The dissection of $\gamma_v N \to N$ and $\gamma_v N \to R$ electromagnetic form factors

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Spectrum and Structure of Excited Nucleons from Exclusive Electroproduction

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Studies of N^*-electrocouplings

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

Elastic and transition form factors of N^*

↙ ↘

Unique window into their quark and gluon structure	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:

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

☞ The majority of new data was obtained at JLab.

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

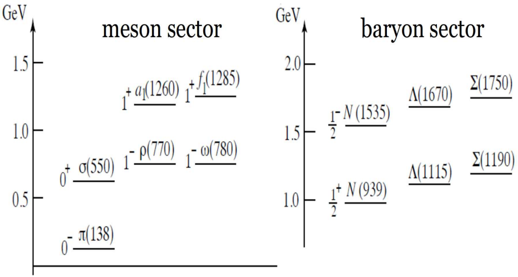
Hadrons, as bound states, are dominated by non-perturbative QCD dynamics

- *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

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:

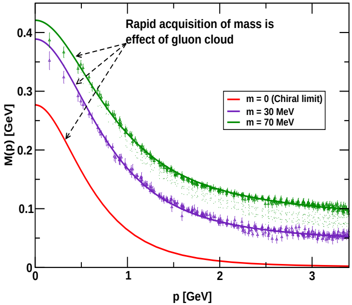
$$S^{-1}(p) = Z_2(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p) = \left(\frac{Z(p^2)}{i\gamma\cdot p + M(p^2)}\right)^{-1}$$

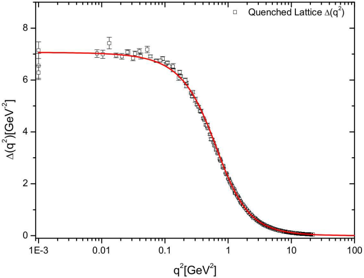
- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98% of the mass of the proton and the large splitting between parity partners.

☞ Dressed-gluon propagator in Landau gauge:

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

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

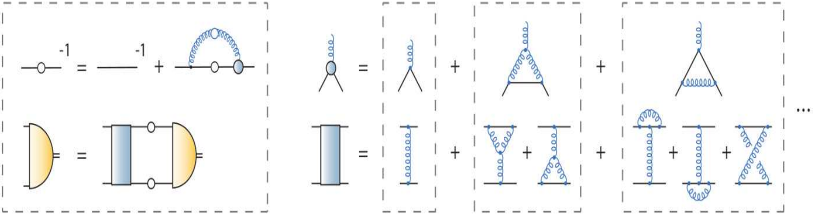




Theory tool: Dyson-Schwinger equations

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.

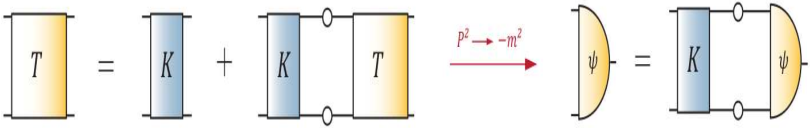
⇒ **modelling only within these constraints!**

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

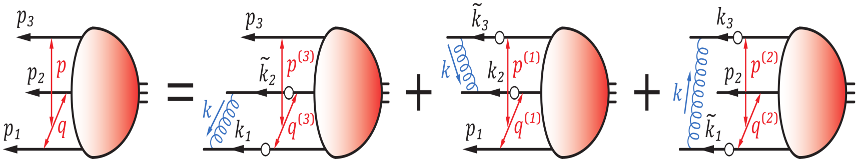
Use **scattering equation** (inhomogeneous BSE) to obtain T in the first place: $T = K + KG_0 T$

Homogeneous BSE for **BS amplitude:**



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

Faddeev equation in rainbow-ladder truncation

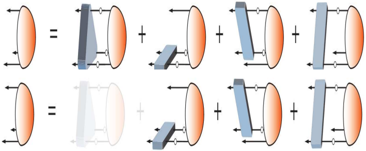


Faddeev equation: Sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.

The attractive nature of quark-antiquark correlations in a 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 $N_c = 2$ QCD: diquarks can form color singlets with are the baryons of the theory.
- In our approach: Non-pointlike color-antitriplet and fully interacting.



Thanks to G. Eichmann.

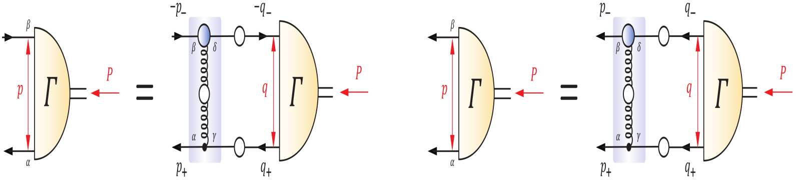
Diquark composition of the Nucleon and Roper

Positive parity state

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

↘ scalar and axial-vector diquarks → ↓ Dominant, right parity, shorter mass-scales

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:

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

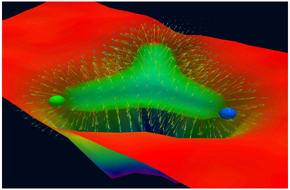
☞ Diquark correlations are soft, they possess an electromagnetic size:

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

Remark about the 3-gluon vertex

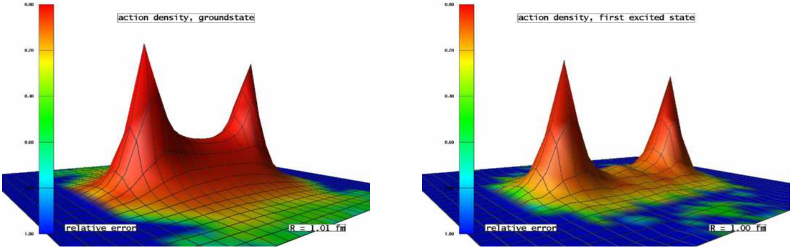
☞ A Y-junction flux-tube picture of nucleon structure is produced in **quenched** lattice QCD simulations that use **static sources** to represent the proton's valence-quarks.

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 quarks.**

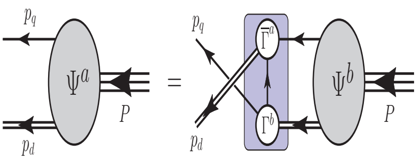


G.S. Bali, PRD 71 (2005) 114513.

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

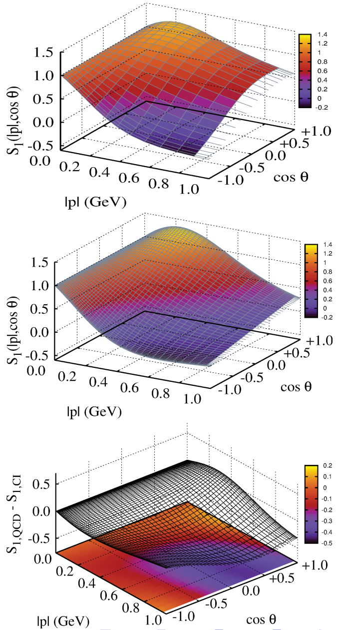
The quark+diquark structure of the nucleon (I)

Faddeev equation in the quark-diquark picture



Dominant piece in nucleon's eight-component Poincaré-covariant Faddeev amplitude: $s_1(|p|, \cos\theta)$

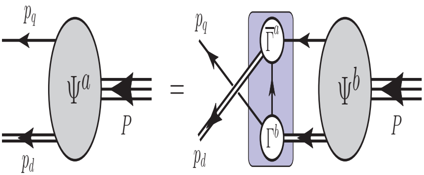
- There is strong variation with respect to both arguments in the quark+scalar-diquark relative momentum correlation.
- Support is concentrated in the forward direction, $\cos\theta > 0$. Alignment of p and P is favoured.
- Amplitude peaks at $(|p| \sim M_N/6, \cos\theta = 1)$, whereat $p_q \sim p_d \sim P/2$ and hence the *natural* relative momentum is zero.
- In the anti-parallel direction, $\cos\theta < 0$, support is concentrated at $|p| = 0$, i.e. $p_q \sim P/3$, $p_d \sim 2P/3$.



The quark+diquark structure of the nucleon (II)

☞ 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.

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

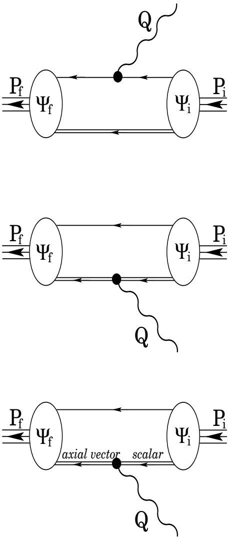
⇓

Six contributions to the current in the quark-diquark picture

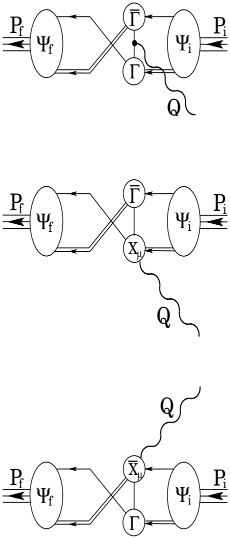
⇓

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.*

One-loop diagrams



Two-loop diagrams



☞ Gluon propagator: Contact interaction.

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

☞ Truncation scheme: Rainbow-ladder.

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

☞ Quark propagator: Gap equation.

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

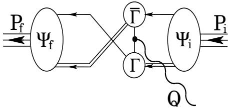
Implies momentum independent constituent quark mass ($M \sim 0.4\,{\rm GeV}$).

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

☞ Form Factors: Two-loop diagrams not incorporated.

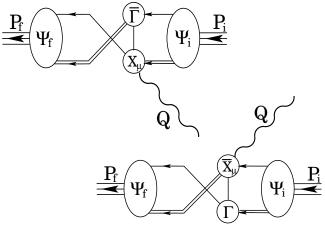
Exchange diagram

It is zero because our treatment of the contact interaction model



Seagull diagrams

They are zero



Series of papers establishes its strengths and limitations

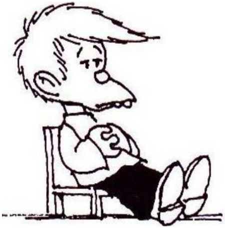
CI framework has judiciously been applied to a large body of hadron phenomena. Produces results in qualitative agreement with those obtained using most-sophisticated interactions.

1. Features and flaws of a contact interaction treatment of the kaon
   C. Chen, L. Chang, C.D. Roberts, S.M. Schmidt S. Wan and D.J. Wilson
   Phys. Rev. C **87** 045207 (2013). arXiv:1212.2212 [nucl-th]
2. Spectrum of hadrons with strangeness
   C. Chen, L. Chang, C.D. Roberts, S. Wan and D.J. Wilson
   Few Body Syst. **53** 293-326 (2012). arXiv:1204.2553 [nucl-th]
3. Nucleon and Roper electromagnetic elastic and transition form factors
   D.J. Wilson, I.C. Cloët, L. Chang and C.D. Roberts
   Phys. Rev. C **85**, 025205 (2012). arXiv:1112.2212 [nucl-th]
4. π- and ρ-mesons, and their diquark partners, from a contact interaction
   H.L.L. Roberts, A. Bashir, L.X. Gutierrez-Guerrero, C.D. Roberts and D.J. Wilson
   Phys. Rev. C **83**, 065206 (2011). arXiv:1102.4376 [nucl-th]
5. Masses of ground and excited-state hadrons
   H.L.L. Roberts, L. Chang, I.C. Cloët and C.D. Roberts
   Few Body Syst. **51**, 1-25 (2011). arXiv:1101.4244 [nucl-th]
6. Abelian anomaly and neutral pion production
   H.L.L. Roberts, C.D. Roberts, A. Bashir, L.X. Gutierrez-Guerrero and P.C. Tandy
   Phys. Rev. C **82**, 065202 (2010). arXiv:1009.0067 [nucl-th]

Weakness of the contact-interaction framework

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

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



Momentum dependence in the gluon propagator

↓

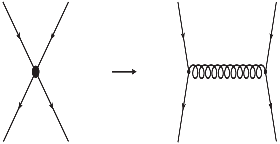
QCD-based framework

↓

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

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

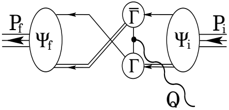
Implies momentum dependent constituent quark mass ($M(p^2=0) \sim 0.33\,\mathrm{GeV}$).

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

☞ Form Factors: Two-loop diagrams incorporated.

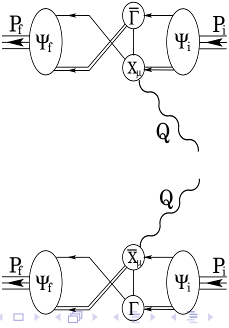
Exchange diagram

Play an important role



Seagull diagrams

They are less important



The γ^*N $\rightarrow$ Nucleon reaction

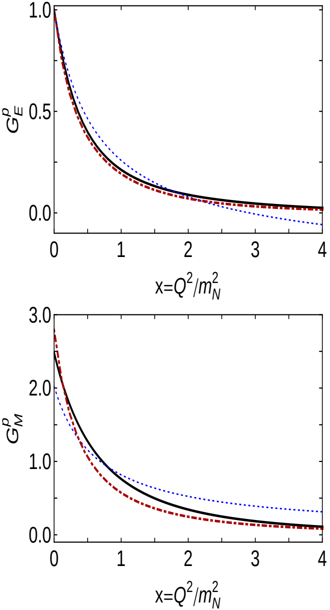
Work in collaboration with:

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

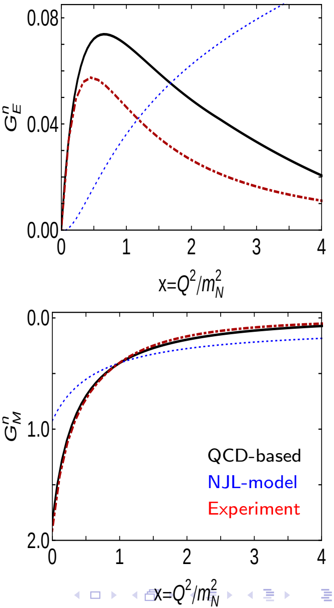
Based on:

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

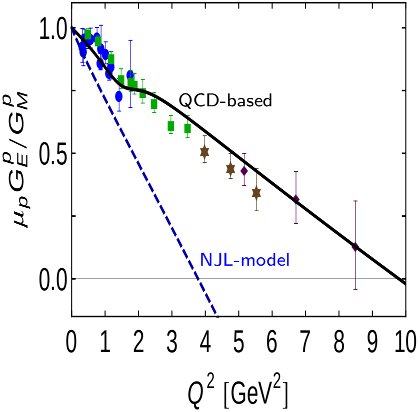
☞ Q^2-dependence of **proton** form factors:

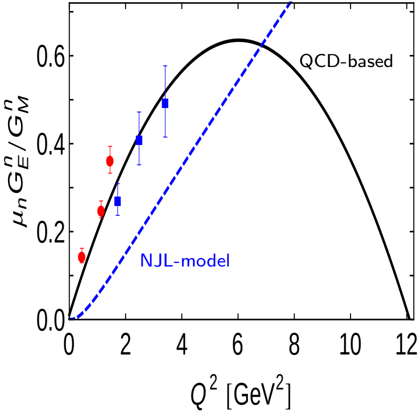


☞ Q^2-dependence of **neutron** form factors:



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





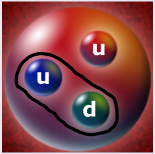
The possible existence and location of the zero in $\mu_p G_E^p / G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction

A world with only scalar diquarks

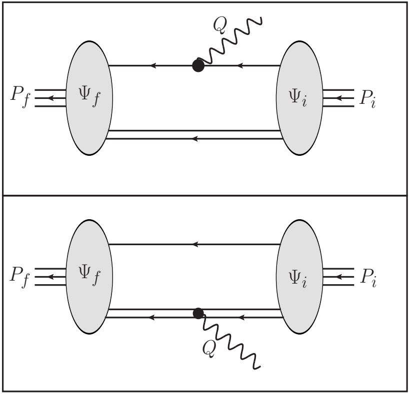
The singly-represented d-quark in the proton $\equiv u[ud]_{0^+}$ *is sequestered inside a soft scalar diquark correlation.*

☞ *Observation:*

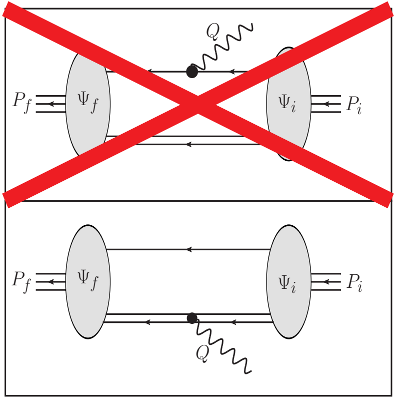
$$\textit{diquark-diagram} \propto 1/Q^2 \times \textit{quark-diagram}$$



Contributions coming from **u-quark**



Contributions coming from **d-quark**

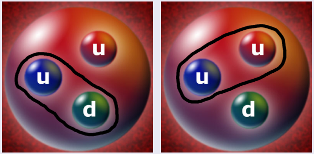


A world with scalar and axial-vector diquarks (I)

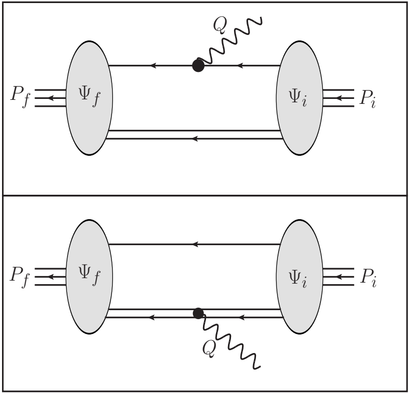
The singly-represented d-quark in the proton is **not always (but often)** *sequestered inside a soft scalar diquark correlation.*

☞ *Observation:*

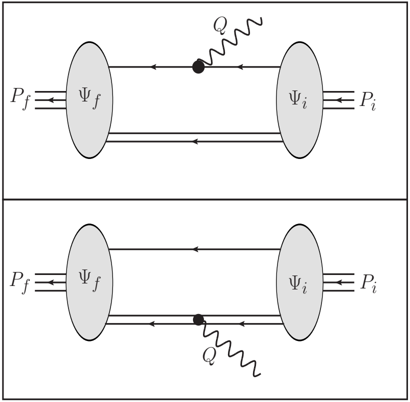
$$\mathcal{P}_{\text{scalar}} \sim 0.62, \quad \mathcal{P}_{\text{axial}} \sim 0.38$$

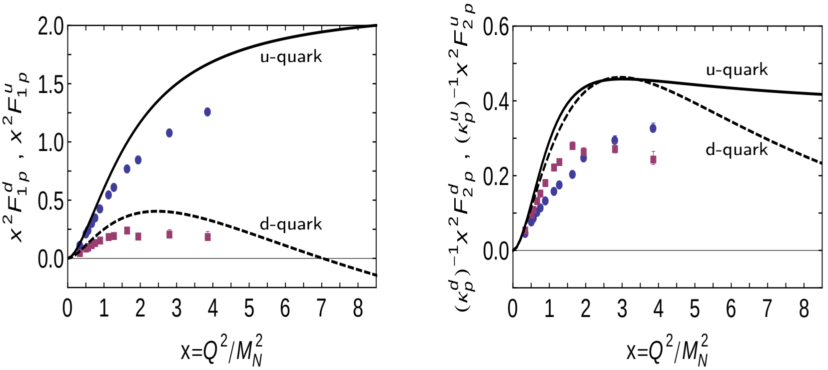


Contributions coming from **u-quark**



Contributions coming from **d-quark**

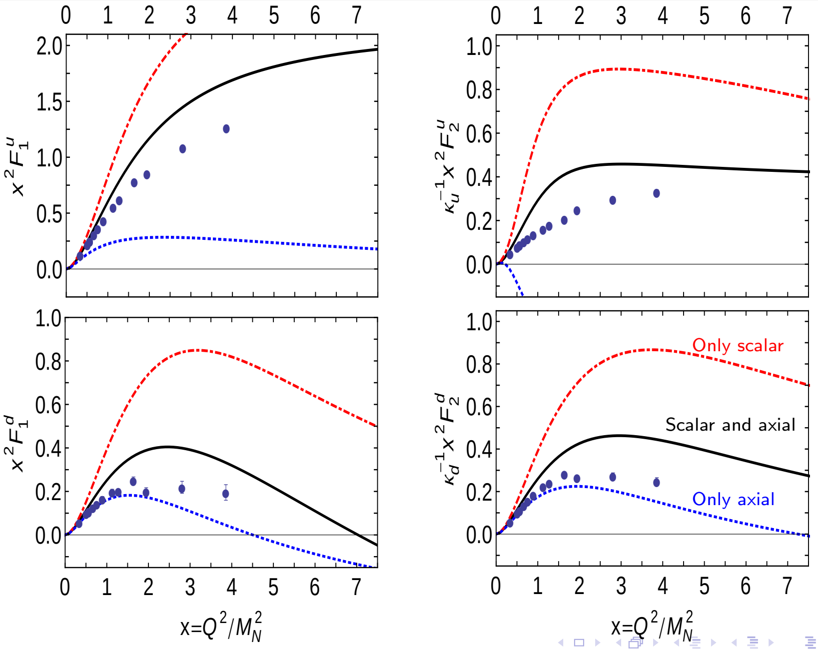


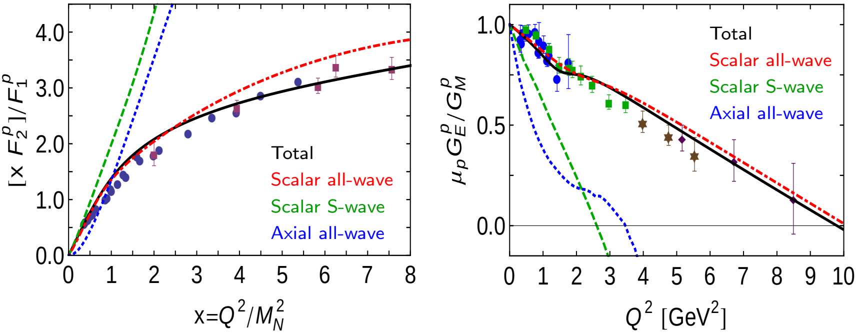


☞ Observations:

- 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)





☞ 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 $\gamma^* N \to$ 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)

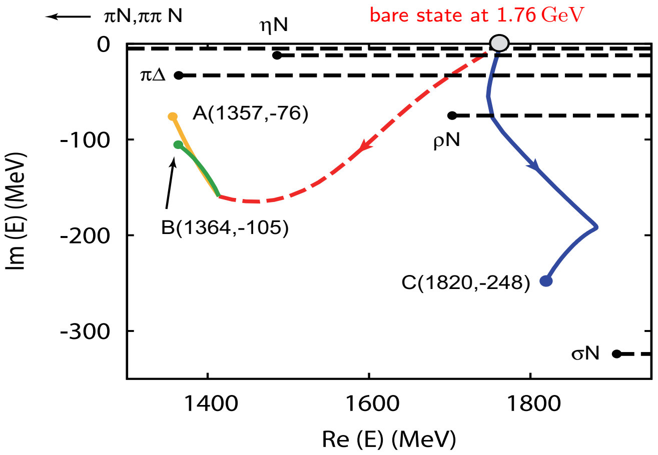
Based on:

- 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.*

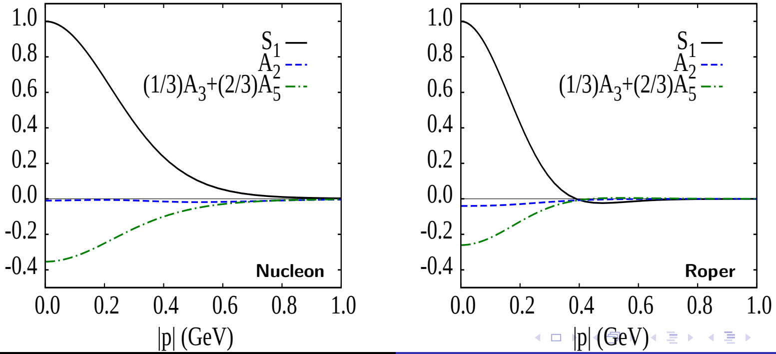
The bare N^* states correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions:

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

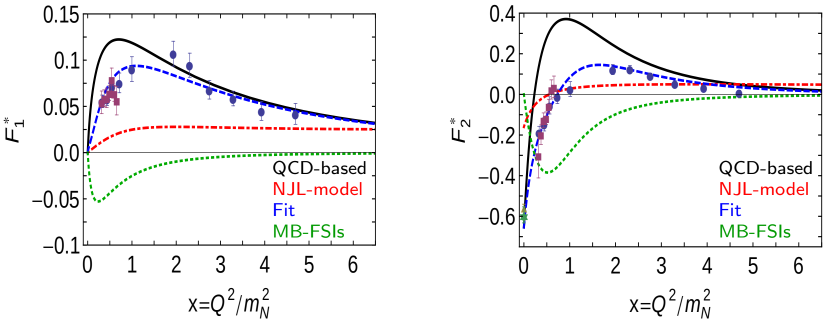
☞ Observation:

- 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 ⇒ A radial excitation.

0th Chebyshev moment of the S-wave components



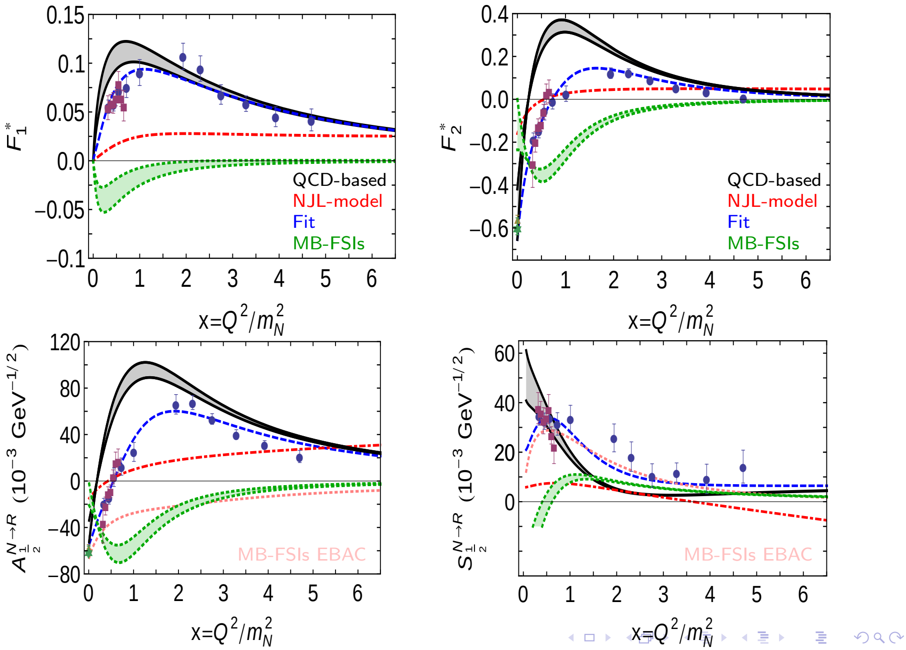
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core



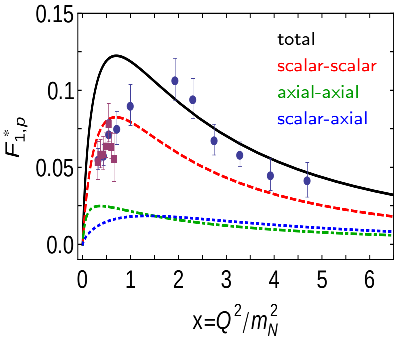
☞ Observations:

- 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.

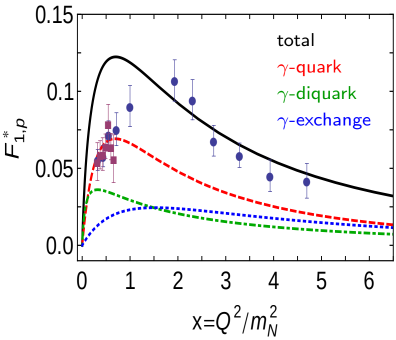
Transition form factors (II)



Diquark dissection

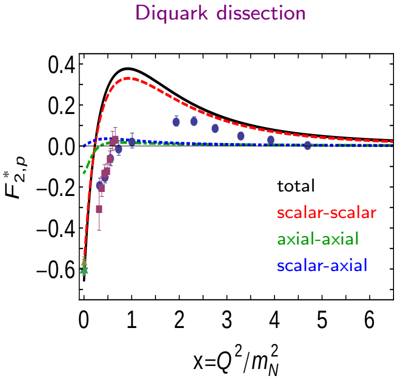


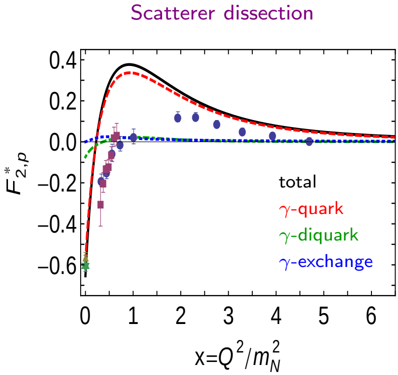
Scatterer dissection



☞ 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.





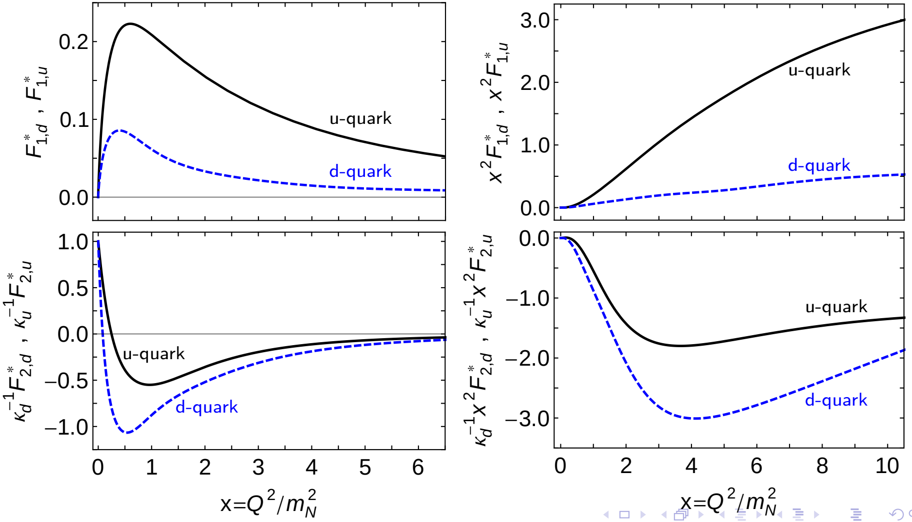
☞ Observations:

- 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 $\gamma^* N \to$ *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 $\gamma^* N \to$ *Roper* reaction:

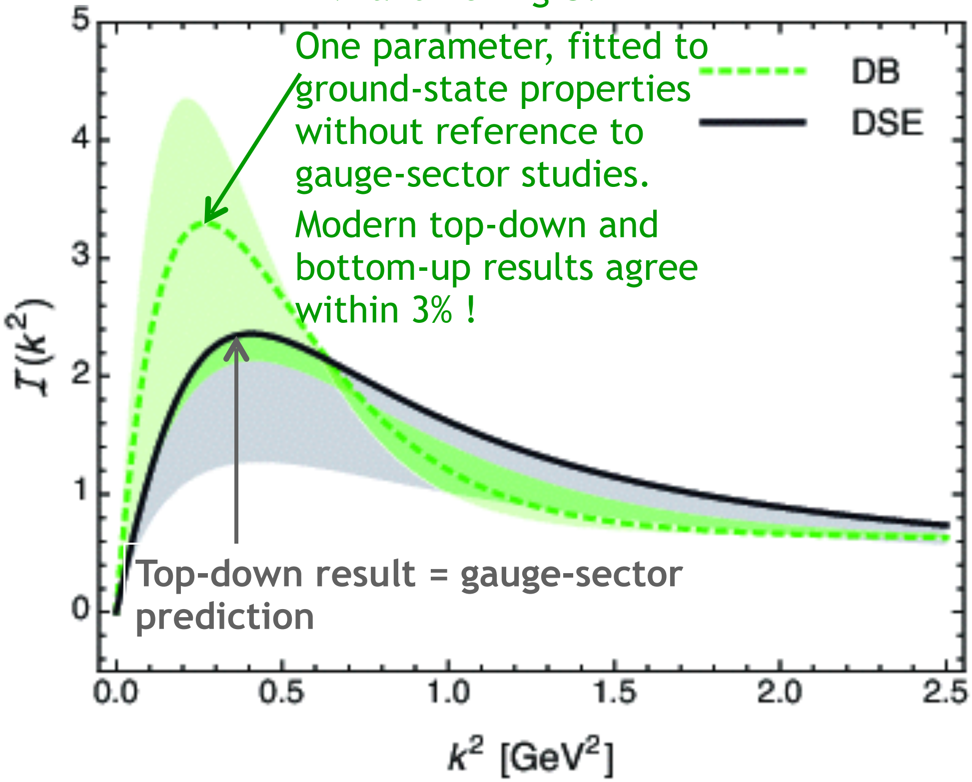
- The Roper is the proton's first radial excitation. It consists on a dressed-quark core augmented by a meson cloud that reduces its mass by approximately 20%.
- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$. The mismatch on $x \lesssim 2$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

Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain), C. D. Roberts (US), arXiv:1412.4782 [nucl-th] , *Phys. Lett. B* ***742*** *(2015) 183*

Top down & Bottom up

- *Top-down approach* – ab initio *computation of the interaction via direct analysis of the gauge-sector gap equations*
- *Bottom-up scheme – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.*
- *Serendipitous collaboration, conceived at one-week ECT* Workshop on* DSEs in Mathematics and Physics, *has united these two approaches*
  - Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation



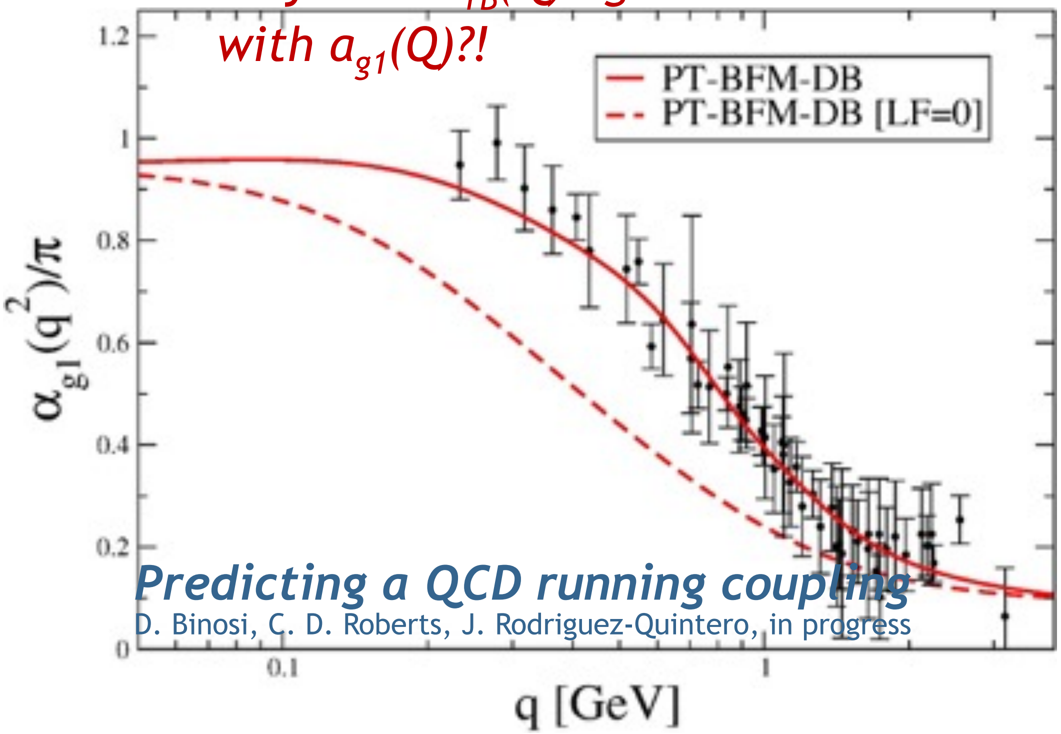
$$\int_0^{1^-} dx_{Bj} \left(g_1^p(x_{Bj}, Q^2) - g_1^n(x_{Bj}, Q^2) \right) \equiv \frac{g_A}{6} \left[1 - \frac{\alpha_{g_1}(Q^2)}{\pi} \right]$$

S.J. Brodsky, H.J. Lu, Phys. Rev. D 51 (1995) 3652
S.J. Brodsky, G.T. Gabadadze, A.L. Kataev, H.J. Lu, Phys. Lett. B 372 (1996) 133
A. Deur, V. Burkert, Jian-Ping Chen, Phys.Lett. B 650 (2007) 244-248

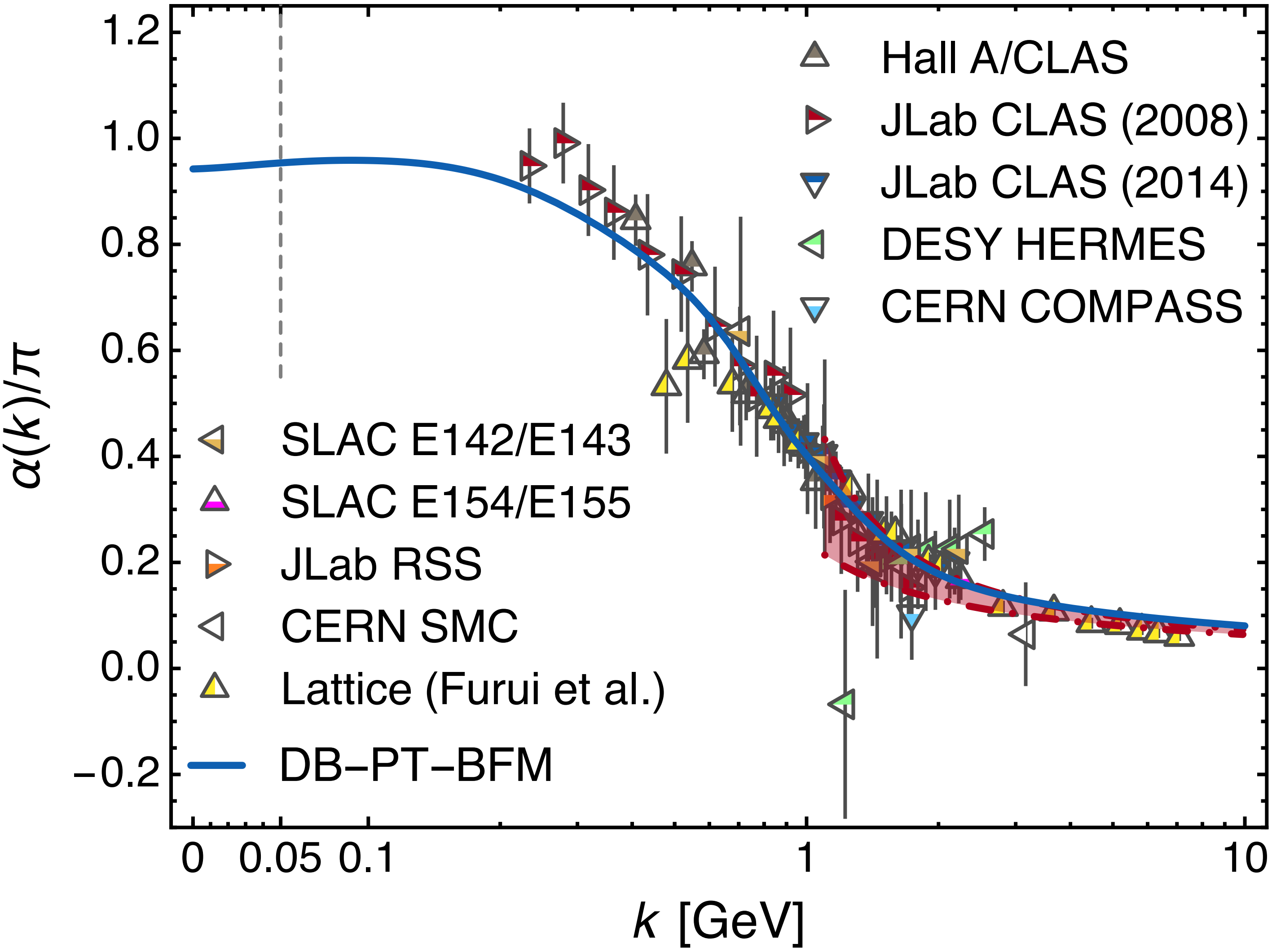
Running coupling in QCD

- Data = running coupling defined from the Bjorken sum-rule
- Curve = predicted RGI running coupling, determined from the Top-Down/Bottom-Up DSE interaction (pictured previously)
  - ✓ No parameters
  - ✓ No matching condition
  - ✓ No extrapolation
  - ✓ Curve completely determined from lQCD information on the propagator of the massless-ghost and massive gluon
  - ✓ Prediction implicitly incorporates infinitely many loops

Why does $a_{TB}(Q)$ agree so well with $a_{g1}(Q)$?!



- *The curve is a running coupling that does NOT depend on the choice of observable*
- *It predicts and unifies an enormous body of empirical data via the matter-sector bound-state equations.*


Hall A/CLAS
JLab CLAS (2008)
JLab CLAS (2014)
DESY HERMES
CERN COMPASS
SLAC E142/E143
SLAC E154/E155
JLab RSS
CERN SMC
Lattice (Furui et al.)
DB–PT–BFM
α(k)/π
k [GeV]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
0.05
0.1
1
10