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Principal Investigator: John R. Hiller (jhiller@d.umn.edu, 218-726-7594)

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Executive Summary: The primary focus of the work was the development of methods for the nonperturbative solution of quantum chromodynamics (QCD) in a form that yields wave functions for the eigenstates, from which hadronic properties can be computed. The principal approach was to use a light-front Hamiltonian formulation. In light-front coordinates, $t + z/c$ plays the role of time, with t the ordinary time, z a space direction, and c the speed of light. This leads to a relativistic formulation that retains useful characteristics of nonrelativistic treatments. A bound state of many constituents can be represented by wave functions that define probabilities for each possible arrangement of internal momenta. These functions satisfy integral equations that can be approximated numerically to yield a matrix representation. The matrix problem can be solved by iterative methods. The approximate wave functions can then be used to compute properties of the bound state. Methods have been developed for model theories and gauge theories, including quantum electrodynamics and theories that are supersymmetric. The work has required the development of new numerical algorithms and computer codes for singular integral equations and eigenvalue problems. A key aspect of the work is the construction of practical procedures for nonperturbative regularization and renormalization. Two methods of regularization have been studied. One is the addition of heavy Pauli–Villars (PV) particles to the Lagrangian, with their metrics and couplings tuned to provide the necessary cancellations in the regularization. The other method of regularization is the addition of supersymmetric partners, to extend a theory to a supersymmetric form. The supersymmetric theories were solved by the supersymmetric discrete light-cone quantization (SDLCQ) method. The most significant accomplishments of the project were the SDLCQ calculation of direct evidence for a Maldacena duality conjecture, construction of a practical light-front quantization for QED in an arbitrary covariant gauge, and invention of the light-front coupled-cluster method, designed to eliminate the need for Fock-space truncations.

Project Report:

The funded period of this project lasted fifteen years. In that time, 41 papers were prepared for publication, with almost all now published in top-ranked journals. The list of publications provided with this report subdivides them by topic. In addition, there were 24 proceedings contributions, representing some of the conference and workshop presentations of the work. The funding of the project was critical for this level of participation in conferences and workshops. Funding of travel was also important for the light-front community as a whole, because it provided the opportunity for the PI to serve as member, secretary, and president of the International Light-Cone Advisory Committee that has guided annual light-front meetings. The Committee is now ILCAC, Inc., and the PI is a member of the Board of Directors.

The primary focus of the work was the nonperturbative solution of quantum field theories, and the principal approach was to use a light-front Hamiltonian formulation. The ultimate objective is the nonperturbative solution of quantum chromodynamics (QCD) in a form that yields wave functions for the eigenstates, from which hadronic properties can be computed.

The published work is, in general, not frequently cited by others. This is because most particle physicists shy away from nonperturbative calculations, preferring instead the well-traveled routes of perturbation theory and modeling. The exception, of course, is lattice gauge theory, but this is the exception that proves the rule. Historically, work that strikes out in a new direction tends to be ignored for many years.

The work has required the development of new numerical algorithms and computer codes for singular integral equations and eigenvalue problems. However, such developments are only the implementation. The key aspect of the work is the construction of practical procedures for nonperturbative regularization and renormalization. Therefore, the main thrust of the project has been along these lines, with new algorithms and codes developed as needed to implement the ideas. This is not to say, though, that there has not been dramatic progress in algorithms and codes.

Two methods of regularization have been studied. One is the addition of heavy Pauli–Villars (PV) particles to the Lagrangian, with their metrics and couplings tuned to provide the necessary cancellations in the regularization. The resulting Hamiltonian eigenvalue problem then includes PV contributions to the eigenstates, which are removed by some limiting process in the calculation of physical quantities. The renormalization of masses and couplings is done by fitting one or more observables to data.

The other method of regularization is the addition of supersymmetric partners, to extend a theory to a supersymmetric form. Several two and three-dimensional theories were investigated, while the PI was a member of the SDLCQ collaboration.¹

The most important result obtained by the SDLCQ collaboration was direct evidence [18] for a supergravity/super-Yang–Mills duality conjectured by Maldacena.² A stress-energy correlator was computed in the strong-coupling regime of the super Yang–Mills theory by the SDLCQ method and compared with the weak-coupling supergravity result. Figure 1 shows the comparison; at large separation r , before computing errors become too large, the two calculations agree. The work of the collaboration also explored finite-temperature effects [20, 19]. For both the Maldacena conjecture and the finite-temperature results, the

¹The acronym SDLCQ stands for supersymmetric discrete light-cone quantization, which is a particular numerical discretization applicable to the solution of supersymmetric theories. For a review, see O. Lunin and S. Pinsky, AIP Conf. Proc. **494**, 140 (1999).

²J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998) [Int. J. Theor. Phys. **38**, 1113 (1999)].

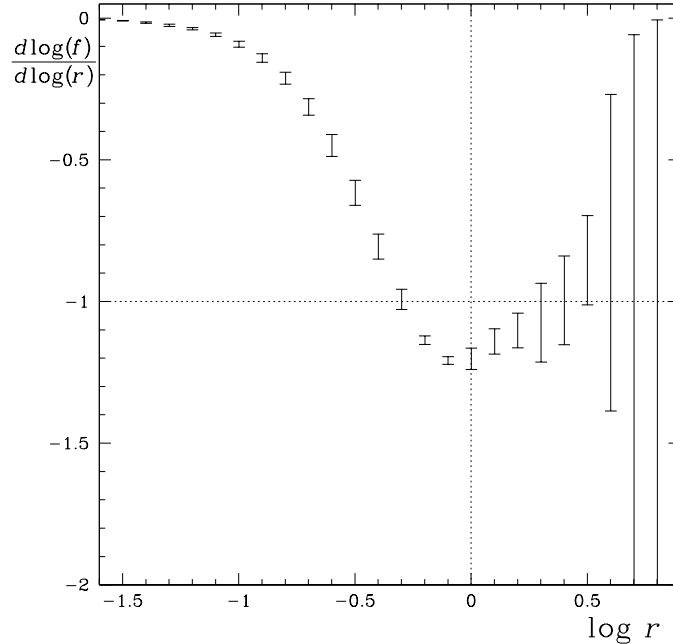


Figure 1: The log-log derivative $d\log_{10}(f)/d\log_{10}(r)$ of the scaled correlation function f versus $\log_{10}(r)$, where r is the separation in the correlator and f is essentially the ratio of the correlator to $1/r^4$. The large- r behavior of the correlator in the supergravity theory is $1/r^5$, corresponding to -1 on the plot.

calculations depended heavily on new algorithms developed by the PI for estimating the spectra of large sparse matrices without full diagonalization.

The work on PV regularization is of longer standing and continues today. The earliest work was done in collaboration with S.J. Brodsky and G. McCartor, with the basic idea put forward by McCartor and implemented by the PI. The work began with a simple model [11, 12] and then built to consideration of Yukawa theory [13, 14, 15, 16] and QED [5]. The use of PV regularization was also explored by the St. Petersburg group of V.A. Franke, S.A. Paston, and E.V. Prokhvatilov, which focused on perturbative equivalence between light-front quantization and covariant Feynman theory. This led to the collaboration on the QED paper [5] and also to their formulation of a PV-based regularization of QCD.³

The more recent work is in collaboration with S. Chabysheva, who had worked with the St. Petersburg group as a student. Rather than immediately continuing to build to more complex theories, this work has focused on the resolution of several fundamental issues. The first issue was the elimination of strong regulator dependence in observables by the nonperturbative restoration of a symmetry. Everyone is familiar with the need to maintain symmetries when regulating a theory, but doing so perturbatively is insufficient in a nonperturbative calculation. The demonstration of this is described in two papers [6, 8], the second being a calculation of the anomalous moment of the electron in QED truncated to keep two photons and no positrons in the eigenstates. Figure 2 shows the

³S.A. Paston and V.A. Franke, *Theor. Math. Phys.* **112**, 1117 (1997) [*Teor. Mat. Fiz.* **112**, 399 (1997)]; S.A. Paston, V.A. Franke, and E.V. Prokhvatilov, *Theor. Math. Phys.* **120**, 1164 (1999) [*Teor. Mat. Fiz.* **120**, 417 (1999)].

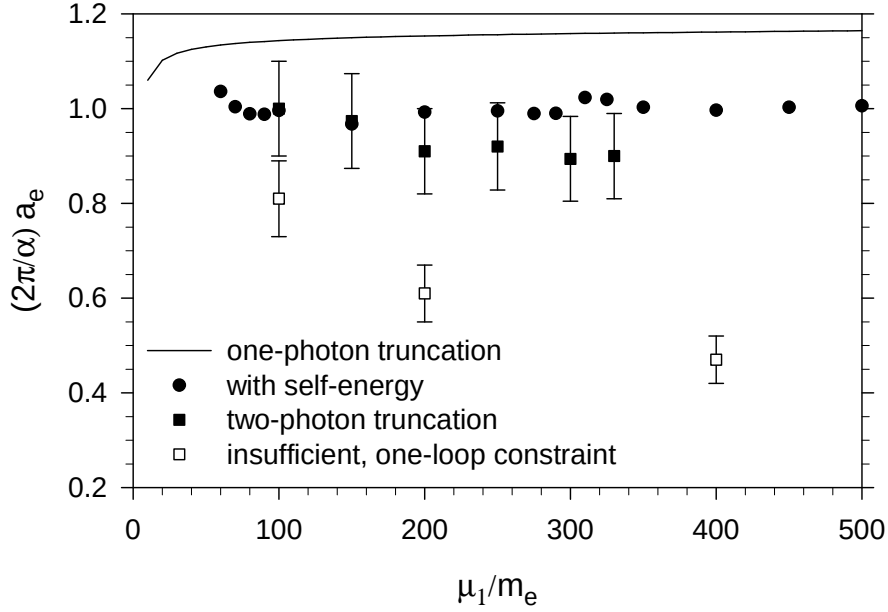


Figure 2: The anomalous moment of the electron in units of the Schwinger term ($\alpha/2\pi$) plotted versus the PV photon mass, μ_1 , with the second PV photon mass, μ_2 , set to $\sqrt{2}\mu_1$ and the PV electron mass m_1 equal to $2 \cdot 10^4 m_e$. The solid squares are the result of the full two-photon truncation with the correct, nonperturbative chiral constraint. The open squares come from use of a perturbative, one-loop constraint. Results for the one-photon truncation [6] (solid line) and the one-photon truncation with the two-photon self-energy contribution [7] (filled circles) are included for comparison.

results for this calculation and for more severe truncations. The two-photon results without proper nonperturbative restoration of the chiral limit show a very strong dependence on the regulator mass μ_1 , while results with the full restoration do not.

The second issue was the limitation to a particular gauge. Most light-front calculations in a gauge theory use light-cone gauge, because this greatly simplifies the fermionic constraint equation. In the work with McCartor it was found in QED that, with the chosen PV regularization, the constraint equation was also simple in Feynman gauge. What Chabysheva and the PI have done is to extend this to arbitrary covariant gauges [10]. This required construction of a light-front analog of the equal-time Stueckelberg quantization of a massive vector field,⁴ in order to quantize the PV photons in an arbitrary gauge. The formalism allows the results of calculations in QED to be tested for gauge independence, by comparison of calculations in a series of different covariant gauges. Figure 3 shows what happens for a calculation of the anomalous magnetic moment of the electron a_e as a function of the gauge parameter ζ . The anomalous moment is nearly independent of ζ , except near the singular limit of $\zeta \rightarrow 0$, where the gauge-fixing term disappears. Away from zero, the small variation with ζ is understood as an effect of numerical and truncation errors.

The third fundamental issue was what to do about the effects of truncation in particle content. The primary problem is that such truncations of Fock space cause uncanceled divergences. They are the nonperturbative analog of what happens if a Feynman diagram is separated into time-ordered diagrams and then approximated by a truncation that eliminates all time-ordered diagrams with more than a fixed number of intermediate par-

⁴E.C.G. Stueckelberg, *Helv. Phys. Acta* **11**, 225 (1938); F. Coester, *Phys. Rev.* **83**, 798 (1951).

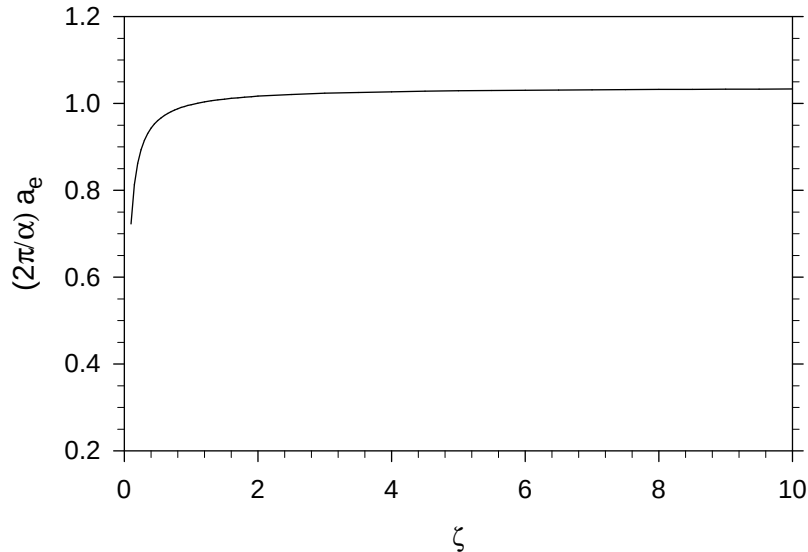


Figure 3: The anomalous magnetic moment a_e , relative to the Schwinger term $\alpha/2\pi$, for the dressed-electron state truncated to include at most the one-electron/one-photon Fock states, as a function of the gauge parameter ζ , with a bare photon mass of $\mu_0 = 0.001 m_e$ and PV photon mass of $\mu_1 = 200 m_e$.

ticles. The diagram truncation introduces infinities that would otherwise be canceled. In a nonperturbative calculation, there are two ways to deal with this. One is to not take all regulator masses to infinity but instead to find plateaus in observables as functions of one or more regulator masses. This is the approach taken in most of the earlier work done on this project, up to and including the two-photon truncation [8]. Figure 2 shows that a plateau in the anomalous moment does exist.

The other approach to dealing with truncation-induced uncanceled divergences is to absorb them into masses and couplings that depend on the Fock sector. This is the sector-dependent renormalization approach first proposed by Wilson and co-workers⁵ and used by Brodsky and the PI in an early QED calculation [4]. The method was later taken up by Karmanov *et al.*;⁶ however, they did not recognize the inconsistencies that arise if the calculations are pressed too far. To clarify the situation, Chabysheva and the PI published [7], where sector-dependent renormalization is shown to lead to ill-defined wave functions, among other problems. Given that the original purpose in using light-front Hamiltonian methods was to have well-defined wave functions, the lack thereof is not acceptable.

The most significant outcome of this project is the resolution of this truncation issue, with the development of the light-front coupled-cluster (LFCC) method by Chabysheva and the PI [1]. The truncation in Fock space is no longer necessary, and the associated uncanceled divergences do not arise. For example, in a one-photon truncation of QED, the second and third diagrams of Fig. 4 are removed, which destroys the associated Ward identity and prevents the vertex loop from canceling the wave function renormalization. In the LFCC method, with no Fock-space truncation, all three diagrams are included. In

⁵R.J. Perry, A. Harindranath, and K.G. Wilson, Phys. Rev. Lett. **65** (1990), 2959; R.J. Perry and A. Harindranath, Phys. Rev. D **43** (1991), 4051.

⁶V.A. Karmanov, J.F. Mathiot, and A.V. Smirnov, Phys. Rev. D **77**, 085028 (2008); Phys. Rev. D **82**, 056010 (2010).

addition, the mass renormalization automatically provides all particles with their physical mass in each Fock sector.

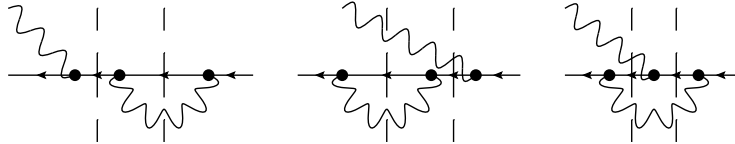


Figure 4: Graphs contributing to the Ward identity in QED. Only the first contributes in a one-photon truncation of the Fock space.

Most of the final work on the project has been on the development of the LFCC method. The basic idea is to construct the Hamiltonian eigenstate $|\psi\rangle$ in the form $\sqrt{Z}e^T|\phi\rangle$, where $|\phi\rangle$ is a state in the valence Fock sector with a minimum number of constituents, T is an operator that increases particle number while conserving quantum numbers, and $\sqrt{Z}$ is a normalizing factor. The exponentiation of T provides an operator that generates an arbitrary number of additional constituents, so that $e^T|\phi\rangle$ can include all Fock sectors with the same quantum numbers. The method is based on the mathematics of the coupled-cluster method used for non-relativistic many-body problems in nuclear physics and chemistry.⁷

The valence state $|\phi\rangle$ is an eigenstate of an effective light-front Hamiltonian $\overline{\mathcal{P}}^- \equiv e^{-T}\mathcal{P}^-e^T$. The operator T must satisfy nonlinear equations determined by a projection P_{nv} onto non-valence sectors: $P_{\text{nv}}\overline{\mathcal{P}}^-|\phi\rangle = 0$. This is an infinite system of equations. The truncation that is made is to truncate T to only a few terms, but not to truncate e^T . In the case of QED, if T is truncated to just one term, the emission of a photon from an electron, the effective Hamiltonian includes all three of the processes in Fig. 4, and the truncation of the dressed-electron problem includes as much physics as a two-photon truncation of Fock space [8].

The LFCC method has been applied to a soluble model [1], QED [2], and to the zero-mode sector of two-dimensional theories [3]. This last consideration is to extend the method to include symmetry-breaking effects, with the eventual aim of treating the Higgs mechanism nonperturbatively. Additional work on ϕ^4 theory and the numerical solution of QED is in progress.

We have also begun to explore the applicability of holographic QCD⁸ to calculations with the LFCC method. The approximate AdS₅/QCD duality, in the limit of massless quarks, motivates few-body analyses of meson and baryon spectra⁹ based on a one-dimensional light-front Schrödinger equation in terms of a modified transverse coordinate ζ . As a preliminary exploration, we developed the idea of using the 't Hooft model¹⁰ to include dependence on quark masses in a second, longitudinal equation [38]. This provides a simple quark model for mesons, which can be used as an approximation to the valence

⁷F. Coester, Nucl. Phys. **7**, 421 (1958); F. Coester and H. Kümmel, Nucl. Phys. **17**, 477 (1960); for a review of the original coupled-cluster method, see R.J. Bartlett and M. Musial, Rev. Mod. Phys. **79**, 291 (2007).

⁸G. F. de Téramond and S. J. Brodsky, Phys. Rev. Lett. **102**, 081601 (2009); S. J. Brodsky and G. F. de Téramond, Phys. Rev. Lett. **96**, 201601 (2006); G. F. de Téramond and S. J. Brodsky, Phys. Rev. Lett. **94**, 201601 (2005).

⁹T. Gutsche, V. E. Lyubovitskij, I. Schmidt and A. Vega, Phys. Rev. D **87**, 016017 (2013); Phys. Rev. D **87**, 056001 (2013).

¹⁰G. 't Hooft, Nucl. Phys. B **75**, 461 (1974).

eigenvalue problem of the LFCC method. The analysis also demonstrated a potentially useful set of basis functions for QCD wave functions.

In addition to these fundamental developments, work was done on related topics. In particular, several papers were published with various co-authors on exclusive processes [32, 33, 34, 35] and on the structure of the proton [36]. Also, with Chabysheva and students, the PI explored other aspects of nonperturbative calculations and numerical methods to support them. These include consideration of zero-momentum modes in discrete light-cone quantization [37]; derivation of the Casimir effect in light-front coordinates, to show that this vacuum effect is not lost in light-front quantization [39]; construction of multivariate polynomials fully symmetric in barycentric coordinates on a triangle, as a basis for light-front wave functions [40]; and implementation of a compression algorithm¹¹ to reduce storage requirements for state vectors in discrete light-cone quantization [41].

To summarize, the project made significant progress in the development of techniques for the nonperturbative solution of quantum field theories. Methods of nonperturbative regularization were carefully investigated and various useful computational algorithms were developed. The most significant accomplishments were the calculation of direct evidence for a Maldacena duality conjecture [18], construction of a practical light-front quantization for PV-regulated QED in an arbitrary covariant gauge [10], and invention of the light-front coupled-cluster method [1] to eliminate the need for Fock-space truncation. Work along these lines continues.

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Light-front coupled-cluster method:

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