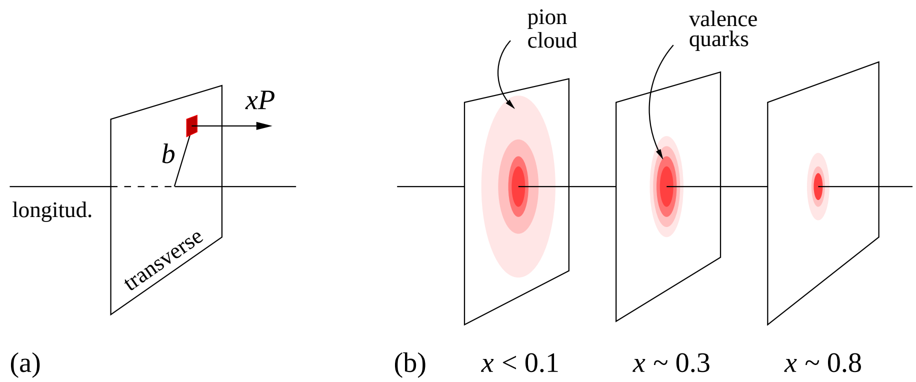

Figure 18: Nucleon tomography. *Left:* The Fourier transform of the GPD describes the transverse spatial distribution of quarks with longitudinal momentum fraction x. *Right:* It produces a set of 2–dimensional "tomographic" quark images of the nucleon [Bu03], which *e.g.* allow one to identify the valence quark core ($x \geq 0.3, b \ll 1\,\text{fm}$) and the pion cloud ($x \leq 0.1, b \sim 1\,\text{fm}$) [St03a].

effort at JLab will compute these same moments as a function of momentum transfer. Thus the moments not only have an attractive physical interpretation but also provide quantities which can be directly compared with the unambiguous predictions of non-perturbative QCD.

The mapping of the GPD's and the construction of a comprehensive set of "quark images" of the nucleon are prime objectives of the 12 GeV Upgrade. This will be an extensive program rather than a single experiment, combining measurements of a variety of channels with structural constraints obtained from theoretical studies and results of future lattice QCD simulations. Important basic information comes from the extensive data on nucleon form factors measured in elastic eN scattering and the parton distributions measured in inclusive deep–inelastic scattering. The crucial new information about the correlation of the spatial and momentum distributions — essential for nucleon imaging and the extraction of the quark orbital angular momentum — will come from measurements of exclusive channels in inelastic scattering at large momentum transfer, namely deeply–virtual Compton scattering (DVCS), $eN \to eN\gamma$, and deeply–virtual meson production (DVMP), $eN \to eNM$ (where $M = \pi$, ρ, K, ϕ, J/ψ, etc.). In these reactions the final–state photon/meson is produced in a short–distance scattering process involving a single quark in the nucleon, which is calculable using well–tested methods of perturbative QCD ("factorization"). Experimentally, such exclusive measurements require a combination of high beam energy, high beam intensity (luminosity) and duty factor, as well as advanced detection equipment — a combination never previously available in eN scattering. The 12 GeV Upgrade at JLab provides capabilities for such measurements in the valence quark region that are globally unique.

In $eN \to eN\gamma$ the DVCS process interferes with the Bethe–Heitler process, in which the final–state photon is emitted by the scattered electron. This interference acts as a natural amplifier for DCVS and allows one to access DVCS at the amplitude level, greatly simplifying the GPD analysis. Experiments aim to extract the interference term in the $eN \to eN\gamma$ cross section through a combination of spin–dependent and independent cross sections and relative asymmetries. To separate the different spin components of the GPDs, measurements of a variety of polarization observables (beam spin and longitudinal/transverse target spin) will be performed. These observables allow one to probe the GPDs in a certain combination of the quark momentum fractions ($x = \xi$), as functions of both x and the invariant momentum transfer, t. The results can be directly translated

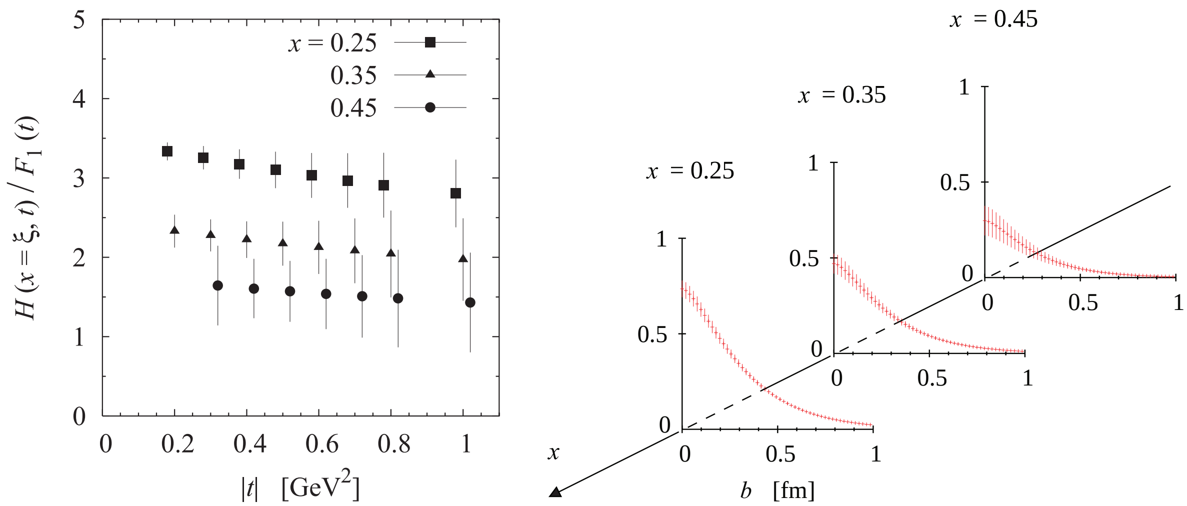

Figure 19: Spatial images of the proton from DVCS. *Left:* Projected JLab 12 GeV results for the Dirac GPD of the proton, $H(x = \xi, t)$, as a function of x and t, as extracted from the DVCS beam spin asymmetry, A_{LU}. Shown is the ratio of the GPD to the the proton's Dirac form, $F_1(t)$. *Right:* Transverse spatial image of the proton obtained by Fourier–transforming the measured GPD [Di02]. The errors were estimated assuming a dipole–like t–dependence.

into certain transverse spatial images of the nucleon. As an example, Fig. 19 shows the projected results for the Dirac form–factor type GPD and its corresponding transverse spatial representation. Complementary information can be obtained about dispersive integrals of the GPDs over the quark momentum fraction. With the help of GPD parametrizations, this information can be used to construct 2–dimensional tomographic images of the nucleon, *cf.* Fig. 18. Results obtained so far at JLab with 6 GeV beam energy [St01, Ch06, Mu06, Ro06] and at other facilities have demonstrated the basic feasibility of such measurements and are providing first useful constraints for GPD phenomenology.

Deeply–virtual meson production (DVMP) provides complementary information for the separation of the different spin and flavor components of the GPDs. In particular, the transverse target spin asymmetry in ρ^0 production is sensitive to the Pauli form factor–type GPD, which is needed to extract the total quark angular momentum in the nucleon, J^q. Figure 20 illustrates how measurements of this observable, combined with theoretical GPD models incorporating data from other processes, can be used to estimate the u–quark angular momentum in the proton. Generally, present data indicate that in DVMP the single–quark reaction mechanism is subject to significant corrections ("higher twists"). Theoretical studies aim to calculate these corrections in order to fully utilize the DVMP data for the GPD analysis.

4.A.6 The physics of nuclei

Lying at the core of every atom, at the 10^{-15} m scale, the nucleus comprises over 99% of the atom's mass. It is a unique many-body system that can be understood quantitatively as assemblies of individual protons and neutrons bound by an effective nuclear force. Nuclear physics describes the dominant two-body $N - N$ force at "long range" (the radius of the nucleus or more precisely the

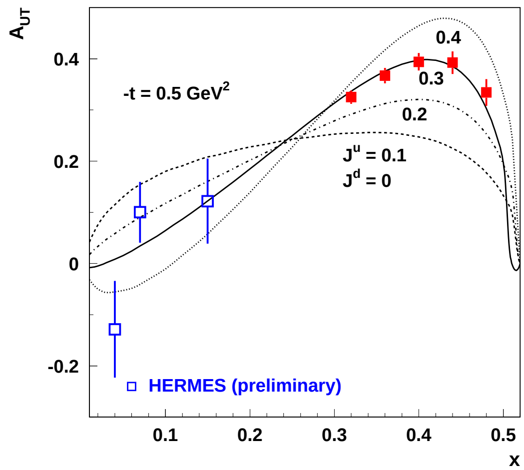

Figure 20: Sensitivity of the transverse target spin asymmetry in deeply–virtual ρ^0 production to the total u–quark angular momentum in the proton, J^u. The curves represent a theoretical prediction based on GPD models in which J^u appears as a free parameter [Go01]. The red data points illustrate the precision of the projected measurements at 12 GeV.

pion Compton wave length) as being mediated by the exchange of pions, the lightest hadron Nature provides. This attractive force is delicately balanced by a force at shorter distances that repels. When protons and neutrons are at “short range”, the nuclear force changes sign and the nucleons repel each other. This delicate interplay is not well understood, yet it enables the existence of atomic nuclei and the chemical elements.

Although the effective $N-N$ force is well constrained phenomenologically by the large body of pp and np elastic scattering data, it is not yet understood under what circumstances it can be described in terms of the exchange of mesons, and when it is more efficient to describe it in terms of the underlying quark-gluon exchange forces. Since the nuclear force is the residue of the even stronger QCD force between quarks, forever confined in the nucleons, one must question whether protons and neutrons are the best *quasi-particles* to describe the nucleus. From the point of view of QCD the nucleus and the nucleon are simply two different eigenstates of the QCD Hamiltonian and there is no reason to expect a simple connection between them. It is natural to ask whether we can discern an imprint of the underlying quarks and gluons. Recently it has proven possible to derive a realistic, density-dependent effective $N--N$ force of the Skyrme type starting from the quark level [Gu06] and this avenue needs to be pursued both theoretically and experimentally. After many decades of research, the basic mystery of the origin of nuclei remains and the question of how nuclei emerge from QCD is one of the key issues of modern-day studies of nuclei [Gu04a].

From this perspective some of the most fundamental questions in modern nuclear physics are:

- How do the nucleon-based models of nuclear physics with interacting nucleons and mesons arise as an approximation to the quark-gluon picture of QCD?
- In probing ever-shorter distances within the nucleus, what is the role of the fundamental constituents of QCD — quarks and gluons — in the description of nuclei?
- How does the nuclear environment modify the quark-gluon structure of nucleons and mesons?

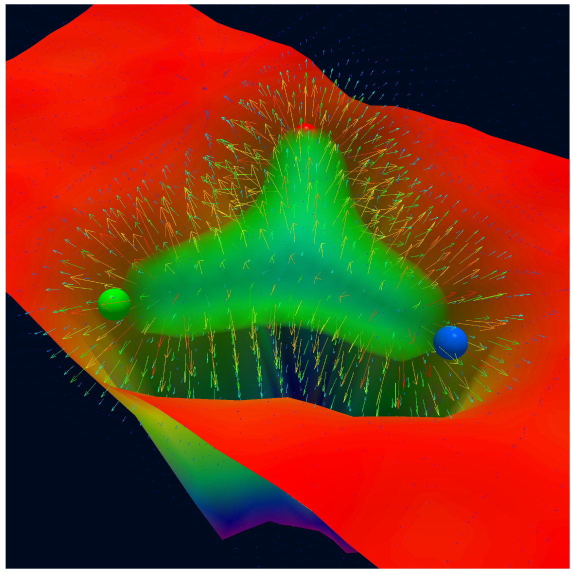

Figure 21: A visualization based on lattice QCD calculations. A baryon is shown (in the static approximation) in the presence of the QCD vacuum. The vacuum action density in a plane passing through the centers of the quarks is represented by the red surface; this vacuum is visibly “expelled” by the presence of the baryon. This suggests that nucleons in a nucleus might experience a different, diminished QCD vacuum relative to free protons and neutrons, an effect which alters their structure within the nuclear medium.

From the point of view of QCD there is no guarantee that the clusters of quarks and gluons occupying shell model orbits in nuclei should have properties identical to those of isolated nucleons. Recent lattice QCD calculations indeed verify that the probability of finding virtual quark-antiquark pairs in the QCD vacuum decreases systematically when quarks are added. Hence, a hole or depletion in the QCD vacuum is created, a picture qualitatively similar to the bag model. This is graphically illustrated in Fig. 21.

Unraveling the origin of the nuclear EMC effect

The question of whether a nucleon bound in the nuclear medium has different properties from those of a free nucleon has been a long-standing issue in nuclear physics. It was first considered seriously with the discovery of the nuclear EMC effect some twenty years ago, in which scattering from quarks inside the nucleus was found to differ in non-trivial ways, notably in the valence region, from the scattering of quarks in a free nucleon. Existing measurements indicate little Q^2 dependence, and an A dependence in the magnitude, but not the overall form, of the structure function modification in nuclei. The nature of the modifications in nuclei depends primarily on Bjorken-x; its most prominent features are an enhancement in the region $0.1 < x < 0.3$ and a depletion in the region $0.3 < x < 0.7$. Despite a huge world-wide effort in experiment and theory, there is as yet no consensus concerning the origin of the EMC effect. Explanations of it are hampered by the enormous challenge of constructing a theory that can consistently account for nuclear binding as well as the structure functions of free nucleons. Further difficulties arise from the lack of evidence for the surplus of antiquarks predicted to arise from pions being exchanged between nucleons (e.g. in Drell-Yan processes). The failure to account for these hard scattering results is a serious problem for nuclear theory.

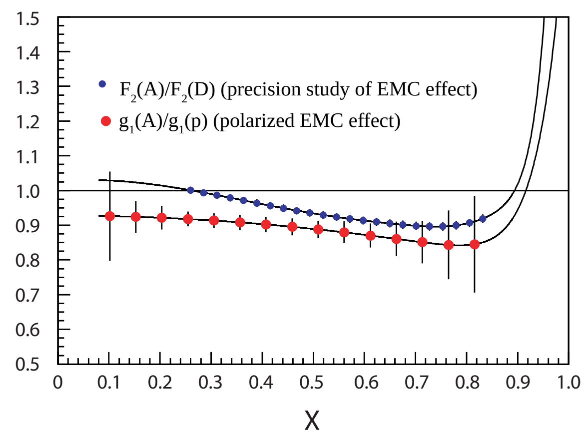

Figure 22: An illustration of the polarized and unpolarized EMC effect studies accessible following the upgrade. The unpolarized measurement shows representative uncertainties for precision studies performed on a variety of nuclei. The polarized measurement compares g_1 in ^{7}Li and in ^{1}H.

Knowing that the valence quark region is depleted does not tell us enough to understand the origin of the EMC effect. We would like to know if u and d valence quarks are depleted in the same manner. Although limits on the nuclear modification of the sea quarks have been derived from Drell-Yan data, some small modification must exist, and there are opportunities to map out the flavor dependence, as in the semi-inclusive DIS studies discussed earlier. Even more straightforward, there is no experimental information on the spin dependence of the EMC effect, which was recently predicted to be twice as large as the regular EMC effect (in one example of a covariant model which does satisfy the criteria given above) [Cl05, Cl06]. A measurement of the spin-dependence of the EMC effect is well within the reach of the 12 GeV Upgrade. This spin-dependent EMC effect emphasizes the quark polarization degrees of freedom within a nucleus, due to the spin-dependence of the coupling between the quarks and the strong binding fields inside the nucleus. In Fig. 22 we highlight a possible measurement of the nuclear ratio of spin structure functions, g_1, in ^{7}Li and ^{1}H.

The CW character of the CEBAF beam also opens promising new opportunities for measurements of structure functions in coincidence with low-energy nucleons or target fragments. This technique is currently being pioneered at JLab, with a recoil proton detector "tagging" scattering events on a nearly on-shell neutron in a deuteron target. The technique can easily be expanded to EMC-type measurements on ^{2}H and ^{3}He. A glimpse at the information obtainable from such experiments has been provided by the analysis of deep-inelastic neutrino scattering events in heavy-liquid bubble chambers. In spite of the poor statistics, these experiments have shown that the structure functions tagged on low-energy protons are different from those determined from inclusive scattering. A large acceptance device at a 12 GeV JLab will essentially function as an electronic "bubble chamber" for deep-inelastic electron scattering events, and will allow reconstruction of the EMC effect from a complete measurement of the x-dependence of exclusive channels on light nuclei.

4.A.7 Search for new physics beyond the Standard Model

Precision parity-violating electron scattering experiments made feasible by the parity quality beams at JLab have already led to remarkable advances in our knowledge of the individual light quark contributions to the structure of the nucleon. They have also demonstrated the sensitivity to search for deviations from the effective electron-quark interaction at low energy that is so accurately predicted by the Standard Model. Deviations from that prediction unambiguously signal the presence of new physics, for example, new gauge bosons (Z's), leptoquarks, or particles predicted by supersymmetric (SUSY) theories — *i.e.* physics beyond the Standard Model.

The 12 GeV Upgrade will greatly extend the ongoing JLab program along the two exciting avenues of discovery just described — new physics and a deeper understanding of hadron and nuclear structure. One of the more compelling new opportunities is a remarkably accurate measurement of the weak charge of the electron, via the parity-violating asymmetry in electron-electron (Moller) scattering. Such a measurement becomes feasible with the upgraded JLab electron beam, with its unique combination of high energy and unprecedented luminosity and stability. The small size of the predicted asymmetry, 40 parts per billion, will require extraordinary control of systematic errors, making it appropriate as a next generation measurement. In addition to its inherent discovery potential, completion of the currently approved program of PVES measurements will ensure the development and testing of the necessary instrumentation for the later measurements at 12 GeV.

The weak charge of the electron is suppressed in the Standard Model by the factor $1 - 4\sin^2\theta_W \simeq 0.05$, where θ_W is the weak mixing angle. Because new processes beyond the Standard Model will not generally be suppressed by the same factor, this measurement offers a powerful window into such phenomena. The achievable accuracy of the electron weak charge measurement provides extraordinary sensitivity to electron substructure ("compositeness") to a scale of nearly 30 TeV, corresponding to *7 millionths* of a Fermi. Such sensitivity to leptonic substructure will be unmatched anywhere in the world until the advent of a linear collider or a neutrino factory. The measurement is also sensitive to the existence of new neutral gauge bosons in the mass range 1 to 2 TeV; such model-dependent limits are comparable to those to be achieved by measurements at the Large Hadron Collider. Furthermore, the measurement will severely constrain the viability of SUSY models which violate R-parity. This has implications for a plausible SUSY dark matter candidate to explain some of the non-luminous and unexplained source of 90% of the mass of the universe – see Fig. 23.

Even within the context of the Standard Model, an improved measurement will have significant consequences. As a measurement of the weak mixing angle, it will be the most precise low energy determination. Indeed, the precision will be on par with the current best high energy measurements. This may shed light on the significant discrepancy at the Z-pole between purely leptonic and semi-leptonic measurements of the weak mixing angle.

The upgraded beam energy will also make possible measurements of parity violation in deep inelastic scattering (PVDIS). On an isoscalar target at moderate x PVDIS is also sensitive to $\sin^2\theta_W$. In fact, it was a measurement of this process by the SLAC E122 experiment [Pr78] that established the Standard Model as the theory of the neutral weak interaction. One interpretation of a recent measurement of neutrino-nucleus DIS by the NuTeV collaboration is that the Standard Model is incomplete. A measurement of the E122 PVDIS asymmetry, with an order of magnitude improvement in accuracy, will test the electro-weak theory with comparable sensitivity. This mea-

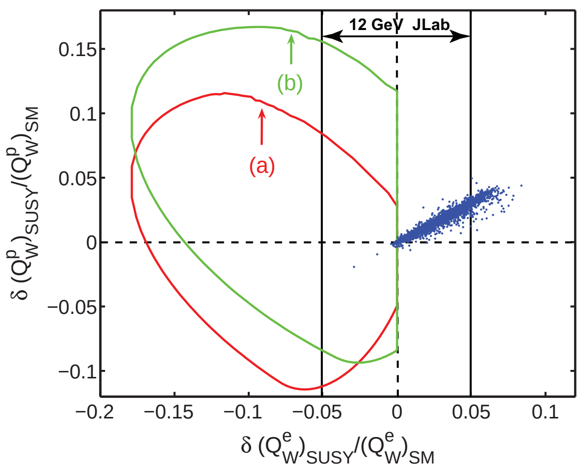

Figure 23: Relative shifts in $Q^e_{\rm weak}$ and $Q^p_{\rm weak}$ from SUSY effects (at 95% confidence level unless otherwise specified). The blue dots denote MSSM loop corrections for approximately 3000 SUSY-breaking parameter choices. The interior of the truncated elliptical regions (a) and (b) give possible shifts due to R-parity non-conserving SUSY interactions (95% confidence) using two different values of $\delta|V_{ud}|^2/|V_{ud}|^2$ [Ra06]. Because the lightest supersymmetric particle is unstable if R-parity is not conserved, these SUSY models offer no candidate for dark matter [Ku02]. The vertical bars illustrate what could be achieved by a 12 GeV Møller experiment at Jefferson Laboratory.

surement becomes feasible with a 11 GeV beam and the presently planned detectors in one of the high luminosity end stations, with rather modest demands on beam time and systematic control.

Such tests of the electro-weak theory in DIS require a thorough understanding of possible nucleon structure effects that could cloud the interpretation of the measurements. These effects are important to study in themselves and have the potential to provide profound new insights into the dynamics of quarks inside nucleons. Examples of potential PVDIS measurements are the value of $d(x)/u(x)$ as $x \to 1$, the search for evidence of charge symmetry violation (CSV) at the partonic level, and the characterization of novel higher twist effects. These topics can be investigated with moderate beam time using a new large-acceptance spectrometer/detector package and the upgraded CEBAF beam. Thus, quite apart from providing a sound basis for the interpretation of a PVDIS measurement to search for physics beyond the Standard Model, this program can lead to important new discoveries regarding the quark structure of nucleons.

Recently, two workshops were held at Jefferson Laboratory to discuss the physics potential and the experimental feasibility of the Møller scattering and PVDIS programs with 11 GeV beams, bringing together leading theorists and experimentalists in the field. In the case of Møller scattering, there was general consensus that a measurement of the parity-violating asymmetry with a total error smaller than 1 part per billion was feasible. There was overwhelming enthusiasm to proceed aggressively with the design of such a measurement that would yield a measurement of the weak mixing angle $\sin^2\theta_W$ with an error between 0.0002 and 0.0003. In the case of PVDIS, it was recognized that 1% asymmetry measurements at $x \sim 0.7$ would be attainable with a large volume, high field solenoidal spectrometer. Such measurements would have tremendous discovery potential. Apart from yielding complementary tests of the electroweak theory in the semi-leptonic sector, the potential observation of the onset of CSV and the characterization of higher twist effects might provide the cleanest way to go beyond the conventional quark-parton description of the nucleon.

4.B The Emerging QCD Frontier: The Electron-Ion Collider

Much of the focus in contemporary nuclear physics research is on mapping and understanding the emergent phenomena from QCD that determine the unique properties of strongly interacting matter: the breaking of chiral symmetry that gives light-quark hadrons most of their mass; the spin, flavor, space and momentum structure of hadrons; the nearly perfect liquid behavior of the hot matter created in RHIC collisions; possible color superconductivity in the dense interior of compact stars. A key to understanding the rich panoply of QCD phenomena is identifying conditions under which the theory is amenable to a controlled solution. Numerical solutions on a space-time lattice have made impressive advances in the treatment of strongly interacting matter in equilibrium at both low and high temperatures. A perturbative expansion in powers of the running QCD coupling constant α_s is successful in describing hadron dynamics in high-energy processes involving large momentum transfer. Interactions of pions and nucleons at low momentum have been successfully analyzed via chiral effective field theories.

Recent theoretical advances have introduced a new QCD regime that may be amenable to a quite different effective field theory approach. This new interpretability frontier occurs in matter probed at moderate momentum transfers, where the QCD coupling is still relatively weak, but at gluon densities high enough to produce extremely strong color fields that can be treated by classical field theory. This regime is dominated by direct manifestations of the defining feature of QCD: the self-interaction of gluons. Gluon splitting and gluon recombination are predicted to reach a competitive balance, leading to a saturation of gluon density that should be universal to all strongly interacting matter probed under suitable conditions. Hints of this saturation have been extracted from measurements of electron-proton collisions at HERA and of deuteron-nucleus and nucleus-nucleus collisions at RHIC. Saturated gluon densities would have a profound influence on heavy-ion collisions at the LHC, and may well be the source of certain general features of high-energy hadron cross sections. In order to tie these phenomena together and map the universal properties of gluon-dominated matter, one needs to probe partonic structure at very low values of Bjorken x, where individual partons carry $<\sim 0.1\%$ of a nucleon's overall momentum, but within a "sweet spot" in momentum transfer (Q^2) where the color interaction is neither too weak nor too strong.

The ideal accelerator to test this classical field theory approach well into the gluon saturation regime with an *a priori* understood probe is an Electron-Ion Collider, EIC. Coherent contributions from many nucleons within a heavy-ion beam particle at such a collider amplify gluon densities, thereby broadening the Q^2 "sweet spot" and extending the effective reach to small x-values by about two orders of magnitude, in comparison with e-p collisions at the same energy per nucleon. In addition to providing precocious entry into the anticipated universal saturation regime, how does the nuclear environment affect the *path* to saturation? Do the momentum and space distributions of gluons in nuclei differ in non-trivial ways from those in nucleons, as has been found for quarks? Are there small clumps of gluons, or are they more uniformly distributed? These questions will be addressed by a combination of deep inelastic inclusive scattering and vector meson production from nucleons and nuclei.

The addition of *polarized* proton and light-ion beams to collide with polarized electrons and positrons at EIC would dramatically expand our understanding of the nucleon's internal wave function. It would greatly extend the kinematic reach and precision of deep inelastic scattering measurements of nucleon spin structure. The contribution of gluons and of sea quarks and anti-quarks of different flavor to the nucleon's spin would be mapped well into the gluon-dominated region. The study of Generalized Parton Distributions (GPD's) in deep exclusive reactions will be pushed far beyond presently accessible energies at JLab, HERA and CERN, extending three-dimensional spatial maps of the nucleon's internal landscape from the valence quark region down into the region dominated by sea quarks, antiquarks and gluons. This extension may be critical for completing the picture of how the nucleon gets its spin, by providing sensitivity via GPD's to the orbital motion of sea partons.

High-energy scattering from nucleons in a collider environment lends itself specifically to study how the creation of matter from energy is realized in QCD when an essentially massless (and colored) quark or gluon evolves into massive (and color-neutral) hadrons. Numerical solutions of QCD on a space-time lattice cannot provide guidance for the dynamical process by which the scattered parton picks up other colored partners from either the QCD vacuum or the debris of the high-energy collision. Rather, we rely on experiment to map the result of these parton fragmentation dynamics. The availability of a high-energy, high-luminosity polarized electron-ion collider, using high-efficiency detectors with good particle identification, will facilitate experiments to measure new features of the fragmentation process, such as its dependence on quark spin, flavor and motion, and on passage through nuclear matter.

In short, EIC is a machine that would expand the intellectual horizons of nuclear physics research into the non-linear heart of QCD, where gluon self-interactions dominate. It would address the following fundamental science questions:

- Does the self-limiting growth of color field strengths in QCD lead to universal behavior of all nuclear and hadronic matter in the vicinity of these limits?
- How does the nuclear environment affect the distribution of gluons in momentum and space?
- What is the internal landscape of a nucleon in the region dominated by sea quarks and gluons?
- How do hadronic final states form from light quarks and massless gluons in QCD?

It would build on the scientific and technical expertise developed over decades at the nation's two premier QCD laboratories at Jefferson Lab and RHIC, but would add new state-of-the-art accelerator technology to reach its design goals.

In this section, we highlight several of the science programs that EIC would foster and outline two design options under consideration, referring the reader to the more detailed White Papers [Ei07, Ea07] that have been written on EIC alone. We also describe briefly below the R&D necessary to demonstrate feasibility of various aspects of accelerator and detector design for such a facility.

4.B.1 Physics of Strong Color Fields

With its wide range in energy, nuclear beams, high luminosity and clean collider environment, the EIC will offer an unprecedented opportunity for discovery and for the precision study of a novel universal regime of strong gluon fields in QCD. The EIC will allow measurements, in a wide kinematic regime, of the momentum and spatial distribution of gluons and sea-quarks in nuclei, of the scattering of fast, compact probes in extended nuclear media, and of the role of color neutral (Pomeron) excitations in scattering from nuclei. These *measurements at the EIC will deepen and corroborate our understanding of the formation and properties of the strongly interacting Quark Gluon Plasma (QGP) in high energy heavy ion collisions at RHIC and the LHC.*

Strong color fields in nuclei. One of the major discoveries of the last decade was just how dominant a role gluons play in the wave function of a proton viewed by a high-energy probe with high spatial resolution (*i.e.*, with large 4-momentum transfer squared Q^2). HERA deep inelastic scattering data revealed that the density of partons, especially gluons, in the plane transverse to the probe momentum grows rapidly with decreasing parton momentum fraction x. This growth is attributable in QCD to the successive emission of soft partons by higher-momentum partons. The resulting gluon field can be treated linearly within QCD when x and Q^2 are not too small. But for given x, the dynamics of the gluon fields becomes highly non-linear below a certain saturation momentum scale Q_s^2, where the recombination of soft gluons into harder ones sets in to tame further growth of the parton densities. If the saturation momentum is large on a typical QCD scale, $Q_s \gg \Lambda_{\rm QCD}$, then the coupling strength $\alpha_s(Q_s^2) \ll 1$ and the gluon dynamics can be described with weak-coupling techniques. The occupation number of gluon field modes with transverse momenta below Q_s saturates at values $\sim 1/\alpha_s(Q_s^2) \gg 1$, so that the probe sees a very strong, essentially classical, color field frozen by time dilation, a system often referred to as the "color glass condensate" (CGC). A goal of theoretical treatments of this high-density QCD matter is to establish a rigorous effective field theory approach for controlled inclusion of higher-order effects beyond the CGC limit.

Since the saturation momentum grows slowly with decreasing x (see Fig. 24), so does the window ($\Lambda_{\rm QCD} \ll Q \ll Q_s$) into the CGC regime. However, a much more effective opening of this window can be arranged by exploiting the Lorentz contraction of a fast-moving nucleus, which amplifies the parton density in proportion to the nuclear diameter, so that $Q_s^2 \propto A^{1/3}$. Thus, as illustrated in Fig. 24, one can enter the predicted saturation regime in e-Au collisions at x-values a couple of orders of magnitude larger than what would be required in e-p collisions at the same Q^2. An electron-ion collider thus represents the most robust and cost-effective approach to study the physics of these strong color fields. Can a clear saturation scale be identified experimentally? Are the properties of partonic matter in the saturation regime indeed *universal* to all hadrons and nuclei? Are these properties consistent with inferences from particle multiplicities and momentum spectra observed at RHIC and with dynamics soon to be explored in heavy-ion collisions at the LHC? Can the properties of saturated gluon fields in heavy nuclei provide a natural explanation for the very rapid thermalization inferred from analysis of relativistic heavy-ion collisions? These questions will be addressed via deep inelastic scattering (DIS) and other cleanly interpretable electromagnetic processes at EIC, as explained in more detail below.

Measurements of momentum distributions of gluons and sea quarks in nuclei. Gluon momentum distributions overwhelm their quark counterparts in the proton for $x <\sim 0.01$. DIS experiments have established that quark and gluon distributions in nuclei exhibit "shadowing": they are modified significantly relative to their distributions in the *nucleon* wavefunction. However, the detailed nature of gluon shadowing at $x <\sim 0.01$ is *terra incognita* in QCD. This physics, bearing directly on the universality of gluon saturation, can be fully studied in electron–nucleus scattering at the EIC, over the broad kinematic coverage shown in Fig. 24.

The inclusive DIS structure functions $F_2^A(x, Q^2)$ and $F_L^A(x, Q^2)$ offer the most precise determination of quark and gluon momentum distributions in nuclei. Independent extraction of F_2^A and F_L^A is only possible via measurements over a range of center of mass energies, an essential

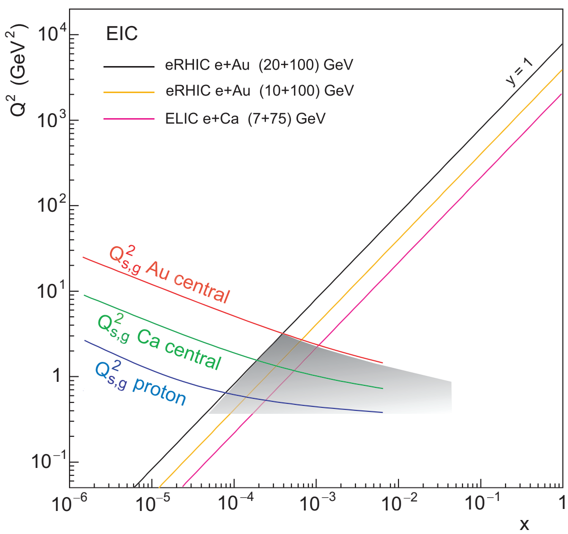

Figure 24: Kinematic acceptance and exposure of the predicted gluon saturation regime in the (x, Q^2) plane for the EIC. The accessible regions fall to the right of the three diagonal straight lines, representing different choices for beam energies (per nucleon in the case of ion beams) and maximum mass of the ion beams. Curves showing the gluon saturation scale Q_s^2 for protons and for central collisions with Ca and Au nuclei are superposed on the kinematic acceptance. The shaded area indicates the kinematically accessible region of saturated gluon density that should be reached in the maximum-energy e+Au collisions considered.

requirement of the EIC. The F_2^A structure function is directly sensitive to the sum of quark and anti-quark momentum distributions in the nucleus; at small x, these are predominantly sea quarks. Information on the gluon distribution in the nucleus, $G^A(x, Q^2)$, can be indirectly garnered from the well-known logarithmic scaling violations of F_2^A with Q^2, $\partial F_2^A/\partial \ln(Q^2)$. In Fig. 25 we show projections for the normalized ratio of $F_2^A(x, Q^2)$ in gold relative to deuterium from a saturation (CGC) model in comparison to the usual linear evolution of perturbative QCD for three models incorporating differing amounts of shadowing. Saturation of gluon densities in the CGC model is manifested by the weak x- and Q^2-dependence of the slope $\partial F_2^{Au}/\partial \ln(Q^2)$ at low x and moderate Q^2. The projected statistical precisions attainable for inclusive DIS measurements with 10 GeV electrons on 100 GeV/nucleon Au nuclei and an integrated luminosity of 4/A fb^{-1}, also shown in Fig. 25, suggest that EIC data can readily distinguish among differing model predictions.

The structure function $F_L^A \equiv F_2^A - 2xF_1^A$ for absorption of longitudinal photons by the proton vanishes in the naive parton model, but in QCD it is proportional at small x to the gluon momentum distribution. Hence, its measurement will allow a new and independent direct determination of $G^A(x, Q^2)$ in the low-x region where little is presently known. The high precision attainable for both F_2 and F_L at EIC will facilitate definitive tests of the universality of saturated gluonic matter. Measurements for different nuclei, x and Q^2 values can be combined in a single plot of the structure functions vs. Q^2x^γ/A^δ to search for values of the adjustable powers γ and δ that yield a universal curve, and hence define the x- and A-dependence of the saturation scale $Q_s^2(x, A)$.

Additional strong sensitivity to gluon densities in nuclei will be provided by semi-inclusive and exclusive final states. An example of the former is di-jet production in e-A collisions, which is dominated at EIC energies by the photon-gluon fusion process. An exclusive example is elastic

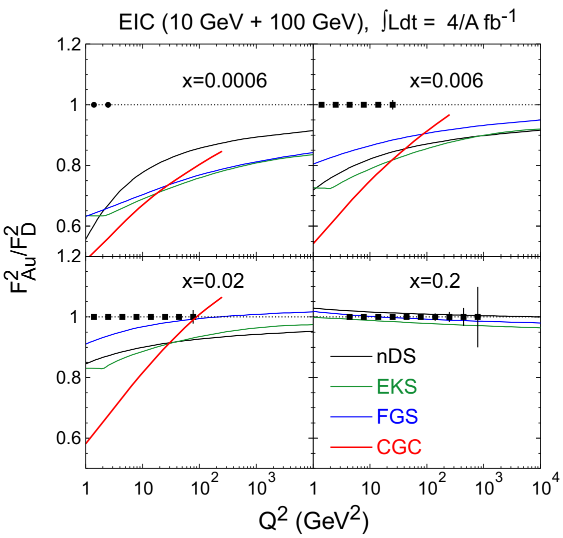

Figure 25: The ratio of the structure function F_2^{Au} in Au nuclei relative to the structure function F_2^{D} in deuterium nuclei as a function of Q^2 for several bins in x. The filled circles and error bars correspond respectively to the estimated kinematic reach in F_2 and the statistical uncertainties for a luminosity of $4/\mathrm{A\,fb}^{-1}$ with the EIC. The curves labeled nDS, EKS and FGS correspond to different parameterizations of parton distributions at the initial scale for pQCD evolution, while the curve labeled CGC corresponds to a Color Glass Condensate model prediction applicable at small x.

vector meson production e+A $\longrightarrow$ $(\rho, \phi, J/\psi)$+A, where forward cross sections for longitudinal virtual photons depend on the square of the gluon density.

The gluon spatial distribution. The spatial distribution of gluons in a nucleus provides a complementary handle on the physics of strong color fields and has important ramifications for a wide range of final states in hadronic and nuclear collisions. Information on the spatial distribution can be inferred from forward vector meson production in e-A, which can be viewed at small x as the result of coherent interactions of quark-antiquark fluctuations of the virtual photon with the nucleus. The differential cross section for the vector mesons, as a function of momentum transfer t along the proton line, can be analyzed to extract a survival probability of these small color dipole fluctuations as a function of impact parameter b at which the dipole traverses the nucleus. The survival probability is, in turn, sensitive to the strength of the gluon field seen. Systematic studies of vector meson production over a wide range of kinematic conditions and for several ion species can thereby illuminate the b-dependence as well as the A-dependence of the saturation scale.

Color neutral (Pomeron) excitations in scattering off nuclei. Another predicted manifestation of strong gluon fields in QCD is an enhanced probability for a high-energy probe to interact with a color-neutral multi-gluon excitation of the vacuum – an excitation that may be associated with the so-called Pomeron – leaving the target nucleus intact. These interactions lead to diffractive final states that may dominate forward scattering. At HERA, an unexpected discovery was that diffraction accounted for 15% of the total e+p cross-section. This is a striking result implying that a proton at rest remains intact one seventh of the time when struck by a 25 TeV electron. The effect may be even more dramatic in nuclei. Several models of strong gluon fields in nuclei suggest that large nuclei will remain intact nearly 40% of the time in EIC collisions, in comparison to the quantum mechanical black disk limit of 50%. Measurements of coherent diffractive scattering on nuclei are easier in the collider environment of EIC than in fixed-target experiments, but nonetheless place strong demands on the forward acceptance of detectors. With suitable detectors, EIC measurements should be able to distinguish the onset of non-linear dynamics for the gluon field, leading to a weak x-dependence but strong Q^2-dependence of the ratio of diffractive structure functions for heavy *vs.* light nuclei. These dependences are distinct from those expected in non–perturbative ("soft" Pomeron) models of diffractive scattering.

Fast probes of an extended gluonic medium. How are the propagation of fast partons and their space-time evolution into hadrons affected by traversal of nuclear matter characterized by strong gluonic fields? Semi-inclusive DIS (SIDIS) experiments at EIC, with high-momentum hadrons detected in coincidence with scattered electrons for a wide range of kinematic conditions and ion species, will use nuclei as femtometer-scale detectors to study these issues in cold nuclear matter. These experiments will provide an essential complement to studies of jet quenching in the hot matter produced in RHIC heavy-ion collisions. The RHIC jet quenching studies have produced a series of striking and surprising results: a strong suppression of high-momentum hadrons usually attributed to rapid energy loss of partons traversing matter of high color charge density, but little apparent dependence of the suppression factor on quark flavor, in sharp contrast to expectations from perturbative QCD models of the parton energy degradation. SIDIS on *fixed* nuclear targets has so far revealed an analogous but weaker suppression of light hadron production in cold nuclear matter. EIC will enormously expand the virtual photon energy range in such studies, from 2–25 GeV in the HERMES experiment at HERA to $10\,\mathrm{GeV} < \nu < 1600\,\mathrm{GeV}$, thereby providing access to the kinematic region relevant for LHC heavy-ion collisions and to such important new issues as the suppression of heavy-flavor mesons travelling through cold nuclear matter.

One of the basic physics questions to be answered here concerns the time scale on which the color of the struck quark is neutralized, acquiring a large inelastic cross-section for interaction with the medium. The parton energy loss models used to interpret RHIC results assume long color neutralization times, with "pre-hadron" formation outside the medium and quark/gluon energy loss as the primary mechanism for hadron suppression. Alternative models assume short color neutralization times with in-medium "pre-hadron" formation and absorption as the primary mechanism. There do exist hints of short formation times from HERMES data and JLab preliminary data, but these must be pursued over the wider kinematic range and much broader array of final-state channels that can be explored at EIC.

4.B.2 A New Era of Hadronic Physics

The EIC will provide definitive answers to compelling physics questions essential for understanding the fundamental structure of hadronic matter. It will allow precise and detailed studies of the nucleon in the regime where its structure is overwhelmingly due to gluons and to sea quarks and anti-quarks. Some of the scientific highlights at the EIC in this area would be: (1) definitive answers to the question of how the proton's spin is carried by its constituents, (2) determination of the three-dimensional spatial quark and gluon structure of the proton, (3) precision study of the proton's gluon distribution over a wide range of momentum fractions, and (4) maps of new spin-dependent features of the quark fragmentation process. In the following we briefly address three of these highlights of future research in hadronic physics.

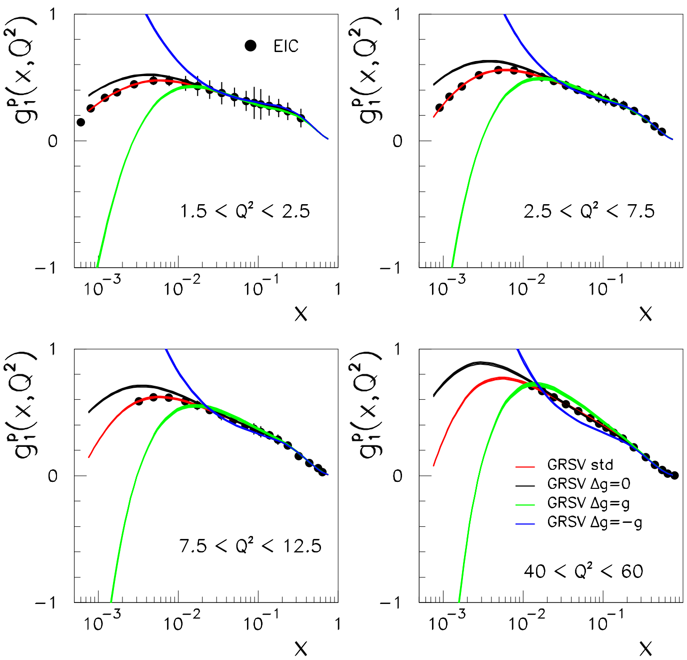

Figure 26: Projected EIC data for the proton structure function $g_1(x, Q^2)$ as a function of x in four Q^2 bins, for 7 GeV electrons colliding with 150 GeV protons at an integrated luminosity of $5\,\text{fb}^{-1}$. The curves show theoretical predictions based on different sets of spin-dependent parton distribution functions that mostly differ in the gluon helicity distribution.

The spin structure of the proton. Few discoveries in nucleon structure have had a bigger impact than the surprising finding that quarks and anti-quarks together carry only about a quarter of the nucleon's spin. Determining the partonic source of the "missing" spin in this complex composite system has developed into a world-wide quest central to nuclear physics. The sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

states that the proton spin projection along its momentum is the sum of the quark and gluon intrinsic spin ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) contributions. EIC with its unique high luminosity, highly polarized electron and nucleon capabilities, and its extensive range in center-of-mass energy, will allow DIS access to quark and gluon spin contributions at substantially lower momentum fractions x than important current and forthcoming experiments at RHIC, DESY, CERN and JLab. A key measurement at the EIC would be of the spin-dependent proton structure function $g_1(x, Q^2)$ of the proton over a wide range in Q^2, and down to $x \sim 10^{-4}$. Studies of the scaling violations of $g_1(x, Q^2)$ prove to be a most powerful and clean tool to determine the spin contribution by gluons. This is demonstrated by Fig. 26, which shows projections for EIC measurements of $g_1(x, Q^2)$ in comparison with four model predictions that make different assumptions regarding the sign and magnitude of the gluon spin contribution to the proton spin. Each of these models is compatible with the currently available polarized fixed-target DIS data. While data from polarized proton collisions at RHIC are already beginning to establish preferences among these particular four models at $x >\sim 0.01$, the RHIC data will not be able to constrain the shape of the gluon helicity distribution at lower x, where the density of gluons rapidly increases. The great power of the EIC in providing precise information on $\Delta G(x <\sim 0.01)$ is evident.

With polarized ^{3}He beams at an EIC, measurements of g_1 would also be possible off polarized neutrons, allowing a precision test of the fundamental Bjorken sum rule, which relates the proton and neutron spin structure via the axial weak coupling strength measured in neutron beta-decay. Furthermore, semi-inclusive DIS measurements, for which a specific hadron is detected from the struck quark jet, would provide information with unprecedented detail on the individual contributions by quark and anti-quark spins to the proton spin, testing models of nucleon structure and lattice QCD calculations.

There are various avenues for investigating the role of orbital angular momenta in nucleon structure. One of them is the study of correlations of the transverse momentum of a parton in the nucleon with the nucleon spin transverse to its momentum. Such correlations produce characteristic patterns of azimuthal-angular dependences for final-state hadrons in SIDIS experiments. Initial experimental results from fixed-target SIDIS indicate the presence of such correlations. Measurements at an EIC would allow precision studies of such orbital effects. An alternative approach will utilize deep exclusive reactions to extract generalized parton distributions (GPDs), to which we turn next. The GPDs provide unique access to the total – spin plus orbital – angular momentum contributions of quarks and gluons, as well as to many other important aspects of nucleon structure. While maps of GPDs in the valence-quark region will be carried out with the 12 GeV Upgrade at JLab, the EIC will allow us to extend such measurements to the region where the quark-antiquark sea and gluons are the dominant degrees of freedom in the nucleon wave function.

Measurements of Generalized Parton Distributions. GPDs unify the concepts of parton density and elastic form factor, and provide a comprehensive framework for describing the quark and gluon structure of the nucleon probed in high–Q^2 processes. In addition to the longitudinal momentum distributions the GPDs describe the spatial distribution of quarks and gluons in the transverse plane, *i.e.*, how the transverse shape of the nucleon changes when probing quarks and gluons at different x. This amounts to a set of two-dimensional "tomographic" quark/gluon images of the proton, analogous to CT scans in medical imaging. This new representation offers unprecedented possibilities for visualizing the nucleon as an extended object in space and testing dynamical models of its structure. Knowledge of the transverse spatial distribution of quarks and gluons is essential also for modeling the dynamics of high–energy pp collisions. In addition, GPDs allow us to quantify how the angular momenta of partons in the nucleon contribute to the nucleon spin.

Measurements of GPDs are possible in hard exclusive processes such as deeply virtual Compton Scattering (DVCS), $\gamma^* p \to \gamma p$, and meson production, $\gamma^* p \to M p$ (where $M = \rho, \phi, J/\psi, \pi, K$etc.) The experimental study of these processes is typically much more challenging than of traditional inclusive DIS. In addition to requiring substantially higher luminosities (because of small cross sections) and the need for differential measurements, the detectors and the interaction region have to be designed to permit full reconstruction of the final state. A properly designed collider would provide unique opportunities for such measurements. A collider can achieve momentum transfers of the order $Q^2 \sim 10$ GeV^2, where higher-twist corrections in meson production are under control, and the wide range of momentum transfers and energies would permit detailed tests of the reaction mechanism and studies of QCD evolution. Measurements of $J/\psi, \rho, \phi$ production and DVCS at collider energies probe the gluon and sea quark GPDs, entirely complementary to what will be achieved by the 12-GeV Upgrade program at JLab. As an example of the potential of an EIC, we show in Fig. 27 projected results for measurements of the DVCS cross section. The Fourier transform of the t–distributions shown here will directly provide access to the transverse spatial distribution of gluons and sea quarks. One can see that excellent statistics can be obtained in fully

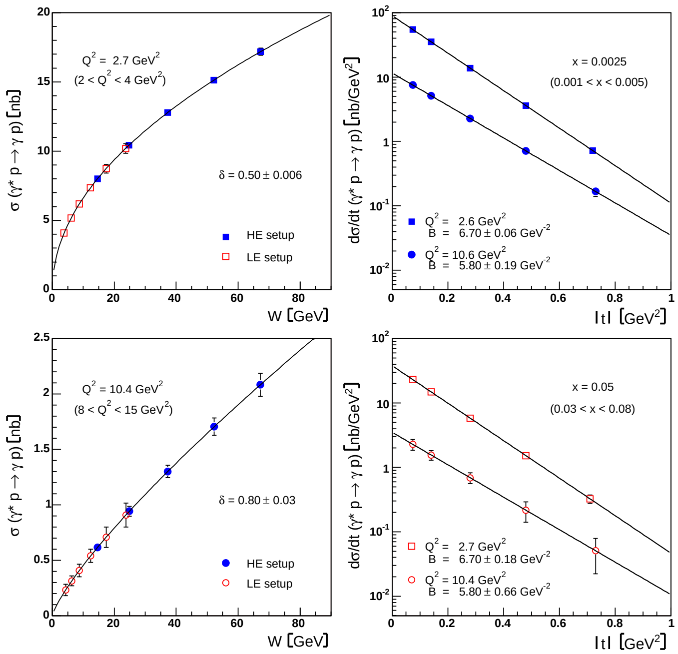

Figure 27: Left: projected results for total DVCS cross section measurements with an EIC, as a function of invariant $\gamma^* p$ mass W, for two values of Q^2. Right: t differential DVCS cross section for two representative values of x and Q^2. The projections assume a high-energy setup (10 GeV on 250 GeV), with an integrated luminosity of $530\,\mathrm{pb}^{-1}$ for the smaller x-value, and a low-energy setup (5 GeV on 50 GeV) with $180\,\mathrm{pb}^{-1}$ for the larger x-value. The estimates of the event rates here assume 100% detector acceptance.

differential measurements in x, Q^2 and t, and over a wide kinematic range, providing the basis for a detailed program of transverse gluon imaging of the nucleon. Measurements of meson production in non-diffractive channels (π, K, ρ^+), which require significantly higher luminosity, would provide information about the spin/flavor structure of the quark GPDs. Finally, with the EIC one could for the first time study hard exclusive processes with nuclear targets, which would allow for completely new studies of color transparency and other aspects of small–x dynamics.

Spin-dependent Quark Fragmentation. Semi-inclusive DIS experiments at a high-luminosity polarized EIC will map the spin-dependence of the process by which quarks transform to jets of hadrons. Recoiling quarks from a polarized proton will initiate the fragmentation process with a spin orientation preference. How does this preference affect the yields, momenta and spin preferences of various types of hadronic fragments, and what do such effects teach us about the fragmentation dynamics? It is already apparent from measurements in electron-positron collisions and in fixed-target SIDIS that there are correlations between the momentum components of hadron fragments transverse to the jet axis and any quark spin preference transverse to its momentum. In addition to systematic exploration of these initial hints at EIC, it may be possible for selected final-state hadrons – e.g., ρ-mesons – reconstructed from their decay daughters to correlate their density matrices with the spin orientation of the fragmenting quark. In combination with the study of in-medium fragmentation in e-A collisions at EIC, such measurements are likely to launch a new stage in modeling how quarks accrete colored partners from the vacuum or their environment to form colorless hadrons.

4.B.3 Accelerator Designs

A high luminosity (at or above 10^{33} cm^{-2}s^{-1}) Electron-Ion Collider, covering the full range of nuclear masses A with variable center-of-mass energy in the range of 20 to 100 GeV/nucleon, and the additional capability of colliding polarized protons and light-ions with polarized electrons and positrons, appears to be the ideal accelerator to explore these fundamental questions of QCD and expand nuclear physics research into the gluon-dominated regime. Presently there are two distinct design approaches to an EIC: eRHIC, based on the RHIC ion complex, and ELIC, using CEBAF as a full energy injector into an electron storage ring. Research and development needed for a detailed design of each approach is outlined in this section.

eRHIC Two accelerator design options for eRHIC were developed in parallel and presented in detail in the 2004 Zeroth-Order Design Report[Er07]. Presently the most promising option is based on the addition of a superconducting Energy Recovery Linac (ERL) to provide the polarized electron beam. This ERL-based design option can achieve peak luminosity of 2.6×10^{33} cm^{-2}s^{-1} for e-p collisions, with the potential for improvement. The peak luminosity per nucleon for electron-Au collisions is 2.9×10^{33} cm^{-2}s^{-1} for 100 GeV/N gold ions colliding with 20 GeV electrons. R&D for a high-current polarized electron source and high-energy and high-current ERL are needed to achieve these design goals. A second option is based on the addition of an electron storage ring to provide polarized electron or positron beams. This option is technologically more mature and promises peak e-p luminosity of 0.47×10^{33} cm^{-2}s^{-1}. The general layout of the ERL-based design option of the eRHIC collider is shown in Fig. 28. A polarized electron beam is generated in a photo-injector and accelerated to the energy of the experiment in the ERL. After colliding with the hadron beam in as many as four detector locations, the electron beam is decelerated to an energy of a few MeV and dumped. A positron beam is possible with the addition of a conversion system and a compact storage ring, at one quarter of the RHIC circumference, for positron accumulation, storage and self-polarization. In the present design, the ERL provides electrons in the energy range from 3 to 20 GeV, leading to a center-of-mass energy range from 25 to 140 GeV in combination with RHIC proton beams.

The main highlights of the ERL-based eRHIC design are:

- luminosity of 10^{33} cm^{-2}s^{-1} and higher in electron-hadron collisions
- high electron beam polarization ($\sim$80%)
- full polarization transparency at all energies for the electron beam
- multiple electron-hadron interaction points (IPs) and detectors
- $\pm$3 m "element-free" straight section(s) for detector(s)
- ability to take full advantage of electron cooling of the hadron beams
- easy variation of the electron bunch frequency to match it with the ion bunch frequency at different ion energies

ELIC ELIC is an electron-ion collider with center of mass energy of 20 to 90 GeV and luminosity up to 8×10^{34} cm^{-2}s^{-1} (at a collision frequency of 1500 MHz). It is described in detail in the 2007 Zeroth Order Design Report [El07] and shown schematically in Fig. 28. This high-luminosity

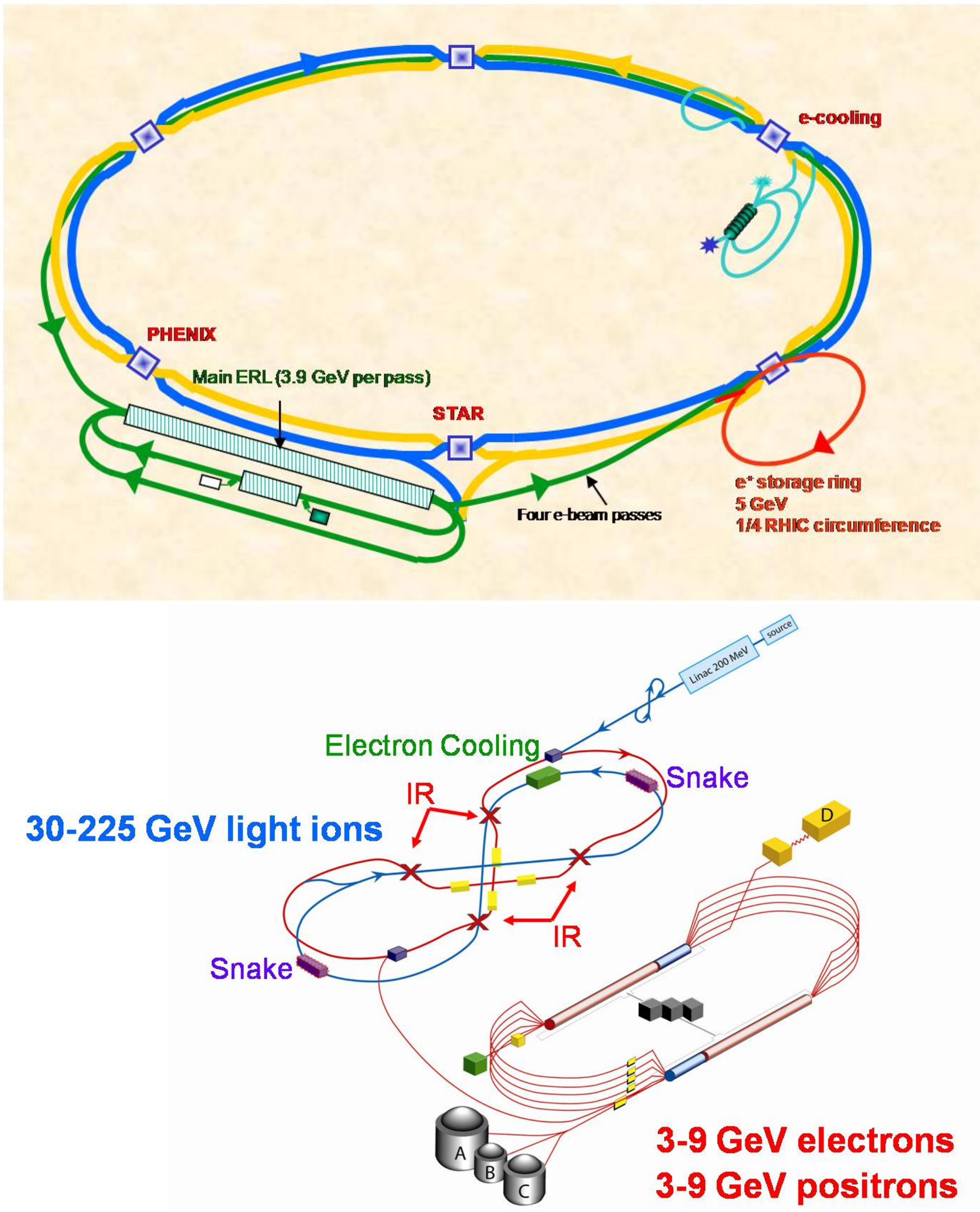

Figure 28: Design layouts of the ERL-based eRHIC, and the CEBAF-based ELIC colliders.

collider is envisioned as a future upgrade of CEBAF, beyond the 12 GeV Upgrade, and compatible with simultaneous operation of the 12 GeV CEBAF (or a potential extension to 24 GeV) for fixed-target experiments. The CEBAF accelerator with polarized injector is used as a full-energy injector into a 3-9 GeV electron storage ring. A positron source is envisioned as an addition to the CEBAF injector for generating positrons that can be accelerated in CEBAF, accumulated and polarized in the electron storage ring, and collide with ions with luminosity similar to the electron-ion collisions. The ELIC facility is designed for a variety of polarized light ion species: p, d, ^{3}He and Li, and unpolarized light to heavy (up to A $\sim$ 200) ion species. To attain the required ion beams, an ion facility must be constructed, a major component of which is a 30-225 GeV collider ring located in the same tunnel and below the electron storage ring. A critical component of the ion complex is an ERL-based continuous electron cooling facility, anticipated to provide low emittance and simultaneously very short ion bunches. ELIC is designed to accommodate up to four intersection points (IP's), consistent with realistic detector designs. Longitudinal polarization is guaranteed for protons, electrons, and positrons in all four IP's simultaneously and for deuterons in up to two IP's simultaneously.

An alternate design approach for ELIC is based on the linac-ring concept, in which CEBAF operates as a single-pass ERL providing full energy electrons for collisions with the ions. Although this approach promises potentially higher luminosity than the ring-ring option, it requires significant technological advances and associated R&D. The main highlights of the ELIC design are:

- "Figure-8" ion and lepton storage rings ensure spin preservation and ease of spin manipulation
- spin transparency to energy for all species
- unprecedented luminosity at the 10^{35} cm^{-2}s^{-1} level
- four interaction regions with $\pm$2 m element-free region
- the present JLab DC polarized electron gun routinely delivers $\sim$85% polarization and meets the beam current requirements for filling the storage ring
- the 12 GeV CEBAF accelerator can serve as an injector to the ring
- collider operation remains compatible with 12 GeV CEBAF operation for a fixed-target program

R&D Required

I. Common R&D Topics In order for either eRHIC or ELIC to reach a luminosity at or above 10^{33} cm^{-2}s^{-1} level, R&D on high energy electron cooling and on the production of polarized ^{3}He beams is required. Electron cooling is required to achieve the design transverse emittances, to counteract the effects of intrabeam scattering, and in the case of ELIC to reach short ion bunches. An electron cooling system based on ERL technology is presently under development for RHIC-II, intended to lead to an order of magnitude higher ion-ion luminosities in RHIC. The same system will be used for eRHIC. ^{3}He ions have not yet been used for experiments. EBIS, the new ion source under construction at BNL, will provide the ability to produce polarized ^{3}He beams, given a ^{3}He source. In addition, R&D will be required on a variety of detector and polarimetry items, such as the development of cost-effective and compact high-rate tracking and associated readout systems, small angle detector instrumentations, multi-level trigger systems and precision ion polarimetry.

II. R&D Required for eRHIC R&D applicable to both the ERL and the ring-ring options for eRHIC is required in order to increase the number of bunches in RHIC from 111 to 166, and for better understanding of the machine tolerances required for ^{3}He polarization preservation in RHIC and its injectors. In addition, the ERL eRHIC design requires R&D on high-current polarized electron sources and on high-energy and high-current energy recovery. To achieve the design eRHIC luminosities, 260 mA average current is required from a polarized electron source. The best existing source, at JLab's CEBAF accelerator, operates at approximately 0.3 mA of average current (1 mA is expected to be reached shortly) with current densities of about 50 mA/cm^2. The development of large cathode guns should provide a path to electron currents of tens to hundreds of milliamps. The eRHIC ERL is envisioned to employ state-of-the-art 703.75 MHz 5-cell SRF cavities. The cavity design was developed at BNL in the course of the electron cooling project and allows the minimization and efficient damping of the higher-order modes, opening a way for higher electron currents. Simulations of multi-bunch and multi-pass breakup instabilities showed that the design eRHIC currents can be achieved in an ERL based on this cavity.

III. R&D Required for ELIC With the exception of electron cooling, no additional R&D is necessary for ELIC at the luminosity level of 10^{33} cm^{-2}s^{-1}. To achieve the ELIC design luminosity of 10^{35} cm^{-2}s^{-1}, R&D is critical in the areas of crab crossing, stability of intense ion beams accumulated at stacking, and electron cooling using a circulator ring. For the former, R&D is required for the design of a 1500 MHz multi-cell crab cavity, for understanding the beam dynamics with crab cavities in both rings, and for achieving phase and amplitude stability requirements. Understanding beam stability of intense ion beams in boosters and the collider ring also requires R&D. One approach is to overcome space charge at injection by increasing the beam size while preserving the 4D emittance, using a circular painting technique for stacking similar to the technique proposed at SNS. An alternate approach is to admit a large beam emittance in the pre-booster and cool it after injection in the collider ring using stochastic cooling for coasting beam. ELIC's electron cooling concept is unique, in that it relies on the use of a circulator ring to ease requirements on the average current from the electron source and on the ERL. Simulation studies are required to establish beam stability conditions and to optimize the beam and cooling ring operating parameters. Lastly, the ELIC design requires a dedicated R&D effort to develop the high-speed data acquisition and trigger systems that would be needed to accommodate the high collision frequencies.

4.C International Opportunities

There are a number of international hadron physics facilities which will become operational within the next few years. The most significant ones are J-PARC in Japan and FAIR in Germany.

The J-PARC (Japan Proton Accelerator Research Complex) is a multi-purpose accelerator facility currently under construction at Tokai, Japan. It consists of a 1 MW 3-GeV proton synchrotron for material/life science research, and a 0.75 MW 50-GeV proton synchrotron for nuclear and particle physics research. The construction of J-PARC is well underway (since 2001) and is scheduled to be completed in early 2009. Intense secondary beams, including neutrinos, kaons, pions, muons, and antiprotons will be produced at J-PARC. The primary proton beam at 50 GeV, possibly polarized at a later stage, will also be avaliable for experiments.

The nuclear and particle physics program at J-PARC includes neutrino oscillations, rare kaon/muon decays, hypernuclear physics, and hadron physics. A neutrino beam from J-PARC

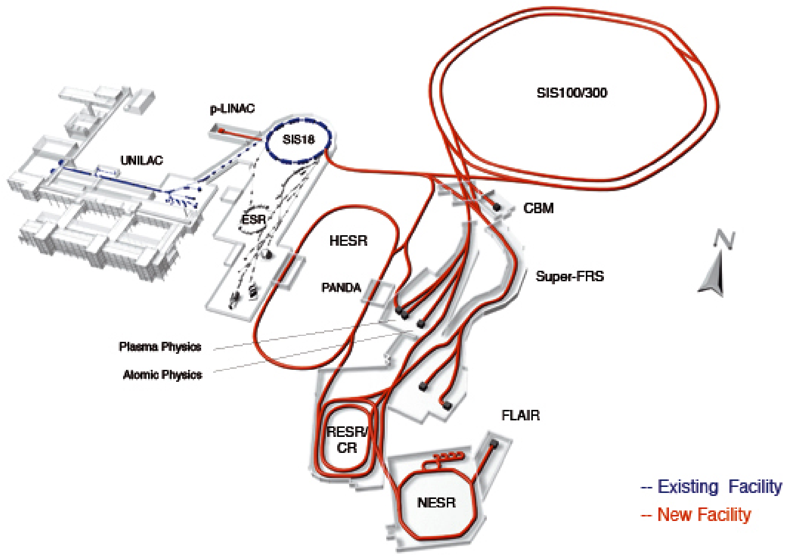

Figure 29: The Facility for Antiproton and Ion Research at GSI showing the exiting components and the planned new construction. The focus for hadron physics will be on research with precision, cooled, stored beams of antiprotons.

with an intensity $\sim$ 100 times greater than the beam available from the KEK 12-GeV proton-synchrotron will be directed at the Super-Kamiokande detector in the T2K neutrino oscillation experiment. The kaon beam flux at J-PARC is expected to be $\sim$ 10 times higher than at the AGS, making J-PARC a unique facility in the world for hypernuclear and rare kaon decay experiments.

J-PARC will start operations for nuclear and particle physics in early 2009. More than half of the $\sim$ 600 users currently considering or preparing experiments at J-PARC are from outside of Japan. A Program Advisory Committee for J-PARC nuclear and particle physics has been formed and $\sim$ 15 experimental proposals have been reviewed. Several hypernuclear experiments to investigate the spectroscopy of Λ and Ξ hypernuclei have been approved. Proposals to study Drell-Yan production and vector-meson production using the 50 GeV proton beam have also been presented. The possibility to accelerate polarized protons would allow many new and unique opportunities for high-energy spin physics.

The Gesellschaft Für Schwerionenforschung (Germany) together with international partners is planning the construction of FAIR, the Facility for Antiproton and Ion Research. The facility, injected by the existing UNILAC and SIS18 accelerators, would add two synchrotrons with magnetic rigidities of 100 (SIS100) and 300 T-m (SIS300), respectively. The hadron physics program will focus on high quality, cooled anti-proton beams in storage rings produced by 29 GeV protons from the SIS100 ring, which are collected, accumulated, and then reaccelerated in SIS100 and injected into the 15 GeV/c High Energy Storage Ring for internal target experiments. A central goal of the research is precision spectroscopy in the charmonium sector and searches for charmed and light hybrid mesons and glueballs. Other topics include gamma-ray spectroscopy of single and double hypernuclei, proton form factors in the time-like region, a search for CP- violation in the charm and strangeness sector, the extraction of generalized parton distributions from pbar-p annihilation and fundamental physics tests with stopped antiprotons. Measurements with a polarized proton internal target will determine single-spin asymmetries. Concepts are also being developed to polarize the anti-proton beam for double spin asymmetry measurements and, in the future to possibly include colliding polarized beams for Drell-Yan measurements of polarized structure functions.

The antiproton capability of FAIR is expected to become available in 2013. FAIR also has major scientific programs in the structure of nuclei far from stability (projected to start in 2011) , relativistic heavy-ion collisions (projected for 2015), atomic physics and plasma physics.

4.D Theoretical Opportunities and Initiatives

Understanding how the immensely rich and complex structure and interactions of hadrons arise from the simple Lagrangian of QCD is one of the central challenges of modern theoretical physics. On one hand, the celebrated property of asymptotic freedom enables quantitative understanding of experiments at sufficiently high energy and thereby provides overwhelming evidence that QCD is the correct theory describing Nature in the energy regime relevant to all currently accessible experiments. On the other hand, the complementary property of infrared slavery renders solution of QCD analytically intractable at the low energies and large distance scales relevant to understanding the fundamental properties of hadrons. This presents theoretical physicists with challenges that are both extraordinarily difficult and extremely important.

As explained in reviewing the accomplishments during the past five years, fundamental progress is being made in understanding hadronic physics from first principles in terms of QCD. Building on this solid foundation, the field now offers truly outstanding opportunities for theoretical progress and discovery. It is important to recognize at the outset that theoretical physics functions at several levels, each of which is important in its own right. Current programatic theoretical research and contemporary experimental efforts define a concrete set of foreseeable challenges which, with sufficient effort by talented theorists, can be met using known theoretical tools and techniques. These are the easiest to identify and will be discussed below in detail. Creative theorists also create new research directions, which open up presently unforeseen challenges and opportunities. Past examples include the realization by theorists that parity violating electron scattering could reveal the strangeness content of the nucleon and the discovery that generalized parton distributions could reveal far more information than form factors or parton distributions, both of which opened up new experimental initiatives that currently define central questions in our field. Finally, crucial contributions arise from the pursuit of pure theoretical physics for its own sake. For example, Ken Wilson's effort to understand how to regulate continuum QCD on a discrete space time lattice gave rise to the powerful computational tool of lattice QCD, and contemporary ideas arising in string theory may unveil some of the mysteries of QCD at high temperature. Whereas these latter two categories cannot be described concretely in a long range plan, they will ultimately have much to do with the long term advancement of our field. Fortunately, a key ingredient for making fundamental progress at all three levels is the same: attracting the most gifted young theorists into our field, effectively communicating the fundamental opportunities in it, and providing the support and mentoring required for successful careers in theoretical physics. Thus, in the field of hadronic physics, we strongly support the central Theory recommendation stated in the introduction: *We strongly recommend new investments in the next generation of nuclear theorists who are critical to the future of the field, and targeted support for initiatives to solve the key scientific problems identified in this LRP.*

Lattice QCD

The recent success in solving full QCD with dynamical quarks in the chiral regime opens an exciting range of research opportunities with the potential for significant impact on experiment, on our understanding of how QCD works, and allowing us to make reliable theoretical predictions where experiments are not possible and where other theoretical techniques fail.

Precision computation of presently calculable observables: In the next five years, new computational resources and theoretical developments will enable precision calculations of a wide range of important observables directly relevant to experiment. The combination of using chiral fermions for both valence and sea quarks, increasingly sophisticated chiral perturbation theory, smaller lattice spacings, larger volumes, and smaller pion masses will enable precision calculation of isovector hadron properties to an accuracy of a few percent. These include electromagnetic form factors, moments of structure functions, generalized form factors corresponding to moments of generalized parton distributions, transition form factors and nucleon polarizabilities. In hadron spectroscopy, the new computational resources will revolutionize our ability to compute the low-lying hadron spectrum with sufficient reliability to both guide and interpret the future experimental program. The use of anisotropic lattices, with temporal lattice spacing smaller than that in the spatial directions, enables the energies to be more precisely resolved, and is crucial for studies of the excitation spectrum. In the study of hadron interactions, the resources will enable precise calculations of many of the two-body processes of interest to nuclear and particle physicists at pion masses close to those of nature.

New observables and theoretical issues: Much of the intellectual vitality and excitement of the field centers on new theoretical developments and ideas for calculating important physical quantities that are presently inaccessible. To calculate flavor-singlet matrix elements, in addition to the connected contributions, it is necessary to calculate disconnected contributions, which are typically several orders of magnitude more computationally expensive. Current developments offer the prospect of calculating flavor singlet form factors, moments of quark distributions, and generalized form factors, thereby addressing the full range of experimental nucleon observables including strangeness contributions. Additional new calculations include gluon distributions, mixing of gluon and flavor singlet operators, operator mixing of higher moments of structure functions and generalized form factors, higher twist operators, the neutron electric dipole moment, and the difference between moments of structure functions of a bound deuteron and two free nucleons. These techniques will also allow for the calculation of $I = 0$ $\pi\pi$ scattering and $I = 1/2$ $K\pi$ scattering.

Past explorations of the spectrum of light hybrid mesons in quenched QCD with large quark masses will be superceded by full QCD calculations in the chiral regime, and future resources will also enable the extraction of decay-width information for exotic mesons. Beyond establishing the spectrum, lattice QCD can compute the photo couplings and transition form factors of excited states and thus make predictions vital to the JLab experimental program in baryon and meson spectroscpy. Calculation of the hyperon-nucleon scattering length has important astrophysical implications, impacting the late time evolution of a supernova and is needed to understand hypernuclear experiments. Calculation of the adiabatic potential between heavy-light systems with infinitely massive heavy quarks, such as B-mesons and Λ_b baryons, will impact our understanding of the nucleon-nucleon potential. The results of the first fully-dynamical lattice QCD calculation of nucleon-nucleon scattering, reported in 2006, make this an opportune time for an initiative to calculate nuclear reactions and properties directly from lattice QCD. But if precision similar to that achieved for mesonic observables is to be attained for nuclear quantities much larger lattice ensembles will be needed.

All of the lattice studies discussed in this section will benefit from the enhanced understanding of low-energy hadron dynamics that continues to be gleaned from effective field theories. The same EFTs being used to address laboratory data are allowing us to understand—and systematically incorporate—corrections to lattice computations due to the effects of finite lattice spacing, finite volume, partial quenching, and unphysical quark masses. The ability to do lattice simulations in unphysical situations and understand the results using EFT is a key benefit, since it facilitates the extraction of results that are important for hadron and nuclear physics. For example, over the next five years examination of finite-volume corrections to lattice QCD calculations will provide the opportunity to extract properties of the Delta resonance, obtain more detailed information on hadron-hadron phase shifts, and gain a first view into the three-nucleon force from full QCD. In order to realize this promise comprehensive EFT calculations of the manner in which lattice results for the relevant systems depend on the finite lattice size must be pursued. The expertise in nuclear EFTs that has been gained over the last 15 years and the involvement of the broader nuclear-theory community make the required advances in the single- and multi-nucleon EFTs achievable.

This use of EFT in concert with lattice simulations will have particular impact on our understanding of hyperon-nucleon interactions, where laboratory data is scarce. For instance, hyperon-nucleon scattering lengths are poorly known, but are needed for the interpretation of hypernuclear experiments, since they constrain hyperon-nucleon potentials. Improvements in our understanding of those potentials could stimulate significant improvements in theories of hot and dense matter relevant to astrophysics, possibly impacting predictions of the late-time evolution of supernovae. Meanwhile, calculation of the adiabatic potential between heavy-light systems with infinitely massive quarks, such as B-mesons and Λ_b baryons, will enhance our understanding of the nucleon-nucleon potential.

Effective field theory applications to hard scattering processes

The soft-collinear effective theory (SCET) allows for a systematic derivation of power corrections to hard scattering factorization theorems. Examples of important future applications include the derivation of $1/Q^2$ suppressed corrections to the factorization theorems for proton and pion form factors. Previous attempts at deriving these corrections have been stymied by endpoint singularities, which can be dealt with using recent advances in SCET. Using operators and power counting the effective theory also allows for a systematic categorization of all sources of power corrections, so that a complete analysis can be performed. Another interesting area for future investigation is transverse momentum dependent distribution functions, including their renormalization group evolution, and the requirement that well defined distributions depend on introducing rapidity regulators. A third example is deep inelastic scattering at large x, a region that may be probed by the 12 GeV Upgrade. So far only renormalon analysis have been used to examine power corrections in this region, and the derivation of a complete factorization theorem is lacking. Recent theoretical advances make the derivation of power corrections to the large x factorization theorem quite feasible. In particular, the analysis of DIS at large x is very similar to the process $b \to s\gamma$ for large photon energies, where techniques from the soft-collinear effective theory have already successfully been used to derive a factorization theorem for power corrections.

The Hadron Spectrum

Realizing the goal of the spectroscopy program of distilling the low-energy degrees of freedom of QCD will require the development of the analysis tools to extract resonance parameters from experimental data and models that can describe these parameters, and hence identify the degrees of freedom. The robust achievement of the NSAC 2009 milestone of a coupled-channel analysis of world baryon resonance data necessitates the adoption of several approaches, such as the dynamical coupled-channel method, and event-by-event analyses, and the establishment of the Excited Baryon Analysis Center at JLab is indicative of the theoretical commitment to these efforts. The search for exotic mesons will require the partial-wave analysis of exclusive reactions, accomodating the known meson resonances. Both these efforts will exploit precise computations in lattice QCD.

Learning how QCD works entails experimental and lattice resonance data confronting QCD-inspired models, expressed through effective degrees of freedom. High-quality data will be able to distinguish between a picture of the baryon as three quarks, and one in which a quark and diquark constitute the effective degrees of freedom. The evolution of our picture of QCD as the masses of the quarks are changed is an important question that can be addressed through comparison with states containing strange and heavier quarks, such as strangonium and cascades, revealing, for example, whether the flux-tube picture of hybrid mesons extends from the heavy-quark regime to the light-quark regime. Finally, the derivation of the electromagnetic properties and transitions of resonances, in concert with experimental measurments, can reveal how charge, currents and orbital angular momentum is distribted.

Topical Theoretical Physics Initiatives in Hadronic Physics

One of the opportunities to strengthen theory and its impact on the field that has been suggested by the NSAC subcommittee on theory and supported by many theorists is support of topical theoretical physics initiatives that address timely challenges. In the context of the opportunities discussed in this section, we provide three illustrative examples representative of theoretical initiatives that could have major impact on the field and further strengthen the national theory effort.

Rigorous connections between between hadron observables and the underlying quark and gluon degrees of freedom: Effective field theory and factorization techniques provide a rigorous framework for addressing crucial contemporary issues in hadronic physics, and the connection of hadrons to quark and gluon degrees of freedom. Examples that could be addressed by a topical initiative include: deriving complete factorization theorems for form factors at subleading order in $1/Q^2$, terms that are necessary for a meaningful comparison to the Jlab-12GeV data; an investigation of the evolution and dependence on rapidity cutoffs of $k_\perp$ dependent parton distributions and generalized parton distributions; a systematic study of power corrections to deep inelastic scattering in the large x region; and chiral perturbation theory extrapolations of lattice QCD calculations of form factors, generalized form factors, and moments of parton distributions. Coordinated high precision lattice calculations of the relevant observables would provide complementary rigorous input from QCD.

Global analysis of gluon polarization: In the next few years, the polarization proton-proton collisions at RHIC will produce a large body of experimental data that contain extremely valuable information about the spin structure of the nucleon and the role of spin in QCD dynamics. The determination of the gluon polarization requires consideration of all existing data through a global analysis making use of results from all probes, from RHIC and from DIS. An early example of such a global analysis is given by Ref. [Hi06]. An important advantage of a global analysis is to consider each measurement directly in its experimental variables, rather than attempting to use derived or unmeasurable variables such as x_g. Also, the global analysis can be consistently carried out at next-to-leading order accuracy.

Global analysis of generalized parton distributions from experiment and lattice QCD: Experiments typically measure convolutions of generalized parton distributions whereas lattice QCD calculates their moments. Now that lattice calculations are entering the regime in which they attain quantitative agreement with many experimental observables, it is useful to develop phenomenological descriptions of GPD's incorporating all known theoretical constraints and perform simultaneous global analyses of all available experimental and lattice data. The resulting insight into hadron structure will be considerably greater than that which could be attained from either analysis separately.

4.E Education and Outreach

Education and outreach are central to the missions of both the Department of Energy and the National Science Foundation. They are the fundamental underpinnings that support the mandates of the agencies to advance the broad interests of society (e.g. in academia, medicine, energy, national security, industry, and government) and to help ensure United States competitiveness in the physical sciences and technology.

Similarly, education and outreach are key components of any vision of the future of the field of nuclear physics, including QCD and Hadron Physics. Education is critical to sustaining, if not enhancing, the pool of talented nuclear physicists needed to realize our research goals, as well as to train future generations of nuclear physicists. We also educate the nuclear physicists who make important contributions to medicine, energy, and national security. But it is also important for the nuclear physics community to extend our education efforts and reach out beyond our field: to inform other physicists and other scientists about the excitement of our research, to introduce the concepts of nuclear physics to future and current school teachers and students, and to enhance the public's understanding of nuclear physics and its applications and the value of nuclear physics to society. Over the past decade, numerous studies have pointed to an increasingly urgent need to prepare more US citizens for leadership roles in basic and applied physical sciences. The recent National Academy of Sciences report [NA07] "Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future", is the latest and most visible report that paints a dire picture for the future of America if there is not a significant increase in the number of Americans entering careers in Science, Technology, Engineering and Mathematics (STEM) fields.

Nuclear science has a long tradition of training graduate students for careers that meet national needs, from providing leadership in basic nuclear physics and higher education, to playing critical roles in nuclear medicine, nuclear energy, national security and government. Most recently this has been documented in the NSAC Education Report [Ed04] which surveyed PhD degree recipients in nuclear science in the 1992-98 period [Su00]. Of that cohort less than 40% were in nuclear science careers in 2003. An example, is Sonja Dietrich who received her PhD from Rutgers University based on dissertation experiments at Jefferson Laboratory. She currently is a medical physicist in clinical radiation medicine at Georgetown University Medical Center. The NSAC report also recommended that to meet the projected need for nuclear scientists, for basic research and higher

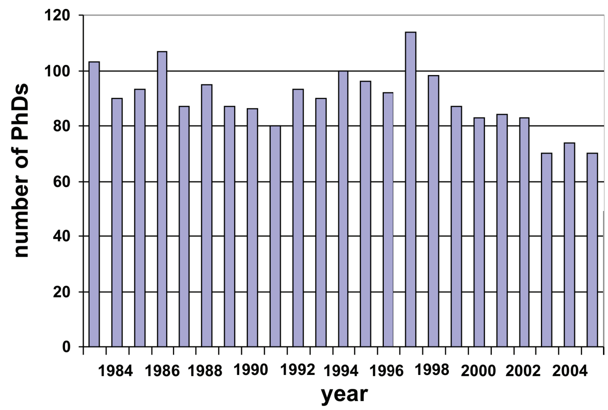

Figure 30: Number of nuclear science PhDs per year. Taken from Survey of Earned Doctorates [Su00].

education as well as to meet national needs, we need to produce at least 100 PhDs per year in nuclear science, the level of production in the early 1990s.

Since that report, the number of nuclear science PhDs per year has decreased to about 70 per year, as summarized in Figure 30. Not only could this erosion in our field compromise how nuclear scientists have traditionally helped to address national needs, but such low numbers could compromise realizing the scientific goals in basic nuclear science, with a sub-critical number of talented researchers, and in higher education, with a sub-critical number of nuclear physics faculty members to train future generations of nuclear physicists. It is especially important to increase the number of US students preparing for careers in nuclear science. While in the past a large fraction of the talented nuclear scientists were international students, there are more opportunities for international scholars to study outside of the US and an increasing number are opting to return to their home countries after their PhD degrees. In addition, many of the careers for nuclear scientists, especially those that work to address the challenges in national security, require US citizenship. Therefore, it is critical to grow the US pool of PhD nuclear scientists. An effective place to focus our efforts, that also leverages the current activities and unique qualities of nuclear physics, is at the undergraduate level. A large fraction of our community is already engaged in undergraduate education by mentoring these students in research, at the national laboratories or the home colleges or universities. Faculty members teach nuclear physics at the introductory level and in courses for physics majors at the advanced level. At times faculty members introduce nuclear physics concepts in courses for non-science majors. Therefore, we endorse the recommendation of the White Paper: A Vision for Nuclear Science Education and Outreach for the Next Long Range Plan: The nuclear science community should increase its involvement and visibility in undergraduate education and research, so as to increase the number of nuclear science PhDs, and the number of scientists, engineers and physics teachers exposed to nuclear science.

To fully realize the goal to increase the number of PhD degrees will also require interventions at the graduate level. Many of these interventions were recommended by NSAC in endorsing the Education Report. While some of the recommendations were to identify new funding opportunities for graduate students and postdocs, others focused on shortening the time to PhD degree and enhancing the professional development of graduate students and postdocs. Our community of nuclear physicists should be committed to not only enhancing the number of PhDs in our field, but should also be committed to preparing them for the wealth of career opportunities, both inside and outside of basic nuclear physics and higher education.

It is also important for the nuclear physics community to extend our education efforts and reach out beyond our field: to inform other physicists and other scientists about the excitement of our research, to introduce the concepts of nuclear physics to future and current school teachers and students, and to enhance the public's understanding of nuclear physics and its applications and the value of nuclear physics to society.

The QCD and Hadron Physics community has a long tradition for reaching beyond our discipline. An example, is the highly successful BEAMS efforts at Jefferson Lab that introduce physics concepts to middle school students. What makes this effort so successful are the plethora of hands-on activities that have been developed for 6th, 7th, and 8th grade students: `http://education.jlab.org/beams/index.html`.

Therefore, we also endorse the second recommendation of the Education and Outreach White Paper: The nuclear science community should develop and disseminate materials and hands-on activities that illustrate and demonstrate core nuclear science principles to a broad array of audiences, so as to enhance public understanding and appreciation of nuclear science and its value to society.

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APPENDIX - Town Meeting Schedule

Friday January 12

08:30-09:00	Introduction: Charges and Guidelines (Ji and Meziani)
09:00-12:00	Session 1: Hadron Structure at Short Distance (discussion leader: Deshpande)
09:00-09:30	Parton distributions at high-energy, Jian-Wei Qiu
09:30-10:00	Parton distributions at large x, J. P. Chen
10:00-10:20	coffee break
10:20-10:50	Transverse Momentum Distributions, N. Makins
10:50-11:20	Report from the GPD workshop, M. Vanderhaegen
11:20-12:00	General discussion and (3 min, 1 slide)
	Short presentations: Souder, Gao, Caldwell, Hyde-Wright
12:00-13:00	Lunch Break
13:00-15:30	Session 2: Hadron Structure at Long Distance (discussion leader: Peng)
13:00-13:30	Electro-magnetic Form Factors, J. Arrington
13:30-14:00	Weak form factors and Standard Model Tests, G. Cates
14:00-14:20	Chiral Dynamics with Pions, Nucleons, and Deltas, D. Phillips
14:20-14:40	Chiral Structure of Few-nucleon Systems, H. Griesshammer
14:40-15:00	Probing Chiral Dynamics with Photons, H. Weller
15:00-15:30	General Discussion and (3', 1 slide)
	presentations: Stoler, Miskimen, Norum
15:30-16:00	coffee break
16:00-18:00	Session 3: Nuclear Physics at Short Distance (Discussion Leader: Keppel)
16:00-16:35	How does short distance behavior affect the nucleus, D. Geesaman
16:35-16:50	Nuclei at short distance scale, R. Ransome
16:50-17:05	QCD processes in the nucleus, W. Brooks
17:05-17:20	Partons in the nucleus, J. Owens
17:20-17:30	Hypernuclear spectroscopy, J. Reinhold
17:30-18:00	General discussion and (3', 1 slide) presentations: Hafidi

Saturday January 13 (joint session with QCD and Hadron Physics Town Meeting)

08:30-08:40	Welcome address
08:40-09:25	JLab 12 GeV Upgrade and science program, A. Thomas
09:25-10:10	RHIC II upgrade and science program, W. Zajc
10:10-10:30	coffee break
10:30-10:50	International opportunities: LHC, B. Wyslouch
10:50-11:10	International opportunities: FAIR, W. Henning
11:10-11:30	International opportunities: J-PARC, N. Saito
11:30-11:40	International opportunities: discussion
11:40-12:20	QCD Theory: challenges, opportunities and community needs, D. Kaplan
12:20-13:30	Lunch Break
13:30-14:00	Computational QCD, J. Negele
14:00-14:35	Gluons at high density, Y. Kovchegov
14:35-15:10	Central questions in proton structure, W. Vogelsang
15:10-15:50	Opportunities in low-x physics, B. Surrow
15:50-16:10	Coffee Break
16:10-16:50	Opportunities in hadron structure, R. Ent
16:50-17:30	e+p/A facilities, L. Merminga
17:30-18:45	Community input and discussion of priorities, Draft EIC Bullet

Sunday January 14

09:00-10:00	Session 4-a: Hadron spectroscopy (Mesons)(discussion leaders: Capstick and Meyer)
09:00-09:30	Theory Overview: from heavy quark to light quark systems, T. Barnes
09:15-09:30	Theory Overview: meson phenomenology, J. Dudek
09:30-10:00	Experimental overview; current and future, A. Dzierba
10:00-10:30	coffee break
10:30-12:00	Session 4-b: Hadron spectroscopy (Excited Baryons)
10:30-11:00	Experimental overview; current and future, V. Burkert
11:00-11:15	Overview: theoretical developments, T.-S.H. Lee
11:15-11:30	Other facilities/detectors for baryon physics, V. Crede
11:30-12:00	Short presentations and general discussion:, Sandorfi, Stepanyan, Stoler, Weygand
12:00-13:00	Lunch Break
13:00-15:00	Session 5: Theory (discussion leader: Negele)
13:00-13:25	Effective Field Theory, I. Stewart
13:25-13:50	Roles of Phenomenology and Model Building, A. Szczepaniak
13:50-14:15	Lattice QCD, K. Orginos
14:15-15:00	General discussion: Edwards, Miller, Savage
15:00-15:30	coffee break
15:30-16:00	Education and Outreach, Jolie Cizewski
16:00-18:00	Recommendations and whitepaper assignments (Ji and Meziani)

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