Exposing the Dressed Quark’s mass

Dressed–quark Mass Function

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DCSB & Confinement

\[ M(p) \]

\[ 0.5 \]

\[ 0.4 \]

\[ 0.3 \]

\[ 0.2 \]

\[ 0.1 \]

\[ p \]

\[ 0.5 \]

\[ 1.0 \]

\[ 1.5 \]

\[ 2.0 \]
Universal Truths
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- Spectrum of excited states, and elastic and transition form factors provide unique information about long-range interaction between light-quarks and distribution of hadron’s characterising properties amongst its QCD constituents.
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- Running of quark mass entails that calculations at even modest $Q^2$ require a Poincaré-covariant approach. Covariance requires existence of quark orbital angular momentum in hadron’s rest-frame wave function.
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Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons.
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Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons. Problem, e.g., DCSB - an established keystone of low-energy QCD and the origin of constituent-quark masses - has not yet been realised in the light-front formulation. Resolution – coherent contribution from countable infinity of higher Fock-state components. (Brodsky, Roberts, Shrock, Tandy – in progress.)
QCD’s Challenges

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4th Workshop on Exclusive Reactions at High Momentum Transfer, 18-21 May 2010
Quark and Gluon Confinement

No matter how hard one strikes the proton, one cannot liberate an individual quark or gluon
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  - Very unnatural pattern of bound state masses
  - e.g., Lagrangian (pQCD) quark mass is small but ... no degeneracy between \( J^P=+ \) and \( J^P=- \)
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- Neither of these phenomena is apparent in QCD’s Lagrangian yet they are the dominant determining characteristics of real-world QCD.
QCD’s Challenges

Understand Emergent Phenomena

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- QCD – Complex behaviour arises from apparently simple rules
Charting the Interaction between light-quarks
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Charting the Interaction between light-quarks

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- Question of light-quark confinement can be translated into the challenge of charting the infrared behavior of QCD’s \textit{universal} $\beta$-function
- This function may depend on the scheme chosen to renormalise the quantum field theory but it is unique within a given scheme.
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- This is a well-posed problem whose solution is an elemental goal of modern hadron physics.
What is the light-quark Long-Range Potential?
Potential between static (infinitely heavy) quarks measured in simulations of lattice-QCD is not related in any known way to the light-quark interaction.
Charting the Interaction between light-quarks

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E.g.: Extant studies of mesons show that the properties of hadron excited states are a great deal more sensitive to the long-range behaviour of $\beta$-function than those of the ground state.
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Steady quantitative progress is being made with a scheme that is systematically improvable. (See nucl-th/9602012 and references thereto.)
Charting the Interaction between light-quarks

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- To realise this goal, a nonperturbative symmetry-preserving DSE truncation is necessary.

- On other hand, at present significant qualitative advances possible with symmetry-preserving kernel Ansätze that express important additional nonperturbative effects $- M(p^2)$ – difficult/impossible to capture in any finite sum of contributions.
\[ S_f(p)^{-1} = Z_2 \left( i\gamma \cdot p + m_f^{\text{bm}} \right) + \Sigma_f(p), \]

\[ \Sigma_f(p) = Z_1 \int_q^\Lambda g^2 D_{\mu\nu}(p - q) \frac{\lambda^a}{2} \gamma_\mu S_f(q) \frac{\lambda^a}{2} \Gamma^f_\nu(q, p), \]
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- \( Z_{1,2}(\zeta^2, \Lambda^2) \) are respectively the vertex and quark wave function renormalisation constants, with \( \zeta \) the renormalisation point.

- \( m_{f}^{bm}(\Lambda) \) is the Lagrangian current-quark bare mass.

- \( D_{\mu\nu}(k) \) is the dressed-gluon propagator.

- \( \Gamma_{\nu}^f(q, p) \) is the dressed-quark-gluon vertex.
\[ S_f(p)^{-1} = Z_2 (i \gamma \cdot p + m_{f}^{bm}) + \Sigma_f(p), \]
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- \( \Gamma_{\nu}^f(q, p) \) is the dressed-quark-gluon vertex.

Suppose one has in-hand the exact form of \( \Gamma_{\nu}^f(q, p) \). What is the associated Symmetry-preserving Bethe-Salpeter Kernel?
Standard form, familiar from textbooks

\[
\left[ \Gamma_j^\pi (k; P) \right]_{tu} = \int_q^{\Lambda} \left[ S(q + P/2) \Gamma_j^\pi (q; P) S(q - P/2) \right]_{sr} K_{rs}^{rs} (q, k; P)
\]

\[
K(q, k; P): \text{Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel}
\]
Bound-state DSE

Bethe-Salpeter Equation

- Standard form, familiar from textbooks

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- Compact. Visually appealing. Correct.
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\[K(q, k; P)\]: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

- **Compact. Visually appealing. Correct.**
- **Blocked progress for more than 60 years.**
L. Chang and C. D. Roberts
0903.5461 [nucl-th], Phys. Rev. Lett. 103 (2009) 081601

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Bethe-Salpeter Equation
General Form

Equivalent exact form:

\[ \Gamma_{5\mu}^{fg}(k; P) = Z_2 \gamma_5 \gamma_{1\mu} \]

\[ - \int_q g^2 D_{\alpha\beta}(k - q) \frac{\lambda^a}{2} \gamma_\alpha S_f(q+) \Gamma_{5\mu}^{fg}(q; P) S_g(q-) \frac{\lambda^a}{2} \Gamma_{\beta}^{g}(q-, k-) \]

\[ + \int_q g^2 D_{\alpha\beta}(k - q) \frac{\lambda^a}{2} \gamma_\alpha S_f(q+) \frac{\lambda^a}{2} \Lambda_{5\mu\beta}^{fg}(k, q; P), \]

(Poincaré covariance, hence \( q_\pm = q \pm P/2 \), etc., without loss of generality.)
Equivalent exact form:

\[
\begin{align*}
\Gamma_{5\mu}^{fg}(k; P) &= Z_2 \gamma_5 \gamma_\mu \\
&- \int_q g^2 D_{\alpha\beta}(k - q) \frac{\lambda_\alpha}{2} \gamma_\alpha \Sigma_f(q^+) \Gamma_{5\mu}^{fg}(q; P) \Sigma_g(q^-) \frac{\lambda_\alpha}{2} \Gamma_{5\beta}^g(q^-, k^-) \\
&+ \int_q g^2 D_{\alpha\beta}(k - q) \frac{\lambda_\alpha}{2} \gamma_\alpha \Sigma_f(q^+) \frac{\lambda_\alpha}{2} \Lambda_{5\mu\beta}^{fg}(k, q; P),
\end{align*}
\]

(Poincaré covariance, hence \(q_\pm = q \pm P/2\), etc., without loss of generality.)

In this form . . . \(\Lambda_{5\mu\beta}^{fg}\)

is completely defined via the dressed-quark self-energy
Bethe-Salpeter equation introduced in 1951
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Newly-derived Ward-Takahashi identity

\[ P_\mu \Lambda_{fg^5}^{\mu \beta}(k, q; P) = \Gamma_f^{\mu}(q_+, k_+) i\gamma_5 + i\gamma_5 \Gamma_g^{\mu}(q_-, k_-) + i [m_f(\zeta) + m_g(\zeta)] \Lambda_{f^5g^{\mu \beta}}(k, q; P), \]
Bethe-Salpeter equation introduced in 1951

Newly-derived Ward-Takahashi identity

\[ P_{\mu} \Lambda_{5\mu\beta}^{fg}(k, q; P) = \Gamma_{\beta}^{f}(q_{+}, k_{+}) i\gamma_{5} + i\gamma_{5} \Gamma_{\beta}^{g}(q_{-}, k_{-}) \]
\[ - i[m_{f}(\zeta) + m_{g}(\zeta)] \Lambda_{5\beta}^{fg}(k, q; P), \]

For first time: can construct \textit{Ansatz} for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex

Consistent means - all symmetries preserved!
Bethe-Salpeter equation introduced in 1951

Newly-derived Ward-Takahashi identity

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P_\mu \Lambda_{5\mu\beta}^{fg}(k, q; P) = \Gamma_{\beta}^{f}(q_+, k_+) i\gamma_5 + i\gamma_5 \Gamma_{\beta}^{g}(q_-, k_-) - i[m_f(\zeta) + m_g(\zeta)]\Lambda_{5\mu\beta}^{fg}(k, q; P),\]

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Procedure & results to expect . . .

see arXiv:1003.5006 [nucl-th]
|                  | exp. |       |       |
|------------------|------|-------|-------|
| mass $\alpha_1$ | 1230 |       |       |
| mass $\rho$     | 775  |       |       |
| mass-splitting  | 455  |       |       |

- Splitting known experimentally for more than 35 years.
- Hitherto, no explanation.
### Mass Splitting

\[ \alpha_1 - \rho \]

|        | exp. | rainbow-ladder | one-loop |
|--------|------|----------------|----------|
| mass \(\alpha_1\) | 1230 | 759            | 885      |
| mass \(\rho\)    | 775  | 644            | 764      |
| mass-splitting   | 455  | 115            | 121      |

- Systematic, symmetry-preserving, Poincaré-covariant DSE truncation scheme of nucl-th/9602012.
- Never better than \(\sim \frac{1}{4}\) of splitting.
- Constructing kernel skeleton-diagram-by-diagram, DCSB cannot be faithfully expressed: \(M(p^2)\) is absent!
Mass Splitting

\[ \alpha_1 - \rho \]

| \begin{array}{|c|c|c|c|}
|---|---|---|---|
| \text{mass} \ \alpha_1 & \text{exp.} & 1230 & \text{rainbow-ladder} |
| \text{mass} \ \rho & 775 & 644 & \text{one-loop} |
| \text{mass-splitting} & 455 & 115 & \text{Ball-Chiu consistent} |
| \text{mass-splitting} & 759 & 885 & 1066 |
| \text{mass-splitting} & 644 & 764 & 924 |
| \text{mass-splitting} & 115 & 121 & 142 |
\end{array} |

New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]

Ball-Chiu Ansatz for quark-gluon vertex

\[
\Gamma^{BC}_\mu(k, p) = \ldots + (k + p)_\mu \frac{B(k) - B(p)}{k^2 - p^2}
\]

Some effects of DCSB built into vertex

Explains \( \pi - \sigma \) splitting but not this problem

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Mass Splitting

Chang & Roberts arXiv:1003.5006 [nucl-th]

|            | exp. | rainbow-ladder | one-loop | Ball-Chiu consistent | Ball-Chiu plus anom. cm mom. |
|------------|------|----------------|----------|----------------------|-------------------------------|
| mass $a_1$| 1230 | 759            | 885      | 1066                 | 1230                          |
| mass $\rho$| 775  | 644            | 764      | 924                  | 745                           |
| mass-splitting | 455 | 115            | 121      | 142                  | 485                           |

New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]

Ball-Chiu augmented by quark anomalous chromomagnetic moment term: 

$$\Gamma_{\mu}(k, p) = \Gamma_{\mu}^{BC} + \sigma_{\mu\nu}(k - p)\nu \frac{B(k) - B(p)}{k^2 - p^2}$$
New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]

**DCSB is the answer.** Subtle interplay between competing effects, which can only now be explicated

Promise of first reliable prediction of light-quark meson spectrum, including the so-called hybrid and exotic states.
Frontiers of Nuclear Science: Theoretical Advances

\[ \Sigma = \Gamma \]

Gap Equation

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Theoretical Advances

\[ S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \]

Gap Equation

- Rapid acquisition of mass is
- effect of gluon cloud

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Rapid acquisition of mass is effect of gluon cloud}
\end{figure}
Mass from nothing.

In QCD a quark’s effective mass depends on its momentum. The function describing this can be calculated and is depicted here. Numerical simulations of lattice QCD (data, at two different bare masses) have confirmed model predictions (solid curves) that the vast bulk of the constituent mass of a light quark comes from a cloud of gluons that are dragged along by the quark as it propagates. In this way, a quark that appears to be absolutely massless at high energies ($m = 0$, red curve) acquires a large constituent mass at low energies.

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\[
S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}
\]
Maris, Roberts, Tandy
nucl-th/9707003

Goldberger-Treiman for pion
Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

\[ \Gamma_{\pi j}(k; P) = \tau_{\pi j} \gamma_5 \left[ iE_{\pi}(k; P) + \gamma \cdot PF_{\pi}(k; P) \right. \]
\[ \left. + \gamma \cdot k \cdot P G_{\pi}(k; P) + \sigma_{\mu\nu} k_\mu P_\nu H_{\pi}(k; P) \right] \]
Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

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+ \gamma \cdot k \cdot P G_{\pi}(k; P) + \sigma_{\mu\nu} k_\mu P_\nu H_{\pi}(k; P) \right]
\]

- Dressed-quark Propagator: \[ S(p) = \frac{1}{i\gamma \cdot p A(p^2) + B(p^2)} \]
Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

\[ \Gamma_{\pi j}(k; P) = \tau^{\pi j} \gamma_5 \left[ iE_{\pi}(k; P) + \gamma \cdot P F_{\pi}(k; P) + \gamma \cdot k \cdot P G_{\pi}(k; P) + \sigma_{\mu\nu} k_\mu P_\nu H_{\pi}(k; P) \right] \]

- Dressed-quark Propagator: \( S(p) = \frac{1}{i\gamma \cdot p A(p^2) + B(p^2)} \)

- Axial-vector Ward-Takahashi identity

\[ f_\pi E_{\pi}(k; P = 0) = B(p^2) \]
Pseudoscalar Bethe-Salpeter amplitude

\[ \Gamma_{\pi j}(k; P) = \tau^{\pi j} \gamma_5 \left[ i E_{\pi}(k; P) + \gamma \cdot PF_{\pi}(k; P) + \gamma \cdot k \cdot P G_{\pi}(k; P) + \sigma_{\mu\nu} k_\mu P_\nu H_{\pi}(k; P) \right] \]

Dressed-quark Propagator:

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\[ f_{\pi} E_{\pi}(k; P = 0) = B(p^2) \]
\[ F_R(k; 0) + 2 f_{\pi} F_{\pi}(k; 0) = A(k^2) \]
\[ G_R(k; 0) + 2 f_{\pi} G_{\pi}(k; 0) = 2A'(k^2) \]
\[ H_R(k; 0) + 2 f_{\pi} H_{\pi}(k; 0) = 0 \]
Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

\[ \Gamma_{\pi j}(k; P) = \tau^\pi j \gamma_5 \left[ i E_{\pi}(k; P) + \gamma \cdot PF_{\pi}(k; P) \right. \\
+ \left. \gamma \cdot k \, k \cdot P \, G_{\pi}(k; P) + \sigma_{\mu\nu} k_{\mu} P_{\nu} \, H_{\pi}(k; P) \right] \]

- Dressed-quark Propagator:

\[ S(p) = \frac{1}{i \gamma \cdot p A(p^2) + B(p^2)} \]

- Axial-vector Ward-Takahashi identity

\[ f_{\pi} E_{\pi}(k; P = 0) = B(p^2) \]
\[ F_R(k; 0) + 2 f_{\pi} F_{\pi}(k; 0) = A(k^2) \]
\[ G_R(k; 0) + 2 f_{\pi} G_{\pi}(k; 0) = 2 A'(k^2) \]
\[ H_R(k; 0) + 2 f_{\pi} H_{\pi}(k; 0) = 0 \]

Exact in Chiral QCD
What does this mean for observables?
What does this mean for observables?

![Graph showing the dependence of \( q^2 F_\pi(q^2) \) on \( q^2 \)]

- Only \( E_\pi \to 1/Q^4 \)
- Including \( F_\pi \to 1/Q^2 \)
What does this mean for observables?

\[ \left( \frac{Q}{2} \right)^2 = 2 \text{ GeV}^2 \]

\[ \Rightarrow Q^2 = 8 \text{ GeV}^2 \]

Pseudovector components dominate ultraviolet behaviour of electromagnetic form factor.
GT for pion
– Contact Interaction

Guttierez, Bashir, Cloët, Roberts:
arXiv:1002.1968 [nucl-th]

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Bethe-Salpeter amplitude can’t depend on relative momentum

⇒ General Form

$$\Gamma_\pi(P) = i\gamma_5 E_\pi(P) + \frac{1}{M_Q} \gamma \cdot PF_\pi(P)$$
Bethe-Salpeter amplitude can’t depend on relative momentum

⇒ General Form

\[ \Gamma_\pi(P) = i\gamma_5 E_\pi(P) + \frac{1}{M_Q} \gamma \cdot PF_\pi(P) \]

Solve chiral-limit gap and Bethe-Salpeter equations

\[ P^2 = 0 : M_Q = 0.40, \quad E_\pi = 0.98, \quad \frac{F_\pi}{M_Q} = 0.50 \]
Bethe-Salpeter amplitude can’t depend on relative momentum

⇒ General Form

\[ \Gamma_\pi(P) = i\gamma_5 E_\pi(P) + \frac{1}{M_Q} \gamma \cdot P F_\pi(P) \]

Solve chiral-limit gap and Bethe-Salpeter equations

\[ P^2 = 0 : \quad M_Q = 0.40 , \quad E_\pi = 0.98 , \quad \frac{F_\pi}{M_Q} = 0.50 \]

Origin of pseudovector component: \( E_\pi \) drives \( F_\pi \)

RHS Bethe-Salpeter equation:

\[ \gamma_\mu S(k + P/2) i\gamma_5 E_\pi S(k - P/2) \gamma_\mu \]
GT for pion
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- Bethe-Salpeter amplitude can’t depend on relative momentum
  ⇒ General Form
  \[ \Gamma_\pi(P) = i\gamma_5 E_\pi(P) + \frac{1}{M_Q} \gamma \cdot P F_\pi(P) \]

- Solve chiral-limit gap and Bethe-Salpeter equations
  \[ P^2 = 0 : M_Q = 0.40, \quad E_\pi = 0.98, \quad \frac{F_\pi}{M_Q} = 0.50 \]

- Origin of pseudovector component: \( E_\pi \) drives \( F_\pi \)
  - RHS Bethe-Salpeter equation:
    \[ \gamma_\mu S(k + P/2)i\gamma_5 E_\pi S(k - P/2)\gamma_\mu \]
  - Has pseudovector component
    \[ \sim E_\pi[\sigma S(k_+)\sigma V(k_-) + \sigma S(k_-)\sigma V(k_+)] \]
Bethe-Salpeter amplitude can’t depend on relative momentum

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Hence \( F_\pi \) on LHS is forced to be nonzero because \( E_\pi \) on RHS is nonzero owing to DCSB
Bethe-Salpeter amplitude: General Form

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This behaviour dominates for \[ Q^2 \gtrsim M_Q^2 \frac{E_\pi}{F_\pi} > 0.8 \text{ GeV}^2 \]
Computation: Elastic Pion Form Factor

- DSE prediction: $M(p^2)$; i.e., interaction $\frac{1}{|x - y|^2}$
- cf. $M(p^2) = \text{Constant}$; i.e., interaction $\delta^4(x - y)$
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Single mass-scale parameter in both studies
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Same predictions for $Q^2 = 0$ properties

Disagreement $> 20\%$ for $Q^2 > M^2$
Trang: PhD Thesis (Kent State U.)
Trang, Tandy, Bashir, Roberts, in progress
Holt & Roberts: arXiv:1002.4666 [nucl-th]

**Ratio – Kaon/Pion**

**u-valence distribution**

data: Badier, *et al.*, Phys. Lett. **B 93** (1980) 354

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Evolved $u_k$, $u_\pi$ Pade fits at $q_0 = 0.57$ GeV to $q = 5$ GeV data: Badier, *et al.*, Phys. Lett. **B 93** (1980) 354
### Ratio – Kaon/Pion

**u-valence distribution**

- **DSE–result obtained using interaction that predicted $F_\pi(Q^2)$**

![Graph showing u/K vs. x]

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Craig Roberts – *Exposing the Dressed Quark’s mass*

4th Workshop on Exclusive Reactions at High Momentum Transfer, 18-21 May 2010... 27 – p. 19/28
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Influence of $M(p^2)$ felt strongly for $x > 0.5$

QCD- $M(p^2) \Rightarrow$ prediction:

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Accessible at Upgraded JLab & Electron-Ion Collider
How does one incorporate dressed-quark mass function, $M(p^2)$, in study of baryons? Behaviour of $M(p^2)$ is essentially a quantum field theoretical effect.
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How does one incorporate dressed-quark mass function, $M(p^2)$, in study of baryons? Behaviour of $M(p^2)$ is essentially a quantum field theoretical effect.

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Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks

Tractable equation is founded on observation that an interaction which describes colour-singlet mesons also generates quark-quark (diquark) correlations in the colour-$\bar{3}$ (antitriplet) channel.
R. T. Cahill et al. Austral. J. Phys. 42 (1989) 129

Faddeev equation
Faddeev equation

\[ p_q \Psi^a \rightarrow p_{dq} \Psi^b \rightarrow p_q \Psi^a \rightarrow p_{dq} \Psi^b \]
Faddeev equation

\[ p_q \Psi^a \quad P \quad \Psi^b = p_d \Psi^a \quad P \quad \Psi^b \]

- Linear, Homogeneous Matrix equation
- Yields wave function (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon’s Rest Frame Amplitude has . . . \( s- \), \( p- \) & \( d- \)–wave correlations
Nucleon-Photon Vertex

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\[ \Psi_f \rightarrow \Psi_i \]

\[ P_f \rightarrow P_i \]

\[ Q \]

\[ \Gamma \]

\[ \mu \]

axial vector scalar

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Cloët, Roberts \textit{et al.}
- arXiv:0710.2059 [nucl-th]
- arXiv:0710.5746 [nucl-th]
- arXiv:0804.3118 [nucl-th]
- arXiv:0812.0416 [nucl-th] – \textit{Survey of nucleon EM form factors}

\[
\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}
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DSE-Faddeev Equation prediction

\[
\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}
\]

- RCQM - Miller
- GPD - Diehl
- Kelly fit
- Galster fit/Kelly \(G_M^n\)
- q(qq) Faddeev&DSE

B. Wojtsekhowski, Jefferson Lab E02-013 Collaboration, in preparation.

Figure courtesy S. Riordan
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DSE-Faddeev Equation prediction

Red solid curve

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DSE-Faddeev Equation prediction

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This evolution very sensitive to momentum-dependence dressed-quark propagator

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\[ \frac{G^n_M(Q^2)}{\mu_n G_D(Q^2)} \]
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Jefferson Lab E12-07-104, 12GeV Proposal.
Gilfoyle, Brooks, Hafidi for CLAS Collaboration

Anticipated error bars show systematic uncertainty.

Solid - Kelly
Dotted - Alberico \textit{et al.}
Squares - CLAS12 anticipated
Green - Previous world data.
Red - J.Lachniet \textit{et al.}
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Blue long-dashed curve

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Sensitivity to \( M(p^2) \) means experiments probe IR behaviour of strong running coupling

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Some current
12 GeV-related projects

Elucidate signals of $M(p^2)$ in $Q^2$-evolution of nucleon elastic and transition form factors; viz.,

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(M. Bhagwat, I. Cloët, H. Roberts)
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- Incorporate “resonant contributions” (pion cloud) in kernels of bound-state equations (e.g., arXiv:0802.1948 [nucl-th] & arXiv:0811.2018 [nucl-th]; and C.S. Fischer et al.)
Epilogue
DCSB exists in QCD.
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- It is manifest in dressed propagators and vertices
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- It is manifest in dressed propagators and vertices
- It predicts, amongst other things, that light current-quarks become heavy constituent-quarks: $4 \rightarrow 400$ MeV
- Pseudoscalar mesons are unnaturally light: $m_\rho = 770$ cf. $m_\pi = 140$ MeV
- Pseudoscalar mesons couple unnaturally strongly to light-quarks: $g_{\pi q\bar{q}} \approx 4.3$
- Pseudoscalar mesons couple unnaturally strongly to the lightest baryons $g_{\pi N\bar{N}} \approx 12.8 \approx 3g_{\pi q\bar{q}}$
DCSB impacts dramatically upon observables
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- Spectrum; e.g., splittings: $\sigma - \pi$ & $a_1 - \rho$
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  - Studies underway will identify observable signals of $M(p^2)$, the most important mass-generating mechanism for visible matter in the Universe
  - DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks
Now is an exciting time . . .
Positioned to unify phenomena as apparently disparate as

- Hadron spectrum
- Elastic and transition form factors, from small- to large-$Q^2$
- Parton distribution functions
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- Parton distribution functions

Key: an understanding of both the fundamental origin of nuclear mass and the far-reaching consequences of the mechanism responsible; namely, *Dynamical Chiral Symmetry Breaking*
| Section                                               | Equation/Expression                                      |
|-------------------------------------------------------|----------------------------------------------------------|
| 1. Universal Truths                                   |                                                          |
| 2. QCD's Challenges                                   |                                                          |
| 3. Charting the Interaction                           |                                                          |
| 4. Bound-state DSE                                     |                                                          |
| 5. BSE – General Form                                 |                                                          |
| 6. $\alpha_1 - \rho$                                  |                                                          |
| 7. Frontiers of Nuclear Science                       |                                                          |
| 8. Goldberger-Treiman for pion                        |                                                          |
| 9. GT – Contact Interaction                           |                                                          |
| 10. Computation: $F_\pi(Q^2)$                         |                                                          |
| 11. Kaon/Pion $u$-valence distribution                |                                                          |
| 12. Unifying Meson & Nucleon                          |                                                          |
| 13. Faddeev equation                                  |                                                          |
| 14. Nucleon-Photon Vertex                             |                                                          |
| 15. $\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}$                |                                                          |
| 16. $\frac{G^n_M(Q^2)}{\mu_n G_D(Q^2)}$               |                                                          |
| 17. Current Projects                                  |                                                          |