Nucleon-to-Roper Electromagnetic Transition Form Factors

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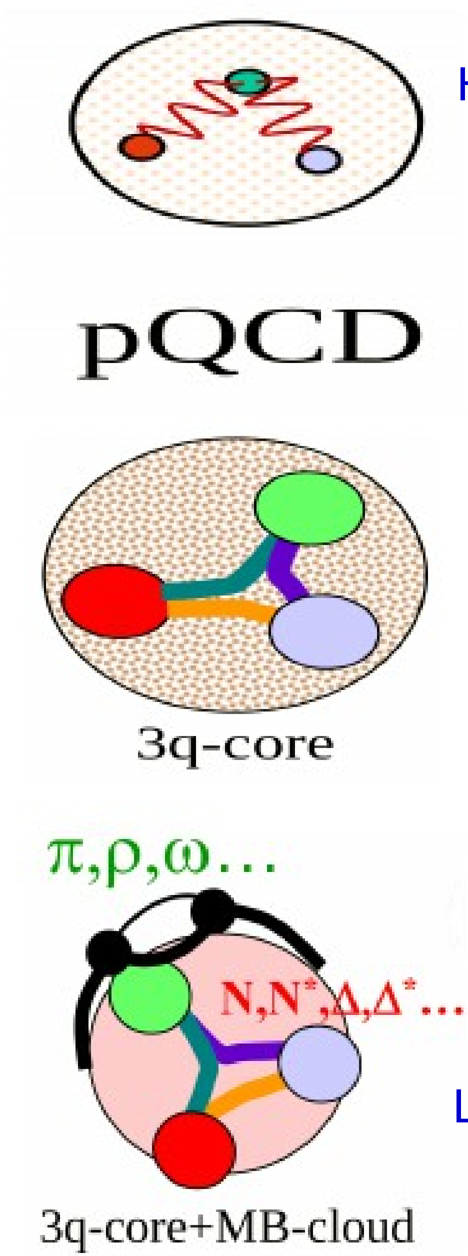
N* form factors. Motivation.



High

Q^2

Low

The QCD saint Grial: the understanding of hadrons in terms of its elementary excitations; namely, quarks and gluons!

Transition form factors of nucleon resonances

Unique window into their quark and gluon structure

Exploiting a broad range of photon virtuality

Provides distinctive information on the roles played by emergent Phenomena in QCD

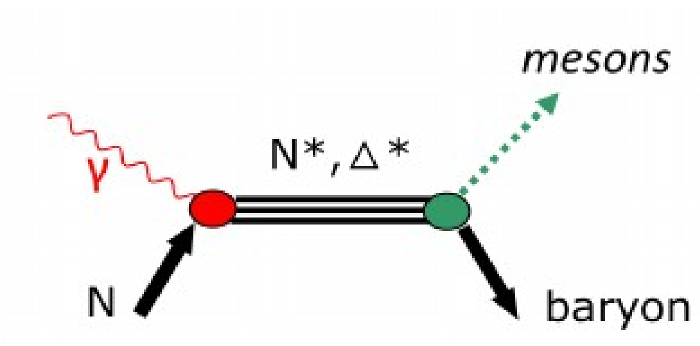
Probes the excited nucleon structures at NP QCD and in the domain transitioning to pQCD

N* form factors. Motivation.

An ambitious experimental effort is worldwide under way

Aces: Multi-GeV polarized beams, large acceptance detectors, polarized p/n targets.

Very precise 2-body processes data in wide kinematics (angle, energy):



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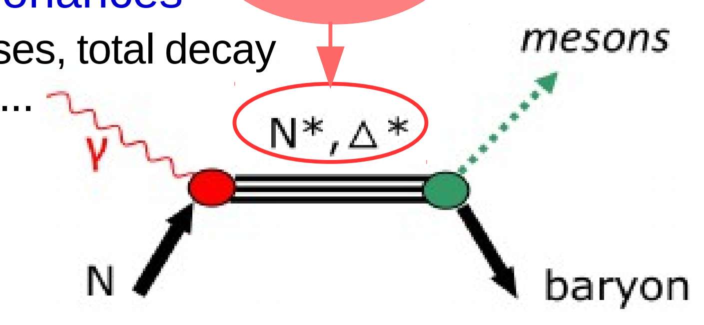
→ Very precise 2-body processes **data** in wide kinematics (angle, energy):

Dispersion relations

Amplitude analysis

Extract s-channel resonances

Baryon properties: masses, total decay widths, branching ratios...



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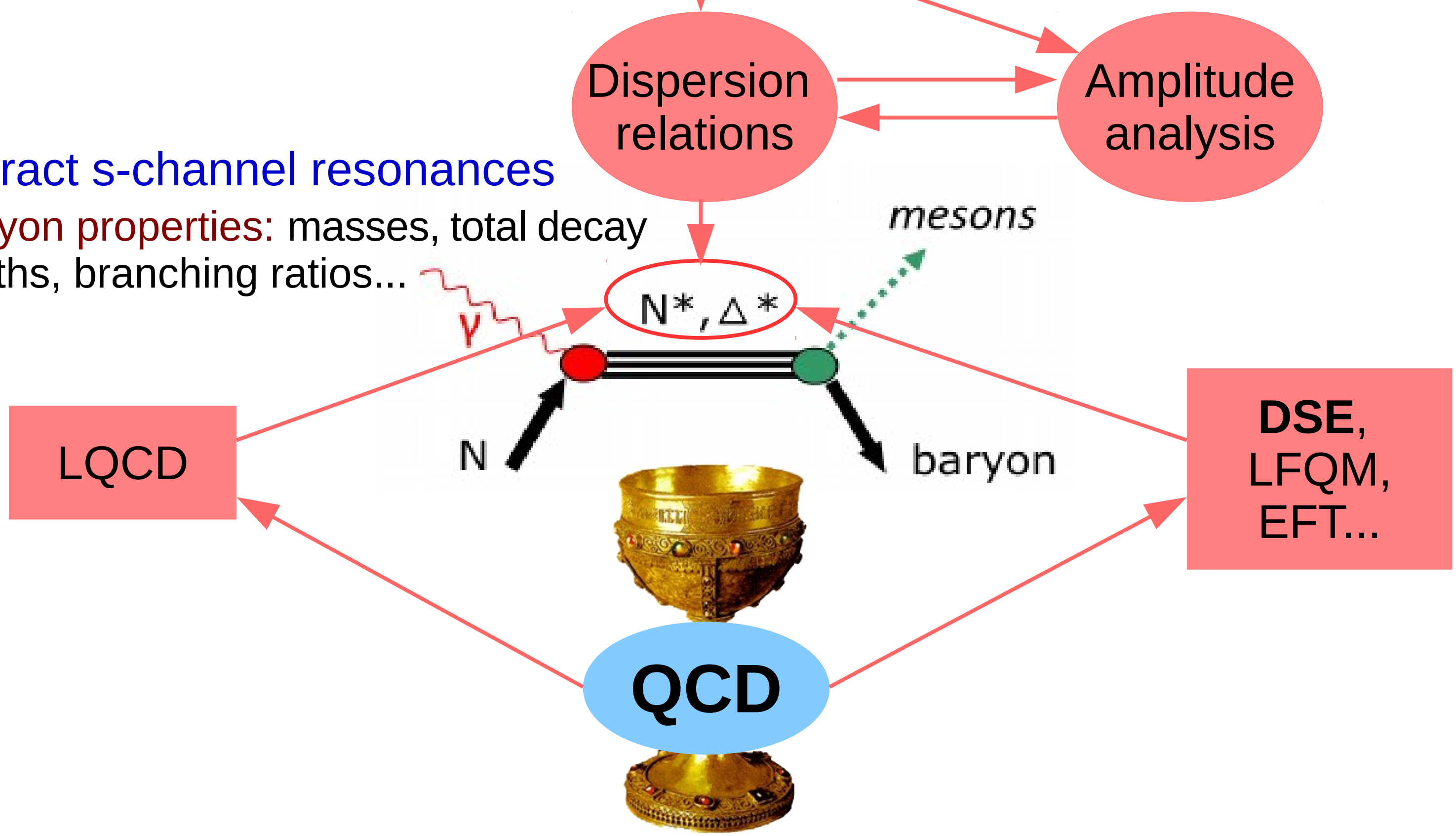
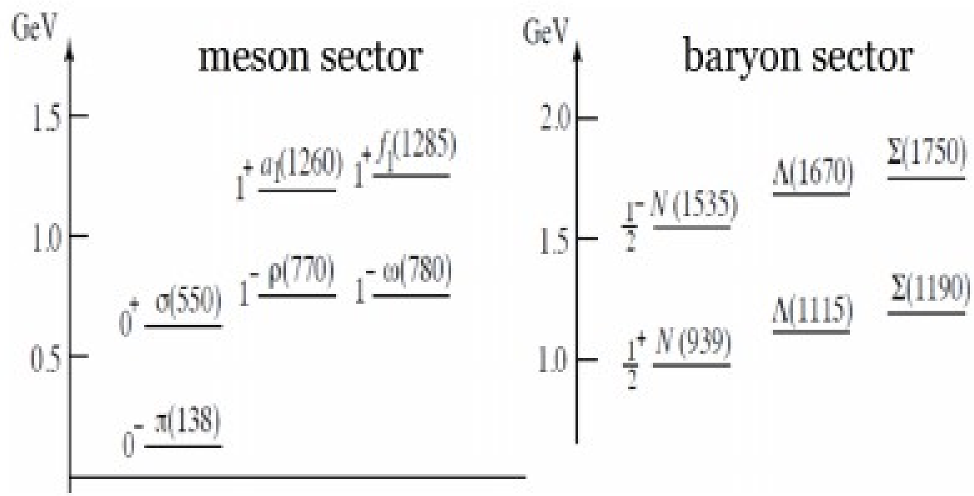


Non-perturbative QCD: Confinement and DCSB

Hadrons are low-energy bound states and therefore dominated by the non-perturbative IR dynamics of QCD.



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

Colored bound states have never been been to exist as particles in nature

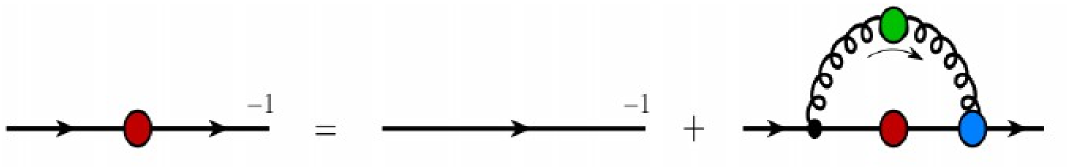
Chiral symmetry Appears dynamically violated in the Hadron spectrum

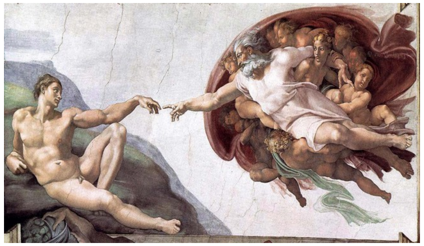
Key complex phenomena, not apparent in the “simple” QCD's Lagrangian, but deriving from it

Emergent phenomena playing a dominat role in the real-world QCD

Non-perturbative QCD: Confinement and DCSB

DSE gap equation for the dressed-quark propagator:





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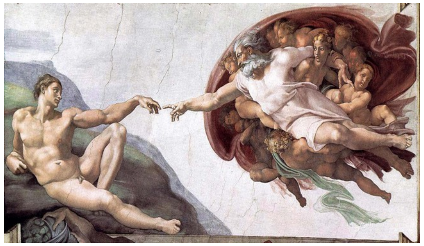
$$S^{-1}(p) = Z_2(i\gamma \cdot p + m) + \Sigma(p)$$

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



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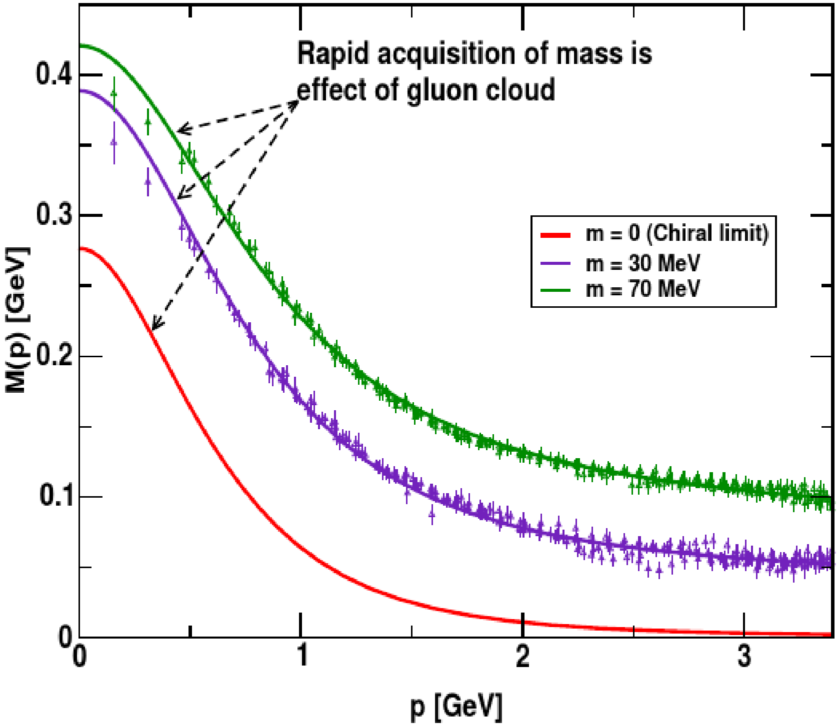

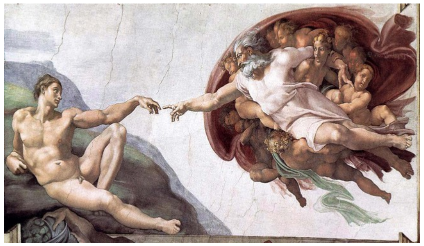

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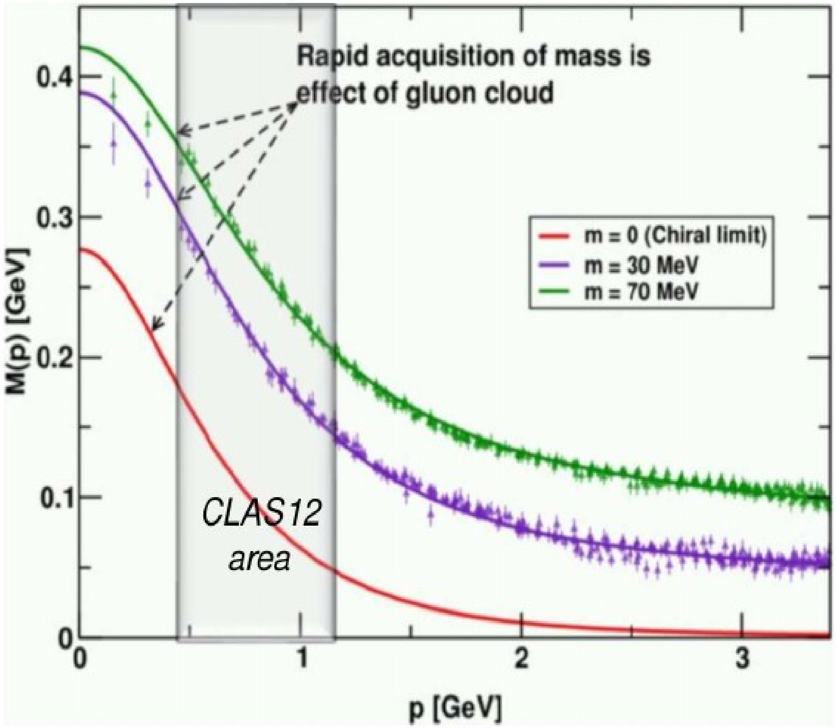
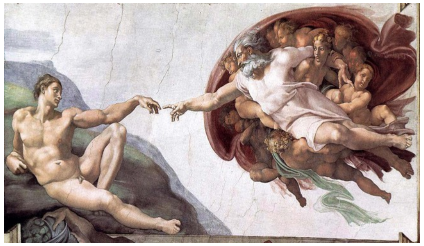


- Mass generated from the interaction of the propagating quarks with gluons
- Light (even massless) quarks acquire a HUGE constituent mass
- Mechanism generating the 98 % of the proton mass and the large splitting between parity partners.



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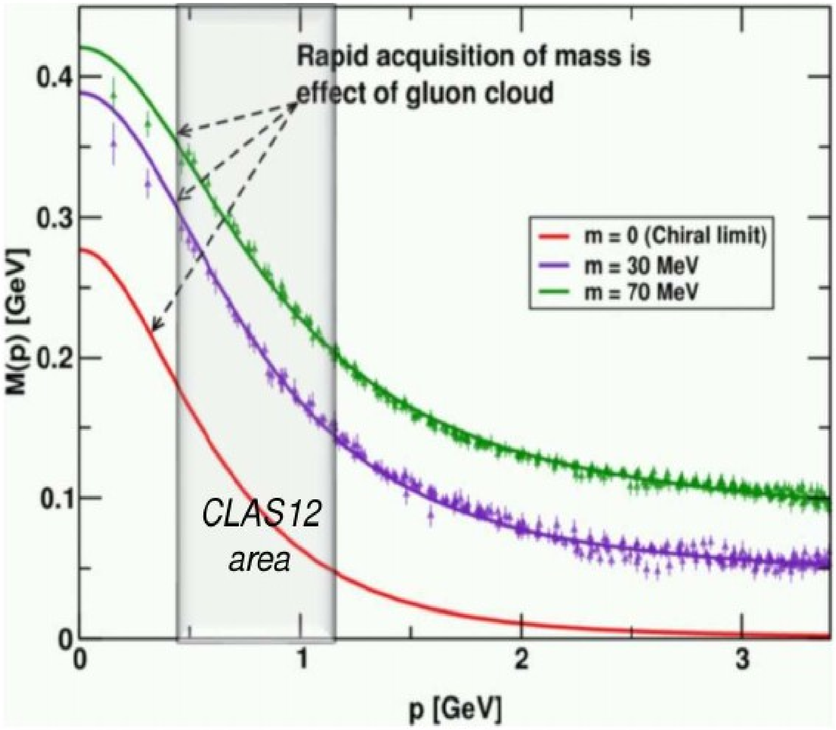

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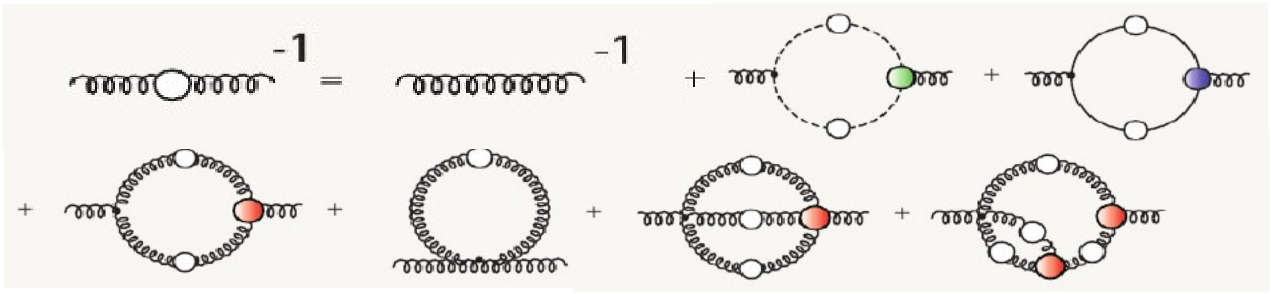
DSE for the gluon propagator in Landau gauge:



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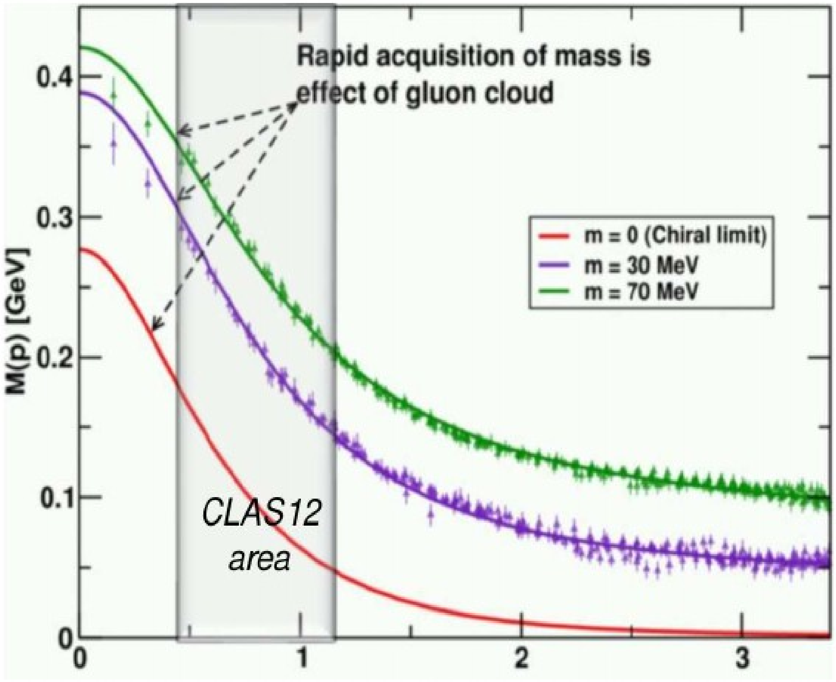
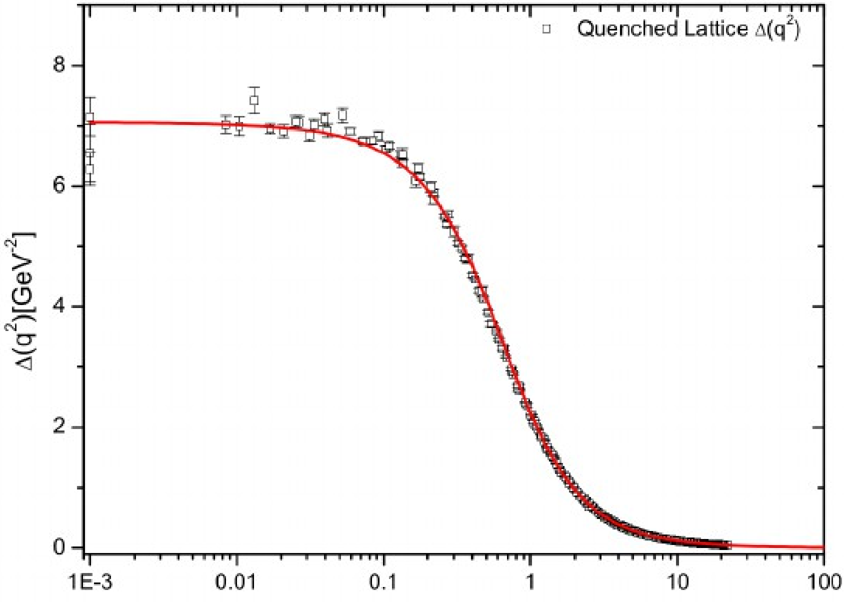


DSE for the gluon propagator in Landau gauge:

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

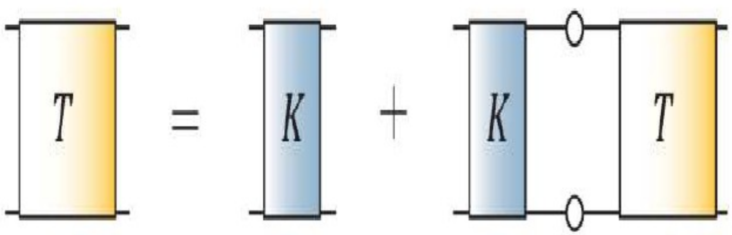
- An inflexion point at $p^2 > 0$.
- Breaks the axiom of reflexion positivity and, therefore, no freely propagating particle can be related with.

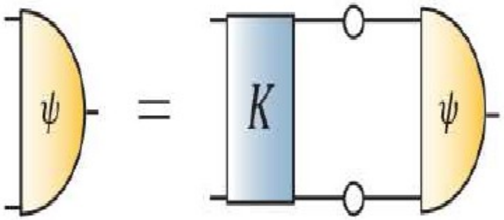


The bound-state problem in QFT

Hadron properties result from poles in the scattering matrices

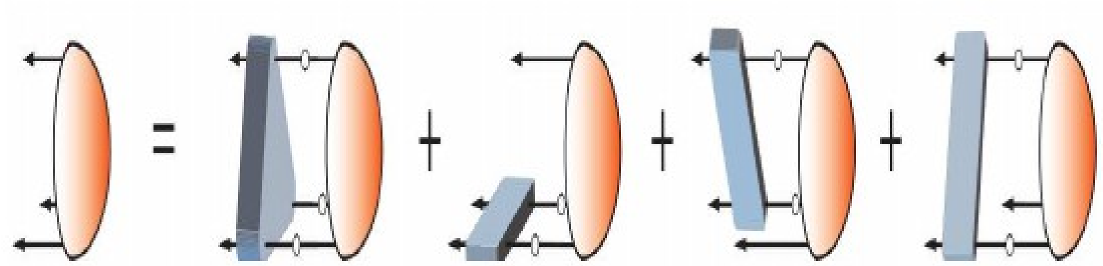
- Two-body (meson) problem:





T matrix obtained first from the inhomogeneous(BS) Bethe-Salpeter equation $\xrightarrow{p^2=-m^2}$ BS amplitude from homegenous BSE

- Three-body (baryon) problem:



Faddeev equation: it sums all possible QFT exchanges and correlations taking place between the three dressed-quarks that constitute the baryon valence-quark content

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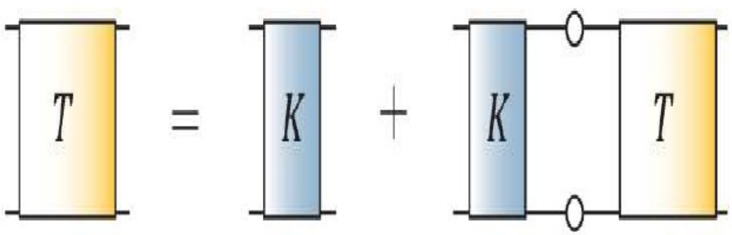

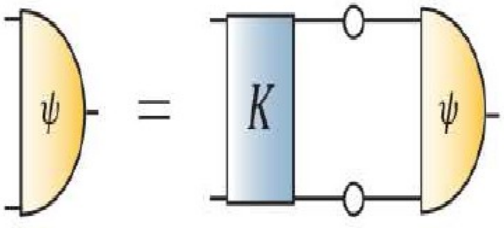

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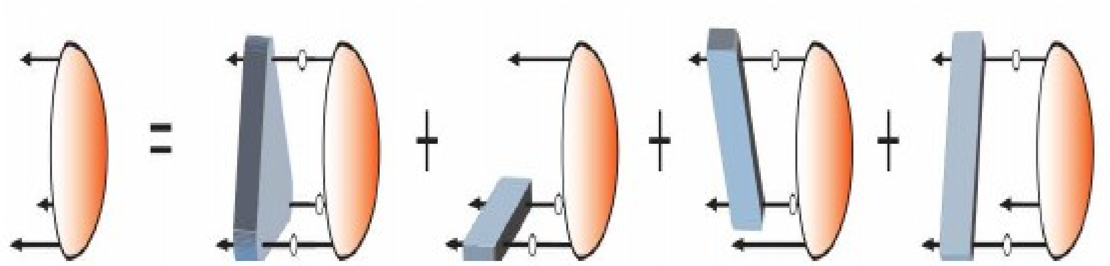

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Diquark correlations: The attractive nature of quark-antiquark correlations in a color-singlet meson is also attractive for $\bar{3}_c$ quark-quark correlations within a color-singlet baryon.

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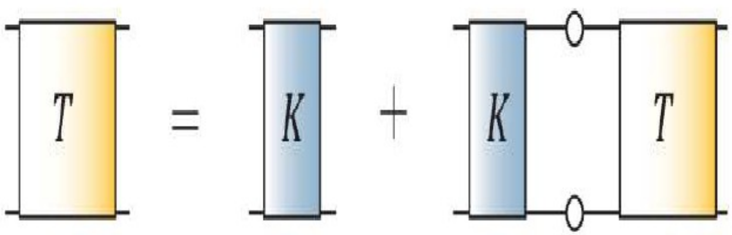

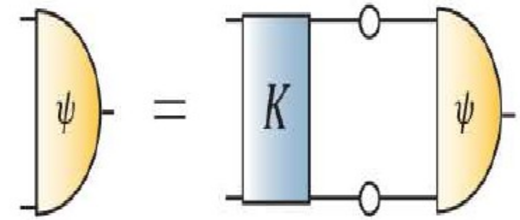

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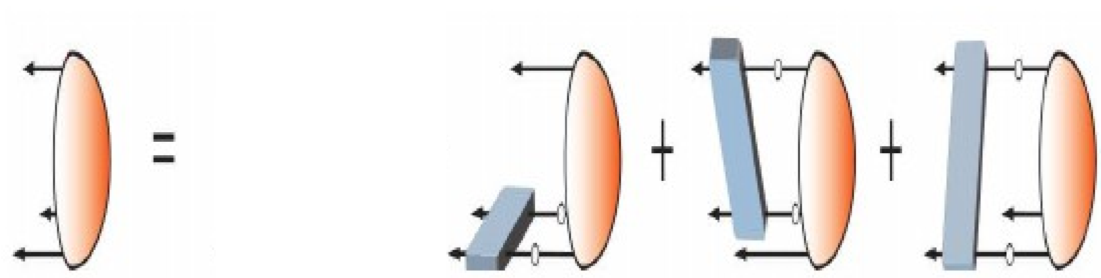

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[J.Segovia, C.D.Roberts, S.M. Schmidt, PLB750(2015)100-106.]

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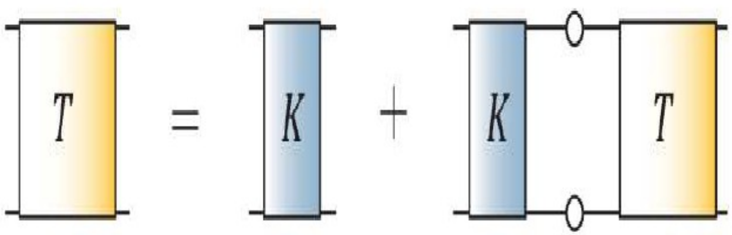

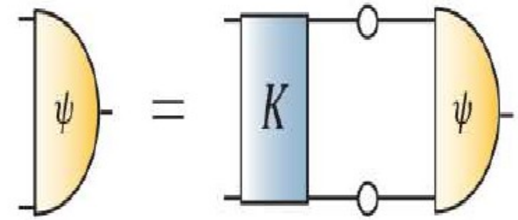

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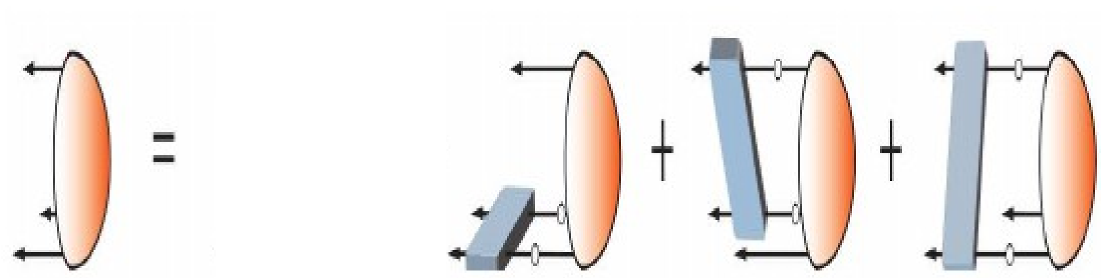

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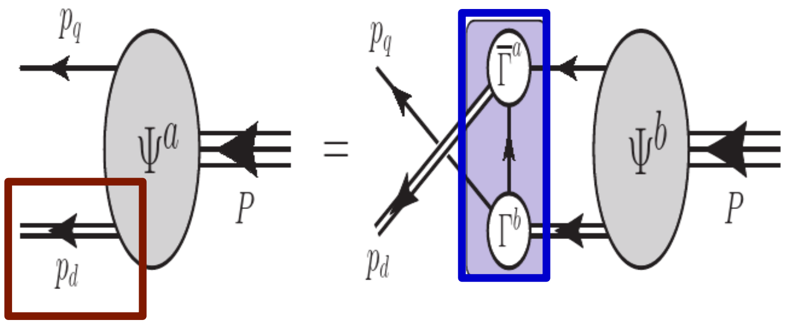
Diquark content dominance;
e.g., for positive parity states

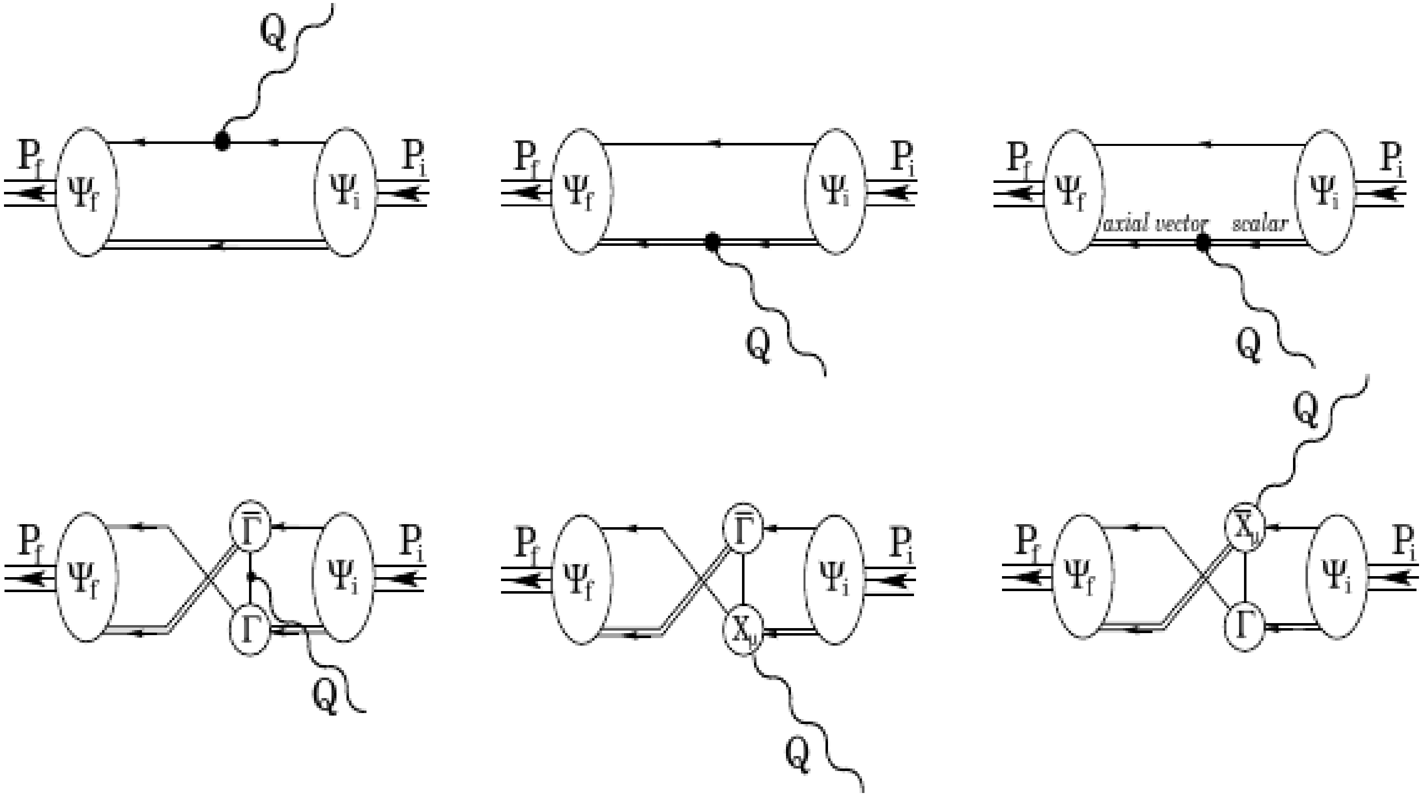
N-like $\Rightarrow$ 0^+, 1^+ diquarks
Δ-like $\Rightarrow$ only 1^+ diquark

The baryon-photon vertex and the EM current



Two-loop diagram is crucial for the dynamical picture of the nucleon as a borromean bound-state, the binding within which is made by two contributions:
(i) Diquark correlation formation
(ii) Quark exchange between quark and diquark.

Thus, U(1) current conservation, within this dynamical quark-diquark picture, leads to six diagrams, depending on how the photon couples to baryon's constituents



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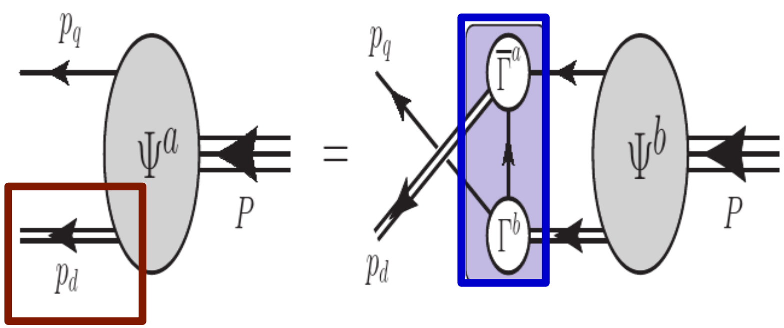

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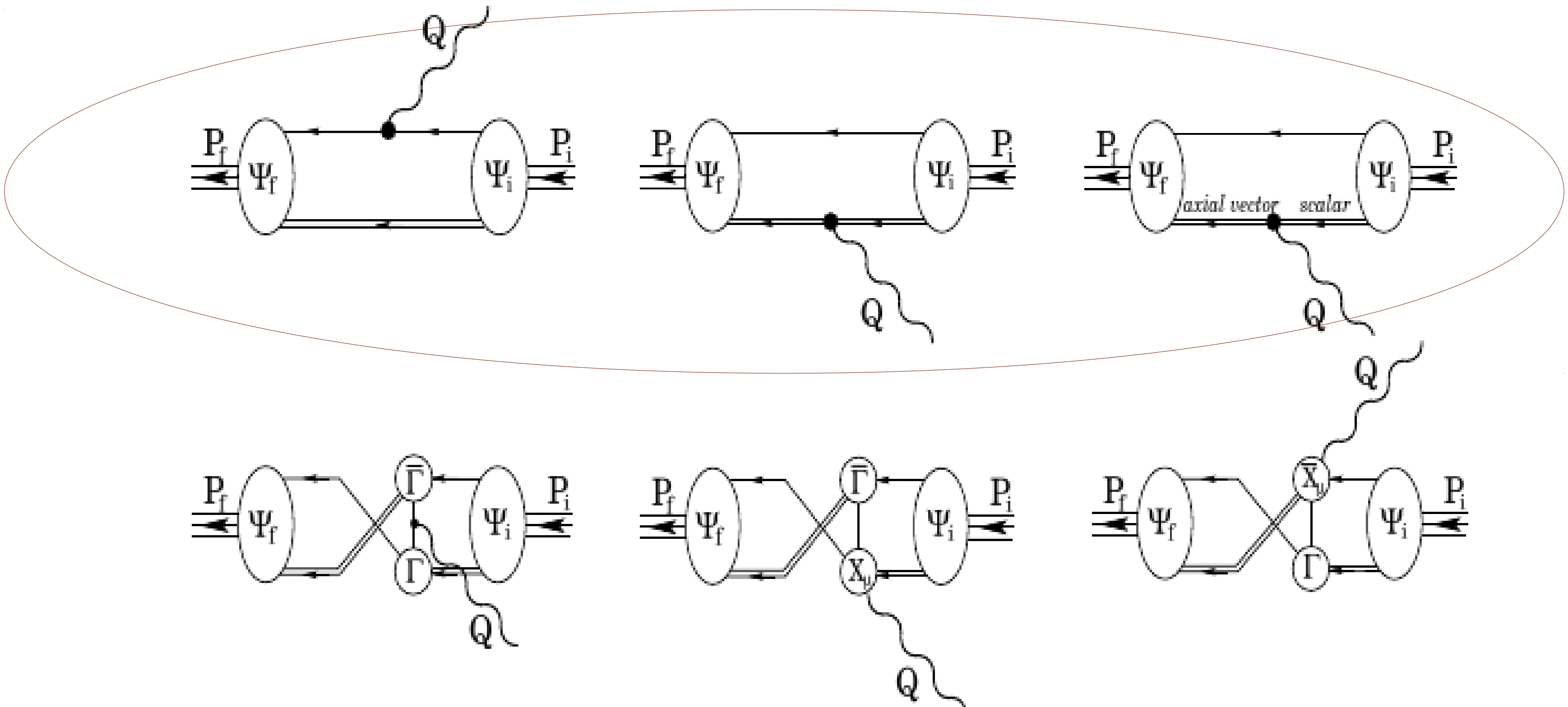

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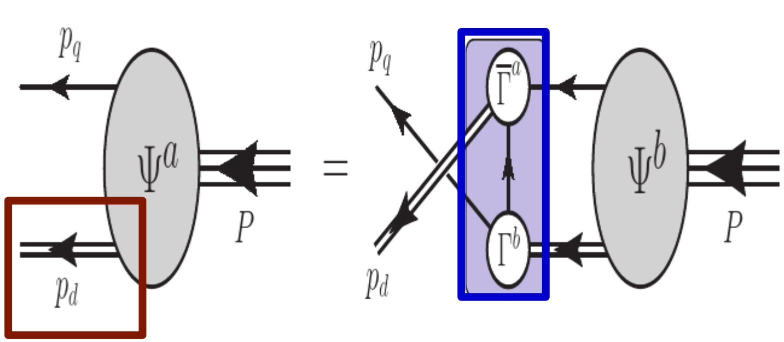

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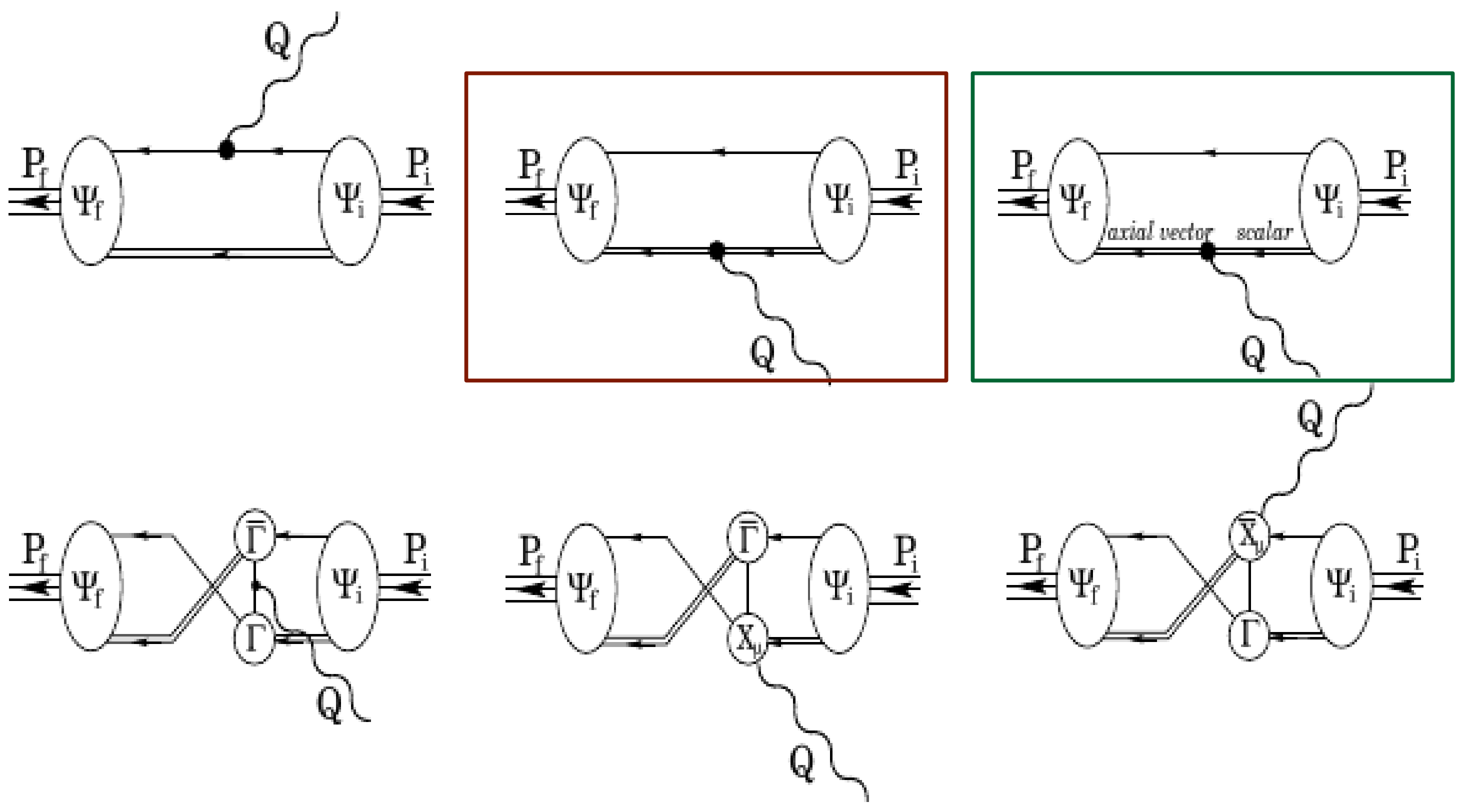
One-loop
coupling the photon to the dressed quark, elastic or induced transitions



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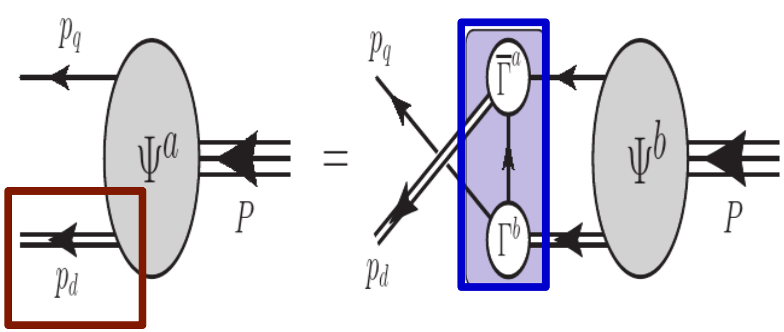

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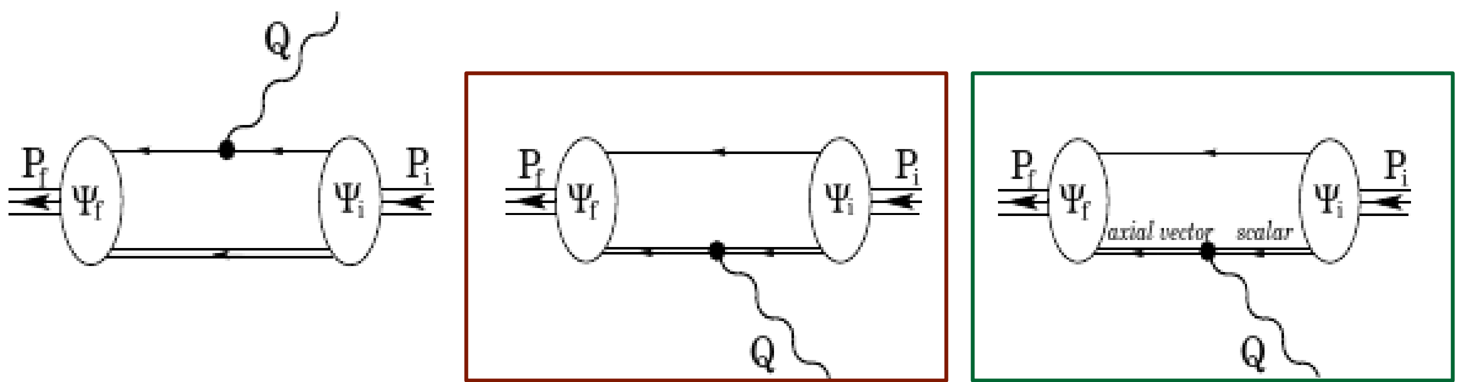
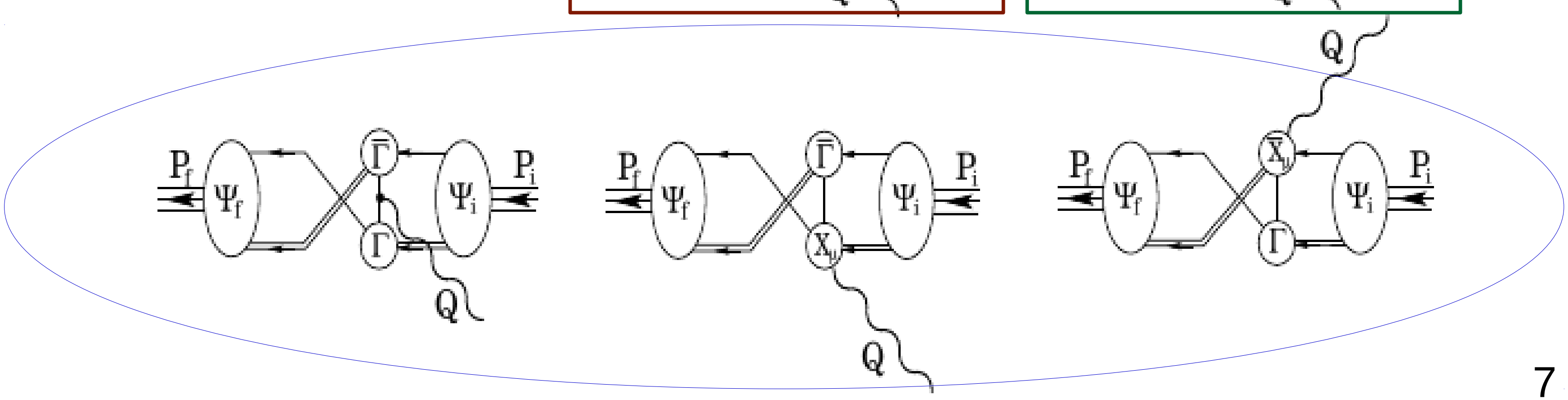


Two-loops



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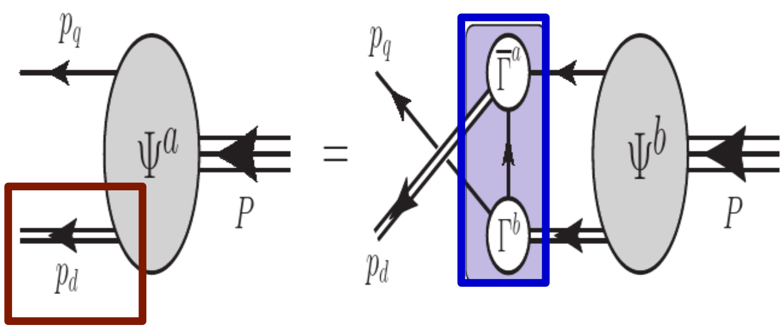

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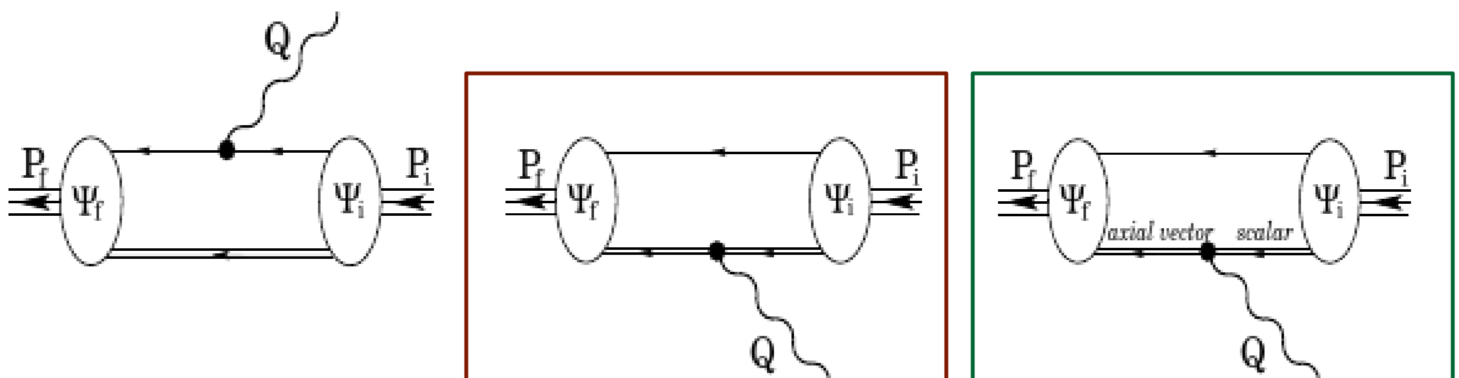
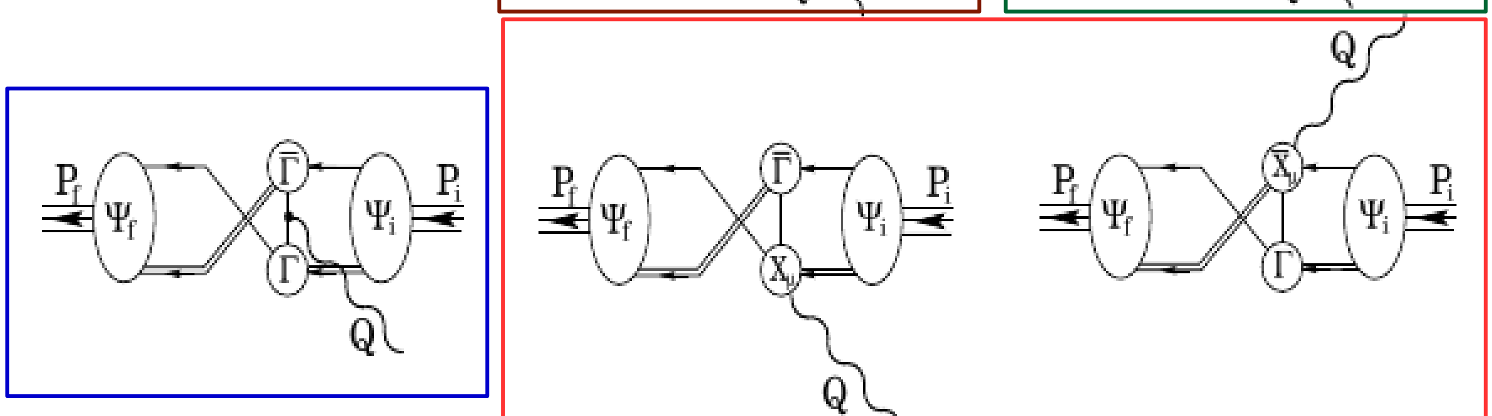


Two-loops
Coupling the photon to the exchanged quark or to the diquark amplitude (seagull terms)



The baryon-photon vertex and the EM current

$\gamma^* N \to N'$

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:

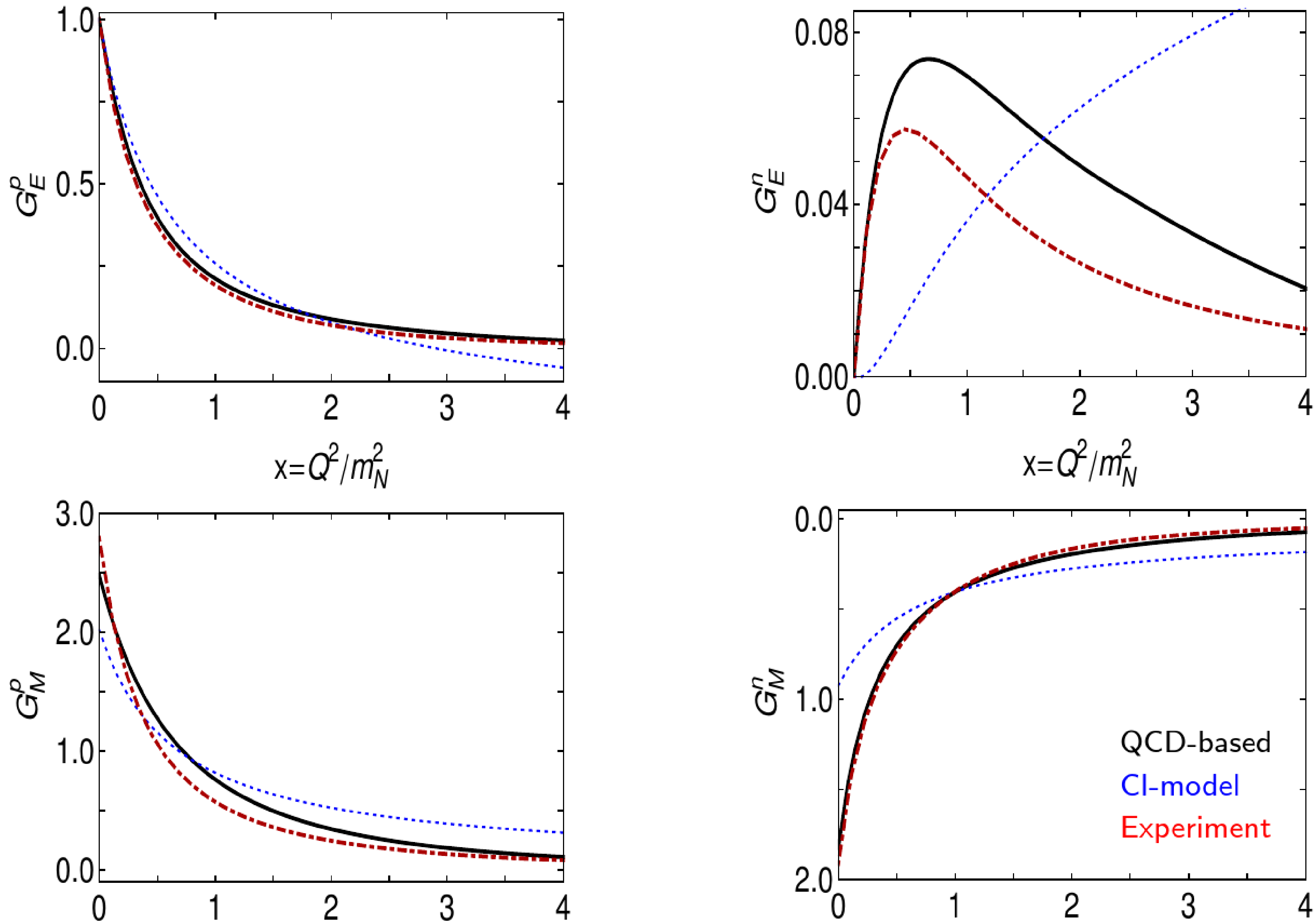
- $G_E^{(*)} \Rightarrow$ Momentum space distribution of electric charge.
- $G_M^{(*)} \Rightarrow$ Momentum space distribution of magnetization.

Nucleon's Sachs form factors. $\gamma^* N(940)\frac{1}{2}^+ \to N(940)\frac{1}{2}^+$

Benchmark case

Proton form factors

Neutron form factors



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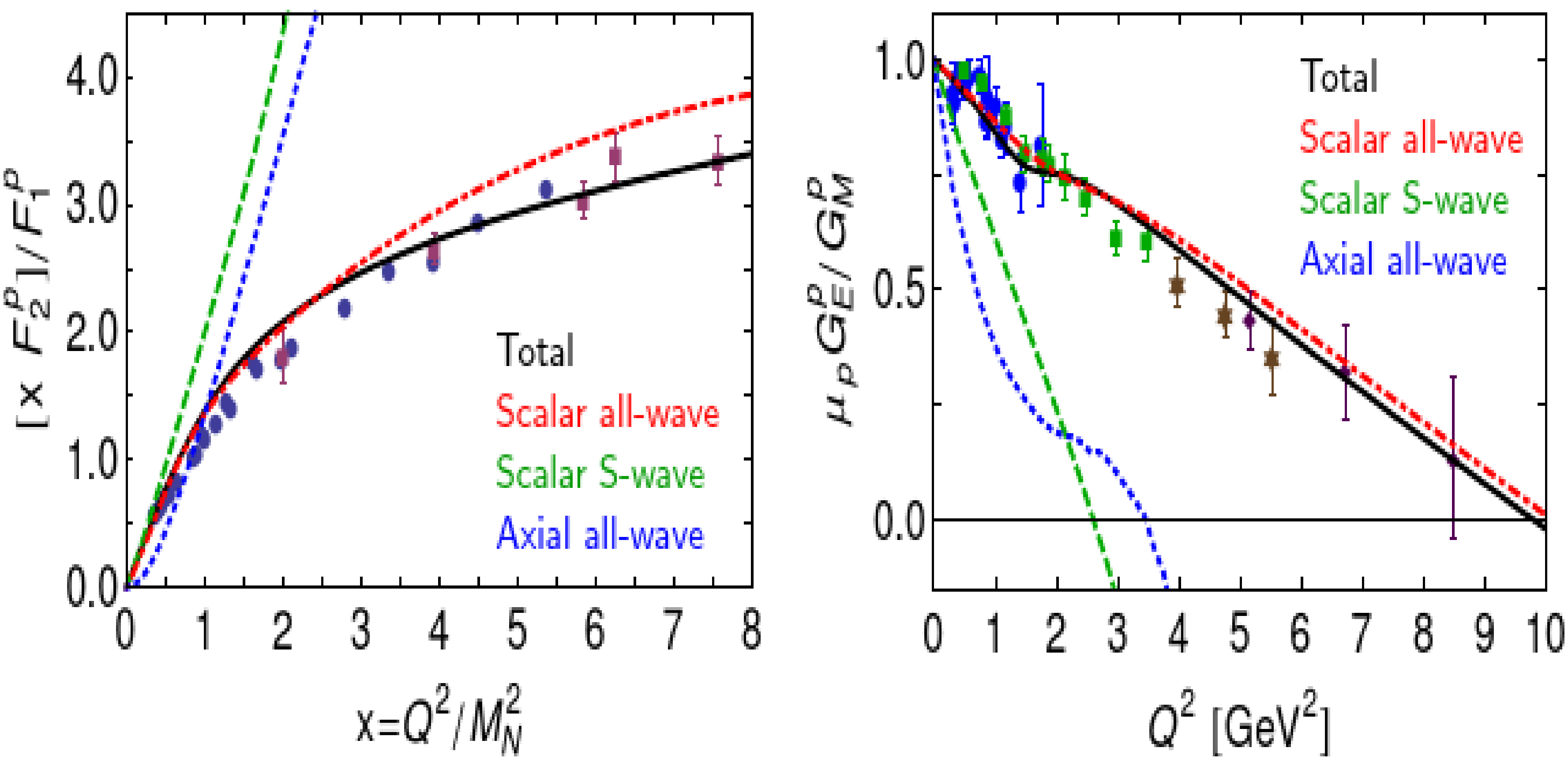
Benchmark case

Diquark correlations content in the proton form factors

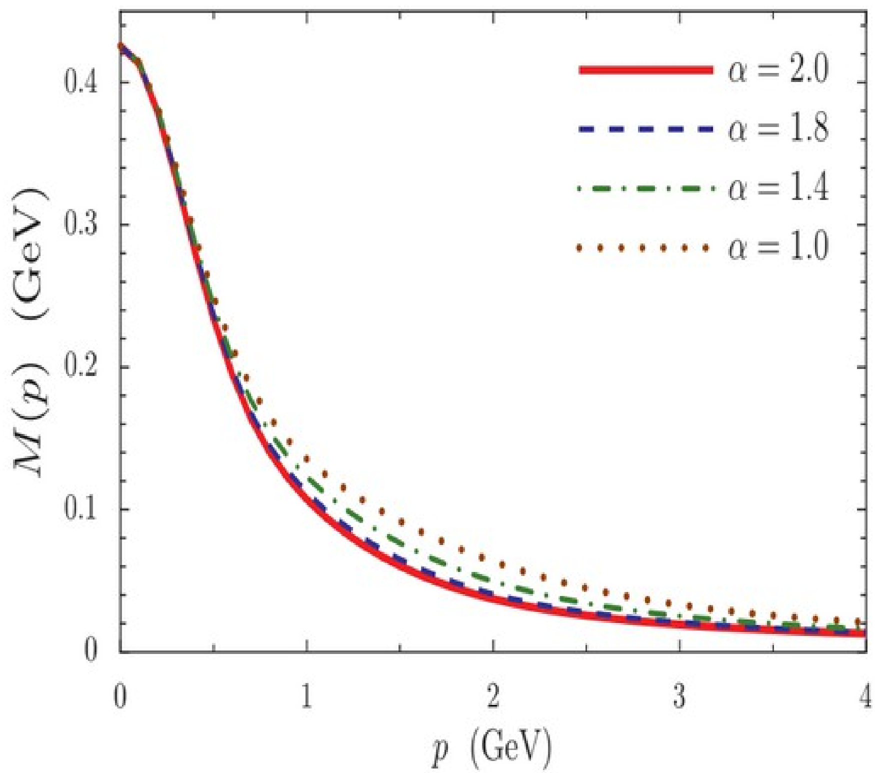


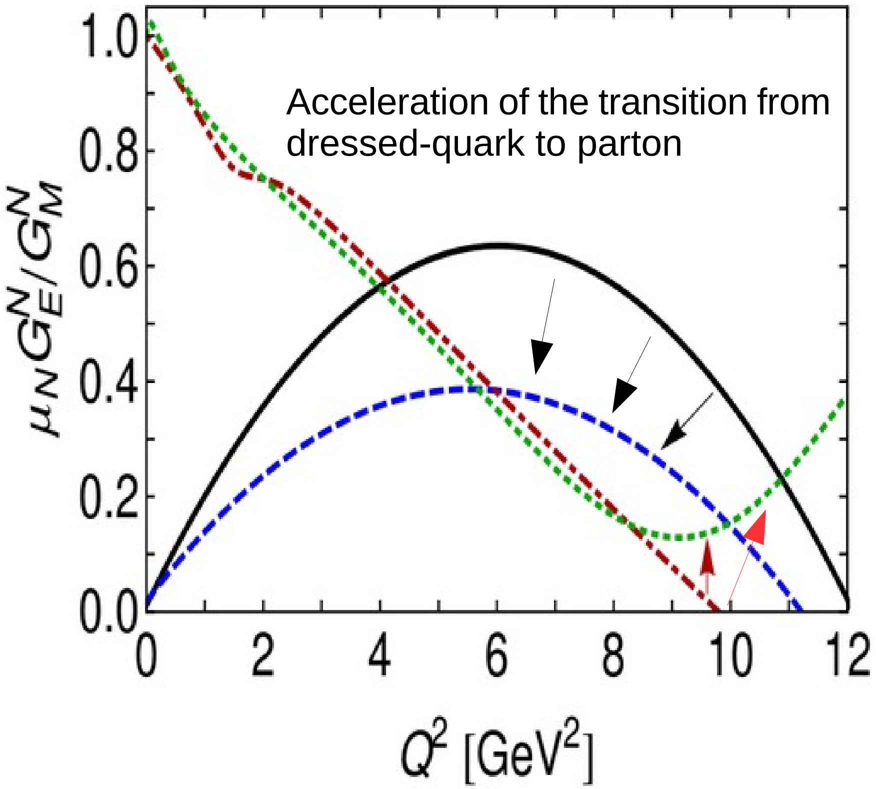
- Scalar diquark's are the dominant contribution and explains the momentum behaviour of the proton EM ratios...
- … but higher quark-diquark orbital angular momentum componentes of the nucleon are critically required to explain the data!

Nucleon's Sachs form factors. $\gamma^* N(940)\frac{1}{2}^+ \to N(940)\frac{1}{2}^+$

Unit-normalized ratios of electric and magnetic (Sachs) form factors

Benchmark case





- Ratio of proton FFs (red dot-dashed) agrees very well with experiment for QCD-based interaction. In the neutron case (black) the qualitative trend is also correct.

- Prediction of a zero-crossing that appears to be a fairly direct test for the (correct) nature and strength of the quark-quark (via gluons) interaction.

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \rightarrow N(1440)\frac{1}{2}^+$

The Roper is the proton's first radial excitation:

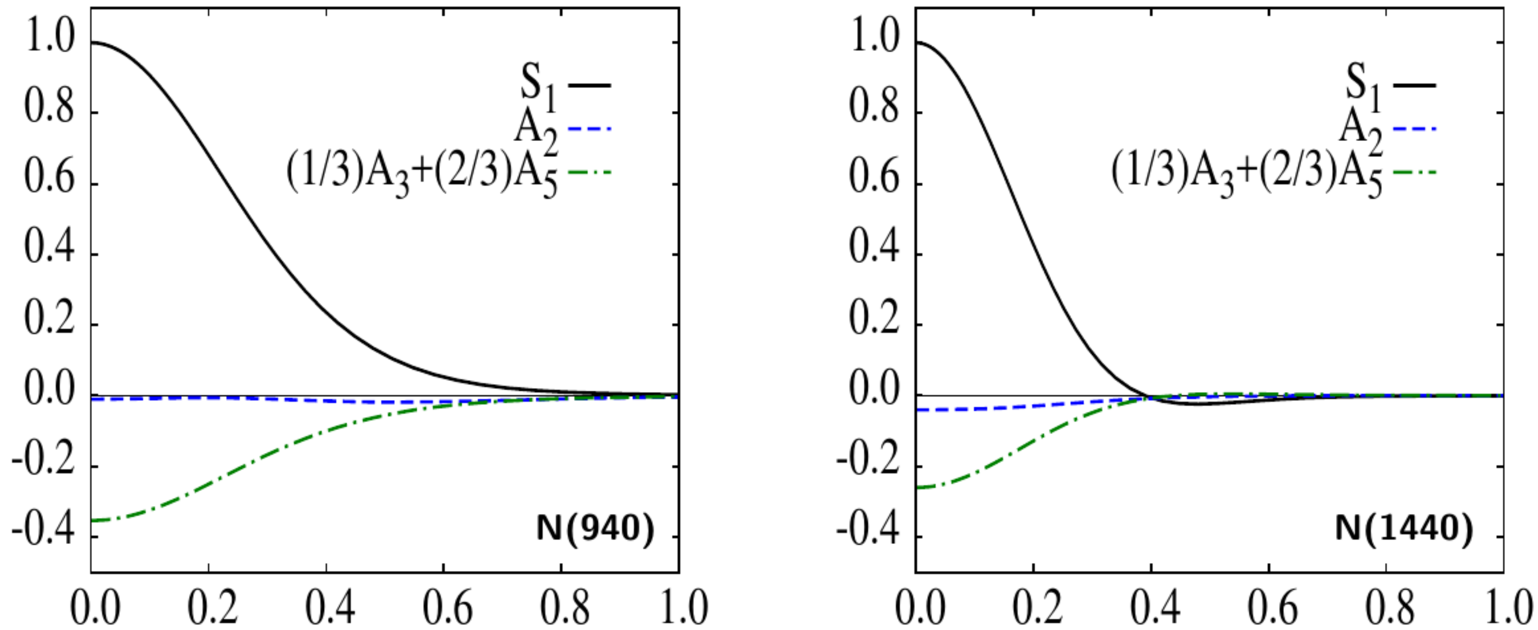
$M^{EBAC}_{Roper} = 1.76$ GeV

$M^{DSE}_{Roper} = 1.73$ GeV

Bare-state mass from a dynamical coupled-channel computation (that means a hadron-structure calculation exlcluding meson-baryon final state interactions). [N. Suzuki et al.; PRL104, 042302 (2010)]

DSE calculation for the first proton's radial excitation with QCD-based interaction but excluding meson-cloud contributions, which are estimated to reduce the dressed-quark core mass by 20 %.
[J. Segovia et al.; PRL115, 171801 (2015)]

- Similar S-wave components of the dominant amplitudes for the scalar and axial-vector diquarks



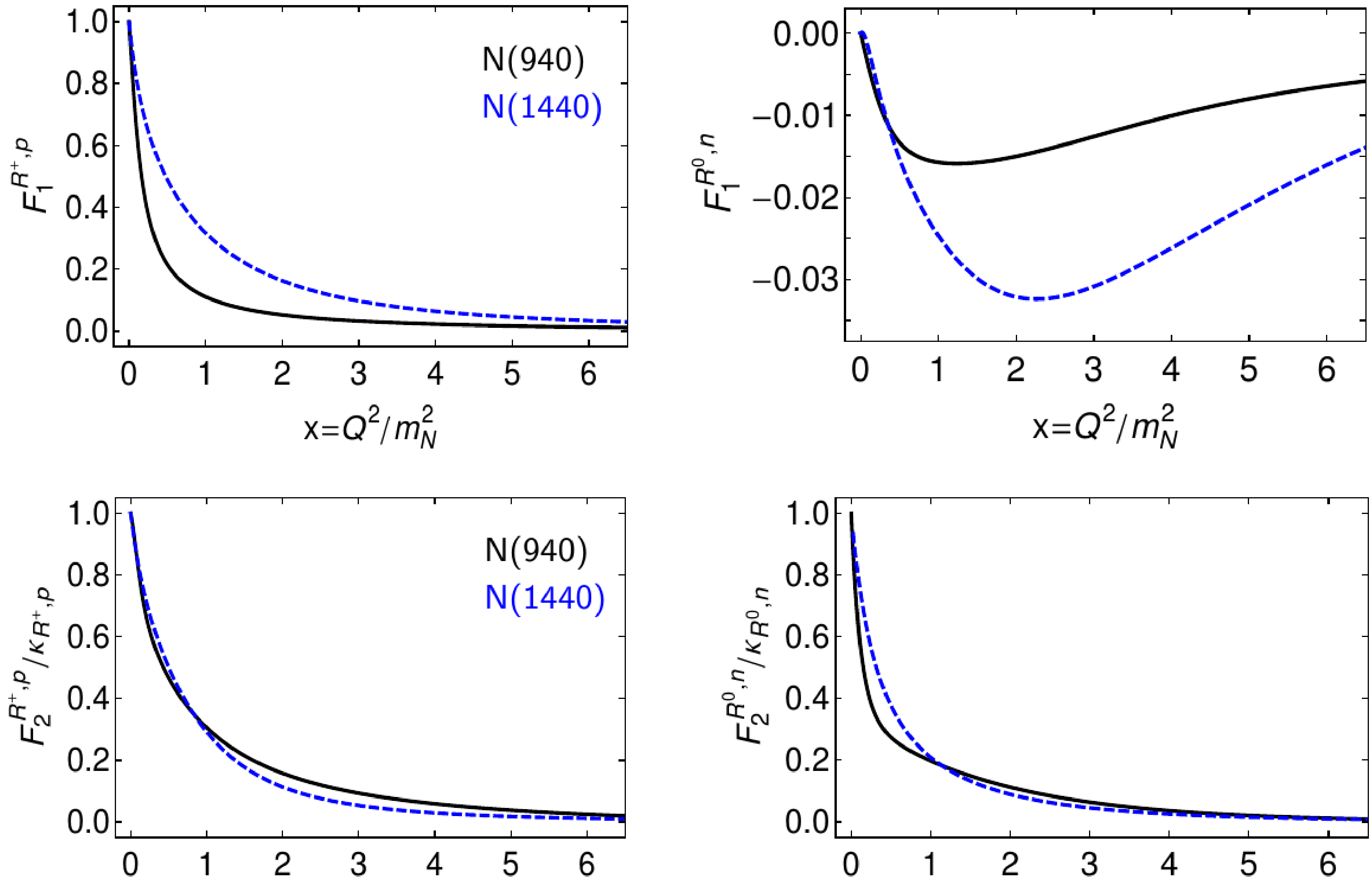
- A single zero in S-wave component is a QM indication of a radial excitation!!!

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \rightarrow N(1440)\frac{1}{2}^+$

Comparison of elastic FFs

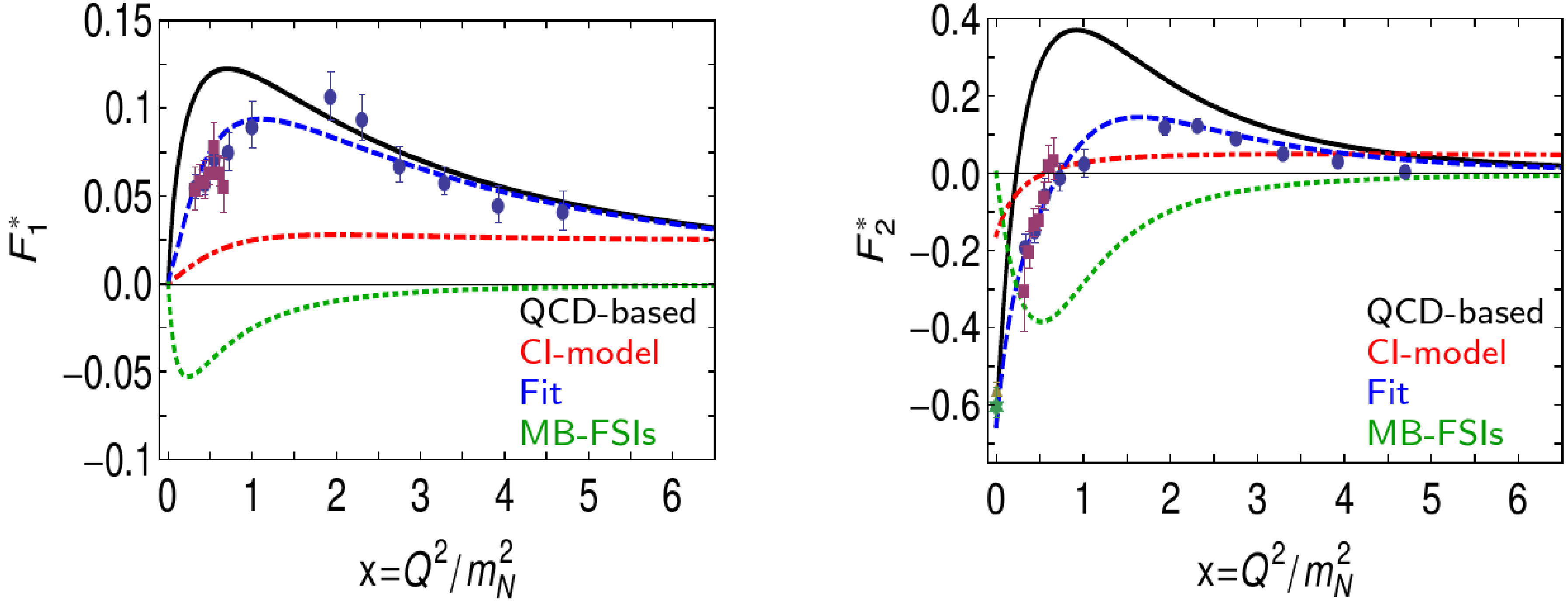
Charged nucleon and resonance

Neutral nucleon and resonance



Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \to N(1440)\frac{1}{2}^+$

Dirac and Pauli (charged channel) transition form factors:

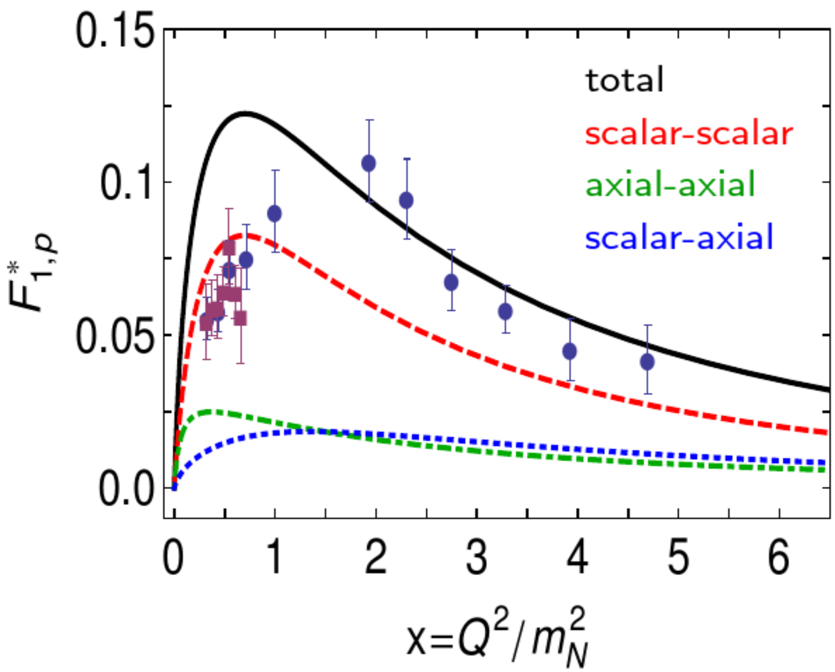


- Good agreement with experimental data, both qualitative and quantitative beyond $x \simeq 2$, is clearly found for both Dirac and Pauli transtion FFs.
- The mismatch on $x \lesssim 2$ can be explained by the effect of the meson-cloud contributions, not sizeable when a high-virtual photon penetrates the cloud and, thereby, unveil the dressed-quark core.
- A fit to experimental data and their comparison to our results exhibits the impact of the meson-baryon final-state interactions.

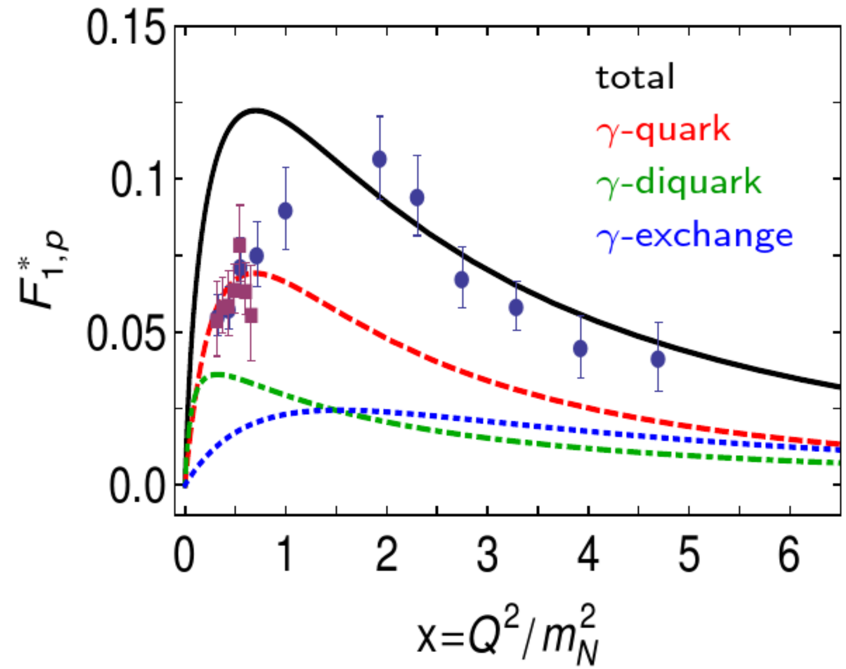
Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \rightarrow N(1440)\frac{1}{2}^+$

Dirac (charged channel) transition form factor:

Diquark dissection



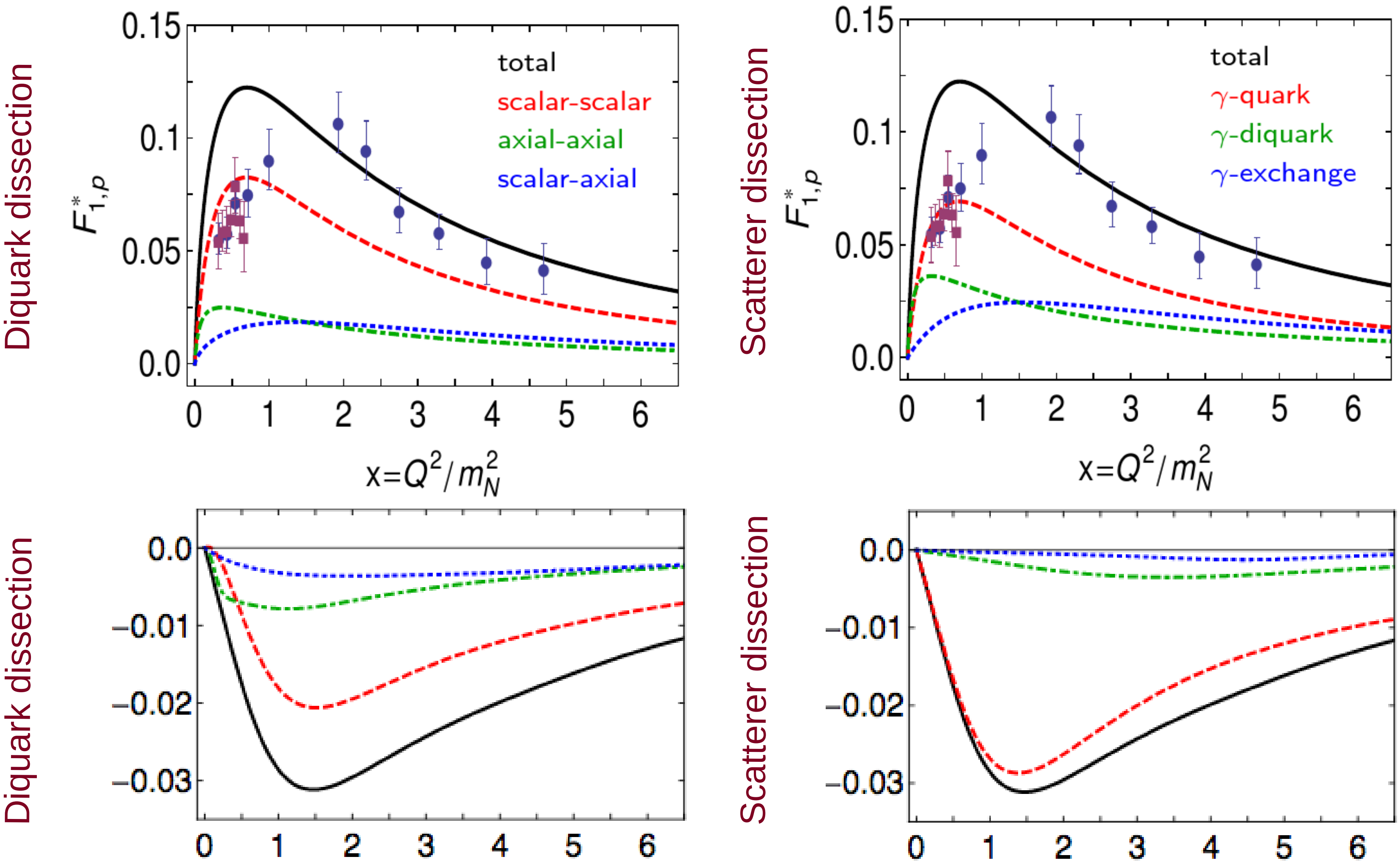
Scatterer dissection



- The Dirac transition form factor is qualitatively displayed, and primarily contributed, by the process driven by a photon striking a bystander dressed quark.
- Other processes are non-negligible and crucial to account from experimental data beyond $x \simeq 2$.
- At low momentum transfer, the MB-FSI contributions appears to be of the same order, but opposite sign, of those involving a photon revealing the diquark structure and, thereby, tend to suppress them.

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \rightarrow N(1440)\frac{1}{2}^+$

Dirac (charged channel) transition form factor:

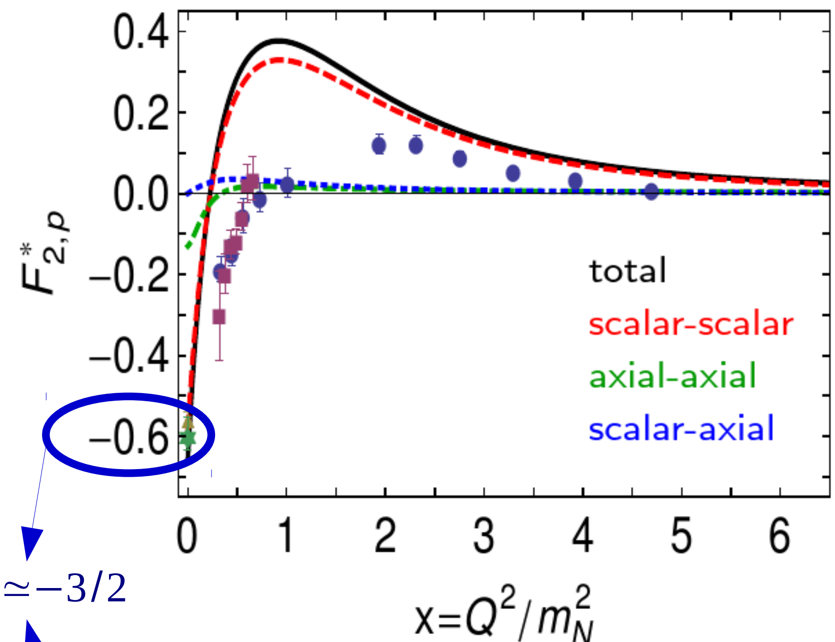


Neutral channel

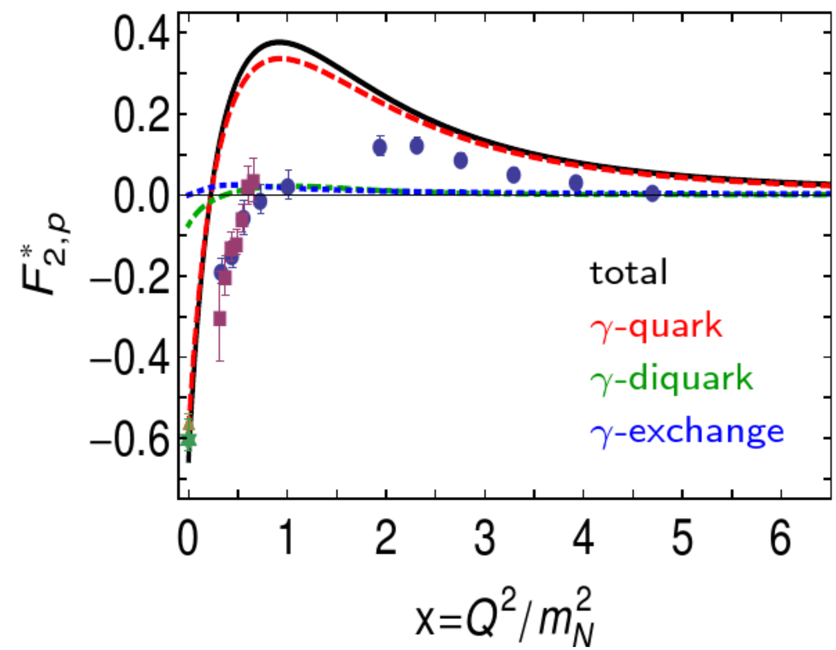
Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \to N(1440)\frac{1}{2}^+$

Pauli (charged channel) transition form factor:

Diquark dissection

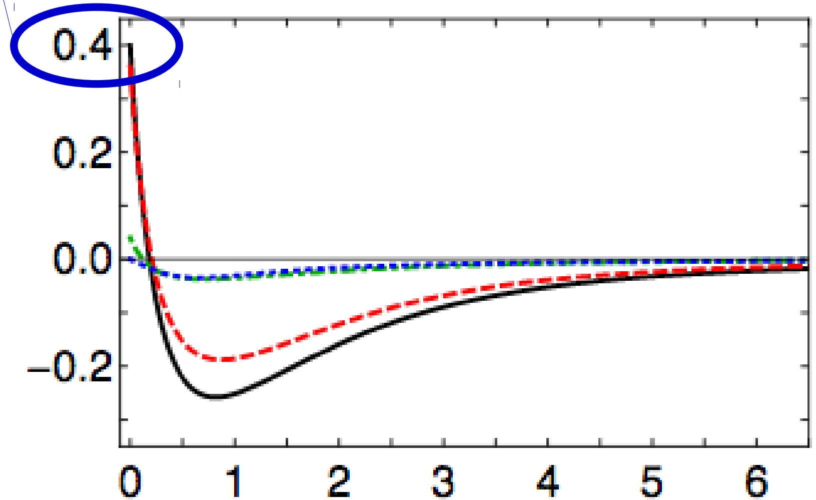


Scatterer dissection

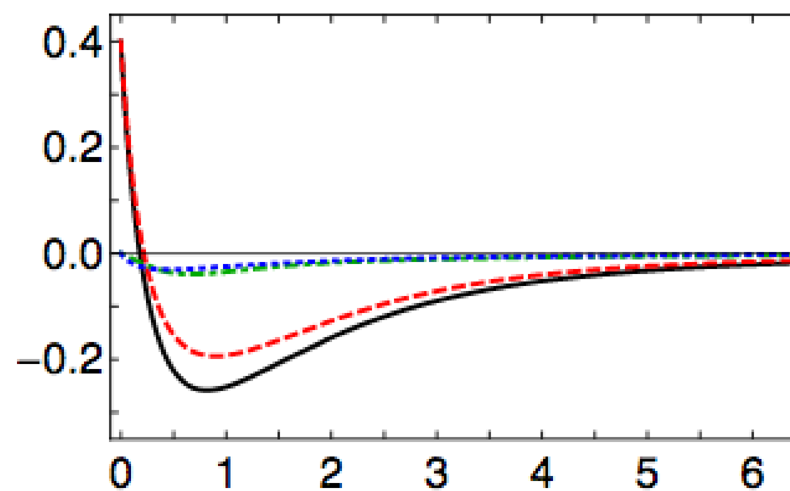


$$\frac{F^*_{2,p}(0)}{F^*_{2,n}(0)} \simeq -3/2$$

Diquark dissection



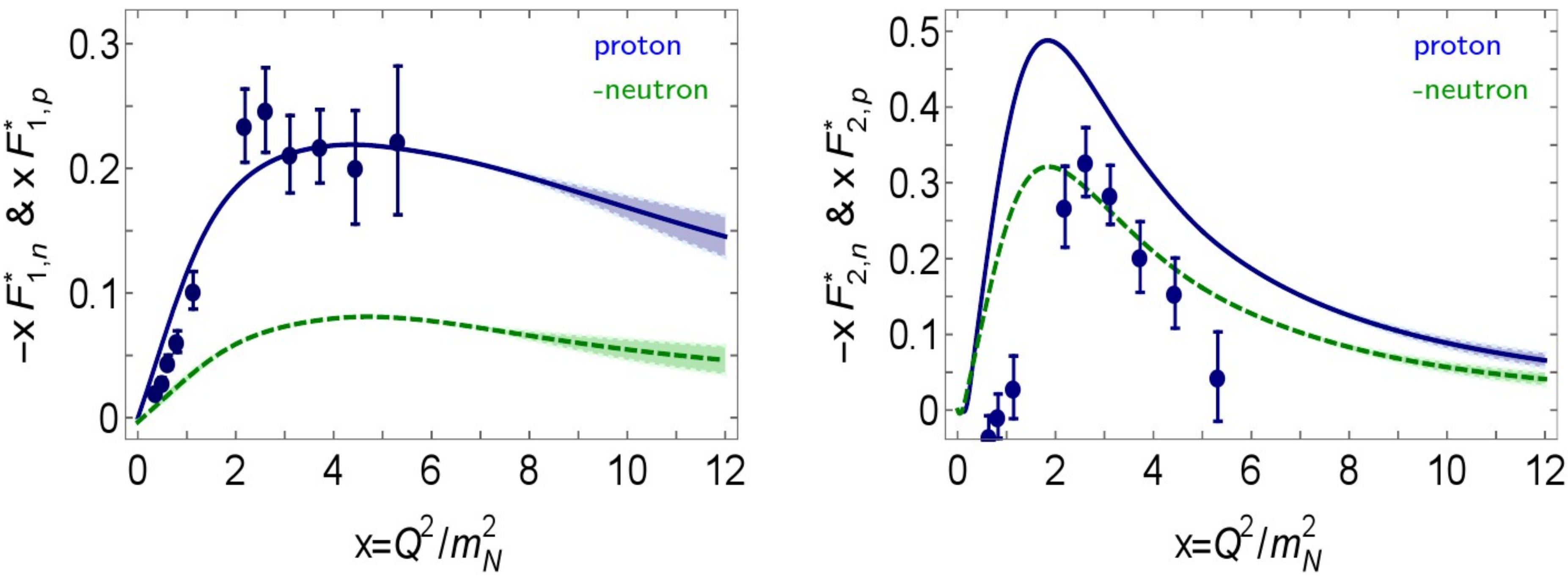
Scatterer dissection



Neutral channel

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \to N(1440)\frac{1}{2}^+$

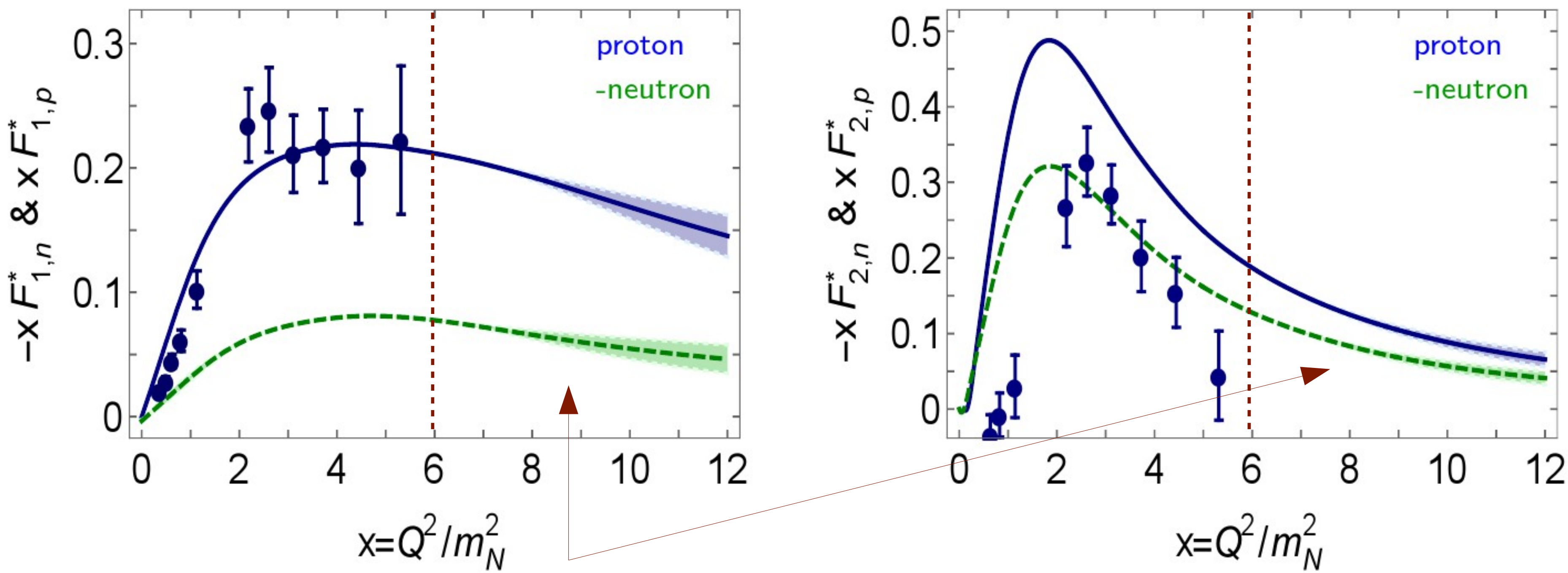
Dirac and Pauli transition form factors at large momentum transfer:



★ CLAS12 detector at JLAb will deliver data on the Roper-resonance electroproduction FFs out to $Q^2 \sim 12\, m_N^2$ in both the charged and neutral channels.

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \to N(1440)\frac{1}{2}^+$

Dirac and Pauli transition form factors at large momentum transfer:

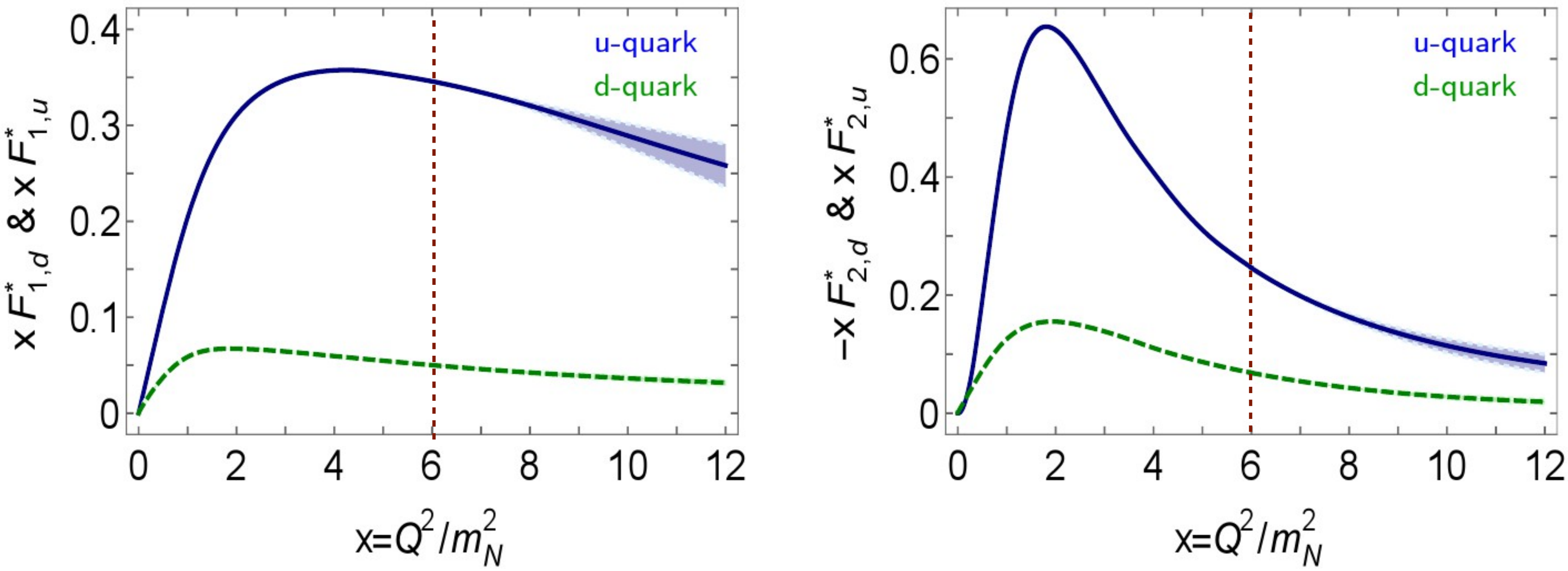


SPM, L. Schlessinger & C. Schwartz; PRL16, 1173 (1996).
L. Schlessinger, Phys.Rev.D, 1411 (1968).

- CLAS12 detector at JLAb will deliver data on the Roper-resonance electroproduction FFs out to $Q^2 \sim 12 m_N^2$ in both the charged and neutral channels.
- A first prediction is here delivered, based on the Schlessinger point Method, for $6 < Q^2/m_N^2 < 12$.
- No indication of the known scaling behaviour for the transition FFs is observed although, as each dressed-quark must roughly share the impulso momentun, this scaling can only be expected to be evident on larger momenta $x \gtrsim 20$.

Nucleon-to-Roper EM transition FFs. $\gamma^* N(940)\frac{1}{2}^+ \to N(1440)\frac{1}{2}^+$

Flavour separation in the Dirac and Pauli transition form factors:



- One can neglect s-quark contributions to nucleon-to-Roper transitions and assume isospin symmetry, to extract thus u-quark and d-quark contributions to the proton-to-Roper transition FFs.

- The suppression of the quark can be well understood if proton and Roper Faddeev wave functions are dominated by the [ud] scalar diquark, the process in which the photon strikes the d-quark being thus suppressed by 1/x at x>1.

Conclusions

In the underlying purpose of understanding hadrons in terms of QCD elementary excitations, an unified study of EM elastic and transition form factors of nucleon resonances using a QCD-based interaction is being pursued.

The QM three-body bound-state problem can be sensibly truncated by considering non-pointlike and fully-dynamical diquarks correlations (the origin of which roots, as for pions, in the correct implementation of DCSB) inside baryons.

Grounded on the dominance of scalar diquark correlations and on the presence of higher orbital angular momentum components, the Q^2- behaviour for the ratios of G_E^p/G_M^p and F_2^p/F_1^p is very well accounted.

The proton-to-Roper transition form factors here presented agree well with the data above $x \simeq 2$, when the virtual photon penetrates the meson cloud and exhibits the dressed-quark core. The mismatch below is due to the MB-FSI, which can be thus estimated.

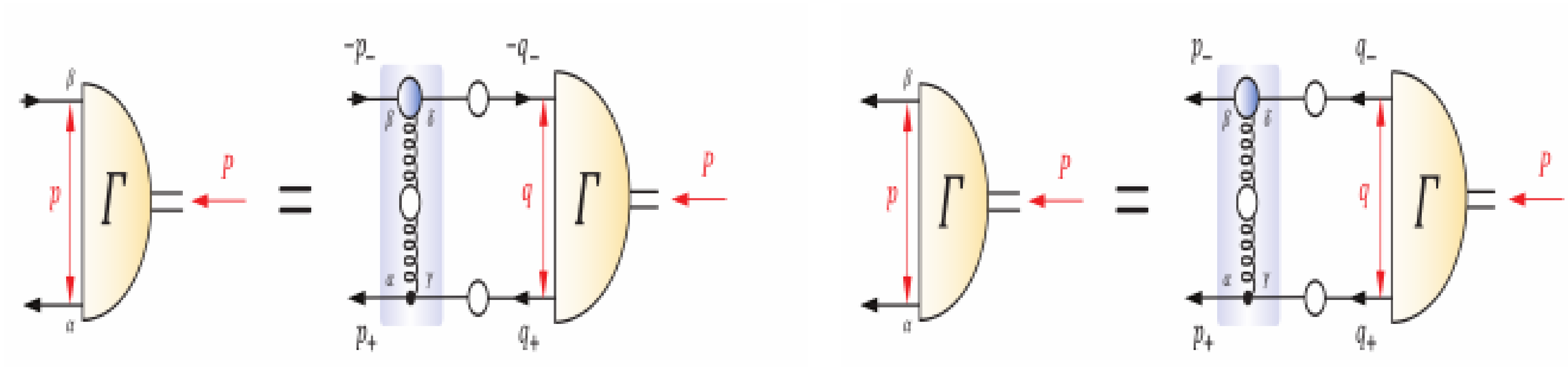
With the help of the SPM method, a first prediction for the large- Q^2 behaviour of nucleon-to-Roper transition FFs, both in the charged and neutral channels, has been delivered. No indication of the expected scaling behaviour.

A flavor-separated analysis for the nucleon-to-Roper transition form factors reveals that, as for the elastic ones, the d-quark contributions appear suppresed with regard to the u-quark ones.

Backslides

Diquark properties

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:

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

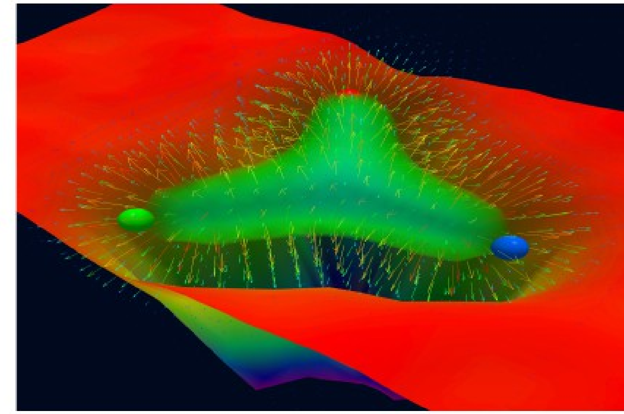
☆ Diquark correlations are soft, they possess an electromagnetic size:

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

Remarks about 3-gluon vertex

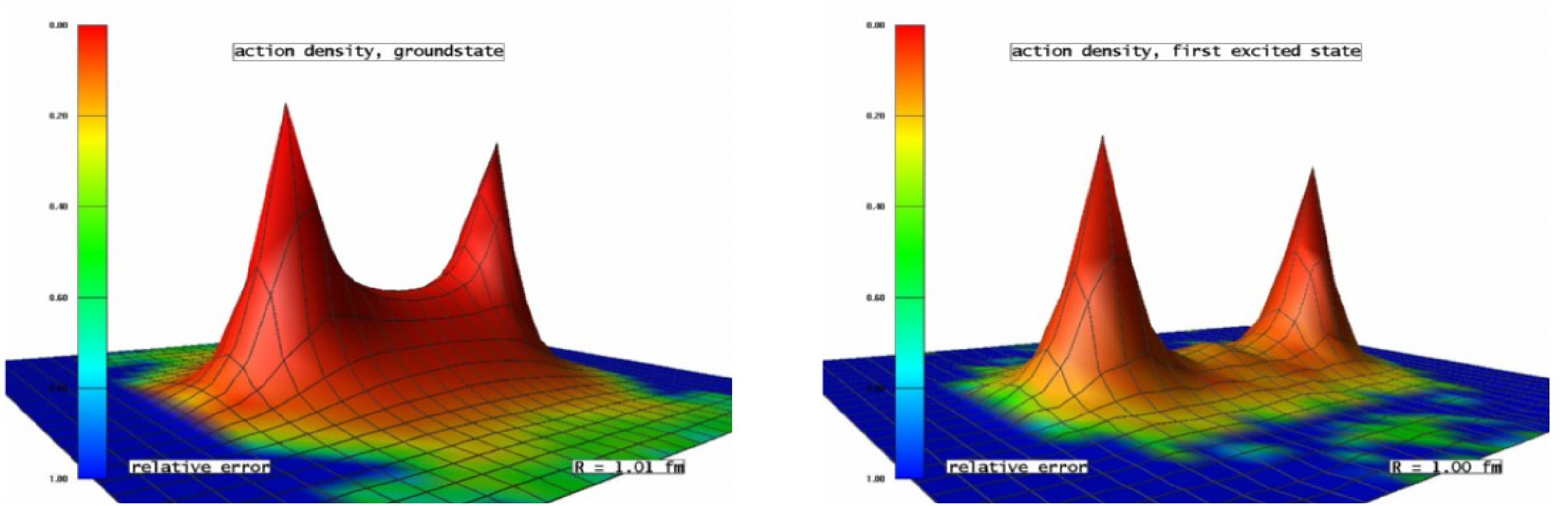
- A Y-junction flux-tube picture of nucleon structure is produced in **quenched** lattice QCD simulations that use **static sources** to represent the proton's valence-quarks.

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.

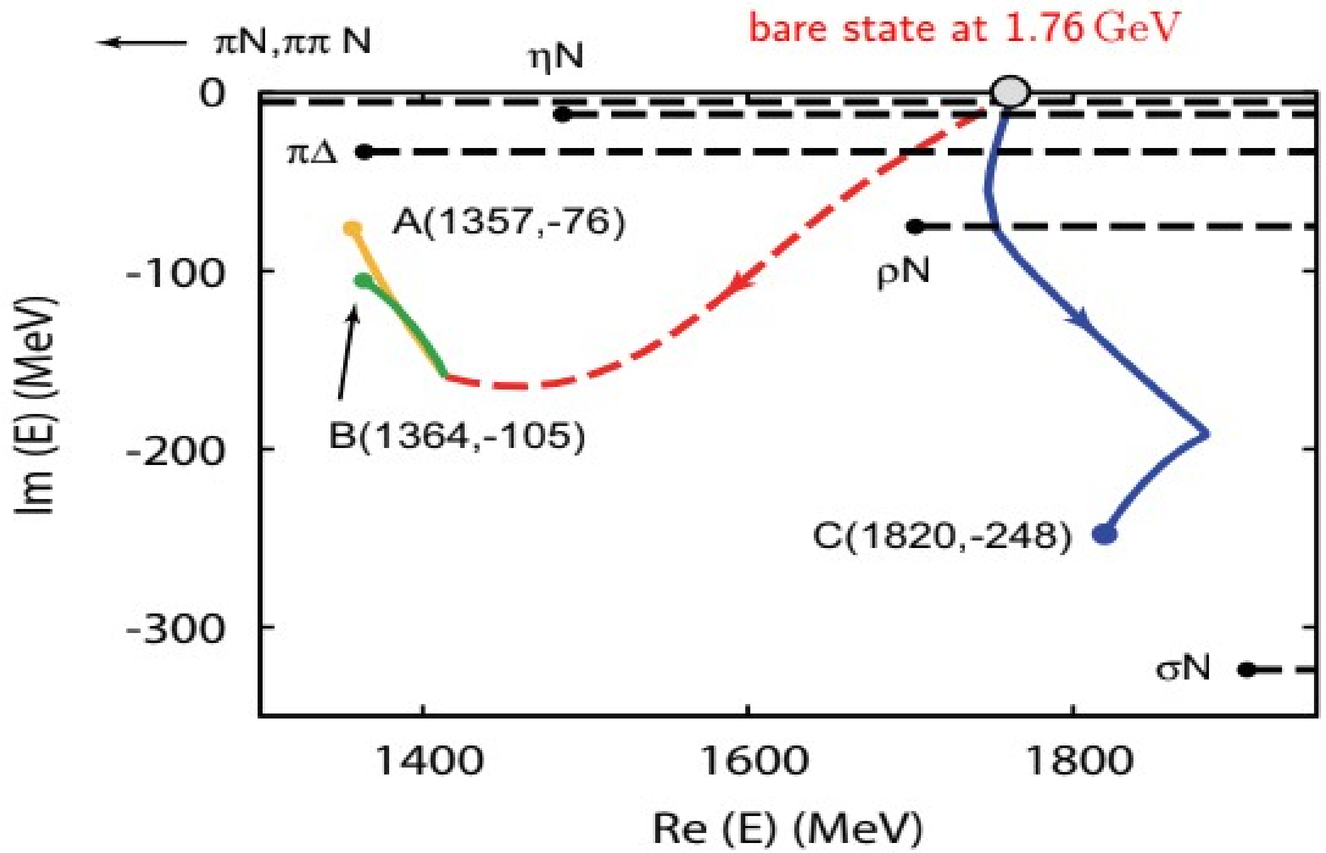
The dominant effect of the non-abelian 3-g and 4-g elementary vertices (multi-gluon interactions) made its way through the DCSB and is expressed by the diquark correlations in the baryon structure.

The Roper: the proton's first radial excitation

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.*

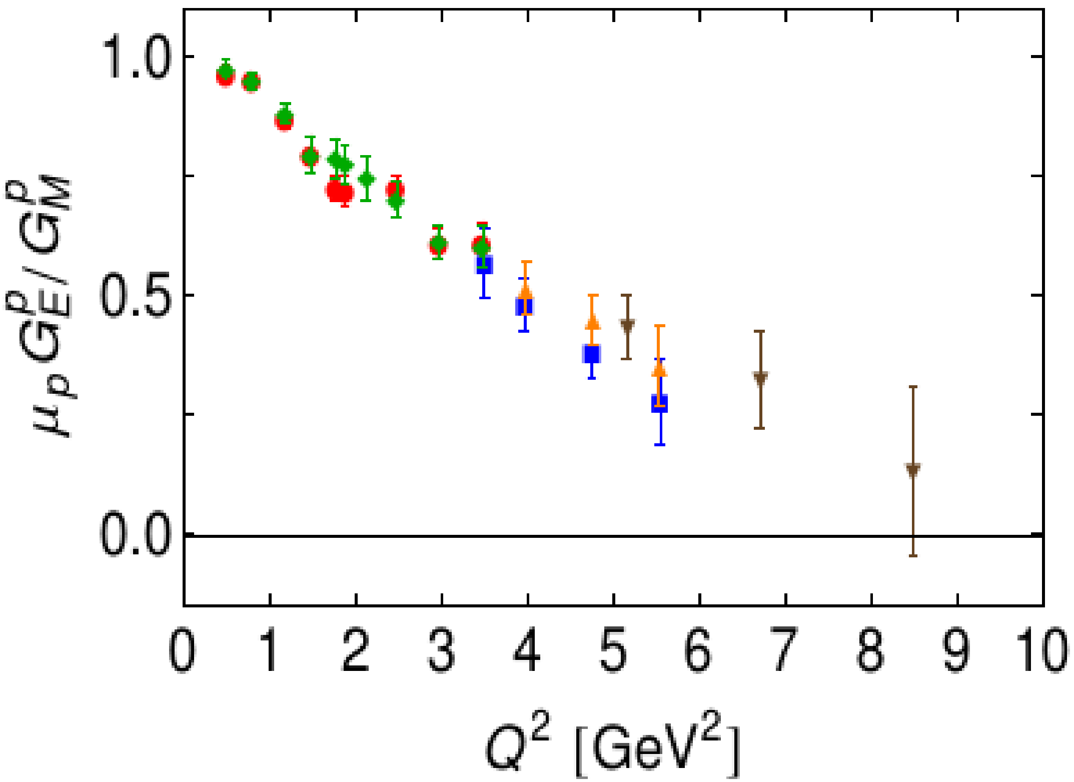
Scaling of Dirac, Pauli and Sachs FFs

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

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

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

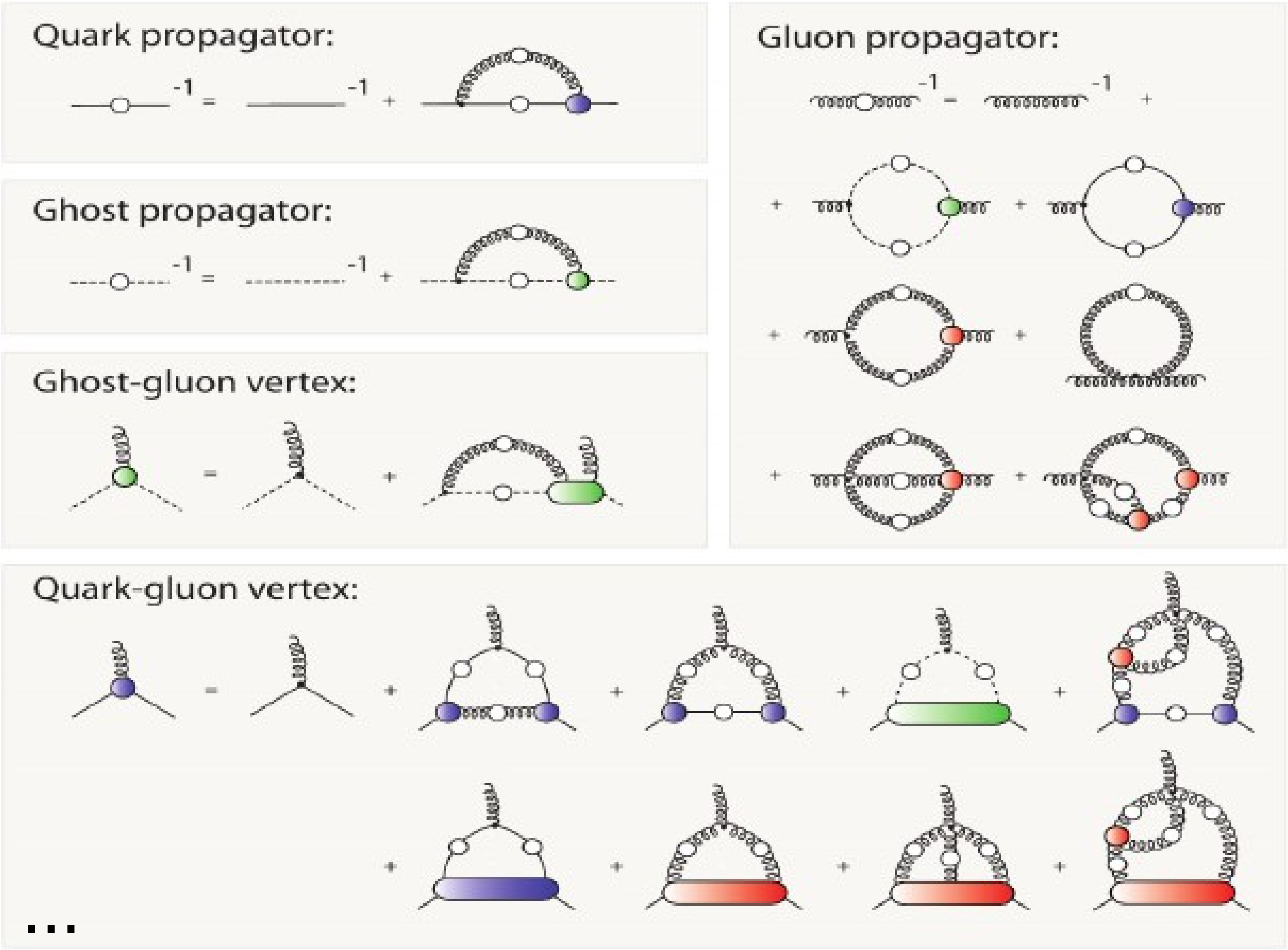
$$G_E^p \sim 1/Q^4 \quad \text{and} \quad G_M^p \sim 1/Q^4 \qquad \Rightarrow \qquad G_E^p / G_M^p \sim \text{const.}$$



- Jones *et al.*, Phys. Rev. Lett. 84 (2000) 1398.
- 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.
- Puckett *et al.*, Phys. Rev. C85 (2012) 045203.

Non-perturbative QCD: DSEs as a computation tool

Green's function are the solutions of the quantum equations of motion (DSEs) for the theory



An infinite tower of integrant equations which couples all the Green's functions!!!

Non-perturbative QCD: DSEs as a computation tool

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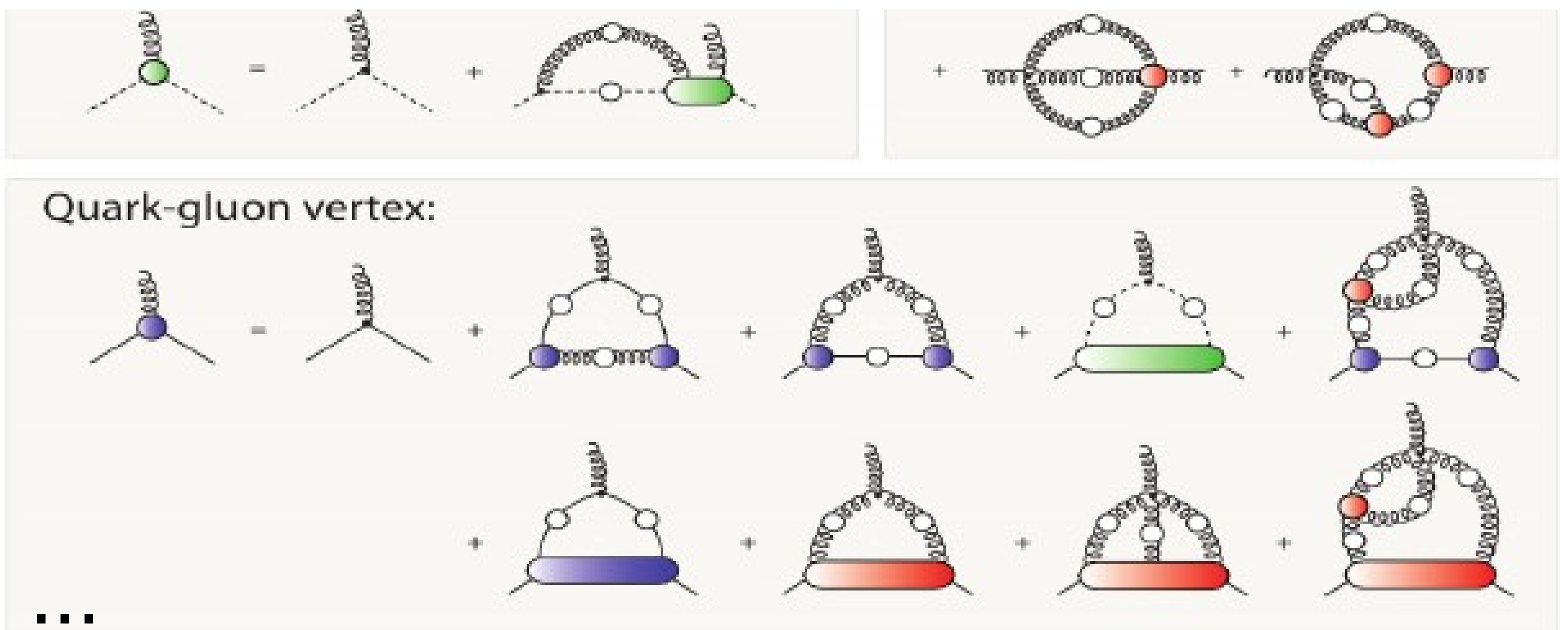
★ Main advantages:

- A continuum QFT theoretical approach bridging a model-independent connection from perturbartive and non-perturbative regimes of QCD.
- Poincaré covariant formulation
- Cover the full quark mass range between chiral limit and heavy quarks



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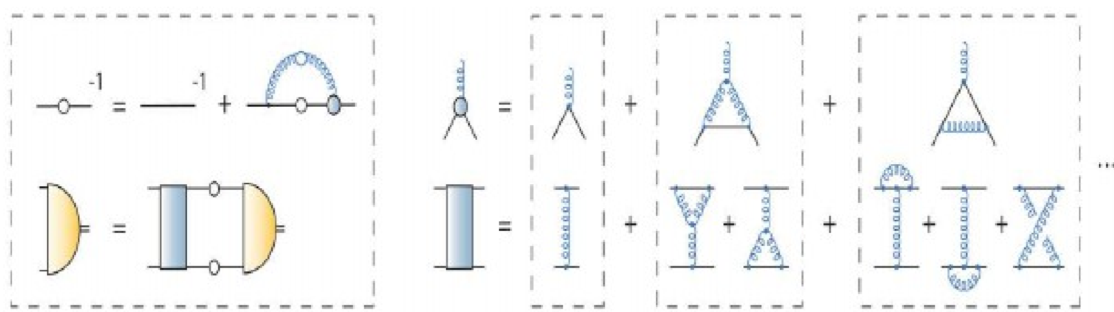
Main caveat comes from: truncation of the infinite set of coupled equations and from the IR modelling.



Schemes and ansätze are constrained by symmetries, renormalizability, the contact with perturbative limits... Few model parameters related to fundamental parameters.

An infinite tower of integral equations which couples all the Green's functions!!!