Strong diquark correlations inside the proton

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The electromagnetic current can be generally written as:

\[ J_\mu(K, Q) = i e \Lambda_+(P_f) \Gamma_\mu(K, Q) \Lambda_+(P_i) \]

- Incoming/outgoing nucleon momenta: \( P_i^2 = P_f^2 = -m_N^2 \).
- Photon momentum: \( Q = P_f - P_i \), and total momentum: \( K = (P_i + P_f)/2 \).
- The on-shell structure is ensured by the Nucleon projection operators.

Vertex decomposes in terms of two form factors:

\[ \Gamma_\mu(K, Q) = \gamma_\mu F_1(Q^2) + \frac{1}{2m_N} \sigma_{\mu\nu} Q_\nu F_2(Q^2) \]

The electric and magnetic (Sachs) form factors are a linear combination of the Dirac and Pauli form factors:

\[ G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4m_N^2} F_2(Q^2) \]
\[ G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \]

They are obtained by any two sensible projection operators. Physical interpretation:

- \( G_E \Rightarrow \) Momentum space distribution of nucleon’s charge.
- \( G_M \Rightarrow \) Momentum space distribution of nucleon’s magnetization.
Perturbative QCD predictions for the Dirac and Pauli form factors:

\[ F_1^p \sim \frac{1}{Q^4} \quad \text{and} \quad F_2^p \sim \frac{1}{Q^6} \quad \Rightarrow \quad Q^2 \frac{F_2^p}{F_1^p} \sim \text{const.} \]

Consequently, the Sachs form factors scale as:

\[ G_E^p \sim \frac{1}{Q^4} \quad \text{and} \quad G_M^p \sim \frac{1}{Q^4} \quad \Rightarrow \quad \frac{G_E^p}{G_M^p} \sim \text{const.} \]
Updated perturbative QCD prediction

\[ Q^2 F_2^p / F_1^p \sim \text{const.} \quad \Rightarrow \Rightarrow \Rightarrow \quad Q^2 F_2^p / F_1^p \sim \ln^2 \left( Q^2 / \Lambda^2 \right) \]

The prediction has the important feature that it includes components of the quark wave function with nonzero orbital angular momentum.

Curve: \( \ln^2 \left( Q^2 / \Lambda^2 \right) \) for \( \Lambda = 0.3 \, \text{GeV} \) which is normalized to the data at \( 2.5 \, \text{GeV}^2 \).\[ \rightarrow \Lambda \text{ is a soft scale parameter related to the size of the nucleon.} \]
Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

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In view of these facts it is of significant interest to look for the (non-perturbative) origin of the observed $Q^2$-dependence of the Dirac and Pauli form factors
Hadron physics is dominated by non-perturbative QCD dynamics

- Explain how quarks and gluons bind together to form hadrons.
- Origin of the 98% of the mass of the proton ⇒ visible universe.

Given QCD’s complexity:
- The best promise for progress is a strong interplay between experiment and theory.

Non-perturbative phenomena

Quark and gluon confinement

- Colored particles have never been seen isolated

Dynamical chiral symmetry breaking

- Hadrons do not follow the chiral symmetry pattern

Neither of these phenomena is apparent in QCD’s Lagrangian

However!

They play a dominant role determining characteristics of real-world QCD
Non-perturbative QCD: Confinement and dynamical chiral symmetry breaking (II)

From a quantum field theoretical point of view: Emergent phenomena are associated with dramatic, dynamically driven changes in the analytic structure of QCD’s propagators and vertices.

☞ Dressed-gluon propagator in Landau gauge:

\[ i\Delta_{\mu\nu} = -iP_{\mu\nu}\Delta(q^2), \quad P_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu / q^2 \]

- An inflexion point at \( p^2 > 0 \).
- Breaks the axiom of reflection positivity.
- No physical observable related with.

☞ Dressed-quark propagator in Landau gauge:

\[ S^{-1}(p) = Z_2(i\gamma \cdot p + m^{bm}) + \Sigma(p) = \left( \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \right)^{-1} \]

- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of i.e. the 98% of the mass of the proton and the large splitting between parity partners.
Definition: The quantum equations of motion (of QCD) whose solutions are the Schwinger functions.

Continuum Quantum Field Theoretical Approach:
- Generating tool for perturbation theory → No model-dependence.
- ALSO Nonperturbative tool → Any model-dependence should be incorporated here.

Nice consequences:
- Allows the study of the quark-quark interaction in the whole range of momenta. → Analysis of the infrared behaviour is crucial to disentangle confinement and dynamical chiral symmetry breaking.
- Connects quark-quark interaction with experimental observables. → e.g. It is via the $Q^2$- evolution of the form factors that one gains access to the running of QCD’s coupling and masses from the infrared into the ultraviolet.
The bound-state problem in quantum field theory

Hadrons are studied via Poincaré covariant bound-state equations

**Mesons**
- A 2-body bound state problem in quantum field theory.
- Properties emerge from solutions of the **Bethe-Salpeter equation**:

\[
\Gamma(k; P) = \int \frac{d^4q}{(2\pi)^4} K(q, k; P) S(q+P) \Gamma(q; P) S(q)
\]

The kernel is intimately related with that of the gap equation.

**Baryons**
- A 3-body bound state problem in quantum field theory.
- Properties emerge from solutions of the **Faddeev equation**.
- The Faddeev equation sums all possible quantum field theoretical exchanges and interactions that can take place between the three valence quarks.
Diquarks inside baryons

The attractive nature of quark-antiquark correlations in a color-singlet meson is also attractive for $\bar{3}_c$ quark-quark correlations within a color-singlet baryon.

Diquark correlations:

- A tractable truncation of the Faddeev equation.
- In $N_c = 2$ QCD: diquarks can form color singlets with are the baryons of the theory.
- In our approach: Non-pointlike color-antitriplet and fully interacting.

Diquark composition of the Nucleon

Positive parity state

- Pseudoscalar and vector diquarks
  - Ignored
  - Wrong parity
  - Larger mass-scales

- Scalar and axial-vector diquarks
  - Dominant
  - Right parity
  - Shorter mass-scales

Thanks to G. Eichmann.
One must specify how the photon couples to the constituents within the baryon.

Six contributions to the current in the quark-diquark picture

- **Coupling of the photon to the dressed quark.**
- **Coupling of the photon to the dressed diquark:**
  - Elastic transition.
  - Induced transition.
- **Exchange and seagull terms.**
Sachs electric and magnetic form factors

**$Q^2$-dependence of proton form factors:**

![Graph of $G^p_E$ and $G^p_M$ vs. $x = Q^2/m_N^2$.]

**$Q^2$-dependence of neutron form factors:**

![Graph of $G^n_E$ and $G^n_M$ vs. $x = Q^2/m_N^2$.]

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Unit-normalised ratio of Sachs electric and magnetic form factors

Contact and QCD-kindred quark-quark interaction predict a zero crossing

- Contact interaction
  - Momentum-independent dressed-quark mass
  - Hard Dirac and Pauli form factors
  - Sachs ratio possesses a zero at very low-$Q^2$.

- QCD-kindred int.
  - Momentum-dependent dressed-quark mass
  - Correct Dirac and Pauli form factors
  - Sachs ratio possesses a zero compatible with experiment.

The possible existence and location of the zero in $\mu_p G_E^p/G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction.

![Graphs showing $\mu_p G_E^p/G_M^p$ and $\mu_n G_E^n/G_M^n$ as functions of $Q^2$.](image)
The singly-represented $d$-quark in the proton $\equiv u[ud]_0^+$ is sequestered inside a soft scalar diquark correlation.

Observation:

\[
diquark-diagram \propto 1/Q^2 \times quark-diagram
\]
The d-quark contributions to the proton form factors should be suppressed respect the u-quark contributions

Remind the experimental data...

![Graph showing data points for u and d quarks with annotations for scaling factors.]
The singly-represented $d$-quark in the proton is not always (but often) sequestered inside a soft scalar diquark correlation.

\[ P_{\text{scalar}} \sim 0.7, \quad P_{\text{axial}} \sim 0.3 \]

Contributions coming from $u$-quark

Contributions coming from $d$-quark
Observations:

- $F^d_{1p}$ is suppressed with respect to $F^u_{1p}$ in the whole range of momentum transfer.
- The location of the zero in $F^d_{1p}$ depends on the relative probability of finding $1^+$ and $0^+$ diquarks in the proton.
- $F^d_{2p}$ is suppressed with respect to $F^u_{2p}$ but only at large momentum transfer.
- There are contributions playing an important role in $F_2$, like the anomalous magnetic moment of dressed-quarks or meson-baryon final-state interactions.
Observations:

- The presence of scalar diquark correlations is sufficient to explain the key feature of the flavour-separated form factors.

- If only axial-vector diquarks are present inside the proton, the behaviour of the flavour-separated form factors is not reproduced.

- A combination of scalar and axial-vector diquarks with being dominant the scalar one produces agreement with the empirically verified behaviour of the flavour-separated form factors.
The reduction of the ratios $F_{d1}^d/F_{u1}^u$ and $F_{d2}^d/F_{u2}^u$ at high $Q^2$ has the immediate consequence that $F_{p2}^p/F_{p1}^p$ has its observed shape.
Experiments are sensitive to the momentum dependence of the running couplings and masses in QCD.

A close collaboration between experiment and theory can effectively constrain the evolution of the quark-quark interaction.

New experiments using upgraded facilities will leave behind meson-cloud effects and will gain access to the region of transition between the non-perturbative and perturbative regimes of QCD.

The possible existence and location of a zero in $G_E^p(Q^2)/G_M^p(Q^2)$ are a fairly direct measure of i.e. the nature and shape of the quark-quark interaction, the width of the transition region and the probability distribution of diquark correlations inside the proton.

The presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavour-separated form factors.

The reduction of the ratios $F_1^d/F_1^u$ and $F_2^d/F_2^u$ at high $Q^2$ implies that $F_2^p/F_1^p$ saturates at large momentum transfer.