Exposing the structure of nucleon excited states using Dyson-Schwinger Equations

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Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

Nanjing University and Nanjing Normal University

May 2017

☞ **With the main collaboration of Roberts' group.**

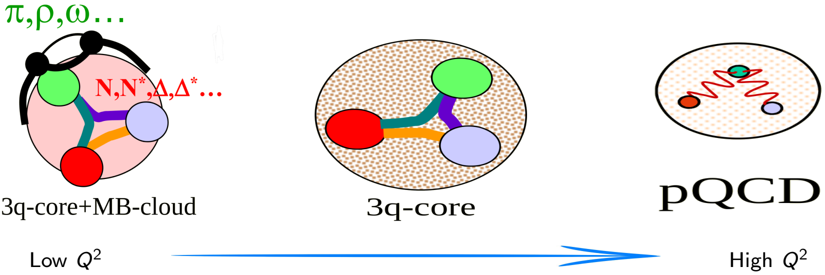
Studies of N^*-electrocouplings (I)

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	Broad range of photon virtuality Q^2
↓	↓
Distinctive information on the roles played by emergent phenomena in QCD	Probe the excited nucleon structures at perturbative and non-perturbative QCD scales



A vigorous experimental program has been and is still under way worldwide
CLAS, CBELSA, GRAAL, MAMI and LEPS

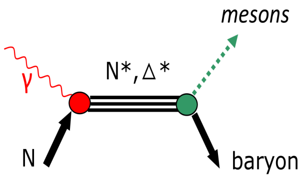
☞ Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.

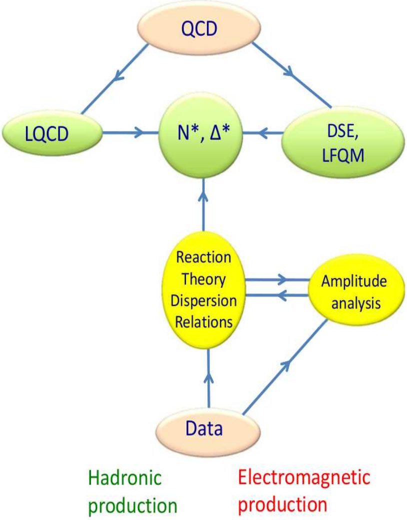
☞ Very precise data for 2-body processes in wide kinematics (angle, energy): $\gamma p \to \pi N$, ηN, KY.

☞ More complex reactions needed to access high mass states: $\pi\pi N$, $\pi\eta N$, ωN, ϕN, ...

⇓

Extract s-channel resonances





CEBAF Large Acceptance Spectrometer (CLAS@JLab)

☞ 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:

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

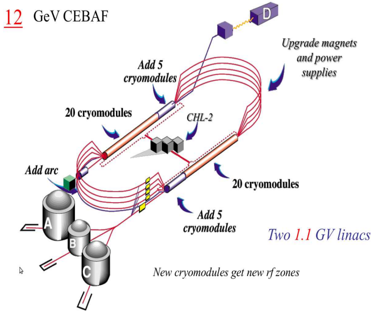
☞ The majority of new data was obtained at JLab.

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

☞ A dedicated experiment will aim to extract the N^* electrocouplings at photon virtualities Q^2 ever achieved so far.

☞ The GlueX@JLab experiment will provide critical data on (exotic) hybrid mesons which explicitly manifest the gluonic degrees of freedom.

The constituent quark-gluon research project is related with the last topic



Non-perturbative QCD:
Confinement and dynamical chiral symmetry breaking (I)

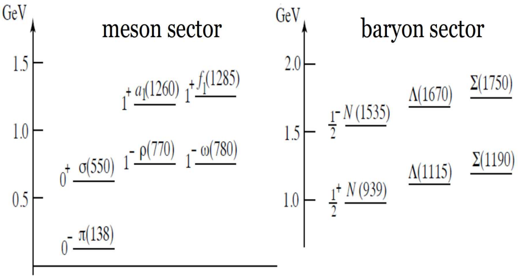
Hadrons, as bound states, are dominated by non-perturbative QCD dynamics

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

Emergent phenomena

↙ Confinement ↓ Coloured 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

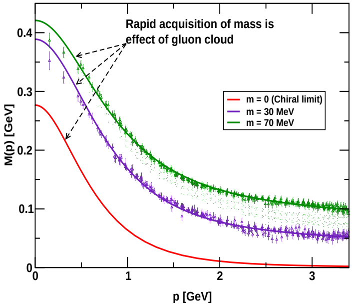
The best promise for progress is a strong interplay between experiment and theory

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:

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

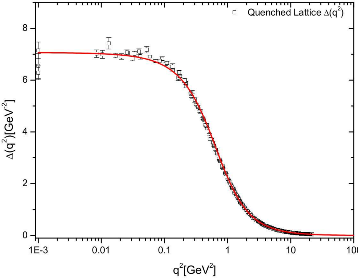
- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98% of the mass of the proton and the large splitting between parity partners.



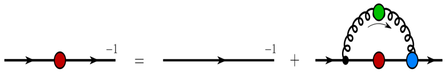
☞ Dressed-gluon propagator in Landau gauge:

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

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



The simplest example of DSEs: The gap equation



- The quark propagator is given by the gap equation:

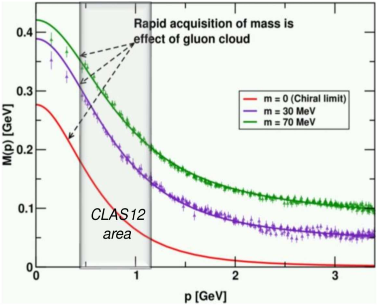
$$S^{-1}(p) = Z_2(i\gamma \cdot p + m^{\mathrm{bm}}) + \Sigma(p)$$

$$\Sigma(p) = Z_1 \int_q^{\Lambda} g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q) \frac{\lambda^a}{2} \Gamma_\nu(q,p)$$

- General solution:

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

- Kernel involves:
  - $D_{\mu\nu}(p-q)$ - dressed gluon propagator
  - $\Gamma_\nu(q,p)$ - dressed-quark-gluon vertex



$M(p^2)$ exhibits dynamical mass generation

Each of which satisfies its own Dyson-Schwinger equation

↓

Infinitely many coupled equations

↓

Coupling between equations necessitates truncation

Symmetries should be preserved by any truncation

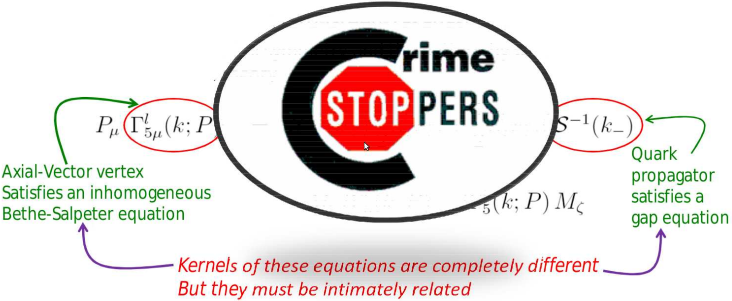
↓

Highly non-trivial constraint → Failure implies loss of any connection with QCD

↓

Symmetries in QCD are implemented by WTIs → Relate different Schwinger functions

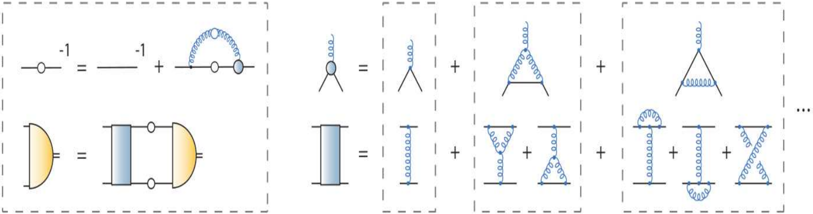
- For instance, axial-vector Ward-Takahashi identity:



These observations show that symmetries relate the kernel of the gap equation – a one-body problem – with that of the Bethe-Salpeter equation – a two-body problem –

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.
- All momentum scales and valid from light to heavy quarks.
- EM gauge invariance, chiral symmetry, massless pion in chiral limit...



- No constant quark mass unless NJL contact interaction.
- No crossed-ladder unless consistent quark-gluon vertex.
- Cannot add *e.g.* an explicit confinement potential.

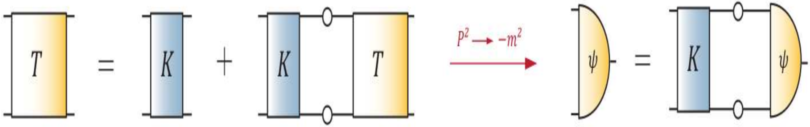
⇒ **modelling only within these constraints!**

The bound-state problem in quantum field theory

Extraction of hadron properties from poles in $q\bar{q}$, qqq, $qq\bar{q}\bar{q}$... scattering matrices

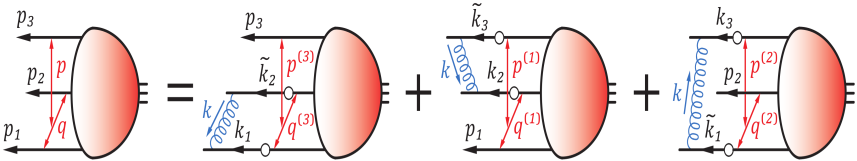
Use **scattering equation** (inhomogeneous BSE) to obtain T in the first place: $T = K + KG_0 T$

Homogeneous BSE for **BS amplitude:**



☞ Baryons. A 3-body bound state problem in quantum field theory:

Faddeev equation in rainbow-ladder truncation

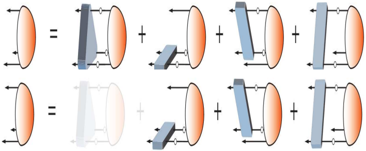


Faddeev equation: Sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.

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

☞ Diquark correlations:

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



Thanks to G. Eichmann.

Diquark composition of the Nucleon (N), Roper (R), and Delta (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, R ⇒ 0^+, 1^+ diquarks; Δ ⇒ only 1^+ diquark

Electromagnetic gauge invariance: current must be consistent with baryon's Faddeev equation.

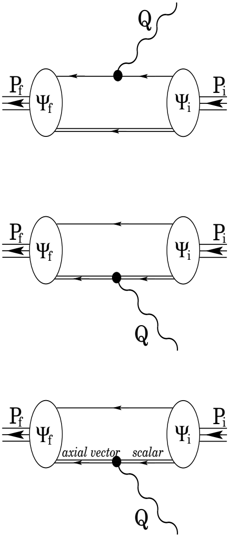
⇓

Six contributions to the current in the quark-diquark picture

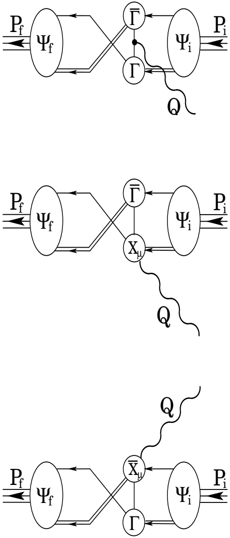
⇓

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



Quark-quark contact-interaction framework

☞ 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.

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

☞ 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 ($M \sim 0.4\,{\rm GeV}$).

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

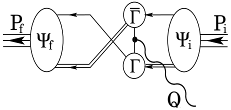
$m_N = 1.14\,{\rm GeV}$ $m_\Delta = 1.39\,{\rm GeV}$ $m_{\rm R} = 1.72\,{\rm GeV}$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams not incorporated.

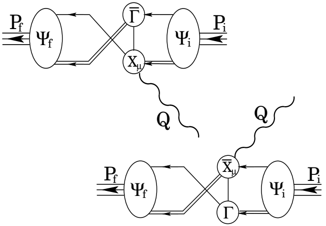
Exchange diagram

It is zero because our treatment of the contact interaction model



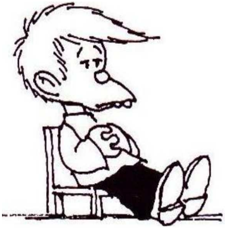
Seagull diagrams

They are zero



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

- *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

↓

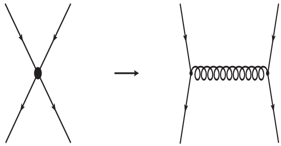
QCD-based framework

↓

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.

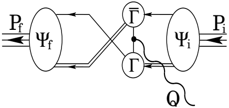
$m_N = 1.18\,\mathrm{GeV}$ $m_\Delta = 1.33\,\mathrm{GeV}$ $m_{\mathrm{R}} = 1.73\,\mathrm{GeV}$

(masses reduced by meson-cloud effects)

☞ Form Factors: Two-loop diagrams incorporated.

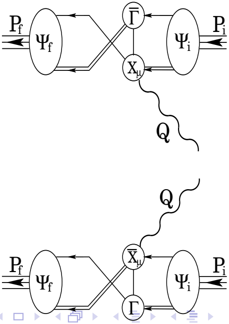
Exchange diagram

Play an important role



Seagull diagrams

They are less important



The γ^*N $\rightarrow$ 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]]

☞ The electromagnetic current can be generally written as:

$$J_\mu(K,Q) = ie\,\Lambda_+(P_f)\,\Gamma_\mu(K,Q)\,\Lambda_+(P_i)$$

- 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:

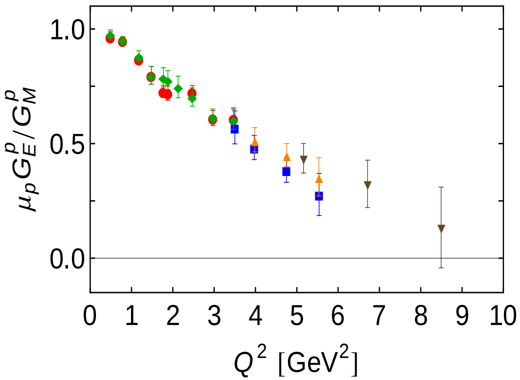
- $G_E \Rightarrow$ Momentum space distribution of nucleon's charge.
- $G_M \Rightarrow$ Momentum space distribution of nucleon's magnetization.

☞ *Perturbative QCD predictions for the Dirac and Pauli form factors:*

$$F_1^p \sim 1/Q^4 \quad \text{and} \quad F_2^p \sim 1/Q^6 \quad \Rightarrow \quad Q^2 F_2^p / F_1^p \sim const.$$

☞ *Consequently, the Sachs form factors scale as:*

$$G_E^p \sim 1/Q^4 \quad \text{and} \quad G_M^p \sim 1/Q^4 \quad \Rightarrow \quad G_E^p / G_M^p \sim const.$$



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- Gayou *et al.*, Phys. Rev. Lett. 88 (2002) 092301.
- Punjabi *et al.*, Phys. Rev. C71 (2005) 055202.
- Puckett *et al.*, Phys. Rev. Lett. 104 (2010) 242301.
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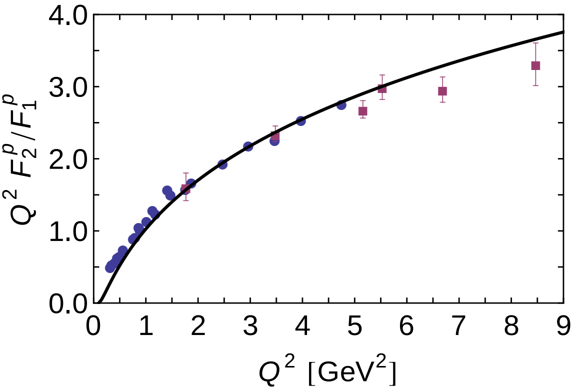
Phenomenological aspects (II)

Updated perturbative QCD prediction

$$Q^2 F_2^p / F_1^p \sim const. \quad \Rightarrow \Rightarrow \Rightarrow \quad Q^2 F_2^p / F_1^p \sim ln^2 \left[Q^2/\Lambda^2\right]$$

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



Andrei V. Belitsky, Xiang-dong Ji, Feng Yuan, Phys. Rev. Lett. 91 (2003) 092003

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

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

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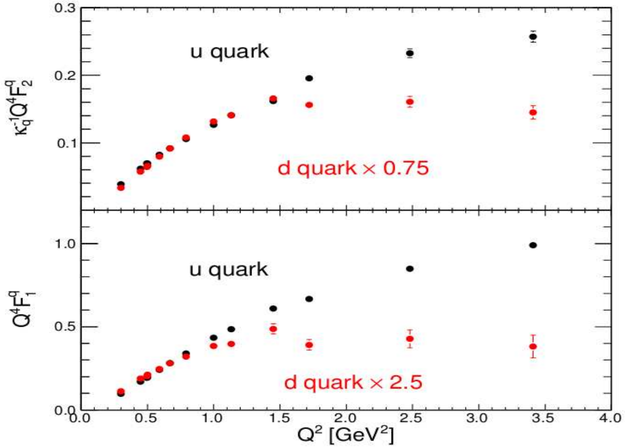
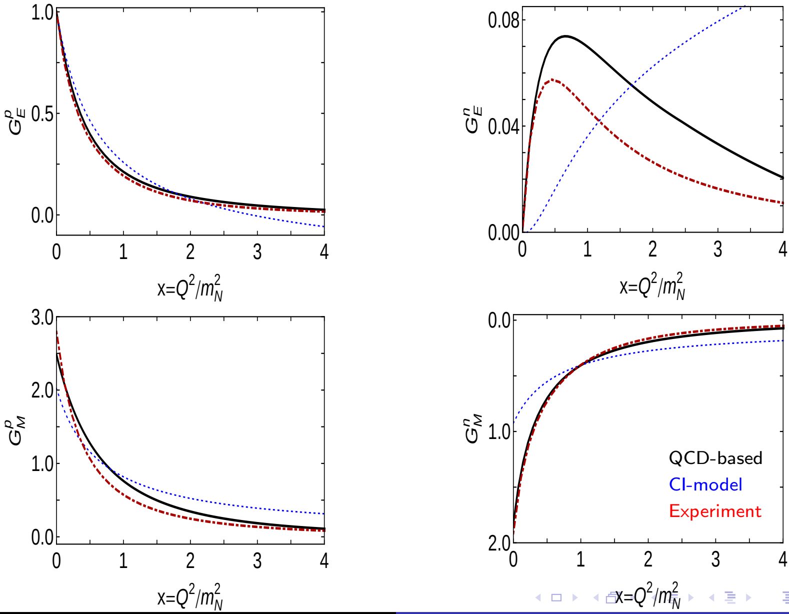
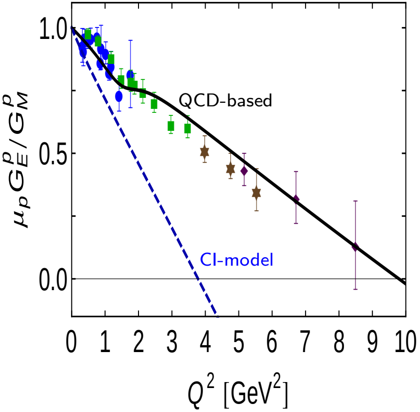
(Received 8 March 2011; published 22 June 2011)

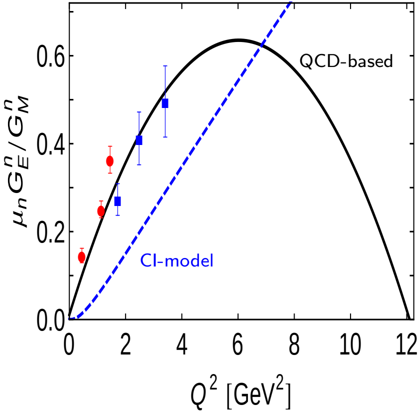


- Q^2-dependence of **proton** form factors:
- Q^2-dependence of **neutron** form factors:



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



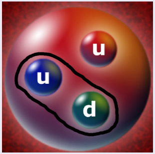


The possible existence and location of the zero in $\mu_p G_E^p / G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction

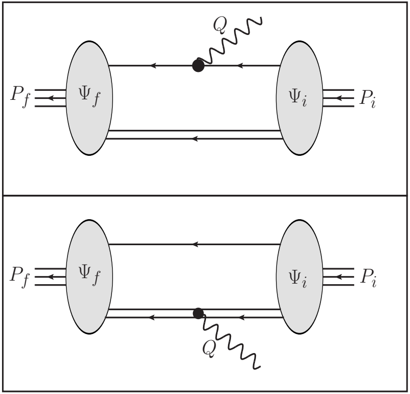
The singly-represented d-quark in the proton $\equiv u[ud]_{0^+}$ *is sequestered inside a soft scalar diquark correlation.*

☞ *Observation:*

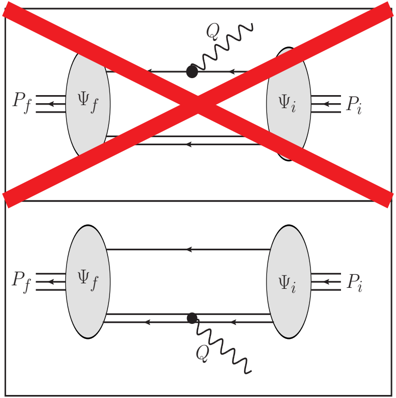
$$\textit{diquark-diagram} \propto 1/Q^2 \times \textit{quark-diagram}$$



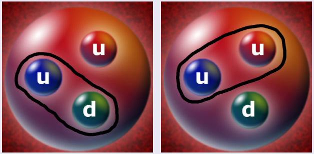
Contributions coming from **u-quark**



Contributions coming from **d-quark**



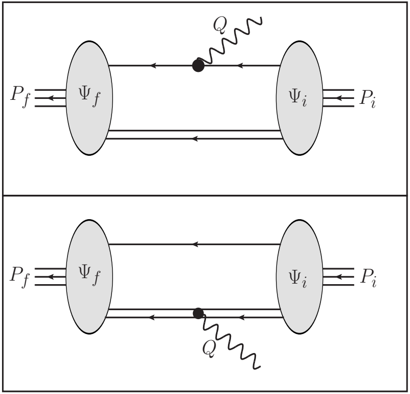
The singly-represented d-quark in the proton is **not always (but often)** *sequestered inside a soft scalar diquark correlation.*



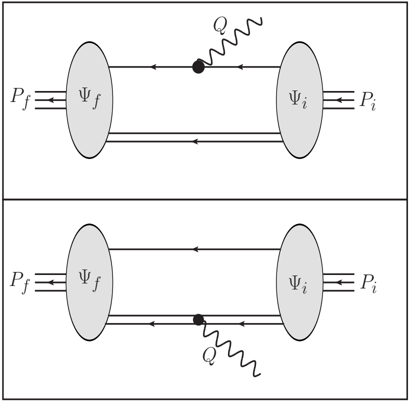
☞ *Observation:*

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

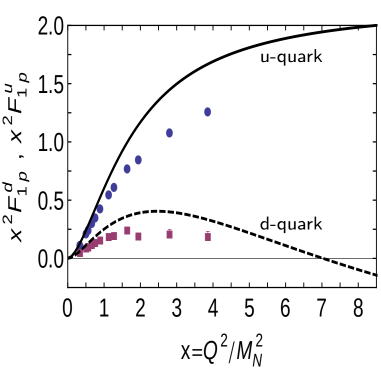
Contributions coming from **u-quark**

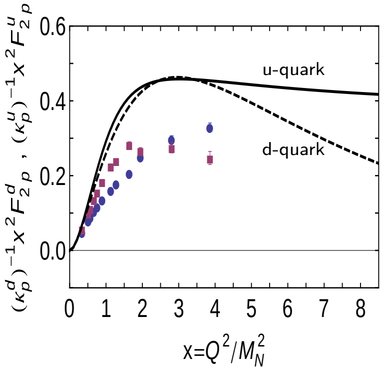


Contributions coming from **d-quark**



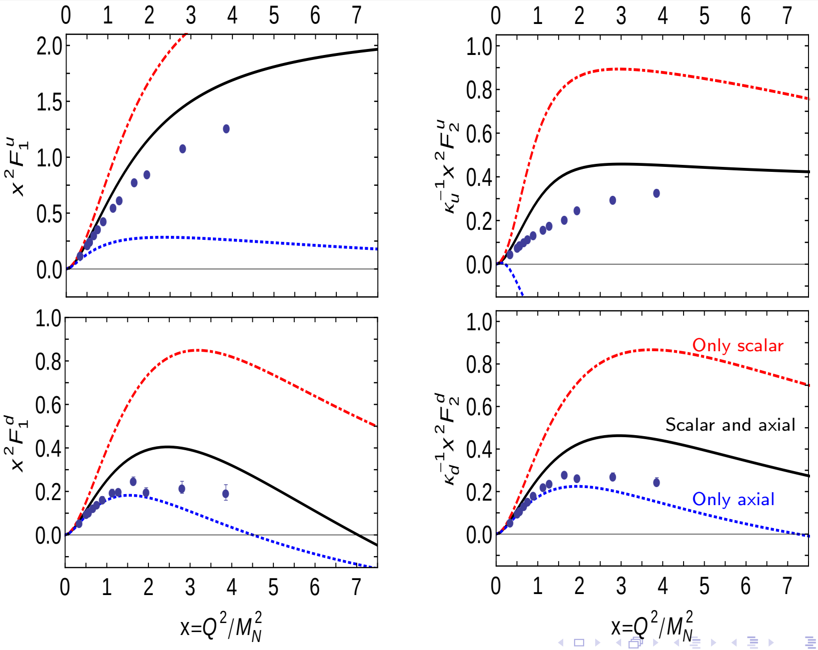
A world with scalar and axial-vector diquarks (II)

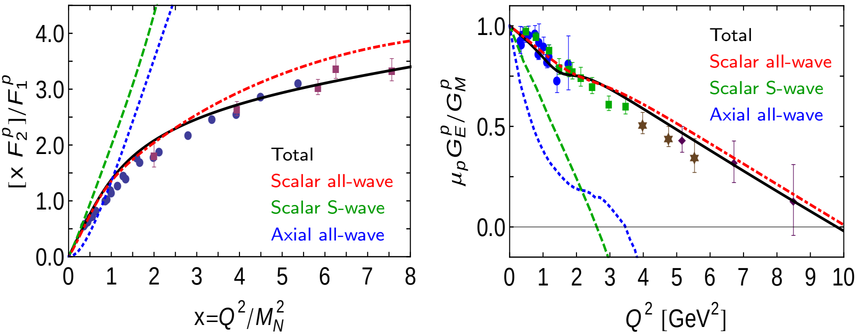




☞ Observations:

- 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.


$x^2 F_1^u$
$\kappa_u^{-1} x^2 F_2^u$
$x^2 F_1^d$
$\kappa_d^{-1} x^2 F_2^d$
Only scalar
Scalar and axial
Only axial
$x=Q^2/M_N^2$
$x=Q^2/M_N^2$



☞ 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 presence of higher orbital angular momentum components in the nucleon is an inescapable consequence of solving a realistic Poincaré-covariant Faddeev equation

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]]

☞ The electromagnetic current can be generally written as:

$$J_{\mu\lambda}(K,Q) = \Lambda_+(P_f)\, R_{\lambda\alpha}(P_f)\, i\gamma_5\, \Gamma_{\alpha\mu}(K,Q)\, \Lambda_+(P_i)$$

- Incoming nucleon: $P_i^2 = -m_N^2$, and outgoing delta: $P_f^2 = -m_\Delta^2$.
- Photon momentum: $Q = P_f - P_i$, and total momentum: $K = (P_i + P_f)/2$.
- The on-shell structure is ensured by the N- and Δ-baryon projection operators.

☞ Vertex decomposes in terms of three (Jones-Scadron) form factors:

$$\Gamma_{\alpha\mu}(K,Q) = \mathpzc{k} \left[\frac{\lambda_m}{2\lambda_+} (G_M^* - G_E^*) \gamma_5 \varepsilon_{\alpha\mu\gamma\delta} \hat{K}_\gamma^\perp \hat{Q}_\delta - G_E^* \mathbb{T}_{\alpha\gamma}^Q \mathbb{T}_{\gamma\mu}^K - \frac{i\varsigma}{\lambda_m} G_C^* \hat{Q}_\alpha \hat{K}_\mu^\perp \right],$$

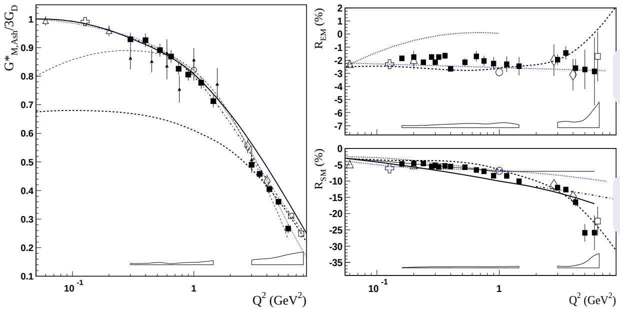
called magnetic dipole, G_M^*; electric quadrupole, G_E^*; and Coulomb quadrupole, G_C^*.

☞ There are different conventions followed by experimentalists and theorists:

$$G_{M,\mathrm{Ash}}^* = G_{M,\mathrm{J-S}}^* \left(1 + \frac{Q^2}{(m_\Delta + m_N)^2} \right)^{-\frac{1}{2}}$$

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)

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

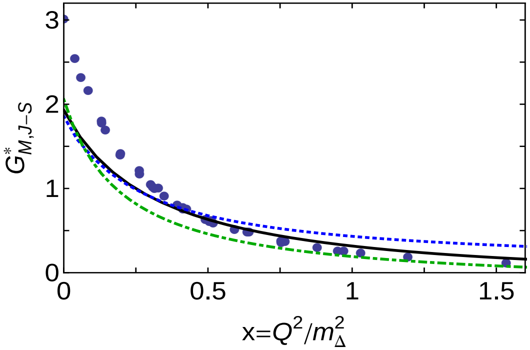
pQCD predictions

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

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

Experimental data do not support theoretical predictions

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

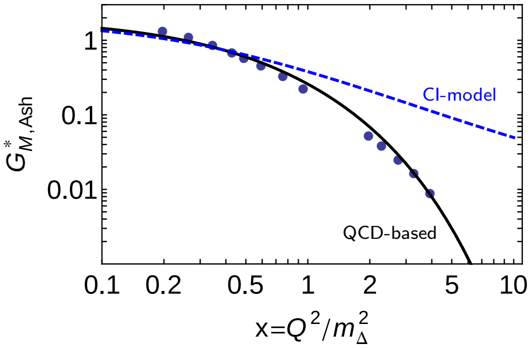


- Solid-black:
  QCD-kindred interaction.
- Dashed-blue:
  Contact interaction.
- Dot-Dashed-green:
  Dynamical + no meson-cloud

☞ 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 $Q^2 \gtrsim 0.75 m^2_\Delta \sim 1.14\,\mathrm{GeV}^2$.

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:

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

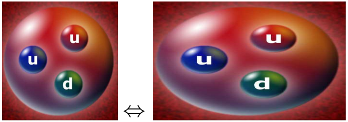
- Jones-Scadron should exhibit:

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

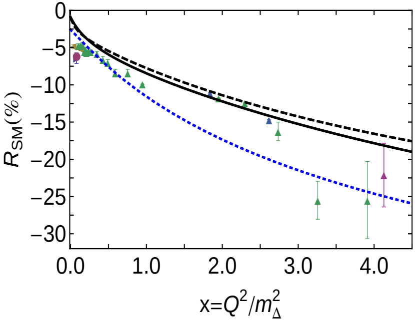
- Meson-cloud effects
  - Up-to 35% for $Q^2 \lesssim 2.0 m_\Delta^2$.
  - Very soft $\rightarrow$ disappear rapidly.
- $G^*_{M,\mathrm{Ash}}$ vs $G^*_{M,\mathrm{J-S}}$
  - A factor $1/\sqrt{Q^2}$ of difference.

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

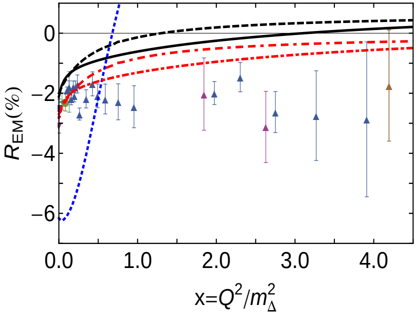
- Deformation of the hadrons involved.
- Modification of the structure of the transition current.



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



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



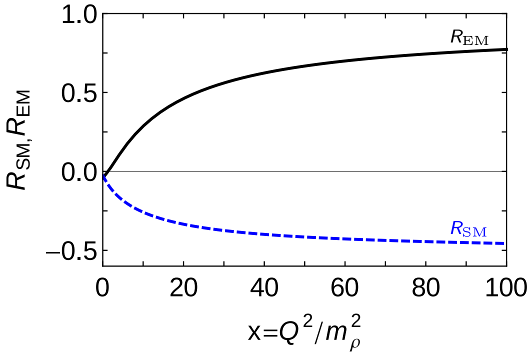
☞ *Zero Crossing in the transition electric form factor:*

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 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 $\gamma^* N \to$ Roper reaction

Work in collaboration with:

- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Bruno El-Bennich (São Paulo)
- Eduardo Rojas (São Paulo)
- Shu-Sheng Xu (Nanjing)
- Hong-Shi Zong (Nanjing)

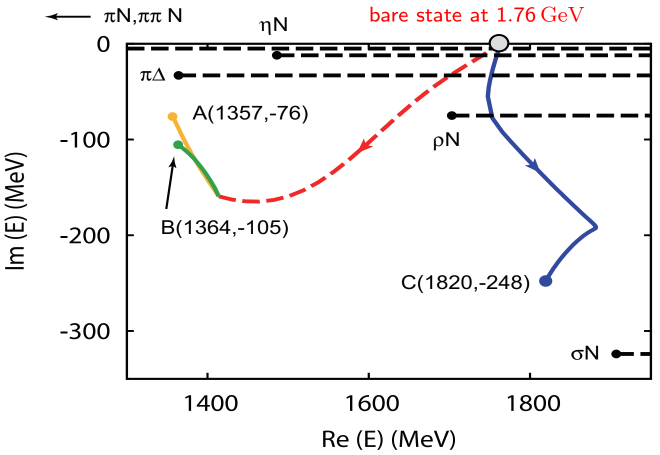
Based on:

- Phys. Rev. Lett. 115 (2015) 171801 [arXiv: 1504.04386 [nucl-th]]
- Phys. Rev. C94 (2016) 042201(R) [arXiv: 1607.04405 [nucl-th]]

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

Disentangling the Dynamical Origin of P_{11} Nucleon Resonances

N. Suzuki,[1,2] B. Juliá-Díaz,[3,2] H. Kamano,[2] T.-S. H. Lee,[2,4] A. Matsuyama,[5,2] and T. Sato[1,2]



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.*

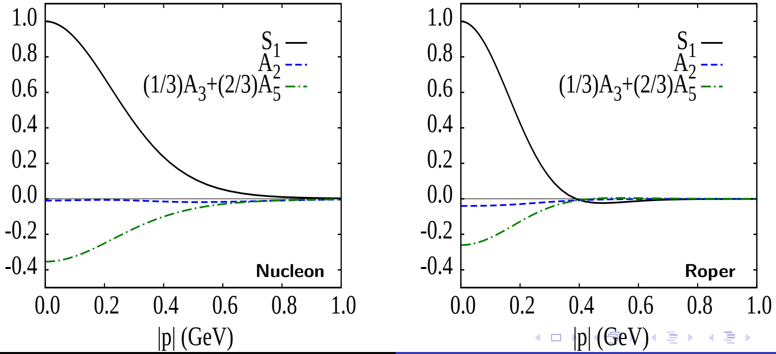
The bare N^* states correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions

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

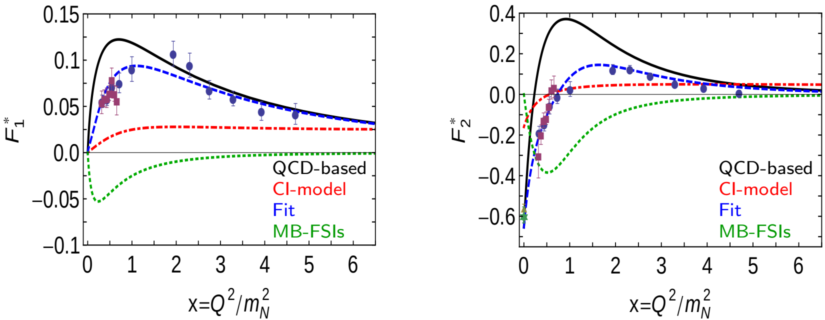
☞ Observation:

- 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



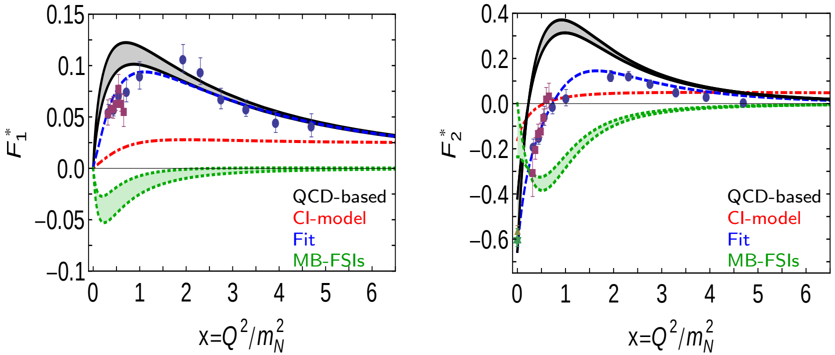
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core



☞ Observations:

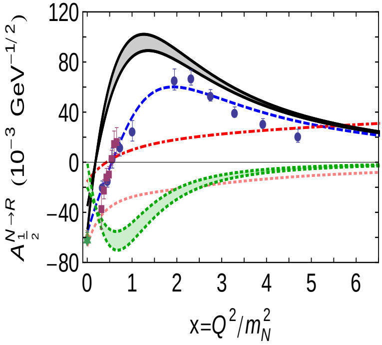
- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$.
- The mismatch between our prediction and the data on $x \lesssim 2$ is due to meson cloud contribution.
- The dotted-green curve is an inferred form of meson cloud contribution from the fit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

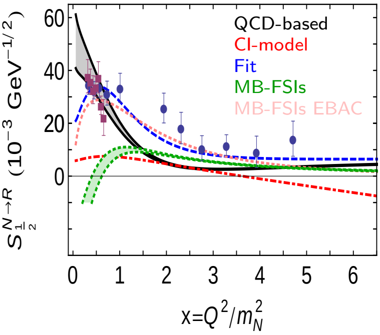
Including a meson-baryon Fock-space component into the baryons' Faddeev amplitudes with a maximum strength of 20%



☞ 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.





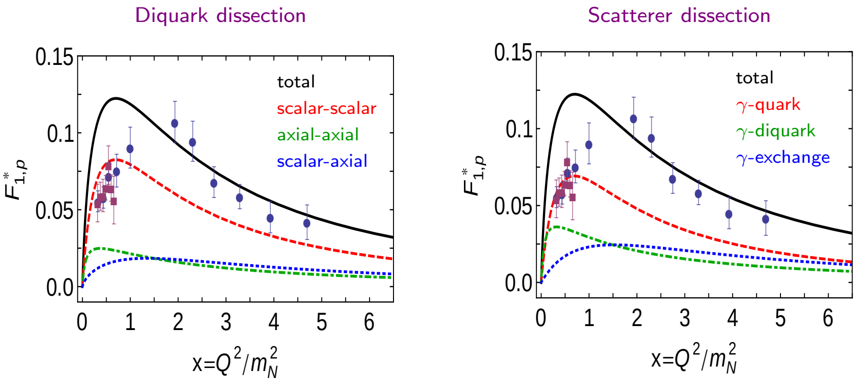
Concerning $A_{1/2}$:

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

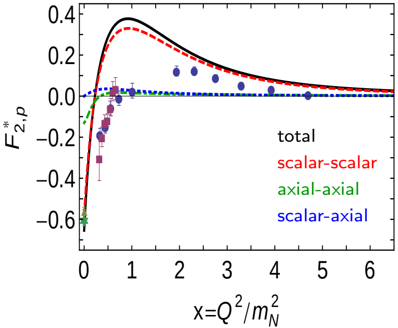
The $\gamma_v p \to R^+$ Dirac transition form factor



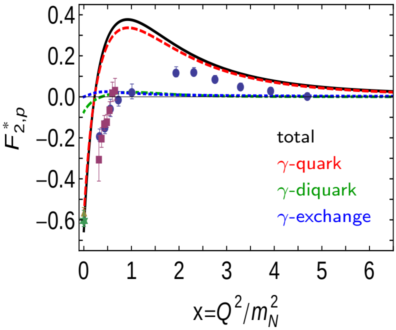
☞ Observations:

- The Dirac transition form factor is primarily driven by a photon striking a bystander dressed quark that is partnered by a scalar diquark.
- Lesser but non-negligible contributions from all other processes are found.
- In exhibiting these features, $F^*_{1,p}$ shows marked qualitative similarities to the proton's elastic Dirac form factor.

Diquark dissection



Scatterer dissection

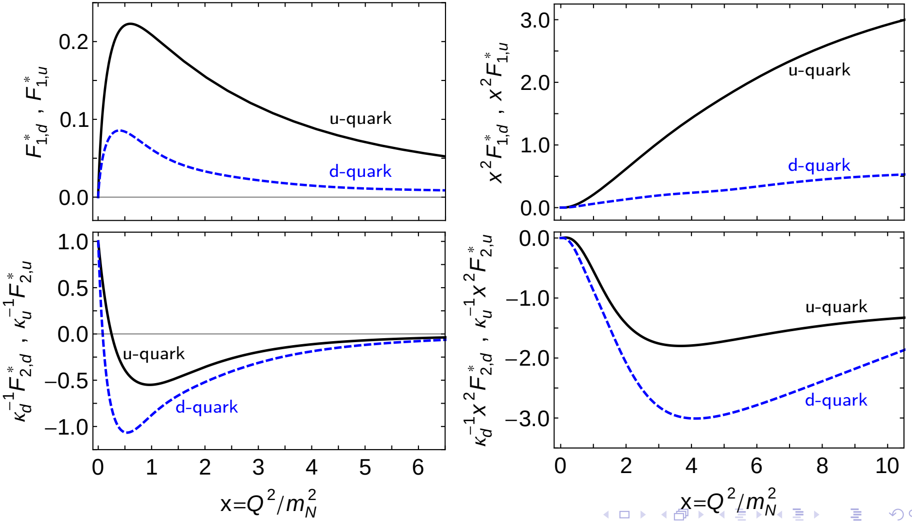


☞ Observations:

- A single contribution is overwhelmingly important: photon strikes a bystander dressed-quark in association with a scalar diquark.
- No other diagram makes a significant contribution.
- $F^*_{2,p}$ shows marked qualitative similarities to the proton's elastic Pauli form factor.

Obvious similarity to the analogous form factor determined in elastic scattering

The d-quark contributions of the form factors are suppressed with respect to the u-quark contributions



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 presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavour-separated form factors.
- Scalar diquark dominance and the presence of higher orbital angular momentum components are responsible of the Q^2-behaviour of G_E^p/G_M^p and F_2^p/F_1^p.

☞ 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.
- Limits of pQCD, $R_{EM} \to 1$ and $R_{SM} \to \text{constant}$, 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.
- Flavour-separated versions of transition form factors reveal that, as in the case of the elastic form factors, the *d*-quark contributions are suppressed with respect the *u*-quark ones.