1 EXECUTIVE SUMMARY

There has been a remarkably fruitful evolution of our picture of the behavior of strongly interacting matter during the almost two decades that have passed since the parameters of the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab were defined. These advances have revealed important new experimental questions best addressed by a CEBAF-class machine at higher energy. Fortunately, favorable technical developments coupled with foresight in the design of the facility make it feasible to triple CEBAF's beam energy from the original design value of 4 GeV to 12 GeV (corresponding to doubling the achieved energy of 6 GeV to 12 GeV) in a cost-effective manner: the Upgrade can be realized for about 15% of the cost of the initial facility. This Upgrade would enable the worldwide community using CEBAF to greatly expand its physics horizons.

Raising the energy of the accelerator to 12 GeV provides three general advantages:

1. It allows crossing the threshold above which the origins of quark confinement can be investigated. Specifically, 12 GeV will enable the production of certain "exotic" mesons, whose existence establishes that the origin of quark confinement is in the formation of QCD flux tubes and whose spectrum encodes information on the mechanism within QCD responsible for their formation. With 12 GeV one also crosses the threshold for charmed quark production.

2. It allows direct exploration of the quark-gluon structure of hadrons and nuclei. It is known that inclusive electron scattering at the high momentum and energy transfers available at 12 GeV is governed by elementary interactions with quarks and gluons. The original CEBAF energy was not fully adequate for study of this critical regime, while with continuous 12 GeV beams one can cleanly access the entire "valence quark region" and exploit the newly discovered Generalized Parton Distributions to access experimentally both the correlations in the quark wavefunctions and their transverse momentum distributions.

3. In addition to these qualitative changes in the physics reach of CEBAF, the 12 GeV Upgrade also allows important new thrusts in CEBAF's present research program, generally involving the extension of measurements to substantially higher momentum transfers (probing correspondingly smaller distance scales). We also note that most experiments that want to run at a presently accessible momentum transfer can do so more efficiently (*e.g.*, consuming less total beam time) at higher electron beam energy.

In the examples highlighted in this executive summary and in the more complete discussions of Chapter 2, these benefits of the energy upgrade will always be significant.

1.A Physics Overview

Chapter 2 provides a summary of the science motivation driving the 12 GeV Upgrade. The research program of the new facility dramatically extends and expands upon the major research themes (or "campaigns") that are driving our present program. These themes coincide with the broad directions of the field of nuclear physics as identified in two key documents: the 1996 Long Range Plan [NS96] of NSAC (the Nuclear Science Advisory Committee of the U.S. Department of Energy and the National Science Foundation) and the recent decadal survey [NA99] of the field by the National Research Council of the National Academy of Sciences. We identify these campaigns here to place our research program in this broader context. Each campaign corresponds to an outstanding question in nuclear physics that the laboratory's users address with a concerted program of experimental and theoretical work. The campaigns are:

On the Structure of the Nuclear Building Blocks:

> <u>Campaign 1:</u> **Testing the Origin of Quark Confinement** – experiments and theory aimed at examining the fundamentally new dynamics that underpins all of nuclear physics: the confinement of quarks.
>
> <u>Campaign 2:</u> **How Are the Nuclear Building Blocks Made from Quarks and Gluons?** – a program of measurements addressing this first question that must be answered in the quest to understand nuclear physics in terms of the fundamental theory of strongly interacting matter: quantum chromodynamics (QCD).
>
> <u>Campaign 3:</u> **Understanding the Origin of the Nucleon-Nucleon Force** – a broad program of experimental and theoretical work focused on moving beyond current phenomenological descriptions of the nucleon-nucleon force (for example, to determine its basic nature as a mixture of meson exchange, quark exchange, and color polarization effects).

On the Structure of Nuclei:

> <u>Campaign 4:</u> **Testing the Limits of the Meson/Nucleon Description of Nuclei** – a broad program of experiments taking advantage of the precision, spatial resolution, and interpretability of electromagnetic interactions to address long-standing issues in the classical nuclear physics of large nuclei.
>
> <u>Campaign 5:</u> **Probing the Limits of the "Standard Model" of Nuclear Physics** – the huge body of experimental and theoretical work now being carried out at Jefferson Lab and in the community at large focusing on few-body systems where directly interpretable experiments can be compared with exact calculations that are now feasible in the context of the "standard model" of nuclear physics.

The two "breakthrough" programs that have been identified as major motivations for the energy upgrade address key issues in Campaigns 1 and 2. The first, a program of *gluonic spectroscopy*, will provide data needed: i) to test experimentally our current understanding that quark confinement arises from the formation of QCD flux tubes; and ii) to explore the mechanism behind the formation of these flux tubes. The second program will explore the *complete quark and gluon wavefunctions* of the nucleons through measurements: i) of quark momentum distributions in the critical, but previously unreachable, valence quark region; and ii) of exclusive reactions that build on the framework of the newly discovered Generalized Parton Distributions. In addition to opening up these two qualitatively new areas of research, the Upgrade is also strongly driven by the fact that it will create important new research thrusts in key areas already under investigation with CEBAF's 6 GeV capability. In Sections 1.A.1, 1.A.2, and 1.A.3 we summarize these three key science drivers of the 12 GeV Upgrade. Section 1.B then completes the picture by summarizing the accelerator and experimental equipment upgrades required to accomplish these physics goals.

1.A.1 The Origin and Nature of Quark Confinement: Discovering and Studying the Exotic Mesons

The 12 GeV Upgrade will allow a breakthrough program to be launched in Campaign 1, "Testing the Origin of Quark Confinement".

In the early 1970s, evidence that the masses of strongly interacting particles increased without limit as their internal angular momentum increased led the theorist Yoichiro Nambu [Na70] to propose that the quarks inside these particles are "tied together" by strings. Numerical simulations of QCD ("lattice QCD") have demonstrated [Ba00] that Nambu's conjecture was essentially correct: in chromodynamics, a stringlike chromoelectric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see Figs. 1 and 2). The phenomenon of confinement is the most novel and spectacular prediction of QCD – unlike anything seen before. It is also the basic feature of QCD that drives all of nuclear physics, from the mass of the proton and other nuclear building blocks to the NN interaction.

The ideal experimental test of this new feature of QCD would be to study the flux tube directly by anchoring a quark and antiquark several fermis apart and examining the flux tube that forms between them. In such ideal circumstances one of the fingerprints of the gluonic flux tube would be its model-independent spectrum [Lu81] (see Fig. 3): its required two degenerate first excited states are the two longest-wavelength vibrational modes of this system, while their excitation energy is required to be π/r since both the mass and the tension of this "relativistic string" arise from the

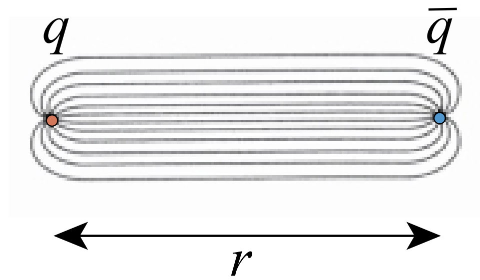

Figure 1: In QCD a confining flux tube forms between distant static charges. The Hall D program is designed to verify this fundamental new feature of chromodynamics.

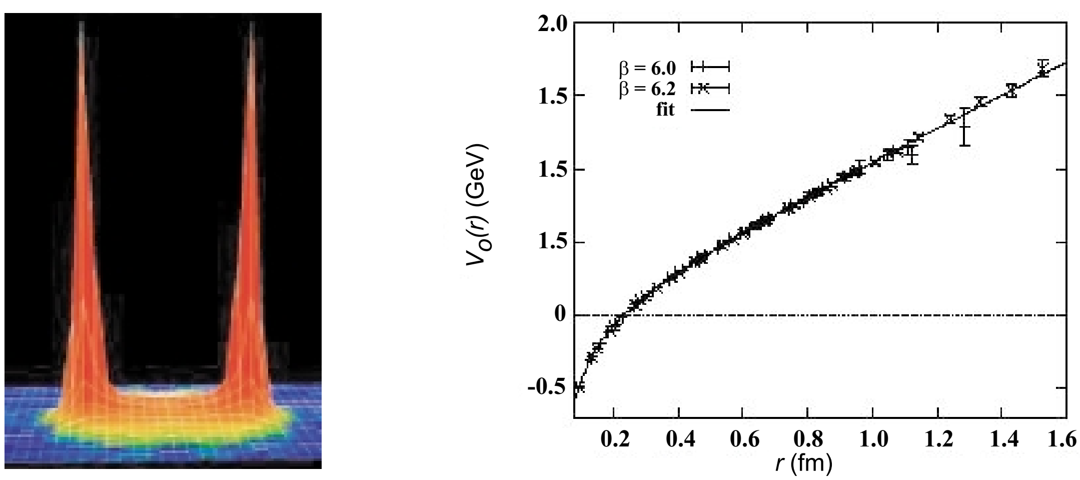

Figure 2: Lattice QCD has confirmed the existence of flux tubes between distant static charges for heavy quarks. In addition to the intense color fields in the immediate vicinity of each quark, one can see the formation [Ba00] along the line connecting the two quarks of a flux tube of constant thickness, leading to the linearly rising potential seen on the right [Ba97].

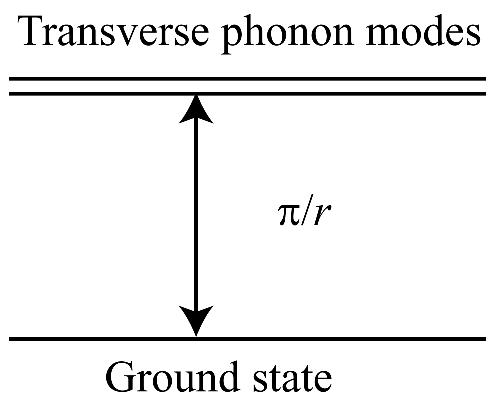

Figure 3: Model-independent spectrum of the glue (flux tube) of Fig. 1.

energy stored in its color force fields. Such a direct examination of the flux tube is of course not possible. In real life we have to be content with systems in which the quarks move. Fortunately, we know both from general principles [Is85] and from lattice QCD calculations [Mo97] that an approximation to the dynamics of the full system that ignores the impact of these two forms of motion on each other works quite well – at least down to quark masses of the order of 1 GeV.

To extend this firm understanding to yet lighter quarks, models are required [Is85], but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV, a new form of hadronic matter must exist in which the gluonic degree of freedom of a quark-antiquark system is excited. The smoking gun characteristic of these new states is that the vibrational quantum numbers of the gluonic "string", when added to those of the quarks, can under certain circumstances produce a total angular momentum J, a total parity P, and a total charge conjugation symmetry C not allowed for ordinary $q\bar{q}$ states. These unusual J^{PC} combinations (such as 0^{+-}, 1^{-+}, and 2^{+-}) are called exotic, and the states are referred to as exotic hybrid mesons [Ba77]. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations, require that these states have masses around 2 GeV; furthermore, they demonstrate that the levels and their orderings will provide experimental information on the mechanism that produces the flux tube.

On the experimental front, tantalizing evidence has appeared in recent years for both exotic hybrids and gluonic excitations with no quarks (glueballs). For the last two years a group of 90 physicists from 26 institutions in seven countries has been working on the design of the definitive experiment to map out the spectrum of these new states required by the confinement mechanism of QCD. Photon beams are expected to be particularly favorable for the production of the exotic hybrids [Is85]. The reason is that the photon sometimes behaves as a "virtual vector meson" with total quark spin $S = 1$. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic J^{PC} are possible. In contrast, when the spins are antiparallel ($S = 0$), as in pion or kaon probes, the exotic combinations are not generated. (In the approximation that flux tube and quark dynamics separate, hybrid production would occur by pure flux tube excitation, and these selection rules would be strictly true. In practice, these two degrees of freedom interact with one another to produce corrections to the rules.) To date, most meson spectroscopy has been done with incident pion, kaon, or proton probes, so it is not surprising that the experimental evidence to date for flux tube excitation is tentative.

In contrast to hadron beams, high-flux photon beams of sufficient quality and energy to perform meson spectroscopy studies have not been available, so there are virtually no data on the photoproduction of mesons with masses in the 1.5 to 3 GeV region. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found. The planned experiment will have a dramatic impact on this situation. Even if initial running is at only 10% of the planned photon fluxes of 10^8/s, the experiment will accumulate statistics during the first year of operation that will exceed the world's supply of published meson data obtained by pion production by at least a factor of 10, and the existing photon production data set by at least a factor of 1000. With the planned detector (see Fig. 4), high statistics, and linearly polarized photons, it will be possible to map out the full spectrum of the decay modes of these gluonic excitations. This experiment is described in Section 4.E; a much more complete discussion of the physics driving the experiment is given in Section 2.A.

When the spectrum and decay modes of these gluonic excitations have been mapped out experimentally, we will have made a giant step forward in understanding one of the most important phenomena discovered in the twentieth century: quark confinement.

1.A.2 The Quark-Gluon Wavefunctions of the Nuclear Building Blocks

The 12 GeV Upgrade will also allow a breakthrough program to be launched in Campaign 2: "How Are the Nuclear Building Blocks Made from Quarks and Gluons?"

The classic program of deep inelastic scattering (DIS) experiments began with the Nobel Prize–winning work of Friedman, Kendall, and Taylor [Bl69] in the 1970s at SLAC. These measurements

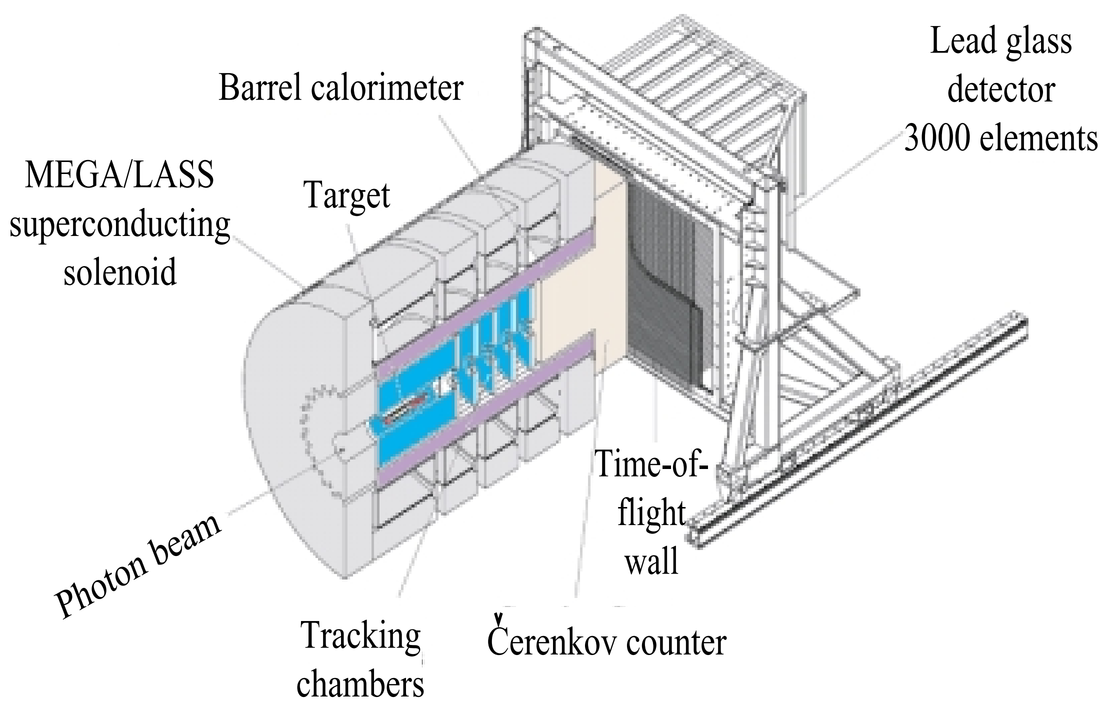

Figure 4: The conceptual design of the proposed detector to study the photoproduction of mesons in the mass region around 2 GeV.

led to the experimental confirmation of the existence of quarks and to precision tests of the fledgling theory of QCD, eventually confirming it as the fundamental theory governing all strongly interacting (*i.e.*, nuclear) matter.

Even though such experiments have been pursued vigorously for nearly 30 years, it is remarkable that there has never been an experimental facility that could measure the DIS cross sections throughout the kinematic regime where the three basic ("valence") quarks of the proton and neutron dominate the wavefunction. At modest values of the momentum transfer Q^2, the valence quarks play a substantial role in determining these cross sections over a large range of the kinematic variable x (which runs from 0 to 1 and is roughly interpretable as the fraction of the momentum of the initial nucleon state along the direction of the incident virtual photon that was carried by the struck quark). The contribution of the valence quarks peaks at $x \simeq 0.2$. However, if one is in the conventionally defined deep inelastic regime, the probability of finding a quark in the high-x "valence quark region" is small, and becomes smaller and smaller as $x \to 1$; moreover, with "pollution" from gluons and quark-antiquark pairs, it is only for $x > 0.5$ that the valence quarks dominate the $x \to 1$ wavefunction. The 12 GeV Upgrade will allow us to map out the quark distribution functions in this "clean" valence quark region with high precision. Such measurements will have a profound impact on our understanding of the structure of the proton and neutron.

Figure 5 shows one example of a measurement that can be done with the proposed Upgrade. (See Section 2.B.1 for details.) The neutron polarization asymmetry A_1^n is determined by the spin wavefunction of the quarks, and most dynamical models predict that in the limit where a single quark carries all of the nucleon's momentum ($x \to 1$), it will also carry all of the spin polarization (so, *e.g.* for the neutron, $A_1^n \to 1$ as $x \to 1$). Existing data on A_1^n end before reaching the region of valence quark dominance, and show no sign of making the predicted dramatic transition $A_1^n \to 1$. There are similar (if less dramatic) paucities of data on all other DIS observables in this region.

Even in unpolarized DIS, where the available data are best, there are unresolved issues. To extract the ratio of such a simple and basic a property as the relative probability of finding a d quark vs. a u quark at high x requires measurements on both the proton and neutron. However, high-x neutron information is difficult to disentangle from nuclear binding corrections. Figure 6 shows the precision with which this fundamental ratio (which is intimately related to the fact that the proton and neutron, and not the Δ, are the stable building blocks of nuclei) can be measured with the proposed Upgrade. (See Section 2.B.1 for details.) The planned experiment will exploit the mirror symmetry of $A = 3$ nuclei through simultaneous measurements of the inclusive structure functions for ^{3}H and ^{3}He. Regardless of the absolute value of the nuclear effects in the two measurements, their differences should be small, permitting the neutron-to-proton ratio (and thus the d/u ratio) to be extracted with precision.

While the historic DIS program will thus continue to be fruitful, it is intrinsically limited in what it can tell us about quark and gluon wavefunctions: structure functions are *probabilities*. Until recently, attempts to determine the quark and gluon *wavefunctions* of the nucleons have been hopelessly handicapped by the lack of a rigorous framework for making a connection between any experimental measurement and these wavefunctions. (For example, while intuitively related to the momentum wavefunction of the quarks, even the valence quark distribution functions are sensitive only to the square of the momentum wavefunction suitably averaged over momenta transverse to the virtual photon direction!) The discovery of Generalized Parton Distributions (GPD's) and their connection to certain totally exclusive cross sections has made it possible in principle to rigorously map out the complete nucleon wavefunctions themselves [Ji97, Ra96]. The GPD's are sensitive to the wavefunction at the *amplitude* level, instead of merely the probability level, and, in particular, explore quark-quark correlations. The 12 GeV Upgrade will provide the accelerator and detectors required to perform the difficult measurements that will allow the first comprehensive exploration of this new "Deep Exclusive Scattering" (DES) domain that is rigorously connected to the quark and gluon wavefunctions.

Standard techniques relate the total cross section for deep inelastic scattering to the imaginary part of the forward elastic scattering process $\gamma^* p \to \gamma^* p$, where p is a target particle (such as a proton). Of key importance is that in the deep inelastic scattering regime the elastic process is dominated by the diagram shown in Fig. 7, where pure electron-quark scattering *factorizes* from the probability for the quark to carry a fraction x of the target's momentum, depicted as the blob at the bottom of the diagram.

The new DES processes that lead to GPD's, and thence to quark and gluon wavefunctions, can be extracted *under appropriate kinematic conditions* from the generic cross sections shown in Fig. 8. Whereas the DIS process involved a γ^* in both the initial and the final state, for these new deep exclusive processes the final particle can be a $\gamma, \gamma^*, \pi, \eta, \rho, \omega, K$, etc. instead of just a γ^*. Furthermore, the initial and final targets can have different momenta (p can scatter to $p\,'$) and can even be of different types (i can scatter to f). If the final particle is a γ^*, forward scattering is possible, and in that case, assuming one is in the scaling region for these cross sections, the GPD's being studied would reduce to standard quark distribution functions. In every other case (once again assuming one is in the appropriate scaling region), these processes access a rich new body of information about the full wavefunction, including nonforward overlaps of their longitudinal parts and their transverse momentum structure.

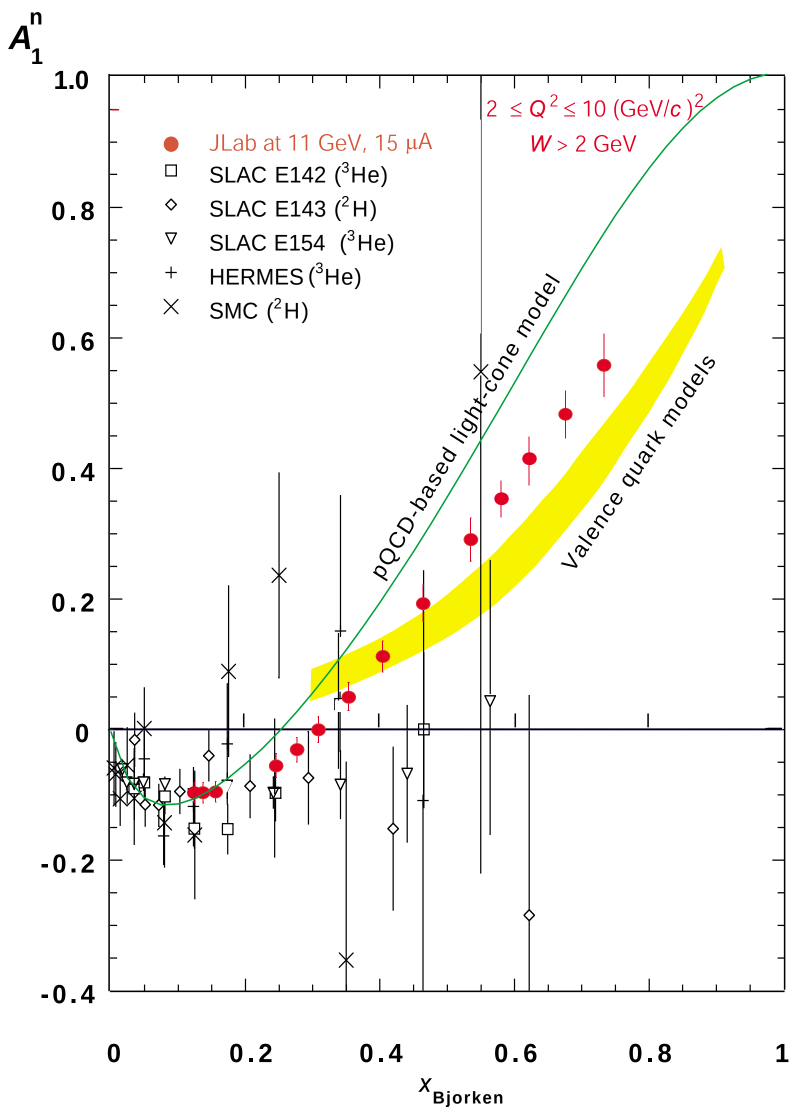

Figure 5: A projected measurement of the neutron polarization asymmetry A_1^n, determined by the spin structure of the valence quarks, made possible by the proposed 12 GeV Upgrade. The shaded band represents the range of predictions of valence quark models; the solid line is the prediction of a pQCD light-cone quark model.

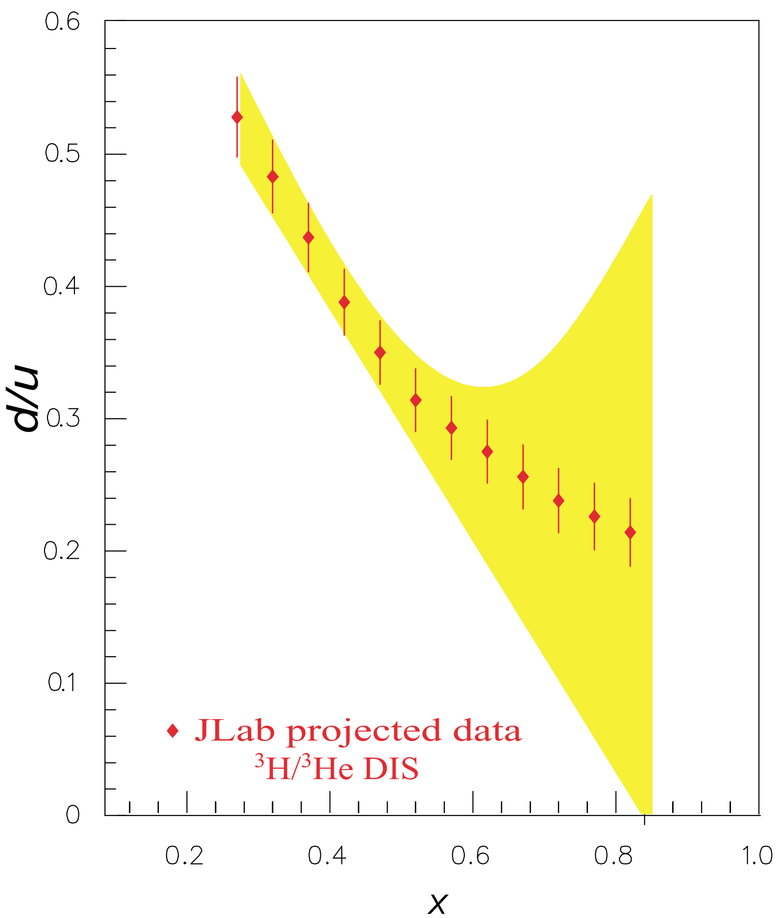

Figure 6: A projected measurement of the ratio of momentum distributions of valence d quarks to u quarks made possible by the proposed 12 GeV Upgrade. The shaded band represents the uncertainty in existing experiments due to nuclear Fermi motion.

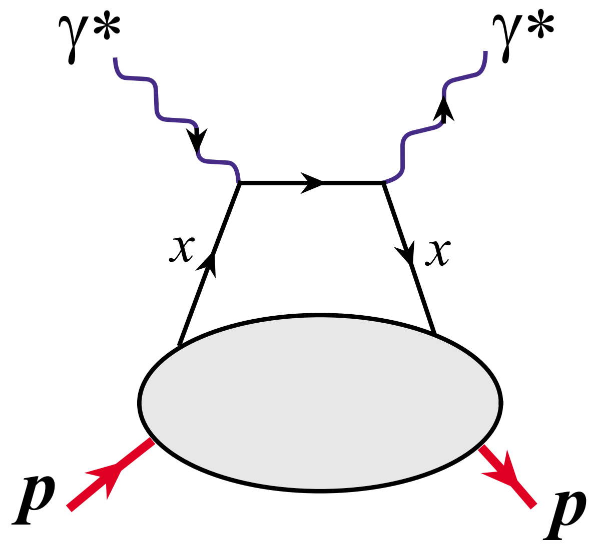

Figure 7: The asymptotically dominant contribution to deep inelastic scattering (DIS).

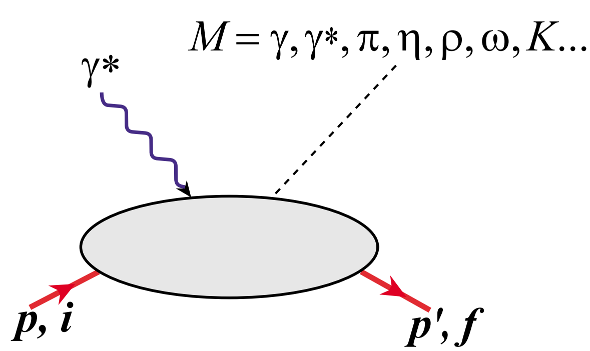

Figure 8: The special deep exclusive scattering (DES) processes that have been identified as providing a new window on the quark-gluon wavefunctions of the nuclear building blocks.

While theoretical guidance is available, the kinematic range over which measurements must be done for the above-mentioned DES scaling to apply must normally (as was the case historically for DIS) be determined experimentally. Moreover, as in DIS, there are two related but conceptually distinct requirements for being in the DES scaling regime so that Fig. 8 can be interpreted in terms of the GPD's and hence the quark-gluon wavefunctions. Wavefunctions are frame-dependent, and those probed in standard DIS and in the new DES processes are *not* those of the rest frame, but rather may be identified with those of a particle whose velocity is approaching the speed of light. Thus one condition for scaling is that the kinematic range of the measurements must bring one close enough to $\beta = 1$ that the wavefunction is close to its asymptotic form. The other condition is that the relevant underlying dynamical processes can be factorized into a "hard" pQCD scattering amplitude and a "soft" amplitude which arises from the wavefunctions.

In the DIS process of Fig. 7 on nucleons, we know that the conditions for scaling are achieved when $Q^2 > 1$ (GeV/c)^2 and the produced inelastic mass $W > 2$ GeV. We can understand these conditions intuitively. In this case we can expect that the "hot" quark between the two pointlike γ^* vertices (the upper line in the figure) will be effectively free from the remaining quarks (within the lower portion of Fig. 7) since these kinematic conditions localize the "hot" quark in space-time to the short-distance regime where asymptotic freedom applies. Moreover, our knowledge of the structure of the excited nucleon resonances strongly suggests that there is no scale greater than 1 GeV to interfere with the rapid evolution of the rest frame wavefunction to its $\beta \to 1$ form.

Similar factorization issues apply to DES. Consider first the $\gamma^* p \to Mp$ reaction with $M = \gamma$, *i.e.*, Deeply Virtual Compton Scattering (DVCS), which can actually proceed *via* a modified version of the Feynman diagram of Fig. 7 with the second γ^* replaced by a γ and with the imaginary part of the graph not taken. Since the two Feynman diagrams are the same, one may expect the two processes to have similar factorization and scaling properties. However, the cases of $\gamma^* p \to Mp$, where M is a meson, represent *terra incognita*. Figure 9 illustrates the essential features. For factorization, the kinematics of the experiment must force the struck quark to be effectively free, as before, but now, in addition, the kinematics must create the $q\bar{q}\,'$ meson by the pQCD process depicted. Note that by judicious choice of the meson and its production characteristics, the data probe complementary aspects of the hadron wavefunction, such as correlations among flavors and momenta of quarks, the transverse momentum distributions, and the role of the quarks' angular momentum and spin in building up the hadron's spin. (Note in addition that since Fig. 9 includes many time-orderings, it includes processes where a quark-antiquark pair is created by the hot photon *and* processes where a $q\bar{q}\,'$ pair in the target is knocked out. There are correspondingly two new types of wavefunctions being probed by these reactions.)

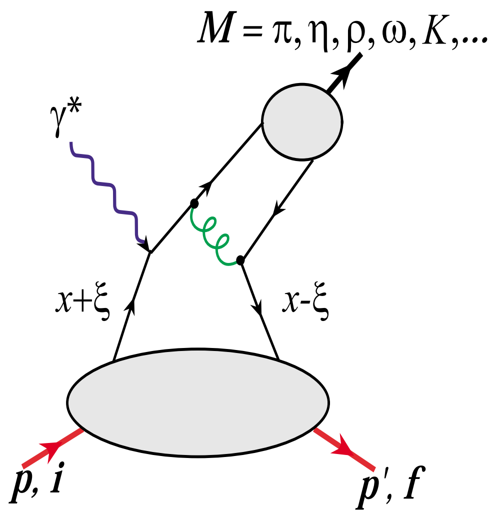

Figure 9: The asymptotically dominant diagram for DES with meson production in which a $q\bar{q}\,'$ pair is "forced" by the γ^* and a hard gluon exchange into the meson $M = \pi, \eta, \rho, \omega, K$, etc. These reactions are governed in their scaling regions by the new Generalized Parton Distributions (GPD's) which depend on three kinematic variables: $t = (p - p')^2$, $\xi = \frac{x_{Bj}}{2 - x_{Bj}}$, and x (defined in the figure).

Figure 10 shows two models for the GPD denoted $H(x, \xi, t)$ from which one can gain some insight into the richness of information available through the study of these new distributions. The figure is a three-dimensional representation at $t = 0$. $H(x, \xi, t)$ is modeled using the so-called double distribution of Radyushkin [Ra99], which parameterizes the usual parton distributions measured in inclusive scattering and parton correlations modeled via quark-antiquark (*i.e.* pion) distributions. In the right-hand surface the "D" term by Polyakov and Weiss [Po99] that represents two-pion contributions is included.

DIS experiments can measure the parton distribution only along the line at $\xi = 0$; $H(x, 0, t = 0)$ is the usual quark distribution for $x > 0$, and the antiquark distribution for $x < 0$. The ability of DES experiments to vary the "skewedness" parameter, ξ, provides access to the full surface and the ability to *measure* the correlations between the partons in the nucleon. ξ is given by the electron kinematics, and defines the fractional momentum difference between the initial- and final-state partons. For $\xi = 0$ the initial- and final-state partons have identical momenta, and for large ξ they carry very different fractions of the nucleon's momentum. At $\xi \to 1$, $H(x, \xi, t)$ takes on the characteristics of quark-antiquark (*i.e.*, meson) distribution amplitudes that are clearly visible in the figure. Additional information on quark-quark correlations can be obtained from mapping out the t-dependence of these surfaces.

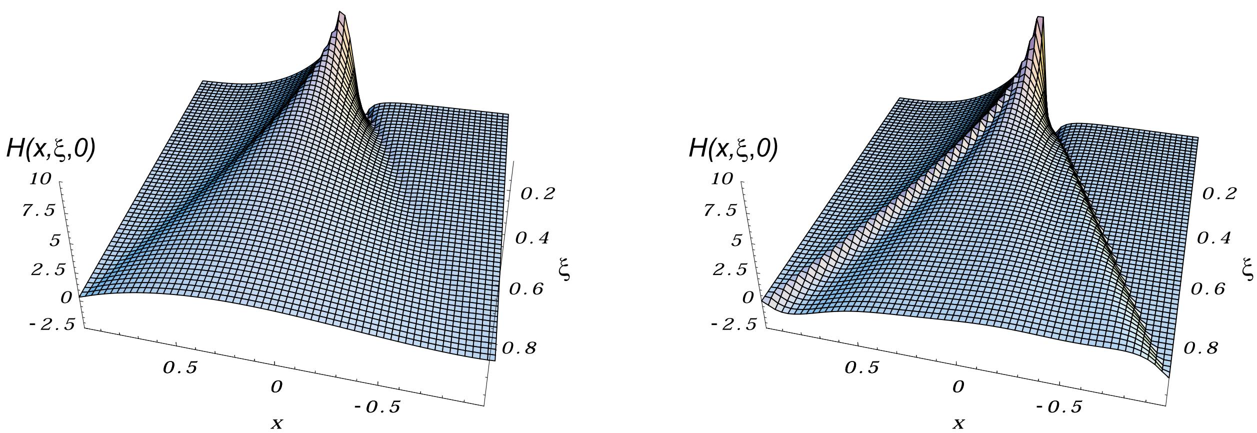

Figure 10: Two possible Generalized Parton Distributions [Vapc] that are consistent with available deep inelastic scattering data (*i.e.*, have identical values for $\xi = 0$) but contain very different quark-quark correlations (see text).

The 12 GeV Upgrade will allow these critical DES cross sections to be systematically measured in the relevant kinematic regions for the first time. In most cases a wide range of kinematic conditions can be achieved covering nearly an order of magnitude in the relevant variables beyond values at which DIS has exhibited scaling. One may therefore expect that the scaling properties of the cross sections can be determined experimentally.

There are thus reasons to be optimistic that either scaling will be achieved in these processes or that the scaling limits can be inferred by extrapolation from the behavior of the measured cross sections, so that the desired direct connection can be made with the wavefunction. Although this seems almost certain in the case of DVCS, as mentioned above, there are reasons to be cautious for other DES cross sections. For example, it is generally believed that the pion elastic form factor, which is asymptotically controlled by the upper part of the diagram of Fig. 9, is dominated by long-distance confinement-based physics for $Q^2 < 10$ (GeV/c)^2. We also recall that determining the GPD's will require not only factorization, but also that the new wavefunctions being probed have evolved to their asymptotic form. However, there is some evidence from the decay characteristics of highly excited mesons that the $q\bar{q}$ sea is produced with a very hard spectrum [Ge93], so that the $qqqq\bar{q}$ component of the nucleon wavefunction may evolve much more slowly than the qqq component to its $\beta \to 1$ limit.

In summary, it seems likely that the Upgrade to 12 GeV will access the required conditions for a DVCS program. Whether, in addition, 12 GeV will be sufficient to determine all of the GPD's described here, to get a first glimpse of them, or only to define how the scaling regime is approached, is a question that awaits experiment. At the least, the Upgrade will provide important information necessary to define the energies and luminosities of a future machine required to complete this vital task.

1.A.3 Other New Research Thrusts in the Major CEBAF Campaigns

The 12 GeV Upgrade will make a broad range of profound contributions to the study of nuclear matter beyond the two breakthrough programs described above. Many such examples of programs that the 12 GeV Upgrade will support are described in Chapter 2; they touch all of the research campaigns outlined above. Seven of them are highlighted here.

- *The pion form factor*

The high-Q^2 behavior of elastic and transition form factors probes the high-momentum components of the valence quark wavefunctions of the nuclear building blocks. Of particular interest in this regard is understanding when the dynamics of the valence quarks makes a transition from being dominated by the strong QCD [Cl95a] of confinement to perturbative QCD. This transition should occur first in the simplest systems; in particular, the pion elastic form factor seems the best hope for seeing this transition experimentally. Figure 11 shows how well the proposed 12 GeV Upgrade can explore this transition. Details of how such an experiment would be executed are described in Section 2.B.3.

- *Duality: the transition from a hadronic to a quark-gluon description of DIS*

At high enough energies, asymptotic freedom guarantees that the DIS cross section can be calculated based on nearly free electron-quark scattering as depicted in Fig. 7. However, confinement guarantees that the experimentally observed final-state particles are hadrons. Thus in the scaling region, the equality of these two sets of cross sections is simply the statement that the results associated with Fig. 7 are rigorously proved; *i.e.*, that QCD is the correct theory of the strong interactions. In contrast, as one proceeds to kinematic conditions that are below the Bjorken limit (*e.g.*, Q^2 well below 2 $(\mathrm{GeV}/c)^2$), cross sections calculated assuming factorizing dynamics of the type depicted in Fig. 7 should be expected to fail to reproduce the hadronic cross sections, which when summed give *by definition* the true inclusive cross section. Low-energy quark-hadron duality suggests that hadronic cross sections, when averaged over an appropriate energy range, *nevertheless* coincide with the naïve leading twist quark-gluon calculations. Thus quark-hadron duality *at low energy* naturally examines the transition between strongly interacting matter and perturbative

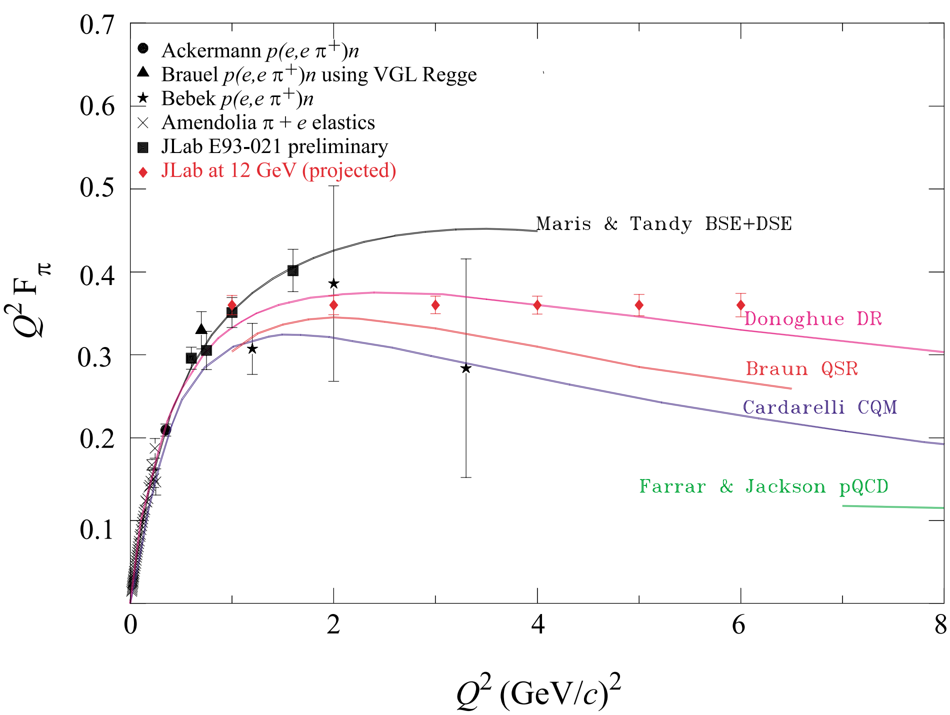

Figure 11: The projected measurements of the pion elastic form factor through the expected transition region from confinement-dominated dynamics to perturbative-dominated dynamics made possible by the proposed 12 GeV Upgrade. Systematic errors are estimated to be comparable to the statistical errors shown for the projected 12 GeV data. Also shown are a few of the dozens of model predictions, all characterized by being confinement-dominated below about 2 $(\mathrm{GeV}/c)^2$ and making a transition to being perturbative-dominated with a value of $Q^2F_\pi \simeq 0.1$ $(\mathrm{GeV}/c)^2$ in the region of 10 $(\mathrm{GeV}/c)^2$.

QCD. In the circumstances of the 12 GeV Upgrade, both Bjorken scaling and the approach to scaling must arise from very few channels. One may therefore expect that the underlying mechanisms of quark-hadron duality may be determined by utilizing the spin/flavor selectivity of 12 GeV electron scattering in both inclusive and exclusive reactions. The key issues addressed by this program are outlined in Section 2.B.4.

• *Color transparency: The nature of hadronic interactions can be investigated via tests of the prediction of "color transparency"*

Transparency is an unusual QCD effect predicted to have its most counterintuitive manifestation in $(e, e'p)$ at very high energy. Under the right conditions, three quarks, each of which would have interacted very strongly with nuclear matter, pass right through it. This can happen because bound states of three quarks must have zero net color charge by the "nonabelian" nature of charge and confinement in QCD, and they can also be arranged to have small color "dipole moments". While the nucleonic example is more exotic, and such measurements may very well succeed, there is evidence that the electroproduction of vector mesons (where the fact that a quark-antiquark pair has zero net color charge seems much more mundane) may provide a more practical setting for observing this phenomenon. Indeed, the evidence suggests that this reaction may show transparency at much lower Q^2 and ν than quasielastic proton scattering, and that it may have its most pronounced experimental signature in just the energy range of the CEBAF Upgrade. For details, see Section 2.C.2.

• *Learning about the* NN *force by the measurement of the threshold* ψN *cross section and by searching for* ψ*-nucleus bound states*

Threshold ψ photoproduction is a unique process since the small $c\bar{c}$ state will be produced by the interaction of its calculable small color dipole moment with a nucleon (in which it is presumed to *induce* a large, but uncalculable, color dipole moment). This simple color van der Waals–type force is a prototype for a possibly important component of the NN force. It is quite possible that this interaction is sufficiently strong that ψN or ψ-nucleus bound states exist; such relatively long-lived objects might be detected in subthreshold ψ production off nuclei. Based on the same picture, one could also look for ϕN states. Details are presented in Section 2.C.1.

• *Measuring short-range correlations in nuclei*

The higher-energy beams that will be available in Halls A, B, and C will support substantial extensions of CEBAF's current program measuring the high-momentum components of nuclear wavefunctions and investigating short-range nucleon-nucleon correlations. In the rare regions of strong nucleon-nucleon overlap that drive these correlations, instantaneous densities of the order of four times nuclear densities (comparable to those in a neutron star and close to those at which the zero temperature quark-gluon phase transition could occur) are expected. Figure 12 gives an example of a DIS measurement that can be made to study short-range correlations in nuclei. With the variety of measurements that can be made in the three halls, the Upgrade can be expected to fully answer this old question from nuclear many-body theory. See Section 2.D for details.

- *The spectroscopy of* $\mathrm{s\bar{s}}$ *mesons*

Figure 13 shows some of what we know about the spectra of $Q\bar{q}$ mesons for q a light quark and $Q = b, c, s$, and u or d. The rigorous results of Heavy Quark Effective Theory (HQET) should only be applicable for $Q = b, c$, but these data suggest that there is a remarkable similarity between the dynamics of "true" heavy-light systems and those where $Q = s$ or even $Q = u$ or d. It appears that the creation of the constituent quark mass through spontaneous chiral symmetry breaking is enough to boost any quark into the heavy-quark world, at least qualitatively. Figure 14 shows heavy quarkonia ($Q\bar{Q}$ systems) starting from the heaviest $b\bar{b}$ system to the lightest. Once again, even though there is no known rigorous explanation, there seems to be a great similarity between the spectra of the heavy quarkonia (which have a well-understood quark-model-like connection to QCD) and light-quark systems.

These interesting data showing possible relationships between heavy- and light-quark systems exist because nature has presented us with an interesting selection of quark masses. Historically the quarks have been divided into two groups based on their masses: the light-quark (u, d) world (or, by extension, the u, d, s world of SU(3)) and the heavy-quark world. It is ironic that in many critical areas we know much more (both experimentally and theoretically) about the heavy-quark world than we know about our own world. In this respect, these figures strongly suggest that it would be desirable to know much more about $s\bar{s}$ spectroscopy. Given that the photon is $s\bar{s}$ rich, a great deal of data will automatically be available from this sector as part of the planned Hall D program, creating the opportunity to correct this situation.

Mapping out the $s\bar{s}$ spectrum presents some challenges. Given that the intrinsic $s\bar{s}$ content of the proton is expected to be small, photon-initiated $s\bar{s}$ spectroscopy will strongly favor the production of diffractive-type $C = -1$ states. The exception will be channels where OZI-violating t-channel exchanges (like those of the $\eta - \eta'$ system) can occur. These effects will result in an uneven population of the spectrum. The very high data rates anticipated in Hall D should nevertheless lead to a data set of sufficient quality that the weakly excited states will still be identifiable. The possibilities for this program are presented in Section 2.A.6.

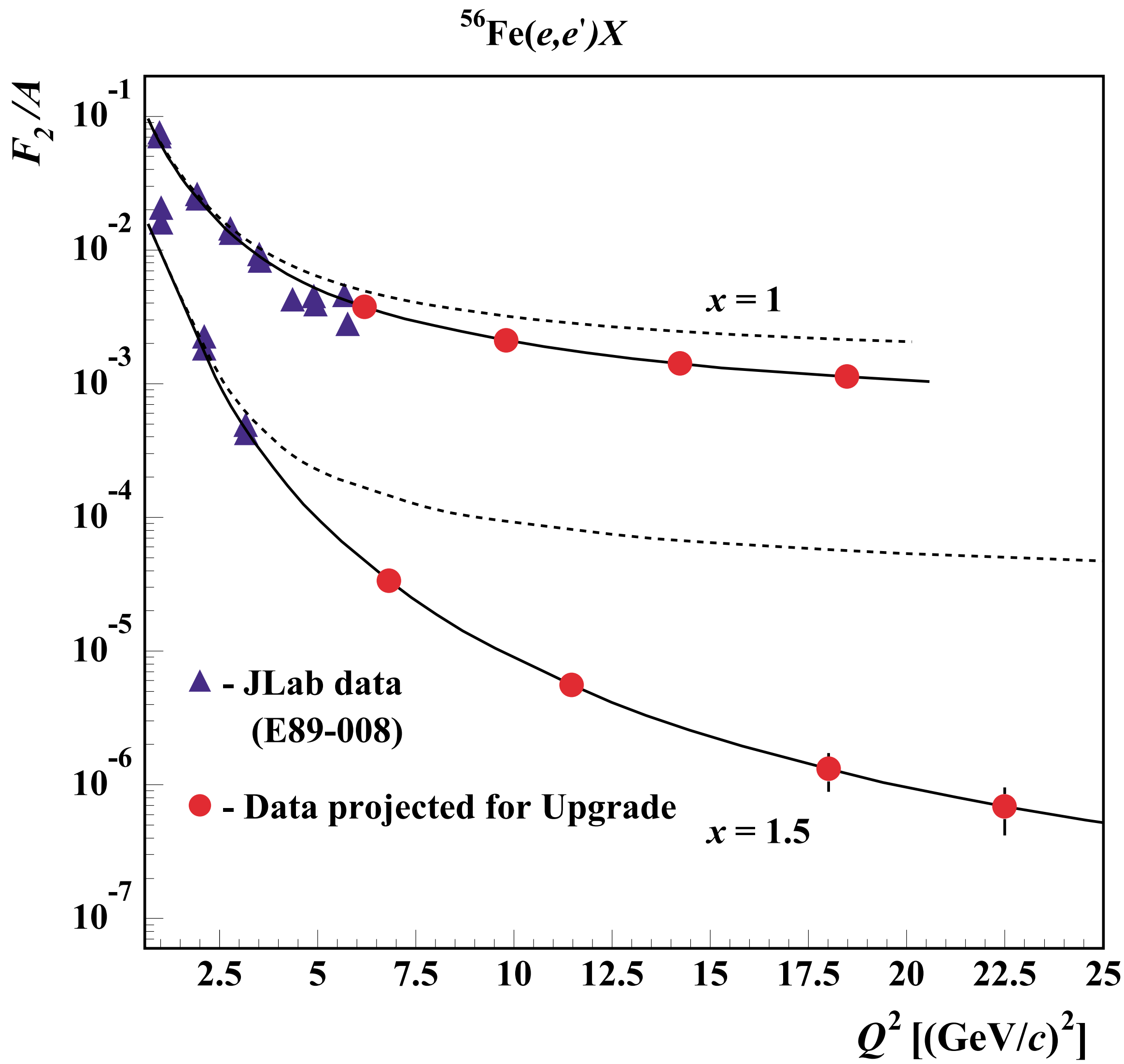

Figure 12: An example of the type of DIS measurement that can be made to study short-range correlations. The experiment is very sensitive to short-range correlations: solid lines are for two-body correlations only, while the dashed line shows the expected full effects of short-range correlations.

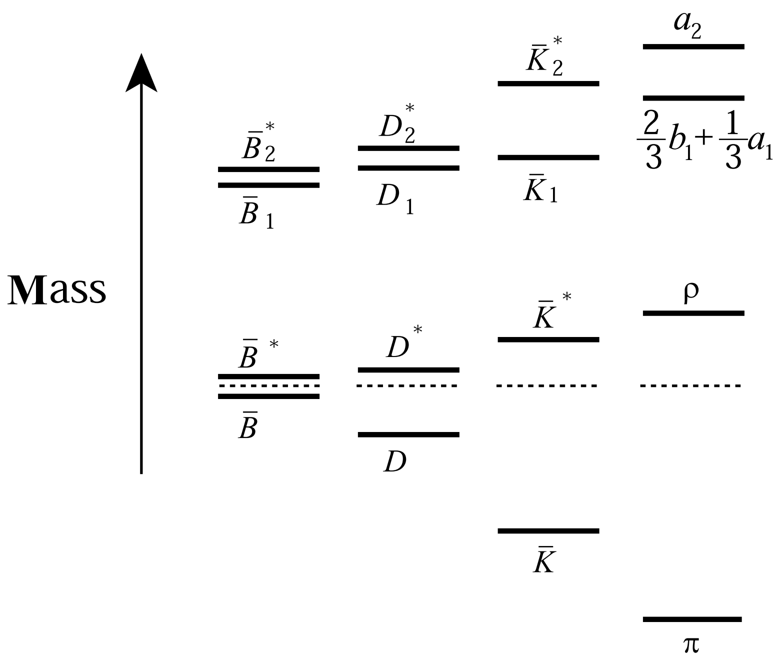

Figure 13: The relative splittings of the $Q\bar{d}$ states are shown to scale from the heaviest to the lightest with the center-of-gravity of the ground state multiplets aligned: $b\bar{d}$, $c\bar{d}$, $s\bar{d}$, and $u\bar{d}$. $\bar{B}^*$ and $\bar{B}$ are the $J^P = 1^-$ and 0^- "ground state" multiplet with light-degrees-of-freedom spin-parity $s_\ell^{\pi_\ell} = \frac{1}{2}^+$, while $\bar{B}_2^*$ and $\bar{B}_1$ with $J^P = 2^+$ and 1^+ are an excited heavy-quark spin multiplet with $s_\ell^{\pi_\ell} = \frac{3}{2}^+$ [Is91].

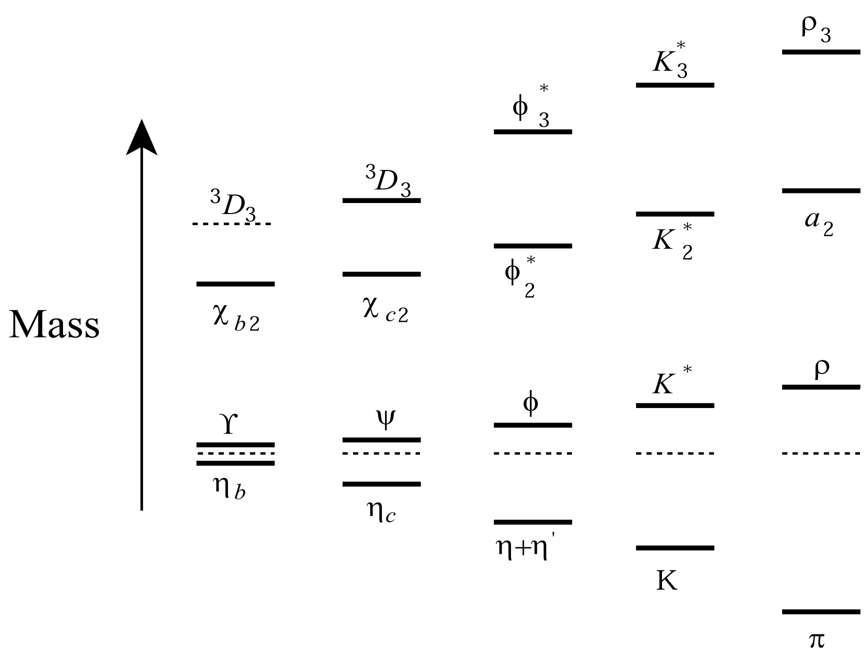

Figure 14: The $Q\bar{Q}$ states from the heaviest to the lightest: $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $s\bar{d}$, and $u\bar{d}$. Shown are the states in each sector with $J^{PC} = 0^-, 1^-, 2^+$, and 3^-; relative splittings are shown to scale with the center-of-gravity of the "ground states" 0^- and 1^- aligned.

• *Primakoff production of light pseudoscalar mesons*

The existence of the pseudoscalar Goldstone bosons due to spontaneous breaking of chiral symmetry and the profound roles played in QCD by the chiral anomalies responsible for their two-photon decays and for the η' mass are very basic phenomena of QCD. As a result, the system of three neutral pseudoscalar mesons, the π^0, η, and η', contains fundamental information about low-energy QCD, including certain critical low-energy parameters, the effects of SU(3)- and isospin-breaking by the u, d, and s quark masses, and the strengths of the two types of chiral anomalies. The 12 GeV Upgrade will in particular allow a new and in many respects unparalleled series of measurements of the radiative decay widths and transition form factors of these special mesons. In particular, the two-photon decay widths will provide the ultimate tests of the predictions of chiral perturbation theory for these chiral-anomaly-driven processes, and the $\gamma \to \gamma^*$ transition form factors at very small Q^2 will provide a model-independent extraction of the electromagnetic interaction radii of these mesons, answering fundamental questions about the relationship of these Goldstone bosons to QCD's other pseudoscalar mesons (recall Figures 13 and 14).

The Primakoff mechanism of electro- and photo-production of neutral mesons in the Coulomb field of a nucleus, described in Section 2.B.3, provides a powerful tool to measure these fundamental quantities. It is explained there how the 12 GeV Upgrade is required to reach much of the relatively high-mass η and η' part of this experimental program, while other properties can be studied as part of the current 6 GeV program.

1.B Upgrade Project Summary

While this White Paper is focused on a description of the science driving the 12 GeV Upgrade, in order to provide a complete overview, Chapter 3 gives a summary of the laboratory's plans for the accelerator, based on a 25 May 1999 internal JLab report, *Interim Point Design for the CEBAF 12 GeV Upgrade*. Chapter 4 outlines our plans for the new detector and detector upgrade projects necessary to carry out the program.

The key features of CEBAF that make the Upgrade so cost-effective are easily defined. By the summer of 1994, CEBAF had installed what was the world's largest superconducting radio-frequency (SRF) accelerator: an interconnected pair of antiparallel linacs, each comprising 20 cryomodules, with each cryomodule in turn containing eight SRF accelerating cavities. On average, these cavities exceed their design specifications by 50% in the two critical performance measures: accelerating gradient and Q. It is the success of this technology that has opened up the possibility of a relatively simple and inexpensive upgrade of CEBAF's top energy. This technological success would not be so readily multiplied if considerable foresight had not also been exercised in laying out the CEBAF tunnel "footprint", which was designed so that the magnetic arcs could accommodate an electron beam of up to 24 GeV. The latent accelerating power of the installed SRF cavities has already brought CEBAF to 6 GeV, 50% above its design energy, and recent successes in SRF development have led to the production of two cryomodules that are more than a factor of 2 more powerful than the original design. With expected further improvements in SRF technology, with the production of a new, compact cryomodule (that contains higher-performing seven-cell cavities but fits in the same space as the original cryomodules based on five-cell cavities), and with the use of space available in the linac tunnels to install ten new cryomodules, 12 GeV can be attained at a modest cost.

In fact, the accelerator portion of the Upgrade is straightforward. The basic elements can be seen in Fig. 15. The Upgrade utilizes the existing tunnel and does not change the basic layout of the accelerator. There are four main changes: additional acceleration in the linacs, stronger magnets for the recirculation, an upgraded cryoplant, and the addition of a tenth recirculation arc. The extra arc permits an additional "half pass" through the accelerator to reach the required 12 GeV beam energy, followed by beam transport to Hall D that will be added to support the meson spectroscopy initiative. Table 1 presents the key parameters of the upgraded accelerator.

Motivated by the science, the 12 GeV Upgrade derives its name from the fact that it will deliver a 12 GeV electron beam to the new end station, Hall D (where it will be used to produce 9 GeV polarized photons for the new gluonic and $s\bar{s}$ spectroscopies) while sending electrons of 2.2, 4.4, 6.6, 8.8, or 11.0 GeV to the existing Halls A, B, and C. Studies of the existing detectors have led to cost-effective plans for their upgrades. The increased physics power of the present halls comes from the qualitative jump in energy and momentum transfer that the Upgrade brings, and from the enhanced instrumentation capabilities planned for the detector complements in each of them. In describing the physics in Halls A, B, and C in what follows, we will often refer to an 11 GeV electron beam, to be precise about the maximum beam energy available in these halls, but we will use the phrase "12 GeV" to describe the overall energy Upgrade.

In Hall A, the Upgrade will add a large angular- and momentum-acceptance, moderate-resolution magnetic spectrometer (to be called the Medium-Acceptance Device, or MAD) together with a high-resolution electromagnetic calorimeter and a ^{3}H target. The spectrometer will provide a tool for high-luminosity, high-x studies of the properties of nucleons with an 11 GeV beam, and also be used for selected investigations of the GPD's, where high luminosity and good resolution

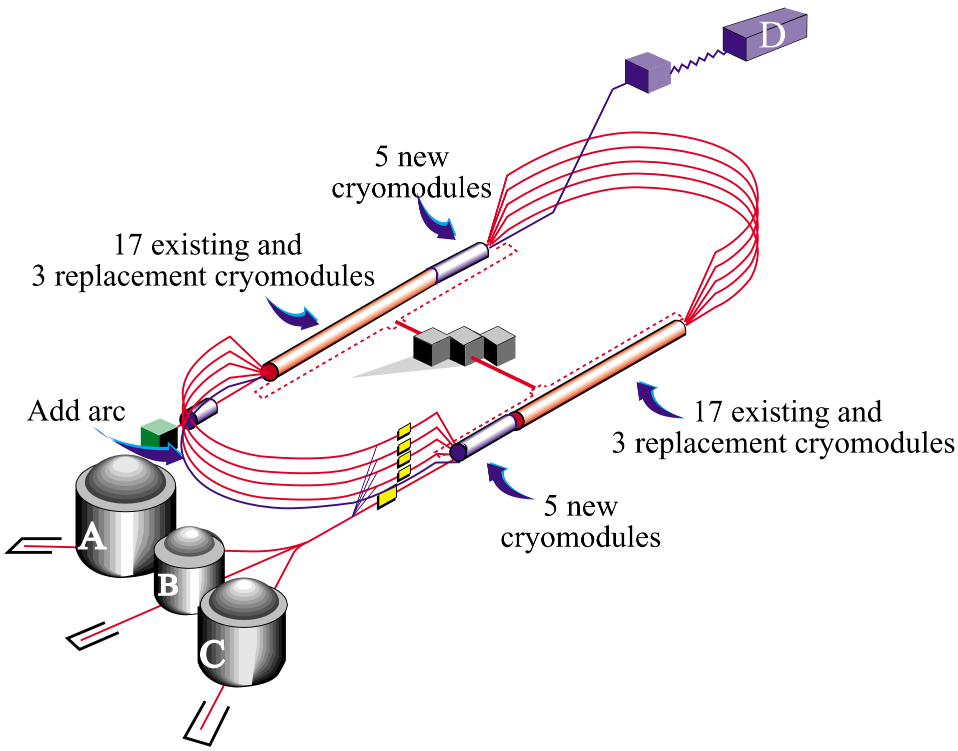

Figure 15: The configuration of the proposed 12 GeV CEBAF Upgrade.

Table 1: Selected key parameters of the CEBAF 12 GeV Upgrade

Parameter	Specification
Number of passes for Hall D	5.5 (add a tenth arc)
Max. energy to Hall D	12.1 GeV (for 9 GeV photons)
Number of passes for Halls A, B, C	5
Max. energy to Halls A, B, C	11.0 GeV
Max. energy gain per pass	2.2 GeV
Range of energy gain per pass	2:1
Duty factor	cw
Max. summed current to Halls A, C* (at full, 5-pass energy)	85 μA
Max. summed current to Halls B, D	5 μA
New cryomodules	10 (5 per linac)
Replacement cryomodules	6 (3 per linac)
Central Helium Liquifier upgrade	10.1 kW (from present 4.8 kW)

*Max. *total* beam power is 1 MW.

are needed. Details are provided in Section 4.B of this White Paper. In Hall B, the CEBAF Large Acceptance Spectrometer (CLAS), which was designed to study multiparticle, exclusive reactions with its combination of large acceptance and moderate momentum resolution, will be upgraded to optimize it for studying exclusive reactions (emphasizing the investigation of the GPD's) at high energy. Most importantly, the maximum luminosity will be upgraded from 10^{34} to 10^{35} cm^{-2} s^{-1}. The present toroidal magnet, time-of-flight counters, Čerenkov detectors, and shower counter will be retained, but the tracking system and other details of the central region of the detector will be changed to match the new physics goals. Details are provided in Section 4.C. In Hall C a new, high-momentum spectrometer (the SHMS, Super-High-Momentum Spectrometer) will be constructed to support high-luminosity experiments detecting reaction products with momenta up to the full 11 GeV beam energy. This feature is essential for studies such as the pion form factor, color transparency, duality, and high-Q^2 N^* form factors. The spectrometer will be usable at very small scattering angles. See Section 4.D for details. Finally, in Hall D, a tagged coherent bremsstrahlung beam and solenoidal detector will be constructed in support of a program of gluonic spectroscopy aimed at testing experimentally our current understanding that quark confinement arises from the formation of QCD flux tubes. This apparatus is described in detail in Section 4.E.