Probing the origin of mass using hadron form factors

Craig Roberts, Physics Division
Hadron Form Factors
Hadron Form Factors

Why?

- Classical QCD ... non-Abelian local gauge theory
- Remove the mass ... there’s no scale left
- **No dynamics in a scale-invariant theory**; only kinematics ... the theory looks the same at all length-scales ... there can be no clumps of anything ... *hence bound-states are impossible*.
- **Our Universe can’t exist**
- **Higgs boson doesn’t solve this problem** ... normal matter is constituted from light-quarks ... the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce
- **Where did it all begin?**
  ... becomes ... *Where did it all come from?*
- Classical chromodynamics ... non-Abelian local gauge theory
- Local gauge invariance; but there is no confinement without a mass-scale
  - Three quarks can still be colour-singlet
  - Colour rotations will keep them colour singlets
  - But they need have no proximity to one another
    ... proximity is meaningless in a scale-invariant theory
- Whence mass ... equivalent to whence a mass-scale ... equivalent to whence a confinement scale
- Understanding the origin and absence of mass in QCD is quite likely inseparable from the task of understanding confinement.
  Existence alone of a scale anomaly answers neither question
Scale-dependent probe of hadron internal structure

Map the transition
- from dressed quasiparticles in the confinement domain
- to Feynman partons in the conformal limit

Theoretically, full machinery of renormalisable quantum field theory is necessary to expose the signatures of this transition
- Power laws and scaling ("easy")
- Anomalous dimensions and scaling violations ("hard")

Scaling violations are QCD

Answers are not enough ... Derivation is understanding

Emergence of mass (confinement) is encoded in a reductive elucidation and explanation of the details of this transition
\[ \Delta_{\mu\nu}^{-1}(q) = \] 

\[ \Pi_{\mu\nu}(q) = P_{\mu\nu}(g)\Pi(q) \]

\[ P_{\mu\nu}(q) = g_{\mu\nu} - q_{\mu}q_{\nu}/q^{2} \]
Running gluon mass
\[ d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2; \zeta)} \]
\[ \alpha_s(0) = 2.77 \approx 0.9\pi, \quad m_g^2(0) = (0.46 \text{ GeV})^2 \]

Gluons are **cannibals** – a particle species whose members become massive by eating each other!

**Expression of trace anomaly:**
Massless glue becomes massive gluon mass-squared function

\[ m_g^2(k^2) \approx \frac{\mu_g^4}{\mu_g^2 + k^2} \]

Combining DSE, lQCD and pQCD analyses of QCD’s gauge sector

**Power-law suppressed in ultraviolet, so invisible in perturbation theory**

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Craig Roberts. Probing the Origin of Mass (54p)
Gauge boson cannibalism
... a new physics frontier ... within the Standard Model

Asymptotic freedom means
... ultraviolet behaviour of QCD is controllable

Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
- Gluons and quarks with
  wavelength $\lambda > 2/\text{mass} \approx 1 \text{ fm}$
  decouple from the dynamics ... Confinement?!

How does that affect observables?
- It will have an impact in any continuum study
- Possibly (probably?) plays a role in gluon saturation ...
  In fact, could be a harbinger of gluon saturation?
All continuum and lattice solutions for Landau-gauge gluon & quark propagators exhibit an inflection point in $k^2$

$\Rightarrow$ Violate reflection positivity = sufficient for confinement

$\Rightarrow$ Such states have negative norm

$\Rightarrow$ All observable states of a physical Hamiltonian have positive norm

$\Rightarrow$ Negative norm states are not observable

Inflexion point corresponds to $r_c \approx 0.5$ fm:
Parton-like behaviour at shorter distances;
But propagation characteristics changed dramatically at larger distances.

$m_g \approx ½ m_p \approx 0.47$ GeV
Confinement is dynamical
A quark begins to propagate

But after each “step” of length $\sigma$, on average, an interaction occurs, so that the quark loses its identity, sharing it with other partons

Finally, a cloud of partons is produced, which coalesces into colour-singlet final states

Confinement is a dynamical phenomenon!
A quark begins to propagate.

But after each "step" of length $\sigma$, on average, an interaction occurs, so that the quark loses its identity, sharing it with other partons.

Finally, a cloud of partons is produced, which coalesces into colour-singlet final states.

Confinement in hadron physics is largely a dynamical phenomenon, intimately connected with the fragmentation effect. It is unlikely to be comprehended without simultaneously breaking chiral symmetry.

Confinement is a dynamical phenomenon!
What’s happening out here?!

QCD’s Running Coupling
QED Running Coupling

- Quantum gauge field theories in four spacetime dimensions,
  - Lagrangian couplings and masses come to depend on a mass scale
  - Can often be related to the energy or momentum at which a given process occurs.
- Archetype is QED, for which there is a sensible perturbation theory.
- QED, owing to the Ward identity:
  - a single running coupling
  - measures strength of the photon-charged-fermion vertex
  - can be obtained by summing the virtual processes that dress the bare photon, viz. by computing the photon vacuum polarisation.
- QED's running coupling is known to great accuracy and the running has been observed directly.
Modern continuum & lattice methods for analysing gauge sector enable analogous quantity to be defined in QCD

Combined continuum and lattice analysis of QCD’s gauge sector yields a parameter-free prediction

Near precise agreement with the process-dependent effective charge defined via the Bjorken sum-rule

N.B. Qualitative change in $\hat{\alpha}_\text{PI}(k)$ at $k \approx \frac{1}{2} m_p$
QCD Effective Charge

- $\hat{\alpha}_{pl}$ is a new type of effective charge
  - direct analogue of the Gell-Mann–Low effective coupling in QED, i.e. completely determined by the gauge-boson two-point function.

- Prediction for $\hat{\alpha}_{pl}$ is parameter-free
  - Draws best from continuum & lattice results for QCD’s gauge sector

- Prediction for $\hat{\alpha}_{pl}$ smoothly unifies the nonperturbative and perturbative domains of the strong-interaction theory.

- $\hat{\alpha}_{pl}$ is
  - process-independent
  - known to unify a vast array of observables

- $\hat{\alpha}_{pl}$ possesses an infrared-stable fixed-point
  - Nonperturbative analysis demonstrating absence of a Landau pole in QCD

- QCD is IR finite, owing to dynamical generation of gluon mass-scale
QCD - a paradigm for extending the Standard Model?

- How do quantum field theories fail?
  - Ultraviolet and infrared divergences
- Asymptotic freedom $\Rightarrow$ QCD is well-defined at UV momenta
- Dynamical generation of gluon mass function, large on $k^2 \approx 0$,
  $\Rightarrow$ the infrared domain of QCD is self-regularizing
- QCD is therefore unique amongst known four-dimensional quantum field theories
  - Potentially self-consistent
  - Defined & internally consistent at all momenta (e.g., no Landau pole)
- If all this is true, then QCD can serve as a basis for theories that take physics beyond the Standard Model
\[ S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \]
Dynamical chiral symmetry breaking (DCSB) is a key emergent phenomenon in QCD

Expressed in hadron wave functions not in vacuum condensates

Contemporary theory indicates that DCSB is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of mass from nothing.

Dynamical, not spontaneous

- Add nothing to $QCD$, No Higgs field, nothing! Effect achieved purely through quark+gluon dynamics.

✓ Trace anomaly: massless quarks become massive
Enigma of Mass
Pion’s Bethe-Salpeter amplitude

Solution of the Bethe-Salpeter equation

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

- Dressed-quark propagator

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

- Axial-vector Ward-Takahashi identity entails

\[ f_\pi E_\pi(k; P = 0) = B(k^2) \]

**Miracle:** two body problem solved, almost completely, once solution of one body problem is known
Rudimentary version of this relation is apparent in Nambu’s Nobel Prize work.
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\[ f_\pi \ E_\pi(p^2) \iff B(p^2) \]

Pion exists if, and only if, mass is dynamically generated.
The quark level Goldberger-Treiman relation shows that DCSB has a very deep and far reaching impact on physics within the strong interaction sector of the Standard Model; viz.,

Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

This emphasises that Goldstone's theorem has a pointwise expression in QCD.

Hence, pion properties are an almost direct measure of the dressed-quark mass function.

Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.

This algebraic identity is why QCD’s pion is massless in the chiral limit

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Observing Mass
Pion’s valence-quark Distribution Amplitude

- Methods have been developed that enable direct computation of the pion’s light-front wave function
- \( \varphi_\pi(x) = \text{twist-two parton distribution amplitude} = \text{projection of the pion’s Poincaré-covariant wave-function onto the light-front} \)

\[
\varphi_\pi(x) = Z_2 \text{tr}_{CD} \int \frac{d^4k}{(2\pi)^4} \delta(n \cdot k - xn \cdot P) \gamma_5 \gamma \cdot n S(k) \Gamma_\pi(k; P) S(k - P)
\]

- Results have been obtained with the DCSB-improved DSE kernel, which unifies matter & gauge sectors

\( \varphi_\pi(x) \propto x^\alpha (1-x)^\alpha, \text{ with } \alpha \approx 0.5 \)

Pion’s valence-quark Distribution Amplitude

- Continuum-QCD prediction: marked broadening of $\varphi_\pi(x)$, which owes to DCSB
Lattice-QCD & Pion’s valence-quark PDA

- Isolated dotted curve = conformal QCD
- Green curve & band = result inferred from the single pion moment computed in lattice-QCD
- Blue solid curve = DSE prediction obtained with DB kernel
- DSE & lQCD predictions are practically indistinguishable
- arXiv:1702.00008, Pion Distribution Amplitude from Lattice QCD
  Jian-Hui Zhang, Jiunn-Wei Chen, Xiangdong Ji, Luchang Jin, Huey-Wen Lin

Pion electromagnetic form factor at spacelike momenta

- PDA Broadening has enormous impact on understanding $F_\pi(Q^2)$

Pion’s electromagnetic form factor

A: Internally-consistent DSE prediction

C: Hard-scattering formula with broad PDA

Figure 2.2: Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.
Pion electromagnetic form factor at spacelike momenta
L. Chang, I. C. Cloët, C. D. Roberts, S. M. Schmidt and P. C. Tandy,

- PDA Broadening has enormous impact on understanding $F_\pi(Q^2)$
- Appears that JLab12 is within reach of first verification of a QCD hard-scattering formula

**Figure 2.2:** Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.
Do endpoint singularities invalidate collinear factorisation at accessible scales?

No ... because the nonperturbatively-generated infrared gluon mass provides the infrared cut-off needed to screen this singularity.

Can be checked – once one has a pion light-front wave function:

- GPD in overlap representation provides direct access to $F_\pi(Q^2)$

- Leading-twist valence-parton LFWF is available
Validity of hard scattering formulae?

- Leading-twist valence-parton light-front wave function
- Direct calculation of $F_\pi(Q^2)$ via overlap representation of GPD
- No assumption of validity of collinear factorisation
- Computational verification ... good approximation on $Q^2 > 7$ GeV$^2$

We give an accurate determination of the vector (electromagnetic) form factor, $F(Q^2)$, for a light meson up to squared momentum transfer $Q^2$ values of 6 GeV$^2$ for the first time from full lattice QCD, including u, d, s and c quarks in the sea at multiple values of the lattice spacing. Our results show good control of lattice discretisation and sea quark mass effects, indicating that higher $Q^2$ values could be reached in future with finer lattices. We study a pseudoscalar meson made of valence s quarks but the qualitative picture obtained applies also to the $\pi$ meson, relevant to upcoming experiments at Jefferson Lab. We find that $Q^2F(Q^2)$ becomes flat in the region between $Q^2$ of 2 GeV$^2$ and 6 GeV$^2$, with a value well above that of the asymptotic perturbative QCD expectation, but well below that of the vector-meson dominance pole form appropriate to low $Q^2$ values. Our calculations open the way for further lattice QCD analysis of high-$Q^2$ form factors to shed light on where the perturbative QCD result emerges.

To obtain a flatter curve in better agreement with our results would require a broader distribution amplitude and a higher scale for $\alpha_s$ for less evolution. Such curves have been obtained for the $\pi$ in a recent Dyson-Schwinger approach [46], and it would be interesting to see if it can reproduce our results for the $\eta_s$. For this purpose we give the parameters for our continuum curve in the supplemental materials.
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<table>
<thead>
<tr>
<th></th>
<th>$m_{s\bar{s}}$</th>
<th>$f_{s\bar{s}}$</th>
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<tbody>
<tr>
<td>DSE 2004</td>
<td>0.69 GeV</td>
<td>0.13 GeV</td>
</tr>
<tr>
<td>Lattice 2017</td>
<td>0.6885(2)</td>
<td>0.1281(39)</td>
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</tbody>
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J. Koponen et al.:

**arXiv:1701.04250 [hep-lat]**

We give an accurate determination of the vector (electromagnetic) form factor, $F(Q^2)$, for a light meson up to squared momentum transfer $Q^2$ values of 6 GeV$^2$ for the first time from full lattice QCD, including u, d, s and c quarks in the sea at multiple values of the lattice spacing. Our results show good control of lattice discretisation and sea quark mass effects, indicating that higher $Q^2$ values could be reached in future with finer lattices. We study a pseudoscalar meson made of valence s quarks but the qualitative picture obtained applies also to the π meson, relevant to upcoming experiments at Jefferson Lab. We find that $Q^2 F(Q^2)$ becomes flat in the region between $Q^2$ of 2 GeV$^2$ and 6 GeV$^2$, with a value well above that of the asymptotic perturbative QCD expectation, but well below that of the vector-meson dominance pole form appropriate to low $Q^2$ values. Our calculations open the way for further lattice QCD analysis of high-$Q^2$ form factors to shed light on where the perturbative QCD result emerges.

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**Preliminary DSE result for s-massive pseudo-$\pi$**

... Internally consistent calculation, producing s-massive PDA $\propto [x(1-x)]^{0.8}$

... Independent confirmation of reality and impact of dilated PDAs on meson form factors

... Move on to baryons
Kaon electromagnetic form factor

- Chiral limit
  - $\pi$ & $K$ are degenerate
  - Internal structure is identical
    
    QCD's Nambu-Goldstone modes

- But ... in physical kaon, the Higgs mechanism plays a role
  - $s$-quark current mass is much greater than that of the $u$-quark
    
    \[ m_s \sim 25 \, m_u \]
  - Translates into IR difference in running masses
    
    \[ M_s(0) \sim 1.25 \, M_u(0) \]

- Comparison between $\pi$ & $K$ properties provides direct access to
  - interplay
  - feedback

  between strong and electroweak mass generating mechanisms
Kaon electromagnetic form factor

- Techniques developed for pion
  - PDA
  - Form factor
  also directly applicable to kaon
- Isolated dotted curve = conformal QCD
- Green curve & band = result inferred from the single pion moment computed in lattice-QCD
- Black solid and red dashed curves = band of DSE predictions
- Agreement between DSE & IQCD predictions, within errors

Kaon electromagnetic form factor

$$\exists Q_0 > \Lambda_{QCD} \mid Q^2 F_K(Q^2) \approx 16\pi\alpha_s(Q^2)f_K^2w_K^2(Q^2)$$

with $f_K = 0.110 \text{ GeV}$ and, for the $K^+$:

$$w_K^2 = e_s w_s^2 + e_u w_u^2, \quad w_s = \frac{1}{3} \int_0^1 dx \frac{1}{1-x} \varphi_K(x), \quad w_u = \frac{1}{3} \int_0^1 dx \frac{1}{x} \varphi_K(x)$$

- Solid blue curve = DSE (Maris-Tandy 2000) prediction
- Hard-scattering formula
  - Short- and long-dashed curves = DSE prediction for PDA yields result within this area
  - Green band = broad, skewed lQCD PDA
- Skewing is not the issue: 12%-15%, DSE- and lattice-QCD agree
- It’s extent of the broadening that generates the uncertainty
- JLab 12 has potential to settle the issue ... Meantime, extend $F_\pi(Q^2)$ analysis on entire spacelike domain $\rightarrow F_K(Q^2)$

The pion: an enigma within the Standard Model
Tanja Horn and Craig D. Roberts
Kaon elastic form factor at all spacelike momenta, Fei Gao, L. Chang, Y.-X. Liu and C. D. Roberts

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Kaon’s electromagnetic form factor

$\exists Q_0 > \Lambda_{\text{QCD}} \mid Q^2 F_K(Q^2) \sim Q^2 \geq Q_0^2 \quad 16\pi\alpha_s(Q^2)f_K^2w_K^2(Q^2)$

with [41] $f_K = 0.110\text{ GeV}$ and, for the $K^+$:

$w_K^2 = e_s w_s^2 + e_u w_u^2$,

$w_s = \frac{1}{3} \int_0^1 dx \frac{1}{1-x} \varphi_K(x), \quad w_u = \frac{1}{3} \int_0^1 dx \frac{1}{x} \varphi_K(x)$
QCD prediction ...

as $Q^2 \to \infty$

$$F_K(Q^2)/F_\pi(Q^2) = f_K^2/f_\pi^2 = 1.4$$

Logarithmic approach to pQCD limit

Direct calculation confirms validity of hard-scattering formula on $Q^2 > 8 \text{ GeV}^2$

$Q^2$-evolution of

- wave functions
- interaction current

essential to agreement between trends of direct calculation and hard scattering formula

- Restore hard-gluons omitted in all truncations used heretofore

Models typically tuned to generate correct power law, but then produce wrong anomalous dimension


Craig Roberts. Probing the Origin of Mass (54p)
Kaon elastic form factor at all spacelike momenta, Fei Gao, L. Chang, Y.-X. Liu and C. D. Roberts

- Hard-scattering formulae are valid on $Q^2 > 8$ GeV$^2$
- At leading order in pQCD, spacelike and timelike form factors are identical
- Confidence in prediction at timelike momenta, using direct mapping of spacelike behaviour
- Data ... problems?:
  - $F_\pi$ = factor of 2 too-large compared with DSE maximum
  - $F_K$ = factor of 1.5 too-large compared with DSE maximum
- Check normalisation
- Repeat experiments

Kaon cf. pion form factor timelike

DSE Prediction
generous error on dilated PDA

CLEO data
Seth et al. PRL 110 (2013) 022002

Holt & Gilman, Rept. Prog. Phys. 75 (2012) 086301: “The prospect for improving the measurements in the time-like region is excellent because of the $e^+e^-$ colliders in operation or recently in operation.”
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- **Current conservation**
  \( F_{uss}(0) = F_{uus}(0) \)

- **Under evolution:**
  \( \varphi_K \to 6 \times (1-x) \Rightarrow \omega_s \to \omega_u \Rightarrow \text{Ratio} \to 1 \)

- **Agreement between direct calculation and hard-scattering formula, using consistent PDA**

- **Ratio never exceeds 1.5 and Logarithmic approach to unity**

- **Typical signal of DCSB-dominance in flavour-symmetry breaking:**
  - \( M_s(0) \sim 1.25 M_u(0) \)
  - but this scale difference becomes irrelevant under evolution

Craig Roberts. Probing the Origin of Mass (54p)
Structure of Baryons
Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks.

Confinement and DCSB are readily expressed.

**Prediction**: owing to DCSB in QCD, strong diquark correlations exist within baryons.

Diquark correlations are not pointlike:
- Typically, \( r_{0^+} \sim r_\pi \) & \( r_{1^+} \sim r_\rho \) (actually 10% larger)
- They have soft form factors.

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Computations underway. First results available.

Di-quark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton’s light-front momentum.

Conformal limit:

\[ 120 x_1 x_2 x_3 \]

\[ \langle x_i \rangle = \frac{1}{3} \] ... peak of the distribution.

Realistic, finite size (0.7 fm)

Pointlike \( 0^+ \) diquark \([u(x_2)d(x_3)]\)

\( (0.6, 0.2, 0.2) \)
First IQCD results for n=0, 1 moments of the leading twist PDA of the nucleon are available

Used to constrain strength ($a_{11}$) of the leading-order term in a conformal expansion of the nucleon’s PDA:

$$\Phi(x_1, x_2, x_3) = 120 x_1 x_2 x_3 \left[ 1 + a_{11} P_{11}(x_1, x_2, x_3) + ... \right]$$

Shift in location of central peak is consistent with existence of diquark correlations within the nucleon
GEP5 Projected results

\[ F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2, \Lambda = 300 \text{ MeV} \]

Nucleon Form Factors
Prediction and measurement of ground-state elastic form factors is essential to increasing our understanding of strong-interaction ... many surprising discoveries already

However, alone, it is insufficient to explore and expose the infrared behaviour of the strong interaction

– the hydrogen ground-state didn’t give us QED

There are numerous nucleon $\rightarrow$ resonance transition form factors.

– The challenge of mapping their $Q^2$-dependence provides a vast array of novel ways to probe the infrared behaviour of the strong interaction, including the environment and energy sensitivity of correlations
- Jones-Scadron convention – simplest direct link to helicity conservation in pQCD

- Single set of inputs ...
  - dressed-quark mass function (same as that which predicted meson properties)
  - diquark amplitudes, masses, propagators
  - same current operator for elastic and transition form factors

- Prediction \( N \rightarrow \Delta \) transition is indistinguishable from data on \( Q^2 > 0.7 \text{ GeV}^2 \)
Predicted transition form factors

- Excellent agreement with data on $x>2$ (3)
- Like $\gamma N \rightarrow \Delta$, room for meson cloud on $x<2$ ... appears likely that cloud
  - Is a negative contribution that depletes strength on $0<x<2$
  - Has nothing to do with existence of zero; but is influential in shifting the zero in $F_2^*$ from $x=\frac{1}{4}$ to $x=1$
  - Is irrelevant on $x>2$ (3)

DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

Baryons

Critical issues:

- is there an environment sensitivity of DCSB and the dressed-quark mass function?

- are quark-quark correlations an essential element in the structure of all baryons?
  - E.g. N*(1535)(1/2)- and N*(1520)(3/2)- must involve unnatural-parity diquarks = pseudoscalar and vector diquarks ... Baryons possess far more complex internal structure than nucleon and Δ

Existing feedback between experiment and theory ⇒ no environment sensitivity for the nucleon, Δ-baryon and Roper resonance:

- DCSB in these systems is expressed in ways that can readily be predicted once its manifestation is understood in the pion, and this includes the generation of diquark correlations with the same character in each of these baryons.
Emergence:

- Confinement and dynamical chiral symmetry breaking in the Standard Model
  - How are they related?
    - Role of the pion seems to be key in answering these questions
- Conformal anomaly
  - Can have neither confinement nor DCSB if scale invariance of (classical) chromodynamics is not broken by quantisation
  - Know a mass-scale must exist, but only experience/experiment informs us of its value
  - Once size known, continuum and lattice-regularised quantum chromodynamics ⇒ gluons and quarks acquire momentum-dependent masses
    - Values are large in the infrared $m_g \propto 500 \text{ MeV} \approx m_p/2$ & $M_q \propto 350 \text{ MeV} \approx m_p/3$
    - Seem to be the foundation for DCSB
    - And can be argued to explain confinement as a dynamical phenomenon, tied to fragmentation functions
Reductive explanation

- Fundamental equivalence of the one- and two-body problems in the matter-sector
  - Quark gap equation \( \equiv \) Pseudoscalar meson Bethe-Salpeter equation

- Entails that properties of the pion – Nature’s lightest observable strong-interaction excitation – are the cleanest means by which to probe the origin and manifestations of mass in the Standard Model

- Numerous predictions that can be tested at contemporary and planned facilities
  - JLab 12GeV, COMPASS, ..., EIC

- Refining those predictions *before experiments begin* will require combination of all existing nonperturbative approaches to strong interaction dynamics in the Standard Model
Epilogue

➢ Reductive explanation

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| 9. | Zhu-Fang CUI (Nanjing U.) |
| 10. | J. Javier COBOS-MARTINEZ (U Michoácan) |
| 11. | Minghui DING (Nankai U.) |
| 12. | Fei GAO (Peking U.) |
| 13. | L. Xiomara Gutiérrez-Guerrero (Sonora U.) |
| 14. | Cédric MEZRAG (ANL, Irfu Saclay) |
| 15. | Mario PITSCHMANN (Vienna) |
| 16. | Si-xue QIN (ANL, U. Frankfurt am Main, PKU) |
| 17. | Eduardo ROJAS (Antioquia U.) |
| 18. | Jorge SEGOVIA (TU-Munich, ANL) |
| 19. | Chao SHI (ANL, Nanjing U.) |
| 20. | Shu-Sheng XU (Nanjing U.) |
| 21. | Adnan Bashir (U Michoácan) |
| 22. | Daniele Binosi (ECT*) |
| 23. | Stan Brodsky (SLAC) |
| 24. | Lei Chang (Nankai U.) |
| 25. | Ian Cloët (ANL) |
| 26. | Bruno El-Bennich (São Paulo) |
| 27. | Roy Holt (ANL) |
| 28. | Tanja Horn (Catholic U. America) |
| 29. | Yu-Xin Liu (PKU) |
| 30. | Hervé Moutarde (CEA, Saclay) |
| 31. | Joannis Papavassiliou (U.Valencia) |
| 32. | M. Ali Paracha (NUST, Islamabad) |
| 33. | Alfredo Raya (U Michoácan) |
| 34. | Jose Rodríguez Qintero (U. Huelva) |
| 35. | Franck Sabatié (CEA, Saclay) |
| 36. | Sebastian Schmidt (IAS-FZJ & JARA) |
| 37. | Peter Tandy (KSU) |
| 38. | Tony Thomas (U.Adelaide) |
| 39. | Shaolong WAN (USTC) |
| 40. | Hong-Shi ZONG (Nanjing U) |