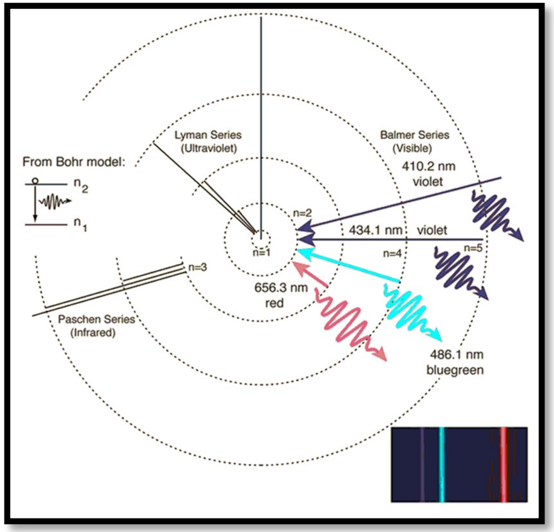
N→N* Transition Form Factors in Continuum QCD

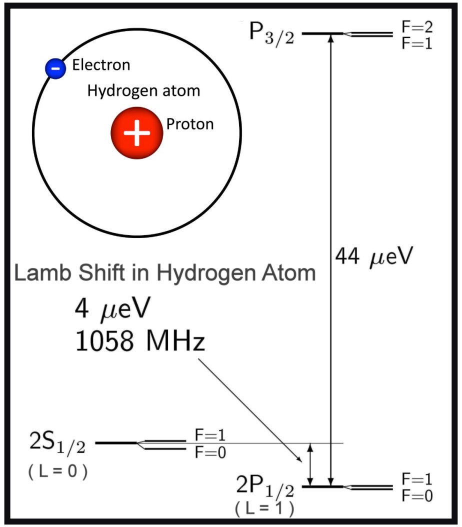
Adnan Bashir

Institute of Physics and Mathematics
University of Michoacán, Morelia, Michoacán, Mexico
Fulbright Visiting Scientist
Jefferson Laboratory, Newport News, Virginia, USA

25th International Spin Symposium (SPIN 2023)
September 26, 2023, Duke University, NC
3D Structure of the Nucleon: GPDs and Form Factors

N → N*: Footprints of QCD





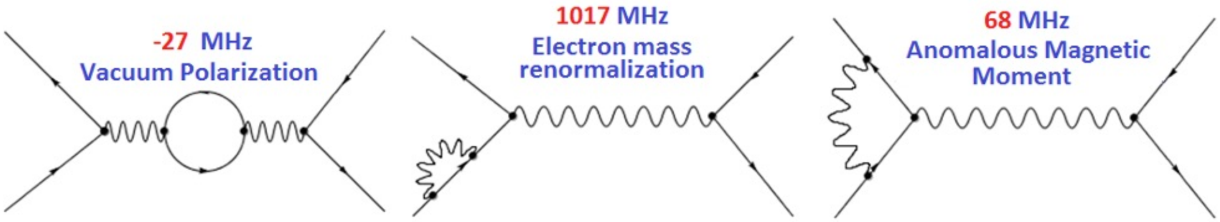
Similarly, **hadronic bound states**, **mesons** and **baryons** and their transition to the **excited states** should provide us insight into the dynamics of **QCD** which is a bigger challenge.

$$\mathcal{L}_{\rm QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j [\gamma_\mu D_\mu + m_j] q_j + \tfrac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu},$$

$$D_\mu = \partial_\mu + i g \tfrac{1}{2} \lambda^a A^a_\mu \,,$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu + \partial_\nu A^a_\mu - \underline{g f^{abc} A^b_\mu A^c_\nu},$$

Dyson: If you don't understand the **Hydrogen atom** (in **QED**) you don't understand anything.



1940s: Renormalized QED

QCD is characterized by two novel **infrared** phenomena:

confinement

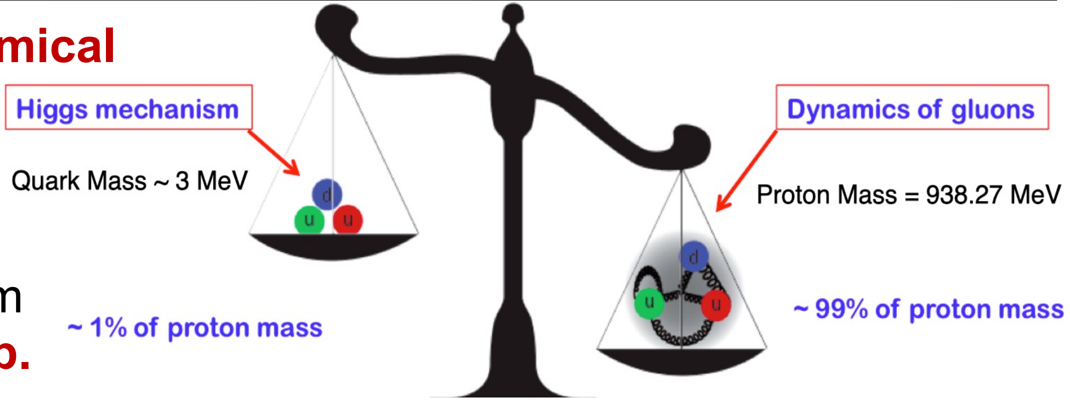
emergent hadron mass (**EHM**).

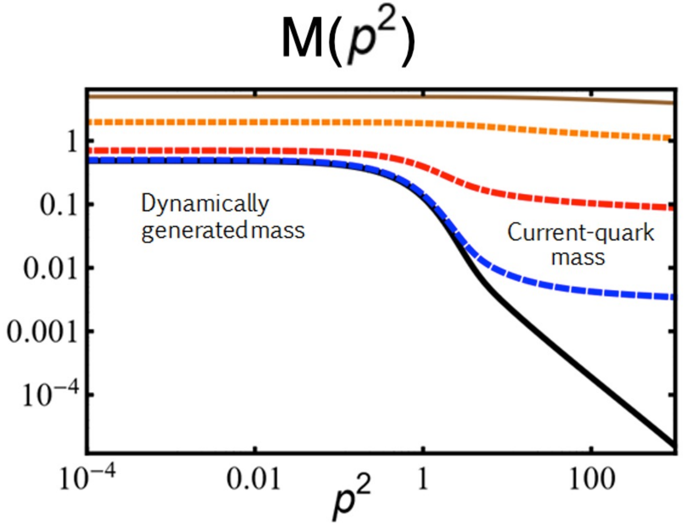
QCD: Quarks → Nucleon Transition Form Factors

Infrared **QCD** entails **confinement** and **dynamical chiral symmetry breaking** (**DCSB**).

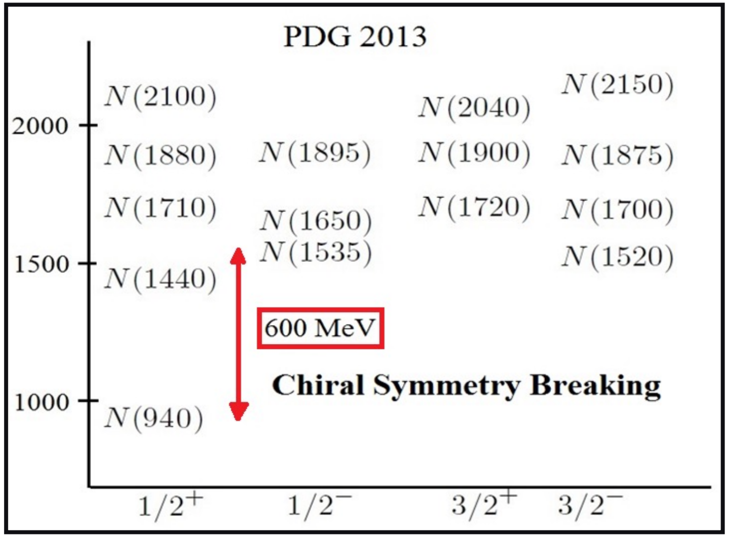
The strength of the **DCSB** is reflected in the mass **spectrum** of hadrons.

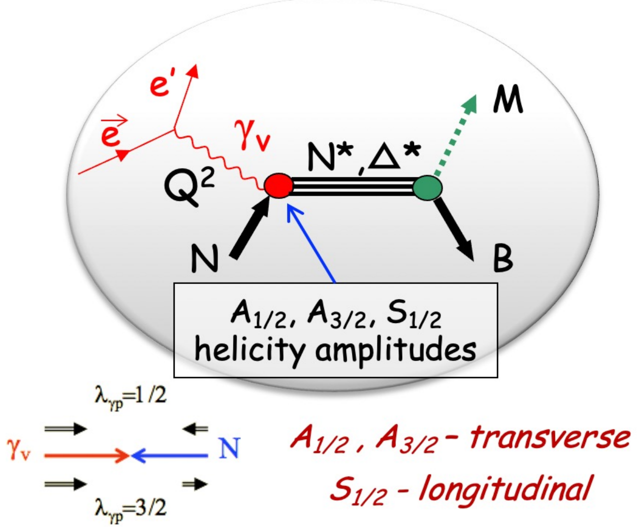
The pattern of **DCSB** is traceable in momentum dependent **observables** measured at the **JLab.**





$$S_f^{-1}(p) = Z_f^{-1}(p^2)(i\gamma \cdot p + \mathrm{M_f}(\mathbf{p^2}))$$

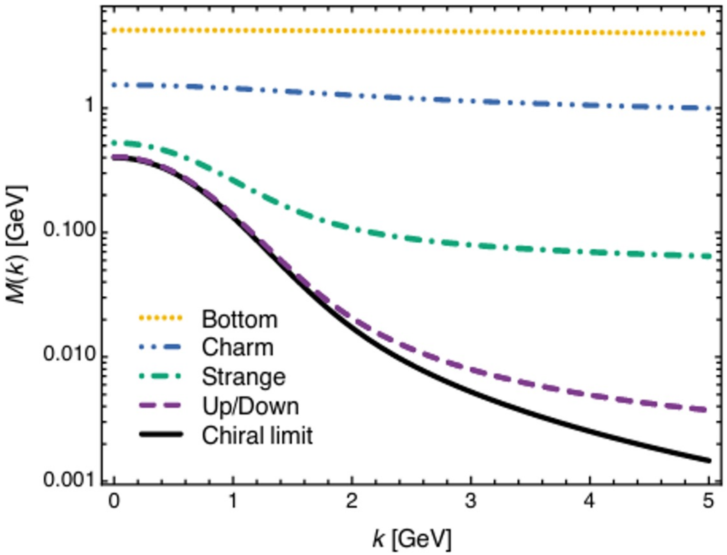


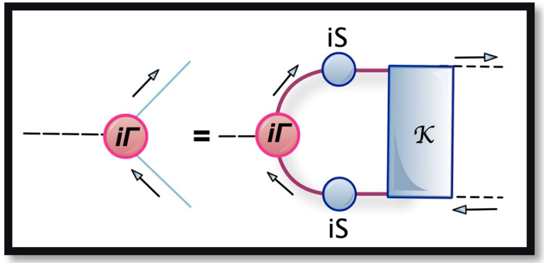


DCSB: From Quarks to Mesons

Pattern of **dynamical chiral symmetry breaking** is observed again in the **Bethe-Salpeter amplitudes** computed by solving the **Bethe-Salpeter equations**.

$$\Gamma_\pi(k,P) = \gamma_5 \left[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P G_\pi(k;P) + \sigma_{\mu\nu} k_\mu P_\nu H_\pi(k;P) \right]$$





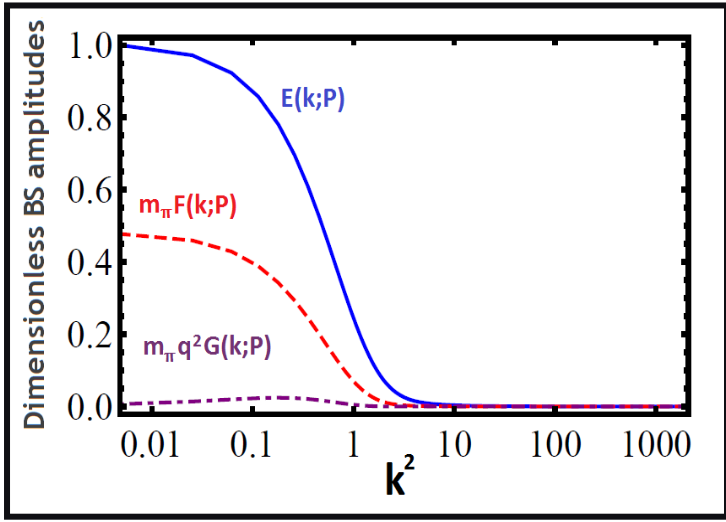
$$S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$$

$$f_\pi E_\pi(k; P=0) = B(p^2)$$

$$F_R(k;0) + 2\, f_\pi F_\pi(k;0) = A(k^2)$$

$$G_R(k;0) + 2\, f_\pi G_\pi(k;0) = 2A'(k^2)$$

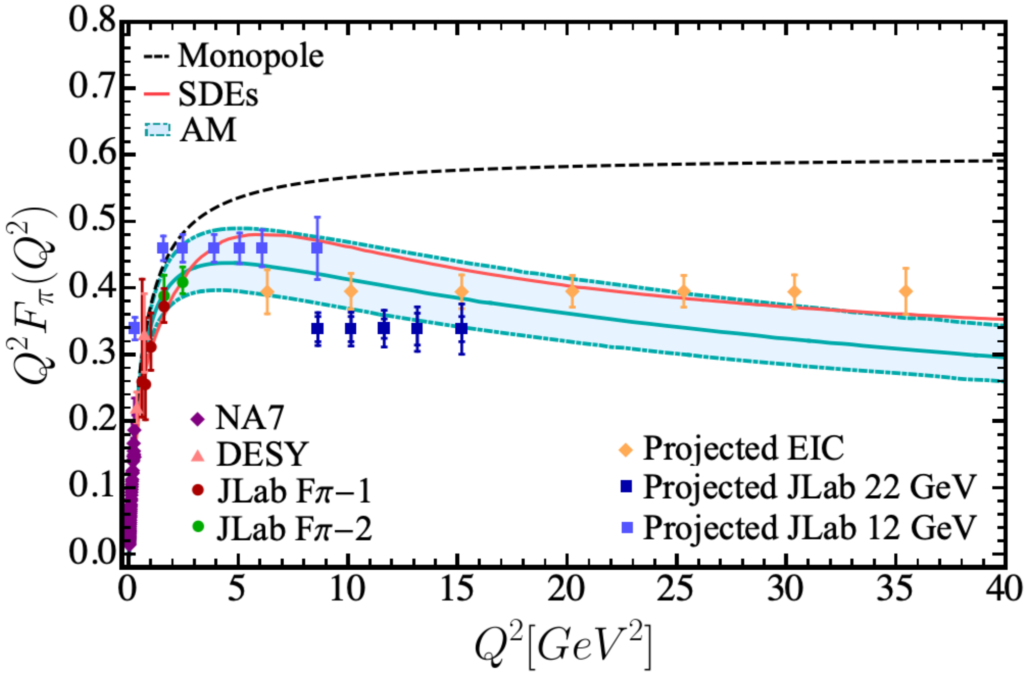
$$H_R(k;0) + 2\, f_\pi H_\pi(k;0) = 0$$

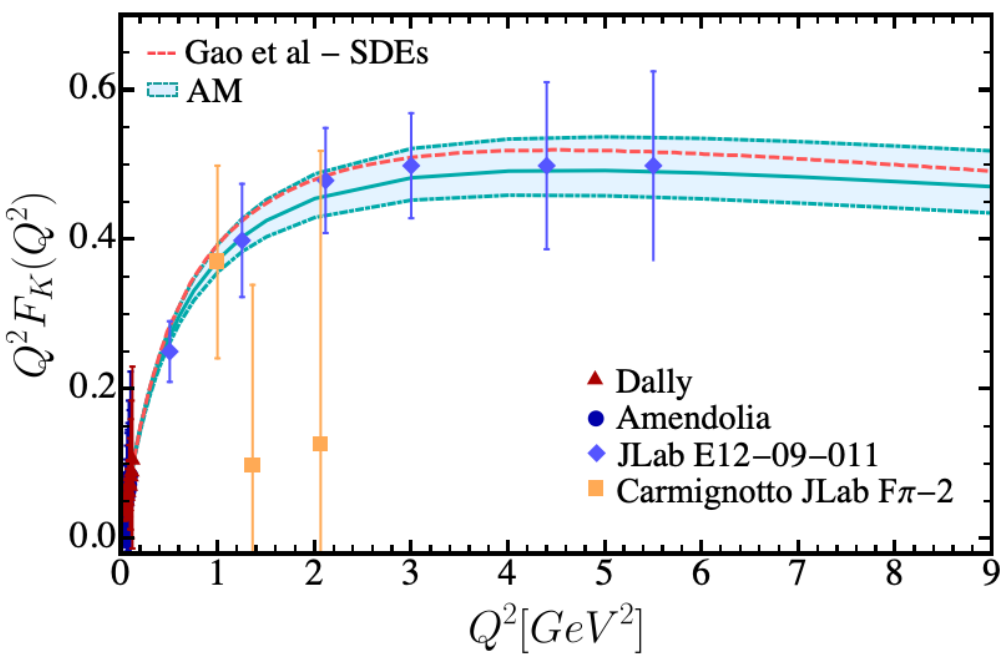


DCSB: From Quarks to Mesons

The Q^2-dependence of the **pion** and **kaon electromagnetic form factors** to larger Q^2 range of photon virtualities accessible to the **JLab12**, **JLab22** and the **EIC programs**:

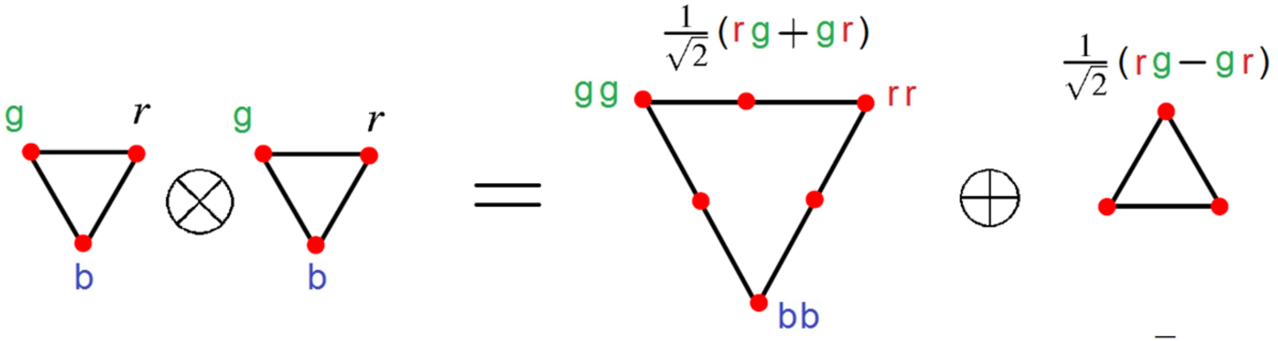
L. Albino, M. Higuera, K. Raya, AB Phys. Rev. D 106 (2022) 3, 034003
M. Higuera, AB, R. Hernández, K. Raya, in progress.





From Mesons to Diquarks

Any interaction capable of creating **pseudo-NG** modes as **bound-states** such as π, **K** reproducing the measured value of their **leptonic decay constants**, will necessarily also generate strong color-antitriplet correlations between any two **dressed quarks** contained within a **hadron**.



$$3 \otimes 3 = 6 \oplus \bar{3}$$

Baryons can only have $\bar{3}$ diquarks becuse only they give a singlet when coupled to 3

$$\bar{3} \otimes 3 = 1 \oplus 8$$

M. Yu, Barbanov et. al., Prog. Part. Nucl. Phys. 116 (2021) 103835

A **scalar, $[ud]_{0^+}$ diquark** is generated in the presence of **DCSB**, in correspondence with the **pion** and **axial vector $\{ud\}_{1^+}$ diquark** would result from the **Bethe-Salpeter equation** along with the theory's **ρ-meson**.

From Mesons to Diquarks

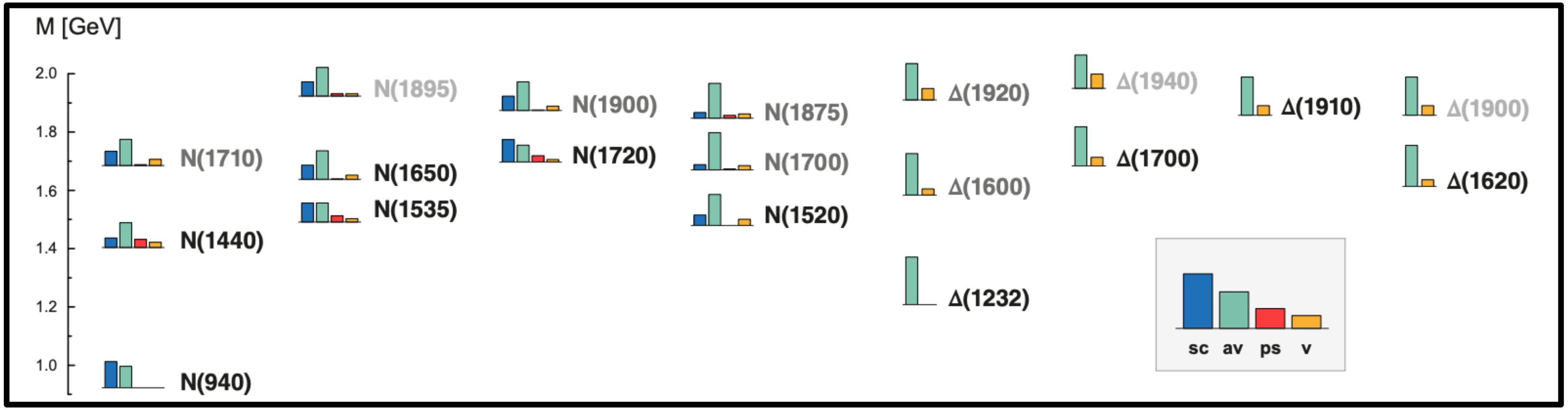
In a nucleon **scalar** and **axial-vector diquark** correlations are the strongest.

Associated **diquark mass-scales** are bounded below by the partnered **meson's mass:** see Table (GeV).

Electromagnetic size of diquarks is bounded below by that of analogous mesonic system.

$I(J^P)$	$0(0^+)$	$1(1^+)$	$0(0^-)$	$0(1^-)$ $1(1^-)$
	0^+	1^+	0^-	1^-
Mass GeV	0.80(7)	0.99(5)	1.22(9)	1.30(6)

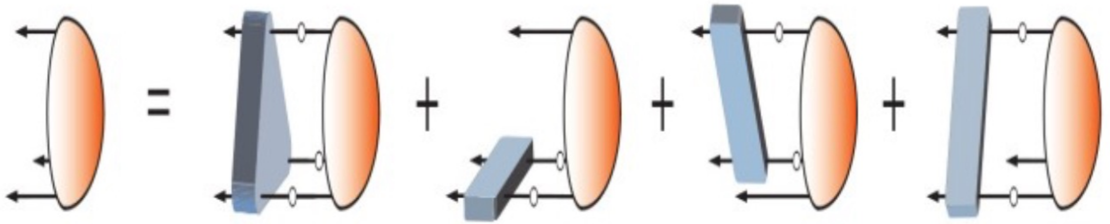
It is important to appreciate that these fully **dynamical diquark correlations** are different from the static, pointlike diquarks which featured in early attempts to understand the baryon spectrum.



M. Yu, Barbanov et. al., Prog. Part. Nucl. Phys. 116 (2021) 103835

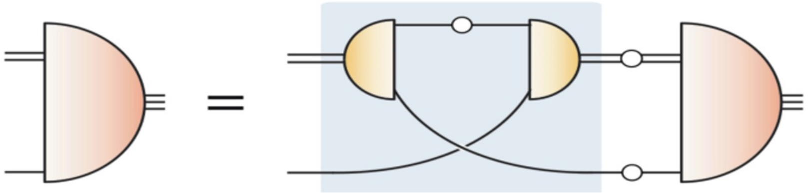
From Diquarks to Baryons

Faddeev equation for a **baryon**:



G. Eichmann, Phys. Rev. D 84 (2011) 014014; G. Eichmann et. Al. Prog. Part. Nucl. Phys. 91 (2016) 1-100

The quark-diquark picture of baryon reproduces results within 5% of the 3-body problem:



Dynamical quark-diquark picture

Less tightly bound:

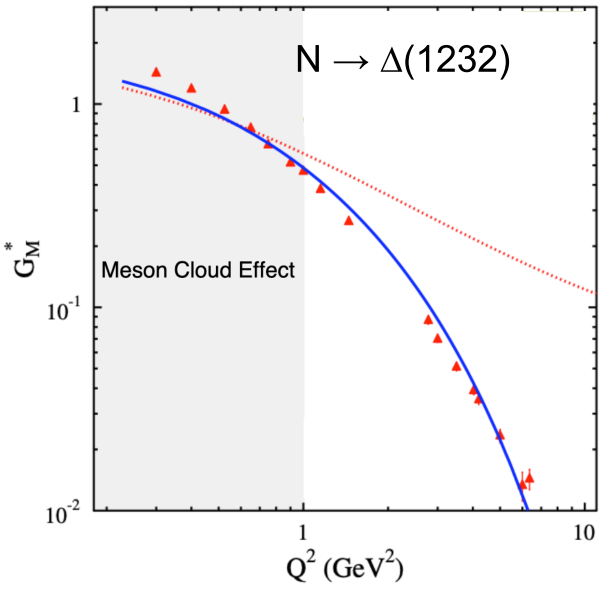
$$\Gamma_{q\bar{q}}(p;P) = -\int \frac{d^4q}{(2\pi)^4} g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S(q+P)\Gamma_{q\bar{q}}(q;P)S(q)\frac{\lambda^a}{2}\gamma_\nu$$

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

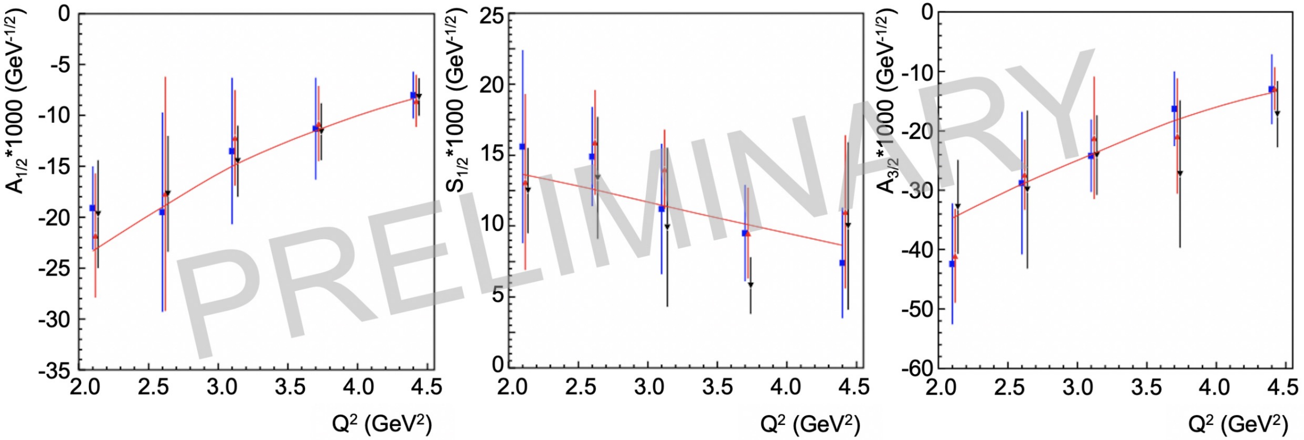
N→Δ(1232), Δ(1600) Transition Form Factors

The **SDE** results reported for **N → Δ(1232)** and **N → Δ(1600)** are compatible with experiment where **meson cloud effect** does not contaminate the **Q^2 evolution**. **N → Δ(1232)**:

J. Segovia, C. Chen, C.D. Roberts, S. Wan Phys. Rev. C88 (2013) 032201(R)
J. Segovia et. al., Few-Body Syst. 55 (2014) 1-33
I. Aznauryan et al., Phys. Rev. C 80, 055203 (2009)



N → Δ(1600): Ya Lu et al., Phys. Rev. D 100, 034001 (2019)



CLAS results on **Δ(1600)3/2+** electrocouplings confirmed the **SDE prediction** based on QCD kindred calculation.

D.S. Carman, R.W. Gothe, V.I. Mokeev, C.D. Roberts, Particles 6 (2023) 1, 416-439.

N → N(1440) Transition Form Factors

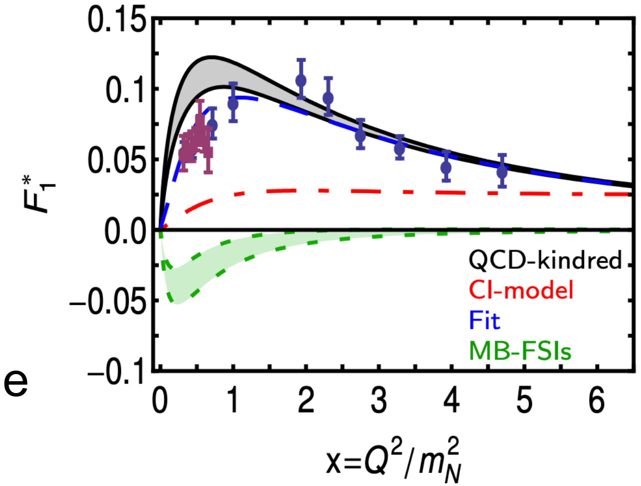
SDE computation of **Dirac** and **Pauli transition form factors**:

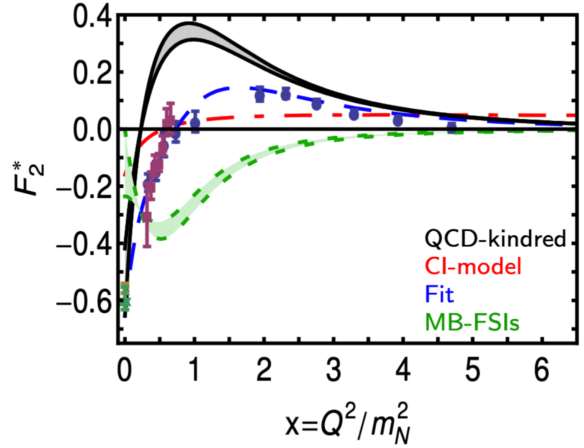
$$\bar{u}_f(P_f)\left[\gamma_\mu^T F_1^{fi}(Q^2) + \frac{1}{m_{fi}}\sigma_{\mu\nu}Q_\nu F_2^{fi}(Q^2)\right]u_i(P_i)$$

It agrees quantitatively in magnitude and qualitatively in trend with data above x $\gtrsim$ 2.

The mismatch between the **SDE prediction** and the data on the domain x $\lesssim$2 is attributed to the **meson cloud** contribution.

The dashed-green band is the inferred form of the **meson cloud** contribution from the fit to the data.



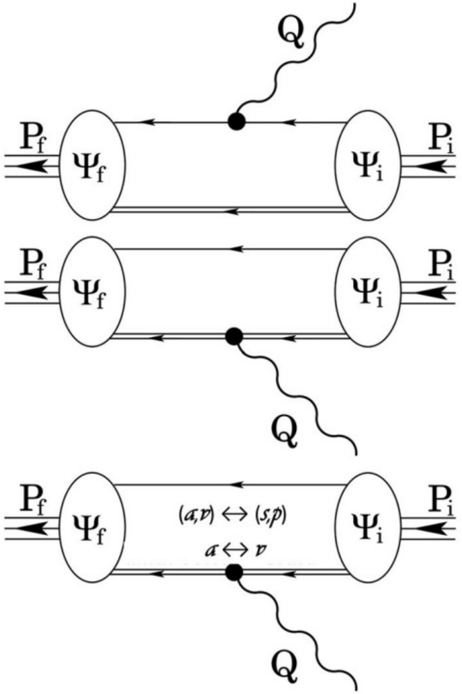


I. Aznauryan et al., Phys. Rev. C 80, 055203 (2009)
V. I. Mokeev et al., Phys. Rev. C 86, 035203 (2012)
V. I. Mokeev et al., Phys. Rev. C 93, 025206 (2016)

C. Chen et. al. Phys. Rev. D 99 (2019) 3, 034013
C. Chen et. al. Phys. Rev. D97 (2018) 3, 034016
J. Segovia, C.D. Roberts, Phys. Rev. C94 (2016) 4, 042201
J. Segovia, et. al., Phys. Rev. Lett. 115 (2015) 17, 171801

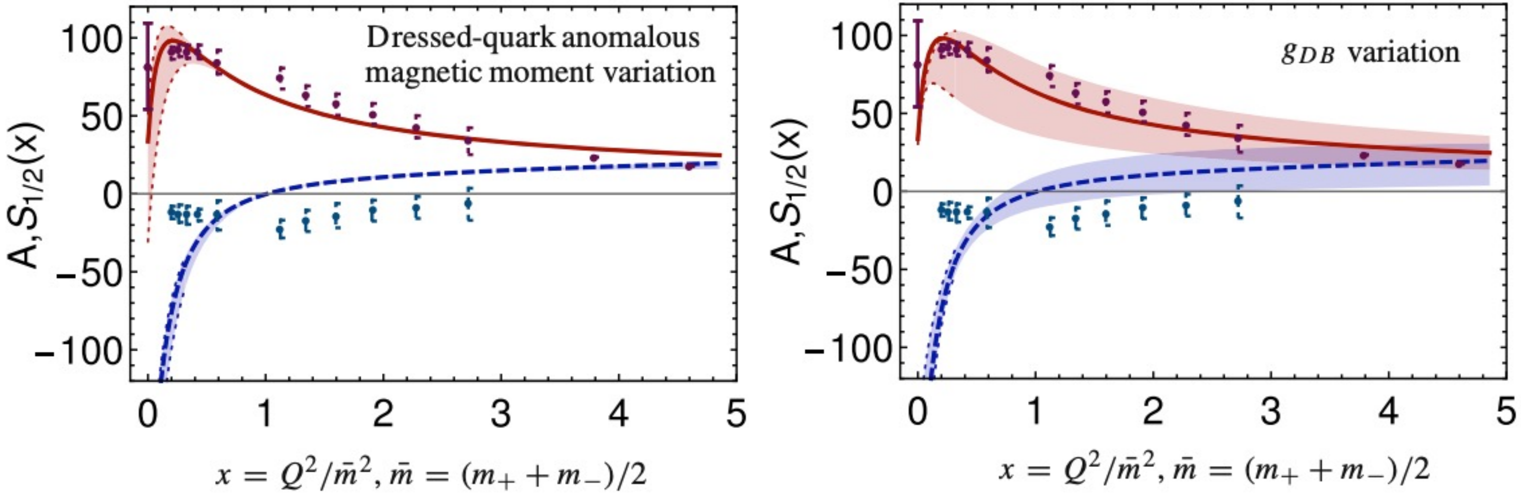
SCI: N → N*(1535) Transition Form Factors

$$\Gamma^*_\mu(P_f,P_i) = ie\,\Lambda^-_+(P_f)\left[\gamma^T_\mu F^*_1(Q^2) + \frac{1}{m_+ + m_-}\sigma_{\mu\nu}Q_\nu F^*_2(Q^2)\right]\Lambda^+_+(P_i)$$



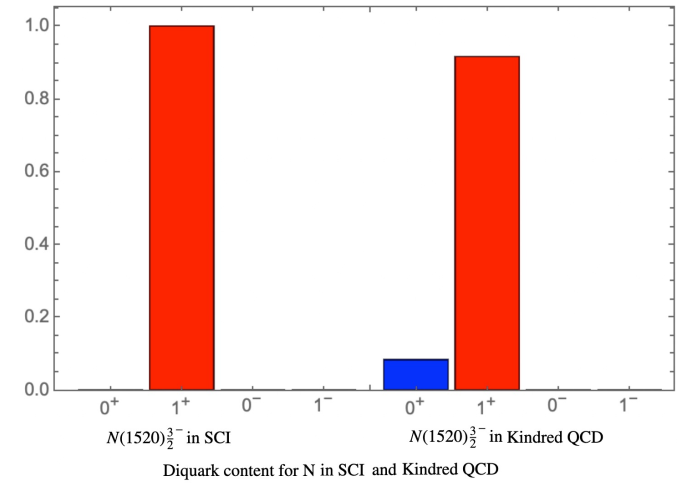
Spin ½ initial and final states but with opposite parity.

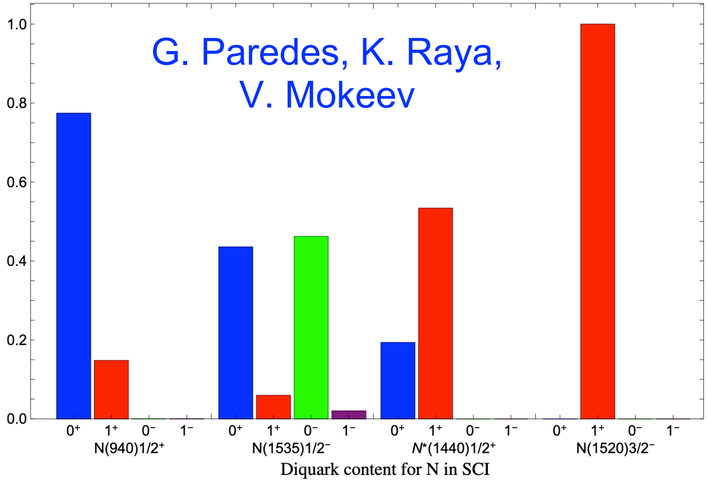
I. Aznauryan et al., Phys. Rev. C 80, 055203 (2009)

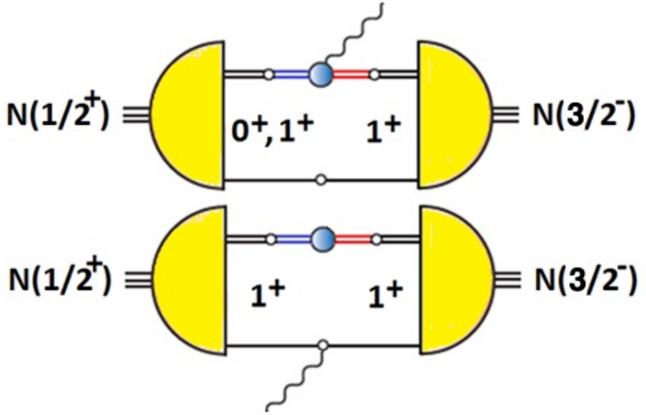


K. Raya, L.X. Gutiérrez, AB, L. Chang, Z-F. Cui, Y. Lu, C.D. Roberts, J. Segovia, Eur. Phys. J. A 57 (2021) 9, 266

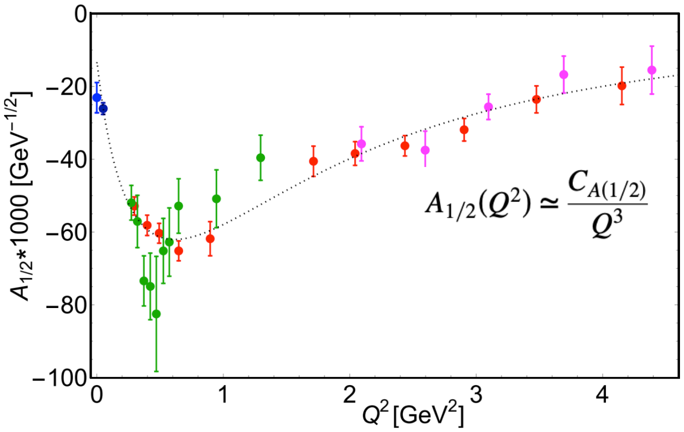
SCI: Towards N*(1520)

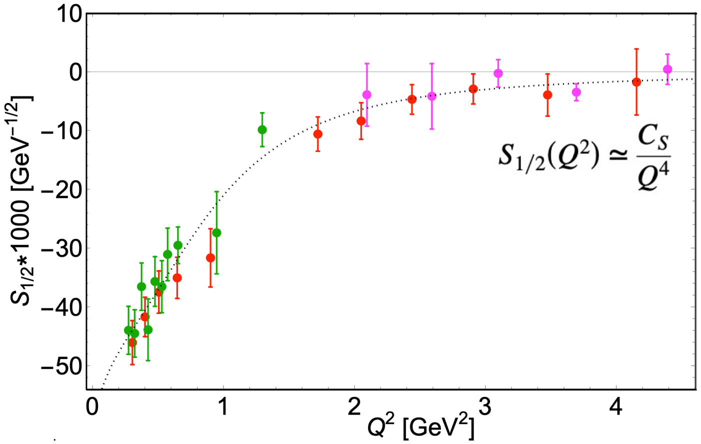


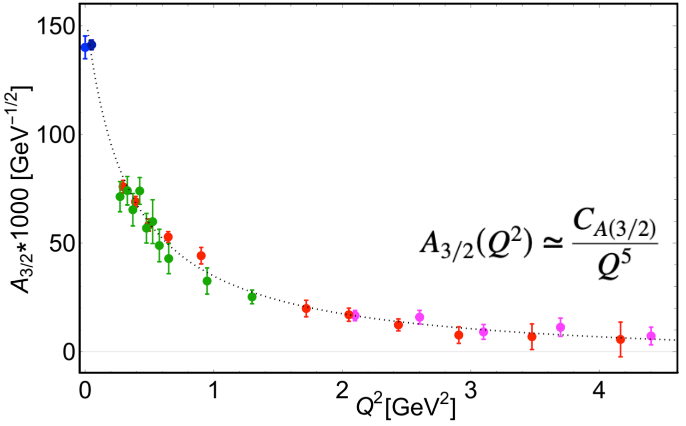




C. Carlson, Phys. Rev. D 34, 2704 (1986).



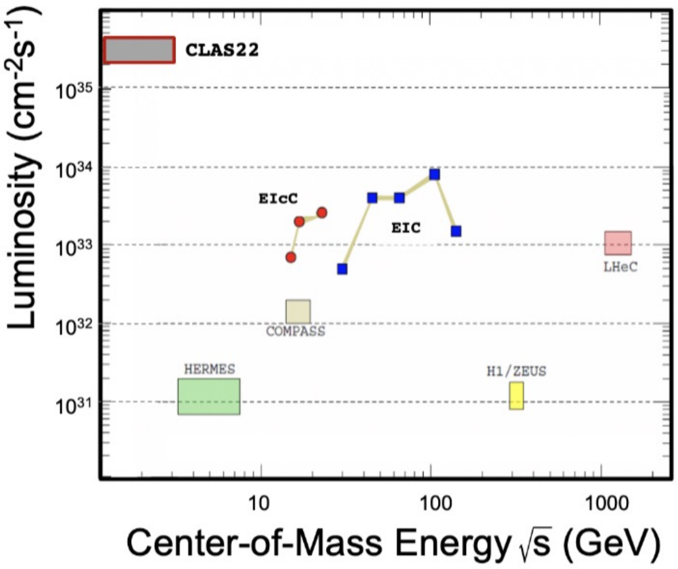




JLAB CLAS22: Promise and Opportunities

Simulations of πN, KY, and $\pi^+\pi^-$p electroproduction with CEBAF@22 GeV show that $\gamma_v pN^*$ electrocouplings can be determined up to **Q^2 ~ 30 GeV^2** for **$\mathcal{L}$ ~ 2 - 5 × 10^{35} cm^{-2}s^{-1}**

Talk by V. Mokeev, Hadron 2023, Genoa, Italy.



The **high luminosity frontier** provides **JLab** a special advantage in comparison with EIC or EIcC.

It offers a unique opportunity to study Nature's simplest 3-body bound state and its electrocouplings with its resonances in a **large domain of momentum transfer**.

CLAS22 will map out the working of QCD from its **non-perturbative** behavior at low **Q^2** to its asymptotic regime where **perturbative QCD** can provide predictions, charting out the pattern of **dynamical chiral symmetry breaking**.

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab
A. Accardi et al., e-print:2306.09360[nucl-ex]