γNN* Electrocouplings in Dyson-Schwinger Equations

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Unterstützt von / Supported by

Alexander von Humboldt
Stiftung / Foundation

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Nucleon Resonances: From Photoproduction to High Photon Virtualities

Trento, October 12-16, 2015

Studies of N^*-electrocouplings

A central goal of Nuclear Physics: understand the properties of hadrons in terms of the elementary excitations in Quantum Chromodynamics (QCD): quarks and gluons.

Elastic and transition form factors of N^*

↙ ↘

Unique window into their quark and gluon structure

↓

Distinctive information on the roles played by DCSB and confinement in QCD

Broad range of photon virtuality Q^2

↓

Probe the excited nucleon structures at perturbative and non-perturbative QCD scales

CEBAF Large Acceptance Spectrometer (CLAS@JLAB)

☞ Most accurate results for the electroexcitation amplitudes of the four lowest excited states.

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

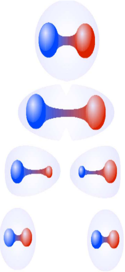
- $8.0\,\mathrm{GeV}^2$ for $\Delta(1232)P_{33}$ and $N(1535)S_{11}$.
- $4.5\,\mathrm{GeV}^2$ for $N(1440)P_{11}$ and $N(1520)D_{13}$.

☞ The majority of new data was obtained at JLab.

Upgrade of CLAS up to $12\,\mathrm{GeV}^2$ → CLAS12 (commissioning runs are underway)

Hadrons, as bound states, are dominated by non-perturbative QCD dynamics

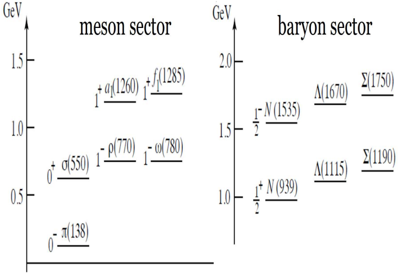
- *Explain how quarks and gluons bind together* ⇒ *Confinement*
- *Origin of the 98% of the mass of the proton* ⇒ *DCSB*



Emergent phenomena

↙ **Confinement** ↓ Colored particles have never been seen isolated

↘ **DCSB** ↓ Hadrons do not follow the chiral symmetry pattern



Neither of these phenomena is apparent in QCD's Lagrangian

however!

They play a dominant role in determining the 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 could be associated with dramatic, dynamically driven changes in the analytic structure of QCD's propagators and vertices.

☞ Dressed-quark propagator in Landau gauge:

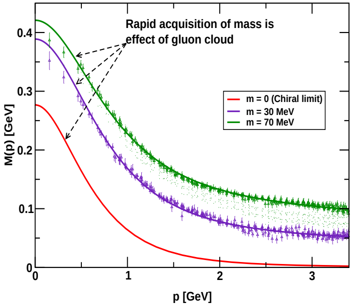
$$S^{-1}(p) = Z_2(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p) = \left(\frac{Z(p^2)}{i\gamma\cdot p + M(p^2)}\right)^{-1}$$

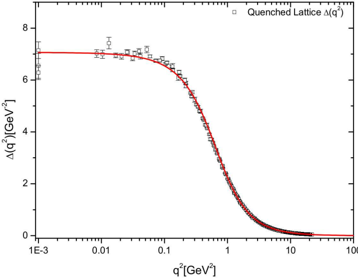
- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98% of the mass of the proton and the large splitting between parity partners.

☞ 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 reflexion positivity.
- No physical observable related with.

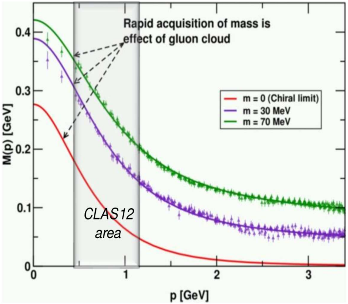




Confinement and dynamical chiral symmetry breaking could be identified with properties of QCD's propagators and vertices (QCD's Schwinger functions)

Dyson-Schwinger equations (DSEs)

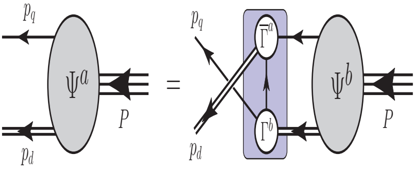
- Definition: The quantum equations of motion whose solutions are the Schwinger functions.
- Continuum Quantum Field Theoretical Approach:
  - Generating tool for perturbation theory
    → No model-dependence.
  - **ALSO** nonperturbative tool
    → Any model-dependence should be incorporated here.
- Poincaré covariant formulation becomes important in processes which involve higher transfer momentum.



- Nice consequences:
  - **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.
  - **Connect 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.

☞ Baryons:

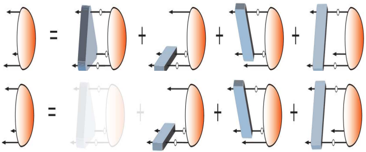
- Properties emerge from solutions of the **Faddeev equation.**
- The Faddeev equation sums all possible quantum field theoretical exchanges and interactions that can take place between the three valence quarks.



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.

Scalar-isoscalar and pseudovector-isotriplet diquark correlations feature within the Nucleon and Roper, whereas only pseudovector-isotriplet appears inside the Delta.

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

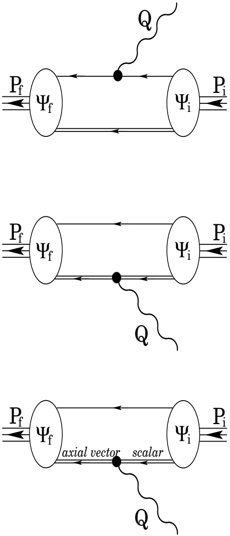
$\Downarrow$

Six contributions to the current in the quark-diquark picture

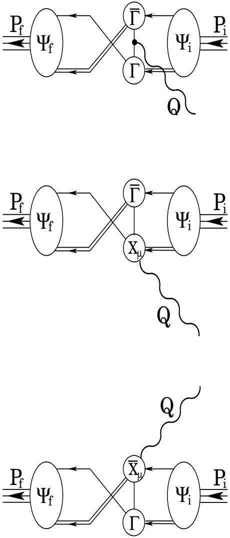
$\Downarrow$

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.

One-loop diagrams



Two-loop diagrams



☞ Gluon propagator: Contact interaction.

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

☞ Truncation scheme: Rainbow-ladder.

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

☞ Quark propagator: Gap equation.

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

Implies momentum independent constituent quark mass ($M \sim 0.4\,\text{GeV}$).

☞ Hadrons: Bound-state amplitudes independent of internal momenta.

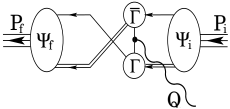
$m_N = 1.14\,\text{GeV}$ $m_\Delta = 1.39\,\text{GeV}$ $m_{\rm R} = 1.72\,\text{GeV}$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams not incorporated.

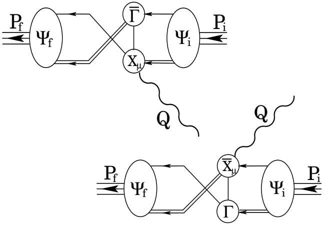
Exchange diagram

It is zero because our treatment of the contact interaction model



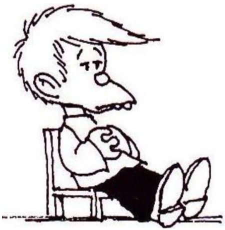
Seagull diagrams

They are zero



A truncation which produces Faddeev amplitudes that are independent of relative momentum:

- *Underestimates the quark orbital angular momentum content of the bound-state.*
- *Eliminates two-loop diagram contributions in the EM currents.*
- *Produces hard form factors.*



Momentum dependence in the gluon propagator

↓

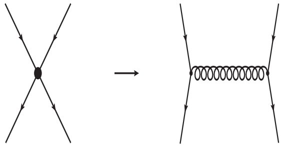
QCD-based framework

↓

Contrasting the results obtained for the same observables one can expose those quantities which are most sensitive to the momentum dependence of elementary objects in QCD.

Quark-quark QCD-based interaction framework

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



☞ Truncation scheme: Rainbow-ladder.

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

☞ Quark propagator: Gap equation.

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

Implies momentum dependent constituent quark mass ($M(p^2=0)\sim 0.33\,\mathrm{GeV}$).

☞ Hadrons: Bound-state amplitudes dependent of internal momenta.

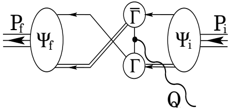
$m_N = 1.18\,\mathrm{GeV}$ $m_\Delta = 1.33\,\mathrm{GeV}$ $m_\mathrm{R} = 1.73\,\mathrm{GeV}$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams incorporated.

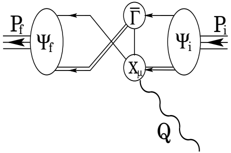
Exchange diagram

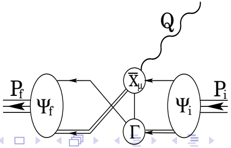
Play an important role



Seagull diagrams

They are less important





The γ^*N $\to$ Nucleon reaction

Work in collaboration with:

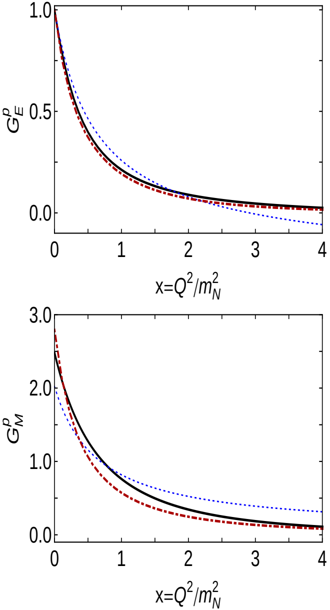
- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Sebastian M. Schmidt (Jülich)

Based on:

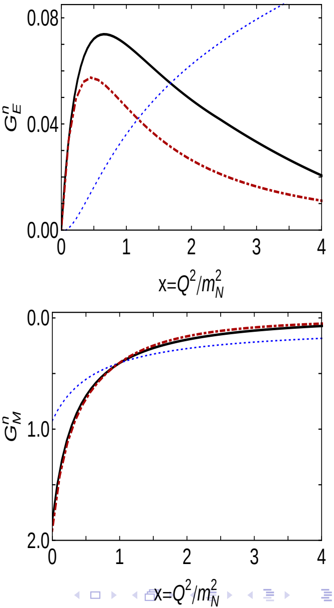
- Phys. Lett. B750 (2015) 100-106 [arXiv: 1506.05112 [nucl-th]]
- Few-Body Syst. 55 (2014) 1185-1222 [arXiv:1408.2919 [nucl-th]]

Sachs electric and magnetic form factors

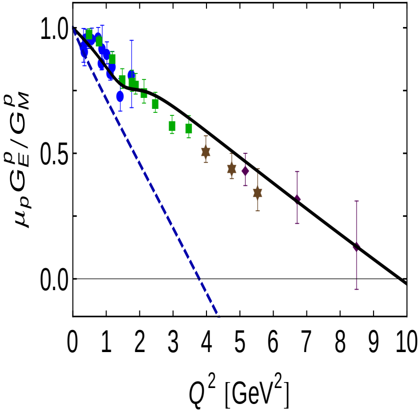
☞ Q^2-dependence of **proton** form factors:

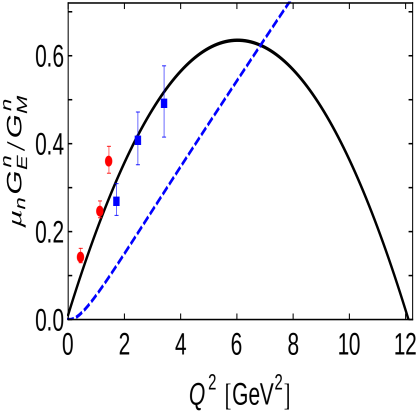


☞ Q^2-dependence of **neutron** form factors:



Both CI and QCD-kindred frameworks predict a zero crossing in $\mu_p G_E^p / G_M^p$





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

Experimental evidence

PRL **106,** 252003 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

G. D. Cates,[1] C. W. de Jager,[2] S. Riordan,[3] and B. Wojtsekhowski[2,*]
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[2]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
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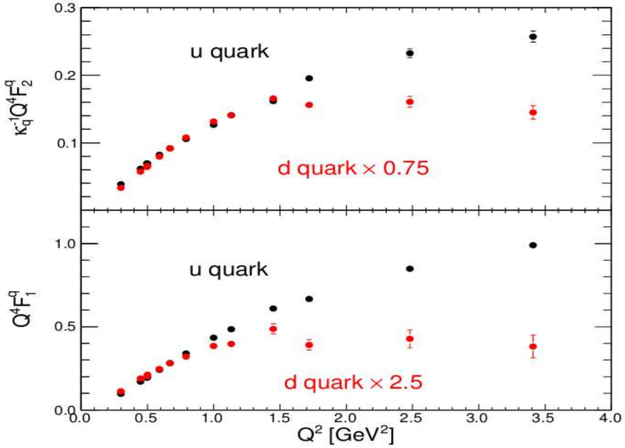
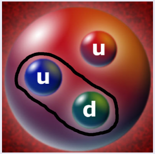
(Received 8 March 2011; published 22 June 2011)



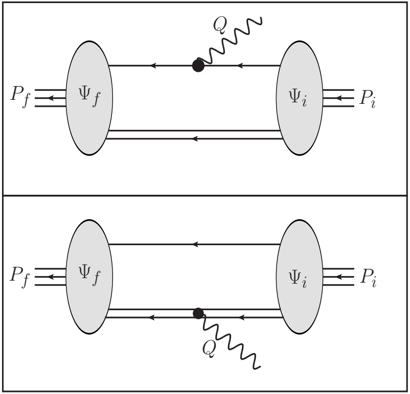
The singly-represented d-quark in the proton $\equiv u[ud]_{0^+}$ *is sequestered inside a soft scalar diquark correlation.*

☞ *Observation:*

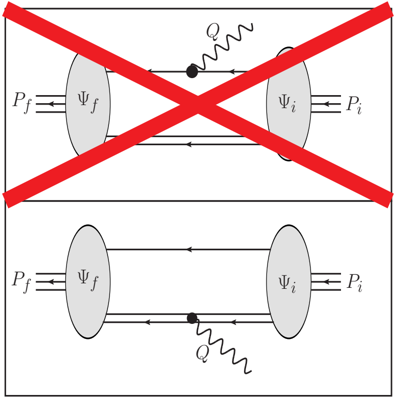
$$\text{diquark-diagram} \propto 1/Q^2 \times \text{quark-diagram}$$



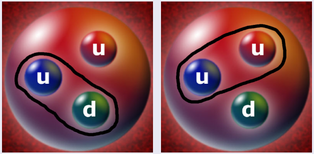
Contributions coming from **u-quark**



Contributions coming from **d-quark**



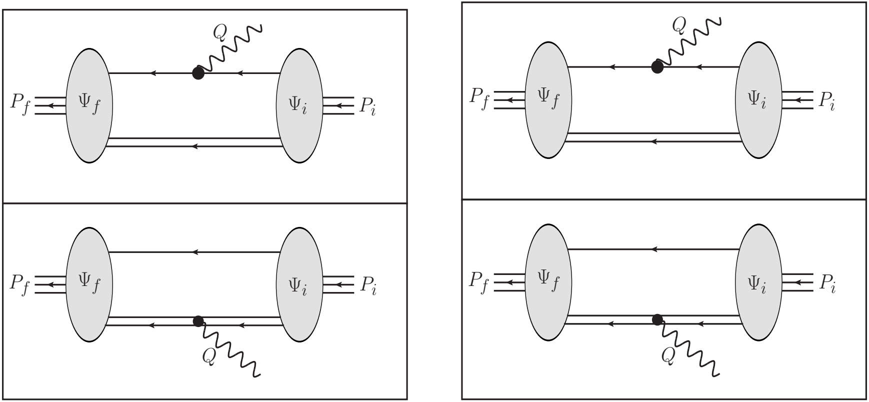
The singly-represented d-quark in the proton is **not always (but often)** *sequestered inside a soft scalar diquark correlation.*

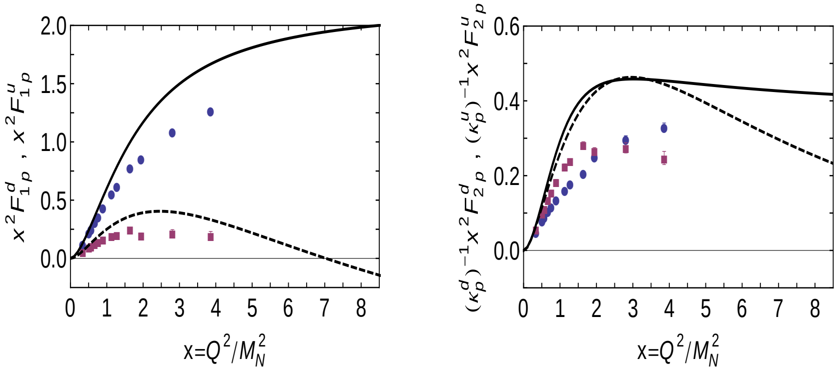


☞ *Observation:*

$$\mathcal{P}_{\text{scalar}} \sim 0.62, \quad \mathcal{P}_{\text{axial}} \sim 0.38$$

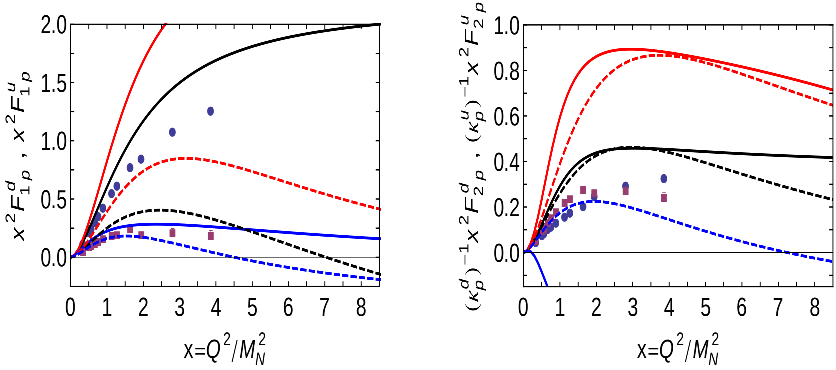
Contributions coming from **u-quark** | Contributions coming from **d-quark**





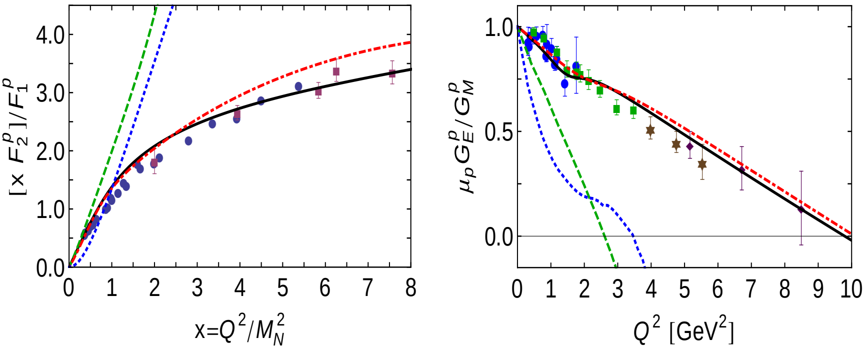
☞ Observations:

- F_{1p}^d is suppressed with respect F_{1p}^u in the whole range of momentum transfer.
- The location of the zero in F_{1p}^d depends on the relative probability of finding 1^+ and 0^+ diquarks in the proton.
- F_{2p}^d is suppressed with respect F_{2p}^u 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.



☞ Observations:

- Axial-vector diquark contribution is not enough in order to explain the proton's electromagnetic ratios.
- Scalar diquark contribution is dominant and responsible of the Q^2-behaviour of the the proton's electromagnetic ratios.
- Higher quark-diquark orbital angular momentum components of the nucleon are critical in explaining the data.

The γ^*N $\rightarrow$ Delta reaction

Work in collaboration with:

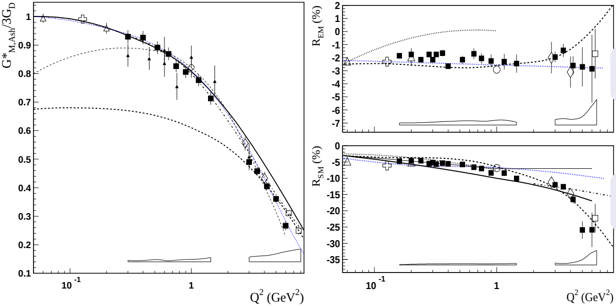
- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Sebastian M. Schmidt (Jülich)
- Chen Chen (Hefei)
- Shaolong Wan (Hefei)

Based on:

- Few-Body Syst. 55 (2014) 1185-1222 [arXiv:1408.2919 [nucl-th]]
- Few-Body Syst. 54 (2013) 1-33 [arXiv:1308.5225 [nucl-th]]
- Phys. Rev. C88 (2013) 032201(R) [arXiv:1305.0292 [nucl-th]]

Experimental results and theoretical expectations

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



☞ *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.*

SU(6) predictions

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

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

CQM predictions

(Without quark orbital angular momentum)

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

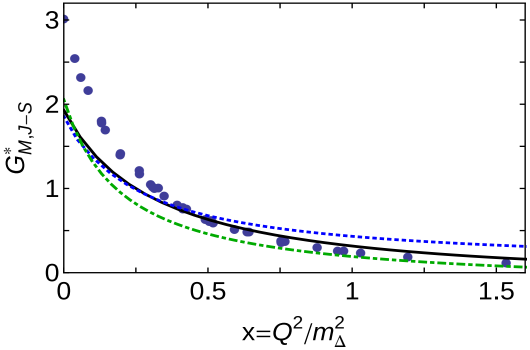
pQCD predictions

(For $Q^2 \to \infty$)

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

Experimental data do not support theoretical predictions

$G^*_{M,J-S}$ cf. Experimental data and dynamical models

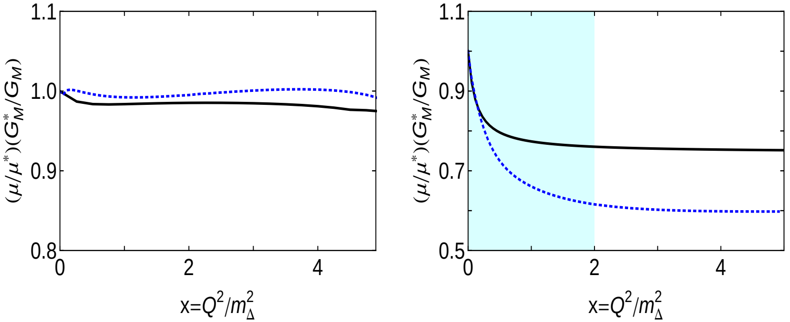


- Solid-black:
  QCD-kindred interaction.
- Dashed-blue:
  Contact interaction.
- Dot-Dashed-green:
  Dynamical + no meson-cloud

☞ Observations:

- All curves are in marked disagreement at infrared momenta.
- Similarity between Solid-black and Dot-Dashed-green.
- The discrepancy at infrared comes from omission of meson-cloud effects.
- Both curves are consistent with data for $Q^2 \gtrsim 0.75 m^2_\Delta \sim 1.14\,\mathrm{GeV}^2$.

Transition cf. elastic magnetic form factors



- Fall-off rate of $G^*_{M,J-S}(Q^2)$ in the $\gamma^* p \to \Delta^+$ must follow that of $G_M(Q^2)$.
- With isospin symmetry:

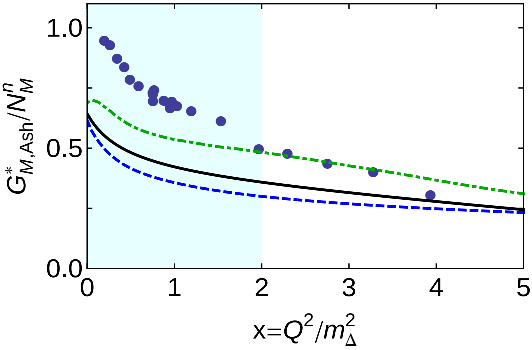
$$\langle p|\mu|\Delta^+\rangle = -\langle n|\mu|\Delta^0\rangle$$

so same is true of the $\gamma^* n \to \Delta^0$ magnetic form factor.

These are statements about the dressed quark core contributions

$\to$ *Outside the domain of meson-cloud effects,* $Q^2 \gtrsim 1.5\,\text{GeV}^2$

Presentations of experimental data typically use the Ash convention
– $G^*_{M,\mathrm{Ash}}(Q^2)$ falls faster than a dipole –



- No sound reason to expect:

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

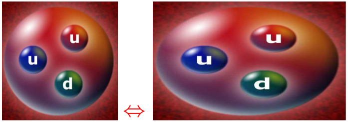
- Jones-Scadron should exhibit:

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

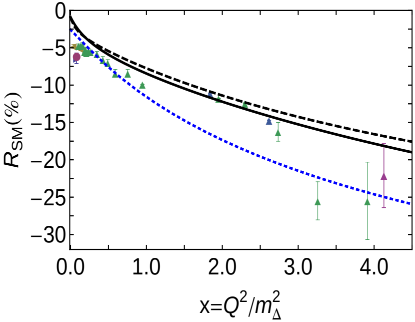
- Meson-cloud effects
  - Up-to 35% for $Q^2 \lesssim 2.0 m^2_\Delta$.
  - Very soft $\rightarrow$ disappear rapidly.
- $G^*_{M,\mathrm{Ash}}$ vs $G^*_{M,\mathrm{J-S}}$
  - A factor $1/\sqrt{Q^2}$ of difference.

☞ $R_{EM} = R_{SM} = 0$ in SU(6)-symmetric CQM.

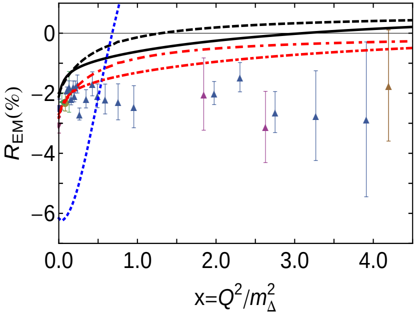
- Deformation of the hadrons involved.
- Modification of the structure of the transition current.



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



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



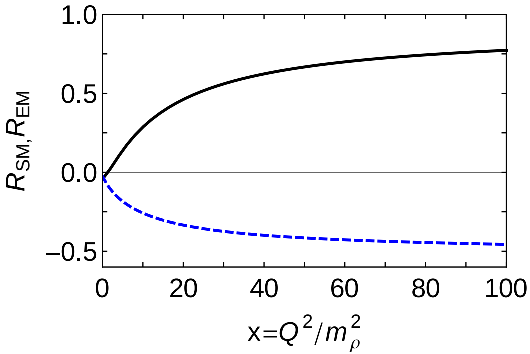
Zero Crossing in the transition electric form factor

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

QCD-kindred interaction $\rightarrow$ *at* $Q^2 \sim 3.25 m_\Delta^2 \sim 4.93\,\mathrm{GeV}^2$

Helicity conservation arguments in pQCD should apply equally to both the results obtained within our QCD-kindred framework and those produced by an internally-consistent symmetry-preserving treatment of a contact interaction

$$R_{EM} \overset{Q^2\to\infty}{=} 1, \quad R_{SM} \overset{Q^2\to\infty}{=} \text{constant}$$



Observations:

- Truly asymptotic Q^2 is required before predictions are realized.
- $R_{EM} = 0$ at an empirical accessible momentum and then $R_{EM} \to 1$.
- $R_{SM} \to \text{constant}$. Curve contains the logarithmic corrections expected in QCD.

The γ^*N $\rightarrow$ Roper reaction

Work in collaboration with:

- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Bruno El-Bennich (São Paulo)
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Based on:

- Accepted by Phys. Rev. Lett., preprint arXiv: 1504.04386 [nucl-th]

PRL **104,** 042302 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

Disentangling the Dynamical Origin of P_{11} Nucleon Resonances

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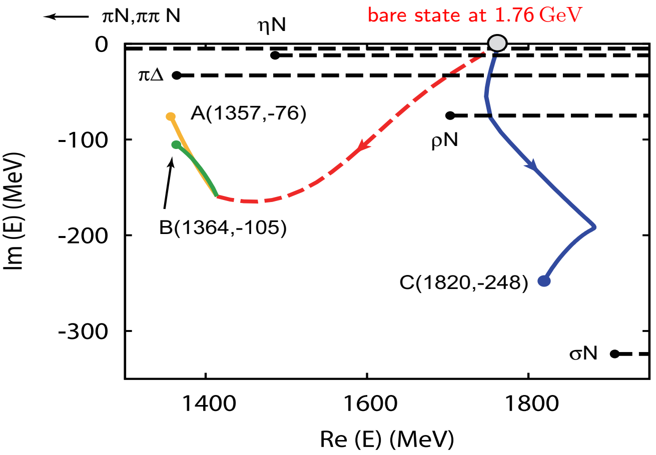


The Roper is the proton's first radial excitation. *Its unexpectedly low mass arise from a dressed-quark core that is shielded by a meson-cloud which acts to diminish its mass.*

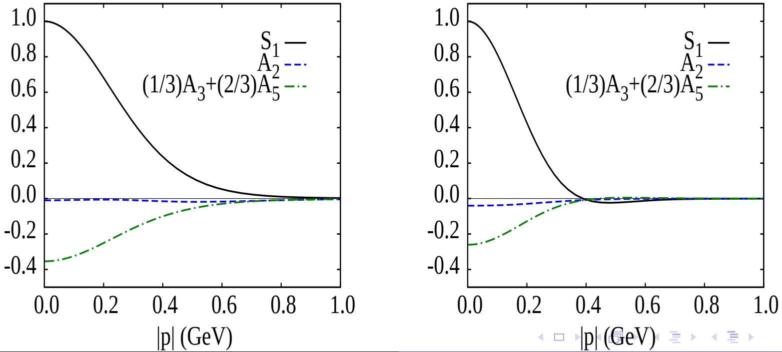
The bare N^* states correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions:

$$M_{\rm Roper}^{\rm DSE} = 1.73\,{\rm GeV} \qquad M_{\rm Roper}^{\rm EBAC} = 1.76\,{\rm GeV}$$

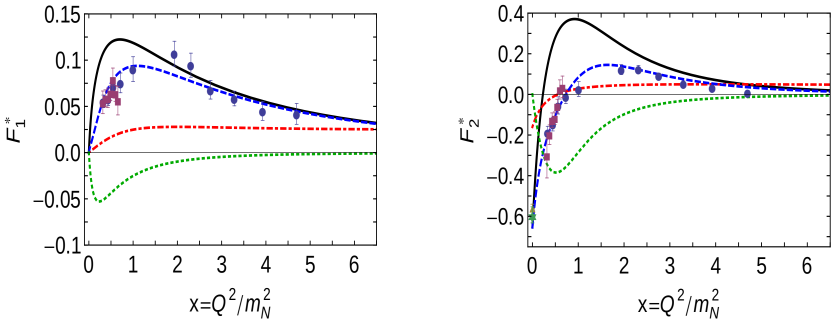
☞ Observation:

- Meson-Baryon final state interactions reduce dressed-quark core mass by 20%.
- Roper and Nucleon have very similar wave functions and diquark content.
- A single zero in S-wave components of the wave function ⇒ A radial excitation.

0th Chebyshev moment of the S-wave components



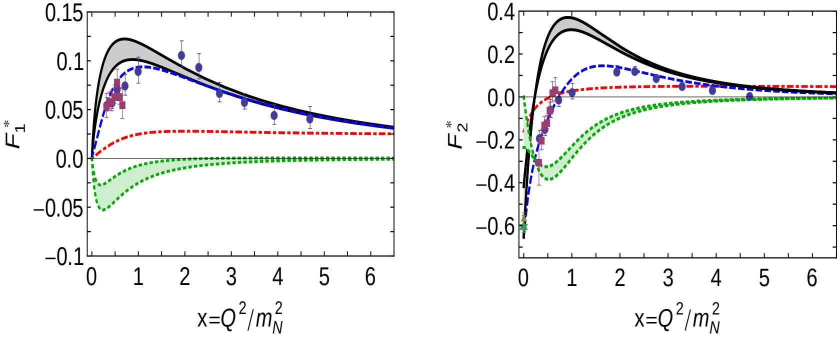
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core



☞ Observations:

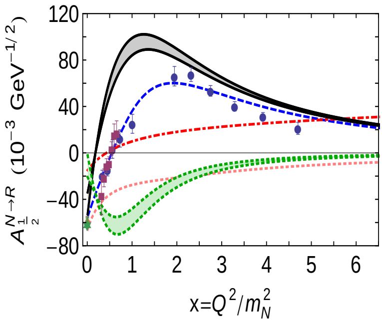
- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$.
- The mismatch between our prediction and the data on $x \lesssim 2$ is due to meson cloud contribution.
- The dotted-green curve is an inferred form of meson cloud contribution from the fit to the data.
- The Contact-interaction prediction disagrees both quantitatively and qualitatively with the data.

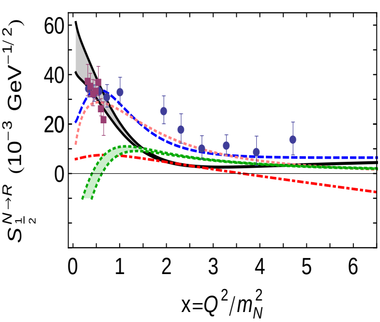
Including a meson-baryon Fock-space component into the baryons' Faddeev amplitudes with a maximum strength of 20%



☞ Observations:

- The incorporation of a meson-baryon Fock-space component does not materially affect the nature of the inferred meson-cloud contribution.
- We provide a reliable delineation and prediction of the scope and magnitude of meson cloud effects.





Concerning $A_{1/2}$:

- Inferred cloud contribution and that determined by EBAC are quantitatively in agreement on $x > 1.5$.
- Our result disputes the EBAC suggestion that a meson-cloud is solely responsible for the $x = 0$ value of the helicity amplitude.
- The quark-core contributes at least two-thirds of the result.

Concerning $S_{1/2}$:

- Large quark-core contribution on $x < 1 \to$ Disagreement between EBAC and DSEs.
- The core and cloud contributions are commensurate on $1 < x < 4$.
- The dressed-quark core contribution is dominant on $x > 4$.

Unified study of nucleon, Delta and Roper elastic and transition form factors that compares predictions made by:

- *Contact quark-quark interaction,*
- *QCD-kindred quark-quark interaction,*

within a DSEs framework in which:

- *All elements employed possess an link with analogous quantities in QCD.*
- *No parameters were varied in order to achieve success.*

The comparison clearly establishes

☞ Experiments on N^*-electrocouplings are sensitive to the momentum dependence of the running coupling and masses in QCD.

☞ Experiment-theory collaboration can effectively constrain the evolution to infrared momenta of the quark-quark interaction in QCD.

☞ New experiments using upgraded facilities will leave behind meson-cloud effects and thereby illuminate the dressed-quark core of baryons.

☞ CLAS12@JLAB will gain access to the transition region between nonperturbative and perturbative QCD scales.

Conclusions

☞ The $\gamma^* N \to$ *Nucleon* reaction:

- The possible existence and location of a zero in $G_E^p(Q^2)/G_M^p(Q^2)$ is a fairly direct measure the nature and shape of the quark-quark interaction.
- The presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavour-separated form factors.

☞ The $\gamma^* N \to$ *Delta* reaction:

- $G_{M,J-S}^{*p}$ falls asymptotically at the same rate as G_M^p. This is compatible with isospin symmetry and pQCD predictions.
- Data do not fall unexpectedly rapid once the kinematic relation between Jones-Scadron and Ash conventions is properly account for.
- Strong diquark correlations within baryons produce a zero in the transition electric quadrupole at $Q^2 \sim 5\,\mathrm{GeV}^2$.
- Limits of pQCD, $R_{EM} \to 1$ and $R_{SM} \to \mathrm{constant}$, are apparent in our calculation but truly asymptotic Q^2 is required before the predictions are realized.

☞ The $\gamma^* N \to$ *Roper* reaction:

- The Roper is the proton's first radial excitation. It consists on a dressed-quark core augmented by a meson cloud that reduces its mass by approximately 20%.
- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$. The mismatch on $x \lesssim 2$ is due to meson cloud contribution.