γNN* ELECTRO-COUPLINGS AT CLAS12

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A central goal of Nuclear Physics: understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD.

Elastic and transition form factors

↙ ↘

Unique window into its quark and gluon structure → Distinctive information on the roles played by confinement and DCSB in QCD

High-Q^2 reach by experiments → Probe the excited nucleon structures at perturbative and non-perturbative QCD scales

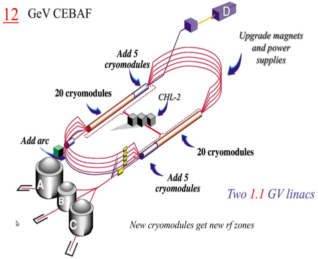
CEBAF Large Acceptance Spectrometer (CLAS)

☞ Most accurate results for the electro-excitation amplitudes of the four lowest excited states.

☞ They have been measured in a range of Q^2 up to:

- $8.0\,\mathrm{GeV}^2$ for $\Delta(1232)P_{33}$ and $N(1535)S_{11}$.
- $4.5\,\mathrm{GeV}^2$ for $N(1440)P_{11}$ and $N(1520)D_{13}$.

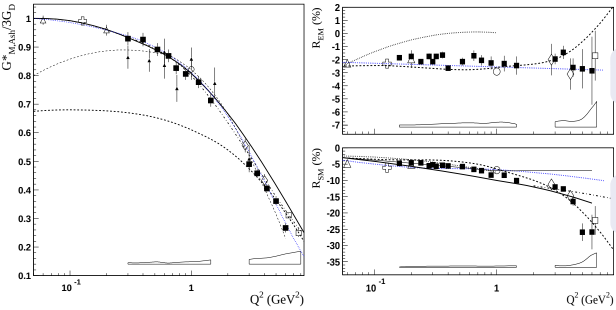
☞ Provide unprecedented information on the spectrum and structure of N^* resonances.



Upgrade of CLAS up to $12\,\mathrm{GeV}^2$ → CLAS12 (New generation experiments in 2015)

$\gamma^* N \to \Delta$ reaction: Experimental results and theoretical expectations

I.G. Aznauryan and V.D. Burkert Prog. Part. Nucl Phys. **67**, 1-54 (2012)



☞ *The R_{EM} ratio is measured to be minus a few percent.*

☞ *The R_{SM} ratio does not seem to settle to a constant at large Q^2.*

pQCD predictions

For $Q^2 \to \infty$

- $G_M^* \to 1/Q^4$.
- $R_{EM} \to +100\%$.
- $R_{SM} \to \text{constant}$.

CQM predictions

Without quark orbital angular momentum:

- $R_{EM} \to 0$.
- $R_{SM} \to 0$.

SU(6) predictions

$$\langle p|\mu|\Delta^+\rangle = \langle n|\mu|\Delta^0\rangle$$

$$\langle p|\mu|\Delta^+\rangle = -\sqrt{2}\,\langle n|\mu|n\rangle$$

Data do not support these predictions

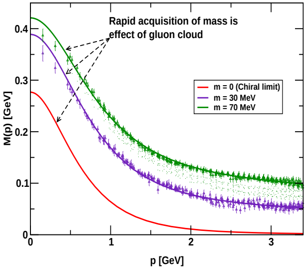
↓

Our aim: try to understand this longstanding puzzle

Emergent phenomena are associated with dramatic, dynamically-driven changes in the analytic structure of QCD's propagators and vertices (QCD's Schwinger functions)

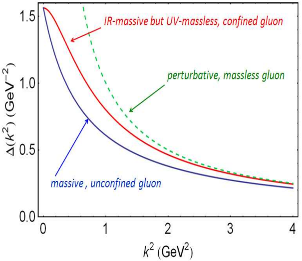
☞ Dressed-quark propagator

- Mass generated from the interaction of quarks with the gluon-medium.
- Quarks acquire a HUGE constituent mass.
- Responsible of the 98% of the mass of the proton.



☞ Dressed-gluon propagator:

- Confined gluon.
- IR-massive but UV-massless.
- $m_G \sim 2-4\Lambda_{QCD}$ ($\Lambda_{QCD} \simeq 200\,\mathrm{MeV}$).

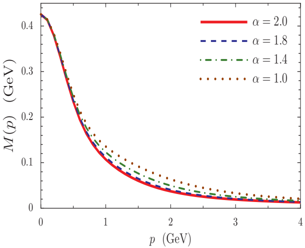


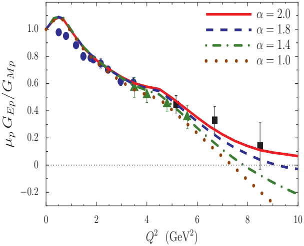
Any 2-point Schwinger function with an inflexion point at $p^2 > 0$:
→ Breaks the axiom of reflexion positivity
→ No physical observable related with

Confinement and Dynamical Chiral Symmetry Breaking (DCSB) can be identified with properties of dressed-quark and -gluon propagators and vertices (Schwinger functions)

Dyson-Schwinger equations (DSEs)

- The quantum equations of motion of QCD whose solutions are the Schwinger functions.
  → Propagators and vertices.
- Generating tool for perturbation theory.
  → No model-dependence.
- Nonperturbative tool for the study of continuum strong QCD.
  → Any model-dependence should be incorporated here.
- Allows the study of the interaction between light quarks in the whole range of momenta.
  → Analysis of the infrared behaviour is crucial to disentangle confinement and DCSB.
- Connect quark-quark interaction with experimental observables.
  → Elastic and transition form factors can be used to illuminate QCD (at infrared momenta).



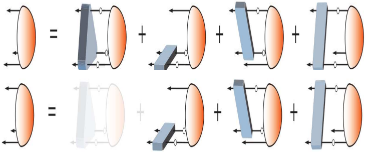


I.C. Cloet, C.D. Roberts, A.W. Thomas
Phys. Rev. Lett. 111 (2013)

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:

- Empirical evidence in support of strong diquark correlations inside the nucleon.
- A dynamical prediction of Faddeev equation studies.
- In our approach: Non-pointlike color-antitriplet and fully interacting.



Thanks to G. Eichmann.

Diquark composition of the nucleon and Δ

Positive parity states

↙ pseudoscalar and vector diquarks ↓ Ignored, wrong parity, larger mass-scales

↘ scalar and axial-vector diquarks ↓ Dominant, right parity, shorter mass-scales → $N \Rightarrow 0^+, 1^+$ diquarks; $\Delta \Rightarrow$ only 1^+ diquark

To compute the electromagnetic properties of the $\gamma^* N\Delta$ reaction in a given framework, one must specify how the photon couples to its constituents.

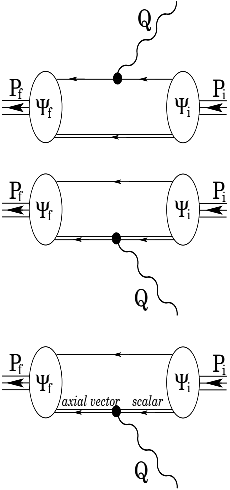
Six contributions to the current

1. Coupling of the photon to the dressed quark.
2. Coupling of the photon to the dressed diquark:
   - ➪ Elastic transition.
   - ➪ Induced transition.
3. Exchange and seagull terms.

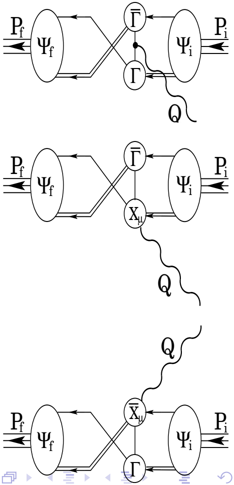
Ingredients in the contributions

1. $\Psi_{i,f} \equiv$ Faddeev amplitudes.
2. Single line $\equiv$ Quark prop.
3. Double line $\equiv$ Diquark prop.
4. $\Gamma \equiv$ Diquark BS amplitudes.

One-loop diagrams



Two-loop diagrams



Symmetry preserving Dyson-Schwinger equation treatment of a vector $\times$ vector contact interaction

☞ Gluon propagator: Contact interaction.

$$g^2 D_{\mu\nu}(p-q) = \delta_{\mu\nu}\frac{4\pi\alpha_{\rm IR}}{m_{\rm G}^2}$$

☞ Truncation scheme: Rainbow-ladder.

$$\Gamma^a_\nu(q,p) = (\lambda^a/2)\gamma_\nu$$

☞ Quark propagator: Gap equation.

$$S^{-1}(p) = i\gamma\cdot p + m + \Sigma(p)$$
$$= i\gamma\cdot p + M$$

- $M \sim 0.4\,\rm GeV$. Implies momentum independent constituent quark mass.
- Implies momentum independent BSAs.

☞ Baryons: Faddeev equation.

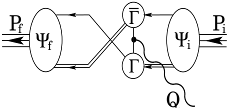
$$m_N = 1.14\,\rm GeV \quad m_\Delta = 1.39\,\rm GeV$$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams not incorporated.

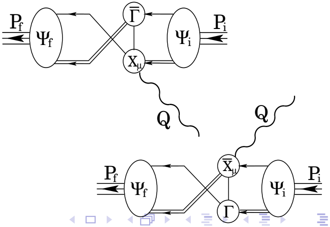
Exchange diagram

It is zero because our treatment of the contact interaction model

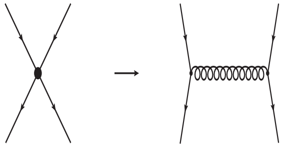


Seagull diagrams

They are zero



☞ Gluon propagator: $1/k^2$-behaviour.



☞ Truncation scheme: Rainbow-ladder.

$$\Gamma^a_\nu(q,p) = (\lambda^a/2)\gamma_\nu$$

☞ Quark propagator: Gap equation.

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

- $M \sim 0.33\,\mathrm{GeV}$. Implies momentum dependent constituent quark mass.
- Implies momentum dependent BSAs.

☞ Baryons: Faddeev equation.

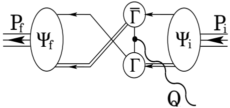
$$m_N = 1.18\,\mathrm{GeV} \quad m_\Delta = 1.33\,\mathrm{GeV}$$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams incorporated.

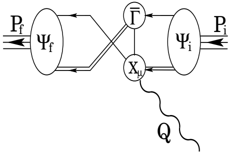
Exchange diagram

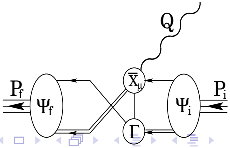
Play an important role

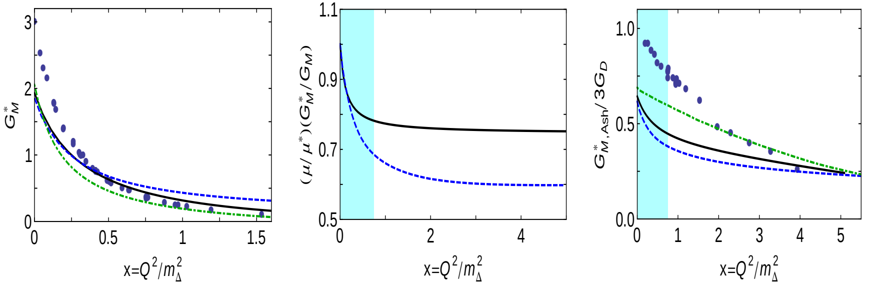


Seagull diagrams

They are less important







☞ Observations:

- Similarity between Solid-black and Dot-Dashed-green.
- The discrepancy at infrared comes from omission of meson-cloud effects.

- No reason to expect:

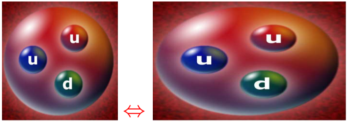
  $G^*_{M,\mathrm{Ash}}/G_M \sim \mathrm{constant}$

- J-S should exhibit:

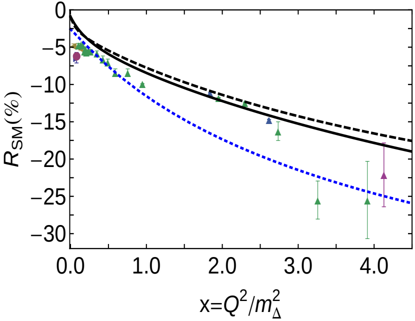
  $G^*_{M,\mathrm{J-S}}/G_M \sim \mathrm{constant}$

- Meson-cloud effects
  - More than 30% for $Q^2 \lesssim 0.75 m_\Delta^2$.
  - Very soft $\rightarrow$ disappear rapidly.
- $G^*_{M,\mathrm{Ash}}$ vs $G^*_{M,\mathrm{J-S}}$
  - $1/Q$ of difference.

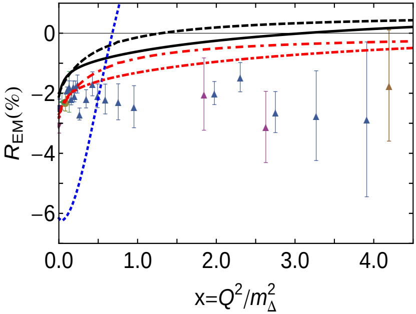
- $R_{EM} = R_{SM} = 0$ in SU(6)-symmetric CQM.
  - Deformation of the hadrons involved.
  - Modification of the structure of the transition current.



- R_{SM}: Good description of the rapid fall at large momentum transfer.



- R_{EM}: A particularly sensitive measure of orbital angular momentum correlations.

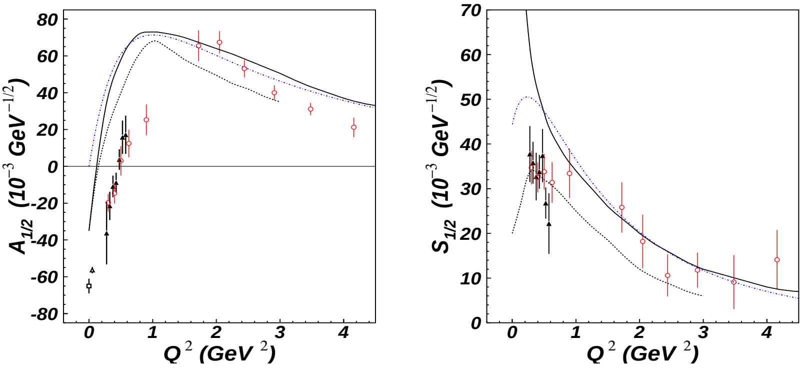


Zero Crossing in the transition electric form factor

Contact interaction → *at* $Q^2 \sim 0.75 m_\Delta^2 \sim 1.14\,\mathrm{GeV}^2$

Sophisticated interaction → *at* $Q^2 \sim 3.00 m_\Delta^2 \sim 4.60\,\mathrm{GeV}^2$

Nucleon to Roper transition electromagnetic form factors



☞ Observations:

- The Roper resonance, $N(1440)P_{11}$, is the lowest radial excitation of the nucleon.
- $A_{1/2}$ helicity amplitude:
  - Large and negative at $Q^2 = 0$.
  - Changes sign in the range $0.4 < Q^2 < 0.65\,\mathrm{GeV}^2$.
  - Becomes large and positive at $Q^2 > 1.5\,\mathrm{GeV}^2$.