

Flavour decomposition of electromagnetic transition form factors of nucleon resonances

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XII Quark Confinement and Hadron Spectrum
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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 DCSB and
confinement in QCD

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 GeV² for $\Delta(1232)P_{33}$ and $N(1535)S_{11}$.
 - 4.5 GeV² for $N(1440)P_{11}$ and $N(1520)D_{13}$.
- The majority of new data was obtained at JLab.

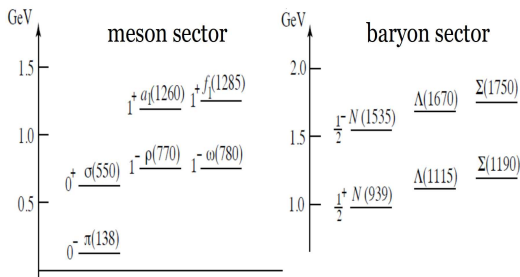
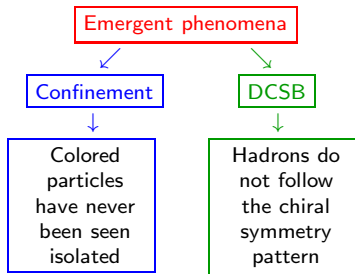


Upgrade of CLAS up to 12 GeV² → CLAS12 (commissioning runs are underway)

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 \Rightarrow Confinement
- Origin of the 98% of the mass of the proton \Rightarrow DCSB



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

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:

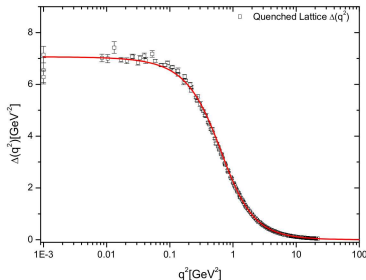
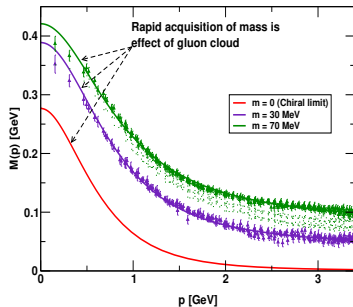
$$S^{-1}(p) = Z_2(i\gamma \cdot p + m^{\text{bm}}) + \Sigma(p) = \left(\frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \right)^{-1}$$

- 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.



The quantum equations of motion whose solutions are the Schwinger functions

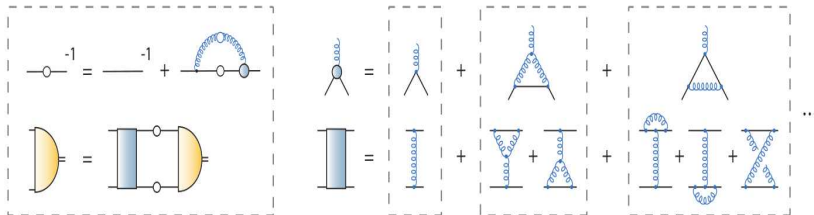
📖 Continuum Quantum Field Theoretical Approach:

- 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...



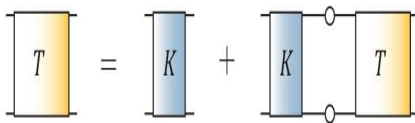
- No constant quark mass unless NJL contact interaction.
- No crossed-ladder unless consistent quark-gluon vertex.
- Cannot add e.g. an explicit confinement potential.

⇒ **modelling only within these constraints!**

The bound-state problem in quantum field theory

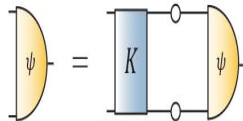
Extraction of hadron properties from poles in $q\bar{q}$, qqq , $qq\bar{q}\bar{q}\dots$ scattering matrices


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



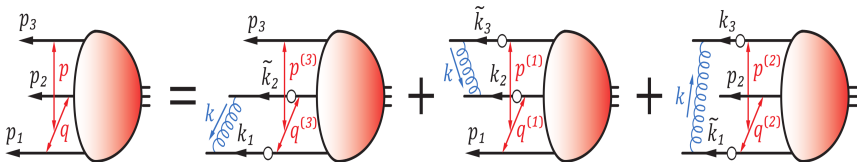
$p^2 \rightarrow -m^2$

Homogeneous BSE for **BS amplitude**:



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

Faddeev equation in rainbow-ladder truncation

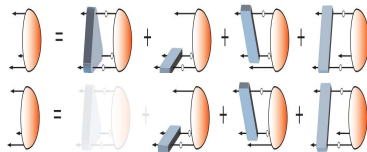


Faddeev equation: Sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.

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

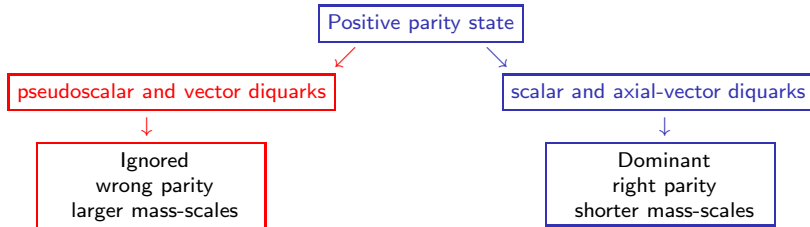
Diquark correlations:

- A tractable truncation of the Faddeev equation.
- In $N_c = 3$ QCD: diquarks can form color singlets which are the baryons of the theory.
- In our approach: Non-pointlike color-antitriplet and fully interacting.



Thanks to G. Eichmann.

Diquark composition of the Nucleon and Roper



One-loop diagrams

Two-loop diagrams

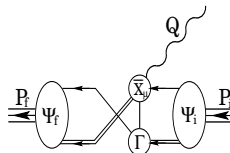
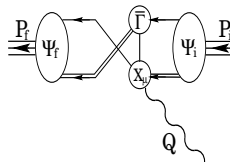
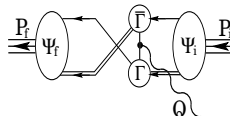
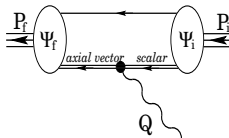
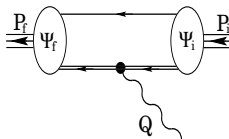
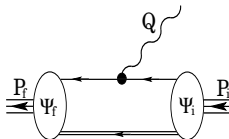
One must specify how the photon couples to the constituents within the baryon.



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.



The $\gamma^*N \rightarrow$ Nucleon reaction

Work in collaboration with:

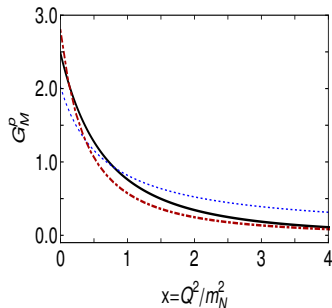
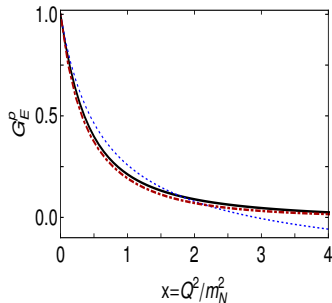
- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Sebastian M. Schmidt (Jülich)

Based on:

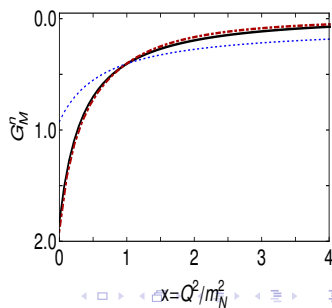
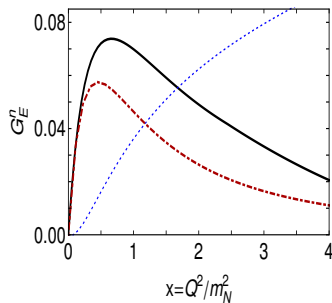
- Phys. Lett. B750 (2015) 100-106 [arXiv: 1506.05112 [nucl-th]]
- Few-Body Syst. 55 (2014) 1185-1222 [arXiv: 1408.2919 [nucl-th]]

Sachs electric and magnetic form factors

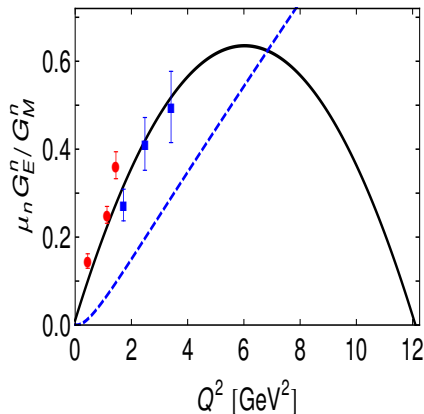
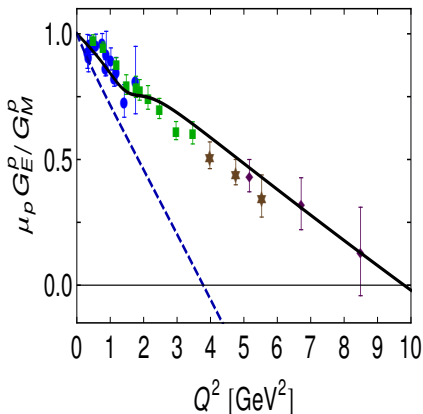
☞ Q^2 -dependence of **proton** form factors:



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



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



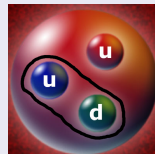
The possible existence and location of the zero in $\mu_p G_E^p / G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction

A world with only scalar diquarks

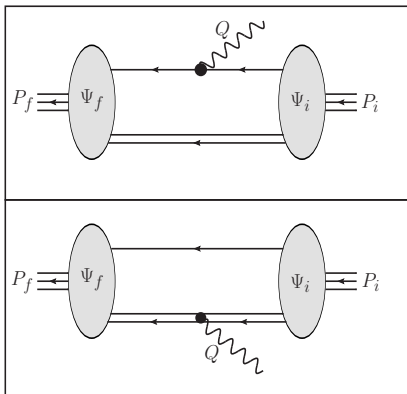
The singly-represented d -quark in the proton $\equiv u[ud]_{0+}$ is sequestered inside a soft scalar diquark correlation.

 **Observation:**

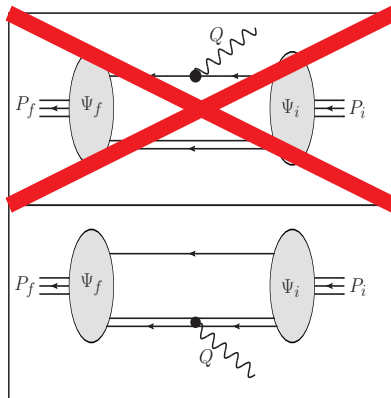
$$\text{diquark-diagram} \propto 1/Q^2 \times \text{quark-diagram}$$



Contributions coming from **u-quark**



Contributions coming from **d-quark**

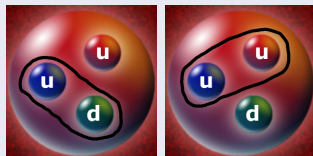


A world with scalar and axial-vector diquarks (I)

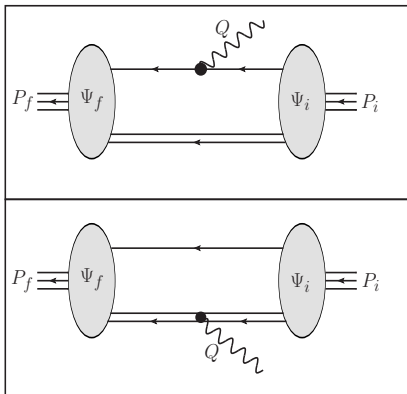
The singly-represented *d*-quark in the proton is **not always (but often)** sequestered inside a soft scalar diquark correlation.

🔍 *Observation:*

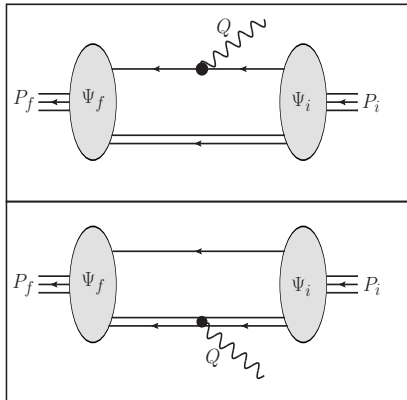
$$\mathcal{P}_{\text{scalar}} \sim 0.62, \quad \mathcal{P}_{\text{axial}} \sim 0.38$$



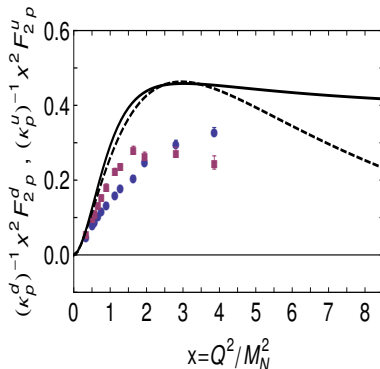
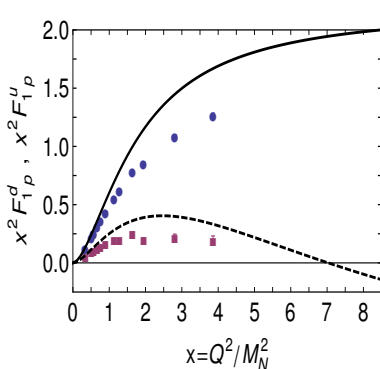
Contributions coming from *u*-quark



Contributions coming from *d*-quark



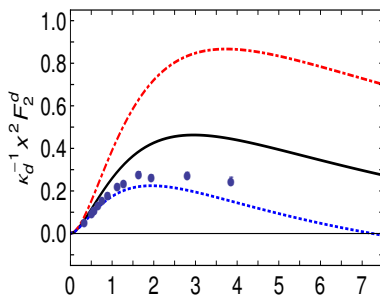
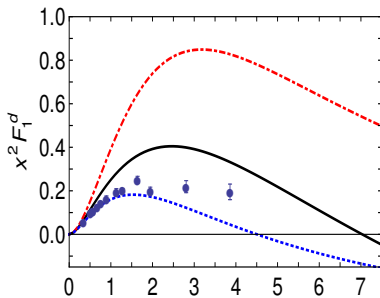
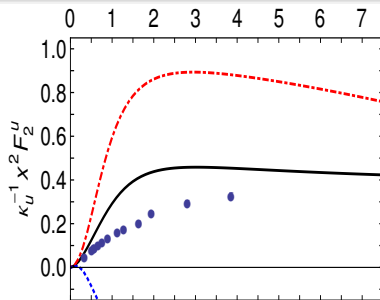
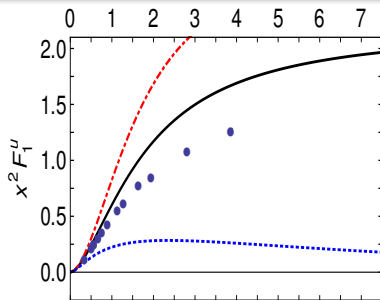
A world with scalar and axial-vector diquarks (II)



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.

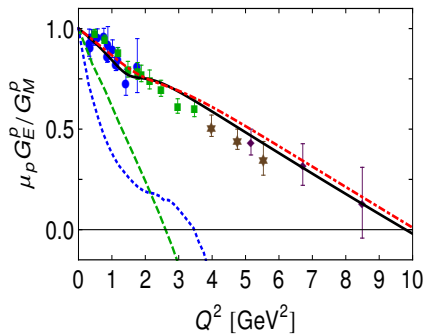
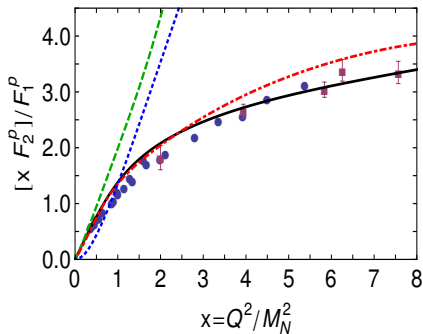
Comparison between worlds (I)



$$x = Q^2/M_N^2$$

$$x = Q^2/M_N^2$$

Comparison between worlds (II)



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 $\gamma^* N \rightarrow$ Roper reaction

Work in collaboration with:

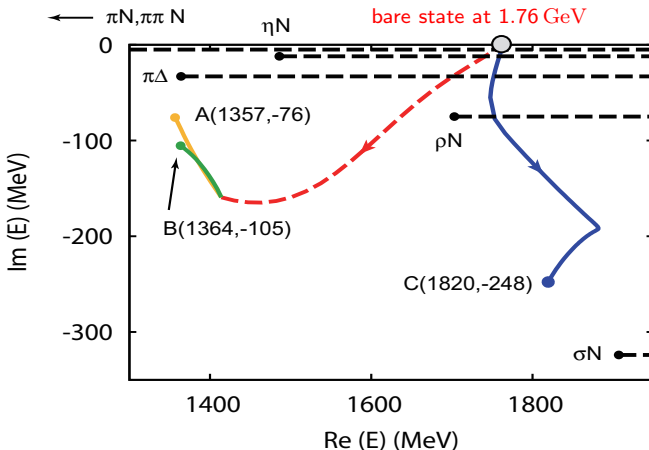
- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Bruno El-Bennich (São Paulo)
- Eduardo Rojas (São Paulo)
- Shu-Sheng Xu (Nanjing)
- Hong-Shi Zong (Nanjing)

Based on:

- Phys. Rev. Lett. 115 (2015) 171801 [arXiv: 1504.04386 [nucl-th]]
- Submitted to Phys. Rev. C (rapid communications) [arXiv: 1607.04405 [nucl-th]]

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.*

Nucleon's first radial excitation in DSEs

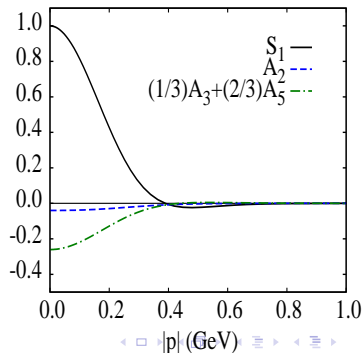
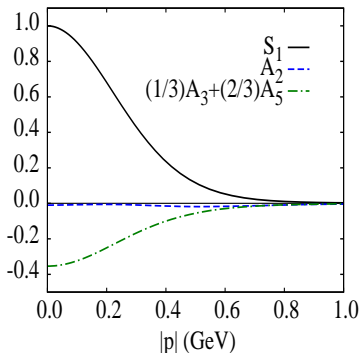
The bare N^* states correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions:

$$M_{\text{Roper}}^{\text{DSE}} = 1.73 \text{ GeV} \quad M_{\text{Roper}}^{\text{EBAC}} = 1.76 \text{ GeV}$$

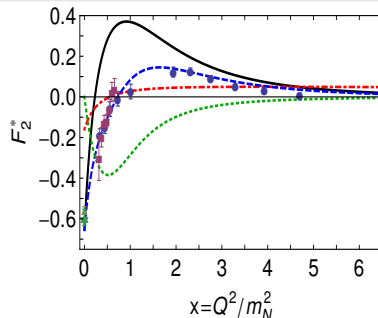
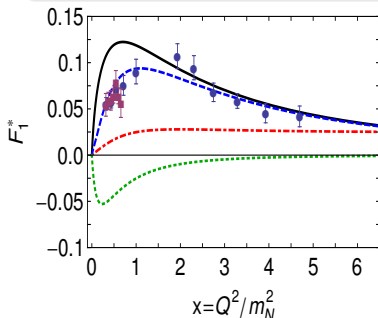
Observation:

- 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 \Rightarrow A radial excitation.

0th Chebyshev moment of the S-wave components



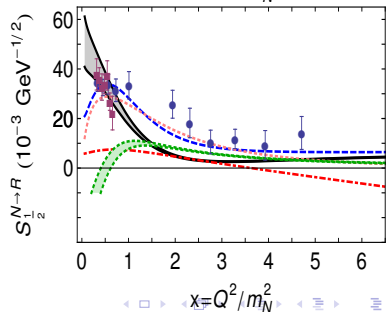
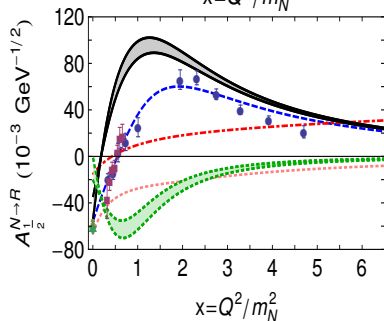
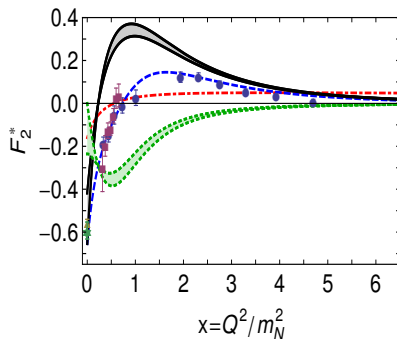
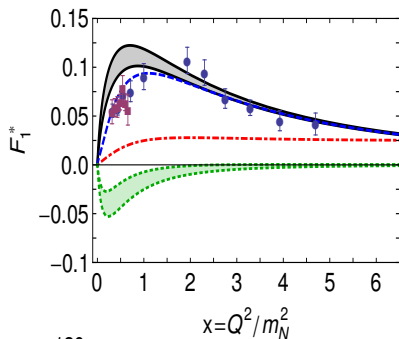
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core

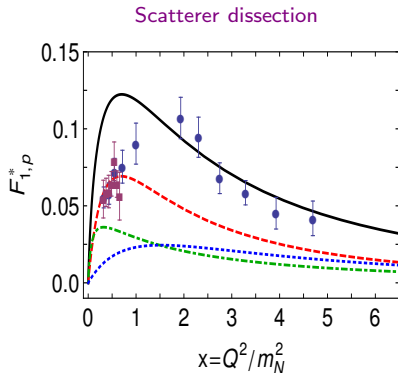
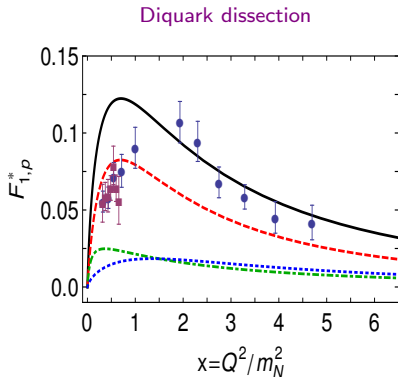


Observations:

- 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.

Transition form factors (II)

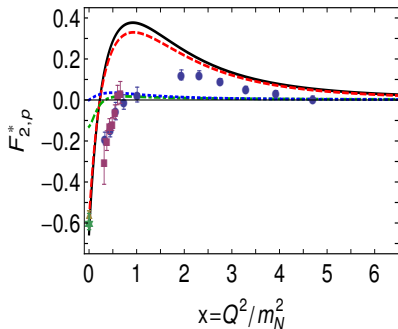




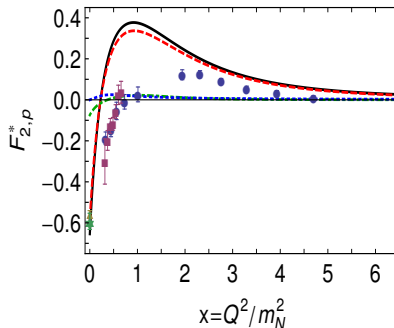
Observations:

- 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

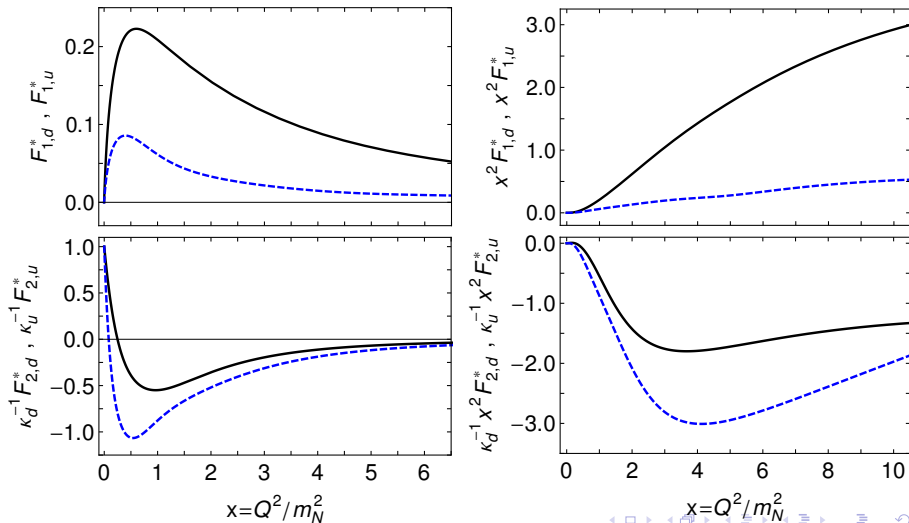


Observations:

- 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.

Flavour-separated transition form factors

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



☞ Quantum Field Theory view of a baryon:

- Poincaré covariance demands the presence of dressed-quark orbital angular momentum in the baryon.
- Dynamical chiral symmetry breaking and its correct implementation produces pions as well as strong electromagnetically-active diquark correlations.

☞ The $\gamma^* N \rightarrow \text{Nucleon}$ 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 $\gamma^* N \rightarrow \text{Roper}$ 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.