The Structure of the Nucleon and its Resonances through the Dyson-Schwinger Equations formalism

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Continuum Functional Methods for QCD at New Generation Facilities

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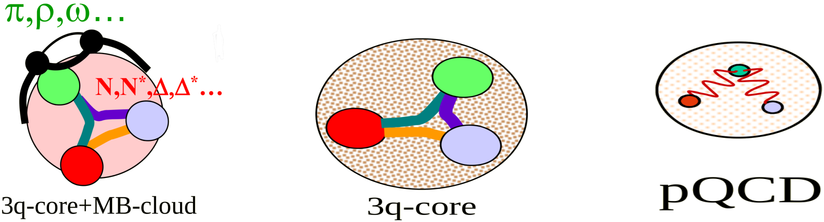
A central goal of Nuclear Physics: understand the properties of hadrons in terms of the elementary excitations in Quantum Chromodynamics (QCD): quarks and gluons.

Transition form factors of nucleon resonances

↙ ↘

Unique window into their quark and gluon structure → Distinctive information on the roles played by emergent phenomena in QCD

Broad range of photon virtuality → Probe the excited nucleon structures at perturbative and non-perturbative QCD scales



Low Q^2 ⟶ High Q^2

A vigorous experimental program has been and is still under way worldwide

CLAS, CBELSA, GRAAL, MAMI and LEPS

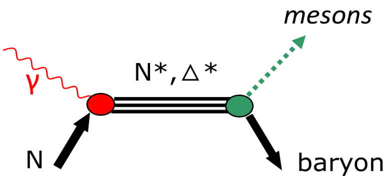
☞ Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.

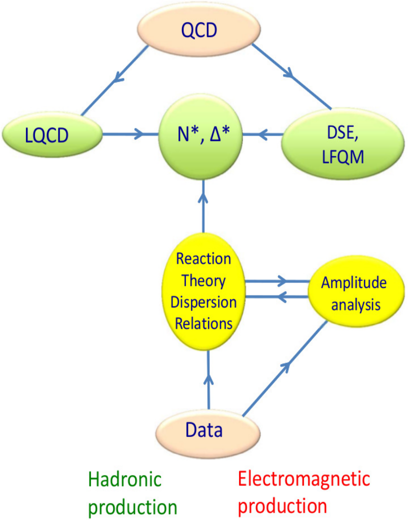
☞ Very precise data for 2-body processes in wide kinematics (angle, energy): $\gamma p \to \pi N$, ηN, KY.

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

$\Downarrow$

Extract s-channel resonances





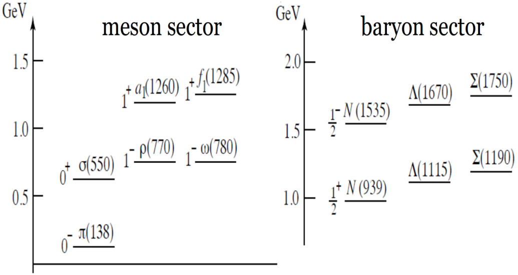
Hadrons, as bound states, are dominated by non-perturbative QCD dynamics

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

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

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 Schwinger functions** *(propagators and vertices).*

☞ Dressed-quark propagator in Landau gauge:

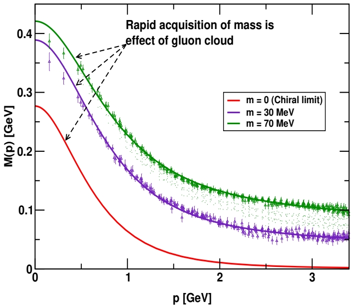
$$S^{-1}(p) = Z_2(i\gamma\cdot p + m) + \Sigma(p) = \left(\frac{Z(p^2)}{i\gamma\cdot p + \mathbf{M(p^2)}}\right)^{-1}$$

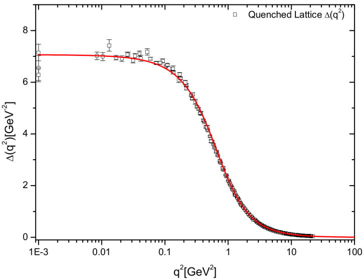
- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98% of the mass of the proton and the large splitting between parity partners.

☞ Dressed-gluon propagator in Landau gauge:

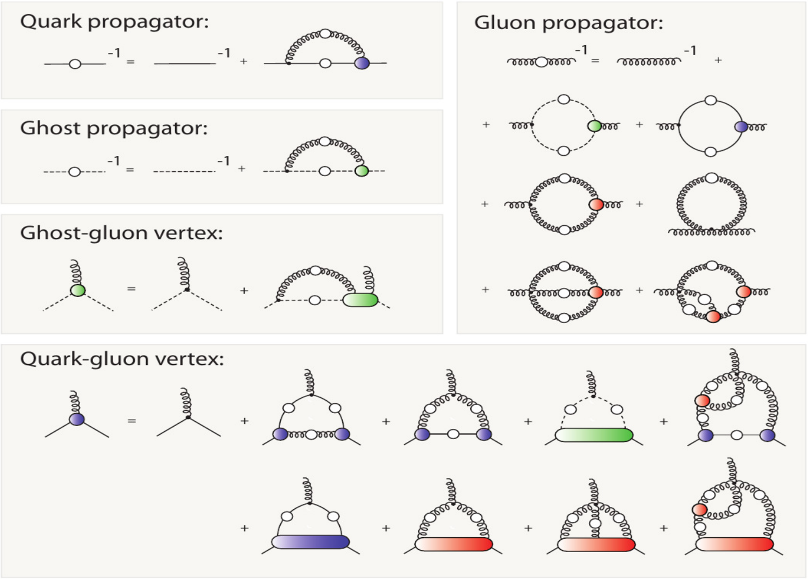
$$i\Delta_{\mu\nu} = -iP_{\mu\nu}\mathbf{\Delta(q^2)}, \quad P_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu/q^2$$

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





The Schwinger functions are solutions of the quantum equations of motion (≡ DSEs)

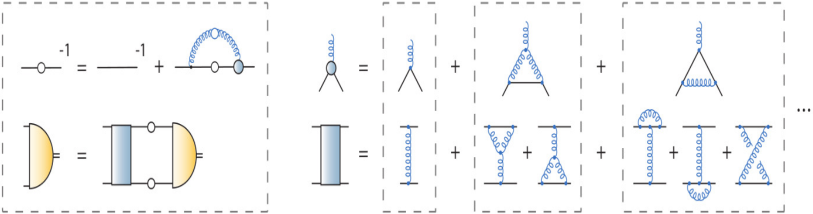


☞ Advantages:

- **Continuum** quantum field theory approach that provides access to:
  - Perturbative regime of QCD → No model-dependence.
  - **Nonperturbative** regime of QCD → Model-dependence should be incorporated here.
- Poincaré **covariant** formulation → Valid for all momentum scales.
- Cover **full quark mass range** → between chiral limit and the heavy quark domain.

☞ The main caveat concerns the complexity of this framework:

- Truncation of the infinite set of equations.
- Modelling in the nonperturbative regime.



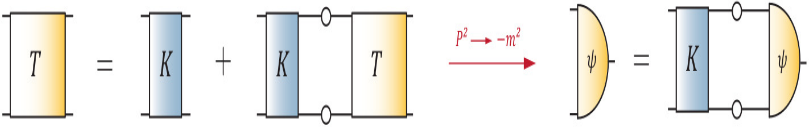
Ansätze are constrained by symmetry properties, multiplicative renormalizability, perturbative limits, few model parameters related with fundamental quantities

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

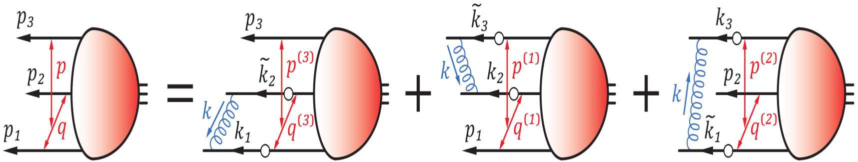
Use **scattering equation** (inhomogeneous BSE) to obtain T in the first place: $T = K + KG_0T$

Homogeneous BSE for **BS amplitude:**



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

Faddeev equation in rainbow-ladder truncation

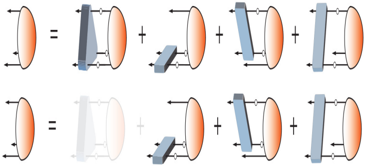


Faddeev equation: Sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.

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.



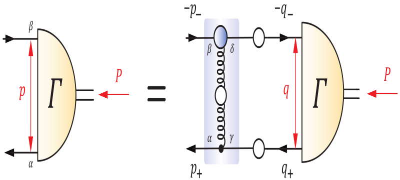
Diquark composition of the $N(940)$, $N(1440)$, $\Delta(1232)$ *and* $\Delta(1600)$

Positive parity states

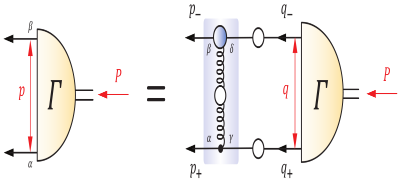
↙ pseudoscalar and vector diquarks ↓ Ignored wrong parity larger mass-scales

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

Meson BSE



Diquark BSE



☞ Owing to properties of charge-conjugation, a diquark with spin-parity J^P may be viewed as a partner to the analogous J^{-P} meson:

$$\Gamma_{q\bar{q}}(p;P) = - \int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{q\bar{q}}(q;P)S(q)\, \frac{\lambda^a}{2}\,\gamma_\nu$$

$$\Gamma_{qq}(p;P)C^\dagger = -\frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{qq}(q;P)C^\dagger S(q)\, \frac{\lambda^a}{2}\,\gamma_\nu$$

☞ Whilst no pole-mass exists, the following mass-scales express the strength and range of the correlation:

$$m_{[ud]_{0^+}} = 0.7-0.8\,\text{GeV}, \quad m_{\{uu\}_{1^+}} = 0.9-1.1\,\text{GeV}, \quad m_{\{dd\}_{1^+}} = m_{\{ud\}_{1^+}} = m_{\{uu\}_{1^+}}$$

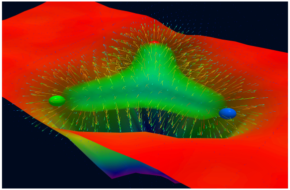
☞ Diquark correlations are soft, they possess an electromagnetic size:

$$r_{[ud]_{0^+}} \gtrsim r_\pi, \qquad r_{\{uu\}_{1^+}} \gtrsim r_\rho, \qquad r_{\{uu\}_{1^+}} > r_{[ud]_{0^+}}$$

Remark about the 3-gluon vertex

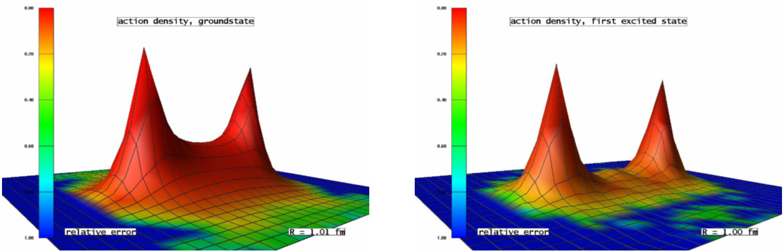
☞ A Y-junction flux-tube picture of nucleon structure is produced in **quenched** lattice QCD simulations that use **static sources** to represent the proton's valence-quarks.

F. Bissey et al. PRD 76 (2007) 114512.



☞ This might be viewed as originating in the 3-gluon vertex which signals the non-Abelian character of QCD.

☞ These suggest a key role for the three-gluon vertex in nucleon structure if they were equally valid in real-world QCD: **finite quark masses and light dynamical/sea quarks.**

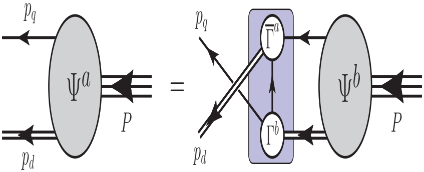


G.S. Bali, PRD 71 (2005) 114513.

The dominant effect of non-Abelian multi-gluon vertices is expressed in the formation of diquark correlations through Dynamical Chiral Symmetry Breaking.

☞ A nucleon (and kindred baryons) can be viewed as a **Borromean bound-state**, the binding within which has two contributions:

- Formation of tight diquark correlations.
- Quark exchange depicted in the shaded area.



☞ The exchange ensures that diquark correlations within the nucleon are fully dynamical: no quark holds a special place.

☞ The rearrangement of the quarks guarantees that the nucleon's wave function complies with Pauli statistics.

☞ Modern diquarks are different from the old static, point-like diquarks which featured in early attempts to explain the so-called missing resonance problem.

☞ The number of states in the spectrum of baryons obtained is similar to that found in the three-constituent quark model, just as it is in today's LQCD calculations.

☞ Modern diquarks enforce certain distinct interaction patterns for the singly- and doubly-represented valence-quarks within the proton.

Baryon-photon vertex

One must specify how the photon couples to baryon's constituents

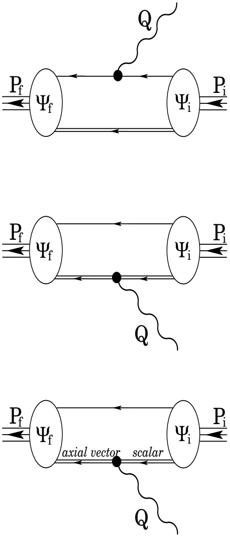
⇓

Six contributions to the current in the quark-diquark picture

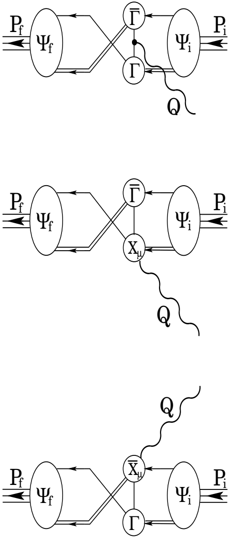
⇓

- *Coupling of the photon to the dressed quark.*
- *Coupling of the photon to the dressed diquark:*
  - ➥ *Elastic transition.*
  - ➥ *Induced transition.*
- *Exchange and seagull terms.*

One-loop diagrams



Two-loop diagrams



$\gamma^* N(940)\frac{1}{2}^+ \to N(940)\frac{1}{2}^+$

Based on:

- **PDAs: Revealing correlations within the proton and Roper**
  C. Mezrag, J. Segovia, L. Chang and C.D. Roberts
  Phys. Lett. B783 (2018) 263-267, arXiv:nucl-th/1711.09101
- **Contact-interaction Faddeev equation and, inter alia, proton tensor charges**
  S.-S. Xu, C. Chen, I.C. Cloët, C.D. Roberts, J. Segovia and H.-S. Zong
  Phys. Rev. D92 (2015) 114034, arXiv:nucl-th/1509.03311
- **Understanding the nucleon as a borromean bound-state**
  J. Segovia, C.D. Roberts and S.M. Schmidt
  Phys. Lett. B750 (2015) 100-106, arXiv:nucl-th/1506.05112
- **Nucleon and Delta elastic and transition form factors**
  J. Segovia, I.C. Cloët, C.D. Roberts and S.M. Schmidt
  Few-Body Syst. 55 (2014) 1185-1222, arXiv:nucl-th/1408.2919

The $\gamma^* N \to N'$ electromagnetic current

☞ The electromagnetic current can be generally written as:

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

- Incoming nucleon: $P_i^2 = -m_N^2$, and outgoing radial excitation: $P_f^2 = -m_{N'}^2$.
- Photon momentum: $Q = P_f - P_i$, and total momentum: $K = (P_i + P_f)/2$.
- The on-shell structure is ensured by the positive-energy projection operators.

☞ Vertex decomposes in terms of two form factors:

$$\Gamma_\mu(K,Q) = \gamma_\mu^{(T)} F_1^{(*)}(Q^2) + \frac{1}{m_N + m_{N'}}\sigma_{\mu\nu} Q_\nu F_2^{(*)}(Q^2)$$

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

$$G_E^{(*)}(Q^2) = F_1^{(*)}(Q^2) - \frac{Q^2}{4m_N^2} F_2^{(*)}(Q^2)$$

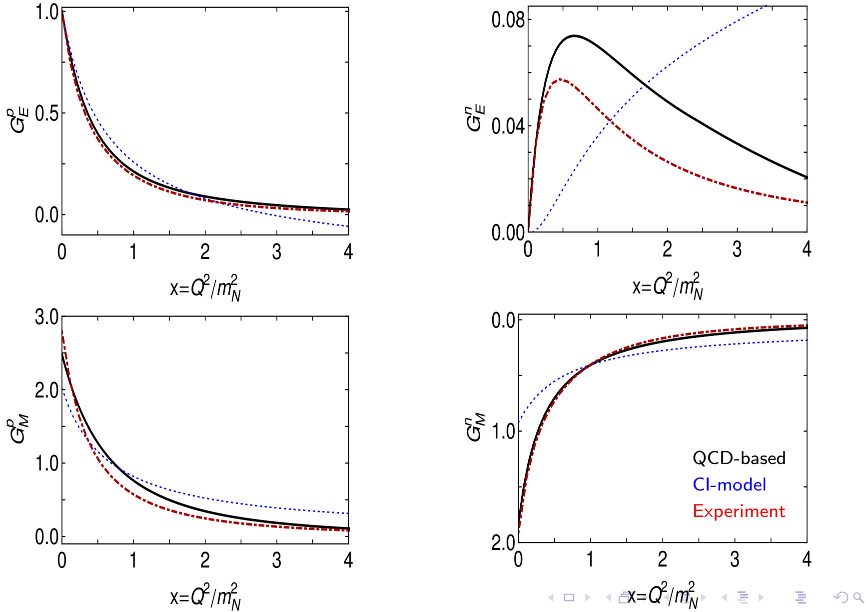
$$G_M^{(*)}(Q^2) = F_1^{(*)}(Q^2) + F_2^{(*)}(Q^2)$$

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

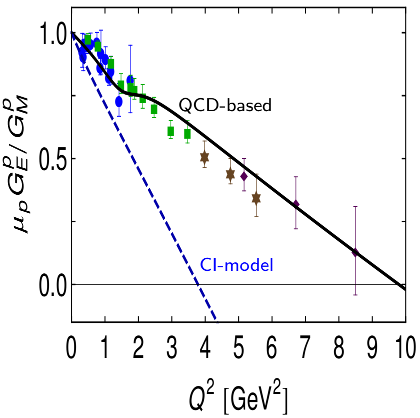
- $G_E^{(*)} \Rightarrow$ Momentum space distribution of electric charge.
- $G_M^{(*)} \Rightarrow$ Momentum space distribution of magnetization.

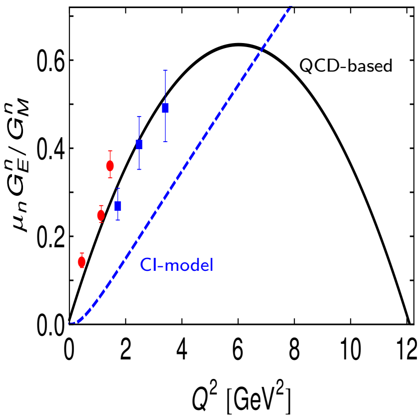
☞ Q^2-dependence of **proton** form factors:

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

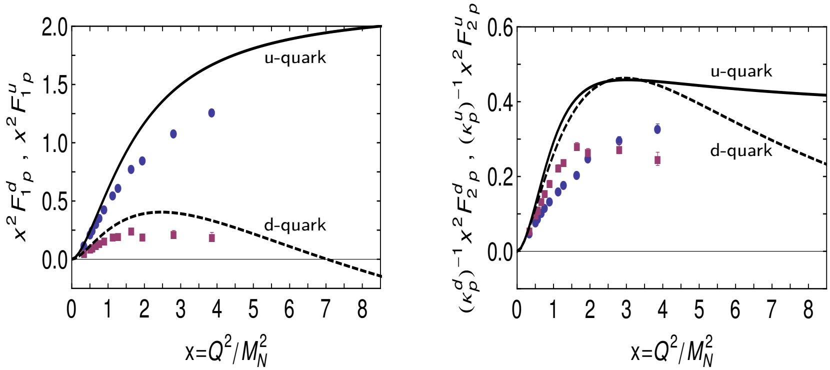


Both CI and QCD-kindred frameworks predict a zero crossing in $\mu_p G_E^p / G_M^p$



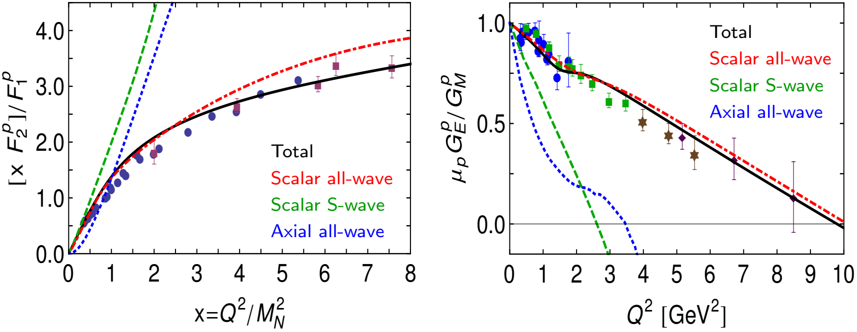


The possible existence and location of the zero in $\mu_p G_E^p / G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction



☞ 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:

- 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

$\gamma^* N(940)\frac{1}{2}^+ \rightarrow N(1440)\frac{1}{2}^+$

Based on:

- **Nucleon-to-Roper electromagnetic transition form factors at large Q^2**
  C. Chen, Y. Lu, D. Binosi, C.D. Roberts, J. Rodríguez-Quintero, and J. Segovia
  Phys. Rev. D99 (2019) 034013, arXiv:nucl-th/1811.08440

- **Structure of the nucleon's low-lying excitations**
  C. Chen, B. El-Benich, C.D. Roberts, S.M. Schmidt, J. Segovia and S. Wan
  Phys. Rev. D97 (2018) 034016, arXiv:nucl-th/1711.03142

- **Dissecting nucleon transition electromagnetic form factors**
  J. Segovia and C.D. Roberts
  Phys. Rev. C94 (2016) 042201(R), arXiv:nucl-th/1607.04405

- **Completing the picture of the Roper resonance**
  J. Segovia, B. El-Bennich, E. Rojas, I.C. Cloët, C.D. Roberts, S.-S. Xu and H.-S. Zong
  Phys. Rev. Lett. 115 (2015) 171801, arXiv:nucl-th/1504.04386

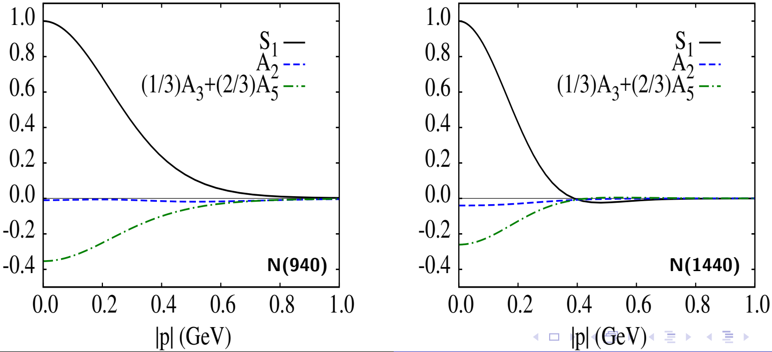
Bare-states of nucleon resonances correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions

$M^{DSE}_{Roper} = 1.73\,\mathrm{GeV} \qquad M^{EBAC}_{Roper} = 1.76\,\mathrm{GeV}$

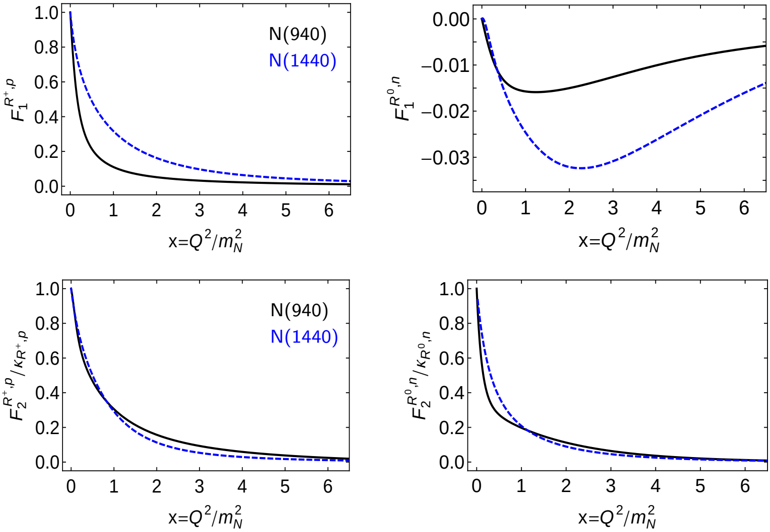
☞ Observations:

- 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.

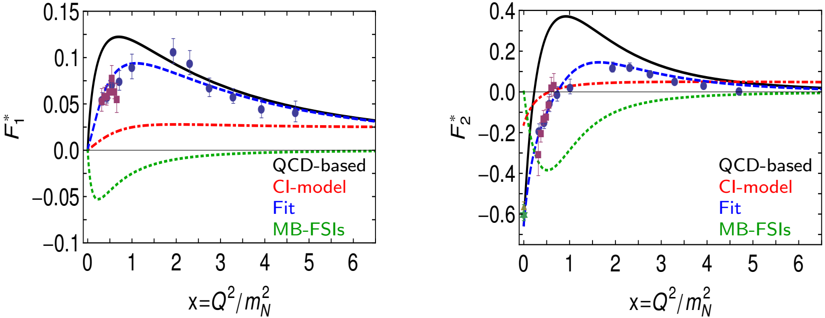
0th Chebyshev moment of the S-wave components



There are qualitative similarities and quantitative differences



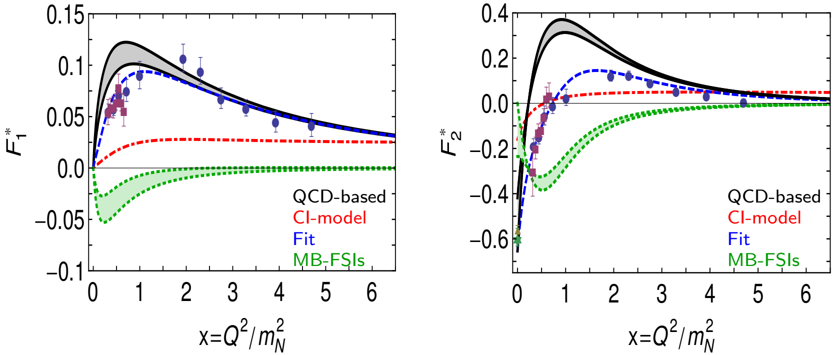
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core



☞ 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.

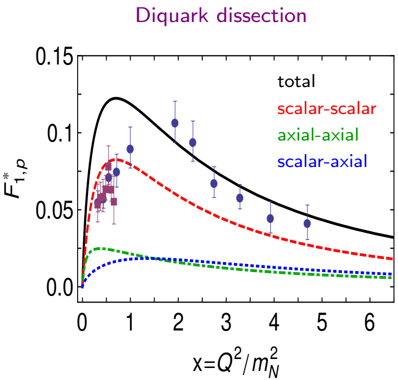
Including a meson-baryon Fock-space component into the baryons' Faddeev amplitudes with a maximum strength of 20%

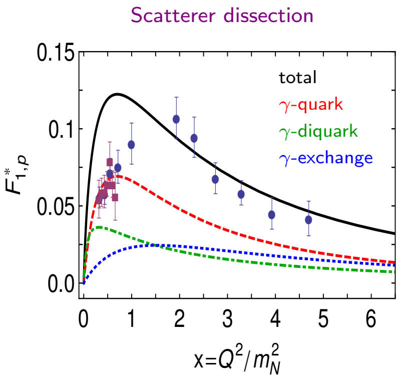


☞ Observations:

- 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.

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

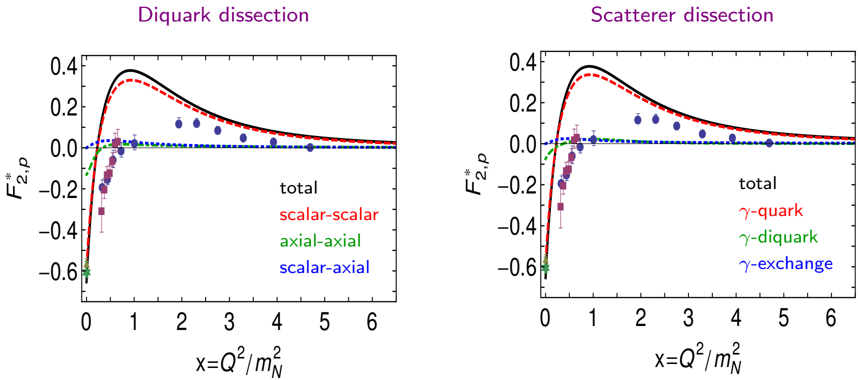




☞ Observations:

- 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.

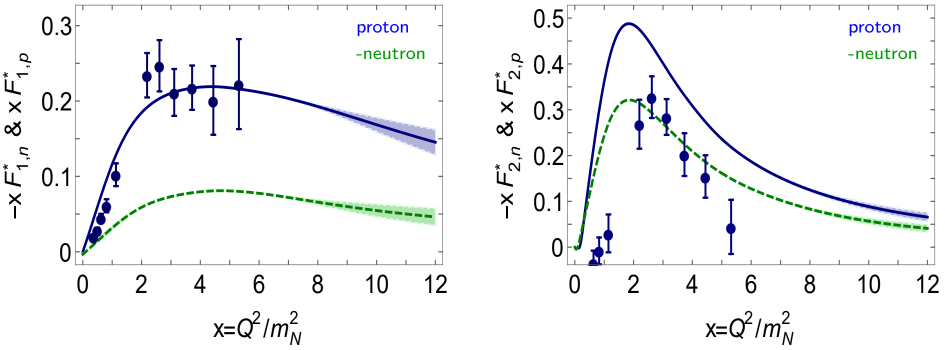
The $\gamma^* p \to R^+$ Pauli transition form factor



☞ 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.

CLAS12 detector at JLab will deliver data on the Roper-resonance electroproduction form factors out to $Q^2 \sim 12 m_N^2$ in both the charged and neutral channels

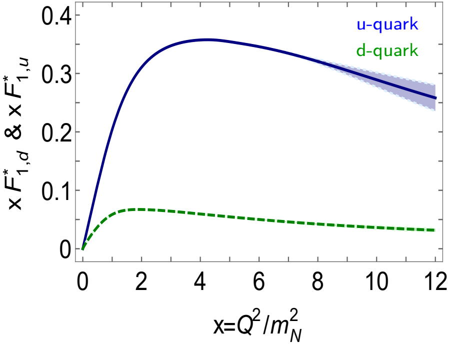


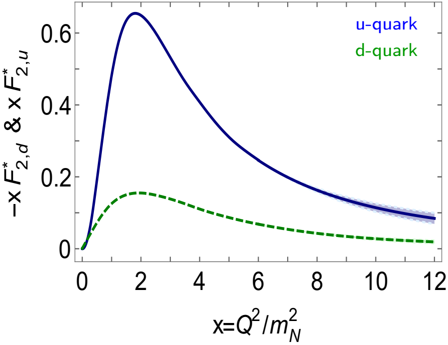
☞ Observations:

- On the domain depicted, there is no indication of the scaling behavior expected of the transition form factors: $F_1^* \sim 1/x^2$, $F_2^* \sim 1/x^3$.
- Since each dressed-quark in the baryons must roughly share the momentum, Q, we expect that such behaviour will only become evident on $x \gtrsim 20$.

Obvious similarity to the analogous form factor determined in elastic scattering

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





☞ Observations:

- With only scalar diquark correlations inside proton and roper, γ–d-quark interactions would receive a $1/x$ suppression on $x > 1$.
- At large x, scalar diquark dominance leads one to expect $F^*_d \sim F^*_u/x$. The details of this x-dependence are influenced by the presence of pseudovector diquarks.

$\gamma^* N(940)\frac{1}{2}^+ \to \Delta(1232)\frac{3}{2}^+$

Based on:

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- **Nucleon and Delta elastic and transition form factors**
  J. Segovia, I.C. Cloët, C.D. Roberts and S.M. Schmidt
  Few-Body Syst. 55 (2014) 1185-1222, arXiv:nucl-th/1408.2919
- **Elastic and transition form factors of the $\Delta(1232)$**
  J. Segovia, C. Chen, I.C. Cloët, C.D. Roberts, S.M. Schmidt and S. Wan
  Few-Body Syst. 55 (2014) 1-33, arXiv:nucl-th/1308.5225
- **Insights into the $\gamma^* N \to \Delta$ transition**
  J. Segovia, C. Chen, C.D. Roberts and S. Wan
  Phys. Rev. C88 (2013) 032201(R), arXiv:nucl-th/1305.0292

☞ The transition 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:

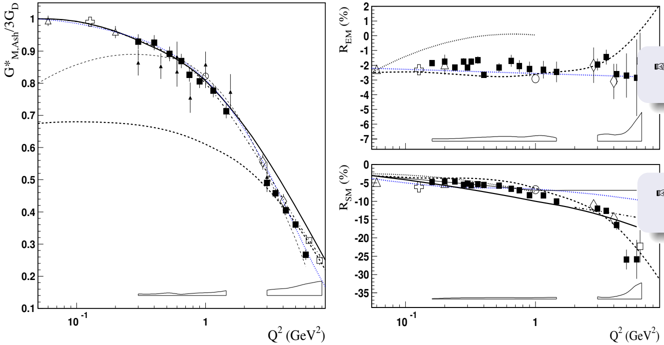
$$\Gamma_{\alpha\mu}(K,Q) = \mathpzc{k}\left[\frac{\lambda_m}{2\lambda_+}(G_M^* - G_E^*)\gamma_5\varepsilon_{\alpha\mu\gamma\delta}\hat{K}_\gamma^\perp\hat{Q}_\delta - G_E^*\mathbb{T}_{\alpha\gamma}^Q\mathbb{T}_{\gamma\mu}^K - \frac{i\varsigma}{\lambda_m}G_C^*\hat{Q}_\alpha\hat{K}_\mu^\perp\right]$$

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

☞ There are different conventions followed by experimentalists and theorists:

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

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



The $SU(6)$ predictions

(Symmetry considerations of baryon's wave function)

$$\langle p|\mu|\Delta^+\rangle = \langle n|\mu|\Delta^0\rangle$$
$$\langle p|\mu|\Delta^+\rangle = -\sqrt{2}\,\langle n|\mu|n\rangle$$

The CQM predictions

(Without quark orbital angular momentum)

$$R_{EM} = 0$$
$$R_{SM} = 0$$

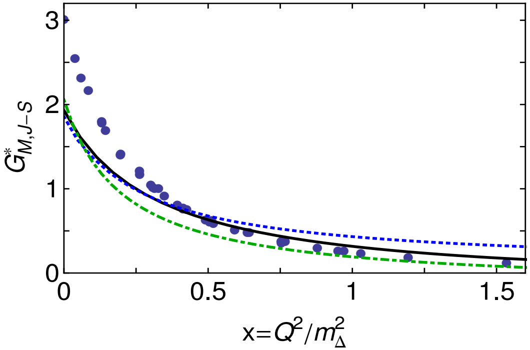
The pQCD predictions

(Helicity arguments at very large photon's momenta)

$$G^*_M \to 1/Q^4$$
$$R_{EM} \to 1$$
$$R_{SM} \to \text{constant}$$

Experimental data do not support theoretical predictions

$G^*_{M,J\text{-}S}$ cf. Experimental data and EBAC analysis



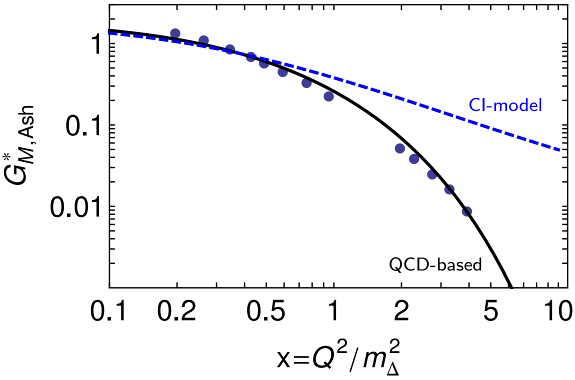
- Solid-black: QCD-kindred interaction.
- Dashed-blue: Contact interaction.
- Dot-Dashed-green: Dynamical + no meson-cloud

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

Presentations of experimental data typically use the Ash convention

– $G^*_{M,Ash}(Q^2)$ falls faster than a dipole –



☞ No sound reason to expect:

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

☞ Jones-Scadron must exhibit:

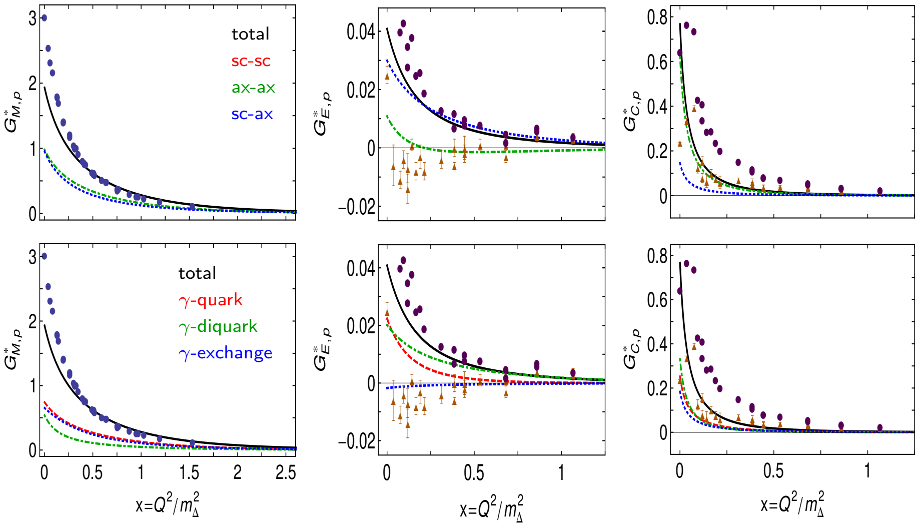
$$G^*_{M,\text{J-S}}/G_M \sim \text{constant}$$

☞ Meson-cloud effects

- Up-to 35% for $Q^2 \lesssim 2.0 m_\Delta^2$.
- Soft → disappear rapidly.

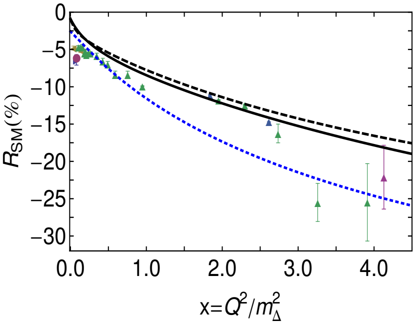
☞ $G^*_{M,\text{Ash}}$ vs $G^*_{M,\text{J-S}}$

- A Difference of $1/\sqrt{Q^2}$.

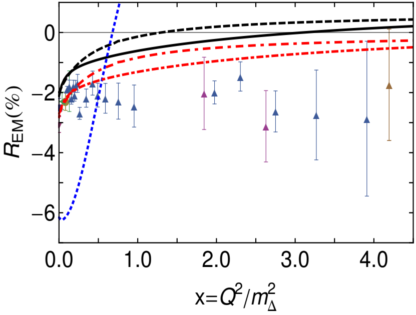


J. Segovia and C.D. Roberts, Phys.Rev. C94 (2016) 042201

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



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



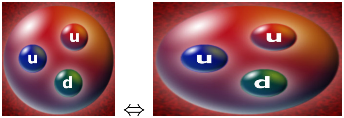
☞ *Zero Crossing in the electric transition form factor:*

$$\textit{Contact interaction} \rightarrow Q^2 \sim 0.75 m_\Delta^2 \sim 1.14\ GeV^2$$

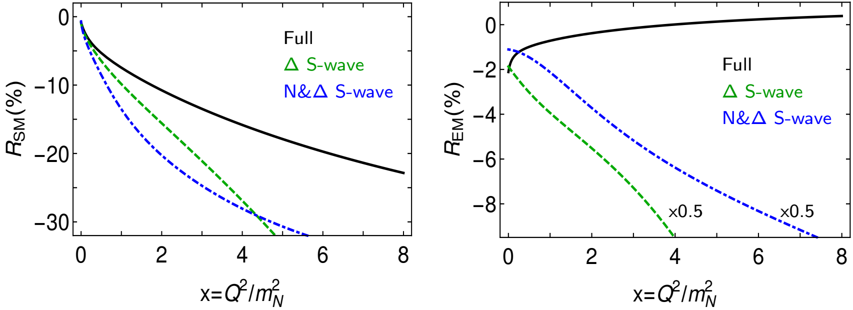
$$\textit{QCD-kindred interaction} \rightarrow Q^2 \sim 3.25 m_\Delta^2 \sim 4.93\ GeV^2$$

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

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



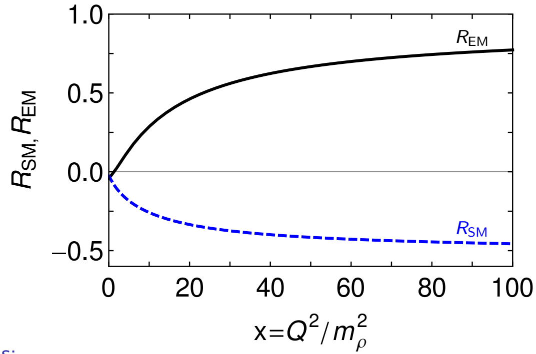
Observable impacts of higher partial waves in the Poincaré-covariant wave functions



Helicity conservation arguments in pQCD should apply equally to:

- *Results obtained within our QCD-kindred framework;*
- *Results produced by a symmetry-preserving treatment of a contact interaction.*

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



☞ Observations:

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

$\gamma^* N(940)\frac{1}{2}^+ \to \Delta(1600)\frac{3}{2}^+$

Based on:

- **Transition form factors: $\gamma + p \to \Delta(1232), \Delta(1600)$**
  Y. Lu, C. Chen, Z.-F. Cui, C.D. Roberts, S.M. Schmidt, J. Segovia, H.-S. Zong
  Submitted to Phys. Rev. D, arXiv:nucl-th/1904.03205
- **Spec. and struc. of octet and decuplet and their positive-parity excitations**
  C. Chen, G. Krein, C.D. Roberts, S.M. Schmidt and J. Segovia
  Submitted to Phys. Rev. D, arXiv:nucl-th/1901.04305
- **Parity partners in the baryon resonance spectrum**
  Y. Lu, C. Chen, C.D. Roberts, J. Segovia, S.-S. Xu and H.-S. Zong
  Phys. Rev. C96 (2017) 015208, arXiv:nucl-th/1705.03988

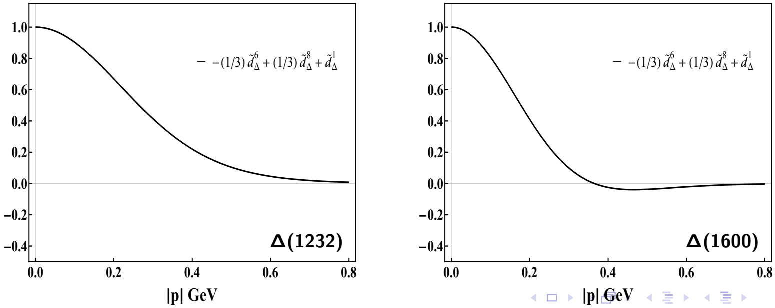
Bound-state kernels which omit meson-cloud corrections produce masses for hadrons that are larger than the empirical values (in GeV):

$$m_N = 1.19 \pm 0.13\,, \qquad m_\Delta = 1.35 \pm 0.12\,,$$
$$m_{N'} = 1.73 \pm 0.10\,, \qquad m_{\Delta'} = 1.79 \pm 0.12\,.$$

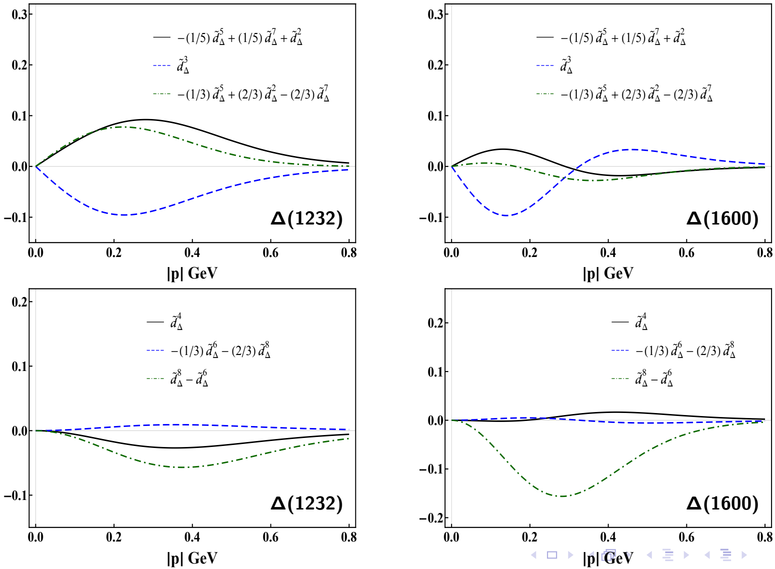
☞ Observations:

- Meson-Baryon final state interactions reduce bare mass by $10-20\%$.
- The cloud's impact depends on the state's quantum numbers.
- A single zero in S-wave components of the wave function $\Rightarrow$ A radial excitation.

0th Chebyshev moment of the S-wave component



P- and D-wave components also posses a zero
(the F-wave components are uniformly small)



	$N(940)$	$N(1440)$	$\Delta(1232)$	$\Delta(1600)$
scalar	62%	62%	–	–
pseudovector	29%	29%	100%	100%
mixed	9%	9%	–	–
S-wave	0.76	0.85	0.61	0.30
P-wave	0.23	0.14	0.22	0.15
D-wave	0.01	0.01	0.17	0.52
F-wave	–	–	~ 0	0.02

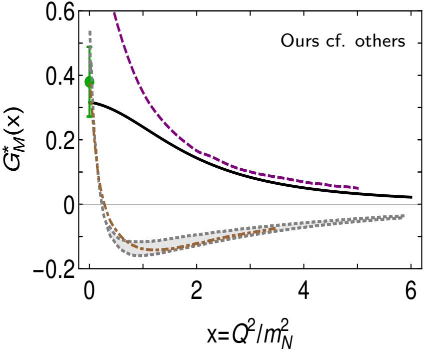
$N(1440)$

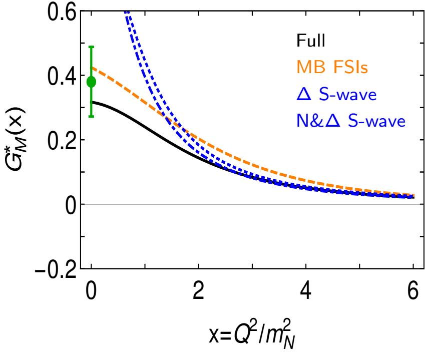
- Roper's diquark content are almost identical to the nucleon's one.
- It has an orbital angular momentum composition which is very similar to the one observed in the nucleon.

$\Delta(1600)$

- $\Delta(1600)$'s diquark content are almost identical to the $\Delta(1232)$'s one.
- It shows a dominant $\ell = 2$ angular momentum component with its S-wave term being a factor 2 smaller.

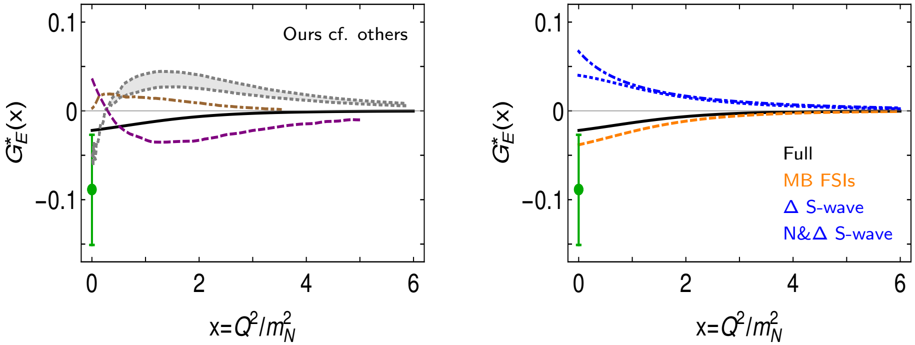
The presence of all angular momentum components compatible with the baryon's total spin and parity is an inescapable consequence of solving a realistic Poincaré-covariant Faddeev equation





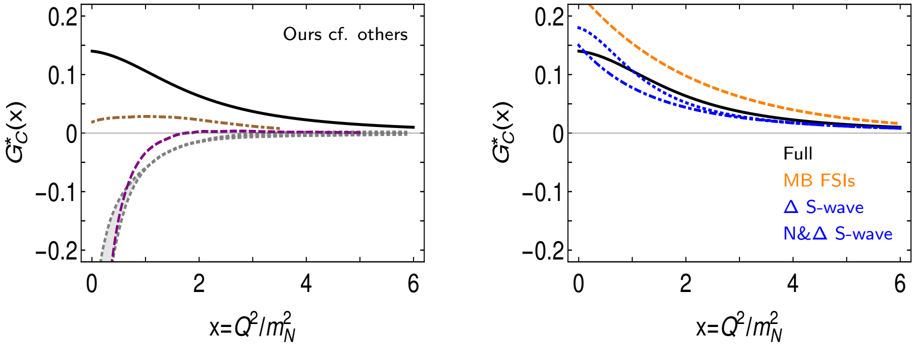
☞ Observations:

- It is positive defined in the whole range of photon momentum and decreases smoothly with larger Q^2-values.
- The mismatch with the empirical result are comparable with that in the $\Delta(1232)$ case, suggesting that MB FSIs are of similar importance in both channels.
- Higher partial-waves have a visible impact on G^*_M: They bring the magnetic dipole moment to lower values which could be compatible with experiment.



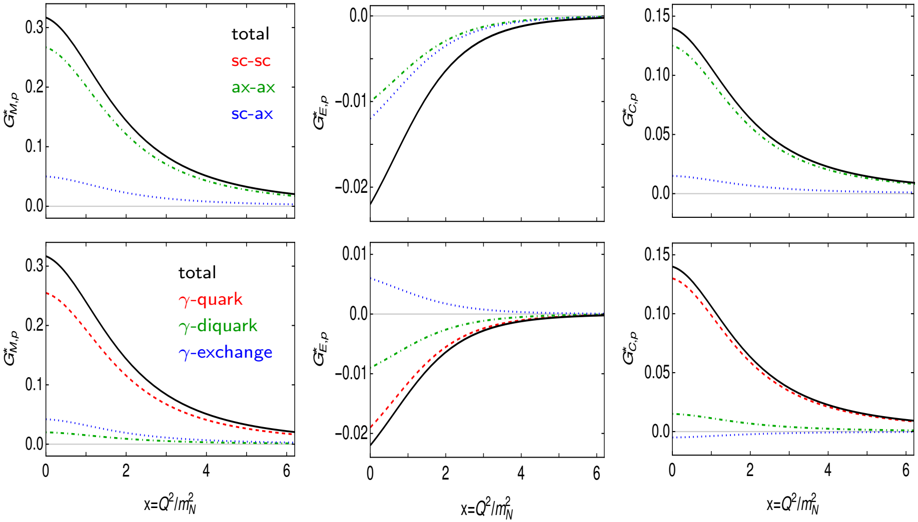
☞ Observations:

- It is negative defined in the whole range of photon momentum and decreases smoothly with larger Q^2-values.
- The mismatch with the empirical result could be due to meson cloud contributions.
- Higher partial-waves have a visible impact on G_E^*: They produce a change in sign which is crucial to get agreement with experiment at the real photon point.

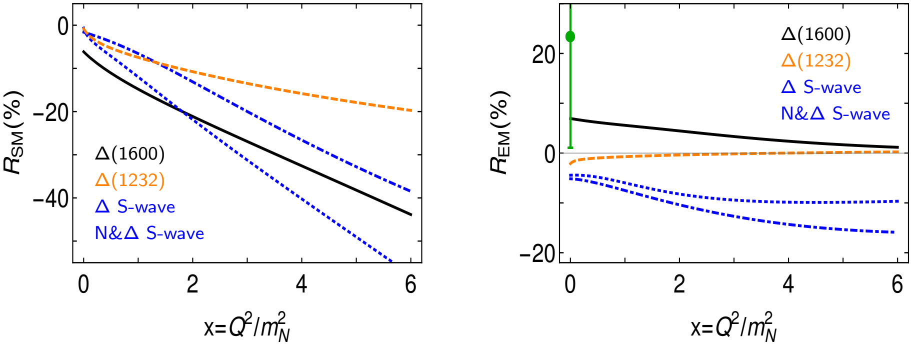


☞ Observations:

- It is positive defined in the whole range of photon momentum and decreases smoothly with larger Q^2-values.
- MB FSIs could be important: a factor of two is observed for G_C^* at the real photon point. Moreover, higher partial-waves have a visible impact on G_C^*.
- Quark model results for all form factors are very sensitive to the wave functions employed for the initial and final states.



Y. Lu *et al.*, arXiv:nucl-th/1904.03205



☞ Observations:

- $R_{SM}^{\Delta'} \gtrsim R_{SM}^{\Delta}$ indicating that higher orbital angular momentum components in the Δ(1600) are more important than in the Δ(1232).
- R_{EM} for the Δ(1600) transition is far larger in magnitude than the analogous result for the Δ(1232) (and opposite in sign).
- Points above are an observable manifestation of the enhanced *D*-wave strength in the Δ(1600) relative to that in the Δ(1232).

☞ **Quantum Field Theory vision of the Nucleon as a Borromean bound-state:**

- The running of the strong coupling constant which is expressed in e.g. the momentum dependence of the dressed-quark mass produces DCSB.
- Dynamical chiral symmetry breaking and its correct implementation produces pions as well as nonpointlike and fully-dynamical correlations inside baryons.
- The Faddeev kernel ensures that every valence-quark participates actively in all diquark correlations to the fullest extent allowed by kinematics and symmetries.
- Poincaré covariance demands the presence of dressed-quark orbital angular momentum in the nucleon.

We insist on our purpose of getting an unified study of EM elastic and transition form factors of nucleon resonances using QCD-based kernels and interaction vertices

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

- The presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavor-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 $\gamma^* N \to$ Nucleon$'$ [$\equiv$N(1440)] reaction:**

- 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 reveal that, as in the case of the elastic form factors, the d-quark contributions are suppressed with respect the u-quark ones.

☞ **The γ^*N $\rightarrow$ Delta reaction:**

- $G^{*p}_{M,J-S}$ falls asymptotically at the same rate as G^p_M. 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, $R_{EM} \rightarrow 1$ and $R_{SM} \rightarrow$ constant, are apparent in our calculation but truly asymptotic Q^2 is required before the predictions are realized.

☞ **The γ^*N $\rightarrow$ Delta$'$ [$\equiv \mathbf{\Delta}$(1600)] reaction:**

- Magnetic dipole and electric quadrupole transition form factors are consistent with the empirical values at the real photon point, but we expect inclusion of MB FSIs to improve the agreement on $Q^2 \sim 0$
- R_{EM} is markedly different for $\Delta(1600)$ than for $\Delta(1232)$, highlighting the sensitivity of G_E^* to the degree of deformation of the Δ-baryons.
- R_{SM} is qualitatively similar for both $\gamma^* N \rightarrow \Delta(1600)$ and $\gamma^* N \rightarrow \Delta(1232)$ transitions, still larger (in absolute value) for the $\Delta(1600)$ case.