NSTAR12: Charting the interaction between light quarks

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Two of the basic motivations for an upgraded JLab facility are the needs: to determine the essential nature of light-quark confinement and dynamical chiral symmetry breaking (DCSB); and to understand nucleon structure and spectroscopy in terms of QCD's elementary degrees of freedom. In addressing these questions one is confronted with the challenge of elucidating the role of quarks and gluons in hadrons and nuclei. In accepting that challenge one steps immediately into the domain of relativistic quantum field theory where within the key phenomena can only be understood via nonperturbative methods.

It is a fundamental fact that the physics of hadrons is dominated by two *emergent phenomena*: confinement; namely, the empirical truth that quarks have not hitherto been detected in isolation; and DCSB, which is responsible, amongst many other things, for the large mass splitting between parity partners in the spectrum of light-quark hadrons, even though the relevant current-quark masses are small. Neither of these phenomena is apparent in QCD's Lagrangian and yet they play a principal role in determining the observable characteristics of real-world QCD.

In connection with confinement it is worth emphasizing at the outset that the potential between infinitely-heavy quarks measured in numerical simulations of quenched lattice-regularised QCD – the so-called static potential – is simply not relevant to the question of light-quark confinement. In fact, it is quite likely a basic feature of QCD that a quantum mechanical potential between light-quarks is impossible to speak of because particle creation and annihilation effects are essentially nonperturbative. A perspective on confinement was laid out in Ref. [1]. Expressed simply, confinement can be related to the analytic properties of QCD's Schwinger functions, which are often loosely called Euclidean-space Green functions. For example, it can be read from the reconstruction theorem that the only Schwinger functions which can be associated with expectation values in the Hilbert space of observables; namely, the set of measurable expectation values, are those that satisfy the axiom of reflection positivity [2]. This is an extremely tight constraint. However, it is a necessary but not sufficient condition.

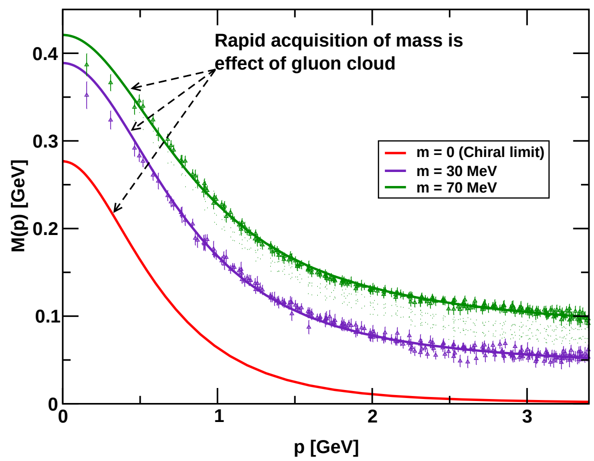
The question of light-quark confinement can be translated into that of charting the infrared behavior of QCD's *universal* β-function. It is important to appreciate that while this function may depend on the scheme chosen to renormalize the quantum field theory, it is unique within a given scheme. An elemental goal of hadron physics during the next ten years must be to design a program of experiment and theory that can together map out the β-function. This is a well-posed problem. It's importance is already widely appreciated and an exploratory attempt has been made [3].

While light-quark confinement remains a conjecture, many statements of fact can be made in connection DCSB. For example, DCSB explains the origin of constituent-quark masses and underlies the success of chiral effective field theory. Understanding DCSB within QCD proceeds from the renormalised gap equation [4]:

$$S(p)^{-1} = Z_2 \, (i\gamma \cdot p + m^{\rm bm}) + Z_1 \int_q^\Lambda g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q) \Gamma^a_\nu(q,p), \tag{1}$$

where $\int_q^\Lambda$ represents a Poincaré invariant regularisation of the integral, with Λ the regularisation mass-scale, $D_{\mu\nu}$ is the renormalised dressed-gluon propagator, Γ_ν is the renormalised dressed-

Figure 1: *Dressed-quark mass function, $M(p)$: solid curves – DSE results [5, 6], "data" – numerical simulations of unquenched lattice-QCD [7]. 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.*



quark-gluon vertex, and $m^{\rm bm}$ is the quark's Λ-dependent bare current-mass. The vertex and quark wave-function renormalisation constants, $Z_{1,2}(\zeta^2,\Lambda^2)$, depend on the gauge parameter.

The solution to Eq. (1) has the form

$$S(p) \;=\; -i\gamma\cdot p\,\sigma_V(p^2,\zeta^2)+\sigma_S(p^2,\zeta^2)=\frac{1}{i\gamma\cdot p\,A(p^2,\zeta^2)+B(p^2,\zeta^2)}=\frac{Z(p^2,\zeta^2)}{i\gamma\cdot p+M(p^2)} \quad (2)$$

and it is important that the mass function, $M(p^2)=B(p^2,\zeta^2)/A(p^2,\zeta^2)$ is independent of the renormalisation point, ζ.

The dressed-quark mass function in QCD is depicted in Fig. 1. It is one of the most remarkable features of the theory. In perturbation theory it is impossible in the chiral limit to obtain $M(p^2)\neq 0$: the generation of mass *from nothing* is an essentially nonperturbative phenomenon. On the other hand, it is a longstanding prediction of nonperturbative DSE studies that DCSB will occur so long as the integrated infrared strength possessed by the gap equation's kernel exceeds some critical value [8]. There are strong indications that this condition is satisfied in QCD [5, 6, 7]. It follows that the quark-parton of QCD acquires a momentum-dependent mass function, which at infrared momenta is $\sim$ 100-times larger than the current-quark mass. This effect owes primarily to a dense cloud of gluons that clothes a low-momentum quark [9]. It means that the Higgs mechanism is largely irrelevant to the bulk of normal matter in the universe. Instead the single most important mass generating mechanism for light-quark hadrons is the strong interaction effect of DCSB; e.g., one can identify it as being responsible for 98% of a proton's mass.

It is widely anticipated that there is an intimate connection between DCSB and light-quark confinement. For example, analogous to quenched QCD, quenched QED in three dimensions (two spacial, one temporal – QED_3) is confining because it has a nonzero string tension [10]. The effect of unquenching; viz., allowing light fermions to influence the theory's dynamics, has been much studied. The nature of QED_3 is such that there is almost certainly a critical number of light flavors above which DCSB is impossible. Moreover, chiral symmetry restoration and deconfinement are coincident owing to an abrupt change in the analytic properties of the fermion propagator when a nonzero scalar self-energy becomes insupportable [11].

The complex of Dyson-Schwinger equations (DSEs) is a powerful tool that has been employed with marked success to study confinement and DCSB, and their impact on hadron observables [8, 12, 13, 14, 15]. Moreover, the existence of a nonperturbative and symmetry preserving truncation scheme [16, 17, 18, 19] has enabled the DSEs to be used to provide an explanation of dynamical chiral symmetry breaking and prove a body of exact results for pseudoscalar mesons [4, 20]. They relate even to radial excitations and/or hybrids [21, 22, 23], and heavy-light

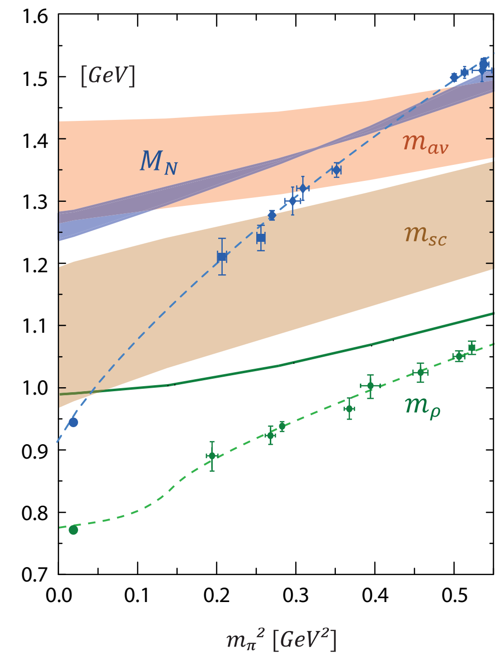


Figure 2: *Thick bands*: Evolution with current-quark mass, $\hat{m}$, of the scalar and axial-vector diquark masses: m_{sc} and m_{av}. Bands demarcate sensitivity to the variation in ω: $r_a = 1/\omega$ can be associated with a confinement length-scale in the quark-quark scattering kernel. (m_π, calculated from rainbow-ladder meson Bethe-Salpeter equation: $\hat{m} = 6.1\,\mathrm{MeV} \Rightarrow m_\pi = 0.138\,\mathrm{GeV}$.) *Solid curve*: Evolution of ρ-meson mass [34]. This observable quantity is insensitive to ω. With m_ρ, results from simulations of lattice-regularised QCD [38] are also depicted along with an analysis and chiral extrapolation [39], *short dashed curve*. *Thin band*: Evolution with $\hat{m}$ of the nucleon mass obtained from the Faddeev equation: $\hat{m} = 6.1\,\mathrm{MeV}$, $M_N = 1.26(2)\,\mathrm{GeV}$ cf. results from lattice-QCD [40, 41] and an analysis of such results [42], *dashed curve*. (Figure adapted from Ref. [35].)

[24, 25] and heavy-heavy mesons [26]. Mesons are described by the fully covariant Bethe-Salpeter equation and the exact results have been illustrated using a renormalisation-group-improved ladder-rainbow truncation of this and the gap equation [20, 27], which also provided a prediction of the electromagnetic pion form factor [28]. (Ladder-rainbow is the leading-order DSE truncation.) In addition, algebraic parametrizations of the dressed-quark propagators and meson bound-state amplitudes obtained from such studies continue to be useful, in particular with the study of B-meson $\to$ light-meson transition form-factors [29] and baryon properties [30, 31, 32, 33].

In quantum field theory a baryon appears as a pole in a six-point quark Green function. The residue is proportional to the baryon's Faddeev amplitude, which is obtained from a Poincaré covariant Faddeev equation that sums all possible exchanges and interactions that can take place between three dressed-quarks. A tractable Faddeev equation for baryons was formulated in Ref. [36]. It is founded on the observation that an interaction which describes colour-singlet mesons also generates quark-quark (diquark) correlations in the colour-$\bar{3}$ (antitriplet) channel [37]. The lightest diquark correlations appear in the $J^P = 0^+, 1^+$ channels and hence only they are retained in approximating the quark-quark scattering matrix. While diquarks do not appear in the strong interaction spectrum; e.g., Refs. [17, 18, 19], the attraction between quarks in this channel justifies a picture of baryons in which two quarks are always correlated as a colour-$\bar{3}$ diquark pseudoparticle, and binding is effected by the iterated exchange of roles between the bystander and diquark-participant quarks.

The Poincaré covariant and quantum field theoretical DSE framework is well suited to addressing the question of light-quark confinement. It may be posed as the problem of developing a detailed understanding of the infrared evolution of the quark-quark scattering kernel, $K_{q\bar{q}}$. With Refs. [34, 35] significant progress has been made in this direction. They enable the direct correlation of meson and baryon properties via a single interaction kernel that preserves QCD's one-loop renormalisation group behaviour and can systematically be improved. The unified framework provides a veracious description of the pion as both a Goldstone mode and a bound

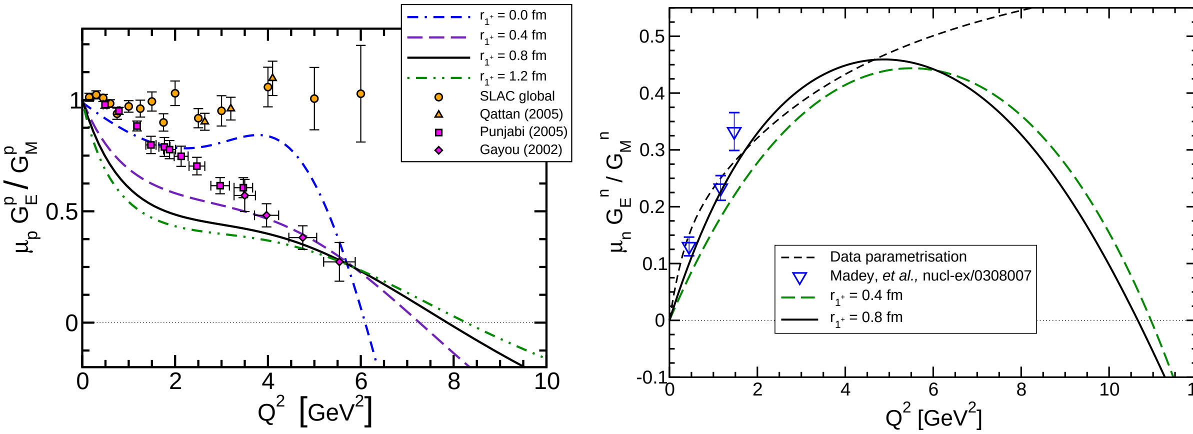


Figure 3: *Left panel* – Result for the normalised ratio of proton Sachs electric and magnetic form factors computed with four different diquark radii. Data: diamonds – [44]; squares – [45]; triangles – [46]; and circles [47]. *Right panel* – Analogous ratio for the neutron computed with two different diquark radii. *Short-dashed curve*: parametrisation of Ref. [48]. *Down triangles*: data from Ref. [49].

state of dressed-quarks. It is the only approach that is capable of doing so because it alone is capable of expressing the behavior in Fig. 1. The studies predict, amongst other things, the evolution of the nucleon mass with a quantity that can methodically be connected with the current-quark mass in QCD. This is depicted in Fig. 2. Notably, the nucleon mass is insensitive to the kernel's single parameter despite the large dependence of the unobservable diquark masses. Systematic corrections to the DSE's leading order truncation have been shown to move results into line with experiment.

An international theory program is underway that exploits the strengths of the DSEs in studies of the spectrum and interactions of hadrons. In connection with this, a comprehensive study of nucleon electromagnetic form factors has just been completed [43]. It evaluates a dressed-quark core contribution, which is defined by the solution of a Poincaré covariant Faddeev equation in which dressed-quarks provide the elementary degree of freedom and correlations between them are expressed via diquarks. The diquarks are nonpointlike and the current depends on their charge radii. A particular feature of the study is a separation of form factor contributions into those from different diagram types and correlation sectors, and subsequently a flavour separation for each of these. Amongst the extensive body of results that one might highlight: $r_1^{n,u} > r_1^{n,d}$, owing to the presence of axial-vector quark-quark correlations; and for both the neutron and proton the ratio of Sachs electric and magnetic form factors possesses a zero.

The latter ratios are depicted in Fig. 3. A sensitivity to the nucleon's electromagnetic current is evident, here expressed via the diquarks' radius. However, irrespective of that radius, the electric form factors possess a zero and the magnetic form factor is positive definite. On $Q^2 \lesssim 3\,\mathrm{GeV}^2$ the proton result lies below experiment. As explained in Ref. [43], this can likely be attributed to omission of so-called pseudoscalar-meson-cloud contributions.

It has long been recognized that the behavior characterized by Fig. 1 has an enormous impact on hadron phenomena [50] and hence that a form factor's pointwise evolution with momentum transfer is a sensitive probe of the nature of the quark-quark scattering kernel. For example, this was made strikingly apparent for the pion in Ref. [51]. It can also be seen for the nucleon. In the left panel of Fig. 4 we depict the proton's Pauli form factor calculated in a confining Nambu–Jona-Lasinio model, whose simplicity and phenomenological efficacy has recently been much exploited [52, 53, 54, 55]. This model possesses a dressed-quark mass but it *does not run*; i.e., it

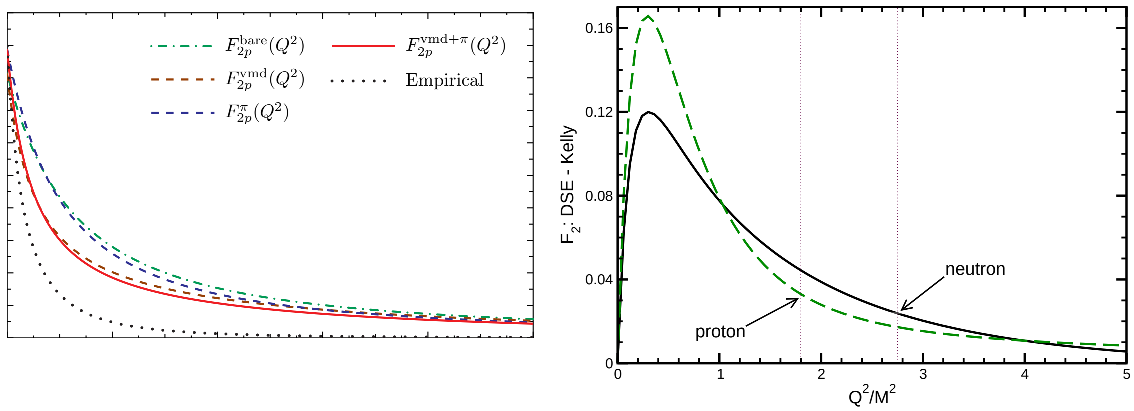


Figure 4: *Left panel* – Confining-NJL model Faddeev equation result for the proton's Pauli form factor: *solid curve*, complete result; and *dotted curve*, parametrization of experimental data [48]. The curves labelled *bare*, *VMD* and π represent intermediates stages in the calculation of the solid curve. *Right panel* – Difference between a DSE-calculated dressed-quark core contribution to the Pauli form factor and a parametrisation of experimental data [48], each normalised by the appropriate anomalous magnetic moment at $Q^2 = 0$: *dashed curve* – proton; *solid curve* – neutron. At $Q^2 \approx 2M_N^2$ the difference between calculation and data in the *left panel* is an order of magnitude larger than in the *right panel*.

assumes a large value that is momentum independent. As apparent in the figure, in this case the agreement between model result and experiment deteriorates quickly with increasing momentum transfer and the ultraviolet power-law behavior is incorrect. This may be contrasted with the behavior in the right panel, which is obtained [43] using a momentum-dependent running quark mass of the type depicted in Fig. 1. This calculation omits the pseudoscalar meson cloud. However, it retains the fully momentum dependent dressed-quark structure, which ensures good agreement with data for $Q^2 \approx 2-3M_N^2$.

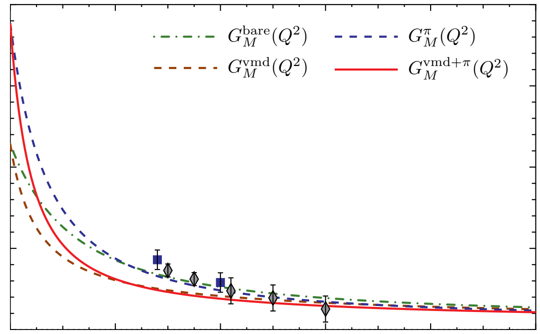
We judge that it is possible to employ precision data on nucleon-resonance transition form factors as a means by which to chart the momentum evolution of the dressed-quark mass function and therefrom the infrared behavior of QCD's β-function; in particular, to locate unambiguously the transition boundary between the constituent- and current-quark domains that is signalled by the sharp drop apparent in Fig. 1. That can be related to an inflexion point in QCD's β-function. Contemporary theory indicates that this transition boundary lies at $p^2 \sim 0.6\,\mathrm{GeV}^2$. Since a probe's input momentum Q is principally shared equally amongst the dressed-quarks in a transition process, then each can be considered as absorbing a momentum fraction $Q/3$. Thus in order to cover the domain $p^2 \in [0.5, 1.0]\,\mathrm{GeV}^2$ one requires $Q^2 \in [5, 10]\,\mathrm{GeV}^2$.

An international theory effort is underway in order to realize the goal of turning experiment into a probe of the dressed-quark mass function. The effort has many facets and the first calculations are being performed at leading-order in the DSE truncation.

Naturally, a reference calculation is needed, one that does not incorporate the running of the dressed-quark mass which is such a singular feature of QCD. A calculation of this type is nearing completion [56] and a preliminary result is presented in Fig. 5. It is evident that the pion is playing a very important role but significant strength is missing in the neighborhood of $Q^2 = 0$, since empirically $G_M(Q^2 = 0) = 3$. This calculation must be analyzed and the origin of each feature and defect determined so that the role of a constant constituent-quark-like mass can unambiguously be identified. The analysis should be complete by mid-2009.

Following this effort the Faddeev equation framework of Refs. [30, 31, 32, 33, 43], described

Figure 5: *Solid curve* – Confining-NJL model Faddeev equation result for the $N \to \Delta$ M1 transition form factor, complete calculation. The curves labelled *bare*, *VMD* and π represent intermediates stages in the calculation. Data from Refs. [57, 58].



briefly above and widely employed in studies of nucleon and Δ properties, will be applied to the $N \to \Delta$ transition. The strong momentum dependence of the dressed-quark mass function is an integral part of this framework. Therefore, in this study it will be possible, e.g., to vary artificially the position of the marked drop in the dressed-quark mass function and thereby identify experimental signatures for its presence and location. This study would begin in mid-2009 and be completed by the beginning of 2010.

In parallel with these efforts, the *ab-initio* rainbow-ladder DSE framework of Refs. [34, 35] is being extended to the Δ resonance. A solution of the Faddeev equation for the Δ should be complete by the end of 2008 [59]. The nucleon-photon current developed in Ref. [35] will then be generalized so that its nucleon form factor studies can be correlated with a calculation of the $N \to \Delta$ transition. The time required to complete this effort is uncertain, given that it involves a PhD student who is now nearing completion of his research, but assuming that a new student is found or a postdoctoral fellow can assume responsibility, a reasonable estimate is for completion by mid-2010. It should be emphasized, however, that for technical reasons this effort can only produce form factors out to modest momentum transfer; viz., $Q^2 \sim 2\,M_N^2$.

In order to extend the calculations it is imperative to improve the numerical methods used in the calculation of form factors and also to improve the rainbow-ladder quark-quark scattering kernel. This is naturally part of the next phase of the theoretical effort.

One should also proceed beyond the leading-order DSE truncation. This is necessary in order to identify and isolate artefacts that may arise through truncation and their impact on predictions for experimental signatures of the transition between the constituent-quark and the current-quark domains. This need notwithstanding, the merits of the rainbow-ladder truncation should not be underestimated. It is exact for $p^2 \gtrsim 1\,\mathrm{GeV}^2$. Furthermore, contemporary estimates show that at smaller p^2 it is still semi-quantitatively accurate for a wide range of observables, the nature of which can be determined *a priori*. Careful application of the rainbow-ladder truncation yields insights that are generally reliable.

A path for proceeding beyond the rainbow-ladder truncation is charted. Owing to the relative ease of dealing with the Bethe-Salpeter equation, it will initially proceed via mesons. The one-parameter model for the infrared behavior of $K_{q\bar{q}}$ in Ref. [34] will be employed in in DSE calculations of the spectrum and interactions of pseudoscalar mesons with masses $< 2\,\mathrm{GeV}$. Comparison with scant 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. It is in a nontrivial vertex that one moves beyond the rainbow-ladder truncation.

The improved $K_{q\bar{q}}$ will be employed in studies of the spectrum and interactions of axial-vector mesons, all of which lie above 1 GeV. The properties of pseudoscalar excited states and axial-vector mesons are a sensitive probe of the long-range part of the interaction between light-quarks. Comparison with scarce data will assist in further improving the map of the light-quark confinement interaction. A well constrained form of $K_{q\bar{q}}$ will thereafter be available. It will enable reliable predictions for the properties of all mesons in the $1-2\,\mathrm{GeV}$ range, including hybrids and exotics. This extended kernel will provide the basis for future *ab initio* Faddeev equation studies of the nucleon and Δ. One may anticipate that those studies could begin in 2013.

In the meantime, following the successful completion of $N \to \Delta$ studies, the dressed-quark Faddeev equation will be employed in nucleon resonance spectroscopy and the calculation of additional nucleon to resonance transitions. The starting point for this effort will be a calculation of the dressed-quark component of the Roper resonance. With experiment [60] now pointing to an interpretation of the $N(1440)$ as a radial excitation of the nucleon, a compelling case can be made for employing a quantum field theoretical approach to QCD that is founded on dressed-quark degrees of freedom in order to determine whether the experimental claim is consistent with the best available theory. A conclusion on this point should be available from the DSE-based Faddeev equation by the end of 2011 and from the *ab initio* rainbow-ladder truncation by 2012.

In parallel with the program outlined here an effort will be underway at the Excited Baryon Analysis Center (EBAC), which will provide the reaction theory necessary to make reliable contact between experiment and predictions based on the dressed-quark core. While rudimentary estimates can and will be made of the contribution from pseudoscalar meson loops to the dressed-quark core of the nucleon and its excited states, a detailed comparison with experiment will only follow when the DSE-based results are used to constrain the input for dynamical coupled channels calculations.

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