Proposal for a Germany–U.S. Nuclear Theory Exchange Program for QCD Studies of Hadrons & Nuclei “GAUSTEQ”

Proposed Project Period: January 2011 – December 2013.

May, 2010

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Abstract

We propose a Germany–U.S. Nuclear Theory exchange program for QCD Studies of Hadrons and Nuclei (“GAUSTEQ”) focussed on the current and future physics programs at Jefferson Lab in the U.S. and GSI-FAIR in Germany. The purpose of the GAUSTEQ program will be to facilitate collaboration between U.S. and German theorists in support of the experimental efforts at both facilities, particularly in areas such as meson and baryon spectroscopy, the quark and gluon structure of hadrons and nuclei, and the properties of hadrons in the nuclear medium.

1 Introduction

We propose a Germany–U.S. Nuclear Theory exchange program "GAUSTEQ" (**G**ermany **A**nd **US** **T**heory **E**xchange in **Q**CD) which will focus research efforts on *QCD Studies of Hadrons and Nuclei*, centered around the current and future research programs of the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Virginia, and the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany.

With the commissioning of the 12 GeV Upgrade of the Continuous Electron Beam Accelerator Facility at Jefferson Lab, and the new Facility for Antiproton and Ion Research (FAIR) currently under construction near GSI, a tremendous potential exists to coordinate experimental and theoretical studies in a wide range of areas, such as meson and baryon spectroscopy, the quark and gluon structure of hadrons and nuclei, and the properties of hadrons in the nuclear medium, to name just a few.

In connection with the recommendations by the Nuclear Science Advisory Committee (NSAC) in its most recent Long Range Plan [1], the GAUSTEQ program will help realize the DOE Office of Science "Performance Measures for Hadronic Physics", namely:

- *By 2015, make precision measurements of fundamental properties of the proton, neutron and simple nuclei for comparison with theoretical calculations to provide a quantitative understanding of their quark substructure* [2].

An important step towards this realization was highlighted in the top recommendation of the Long Range Plan:

- *We recommend the completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement* [1].

As Jefferson Lab and GSI-FAIR share many of the same physics goals, the research performed through the GAUSTEQ program will directly impact each of the areas of physics listed in the NSAC recommendations.

The GAUSTEQ program will help to fully utilize the capabilities of the U.S. and German hadron and nuclear physics communities in support of the current and future experimental programs at Jefferson Lab and GSI-FAIR. The Jefferson Lab user community is the largest nuclear physics community in the world, with some 1200 nuclear physics users, while GSI has around 1300 users, of which 75% are in nuclear physics. Together they comprise over 2000 nuclear experimentalists and theorists who utilize these facilities. GSI has also recently founded the Helmholtz Institute Mainz (HIM) as a new branch of GSI on the campus of Mainz University, with strong groups in experimental and theoretical hadron physics. Combined, this represents a unique opportunity for harnessing the extensive expertise available in these communities to advance the study of hadrons and nuclei. A preliminary list of participants who are ready to utilize the GAUSTEQ program is included in Table 1 below.

We anticipate operation of the GAUSTEQ program along similar lines to the successful JUSTIPEN exchange program between the U.S. and Japan [3]. In particular, GSI (with its Darmstadt and Mainz braches) will serve as the German "hub" for U.S. physicists (faculty, postdocs and students) visiting for short- and long-term visits, and Jefferson Lab will serve as the corresponding U.S. "hub". U.S. participants will also be able to visit collaborators at other institutions in Germany, provided a portion of the time is spent at the Darmstadt or Mainz braches of GSI (see Sec. 3 below). The program will be officially managed through Old Dominion University in Norfolk, Virginia, where one of the PIs (Dudek) is a joint faculty member. Old Dominion is in close proximity to Jefferson Lab, and has a significant presence at JLab in both nuclear theory and experiment. Support for German physicists visiting the U.S. would be provided through a reciprocal program funded by the German agencies.

In the following we outline the scope and operations of the proposed program, starting with an initial list of participating physicists and institutions, as well as program guidelines and a proposed budget. We follow this with a more detailed discussion of the scientific opportunities presented by the U.S.-German collaboration and the theoretical tools which will be developed in the process of attaining the GAUSTEQ program's goals.

2 Collaborators

Currently there are 26 U.S. collaborators from 17 institutions who have made an explicit commitment to the GAUSTEQ program, through either established or planned projects with researchers at GSI and 15 other institutions in Germany. Table 1 lists the U.S. participants together with their German contacts.

The U.S. institutions with which the presently identified participants are affiliated are:

- Argonne National Laboratory
- College of William & Mary
- Florida State University
- Hampton University
- Indiana University
- Iowa State University
- Jefferson Lab
- Massachusetts Institute of Technology
- New Mexico State University
- North Carolina State University
- Ohio University
- Old Dominion University
- Pennsylvania State University
- Stanford Linear Accelerator Center
- Temple University
- University of Pittsburgh
- University of Washington

The corresponding institutions of the German collaborators are:

- DESY
- Forschungszentrum Jülich
- Gesellschaft für Schwerionenforschung (GSI)
- Helmholtz Institut Mainz (branch of GSI)
- Technical University of Darmstadt
- Technical University of Dortmund
- Technical University of Munich
- University of Bochum
- University of Bonn

- University of Heidelberg
- University of Mainz
- University of Munich
- University of Regensburg
- University of Rostock
- University of Tübingen
- University of Wuppertal

Note that this list is *not exclusive*. The program will be open to theorists from any U.S. institution to apply for funding to collaborate with German counterparts on physics that benefits the Jefferson Lab and GSI-FAIR experimental physics programs, according to the guidelines spelled out in Sec. 3.

3 Guidelines

Applications for travel through the GAUSTEQ program will be judged on the basis of the following guidelines.

- Applicants should explain in their proposals, which should be 1–2 pages long, the benefits of their proposed travel to the experimental research programs at Jefferson Lab or GSI-FAIR.
- The typical length of supported stay is expected to be about 2 weeks. However, applications for travel for longer periods will also be considered.
- It is expected that applicants will spend approximately 50% of their time at the Darmstadt or Mainz (HIM) branches of GSI during their visits to Germany.
- At the completion of travel supported by the GAUSTEQ program, participants will be required to submit to the Coordinating Committee a brief (1–2 page) report summarizing the accomplishments during the travel.
- The program is *not* intended to support conference attendance, and therefore cannot pay for conference registration fees or support during conferences attended while on travel through the GAUSTEQ program.
- Applications can be made at any time by contacting one of the investigators of the GAUSTEQ proposal.

The applications will be reviewed by the Coordinating Committee for compliance with these guidelines.

4 Coordinating Committee

The PIs will appoint a Coordinating Committee (CC) consisting of representatives from the U.S. and Germany who will convene on a regular basis to evaluate and process applications in a timely manner. The CC will also review the success of the program on an annual basis and advise the PIs on priority areas of research which need the greatest focus. The following have agreed that they would serve on the CC:

- M. Burkardt (New Mexico State U.)
- W. Melnitchouk (Jefferson Lab; PI representative on the CC)
- M. R. Pennington (Jefferson Lab)
- A. Szczepaniak (Indiana U.)
- J. Vary (Iowa State U.).

The German members of the CC would be:

- P. Kroll (U. Wuppertal)
- F. Mass (Helmholtz Institut Mainz)
- K. Peters (GSI)
- A. Schäfer (U. Regensburg)
- J. Wambach (GSI).

5 Proposed Budget

The costs of travel to GSI and local expenses in the Darmstadt and Mainz areas in Germany are detailed here. The $ amounts are based on an exchange rate of 1 EUR ≈ $1.36, which was current at the time of submission of the application.

- Round-trip airline tickets from the U.S. to Frankfurt, Germany, and transportation between Frankfurt and Darmstadt or Mainz: $1,400 (assuming mostly summer travel).
- Accommodation at the GSI guest house in Darmstadt (subsidised by GSI): approximately $50/night. Under exceptional circumstances, if accommodation at the GSI guest house is not available, the traveler may apply for reimbursement at a higher rate. The HIM will also subsidize accommodation in Mainz which exceeds $50/night.
- Per diem in the Darmstadt and Mainz areas: $75/day.

Allowance is made for approximately 10 visits from the U.S. per year (by faculty, postdocs, as well as students) of 14 days duration, and 2 visits of 1 month (30 days) duration, which amounts to $41,800 per year. The relative break up will be subject to community demand, and the allocations will be flexible enough so as to respond to the demand.

The proposal is being submitted through Old Dominion University (ODU), at which one of the co-PIs, J. Dudek, is a joint faculty. The standard overhead at ODU at the off-campus rate is 26%, which will cover all administrative support associated with this program. In addition, Jefferson Lab will provide facilities to set up and maintain the web site for the GAUSTEQ program.

The total requested amount (including overhead) is $52,668 in year 1. The amounts for years 2 ($54,248) and 3 ($55,875) include 3% increments for inflation. The total 3-year request is therefore $162,791 (or $163,000 to the nearest $1k).

6 Scientific Opportunities

There are several broad areas of hadron and nuclear physics which have been identified as being highly complementarity between the Jefferson Lab and GSI-FAIR physics programs. These include meson and baryon spectroscopy, the quark and gluon structure of hadrons, and the properties of hadrons in the nuclear medium. Here we outline several examples of research topics whose investigation will be facilitated through the GAUSTEQ program.

6.A Spectroscopy

6.A.1 *Mesons*

One of the main breakthrough programs at both Jefferson Lab and GSI-FAIR will be the systematic investigation of dynamical gluonic degrees of freedom, responsible for quark confinement in QCD, through the study of the spectrum of mesons with exotic J^{PC} quantum numbers (namely, ones which cannot be formed from a quark and antiquark alone). The GlueX collaboration in Hall D at Jefferson Lab plans a systematic exploration of the exotic light-meson spectrum through photoproduction [4], while the PANDA collaboration at FAIR will study charm exotics mesons in proton–antiproton collisions [5]. These complementary programs offer a unique opportunity for synergy between the two communities.

The spectrum of mesons directly reflects the nonperturbative degrees of freedom of QCD at low energies; the absence to date of firm candidate states having $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \cdots$, nor having isospin or strangeness greater than one, strongly suggests the constituent quark–constituent antiquark bound state picture we are familiar with. However, it seems unlikely that the strongly-coupled theory of QCD does not have a broader spectrum in which the gluonic field plays an explicit role.

The most striking signature of dynamical gluonic degrees of freedom is "hybrid" states in which the gluonic field contributes J^{PC} quantum numbers to couple with those of constituent quarks, producing states that have J^{PC} quantum numbers not available to a quark–antiquark pair. On the other hand, it is also plausible that systems of higher isospin or strangeness could arise from bound molecules of mesons or from short-distance bound states of constituent quarks (multiquarks), in this case as well as exotic flavor we have another possibility for exotic J^{PC}.

In the near future we will have copious and unprecedented data from experiments designed to produce exotic states in both the light and heavy quark regions. GlueX in Hall D of the 12 GeV upgraded Jefferson Lab will produce light meson systems through photoproduction, there being support for the idea that this method preferentially produces exotic hybrids. PANDA at GSI-FAIR will use $p\bar{p}$ annihilation at high energy to produce a glue-rich environment in which charmonium states of all quantum numbers will be produced along with highly excited light meson systems and possibly glueballs.

Results coming out of these experiments will move the theoretical field into a data-driven phase. The positive effects of this are being seen already in the charmonium sector where rapid theoretical progress is now being made, motivated by the observation of new and mysterious states by CLEO and the B-factories.

There are many areas of commonality between the theory describing PANDA physics and GlueX physics. Constituent quark models place much emphasis on the spectral similarities between charmonium and the light meson spectrum. In lattice QCD, the techniques used to extract a light meson spectrum are rather similar to those used in the heavy-quark sector and indeed the spectrum of charmonium is often used as a tool to validate these calculations ahead of computation of less certain light-quark quantities.

6.A.2 *Baryons*

The investigation of the excited baryons (N^*) has long been an important component in developing a fundamental understanding of strong interactions. With the recent data from JLab, MIT-Bates, Mainz, and Bonn, the theoretical effort in this direction has been intensified to analyze these new data as well as the very extensive πN reaction data. The objective is to map out the quark-gluon substructure of the N^* states. The most focused theoretical analysis is being carried out at the Excited Baryon Analysis Center (EBAC) of JLab within the dynamical coupled-channels reaction theory [6]. The channels included are two-particle channels ($\pi N, \gamma^* N, \eta N, K\Lambda, K\Sigma, \omega N$) and also the crucial three particle $\pi\pi N$ channel which has resonant $\pi\Delta, \rho N, \sigma N$ resonant components. The preliminary results of the baryon spectrum at invariant mass below 2.5 GeV and the associated mesonic and electromagnetic N-N^* transition form factors have been obtained [7, 8, 9].

With the 12 GeV upgrade, the data for investigating heavy baryons ($\Lambda_c, \Xi_C, \Omega_c$) will be available. For example, it is possible to access Λ_c baryons through the reaction $\vec{\gamma}p \to \bar{D}^0\Lambda_c^+$ at Hall D. This process can be analyed within the same theoretical framework developed at EBAC because it is closely related to $\vec{\gamma}p \to K^+\Lambda$ due to the similarity of their constituent quark substructure. On the other hand, a group led by M. Lutz at GSI has proposed a molecular state model of charmed baryons and their production mechanism is $\vec{\gamma}N \to D(\bar{D}N), D(\bar{D}\Lambda), D(\bar{D}\Sigma)$. Their prediction will require very different theoretical analysis of the data. Similar differences need to be investigated for analyzing possible charmed baryon data from GSI. The proposed exchange program will allow the two groups to develop collaborative effort in using the new experimental opportunities at JLab and GSI to explore the new territory of baryon spectroscopy.

6.B Quark and Gluon Structure of Hadrons and Nuclei

Scattering processes with momentum transfers of several GeV probe hadron structure at a resolution scale where it can be described in terms of the quark and gluon degrees of freedom of QCD. The key to understanding such reactions is the method of factorization, by which the cross sections are separated into a short–distance quark/gluon subprocess, calculable in perturbative QCD, and the distributions of the partons in the initial and final hadrons, governed by long–distance, nonperturbative interactions. The parton distributions are universal characteristics of the hadrons and can be probed in deep–inelastic ep scattering (DIS) as well in $pp/\bar{p}p$ scattering with hard processes. This remarkable property has long been used in inclusive DIS, where Drell–Yan pair production in $pp/\bar{p}p$ scattering provides useful information about the sea quark distributions, for example, complementing the basic information about quark distributions available from ep scattering.

Recently, the concept of factorization has been extended to much larger classes of hard scattering processes, involving identified hadrons in the final state, which probe the quark and gluon structure of hadrons in much more detail than inclusive DIS. Exclusive processes such as $eN \to e'N'\gamma$ or $e'N'\pi(\rho, K, \ldots)$ are governed by the generalized parton distributions (GPDs), which combine aspects of parton densities and elastic form factors and convey a 3–dimensional image of the quark– and gluon structure of the nucleon [10]. Semi–inclusive processes such as $eN \to e'\pi X, e'KX$ *etc.* access the transverse spin–dependent parton densities as well as transverse momentum–dependent distributions (TMDs), which describe subtle features such as spin–orbit interactions of quarks in QCD [11].

The measurement of such processes in *ep* scattering is one of the key objectives of the 12 GeV Upgrade of Jefferson Lab [4]. The possibility to study corresponding high–momentum transfer reactions in $\bar{p}p$ annihilation at PANDA offers many fascinating perspectives, significantly enhancing our understanding of the reaction mechanism and complementing the information on GPDs and TMDs available in *ep* scattering. Preparing the conceptual and technical framework for a joint analysis of the forthcoming Jefferson Lab 12 GeV and PANDA data is one of the main objectives of the proposed theory cooperation.

More specifically, this will include investigations into spacelike (at JLab) and timelike (at FAIR) nucleon form factors; spacelike (JLab) and timelike (FAIR) GPDs in two–photon processes [12, 13], including transversely polarized protons either at a polarized target in PANDA or at GSI PAX [14, 15]; the physics program of a future Electron Nucleon Collider (ENC) using the PANDA apparatus at GSI-FAIR; quark transversity distributions in polarized Drell–Yan pair production (GSI PAX) [14] and semi–inclusive DIS (JLab at 12 GeV) [16]; and TMDs in both unpolarized and polarized $\bar{p}p$ and *ep* scattering [11] to measure quark intrinsic transverse momentum and quark spin–orbit interactions.

6.C Hadrons in the Nuclear Medium

Experiments at Jefferson Lab and GSI-FAIR offer tremendous opportunities to explore the quark and gluon structure of nuclei. The 6 GeV program at Jefferson Lab has already provided new data on the classical nuclear EMC effect (difference between nuclear and nucleon structure functions), but the 12 GeV Upgrade offers an ideal tool to test details of the EMC effect, including its spin dependence, and hence test the various models which have been proposed [17]. Again at 6 GeV, subtle measurements of spin dependent quasi-elastic scattering on ^{4}He appear to provide evidence for changes in the electric and magnetic form factors of the bound proton [18]. A new systematic study of the Coulomb sum rule should also offer important constraints.

In the future, both facilities will have important programs looking at the properties of mesons in-medium, with the results of importance when one models heavy-ion collisions leading to nuclear matter at densities much higher than that of nuclear matter. For example, experiments at FAIR will measure cross sections of charmed mesons interacting with light hadrons in free space and with an atomic nucleus, to study possible changes in charmed meson properties such as masses and sizes [19, 20]. Complementary experiments at the 12 GeV JLab Upgrade will scatter high-energy photons from nuclei to produce charmed hadrons that will interact with the nuclear medium. Both sets of experiments will provide important insight into chiral symmetry restoration in a nuclear medium, and provide valuable constraints on models of confinement and chiral symmetry breaking [21].

7 Theoretical Tools

With the enormous interest in exotic mesons, the nature of confinement, generalized parton distributions, transversity, the origin of the spin of the nucleon and the modification of hadron properties in-medium, to mention just a few of the subjects which will be addressed at JLab and GSI-FAIR, a concerted theoretical effort will be needed to meet the challenge of interpreting the experimental data. As no single theoretical approach is likely to be sufficient for the task, an approach based on a variety of theoretical tools will be required, including first principles methods based on lattice QCD, as well as effective field theory and more phenomenological approaches using the Dyson-Schwinger equations and phenomenological Lagrangians. Complementing these endeavors will be a concerted effort by the light-front community to directly tackle strongly interacting systems using light-front techniques.

7.A Lattice QCD

Recent advances in lattice field theory, developments in computer technology and investment in computer resources for fundamental QCD research have now made lattice QCD a powerful quantitative tool that provides an unprecedented opportunity to understand the phenomena arising from QCD from first principles and to make precision calculations of the predictions of QCD. The theme of future calculations will be on capitalizing on these advances to enable predictions at quark masses approaching their physical values.

A detailed knowledge of the meson and baryon spectra from first principles will distill the key degrees of freedom needed to describe the bound states of the theory. The study of the spectrum of resonances requires that the energy levels of the theory be resolved with high precision. This can be accomplished through the use of an anisotropic lattice, with temporal lattice spacing smaller than that in the spatial direction, with subsequent determination of the energies using the variational method. An variational basis has been developed for baryons [22, 23], and applied to the calculation of the low-lying baryon spectrum in the quenched approximation to QCD [23].

In addition to the spectrum of particles constructed from the light quarks, lattice QCD can study particles containing the heavy quarks, and in particular that of charmonium. The low-lying charmonium spectrum in the quenched approximation has been computed, with in many cases the continuum quantum numbers unambiguously determined [24]. Thus lattice QCD calculations are a vital complement to both the Jefferson Lab and GSI-FAIR spectroscopy studies.

Lattice QCD can also compute the properties of resonances, and in particular their electromagnetic transitions. The $N - \Delta$ transition form factors have been computed [25, 26], and the first calculation of the transition between the nucleon and its radial excitation recently performed [27]. Radiative transitions in charmonium have been investigated [28], spurring additional experimental searches by CLEO-c [29], illustrated in Figure 1.

The Lattice Hadron Physics Collaboration, whose nucleus is at Jefferson Lab, has made important inroads recently into computing fundamental properties of hadrons, such as the axial vector charge [30], together with the lowest moments of the generalized parton distributions [31]. These latter calculations enable the total angular momentum of the quarks in a nucleon to be determined, complementing the experimental studies of DVCS, as shown in Figure 2. Other ground-breaking calculations include the first studies of the TMD distribution functions [32], and of the gluon content in the pion [33].

The future emphasis will be on calculations using a fully consistent Domain Wall Fermion formulation for both the sea and valence quarks. The first steps are now being taken, using both dedicated resources, and leadership-class machines. A further challenge is the calculation of the flavor-singlet sea-quark and gluon contributions to hadron structure, both of which are the subjects of intense effort. Lattice calculations are therefore addressing questions that go to the heart of the hadron-structure programs of both GSI and JLab.

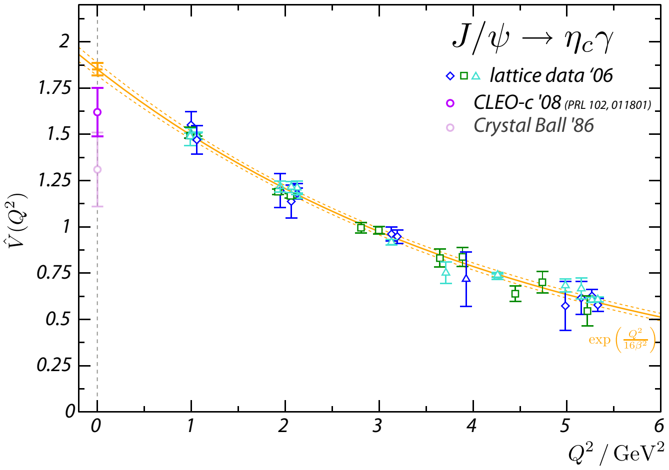

Figure 1: *The figure shows lattice data for the form factors $J/\psi \to \eta_c\gamma^*$ together with a fit to the lattice data; also shown are values for the photocouplings obtained from the experimental partial widths.*

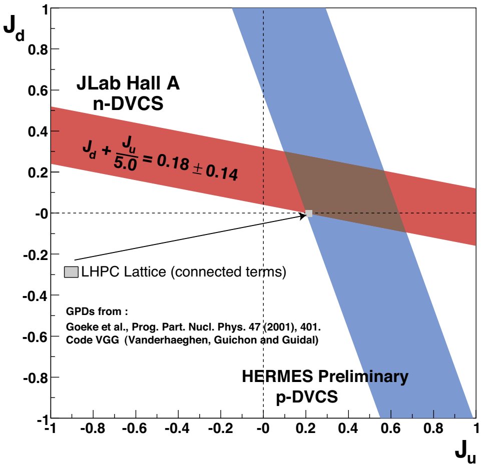

Figure 2: *The figure shows the experimental bounds placed on the total angular momentum carried by the quark within a nucleon, together with the lattice determination.*

Furthermore, an exciting new avenue for lattice studies is how the nuclear force arises from QCD [34]. The high-precision calculation of the $I = 2$ $\pi\pi$ scattering length has been made, showing good agreement with the experimental values [35], and the first evidence for a three-body force unambiguously demonstrated [36]. The formalism for extracting the NN scattering length from lattice QCD has been constructed [37], but the numerical challenges are far more daunting than those for mesons. Nevertheless, exploratory calculations of the nucleon-nucleon scattering length have been performed demonstrating the viability of the method [38], and intense human and computational effort is being devoted to enabling lattice computations to confront physics at the physical quark masses.

7.B Effective Field Theory

As yet, none of these lattice calculations can be performed at the physical masses of the up and down quarks. The computational resources required for all of them increase dramatically as these quark masses are lowered, and so it will be some time before the lattice alone can make the connection between the QCD action and quantities measured in the laboratory. On the other hand, the light-quark-mass dependence of these observables can be rigorously computed in chiral perturbation theory (χPT) [39, 40, 41, 42, 43, 44, 45, 46], providing model-independent constraints on the extrapolations of lattice data to physical quark masses.

Furthermore, chiral perturbation theory does not just predict the dependence of hadronic observables on light-quark masses—it also predicts their behavior as functions of kinematical parameters. For example, χPT predictions for the behavior of some moments of proton and neutron structure functions [47] (*cf.* Ref. [48]) have recently been confirmed using data from the CLAS EG1b experiment [49]. The calculations of Ref. [47] do not, however, treat the $\Delta(1232)$ as a dynamical degree of freedom, and future work will seek to add decuplet baryons to the χPT particle content [41, 50, 51].

7.C Dyson-Schwinger Equations

In an international effort, QCD's Dyson-Schwinger equations (DSEs) are being employed to study and understand a variety of phenomena relevant to the programs proposed at GSI-FAIR and the upgraded Jefferson Lab, including light-quark confinement and dynamical chiral symmetry breaking; nucleon structure and interactions; and parton distribution functions. A strong common interest is shared by members of the Theory Group at Argonne and the Institute for Nuclear Physics at Technical University of Darmstadt. Indeed, these groups are already affiliated loosely through the German Helmholtz Foundation's *Virtual Institute* on *Dense Hadronic Matter and QCD Phase Transitions.*

The existence of a nonperturbative and symmetry preserving truncation scheme has enabled use of QCD's Dyson-Schwinger equations to provide an explanation of dynamical chiral symmetry breaking (see Fig. 3). Crucial to connecting this with light-quark confinement is the development of a detailed understanding of the infrared evolution of the quark-antiquark scattering kernel, $K_{q\bar{q}}$. We propose to employ an efficacious one-parameter model for the infrared behavior of $K_{q\bar{q}}$ [54] in DSE calculations of the spectrum and interactions of pseudoscalar and axial-vector mesons, which are sensitive to the long-range part of the interaction between light-quarks. Comparison with extant data will inform improvements of the *Ansatz*, as will continuing DSE and lattice QCD research on the pointwise behavior of the dressed-quark-gluon vertex. A well constrained form of $K_{q\bar{q}}$ will then enable reliable predictions for the properties

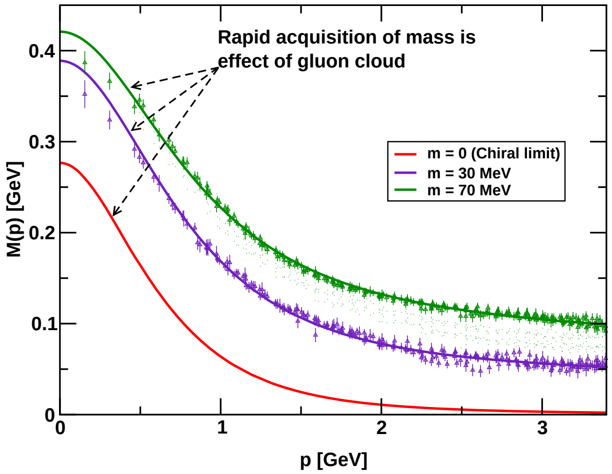

Figure 3: *Dressed-quark mass function, $M(p)$: solid curves – DSE results [52], "data" – numerical simulations of unquenched lattice-QCD [53]. In this figure one observes the current-quark of perturbative QCD evolving into a constituent-quark as its momentum becomes smaller. The constituent-quark mass arises from a cloud of low-momentum gluons attaching themselves to the current-quark. This is dynamical chiral symmetry breaking: an essentially nonperturbative effect that generates a quark mass* from nothing*; namely, it occurs even in the chiral limit.*

of all mesons in the $1-2$ GeV range, including hybrids and exotics. For baryons, we propose to employ the form of $K_{q\bar{q}}$ made available from meson studies in *ab initio* studies of nucleon properties, including form factors, via the Faddeev equation. This is a significant step toward a unified, symmetry-preserving description of mesons and baryons that is systematically tied to QCD.

Finally, we propose to employ this framework, with the well constrained form of $K_{q\bar{q}}$ already described, to compute the valence quark distributions in the pion and kaon. These predictions will complete a consistent description of the mesons' valence distributions and electromagnetic form factors at leading order in the symmetry-preserving DSE truncation. The methods will be extended to enable the calculation of nucleon valence-quark distributions within the Faddeev equation framework, and subsequently the computation of meson and nucleon GPDs.

7.D Light-Front Dynamics

The light–front (LF) formulation of relativistic dynamics is an essential tool for describing hadronic and nuclear structure probed in reactions at high energies and/or high momentum transfers. It also serves as the basis of an *ab initio* Hamiltonian approach to quantum field theories such as QCD, which is in principle capable of predicting the masses and wave functions of bound states, and lends itself to large–scale numerical treatment [55]. Methods based on LF dynamics have made significant progress in recent years, and have shown great promise in applications to several challenging problems of hadron structure in QCD.

In the framework of the GAUSTEQ program we plan a vigorous effort to develop these methods further and apply them to a broad range of problems, including the phenomenology of hadronic reactions studied at JLab and GSI, and first–principles calculations of properties of strongly interacting many–body systems and QCD. Particular emphasis will be put on promoting cooperation between LF theorists and researchers working in related fields (QCD factorization, lattice, effective field theory), to gain new perspectives and jointly apply the theoretical and calculational tools.

Methods of LF quantization are uniquely suited for the description of meson and baryon structure as probed in high momentum transfer reactions at JLab and GSI. Their basic objects are the LF wave functions, which provide a relativistically covariant (boost–invariant) and process–independent formulation of hadron structure, while maintaining a close connection to the non-relativistic formulation with its well–tested concepts (orbital angular momentum, heavy quark potentials, *etc.*). The LF wave functions of hadrons in QCD are directly connected to the parton densities and GPDs which are used to describe hadron structure in the more general context of QCD factorization. Research within the proposed exchange program will include the following:

- *Relativistic quark models for meson/baryon spectra and decays.* Relativistic quark models based on the LF formulation are unique in that they describe both the spectrum and the production/decay matrix elements of mesons and baryons, including excited states. They are an essential tool for analyzing the production and decays of meson states (including exotics) in the few–GeV region in the JLab GlueX experiment, as well as the spectroscopy of charmonium and other states in $\bar{p}p$ scattering at GSI. Investigations will focus on the calculation of the relevant transition matrix elements, and improving the phenomenological description by importing information from lattice (heavy quark potential) and Hamiltonian QCD calculations.
- *Proton spin problem and orbital angular momentum.* LF methods provide a consistent and transparent framework for introducing the orbital angular momentum of partons in QCD. The participants of this program plan to perform detailed studies of the role of orbital angular momentum in the nucleon GPDs (including form factors at high momentum transfer) and TMDs. These results will provide essential input for corresponding experiments at JLab and GSI [56].
- *QCD final–state interactions in single–spin asymmetries.* Recent theoretical studies of the single spin asymmetries observed in semi-inclusive hadron production have revealed an essential role of QCD final-state interaction effects, not included in the hadronic wave functions. Future research in this field will focus on final–state interaction effects in other observables, their relations to TMDs and QCD factorization (gauge links), as well as the study of spin effects in two–photon exchange.

At the more fundamental level, LF quantization provides the framework for an *ab initio* Hamiltonian approach to strongly interacting quantum systems, including quantum field theories such as QCD. Contrary to lattice gauge theory, which is based on the Euclidean (imaginary–time) formulation, the LF Hamiltonian methods work directly in Minkowski space and can therefore access also properties of highly excited states, such as energies, wave functions, and transition matrix elements. In applications to QCD, the treatment of the nonperturbative vacuum structure (spontaneous chiral symmetry breaking, vacuum condensates, *etc.*) in the LF approach presents some subtle problems related to so–called “zero modes”, which have been the subject of intense study [57]. A long–term effort is under way to develop these methods to a stage where they can predict masses and wave functions of hadrons directly on the basis of the QCD Lagrangian.

7.E Phenomenological Lagrangians

An important theoretical tool that can be brought to bear on a number of the research opportunities described herein is that of the phenomenological Lagrangian. In this approach, particles are treated as point-like, to some extent, but the key characteristic is that interaction vertices are constructed in a general way, consistent with the Lorentz and spinor properties of the particles present in the vertex. The fact that the particles being treated have internal structure is accounted for with vertex form factors that modulate the high-energy behavior of the vertices, and therefore of any process in which the vertices appear. This approach allows the treatment of a number of processes over a wider energy range, more easily than an effective Lagrangian would.

This approach has been applied to the process $e^+e^- \to V_c \to p\bar{p}$, where V_c is a vector charmonium state. In the near future, decays of charmonium states to $N\bar{N}M$, where M is a light pseudoscalar meson, will be examined using this approach. These processes will provide information on light baryon resonances complementary to information extracted from meson photo- and electroproduction experiments carried out at JLab. This approach can also be used to estimate the charmonium yields from $p\bar{p} \to X_c M$, where X_c is a non-exotic charmonium state. Such estimates are needed for the PANDA physics program for formulating detector strategies and to evaluate luminosity requirements, as well as for detailed detector simulations with theoretically preferred final states.

7.F Partial Wave Analysis

Three particle final states, such as those depicted in Fig. 4, are of prime interest to both meson and baryon spectroscopy. Here the three pions can couple to isospin 1 and have negative G-parity, thus it is a possible decay channel of the exotic $J^{PC} = 1^{-+}$ meson. The standard partial wave analyses (PWA) of three-particle final states are based on the isobar model in which the three particle state is effectively replaced by a quasi-two-particle one in which a selected pair of particles is isolated and does not interact with the spectator, Fig. 4(a). Such an approximation violates several fundamental constraints on the three-particle decay amplitudes, such as unitarity in two-particle sub-channels (Fig. 4(b)) and duality between particles/resonances and forces (Fig. 4(c)). The neglected effects may be particularly important when there is large kinematical overlap which is often the case.

The formalism for describing these types was being developed several years ago when the first hadron production data had become available [58], however, due to unavailability of adequate computer resources and sparse data it was hardly used. Furthermore, the reaction formalism uses as input two-body amplitudes, which 3 decades ago were poorly known, but which in the past years have seen significant development [59]. Our proposal is to develop the theoretical amplitudes for various three-particle final state, *i.e.* 3π, $2\pi p$, $K\bar{K}p$ and software for multichannel-fits of large data sets. This is necessary for model-independent identification of resonances decaying into these channels, data for which will be produced in copious quantities in future experiments at Jefferson Lab and GSI-FAIR.

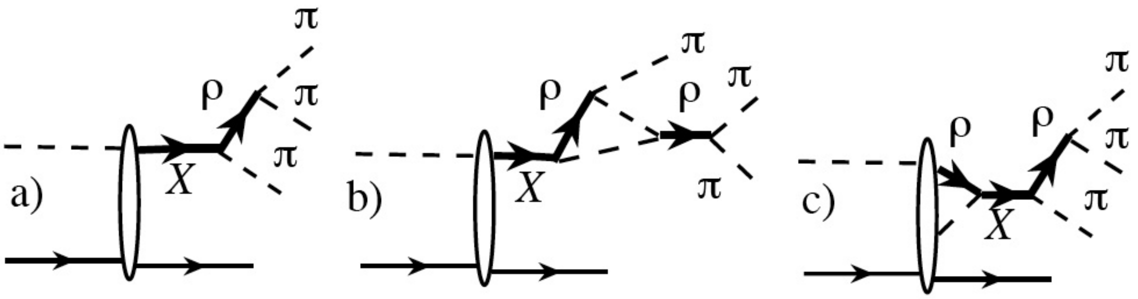

Figure 4: *Peripheral production of three pions. (a) The isobar model assumes production of a resonance X that decays to an unstable particle ρ and a pion, with the ρ subsequently decaying to two pions. (b) Example of interactions necessitated by unitarity, where one of the pions from the ρ decay interacts with the spectator pion to form the second ρ. (c) An example of a production mechanisms not considered by the isobar model, where the ρ and π mesons are produced directly and rescatter.*

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- Secretary/Treasurer, Topical Group on Hadronic Physics (GHP) of the APS (2003–2009)
- Member of Jefferson Lab Program Advisory Committee, PAC32 (2007)
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- Correspondent for the Institute for Nuclear Theory "Physics News" web page (2007–)
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Selected Publications

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- *γZ corrections to forward-angle parity-violating ep scattering*
  A. Sibirtsev, P. Blunden, W. Melnitchouk and A. W. Thomas, arXiv:1002.0740 [hep-ph]
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- *Confirmation of quark-hadron duality in the neutron F_2 structure function*
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- *Equivalence of pion loops in light-front and equal-time dynamics*
  C.-R. Ji, W. Melnitchouk and A. W. Thomas, Phys. Rev. **D 80**, 054018 (2009)
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- *Duality in Semi-Inclusive Pion Electroproduction*
  F. E. Close and W. Melnitchouk, Phys. Rev. **C 79**, 055202 (2009)
- *Spin structure functions of ^{3}He at finite Q^2*
  S.A. Kulagin and W. Melnitchouk, Phys. Rev. **C 78**, 065203 (2008)
- *Target mass corrections for spin-dependent structure functions in collinear factorization*
  A. Accardi and W. Melnitchouk, Phys. Lett. **B 670**, 114 (2008)
- *Finite-Q^2 corrections to parity-violating deep inelastic scattering*
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  O. Lalakulich, W. Melnitchouk and E. Paschos, Phys. Rev. **C 75**, 015202 (2007)
- *Quark-hadron duality in electron scattering*
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Selected Publications

- *Highly excited and exotic meson spectrum from dynamical lattice QCD*
  J. J. Dudek, R. G. Edwards, M. J. Peardon, D. G. Richards and C. E. Thomas, Phys. Rev. Lett. **103**, 262001 (2009)
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- Competitive State Scholarshop from the State of Bavaria (Bayerische Begabtenförderung), Germany (1984-1988)

Service

- Reviewer of research grant applications for the U.S. Department of Energy (DOE) Office of Nuclear Physics and the National Science Foundation (NSF) (2005 - present)
- Referee for international scientific journals, including Physical Review, European Physical Journal, and Nuclear Physics

- Guest Editor of Annalen der Physik (Berlin), Special Topic Issue: *"New developments in hadron spectroscopy and reactions"*, Volume 13 (2004), Issue No. 11–12, pp. 627–753
- Convener of *ep* Physics Working Group, Electron–Ion Collider (EIC) Collaboration (since 2007)
- Co-spokesperson, JLab 12 GeV approved experiment E12-06-108 *Hard Exclusive Electroproduction of pi0 and eta with CLAS12*
- Organizer of international workshops and conferences: *Physics and methods in meson spectroscopy – Int. Joint Workshop CERN COMPASS-Jefferson Lab-GSI FAIR*, Munich, Germany, 22–24 Oct. 2008; *Strangeness polarization in semi-inclusive and exclusive Lambda production*, ECT*, Trento, Italy, 27-30 Oct. 2008; *Compton Scattering from low to high momentum transfer*, ECT* Trento, Italy, 31 Mar.–4 Apr. 2003
- Invited lecturer at summer schools and graduate colleges: National Nuclear Physics Summer School (NNPSS), Florida State U., 13 Jul. 2007; 1st Summer School on QCD Spin Physics, Brookhaven National Lab, 5–12 Jun. 2004; Graduate College (Graduiertenkolleg), University at Giessen, Germany, 24 Jul. 2003

Selected Publications

- *Transverse target spin asymmetry in inclusive DIS with two-photon exchange*
  A. Afanasev, M. Strikman and C. Weiss, Phys. Rev. **D 77**, 014028 (2008)
- *Electroproduction of* $\phi(1020)$ *mesons at* $1.4 < Q^2 < 3.8\ \mathrm{GeV}^2$ *measured with CLAS*
  CLAS Collaboration (J.P. Santoro *et al.*), Phys. Rev. **C 78**, 025210 (2008)
- *Exclusive annihilation* $p\bar{p} \to \gamma\gamma$ *in a generalized parton picture*
  A. Freund *et al.*, Phys. Rev. Lett. **90**, 092001 (2003)
- *DVCS amplitude at tree level: Transversality, twist-3, and factorization*
  A. V. Radyushkin and C. Weiss, Phys. Rev. **D 63**, 114012 (2001)
- *Transversity distributions in the nucleon in the large–*N_c *limit*
  P. Schweitzer, D. Urbano, M. V. Polyakov, C. Weiss, P. V. Pobylitsa and K. Goeke, Phys. Rev. **D 64**, 034013 (2001)
- *Polarized antiquark flavor asymmetry in Drell-Yan pair production*
  B. Dressler, K. Goeke, M. V. Polyakov, P. Schweitzer, M. Strikman and C. Weiss, Eur. Phys. J. **C 18**, 719 (2001)
- *Skewed and double distributions in the pion and the nucleon*
  M.V. Polyakov and C. Weiss, Phys. Rev. **D 60**, 114017 (1999)
- *A chiral Lagrangian for excited pions*
  M. K. Volkov and C. Weiss, Phys. Rev. **D 56**, 221 (1997)
- *Nucleon parton distributions at low normalization point in the large* N_c *limit*
  D.I. Diakonov, V.Yu. Petrov, P.V. Pobylitsa, M.V. Polyakov and C. Weiss, Nucl. Phys. **B480**, 341 (1996)

Current and Pending Support

The Jefferson Lab Theory Center, of which Melnitchouk and Weiss are members, is supported by the DOE contract number DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates Jefferson Lab. Dudek is a faculty at Old Dominion University, supported 50% by the Jefferson Lab Theory Center. His research is also supported by the above DOE contract, DE-AC05-06OR23177.

Facilities and Resources

Old Dominion University will provide administrative support for handling travel documentation, and Jefferson Lab Computing Center will provide support in setting up and maintaining the GAUSTEQ program's website.

GSI will provide office space and computer facilities during the program participants' visits to GSI. It is expected that other collaborating institutions visited in Germany, which are listed in this proposal, will provide similar infrastructure support. GSI will also provide a subsidised rate for accommodation at the GSI guest house during participants' visits to GSI.

Table 1: Initial U.S. personnel and corresponding German collaborators who have expressed interest in the GAUSTEQ program. Note that this list is not exclusive.

U.S.	**German**
A. Accardi (Hampton U. / Jefferson Lab)	M. Schlegel (University of Tübingen)
S. J. Brodsky (SLAC)	M. Diehl (DESY) H.-J. Pirner (University of Heidelberg)
M. Burkardt (New Mexico State University)	P. Hägler (TU Munich)
S. Capstick (Florida State University)	M. Lutz (GSI)
C. Carlson (College of William & Mary)	M. Vanderhaeghen, F. Maas (University of Mainz)
J. Collins (Pennsylvania State University)	M. Diehl (DESY)
W. Detmold (William & Mary / Jefferson Lab)	C. Fischer (TU Darmstadt) H.-W. Hammer (University of Bonn)
J. J. Dudek (Old Dominion U. / Jefferson Lab)	G. Bali (University of Regensburg)
R. Edwards (Jefferson Lab)	P. Hägler (TU Munich)
C.-R. Ji (North Carolina State University)	M. Diehl (DESY) M. Beyer (University of Rostock)
T.-S. H. Lee (Argonne National Lab / JLab)	A. Sibirtsev (University of Bonn) S. Krewald (FZ Jülich)
A. Metz (Temple University)	M. Vanderhaeghen, F. Maas (University of Mainz)
W. Melnitchouk (Jefferson Lab)	J. Blümlein (DESY-Zeuthen) W. Weise (TU Munich) H. Fritzsch (University of Munich) E. Paschos (TU Dortmund)
G. A. Miller (University of Washington)	P. Kroll (University of Wuppertal) M. Vanderhaeghen, F. Maas (University of Mainz)
B. Musch (Jefferson Lab)	P. Hägler (TU Munich)
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M. R. Pennington (Jefferson Lab)	C. Fischer (TU Darmstadt) M. Lutz (GSI) C. Hanhart (FZ Jülich)
D. R. Phillips (Ohio University)	U.-G. Meißner (University of Bonn/FZ Jülich)
D. G. Richards (Jefferson Lab)	P. Hägler, A. Vairo, N. Brambilla (TU Munich)
C. D. Roberts (Argonne National Lab)	C. Fischer (TU Darmstadt)
W. Roberts (Florida State University)	K. Peters (GSI)
E. Swanson (University of Pittsburgh)	M. Lutz (GSI)
A. Szczepaniak (Indiana University)	K. Peters (GSI)
J. Vary (Iowa State University)	H.-J. Pirner (University of Heidelberg)
C. Weiss (Jefferson Lab)	M. Polyakov (University of Bochum)