Jefferson Lab Theory Center in the 12 GeV Era: Response to DoE S&T Review 2012 Recommendation

Recommendation from Review May 2012:

Develop a plan for the Theory Center which identifies the theoretical efforts needed to support the 12 GeV science program, articulates the role that the Theory Center will play in addressing those needs, and defines goals for how to implement the plan, within constrained budgets. The plan should include lessons-learned from the 6 GeV program. Submit to DoE by July 2013.

Response:

Jefferson Laboratory
July 2013

1. Overview

The mission of the Theory Center is to produce world-class research across a broad front in nuclear physics, from the study of few nucleon forces to the tomography of hadrons. Importantly, the Theory Center provides the theoretical context and motivation for the on-going and future experimental program at Jefferson Lab, as well as support for the analysis and interpretation of experimental results.
Research in the Theory Center presently encompasses:

(i) studies of exclusive and semi-inclusive meson production processes that underpin the determination of generalized parton and transverse momentum distributions,
(ii) developments in perturbative QCD required for the phenomenological extraction of multi-dimensional imaging of parton distributions from 12 GeV data, and forefront research relating the determination of internal orbital angular momentum to operators that can be computed on the lattice and to experimentally accessible observables,
(iii) the calculation of electromagnetic form factors and the two photon corrections required to extract these from key experiments,
(iv) the extraction of structure functions, both unpolarized and polarized, in the JLab kinematic range and their evolution to the regime of other accelerators including the LHC,
(v) the development of innovative methods in lattice QCD, exploiting forefront technologies like graphical processor units (gpus) with the creation of the appropriate software (which is then made accessible to the wider community), to compute the spectrum and structure of hadrons relevant to the experimental program on baryons and mesons,
(vi) the development of effective theories for QCD, and the identification of the appropriate degrees of freedom required for describing the strong coupling regime of confinement, and for studying the response of light nuclei (up to ^{12}C) to electromagnetic and weak currents,
(vii) photon-Z boson contributions to parity violation experiments determining the weak charge of the nucleon,
(viii) the role of correlations between nucleons in light nuclei and the effect these have on their properties,
(ix) solving the nuclear many body problem by exact quantum Monte Carlo methods, and the development of an *ab initio* description of the nuclear force from lattice QCD,
(x) the exploration of physics *Beyond the Standard Model (BSM)*, for instance the consequences of the existence of additional U(1) bosons,
(xi) the study of the QCD regime of high gluon densities, as well as other aspects of building the physics case for future projects such as an Electron-Ion Collider.

With this research portfolio, the Theory Center contributes to all thirteen current Office of Science milestones for hadronic physics, especially HP13-15, which are specific to the physics of the upgrade. The list above is neither comprehensive nor exclusive. Indeed, research in the Theory Center has the flexibility to adapt over the years ahead to the challenges of discovery, both at JLab and elsewhere. The talent and expertise of the staff will ensure that the group successfully remains at the forefront of nuclear physics research.

The successes of the past program have been previously detailed in Annual Reports to DoE and the documentation for the very recent Comparative Review. The program for the future is set out below in the broad areas of Lattice QCD, Effective Field Theories and Few Body Physics, Parton Interactions and Phenomenology, and precision Standard Model tests. The Theory staff engaged in each project is given in bold for individual projects. Details of new appointees, and aspirations for future positions, are collected in the "Staffing Developments" section later in this document.

2. Lattice QCD

The JLab lattice group, through its leadership of the Hadron Spectrum Collaboration, has completed the first comprehensive calculation and analysis of the spectrum of hadrons, for both mesons and baryons, and revealed their flavor structure. Thus mesons with both isovector and the more complex isoscalar quantum numbers have been computed up to spin 4, revealing a spectrum very like that observed in nature, allbeit for a world with *up* and *down* quarks eight times heavier than those in nature. Nevertheless, this comprehensive treatment is a remarkable achievement, requiring the development of an ingenious formalism to expose the overlap of excited states of increasing complexity with a multiplicity of quark and gluonic operators.

This success has been enabled by the ability of members of the Theory and Scientific Computing groups to marry the appropriate theoretical tools with cutting edge computational technology. Jefferson Lab deploys cost-optimized computing for lattice QCD calculations as a national facility for the U.S. lattice gauge theory community. This continues to benefit us locally at JLab, but importantly has benefits for the whole community. This computing capitalizes on the DoE's investment in leadership-class computing to facilitate the calculations needed to advance our understanding of nuclear and high energy physics. To make best use of these facilities, innovative development of novel software tools (*Chroma*), supported by SciDAC, has allowed the calculation of observables of direct relevance to the TJNAF experimental program. When combined with the power and speed of the dedicated Graphical Processing Unit (GPU), and other many-core, infrastructures, results of unrivaled precision for the hadron spectrum, for instance, have been produced. The ability to apply leading edge technology to basic nuclear physics problems requires close cooperation between theory and scientific computing colleagues, both at JLab and further afield. The local expertise in heterogeneous computing, and the ability to develop codes that will run on whatever is the latest computing architecture, has ensured the group defines the research frontier. This capability is the driver for extending methods applied very successfully to compute the hadron spectrum, to the rapidly developing areas of hadron scattering and hadron structure. This will be facilitated by the fact that key personnel (Joo and Winter), who provide technical support to LQCD through SciDAC, are well placed to exploit breakthroughs by both *nVidia* and *Intel* on accelerated computing technologies. Indeed, *Inte*l is using the *Chroma* code to benchmark the performance of their latest development devices. These integrated software/hardware advances at JLab are leading the march of computing to the exascale. The application of these advances beyond lattice QCD is something we want to pursue in the decade ahead.

An increasing focus of our lattice effort is the computation of hadronic scattering amplitudes, with emphasis on providing the decay couplings of well-established mesons as a benchmark for extension to hybrid states, where the decay couplings will aid the experimental searches of GlueX and CLAS12.

These projects will be pursued in the following individual research plans sketched below:

- Exploration of the baryon and meson spectra for light quark systems at increasingly realistic values of the quark masses is of direct relevance to the excited hadron program with CLAS12 and GlueX. **[Dudek, Edwards, Joo, Richards, Roberts]**
- Meson resonances in coupled-channel systems through the discrete spectrum of states in finite-volume lattice QCD computations will be studied. Most resonances produced in contemporary experiments decay into more than one channel - these will be studied, initially in two-body final states, before moving to higher multiplicities. The need for unitary and analytic parameterizations of partial wave amplitudes in these studies requires considerable synergy with the Amplitude Analysis program of *JPAC* (to be discussed in detail later). The coupling of excited

hadrons to photons is an important area of study since the aim of GlueX is to photo-produce meson resonances. Vector current three-point functions will be computed in order to extract meson transition form-factors, including those for exotic mesons. These will be combined with existing photoproduction phenomenology to estimate production rates for GlueX. **[Dudek, Edwards, Richards, Roberts, Van Orden]**

- Calculations of baryon spectroscopy with charm and bottom quarks will be refined removing much of the systematic uncertainties due to finite lattice spacing effects. This is relevant to experimental studies with BES and LHCb, and the future PANDA@FAIR program. **[Orginos, Walker-Loud]**
- Studies of multi-hadron physics aim to show how atomic nuclei arise within QCD. The interactions of two or more hadrons have already been investigated on the lattice, breaking new ground in the field. New algorithms, which include numerical linear algebra methods, as well as more efficient reformulations of lattice fermion actions, will be developed and improved to enable calculations otherwise inaccessible to current computational resources. **[NPLQCD: Orginos, Walker-Loud]**
- A major thrust of the JLab lattice group will be a concerted effort to study hadron structure: form factors, transition amplitudes, and multi-dimensional distributions, motivated by the need to keep pace with experiments at 12 GeV. This will require a program of isotropic clover lattice generation and the development of the necessary algorithms. The aim is to make a significant step forward in structure calculations at near physical values of the quark masses**. [Edwards, Joo, Orginos, Richards, Walker-Loud]**

3. Effective Field Theory and Few Body Physics Studies

An important on-going series of studies is in Effective Field Theories. These seek to encode the essence of the Standard Model, in specific kinematic regimes. Their advantage is that they can, for instance, more naturally incorporate aspects of the real world of hadron physics, like chiral symmetry breaking relevant to very light quark masses. Moreover, effective field theory methods are calculationally less intensive than those for Lattice QCD, and by their relative simplicity can provide a means of linking the heavy and light quark mass regimes to experiment. They are also the appropriate vehicle for studying the response of nuclei to electroweak currents, and so can extend the on-going program of *ab initio* calculations of the properties and interactions of light nuclei.

Individual research plans in this area are:

- The program of research on the application of chiral effective field theory to nuclei will be expanded in scope with the inclusion, beyond pions and nucleons, of explicit Δ–isobar degrees of freedom, and expanded in range to studies of electroweak processes in A=2-12 nuclei**. [Schiavilla]**
- Quasi-elastic electron and neutrino scattering off light nuclei, including ^{12}C, will be calculated with quantum Monte Carlo methods. Inclusive neutrino scattering has become a hot topic in recent years in view of the anomaly observed in charge-changing quasi-elastic data on ^{12}C, *i.e.* the excess, at relatively low energies, of the measured cross section relative to theoretical calculations. However, these estimations are based on rather crude models of nuclear structure—Fermi gas or local density approximations of the nuclear matter spectral function—as well as simplistic treatments of the reaction mechanism. Consequently, it is timely to use quantum Monte Carlo methods to provide exact calculations of the inclusive electroweak response within a much more realistic treatment of nuclear dynamics. **[Schiavilla]**

- Within covariant spectator theory (CST) the deuteron form factors and the deuteron static moments will be calculated. More long term are extensions of the CST approach from the spectrum of light mesons to the heavy quark sector (where it should work very well) and the baryon spectrum. **[Gross]**
- The impact of the constraints imposed by the $1/N_c$ expansion on the spectrum, and the strong and electromagnetic transitions of excited baryons, will be investigated. The aim is to use the $1/N_c$ expansion to link both experimental and lattice data, and so bring transparency to an understanding of the properties of the baryon sector. The $1/N_c$ framework will also be applied to studies in holographic models of QCD, in particular the problem of scale symmetry breaking and consistency relations based on the trace anomaly equation and through the evaluation of small Wilson loops following the holographic construction**. [Goity]**
- The development of accurate methods of monitoring the flux in neutrino scattering experiments is crucial for precision results. A proposal is to use the reaction $\nu d \rightarrow \mu^- pp$ as such a method. Calculations to benchmark this process by applying techniques used for the accurate determination of deuteron electro-disintegration to this reaction will be performed. **[Schiavilla, Van Orden]**

4. Parton Interactions and Phenomenology

The internal structure and dynamics of hadrons are exposed by experimental studies of their deep structure. This can most usefully be examined within a framework that separates short and long-distance interactions. Such a framework is provable in perturbative QCD for an increasing range of phenomena. These enable the traditional longitudinal momentum parton distributions to be systematically studied within the proton and neutron, and within a range of nuclei, allowing a flavor separation of parton distributions for unpolarized and increasingly for polarized distributions. The expansion of such research to encompass transverse degrees of freedom, whether in impact parameter or momentum space, is a major challenge of the 12 GeV physics program. Much of the general theoretical foundation still requires amplification to link to quantities that can be experimentally measured and distributions that can be phenomenologically determined. This integration of theoretical developments with phenomenology is one that the JLab Theory Center is well placed to exploit. The innovative workshop series on *QCD Evolution* has brought a motivation and synergy with researchers across the globe. The *JLab Physics Analysis Center* will build on these activities, as described later. Individual research plans in this area are:

- A global analysis of parity-violating elastic electron-nucleon scattering data, using new calculations of radiative effects, will be performed to determine the weak mixing angle and constraints on BSM physics. A new framework is being developed using non-forward dispersion relations to obtain a unified description of two-boson (γ-Z, γ-γ) exchange corrections valid at both low and high Q^2 (and at small and large scattering angles). **[Melnitchouk]**
- The CTEQ-JLab (CJ) global QCD analysis of PDFs will in future include all data on transverse and longitudinal structure functions (without assuming the longitudinal/transverse ratio), as well as the effects of heavy quarks, and constraints from LHC data. The relation between target mass corrections in the operator product expansion and collinear factorization formalisms is being investigated. **[Melnitchouk]**

- A new global QCD analysis of spin-dependent Parton Distribution Functions (PDFs) is being performed within the Jefferson Lab Angular Momentum (JAM) Collaboration, aimed at fully utilizing JLab data on polarization asymmetries. The JAM analysis will incorporate data from semi-inclusive deep inelastic scattering (DIS) and hadron-hadron collisions to provide constraints on the polarized sea quark and gluon distributions, in addition to the high-x constraints on valence PDFs from inclusive DIS data. A detailed analysis of nuclear corrections in ^{3}He is currently being completed, and target mass corrections for semi-inclusive DIS will be computed. The technology developed for the JAM project will be used in exploratory studies of global QCD analyses of transversity and transverse momentum dependent distributions (TMDs). **[Melnitchouk]**
- A key focus in the run up to the 12 GeV era is the development of phenomenological tools required to extract 3D distributions of the nucleon from forthcoming experimental data. The emphasis is on building a new generation of models of nucleon Generalized Parton Distributions (GPDs) that take into account their Regge behavior, reflect the nucleon structure in impact parameter space and respect the constraints of positivity. This requires continued theoretical effort on the momentum evolution of both TMDs and GPDs, together with close cooperation with experimental colleagues to ensure that methods are practicable. Lattice structure results the group is anticipating may also constrain the modeling of multi-dimensional distributions. **[Prokudin, Radyushkin, new position A]**
- The space-time evolution of chiral EFT processes in light-front formulation will be studied, in calculations of peripheral orbital angular momentum and light-cone momentum densities in the nucleon. The phenomenology of exclusive and semi-inclusive processes at JLab 12 GeV will be investigated by developing a quantitative QCD-based reaction model for exclusive meson production (in particular for the π, φ and J/ψ) using light-front methods and GPDs. Realistic descriptions of semi-inclusive production and TMDs at low W based on Monte-Carlo simulations and modeling of non-perturbative mechanisms will be set up. **[Weiss]**
- Multiparton correlations will be explored as the "next frontier" in nucleon structure after one-body densities (PDFs, GPDs), using effective approaches to non-perturbative QCD. The experimental consequences and opportunities for JLab 12 GeV, COMPASS, EIC, and high-energy *pp* collisions at LHC will be worked out. The unique capabilities of the EIC@JLab design (light ions, polarization) will allow the exploration of new types of measurements enabling detailed control of final states (target fragmentation, hadron correlations, nuclear spectator tagging). **[Radyushkin, Weiss, new position A]**
- The relation between color dipoles and light-ray operators (between DGLAP and BFKL evolution equations) will be determined. The rapidity evolution of gluon transverse momentum-dependent distributions (TMDs) will be investigated. Both issues are relevant to linking the 12 GeV physics program with that of a future Electron-Ion Collider. **[Balitsky]**

These projects not only impact on the plans for 12 GeV experiments, but on detailing the physics case for a Medium-Energy Electron Ion Collider. This will be worked on together with the wider theory community and our experimental colleagues. **[Weiss, Melnitchouk, Balitsky, Prokudin, Radyushkin, new position A]**

5. Precision Standard Model Tests

JLab physics largely encompasses physics within the Standard Model, QCD and electroweak dynamics. Nevertheless the program will always have a component that seeks to exploit precision knowledge of Standard Model physics as a way experiment may unmask hints of what lies beyond, whether with additional gauge bosons, or other as yet unknown partners in interactions to be discovered. Theoretical studies aimed at exploring the consequences of new physics for precision studies will continue, as now, in close collaboration with our HEP colleagues at the College of William & Mary and other U.S. institutions. State-of-the-art corrections, like those from the γ-Z box for the determination of the proton's weak charge from the Q_{weak} experiment will be critical for many precision studies like those envisaged for Moller and SOLID. Theory expertise and experience will be essential in determining these needs. This will continue to be led by Melnitchouk.

6. JLab Physics Analysis Center

A key component of the support Theory will provide to the 12 GeV experimental program is the *JLab Physics Analysis Center (JPAC)*. The *JPAC* project draws on world theoretical expertise in developing appropriate phenomenological tools and computational frameworks required for extracting the details of quark and gluon dynamics from experimental data of unprecedented precision and scope. As noted in the recent report to NSAC, *Implementing the 2007 Long Range Plan*: "The GlueX experimental program is coupled with both detailed lattice QCD predictions and the strong support of the Jefferson Lab Theory Center in analyzing and interpreting the expected new data. This puts the U.S. in a unique position to explore this important new science made possible by the 12 GeV CEBAF Upgrade."

The mission of *JPAC* over the next decade is to maximize the physics output from the 12 GeV program. To this end, the JLab Physics Analysis Center will provide leadership in:

I. the analysis of high statistics data on the increasing number of inter-related channels and polarization observables required to definitively extract the baryon and meson spectrum up to 2.5 GeV from world data including that taken at JLab at 6 and 12 GeV , with a particular focus on establishing the existence of hadrons for which excitation of gluon fields is essential,

II. the phenomenological extraction of parton distributions as functions of both longitudinal momentum, and transverse spatial or momentum dimensions, using concepts defined in perturbative QCD.

These analyses require continuing engagement and collaboration between experimentalists and theorists both at Jefferson Lab, at U.S. universities and the wider hadron physics community. Jefferson Lab with its position in the experimental community, its experience with EBAC (the Excited Baryon Analysis Center) and the expertise of its staff in both theoretical and phenomenological analyses is acknowledged as best placed within the U.S. to lead this global endeavor, networking with other accelerator laboratories, particularly Beijing Electron Positron Collider (BEPC), GSI-Darmstadt, and university collaborators, to develop and share analysis methodologies.

This project includes:

- the facilitation of pooling of world expertise in scattering and reaction theory, and in parton dynamics with well documented underpinning formalisms,
- the training of a generation of theoretical and experimental graduate students and postdocs to carry out such analyses,
- the promotion of a culture change within both experimental and theoretical communities, whereby they work together with common methodologies and the sharing of data,
- a forum for communicating this expertise with regular workshops/graduate schools and meetings in the U.S., Europe and Asia, focused in the short term on Jefferson Lab, Julich, GSI and Beijing.

This initiative from the theoretical community is essential to the success of the discovery-class program at 12 GeV.

6.1 Working Groups have been set up to study the following immediate issues (the lead participants from JLab and from many other co-operating institutions are listed for each activity):

- **WGB:** Incorporation of the results from the 6 GeV baryon program at CLAS on a range of polarization observables, as their analysis becomes complete, into on-going multi-channel Amplitude Analyses determining the spectrum and detailed channel couplings of N* and Δ* states. [Participants: Bonn/Gatchina team with the CLAS group] Extension to 12 GeV results. [Participants: Doering and GWU team with CLAS12]

- **WGE:** Studying the world's largest sample of η and η' decay events. Their Dalitz plot distribution and representation in terms of amplitudes that satisfy analyticity, unitarity and chiral constraints has begun. Identifying η and η' samples in their hadronic decay modes with precision is essential for the extraction of potentially small partial wave signals in πη and πη' decay modes in photoproduction reactions. [Lead Participants: Amaryan (ODU), **Pennington** (JLab), Guo, **Szczepaniak** (IU/JLab), plus EU MESONet collaboration]

- **WGC:** Studying the effects of the overlap of the baryon and meson production vertices in the 12 GeV environment. Considering methodologies to separate final states into excited meson and excited baryon decays, using 6 GeV data from CLAS, and world knowledge of baryon interactions encoded in the SAID parametrization. [Lead Participants: Schott,Workman (GWU), Mokeev, Salgado (JLab), **Szczepaniak** (IU/JLab)]

- **WGA:** Coding of amplitudes in the generic AMPTOOLs software developed at IU, and its application to CLAS12, GlueX and PANDA@FAIR project, utilizing gpus, Xeon Phis and forthcoming compute architectures.[Lead Participants: Mitchell, Shepherd (IU), Ito, Salgado, Weygand(Jlab), Fritsch (Mainz)]

- **WGD**: Developing a comprehensive Regge analysis of photo and hadro-production data, as a guide to the competing reaction mechanisms underlying events at 12 GeV in both GlueX and CLAS12. [Lead Participants: **Pennington** (JLab), **Szczepaniak** (IU/JLab), Doering (Bonn/GWU), Haberzettl (GWU), Fox, Mathieu (IU)]

- **WGF:** Studying final state interactions and the role of multi-particle unitarity, using Belle, BaBar, BES and LHCb data as testing grounds for the ways to handle this effectively and efficiently, so that methods can then be applied to the statistics expected with GlueX. [Lead Participants: Ablikim (BES), Meadows, Palano (LHCb), **Pennington** (JLab)]

- **WGS:** Studying consistent analytic parametrizations for amplitudes that fulfill essential S-Matrix principles and can be used in a practical way in fitting data on reactions with multi-hadron final states. [Participants: Doering, Hanhart, Kubis (Bonn/Julich), Dai, Danilkin, Guo, **Pennington** (JLab)]
- **WGW:** Investigating partial wave ambiguities. The aim is to provide a methodology for exposing the ambiguities inevitably present in partial wave solutions, and what physics can be used to select amongst a multitude of possible amplitudes. [Participants: TUMunich, Mainz, Bonn-Gatchina, GWU, JLab]
- **WGT:** Extracting Transverse Momentum-Dependent Distributions from experimental data on Semi-Inclusive Deep Inelastic Scattering incorporating developments in perturbative QCD on factorization theorems and their momentum evolution of TMDs. Extension to Generalized Parton Distributions will come later. **[**Lead participants: Anselmino, Boglione (Torino), Bacchetta (Pavia), Ma (Beijing), **Prokudin** (JLab), Vanderhaeghen (Mainz)]

All these groups (apart from WGT) have, or shortly will have, Hall B (CLAS12) and Hall D (GlueX) involvement. Whilst the *JPAC* activities in Amplitude Analyses involve just two JLab Theory staff members (one full-time, the other joint with IU), with postdoc support, there will be considerable overlap with our lattice colleagues, who are computing scattering in a finite box, often using similar methodologies. This is a source of synergy that only an environment like that at JLab can provide.

Group WGT (on TMD phenomenology) is already an active collaboration among theorists worldwide and has engagement with colleagues from Halls A, B and C at JLab. Here too incorporation of planned lattice calculations of distributions of quarks and gluons will provide a more complete three-dimensional tomography of the nucleon than could the experimental program alone.

The working groups listed should all have results by September 2014, when a specific workshop on Amplitude Analysis methods for JLab12 will be held. The working group on TMDs and GPDs will hold a separate workshop in the *QCD Evolution* series. A new set of milestones will be set at these meetings and working group targets revised as appropriate. Three members of the Theory Center are members of the GlueX collaboration (Dudek, Pennington, Szczepaniak), the latter also being a member of CLAS12).

As training and dissemination are essential to the success of this project, a series of schools and workshops are planned. Following an Advanced Study Institute on *Techniques in Amplitude Analyses* that took place May-June 2012 at the College of William & Mary, workshops have been organized by TU Munich in May and July 2013, and a school at Fleckin-Zechlin (near Berlin) organized by the Helmholtz Institut Mainz for September 2013. These will continue to alternate between the U.S. and Europe over the next decade. There is also a need to bring the expertise of the meson and baryon communities much closer together; for instance, combining the new ATHOS series of workshops on Tools and Techniques for Amplitude Analyses with the international PWA series. The holding of ATHOS2014/15 in the eastern U.S. is aimed to facilitate this. A program aimed at training young researchers in multi-dimensional parton distributions and their physics is being planned jointly with the Mainz and Torino groups.

The website for the *JPAC* project is presently being developed and though it will be hosted at JLab, it will be maintained by Ron Workman of the Said Project at GWU. This is an illustration of the integrated and collaborative way in which we plan to operate.

An effective way to perform the partial wave analyses required for spectroscopy is through the use of GPU clusters, sharing developments with lattice QCD. In such ways, the expertise of the Theory Center in exploiting Monte Carlo methods and in the use of emerging computing technologies transcends the realm of nuclear theory. We look to sharing this experience with other researchers more widely in other disciplines across Computational Science linking to regional universities to mutual benefit. The aim is to build capacity to attain critical mass in mastering innovative methodologies within the SURA consortium of universities especially. Initially a number of workshops will be planned to promote such engagement.

7. Lessons Learned From 6 GeV

The Theory Center has played a successful role in the interpretation of results on a whole range of physics from short range nucleon correlations to the spectroscopy of baryons from the 6 GeV program. This has in turn shaped the 12 GeV physics program, defining the physics questions, setting its targets and helping to develop the proposals for the range of experiments that have now been approved. This will continue as 12 GeV running begins. This is a dynamic program where new issues arise and changing questions will be addressed, in response to new experimental data and worldwide theoretical developments.

One significant area in the 6 GeV era identified as requiring a Theory initiative was the study of excited baryons, not on the lattice, but from the analysis of experimental data. In response to this need, the Excited Baryon Analysis Center (EBAC) was setup with additional funding from DoE. The aim of the EBAC Project was to provide a consistent framework for extracting the baryon spectrum from data, largely from CLAS at 6 GeV, but also MAMI@Mainz and ELSA@Bonn. The mission was to determine the spectrum of baryon states up to 2 GeV. To reveal the make-up of these states requires a specific Lagrangian of hadronic interactions, in which the degrees of freedom are defined. The EBAC Project was led by Harry Lee from Argonne over a six-year period, supported by a cohort of three postdocs in any one year. This resulted in a consistent treatment of extensive hadro- and electro-production data on a whole range of final states and the determination of the spectrum and couplings of excited baryons up to 1.8 GeV, summarized in the EBAC May 2013 paper [arXiv:1305.4351]. Given the tens of thousands of data points, a large component from CLAS, this is a major achievement.

However, a drawback of the way EBAC operated was its management at a distance. Harry Lee visited JLab on a monthly basis for a week at a time initially, but in the final two years of the project less frequently. While communication between the project leader and the EBAC postdocs was often exemplary, all communication with the experimentalists about the analysis had to go through the project leader and not through the postdocs. This led to an unfortunate disconnect. Other members of the JLab Theory Center, as well as those of the wider baryon community, at GWU for instance, did not feel at all engaged with the project, and were in fact even skeptical of its approach. All credit should be given to Harry Lee for taking on the challenge of this program. However, calculations and fitting within the specific Sato-Lee Lagrangian have become increasingly cumbersome for energies above 1.6 GeV when several inelastic channels become important. This has meant that their analysis took longer to converge than more flexible Amplitude Analyses like that of the Bonn-Gatchina group, whose results appeared in the PDG Tables already in 2012. However, it is really only within a framework of an underlying Lagrangian that the structure of the excited baryons in terms of effective degrees of freedom can be addressed: this was a major aim of the EBAC Project, as set out by Harry Lee.

The *JPAC* Project aims to determine the spectrum and internal structure of hadrons, both mesons and baryons, in as model-**in**dependent a way as possible. The group will engage world expertise wherever it comes from, will actively and collaboratively engage with the experiments that provide the data. Indeed, key theorists are and will continue to be members of the experimental collaborations, both CLAS12 and GlueX. The analyses by *JPAC* will be an integral part of the analysis of these experimental programs and not separate from them. *JPAC* is an integral part of the Theory Center with synergies with the work of their colleagues, in particular that of the LQCD group. Moreover, *JPAC* will actively collaborate with groups worldwide in this endeavor. As seen from the pattern of Working Groups above, the direction will not be shaped by JLab alone, but informed by expertise at the many other institutions with experience in state-of-the-art Amplitude Analyses and in multi-dimensional parton distributions.

While data from the final running period at 6 GeV with CLAS are being processed, particularly those using polarized beams and polarized targets, an MoU has been agreed with Bonn. Key Theory members of the Bonn-Gatchina team will be integrated into CLAS so that they have access to these data as they become available, and can include these in their baryon analysis. The Bonn and Gatchina members will continue to work with the *JPAC* Project in the future.

8. Staffing Developments

The Theory Center cannot contribute alone to the broad research frontier that underpins the JLab experimental program, but must build capacity across the wider nuclear physics community. To this end, being able to work with other institutions to create new positions, both bridge and joint, continues to be critical to maintaining the vibrancy of the U.S. nuclear theory program as a whole. To support and promote these efforts, the Theory Center must maintain its portfolio of research across the range of nuclear and hadron physics. Indeed, with recent appointments and those foreseen for the near future we aim to strengthen this further in the following ways:

(1) Leader of the JPAC Project is Adam Szczepaniak, who will hold a joint appointment with Indiana University from September 2013.
(2) Joint staff member with the College of William & Mary, replacing Will Detmold, who has moved to MIT. Andre Walker-Loud appointed from August 2013.
(3) Bridge appointment with GWU to support their work in hadron physics. Michael Doering appointed from January 2014.
(4) Future bridge appointment with the College of William & Mary in advance of the retirement of Carl Carlson to link his replacement to the on-going JLab physics program.
(5) Future bridge appointment in hadron physics at Indiana University.
(6) Future joint appointment in hadron physics at a neighboring university on the retirement of Franz Gross from his 0.5 FTE position at JLab.
(7) Continue support for computational scientists to develop algorithms for heterogeneous architectures that in turn support innovative developments in lattice QCD (dependent on future funding, particularly SciDAC).

9. Summary

This document sets out a clear strategy for the Theory effort at JLab in the 12 GeV era to:

(i) support and enhance the world-leading JLab lattice effort, recognizing that plans over the next few years to study hadron dynamics on the lattice has considerable overlap in methodologies with *JPAC*,

(ii) strengthen collaborations between the lattice and the few body nuclear structure communities and the wide range of phenomenology efforts,

(iii) take advantage of opportunities offered by high performance computing and lead the application of this advance to the exascale not only for the research of the JLab Theory Center, but the wider community too,

(iv) continue building the international collaboration required to extract definitive results on the physics of the hadron spectrum and structure from JLab data with the 12 GeV upgrade, working in partnership with the experimental collaborations involved,

(v) maximize the physics output from the 12 GeV program, while playing a leading role in developing and promoting the physics case for an Electron Ion Collider and in campaigning for frontline computational nuclear physics for the next NSAC Long Range Plan.