Dynamical diquark correlations: origins and impacts

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Quantum Chromodynamics in its non-perturbative regime

Emergence

Low-level rules producing high-level phenomena with enormous apparent complexity

Start from the QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a + \frac{1}{2\xi}(\partial^\mu A_\mu^a)^2 + \partial^\mu \bar{c}^a \partial_\mu c^a + g\, f^{abc}(\partial^\mu \bar{c}^a)A_\mu^b c^c\,.$$

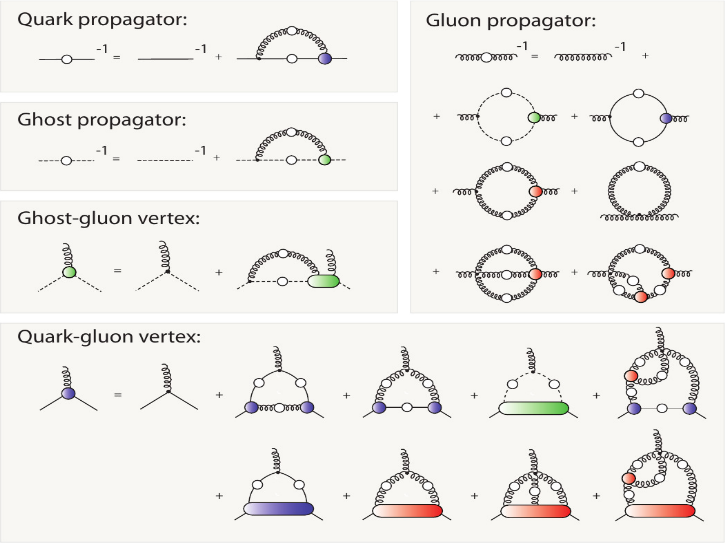
Lattice-regularized QCD, Continuum Schwinger-function methods, ...

And obtain:

- Dynamical generation of fundamental mass scale in pure Yang-Mills (gluon mass).
- Quark constituent masses and dynamical chiral symmetry breaking.
- Bound state formation: mesons, baryons, glueballs, hybrids, multiquark systems...
- Signals of confinement.

These (emergent) phenomena is not apparent in the QCD Lagrangian; however, they characterized the nonperturbative regime of QCD where hadrons live

Emergent phenomena *could be associated with dramatic, dynamically driven changes in the analytic structure of QCD's Schwinger functions, which are solutions of the DSEs*



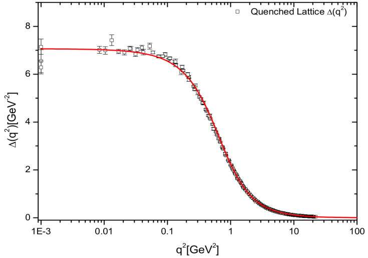
Non-perturbative QCD: Dynamical generation of gluon mass

☞ Dressed-gluon propagator in Landau gauge:

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

- An inflexion point at $q^2 > 0$.
- Breaks the axiom of reflexion positivity.
- Gluon mass generation ↔ Schwinger mechanism.

A.C. Aguilar *et al.*, Phys. Rev. D78 (2008) 025010;
I.L. Bogolubsky *et al.*, Phys. Lett. B676 (2009) 69.

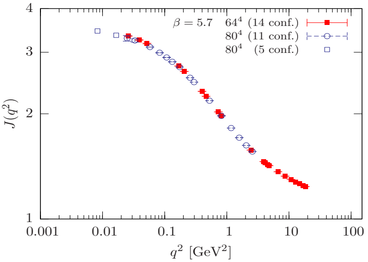


☞ Dressed-ghost propagator in Landau gauge:

$$G^{ab}(q^2) = \delta^{ab}\,\frac{\mathbf{J}(\mathbf{q}^2)}{q^2}$$

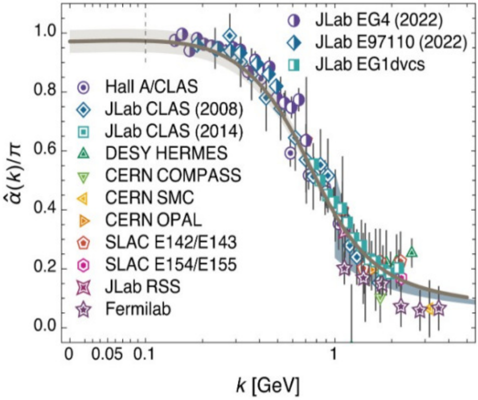
- No power-like singular behavior at $q^2 \to 0$.
- Good indication that $J(q^2)$ reaches a plateau.
- Saturation of ghost's dressing function.

Ph. Boucaud *et al.*, JHEP 0806 (2008) 099;
C. Fischer *et al.*, Annals Phys. 324 (2009) 2408.



Non-perturbative QCD:
Saturation at IR of process-independent effective-charge

D. Binosi *et al.*, Phys. Rev. D96 (2017) 054026;
A. Deur *et al.*, Prog. Part. Nucl. Phys. 90 (2016) 1-74.



- Data = running coupling defined from the Bjorken sum-rule.

$$\int_0^1 dx \left[g_1^p(x,k^2) - g_1^n(x,k^2) \right] = \frac{g_A}{6}\left[1 - \frac{1}{\pi}\alpha_{g_1}(k^2) \right]$$

- Curve determined from combined continuum and lattice analysis of QCD's gauge sector (massless ghost and massive gluon).

- The curve is a running coupling that does NOT depend on the choice of observable.
  - No parameters.
  - No matching condition.
  - No extrapolation.

- It predicts and unifies an enormous body of empirical data via the matter-sector bound-state equations.

- Perturbative regime:

$$\alpha_{g_1}(k^2) = \alpha_{\overline{\rm MS}}(k^2)\left[1 + 1.14\alpha_{\overline{\rm MS}}(k^2) + \ldots \right]$$

$$\hat{\alpha}_{\rm PI}(k^2) = \alpha_{\overline{\rm MS}}(k^2)\left[1 + 1.09\alpha_{\overline{\rm MS}}(k^2) + \ldots \right]$$

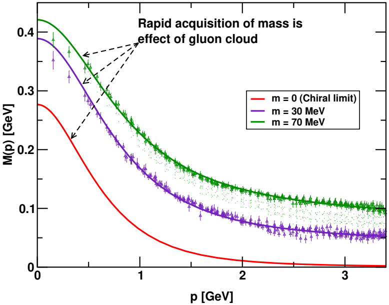
Non-perturbative QCD: Dynamical generation of quark mass

☞ 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 proton's mass, the large splitting between parity partners, ...

M.S. Bhagwat *et al.*, Phys.Rev. C68 (2003) 015203.



☞ Goldberger-Treiman relation at the quark level:

Quark propagator: $S^{-1}(p) = i\gamma\cdot p\, A(p^2) + B(p^2)\,,$

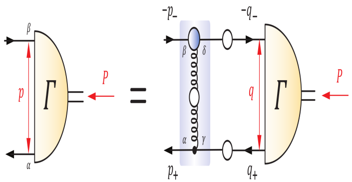
Pion's BS-amplitude: $\Gamma_\pi(p,P) \propto \gamma^5 E_\pi(p;P)\,.$

$$\mathbf{f_\pi E_\pi(p;0) = B(p^2)}$$

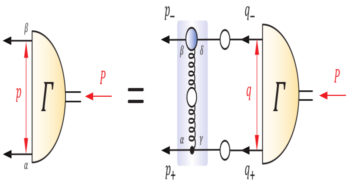
Properties of the massless pion are a direct measure of the dressed-quark mass function

Cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe

Any interaction able to create Goldstone modes as bound-states of light dressed-quark and -antiquark will generate strong $\bar{3}_c$ correlations between any two dressed quarks.



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:

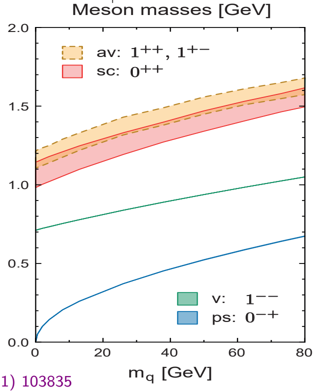
$$r_{[ud]_{0^+}} \gtrsim r_\pi, \qquad r_{\{uu\}_{1^+}} \gtrsim r_\rho, \qquad r_{\{uu\}_{1^+}} > r_{[ud]_{0^+}}$$

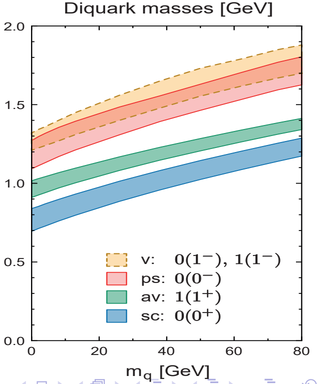
Octet and decuplet baryons

	[nn]	{nn}	[ns]	{ns}	{ss}
N	●	●			
Δ		●			
Λ	●		●	●	
Σ		●	●	●	
Ξ			●	●	●
Ω					●

Other baryons as parity partners

- ☞ $[I=0, J^P=0^+]$: Isoscalar-scalar.
- ☞ $[I=1, J^P=1^+]$: Isovector-pseudovector.
- ☞ $[I=0, J^P=0^-]$: Isoscalar-pseudoscalar.
- ☞ $[I=0, J^P=1^-]$: Isoscalar-vector.
- ☞ $[I=1, J^P=1^-]$: Isovector-vector.



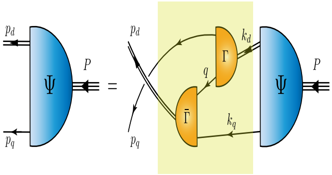


M. Yu. Barabanov *et al.*,
Prog. Part. Nucl. Phys. 116 (2021) 103835

The quark+diquark structure of a baryon

☞ A baryon 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 baryon are fully dynamical: no quark holds a special place.

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

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

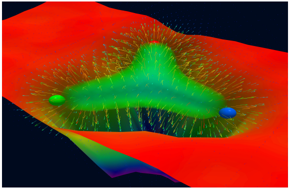
☞ Modern diquarks enforce certain distinct interaction patterns for the singly- and doubly-represented valence-quarks within the baryon.

S.-S. Xu *et al.*, Phys. Rev. D92 (2015) 114034; Y. Lu *et al.*, Phys. Rev. C96 (2017) 015208;
C. Chen *et al.*, Phys. Rev. D100 (2019) 054009; P.-L. Yin *et al.*, Phys. Rev. D100 (2019) 034008.

Remark about the 3-gluon vertex

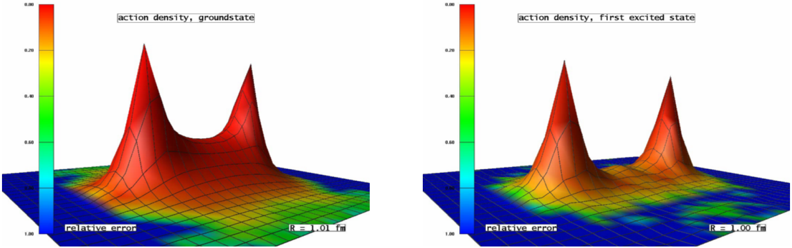
☞ A Y-junction flux-tube picture of nucleon structure is produced in **quenched** lattice QCD simulations that use **static sources** to represent the proton's valence-quarks.

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.**

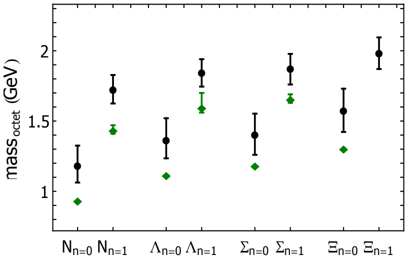


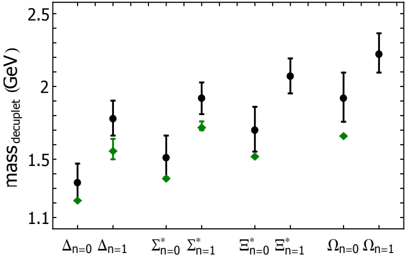
G.S. Bali, PRD 71 (2005) 114513.

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

Masses of the octet and decuplet baryons

- The computed masses are uniformly larger than the corresponding empirical values.
- The quark-diquark kernel omits all resonant contributions associated with meson-baryon final state interactions, which typically generate a measurable reduction.
- The Faddeev equations analyzed to produce the results should be understood as producing the dressed-quark core of the bound state, not the completely dressed and hence observable object.

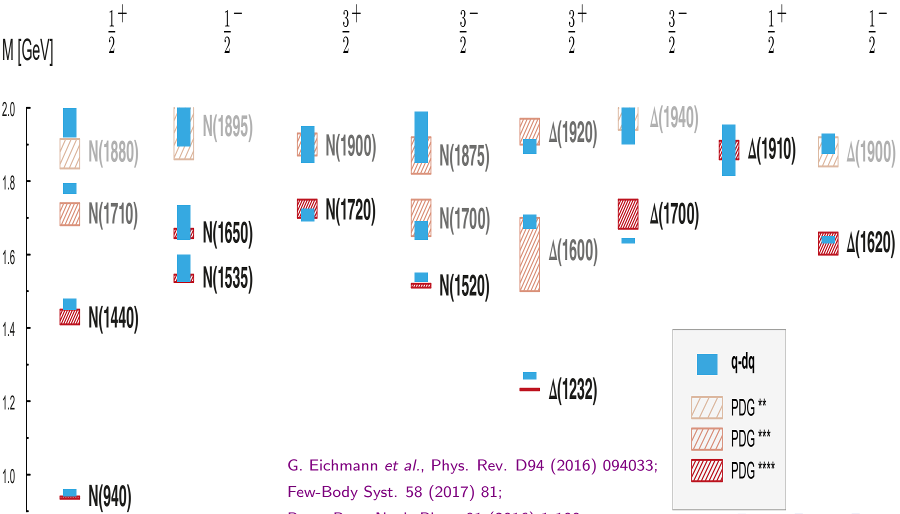




C. Chen *et al.*, Phys. Rev. D100 (2019) 054009.

Baryon spectrum within the quark+diquark picture

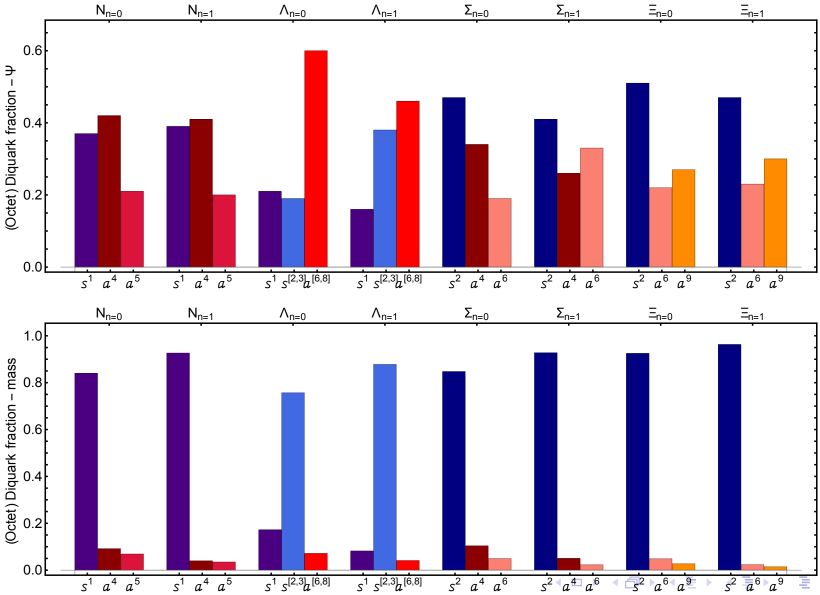
- Spectrum in one to one agreement with experiment.
- Correct level ordering (without coupled-channels effects).
- Three-body agrees with quark-diquark where applicable.



G. Eichmann *et al.*, Phys. Rev. D94 (2016) 094033;
Few-Body Syst. 58 (2017) 81;
Prog. Part. Nucl. Phys. 91 (2016) 1-100.

Diquark content of the octet and decuplet

Only axial-vector diquarks are present in the decuplet baryons. For the octet case...



A measurable consequence of diquark content

$\Lambda - \Sigma$ mass splitting

Whilst the Λ and Σ are associated with the same combination of valence-quarks, their spin-flavor wave functions are different.

$\Downarrow$

Λ contains more of the (lighter) scalar diquark correlations than Σ

$$u_\Lambda = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2}\, s[ud]_{0^+} \\ d[us]_{0^+} - u[ds]_{0^+} \\ d\{us\}_{1^+} - u\{ds\}_{1^+} \end{bmatrix} \leftrightarrow \begin{bmatrix} s^1_\Lambda \\ s^{[2,3]}_\Lambda \\ a^{[6,8]}_\Lambda \end{bmatrix} \; ; \quad u_\Sigma = \begin{bmatrix} u[us]_{0^+} \\ s\{uu\}_{1^+} \\ u\{us\}_{1^+} \end{bmatrix} \leftrightarrow \begin{bmatrix} s^2_\Sigma \\ a^4_\Sigma \\ a^6_\Sigma \end{bmatrix}$$

	N	Λ	Σ	Ξ	Δ	Σ^*	Ξ^*	Ω
The.	1.19(13)	1.37(14)	1.41(14)	1.58(15)	1.35(12)	1.52(14)	1.71(15)	1.93(17)
Exp.	0.94	1.12	1.19	1.31	1.23	1.38	1.53	1.67
The.	1.73(10)	1.85(09)	1.88(11)	1.99(11)	1.79(12)	1.93(11)	2.08(12)	2.23(13)
Exp.	1.44(03)	$1.51^{+0.10}_{-0.04}$	1.66(03)	-	1.57(07)	1.73(03)	-	-

Consequence of solving Poincaré-covariant bound-state equations

non-relativistic | **relativistic**

Mesons: $P = (-1)^{L+1}$

S	L	J^{PC}
0	0	0^{-+}
1	0	1^{--}
0	1	1^{+-}
1	1	0^{++}

~~$P = (-1)^{L+1}$~~

Bethe,Salpeter, Llewelyn-Smith 1950ies

$$\Gamma_\pi(P,p) = \gamma_5 \, [F_1(P,p) + F_2(P,p) i\not{P} + F_3(P,p) pP i\not{p} + F_4(P,p)[\not{p}\,,\not{P}]]$$

s-wave (F_1, F_2); p-wave (F_3, F_4)

Baryons: $P = (-1)^{L}$

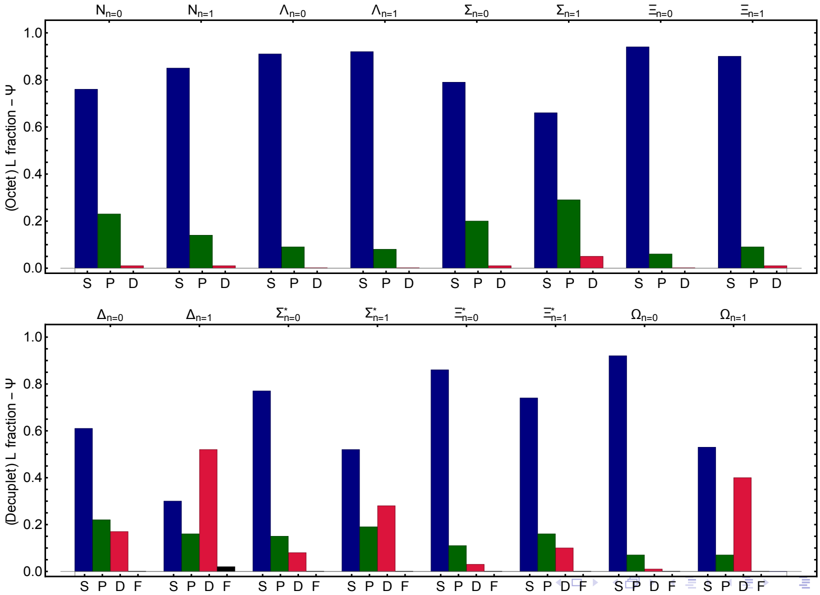
S	L	J^P
1/2	0	$1/2^+$
3/2	2	

~~$P = (-1)^{L}$~~

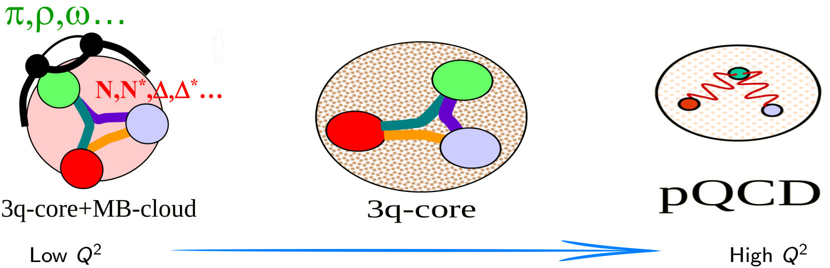
J^P	total	s-wave	p-wave	d-wave	f-wave
$1/2^+$	64	8	36	20	
$3/2^+$	128	4	36	60	28

Angular momenta of the octet and decuplet

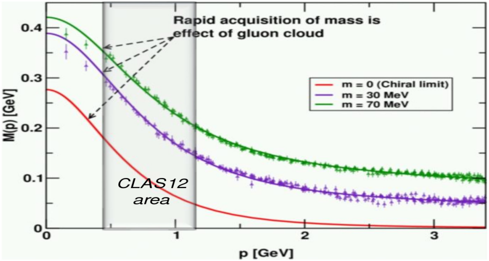
The P- and D-wave components play a measurable role in octet and decuplet baryons



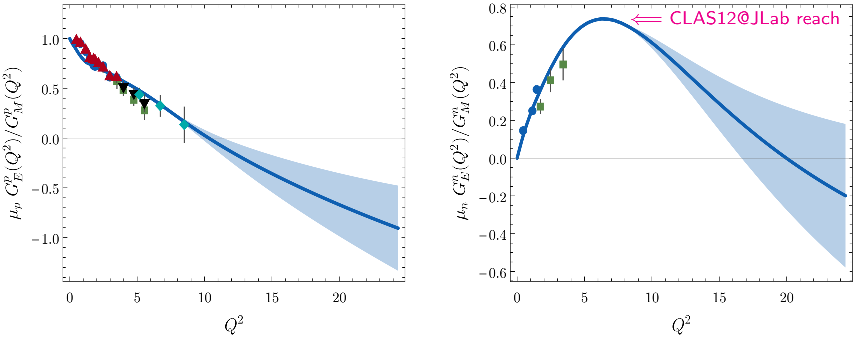
☞ CLAS12 aims to measure the N^* photo- and electro-couplings at Q^2 ever achieved so far and thus trying to distinguish between different effective degrees of freedom.



☞ CLAS12 aims to extract information about fundamental quantities in QCD at an intermediate energy region.



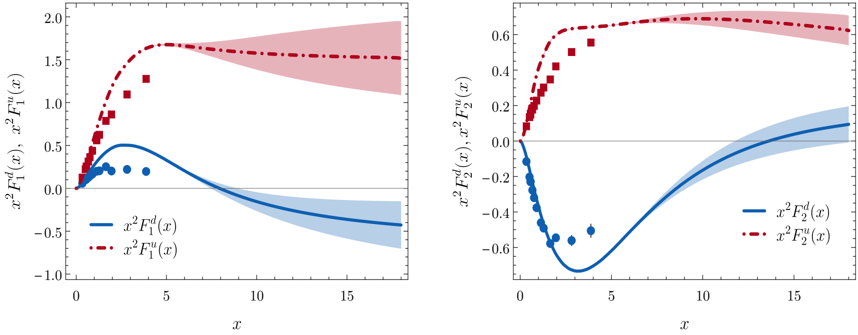
The $\gamma^{(*)}N(940) \to N(940)$ reaction (I)



Z.-F. Cui *et al.*, Phys. Rev. D102 (2020) 014043.

☞ Observations:

- There is no evidence for scaling in Dirac and Pauli form factors, and thus in the electromagnetic Sach form factors.
- Our analysis predicts a zero for the proton's electromagnetic ratio at $Q^2 = 10.3^{+1.1}_{-0.7}\,\text{GeV}^2$.
- The neutron's electromagnetic ratio has a peak at $Q^2 \approx 6\,\text{GeV}^2$ and then crosses zero for $Q^2 = 20.1^{+10.6}_{-3.5}\,\text{GeV}^2$.
- All these features can be related with both quark-quark and angular momentum correlations within the nucleon.



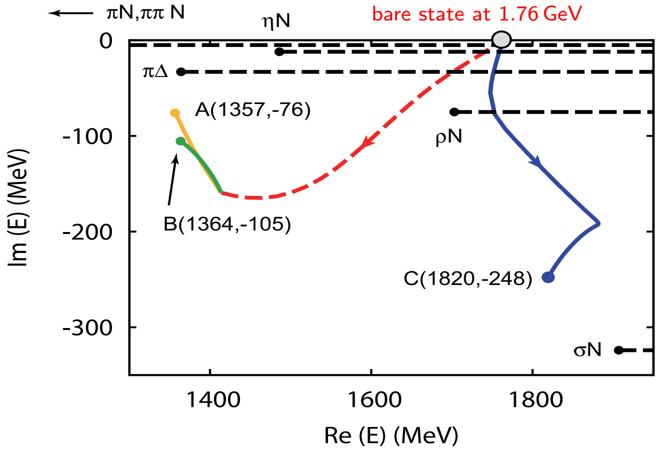
☞ Observations:

- F_1^d is smaller than F_1^u, even allowing for the difference in normalisation, and decreases more quickly as $x = Q^2/m_N^2$ increases.
- The location of the zero in F_1^d is a measure of the relative probability of finding pseudovector and scalar diquarks in the proton.
- The u- and d-quark Pauli form factors are roughly equal in magnitude on $x \lesssim 5$; *i.e.* F_2^d is suppressed with respect F_2^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.

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.*

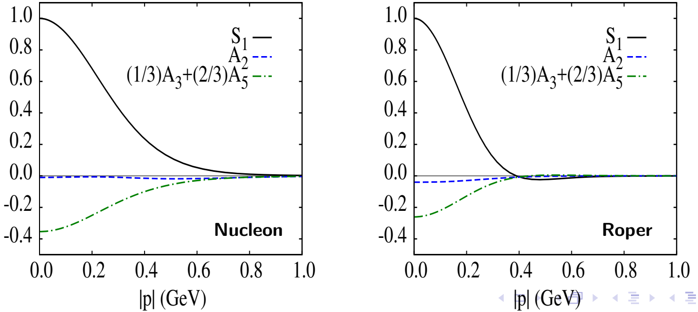
Bound-state kernels which omit meson-cloud corrections produce masses for hadrons that are larger than the empirical values (in GeV):

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

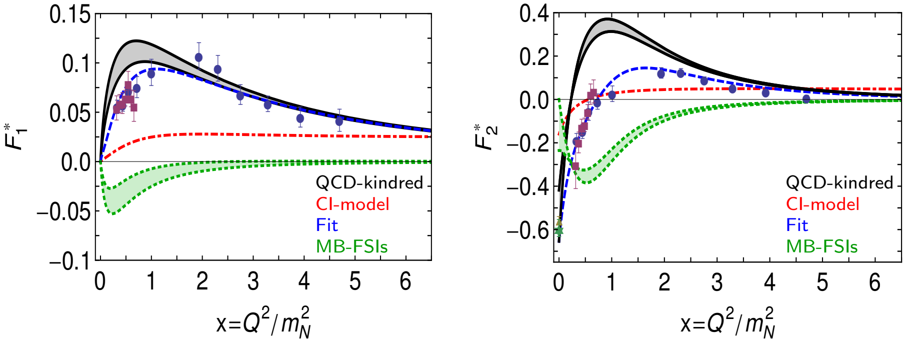
☞ Observation:

- Meson-Baryon final state interactions reduce dressed-quark core mass by $(10-20)\%$. The cloud's impact depends on the state's quantum numbers.
- 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



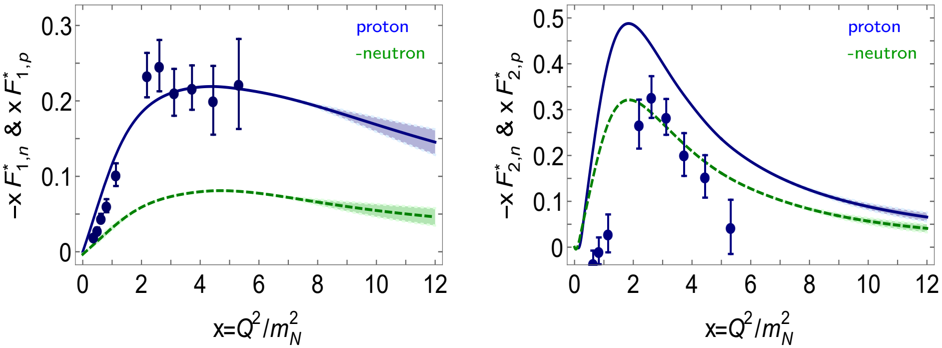
Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core



☞ 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.

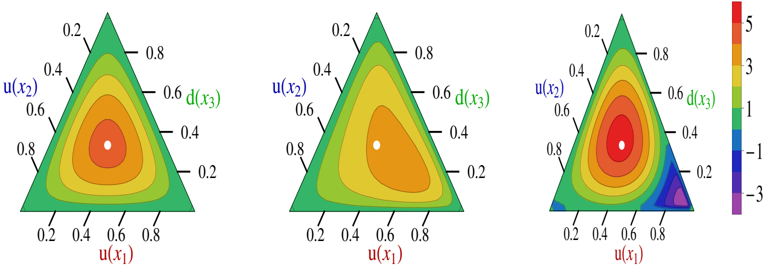
CLAS12 at JLab aims to deliver data on the Roper-resonance electroproduction form factors out to $Q^2 \sim 12 m_N^2$ in both charged and neutral channels



☞ 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 $x \gtrsim 20$.

Barycentric plots: *left panel* – conformal limit PDA, $\varphi_N^{\rm cl}([x]) = 120 x_1 x_2 x_3$; *middle panel* – computed proton PDA evolved to $\zeta = 2$ GeV, which peaks at $([x]) = (0.55, 0.23, 0.22)$; and *right panel* – Roper resonance PDA at $\zeta = 2$ GeV. The white circle in each panel serves only to mark the centre of mass for the conformal PDA, whose peak lies at $([x]) = (1/3, 1/3, 1/3)$.

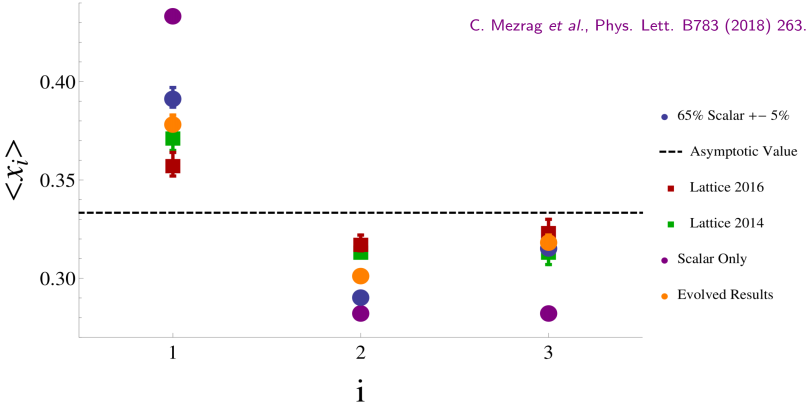


☞ Observations:

- Proton: The leading-twist PDA of the ground-state nucleon is both broader than $\varphi_N^{\rm cl}([x])$ and decreases monotonically away from its maximum in all directions.
- Proton: The peak of the φ-distribution is shifted toward the region where the single quark carries most of the nucleon light-cone momentum fraction.
- Roper: The excitation's PDA is not positive definite which echos features of the wave function for the first radial excitation of a quantum mechanical system.

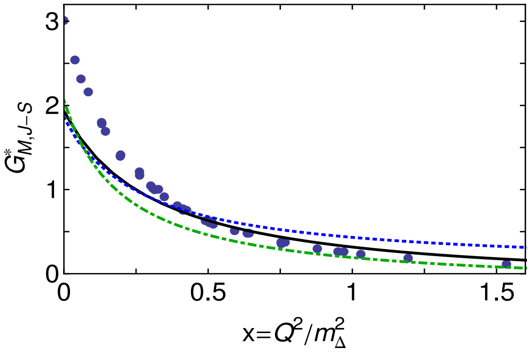
C. Mezrag *et al.*, Phys. Lett. B783 (2018) 263.

Nucleon and Roper PDAs (II)



	Scalar	S+AV	Evolved	Braun:2014wpa	Bali:2015ykx
$\langle x_1 \rangle_\varphi$	0.434	0.392(5)	0.379(4)	0.372(7)	0.358(6)
$\langle x_2 \rangle_\varphi$	0.283	0.291(2)	0.302(1)	0.314(3)	0.319(4)
$\langle x_3 \rangle_\varphi$	0.283	0.316(4)	0.319(3)	0.314(7)	0.323(6)
$10^3\, f_N$ (GeV^2)	2.97	4.05	3.78(14)	2.84(33)	3.60(6)

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



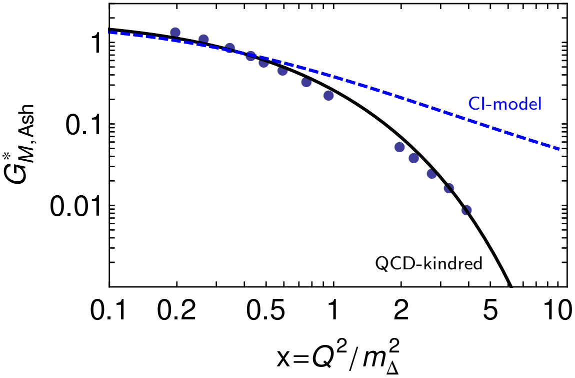
- Solid-black: QCD-kindred interaction.
- Dashed-blue: Contact interaction.
- Dot-Dashed-green: Dynamical + no meson-cloud

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

Presentations of experimental data typically use the Ash convention

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



- No sound reason to expect:

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

- Jones-Scadron must exhibit:

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

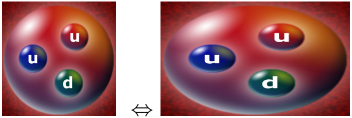
- Meson-cloud effects
  - Up-to 35% for $Q^2 \lesssim 2.0 m^2_\Delta$.
  - Soft $\to$ disappear rapidly.

- $G^*_{M,\text{Ash}}$ vs $G^*_{M,\text{J-S}}$
  - A Difference of $1/\sqrt{Q^2}$.

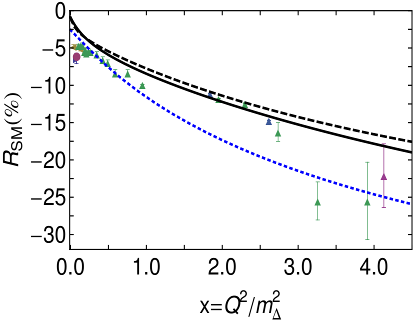
The $\gamma^{(*)}N(940) \to \Delta(1232)$ reaction (III)

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

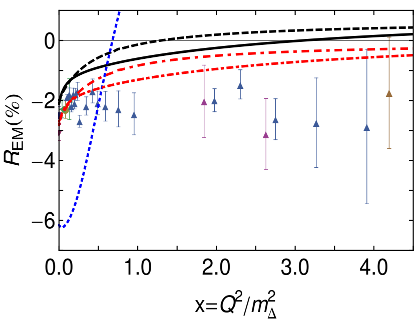
- Deformation of the hadrons involved.
- Modification of the transition current.



☞ 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:*

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

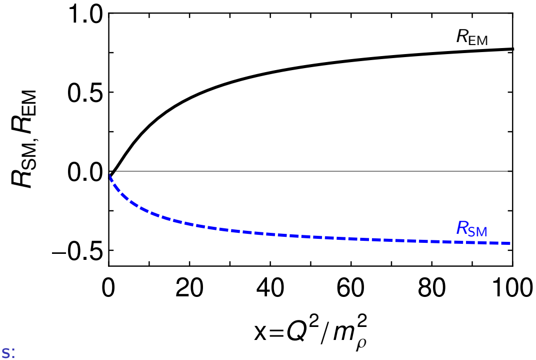
$$\textit{QCD-kindred interaction} \rightarrow Q^2 \sim 3.25 m_\Delta^2 \sim 4.93\ GeV^2$$

The $\gamma^{(*)} N(940) \to \Delta(1232)$ reaction (IV)

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.

	$N(940)$	$N(1440)$	$\Delta(1232)$	$\Delta(1600)$
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

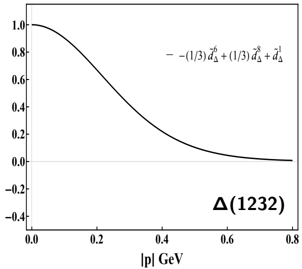
$N(1440)$

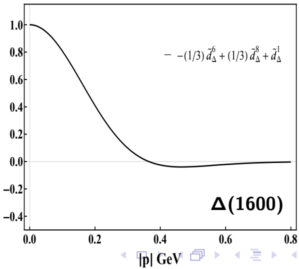
- Roper's diquark content are almost identical to the nucleon's one.
- It has an orbital angular momentum composition which is very similar to the one observed in the nucleon.

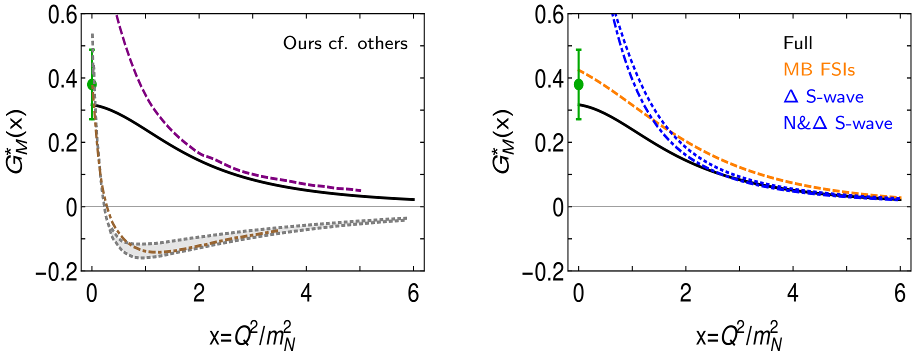
$\Delta(1600)$

- $\Delta(1600)$'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.

0th Chebyshev moment of the S-wave component



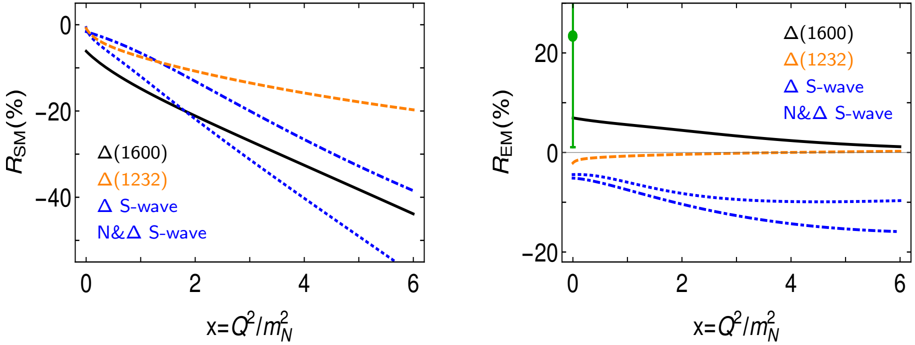




☞ Observations:

- 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.

The $\gamma^{(*)} N(940) \to \Delta(1600)$ reaction (III)

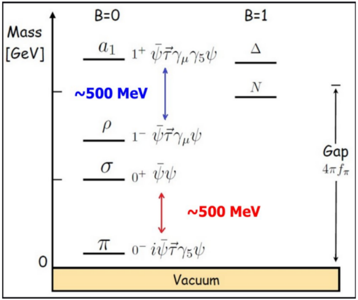


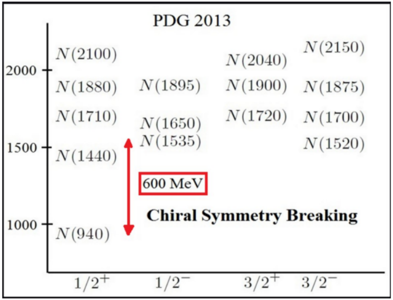
☞ Observations:

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

☞ Just as we learned from the excited states of the hydrogen atom, we continue our quest of learning about excited states of the nucleon.

☞ In particular, the role of DCSB could be well understood by analyzing structural differences between parity partners.

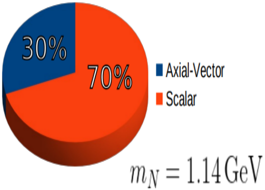




☞ The Faddeev amplitude for the nucleon and its parity partner:

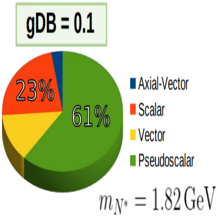
$$\begin{aligned}\psi^\pm u(P) = &\ \Gamma^1_{0^+}\Delta^{0^+}(K)\,\mathcal{S}^\pm(P)u(P) && \text{—— Scalar } (0^+)\\ &+ \textstyle\sum_{f=1,2}\Gamma^f_{1^+\mu}\Delta^{1^+}_{\mu\nu}(K)\mathcal{A}^{\pm f}_\nu(P)u(P) && \text{– Axial vector } (1^+)\\ &+ \Gamma^1_{0^-}(K)\Delta^{0^-}(K)\mathcal{P}^\pm(P)\,u(P) && \text{—— Pseudoscalar } (0^-)\\ &+ \Gamma^1_{1^-\mu}\Delta^{1^-}_{\mu\nu}(K)\mathcal{V}^\pm_\nu(P)u(P), && \text{—— Vector } (1^-)\end{aligned}$$

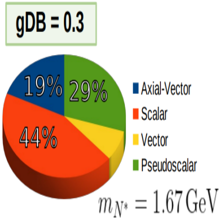
☞ As expected, the nucleon is mostly composed by scalar diquarks, while also exhibiting a sizeable axial-vector diquark.

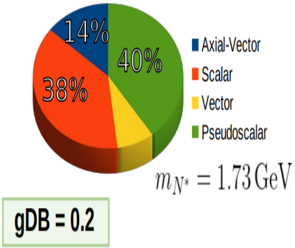


☞ With the preferred value of g_{DB}, the nucleon parity partner exhibits a similar contribution from $0^+/0^-$ diquarks.

☞ The variation of g_{DB} as $(1 \pm 0.5) \cdot g_{DB}$ produces:







K. Raya *et al.*, Eur. Phys. J. A57 (2021) 266.

The $\gamma^{(*)}N(940) \to N(1535)$ reaction (I)

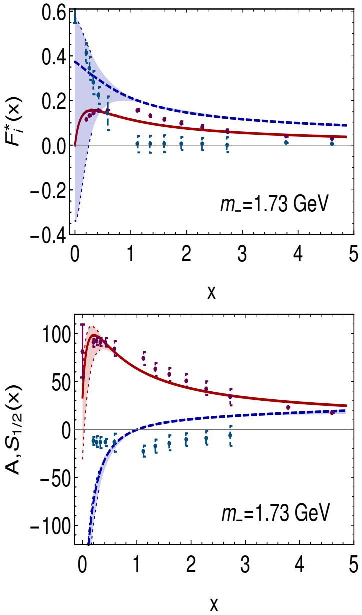
- The form factor F_1^* is insensitive to the quark AMM; conversely, F_2^* is rather sensitive to it.

- F_1^* displays a fair agreement with CLAS data, whereas F_2^* becomes too hard as $\mathbf{x} = \mathbf{Q}^2/\bar{\mathbf{m}}^2$ increases, but it agrees in magnitude with data for $\zeta = 1/3$.

- The transverse helicity amplitude $A_{1/2}$ is sensitive to the AMM, but still in agreement with the experiment. The longitudinal one, $S_{1/2}$, is the exact opposite.

$m_{N(940)} = 1.14\,, \quad m_{N(1535)} = 1.73\,,$ **gDB = 0.2**

baryon	s	a_1^1	a_2^1	p	v_1	v_2
$N(940)\frac{1}{2}^+$	0.88	0.38	−0.06	0.02	0.02	0.00
$N(1535)\frac{1}{2}^-$	0.66	0.20	0.14	0.68	0.11	0.09

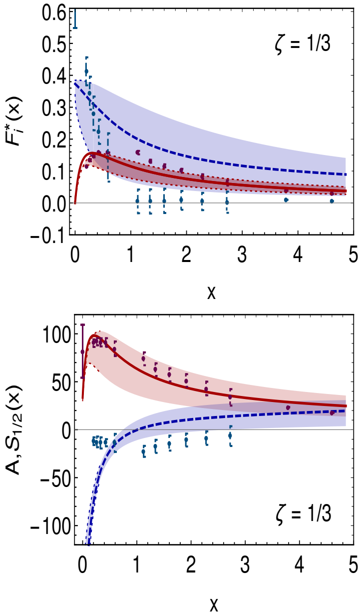


K. Raya *et al.*, Eur. Phys. J. A57 (2021) 266.

- Both form factors and helicity amplitudes are quite sensitive to the value g_{DB}, *i.e.* to both the mass and diquark content of the nucleon parity partner.
- In fact, harder form factors and helicity amplitudes are produced by the heaviest $N(1535)$. This corresponds to the case in which the 0^- diquark overwhelms the rest.
- The best agreement with data is obtained when the 0^+ and 0^- diquark content is balanced.

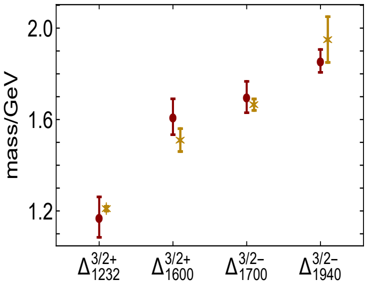
$N(1535)\frac{1}{2}^-$	s	a_1^1	a_2^1	p	v_1	v_2
g_{DB} 1.5	0.76	0.27	0.18	0.49	0.12	0.08
g_{DB} 1.0	0.66	0.20	0.14	0.68	0.11	0.09
g_{DB} 0.5	0.35	0.04	0.00	0.92	−0.05	0.18

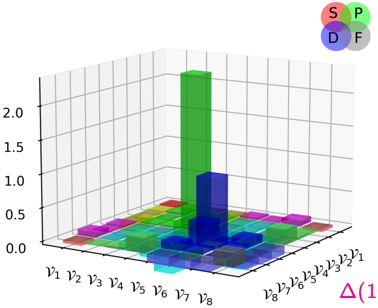
K. Raya *et al.*, Eur. Phys. J. A57 (2021) 266.



Masses of lowest-lying $(\frac{3}{2}, \frac{3}{2}^{\pm})$ Δ-baryons: the indicated uncertainty stems from a $\pm 5\%$ change in the $(1, 1^{\pm})$ diquark masses. The mean difference between theory and experiment is $\delta_{MB} = 0.17\,\text{GeV}$. The remaining columns display the mass and amplitude fractions contributed by the $(1, 1^{\pm})$ diquarks.

Baryon	mass/GeV		mass %		amplitude %	
	1^+	$1^+\&1^-$	1^+	1^-	1^+	1^-
$\Delta(1232)\frac{3}{2}^+$	1.346	1.346(89)	99.98	0.02	96.97	3.03
$\Delta(1600)\frac{3}{2}^+$	1.786	1.786(79)	99.96	0.04	96.57	3.43
$\Delta(1700)\frac{3}{2}^-$	1.872	1.871(69)	99.98	0.02	94.20	5.80
$\Delta(1940)\frac{3}{2}^-$	2.030	2.043(50)	99.37	0.63	88.73	11.27

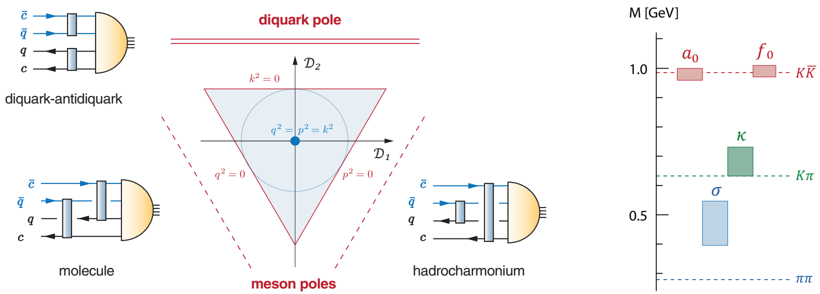


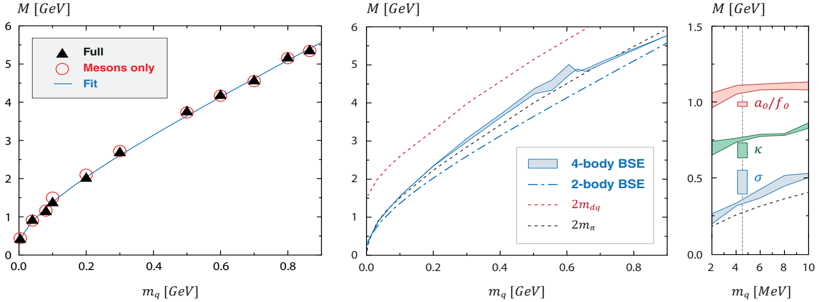


$\Delta(1700)\frac{3}{2}^-$

L. Liu *et al.*, Phys. Rev. D105 (2022) 114047.

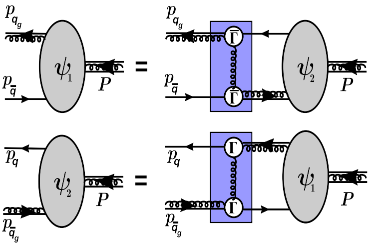
Diquark content in exotic matter?

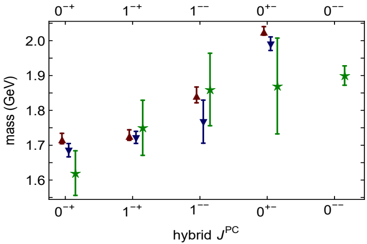




G. Eichmann *et al.*, Few Body Syst. 61 (2020) 38.

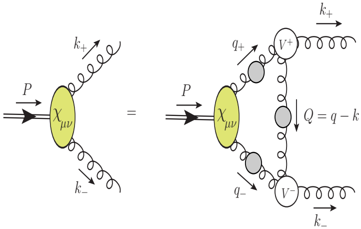
☞ Hybrid mesons: Existence of strong two-body correlations in the gluon-quark, $q_g = [gq]$, and gluon-antiquark, $\bar{q}_g = [g\bar{q}]$ channels.

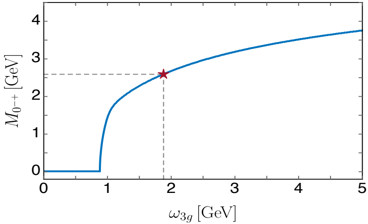




S.-S. Xu *et al.*, Eur. Phys. J. A Lett. 55 (2019) 113.

☞ Glueballs: The infrared suppression of the three-gluon vertex is essential to achieve agreement with lattice-QCD predictions for the 0^{-+} glueball mass.





E.V. Souza *et al.*, Eur. Phys. J. A56 (2020) 25.

Epilogue

- The wealth of new and anticipated information demands that the issue of correlations within hadrons be settled.
  - The features of baryons, and their unification with the properties of mesons, depend on a veracious expression of EHM in the hadron's bound-state and scattering problems.
  - The existence of non-pointlike, fully dynamical quark-quark correlations, as well as quark-gluon and gluon-gluon ones, is an important consequence of EHM.
  - There is evidence for such clusters in simulations of lQCD; and their presence within baryons is predicted to have numerous observable consequences, some of which already have strong experimental support.

- Modern facilities will probe hadronic interiors as never before.
  - JLab-12 and -22 will push form factor measurements to unprecedented values of momentum transfer and use different charge states, enabling flavour separations.
  - COMPASS, EIC and EicC would measure valence-quark distribution functions with previously unattainable precision.
  - Collaborations like Belle-II, BES-III and LHCb, are discovering new hadrons whose structure does not fit once viable paradigms.

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