



Luis Albino

Postdoctoral researcher - SECIHTI
Department of Physics - FICEN
Sonora University

Ciencia y
Tecnología

Secretaría de Ciencia, Humanidades,
Tecnología e Innovación



Electromagnetic Properties of Radially Excited Nucleons and Δ Baryons Within a Contact Interaction

15th International Workshop
on the Physics of Excited Nucleons

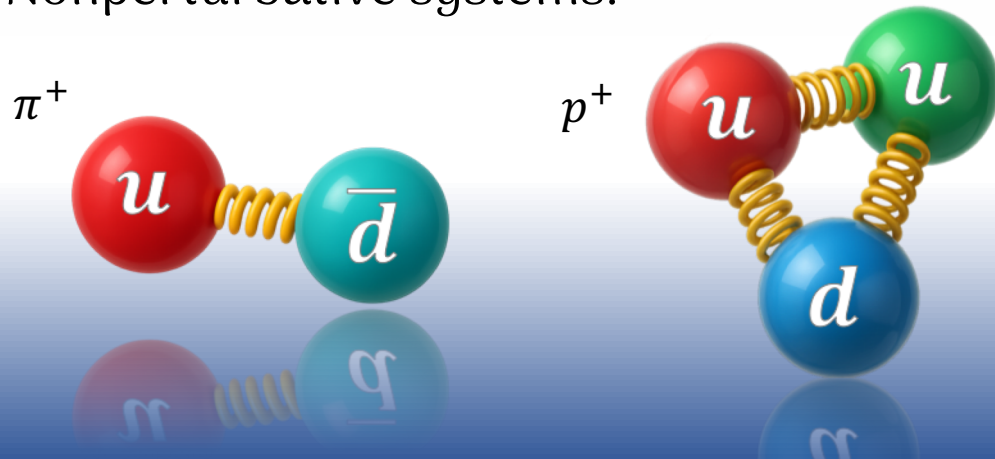
Sevilla, Spain, september 7-11, 2026

Bound states: A testing ground for QFTs

Elucidating the simplest bound states and their excitations constitutes a fundamental endeavor in understanding the underlying mechanisms of a quantum field theory (QFT).

Hadrons

Described by Quantum Chromodynamics (QCD).
Strongly interacting bound states.
Color singlet objects in nature.
Nonperturbative systems.



QCD: Emergent phenomena

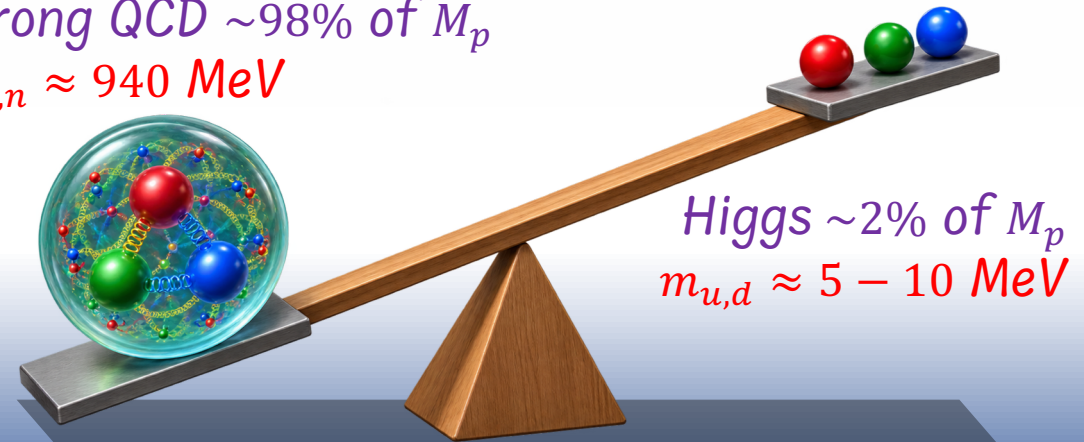
Dynamical Chiral Symmetry Breaking (DCSB)
Confinement
Gluon mass generation (in pure Yang-Mills)

Nucleons

Dominant mass of visible universe
 m_f - Spontaneous Symmetry Breaking
Higgs mechanism is not enough!

Strong QCD $\sim 98\%$ of M_p

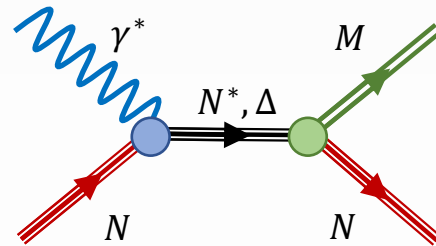
$M_{p,n} \approx 940 \text{ MeV}$



Excited states and transitions

Photo- and electro-production

CEBAF at Jlab
ELSA at Bonn U.
MAMI in Mainz
LEGS at BNL

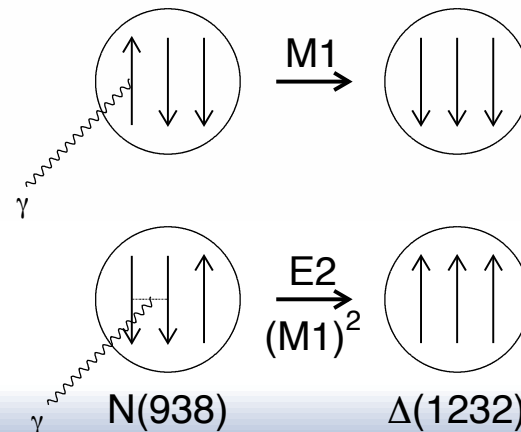


Standard picture: spin-flip

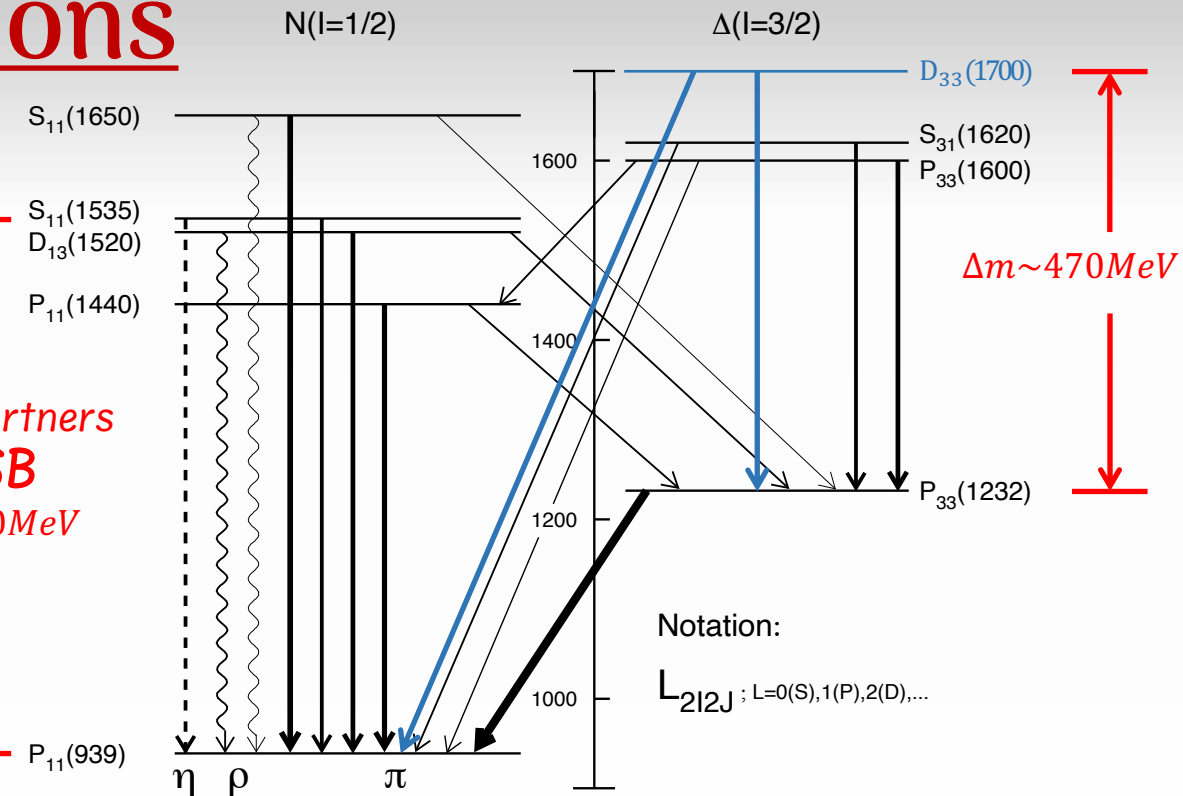
- 1) Magnetic dipole M1
- 2) Electric quadrupole E2
- 3) Coulomb quadrupole C2

Equivalence: Jones-
Scadron FFs G_M^* , G_E^* , G_C^*

Synergy between
experiment and theory



Parity partners
DCSB
 $\Delta m \sim 590 \text{ MeV}$



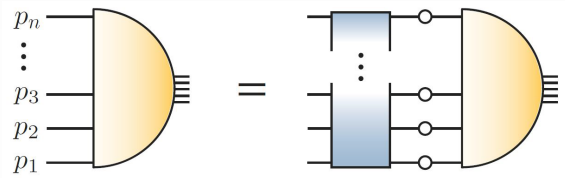
**Nucleon resonances are the key to
additional and novel features of QCD!!**

Theoretical challenges

Mass spectrum
Wave functions
Distribution functions

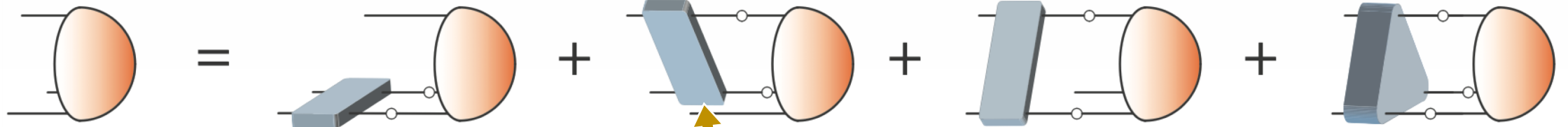
Bound states: continuum approach

n -valence-quark equation



Masses (pole position) and amplitudes for n -valence-quark (antiquark) hadrons obtained as solutions of Poincaré-covariant equations for the corresponding bound state.

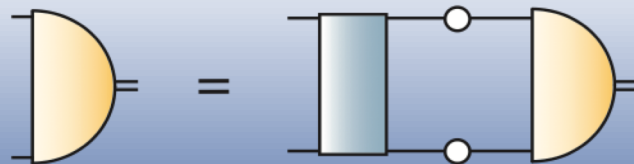
Faddeev equation



Quark-diquark interactions

Three-body interactions

Bethe-Salpeter equation



Interaction kernels: sum of all possible n -body contributions

*Knowledge of QCDs n -point
Green functions required*

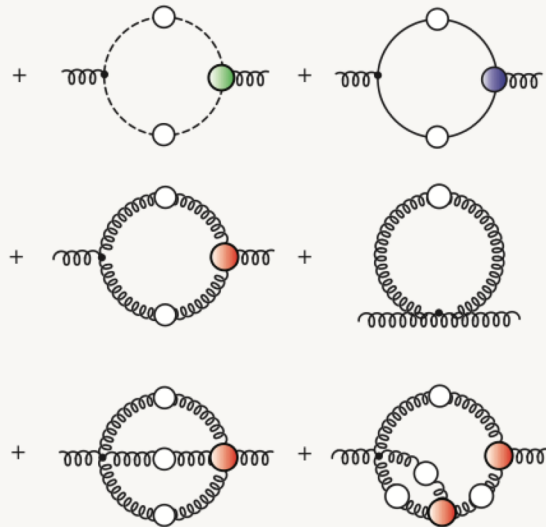
Schwinger-Dyson Equations

Quark propagator:

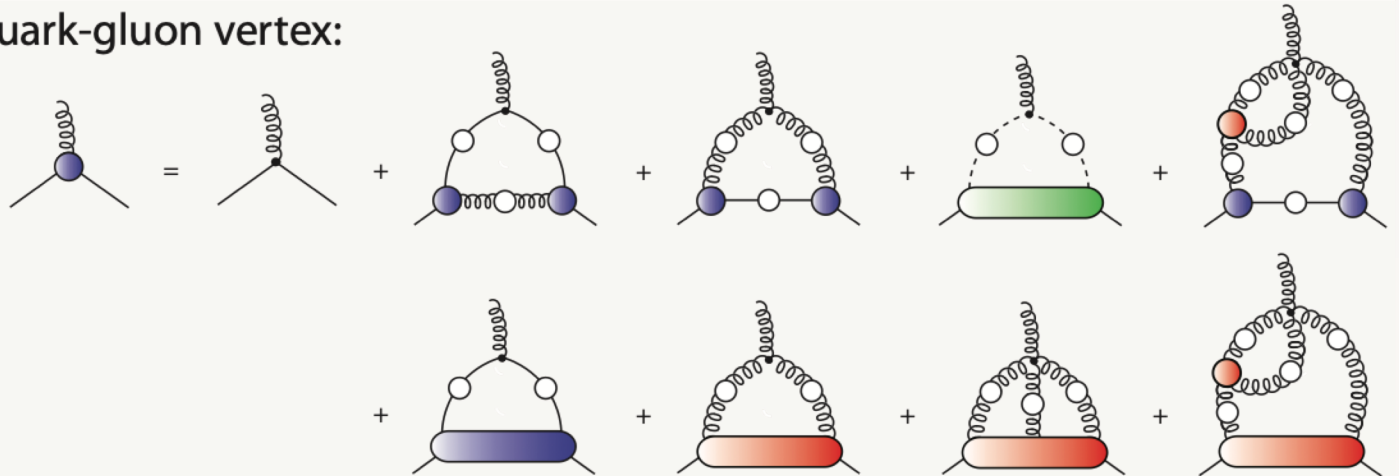
$$\text{---}\bigcirc\text{---}^{-1} = \text{---}^{-1} + \text{---}\bigcirc\text{---}$$

Gluon propagator:

$$\text{---}\bigcirc\text{---}^{-1} = \text{---}^{-1} +$$



Quark-gluon vertex:

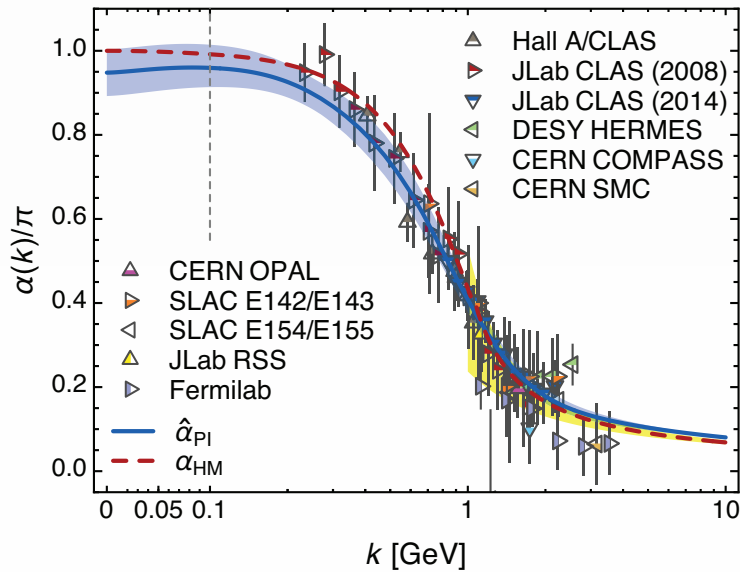


- Fundamental field equations of any QFT
- Self-consistent, coupled system
- Poincaré covariance
- Gauge invariance
- Derivation independent of couplings
- Bridge between low and high energy regimes

Non-perturbative insights

SDEs and LQCD suggest infrared finite running coupling, gluon dressing and quark mass function

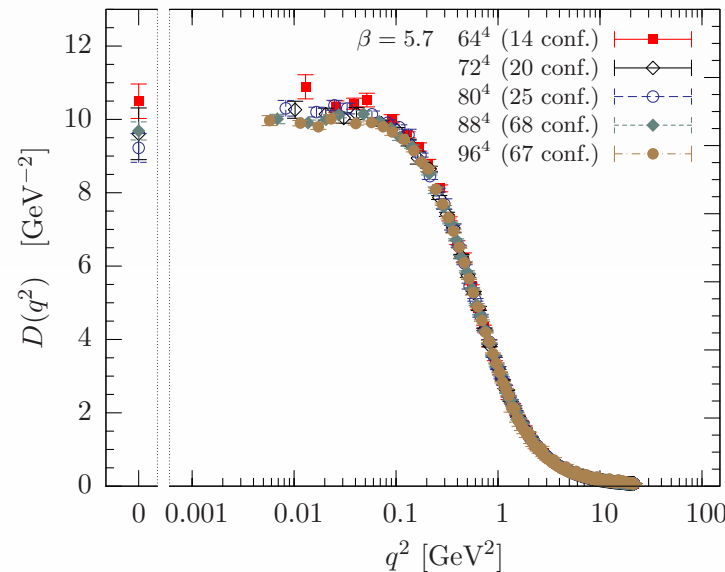
Running coupling



$$\alpha(\zeta^2) = g^2(\zeta^2)/[4\pi]$$

$$\alpha \approx \pi$$

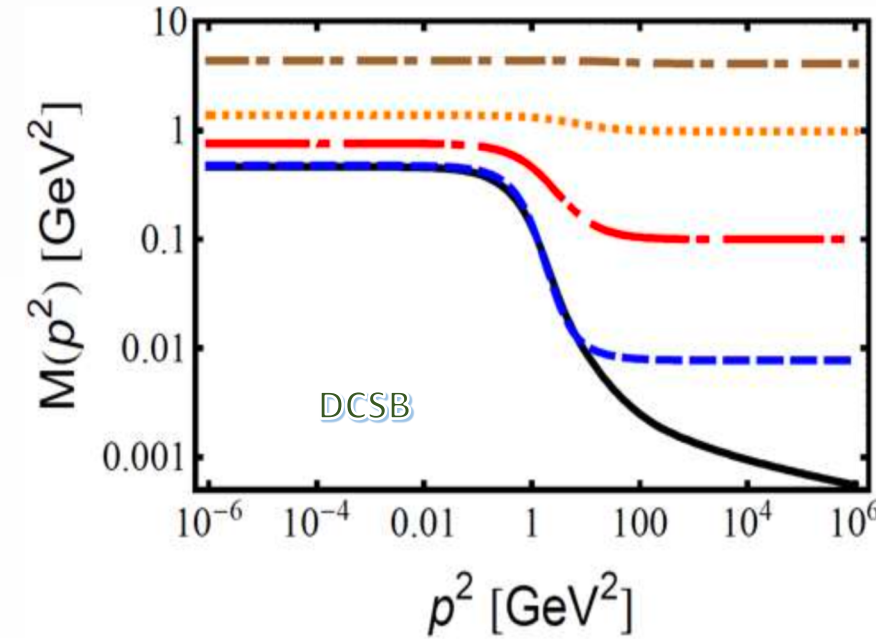
Gluon propagator



$$\mathcal{D}_{\mu\nu}(q) = \Delta(q^2) \left[\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right] + \xi \frac{q_\mu q_\nu}{q^4}$$

$$m_g \approx 500 \text{ MeV}$$

Quark mass

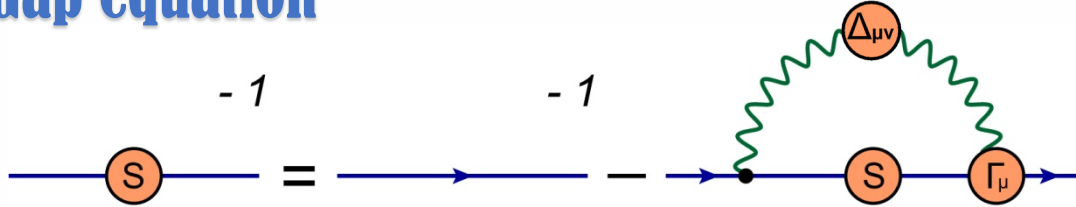


$$\mathcal{S}_f(p) = \frac{\mathcal{Z}_{2f}(p^2)}{i\gamma \cdot p + \mathcal{M}_f(p^2)}$$

$$M_{u,d} \approx 300 - 500 \text{ MeV}$$

Symmetry-Preserving Contact Interaction (SCI)

Gap equation



Insightful picture of hadrons motivated by the effective gluon mass and the IR enhancement of the running coupling. Primary goal: Elucidate the sensitivity of electromagnetic form factors to the pointwise behaviour of quark interactions.

$$\mathcal{S}_f^{-1}(p) = \mathcal{Z}_{2f} (i\gamma \cdot p + m_f^0) + C_F \mathcal{Z}_{1f} \int_{dq}^{\Lambda} g_s^2 \mathcal{D}_{\mu\nu}(p-q) \gamma^\mu \mathcal{S}_f(q) \Gamma_f^\nu(p, q)$$

RL truncation Vertex and replaced by bare counterparts

$$\mathcal{Z}_{1f} g_s^2 \mathcal{D}_{\mu\nu}(p-q) \Gamma_f^\nu(p, q) \rightarrow k^2 \mathcal{G}(k^2) \mathcal{D}_{\mu\nu}^0(k) \gamma^\nu$$

Solution

$$\mathcal{S}_f^{-1}(p) = i\gamma \cdot p + M_f \quad \leftarrow M_{u,d} = 370 \text{ MeV}$$

Momentum-indep. vector-exchange interaction

$$k^2 \mathcal{G}(k^2) \mathcal{D}_{\mu\nu}^0(k) \rightarrow 4\pi\alpha_{IR} \frac{\delta_{\mu\nu}}{m_g^2}$$

$\alpha_{IR} = 0.93\pi$ $m_g = 500 \text{ MeV}$

Symmetry-preserving regularization

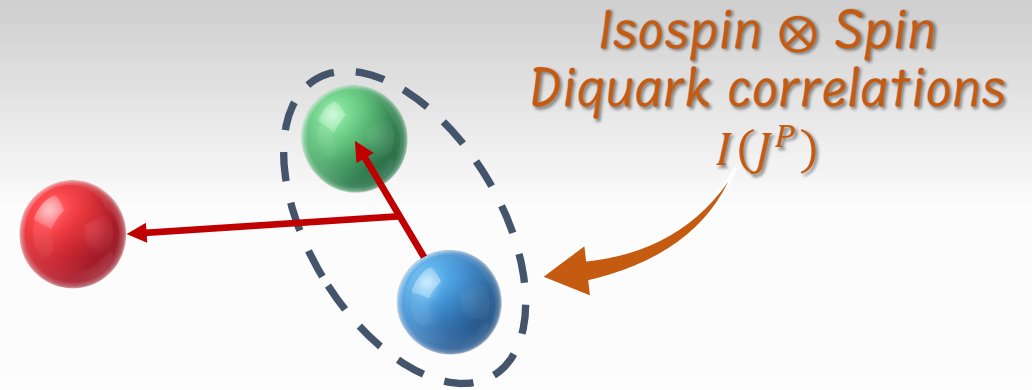
$$\frac{1}{s + M_f^2} \rightarrow \int_{\tau_{uv}^2}^{\tau_{ir}^2} d\tau e^{-\tau(s + M_f^2)}$$

$$\Lambda_{uv} = 1/\tau_{uv} = 0.905 \text{ GeV} \quad \leftarrow \text{Sets the scale}$$

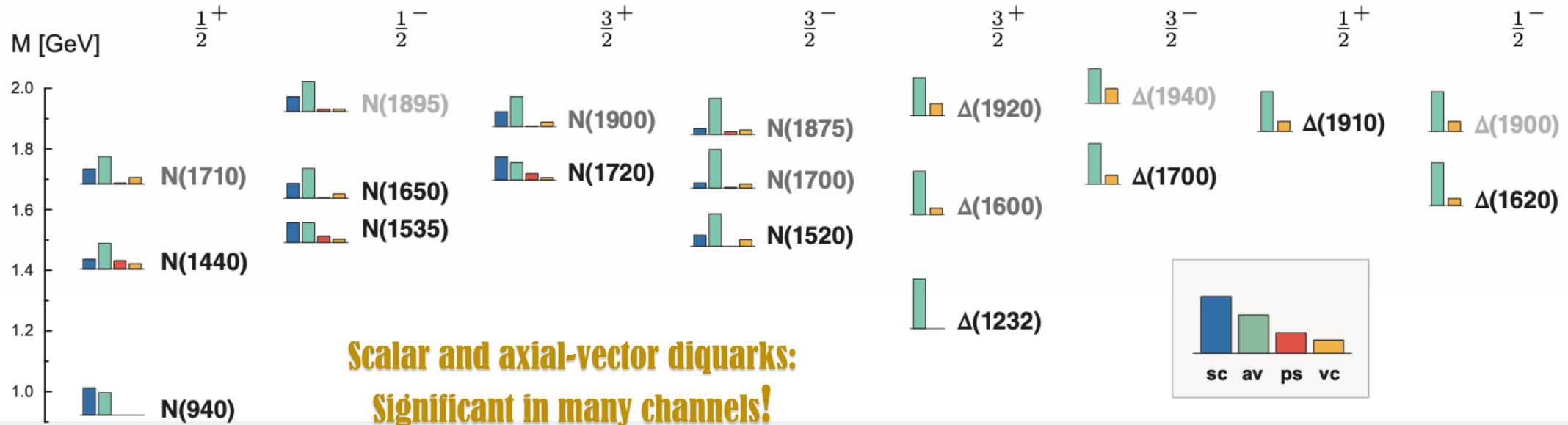
$$\Lambda_{ir} = 1/\tau_{ir} = 0.240 \text{ GeV} \quad \leftarrow \text{Implements confinement}$$

Quark-Diquark picture

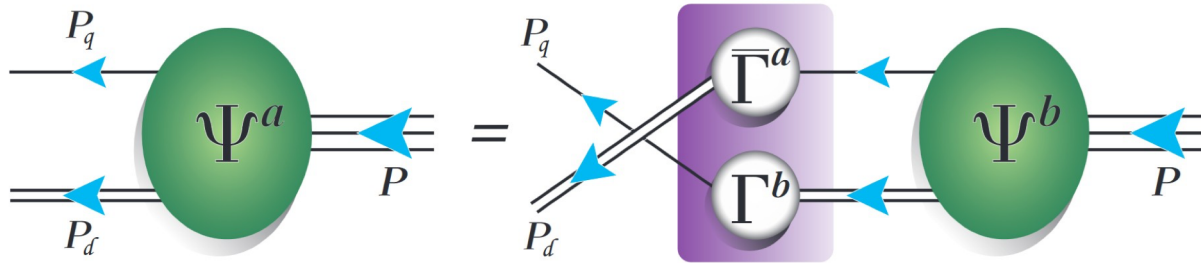
Continuum studies provide compelling evidence that baryon bound states are dominated by strong diquark correlations, while irreducible three-body forces contribute only subleading effects



Scalar (*sc*), axial-vector (*av*) pseudoscalar (*ps*) and vector (*vc*) diquark correlations have proved to be a simplifying, yet accurate description of baryons.



Faddeev Equation



Static approximation $S^T(k) \rightarrow \frac{g_B^2}{M_u}$ Enhances baryon masses

Nucleons: $I(J^P) = \frac{1}{2}(\frac{1}{2}^\pm)$

$$\Psi_3^N(p_i, \alpha_i, \tau_i) = \mathcal{N}_3^{(qq, 0^+)} \xrightarrow{sc} + \mathcal{N}_3^{(qq, 1^+)} \xrightarrow{av} + \mathcal{N}_3^{(qq, 0^-)} \xrightarrow{ps} + \mathcal{N}_3^{(qq, 1^-)} \xrightarrow{vc}$$

Deltas: $I(J^P) = \frac{3}{2}(\frac{3}{2}^\pm)$

$$\Psi_3^\Delta(p_i, \alpha_i, \tau_i) = \mathcal{D}_3^{(qq, 1^+)} \xrightarrow{av}$$

Suppressed for $N(940)$

Not possible to combine isospin $I = 0 \oplus I = 1/2$ to obtain $I = 3/2$.

SCI only supports $1(1^+)$ axial-vector diquark

Faddeev amplitude (FA)

Baryon (B) FA in the quark-diquark picture

$$\Psi_B = \Psi_1^B + \Psi_2^B + \Psi_3^B$$

Subscript identifies bystander quark

Diquark correlations

Diquark	$I(J^P)$	Mass
Isoscalar-scalar (sc)	$0(0^+)$	$m_{sc} = 0.78 \text{ GeV}$
Isovector-axial-vector (av)	$1(1^+)$	$m_{av} = 1.06 \text{ GeV}$
Isoscalar-pseudoscalar (ps)	$0(0^-)$	$m_{ps} = 1.15 \text{ GeV}$
Isoscalar-vector (vc)	$0(1^-)$	$m_{vc} = 1.33 \text{ GeV}$

Insights on radially excited wave-functions

In a momentum-dependent (QCD-kindred) treatment of baryons, the Poincaré-covariant wave function entails angular momentum contributions. In the baryon rest frame, the quarkcore Faddeev amplitudes can be decomposed into quark-diquark angular momentum projections:

$$J^P = \frac{1}{2}^{\pm} \Rightarrow S\text{-}, P\text{- and } D\text{-wave } (L = 0,1,2) \text{ contributions,}$$

$$J^P = \frac{3}{2}^{\pm} \Rightarrow S\text{-}, P\text{-}, D\text{- and } F\text{-wave } (L = 0,1,2,3) \text{ contributions.}$$

Order-zero Chebyshev projections of the S- and P-wave components:

Positive parity: clear pattern of *zeros*!

$N(940)\frac{1}{2}^{+}$ and $\Delta(1232)\frac{3}{2}^{+}$ do not possess *zeros*.

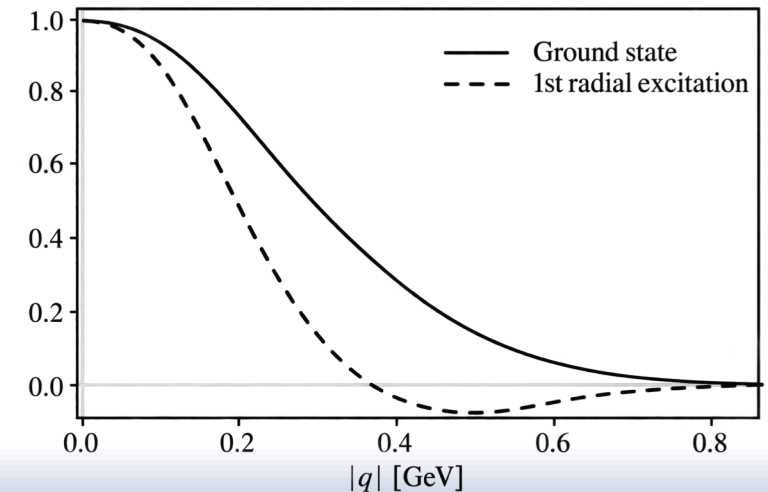
$N(1440)\frac{1}{2}^{+}$ and $\Delta(1600)\frac{3}{2}^{+}$ exhibit single *zeros* at $|q| \approx 0.4 \text{ GeV} \approx 1/[0.5\text{fm}]$.

Negative parity: no simple pattern of *zeros*!

$N(1535)\frac{1}{2}^{-}$ and $\Delta(1700)\frac{3}{2}^{-}$ contain single *zeros* in at least one component.

$N(1650)\frac{1}{2}^{-}$ and $\Delta(1940)\frac{3}{2}^{-}$ do not exhibit *zeros* in most of the components.

$$J^P = \frac{1}{2}^{+}, \frac{3}{2}^{+}$$



Nodal structure of the Faddeev kernel

The Faddeev equation for the n -th radial excitation of a baryon B_n is solved as an eigenvalue problem

$$\lambda_n(P) \Psi_{B_n}^{[\mu]}(P) = -4 \int \frac{d^4 q}{(2\pi)^4} \Pi_n(q) \Gamma_{[\alpha]}^{Din} \left(k - \frac{q_+}{2} \right) S^T(q_+ - k) \bar{\Gamma}_{[\mu]}^{Dex} \left(q - \frac{k_+}{2} \right) S^T(q) \Delta_{[\alpha\nu]}^{Din}(q_+) \Psi_{B_n}^{[\nu]}(P)$$

where $\lambda_n(P) = 1$ for $P^2 = -m_{B_n}^2$.

The SCI kernel does not generate nodes dynamically. For radially excited states, nodes are instead inserted as:

$$\Pi_n(q) = \prod_{i=1}^n \left(1 - d_n^{(i)} q^2 \right) \quad \text{Note that } \Pi_0(q) = 1 \text{ for ground states.}$$

Additional ingredients

Internal (external) diquark
Bethe-Salpeter amplitudes

$$\Gamma_{[\alpha]}^{Din}(k)$$

Scalar (pseudoscalar)
diquark propagator

$$\Delta^{0\pm}(k) = \frac{1}{k^2 + M_{0\pm}^2}$$

Axial-vector (vector)
diquark propagator

$$\Delta_{\alpha\beta}^{1\pm}(k) = \frac{1}{k^2 + M_{1\pm}^2} \left(\delta_{\alpha\beta} + \frac{k_\alpha k_\beta}{M_{1\pm}^2} \right)$$

Ground state solutions

Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	s	a_1^1	a_2^1	p	v_1	v_2
$N(940)$	$\frac{1}{2}(\frac{1}{2}^+)$	0.94 GeV	1.14 GeV	0.88	-0.38	-0.06	-0.02	-0.02	0.00
$N(1535)$	$\frac{1}{2}(\frac{1}{2}^-)$	1.51 GeV	1.82 GeV	0.35	0.04	0.00	-0.92	-0.06	0.18

Spin-orbit repulsion

$$g_{DB} = \begin{cases} 1.0 & \text{for } P_D = P \\ 0.1 & \text{for } P_D = -P \end{cases}$$

Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	a
$\Delta(1232)$	$\frac{3}{2}(\frac{3}{2}^+)$	1.21 GeV	1.39 GeV	1
$\Delta(1700)$	$\frac{3}{2}(\frac{3}{2}^-)$	1.67 GeV	1.72 GeV	1

SCI: Axial-vector diquark contributes 100% to Ψ_B

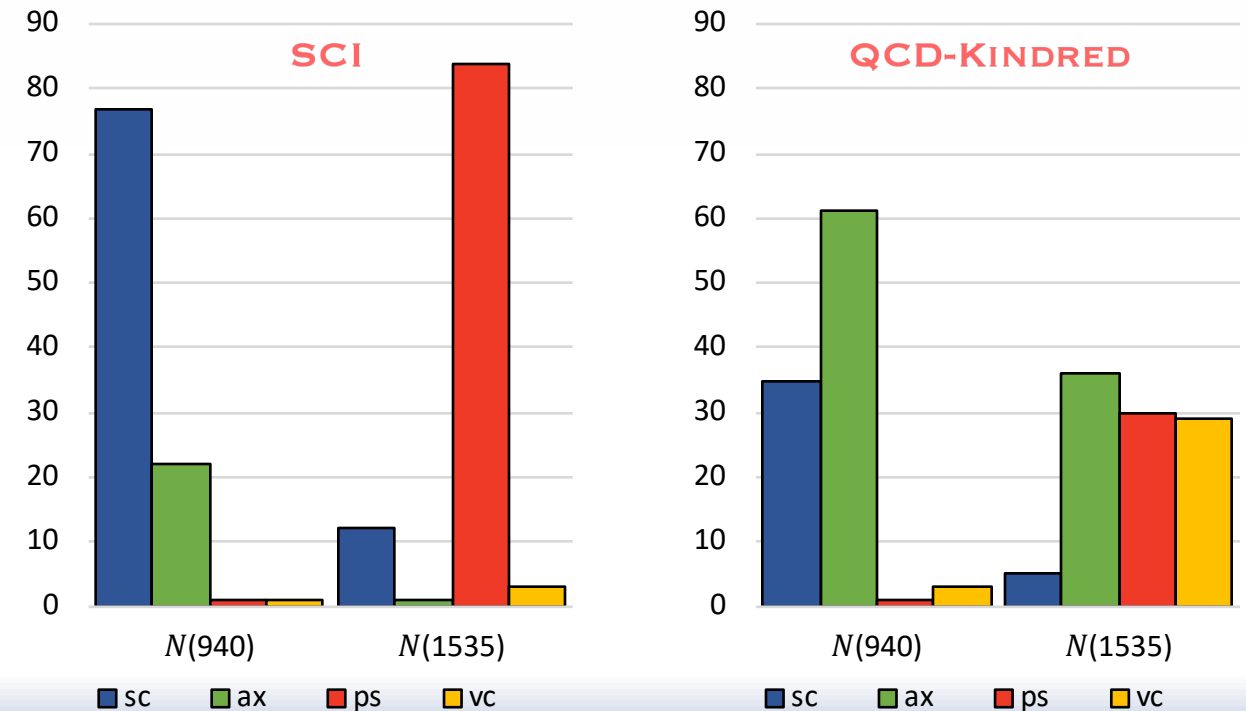
Inflated baryon masses

$$g_N = 1.18 \quad \text{and} \quad g_\Delta = 1.56$$

Room for meson cloud effects corrections (δm_B):

$$\delta m_N \sim 0.20 \text{ GeV} \quad \text{and} \quad \delta m_\Delta \sim 0.12 \text{ GeV}$$

DIQUARK CONTRIBUTIONS - Ψ_B



1st radial excitations

Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	s	a_1^1	a_2^1	p	v_1	v_2
$N(1440)$	$\frac{1}{2}(\frac{1}{2}^+)$	1.37 GeV	1.72 GeV	0.48	-0.55	0.45	-0.07	-0.03	0.02
$N(1650)$	$\frac{1}{2}(\frac{1}{2}^-)$	1.67 GeV	1.95 GeV	-0.01	0.02	-0.02	0.83	0.41	-0.38

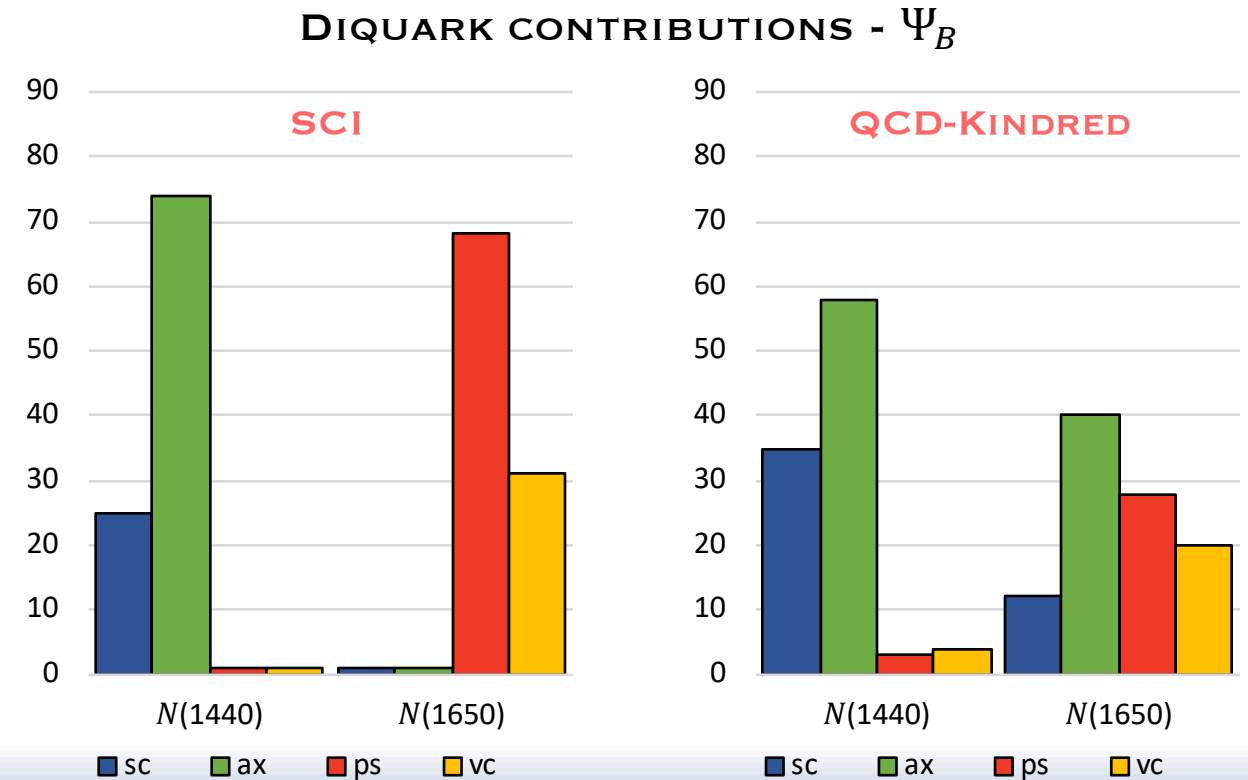
Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	a
$\Delta(1600)$	$\frac{3}{2}(\frac{3}{2}^+)$	1.52 GeV	1.69 GeV	1
$\Delta(1940)$	$\frac{3}{2}(\frac{3}{2}^-)$	1.95 GeV	2.09 GeV	1

$n = 1$ nodes and zeros

$$d_1^{(1)} = 1.8 - 2.8 \text{ GeV}^{-2} \Rightarrow q = 0.6 - 0.8 \text{ GeV}$$

Previous analysis

$$M_q^2 d_1^{(1)} = 1/(1.0 \pm 0.2) \Rightarrow q = 0.3 - 0.4 \text{ GeV}$$



2nd radial excitations

Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	s	a_1^1	a_2^1	p	v_1	v_2
$N(1710)$	$\frac{1}{2}(\frac{1}{2}^+)$	1.70 GeV	1.88 GeV	0.45	-0.50	0.52	0.06	-0.03	0.02
$N(1895)$	$\frac{1}{2}(\frac{1}{2}^-)$	1.91 GeV	2.04 GeV	-0.01	0.02	-0.02	0.86	0.34	-0.37

Baryon	$I(J^P)$	Mass (exp.)	Mass (SCI)	a
$\Delta(1920)$	$\frac{3}{2}(\frac{3}{2}^+)$	1.90 GeV	1.90 GeV	1
$\Delta(????)$	$\frac{3}{2}(\frac{3}{2}^-)$	??? GeV	2.13 GeV	1

PDG status ($n=2$): $\frac{3}{2}(\frac{3}{2}^+)^{**}$ and no evidence for $\frac{3}{2}(\frac{3}{2}^-)$

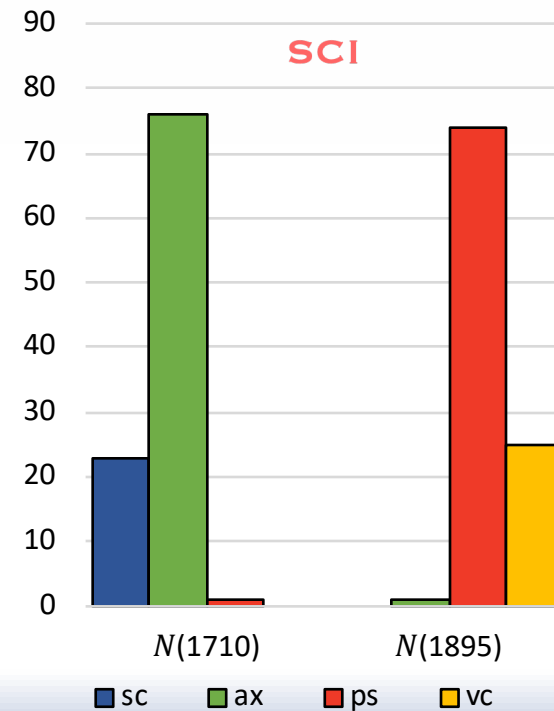
$n = 2$ nodes and zeros

$$d_2^{(1)} = 0.1 - 0.2 \text{ GeV}^{-2} \Rightarrow q = 2.2 - 3.2 \text{ GeV}$$

$$d_2^{(2)} = 4.0 - 5.0 \text{ GeV}^{-2} \Rightarrow q = 0.4 - 0.5 \text{ GeV}$$

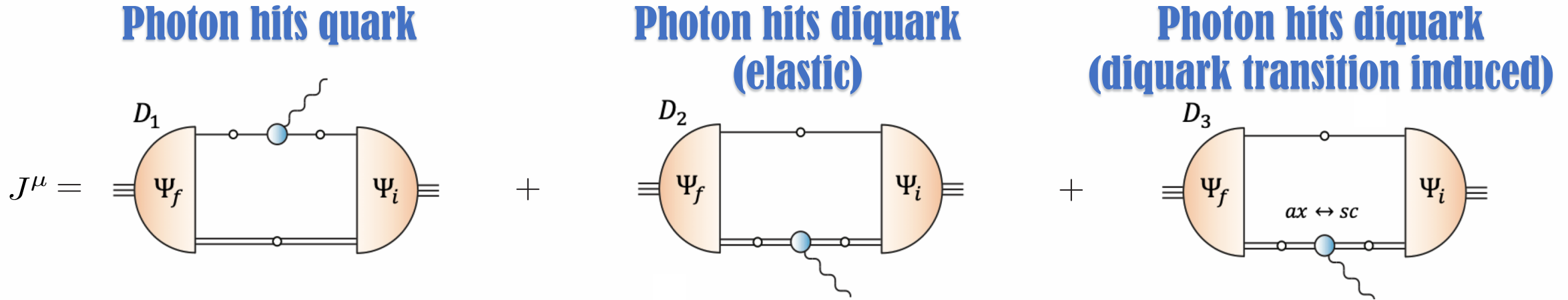
Compared to $n = 1$ nodes: $d_2^{(1)} < d_1^{(1)} < d_2^{(2)}$

DIQUARK CONTRIBUTIONS - Ψ_B



Electromagnetic current

In the quark-diquark approach, either Elastic and Transition currents can be separated into 3 fundamental contributions

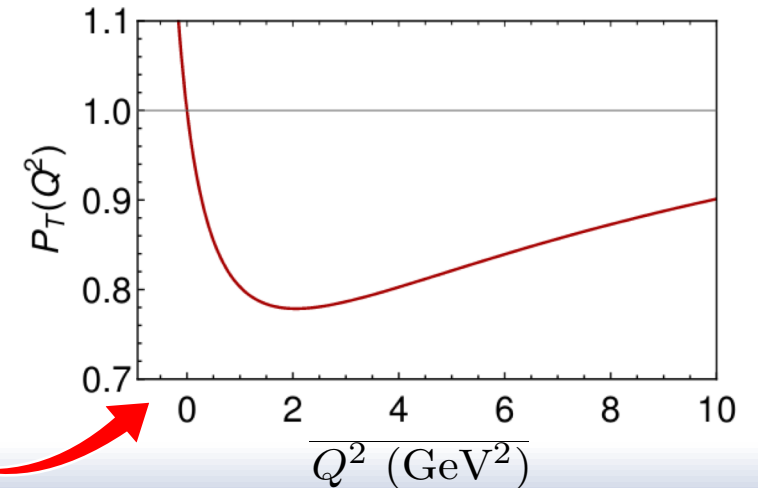


Quark-Photon vertex

$$\Gamma_\mu(Q) = \gamma_\mu^L + \gamma_\mu^T P_T(Q^2) + \frac{\eta}{2M} \sigma_{\mu\nu} Q_\nu \exp(-Q^2/4M^2)$$

- Vector Ward-Green Takahashi identity ensured
- Dressing consistent with truncation
- Anomalous Magnetic Moment η incorporated

Vector meson pole
 $Q^2 \approx -900 \text{ MeV}^2$



Orthogonalization

Current conservation in $\gamma + B_n \rightarrow B_{n'}$ electromagnetic (EM) processes requires

$$Q_\mu J_\mu^{n \rightarrow n'}(Q, P) = 0$$

Within the **impulse approximation**, this condition is satisfied. However, the standard FA solutions in the SCI do not satisfy EM current conservation in transition processes between different radial states.

Following a Gram-Smith procedure, it is possible to construct orthogonal FA amplitudes for excited states:

$$\Psi_{B_n}^\perp(P) = \Psi_{B_n}^s(P) + \sum_{i=0}^{n-1} \kappa_i \lambda_i \Psi_{B_i}^c(P)$$

$\Psi_{B_n}^s(P)$: Standard n -th radial state solution $\Rightarrow \lambda_n = \lambda_n(m_{B_n}^2) = 1$.

$\Psi_{B_i}^c(P)$: Off-shell continuations of lower-lying states $\Rightarrow \lambda_i = \lambda_i(m_{B_n}^2) \neq 1$.

Ward-Takahashi identities for quark-photon and diquark-photon vertices are invoked to fix the κ -coefficients and ensure current conservation in EM transitions.

$\Delta(1600)$ - Elastic Form Factors

Lorentz structure for the EM current of a spin-3/2 baryon

$$J^{\mu,\lambda\omega}(P, Q) = \Lambda_+(P_f) R_{\lambda\alpha}(P_f) \Gamma^{\mu,\alpha\beta}(P, Q) \Lambda_+(P_i) R_{\beta\omega}(P_i)$$

This current can be conveniently expressed in terms of four independent form factors: two **Dirac-like** and two **Pauli-like** form factors:

$$\Gamma_{\mu,\alpha\beta}(K, Q) = \left[(F_1^* + F_2^*) i \gamma_\mu - \frac{F_2^*}{m_\Delta} K_\mu \right] \delta_{\alpha\beta} - \left[(F_3^* + F_4^*) i \gamma_\mu - \frac{F_4^*}{m_\Delta} K_\mu \right] \frac{Q_\alpha Q_\beta}{4m_\Delta^2}$$

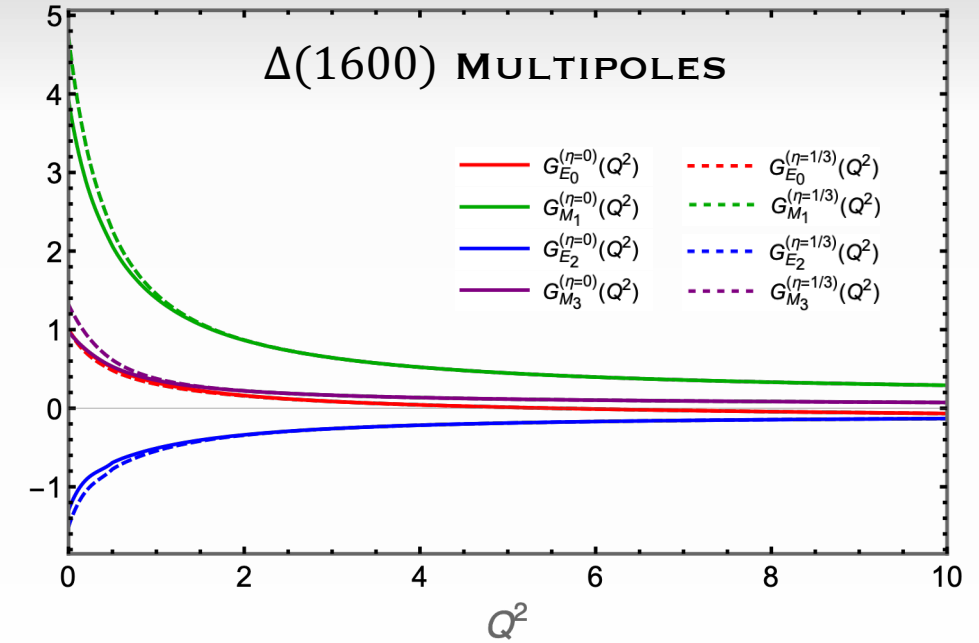
Multipole (Sachs-type) form factors

$$\text{Electric monopole: } G_{E0}(Q^2) = \left(1 + \frac{2\tau_\Delta}{3} \right) (F_1^* - \tau_\Delta F_2^*) - \frac{\tau_\Delta}{3} (1 + \tau_\Delta) (F_3^* - \tau_\Delta F_4^*),$$

$$\text{Magnetic dipole: } G_{M1}(Q^2) = \left(1 + \frac{4\tau_\Delta}{5} \right) (F_1^* + F_2^*) - \frac{2\tau_\Delta}{5} (1 + \tau_\Delta) (F_3^* + F_4^*),$$

$$\text{Electric quadrupole: } G_{E2}(Q^2) = (F_1^* - \tau_\Delta F_2^*) - \frac{1}{2} (1 + \tau_\Delta) (F_3^* - \tau_\Delta F_4^*),$$

$$\text{Magnetic octupole: } G_{M3}(Q^2) = (F_1^* + F_2^*) - \frac{1}{2} (1 + \tau_\Delta) (F_3^* + F_4^*),$$



	SCI	QCD-Kindred
$r_{E0}[\text{fm}]$	0.64 – 0.68	1.02
$G_{M1}(0)$	3.91 – 4.72	1.50
$r_{M1}[\text{fm}]$	0.64 – 0.67	0.64
$-G_{E2}(0)$	1.29 – 1.50	3.00
$r_{E2}[\text{fm}]$	0.72 – 0.73	0.48
$G_{M3}(0)$	0.97 – 1.32	0.80
$r_{M3}[\text{fm}]$	0.57 – 0.64	0.39

Charge density

Fourier transform of the n -radial state elastic form factor (EFF)

$$\rho_n(r) = \frac{1}{4\pi^2} \int_0^\infty dQ^2 q F_n(Q^2) j_0(Q r)$$

where j_0 is the spherical Bessel function. However, the computed EFF is only available within a limited Q^2 –range.

Exponential approach

$$\rho_n(r) = a_n e^{-\sigma_n r} L_N^2(\varrho_n r)$$

The Laguerre polynomial L_n naturally introduces nodes:

$$L_0(\varrho_0 r) = 1$$

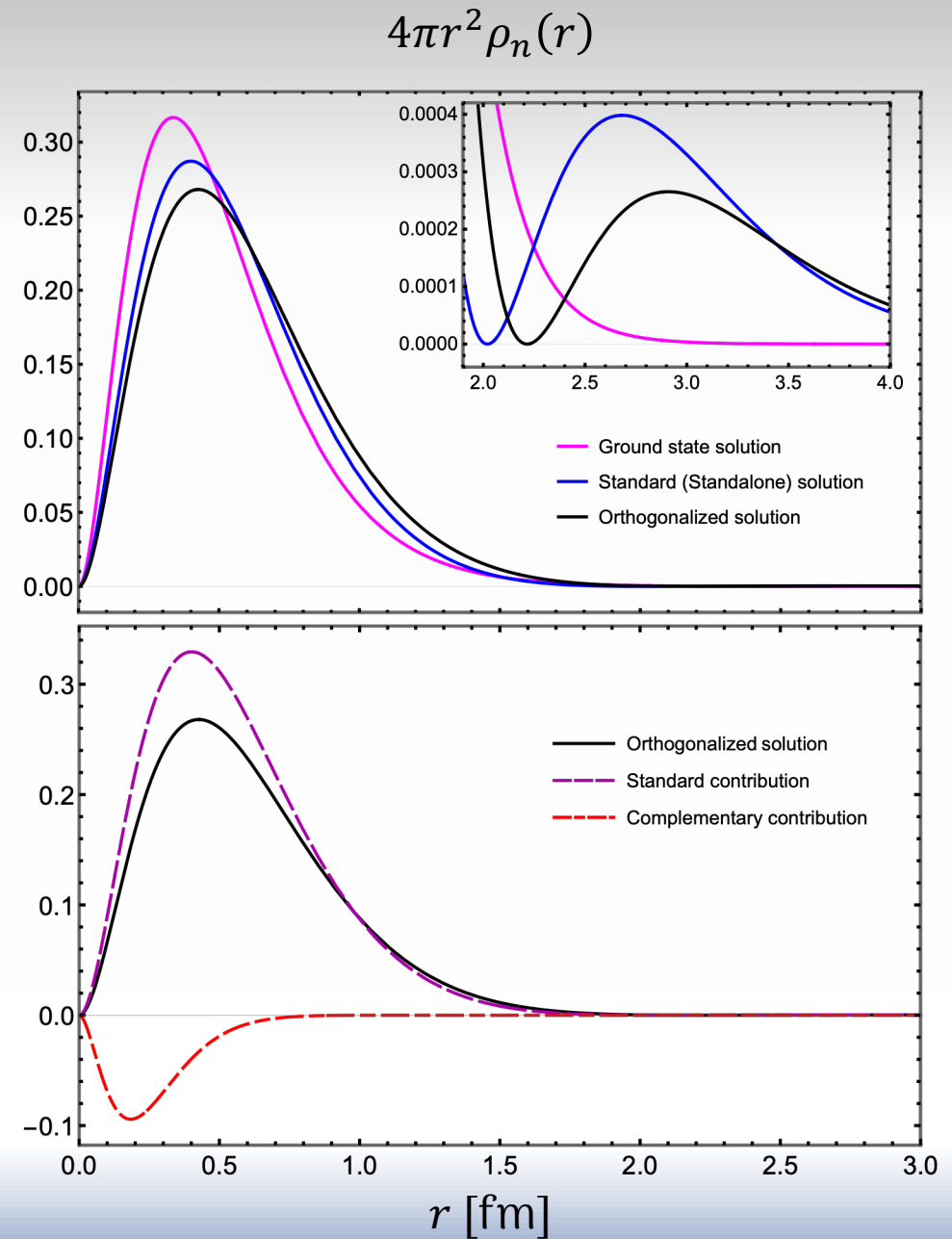
$$L_1(\varrho_1 r) = 1 - \varrho_1 r$$

$$L_2(\varrho_2 r) = \frac{1}{2} (2 - 4\varrho_2 r + \varrho_2^2 r^2)$$

**1st excited state:
zeros at $r \sim 2$ fm**

Charge radii (standard vs orthogonal)

$$r_{E0}^S = 0.64 \text{ fm} \rightarrow r_{E0}^\perp = 0.68 \text{ fm} \quad \text{Enhanced radius} \sim 6\%$$



$\gamma + N \rightarrow \Delta(1600)$ Transition Form Factors

The EM current for the transition of $\frac{1}{2} \left(\frac{1}{2}^+ \right) \rightarrow \frac{3}{2} \left(\frac{3}{2}^+ \right)$ is expressed in terms of Jones-Scadron (G_i^*) FFs

$$J_{\mu\lambda}(K, Q) = \Lambda_+(P_f) R_{\lambda\alpha}(P_f) i\gamma_5 \Gamma_{\alpha\mu}(K, Q) \Lambda_+(P_i)$$

where the $\gamma N \Delta$ vertex is expressed as

$$\Gamma^{\alpha\mu} = b \left[\frac{i\omega}{2\lambda_+} (G_M^* - G_E^*) \gamma_5 \varepsilon^{\alpha\mu\gamma\delta} K^\gamma \hat{Q}^\delta - G_E^* \mathcal{P}_Q^{\alpha\gamma} \mathcal{P}_K^{\gamma\mu} - \frac{i\tau}{\omega} G_C^* \hat{Q}^\alpha K^\mu \right]$$

with

$$\tau = \frac{Q^2}{2(m_\Delta^2 + m_N^2)} \quad b = \sqrt{\frac{3}{2}} \left(1 + \frac{m_\Delta}{m_N} \right) \quad \lambda_\pm = \frac{(m_\Delta \pm m_N)^2 + Q^2}{2(m_\Delta^2 + m_N^2)} \quad \omega = \sqrt{\lambda_+ \lambda_-}$$

Diquark contributions

Photon hits quark

$$\begin{aligned} \gamma p &\rightarrow \Delta^+: (u, \{ud\}_{1+}) \& (d, \{uu\}_{1+}) \\ \gamma n &\rightarrow \Delta^0: (u, \{dd\}_{1+}) \& (d, \{ud\}_{1+}) \end{aligned}$$

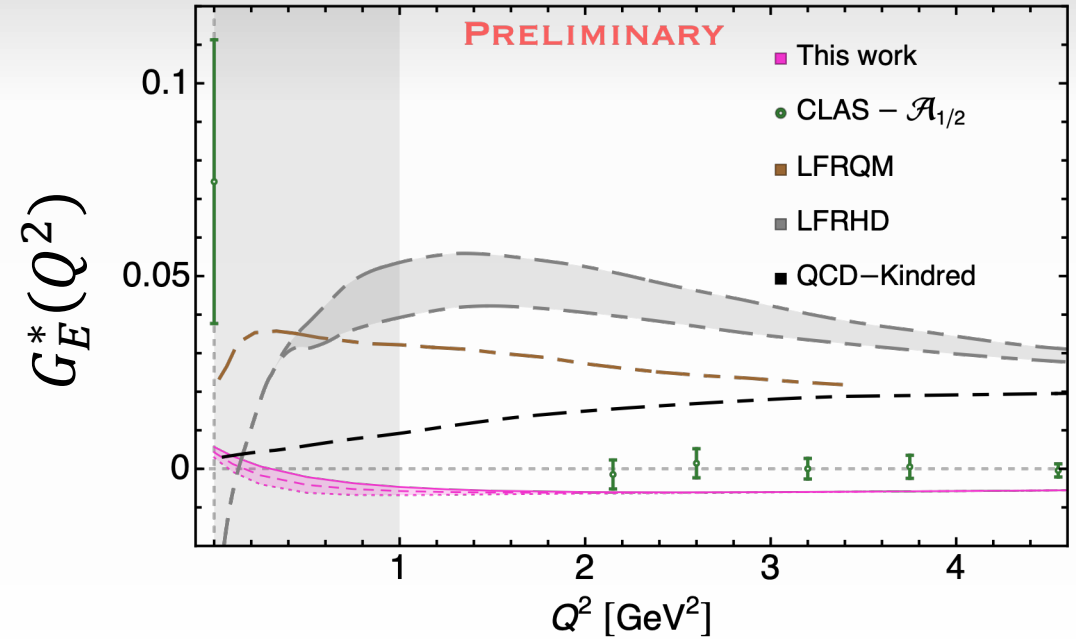
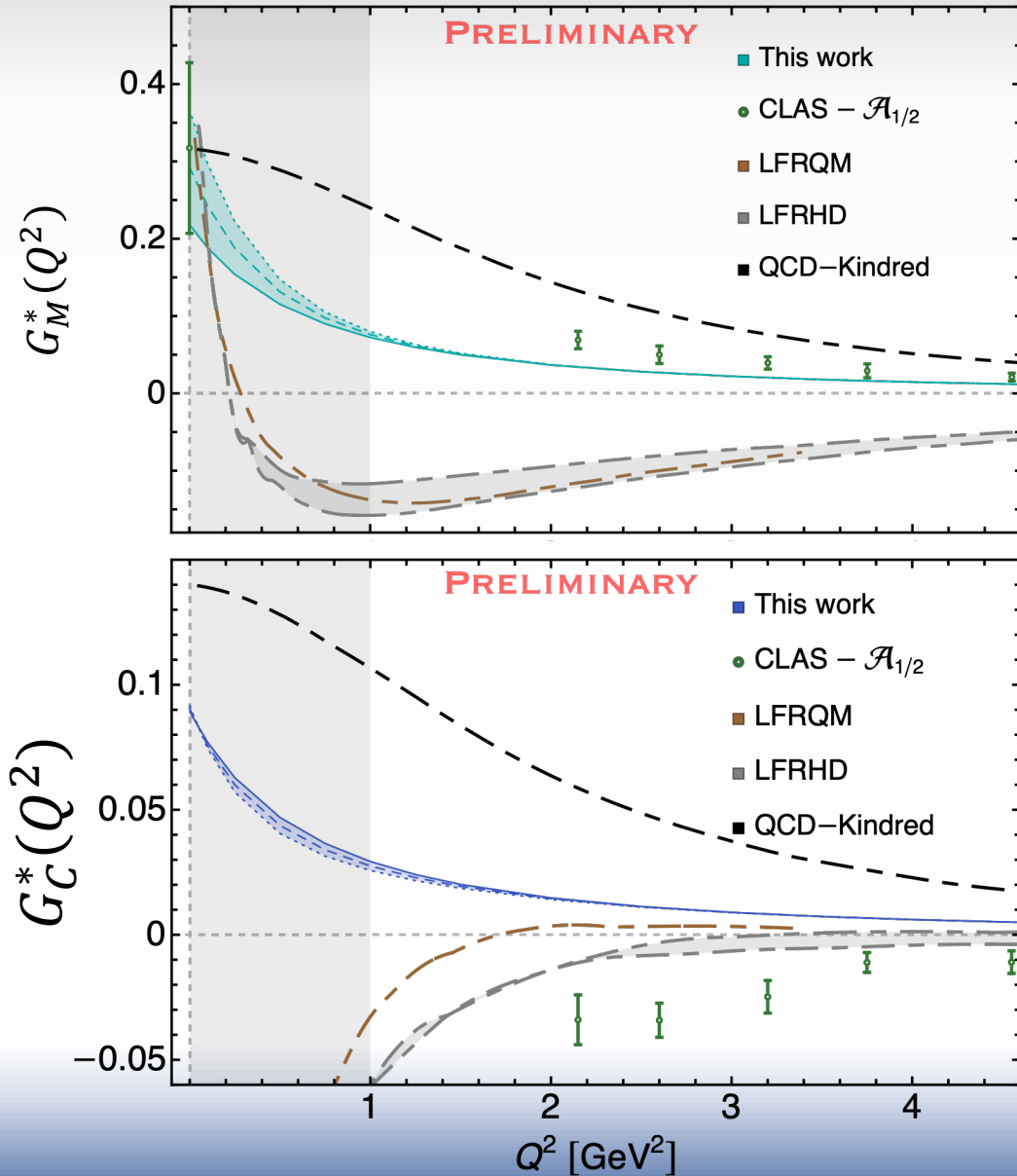
Photon hits diquark
(elastic)

$$\begin{aligned} \gamma p &\rightarrow \Delta^+: (u, \{ud\}_{1+} \rightarrow \{ud\}_{1+}) \\ &\quad (d, \{uu\}_{1+} \rightarrow \{uu\}_{1+}) \\ \gamma n &\rightarrow \Delta^0: (u, \{dd\}_{1+} \rightarrow \{dd\}_{1+}) \\ &\quad (d, \{ud\}_{1+} \rightarrow \{ud\}_{1+}) \end{aligned}$$

Photon hits diquark
(diquark transition induced)

$$\begin{aligned} \gamma p &\rightarrow \Delta^+: (u, [ud]_{0+} \rightarrow \{ud\}_{1+}) \\ \gamma n &\rightarrow \Delta^0: (d, [ud]_{0+} \rightarrow \{ud\}_{1+}) \end{aligned}$$

$\gamma + N \rightarrow \Delta(1600)$ Transition Form Factors



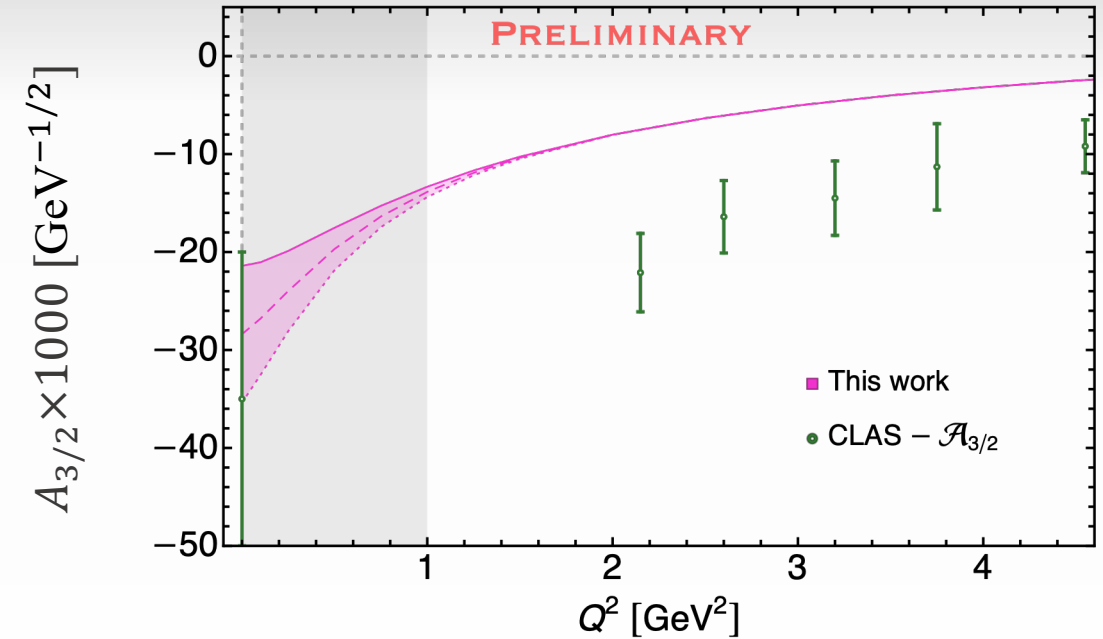
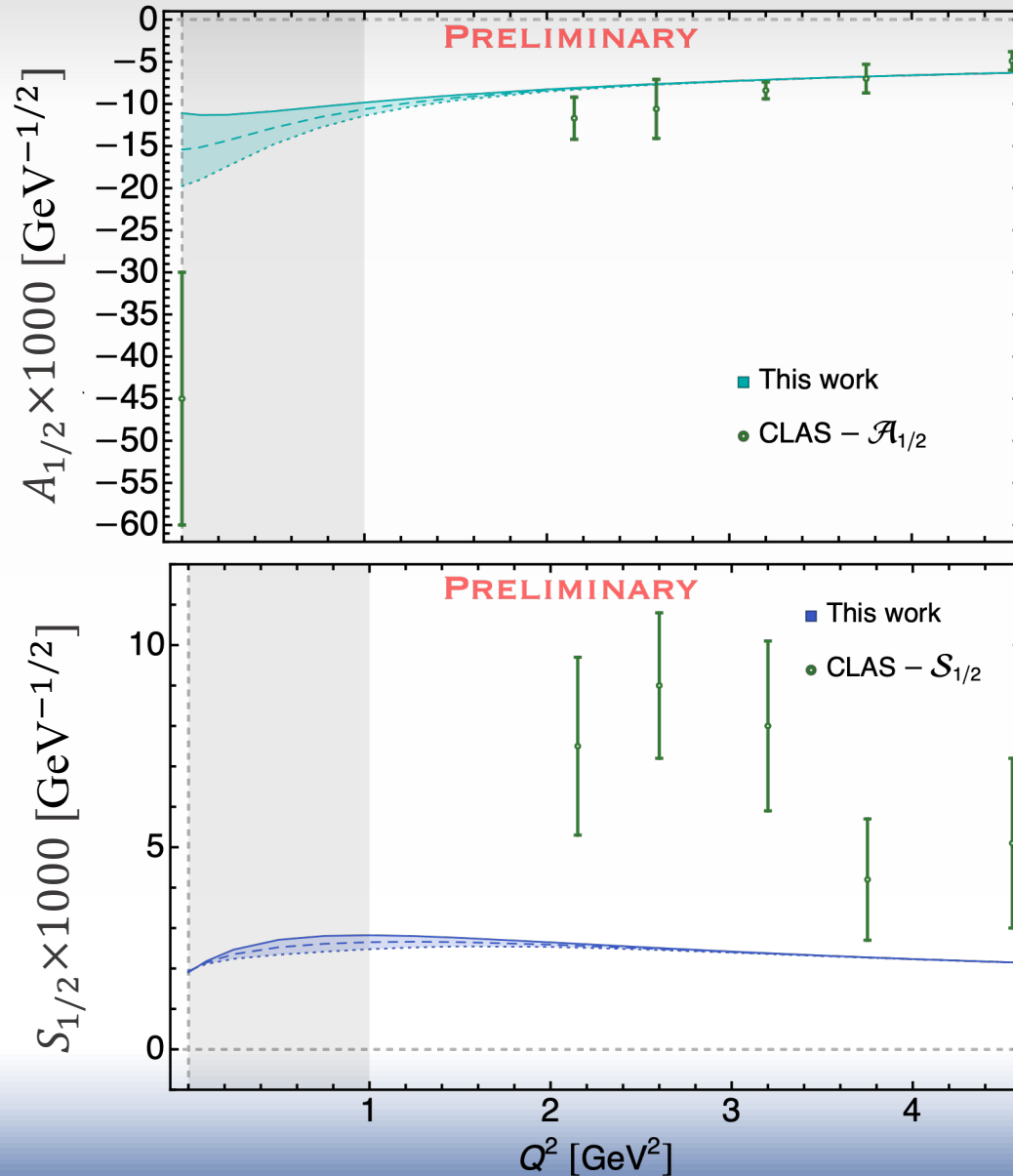
LFRHD = Light Front Relativistic Hamiltonian Dynamics
 LFRQM = Light Front Relativistic Quark Model

SCI results:

- Close alignment of G_M with experimental data.
- Experimental behavior achieved for G_E but IR suppressed.
- Good agreement of G_C with QCD-kinfred but sign flip respect to experimental data.

Helicity Amplitudes

Data - Exclusive meson electroproduction off Protons:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings23



For $\frac{1}{2} \left(\frac{1}{2}^+ \right) \rightarrow \frac{3}{2} \left(\frac{3}{2}^+ \right)$, linear relation with Jones-Scadron FFs:

$$A_{1/2}(Q^2) = -f(Q^2)[G_M^*(Q^2) - 3G_E^*(Q^2)]$$

$$A_{3/2}(Q^2) = -\sqrt{3} f(Q^2)[G_M^*(Q^2) + G_E^*(Q^2)]$$

$$S_{1/2}(Q^2) = +\frac{1}{\sqrt{2}} f(Q^2) \frac{\sqrt{Q_+^2 Q_-^2}}{m_\Delta^2} G_C^*(Q^2)$$

$$\text{with } f(Q^2) = \frac{1}{4\sqrt{2}} \frac{(m_\Delta + m_N)}{m_N} \sqrt{\frac{Q_\pm^2}{m_N(m_\Delta^2 - m_N^2)}} \quad \text{and} \quad Q_\pm^2 = (m_\Delta \pm m_N)^2 + Q^2$$

Summary

- Dynamical diquark correlations play a crucial role in the internal structure of hadrons.
- The strong diquark correlations revealed by the DSE-BSE-Faddeev equations provide insight into the nature of quark interactions within baryons.
- The existence of non-point diquarks is closely connected to the emergence of hadron masses and Dynamical Chiral Symmetry Breaking (DCSB).
- Electromagnetic transition form factors (TFFs) are sensitive to baryon wave functions and provide an essential path to understanding DCSB.
- TFFs are therefore important for identifying dynamical diquark correlations and serve as test for the presence of such correlations within baryons.
- Available experimental data provide a groundwork for testing QCD-inspired models, providing crucial validation for theoretical predictions.
- The SCI model offers a simplified yet insightful approach to calculating form factors, reproducing the overall behavior while reducing computational complexity.

THANKS

Helicity amplitudes

Breit frame interpretation: probability amplitudes for the possible spin projections of the involved baryons on photon polarization states $\epsilon_\mu^{(\lambda=0,\pm 1)}$. The total cross-section depends on these helicities. Namely, for real photons (only transverse polarizations)

$$\sigma_{tot} = (\sigma_{3/2} + \sigma_{1/2})/2$$

$\xrightarrow{+1}$
Photon

$\xleftarrow{-1/2}$
Nucleon

$\xrightarrow{+1/2}$
Nucleon

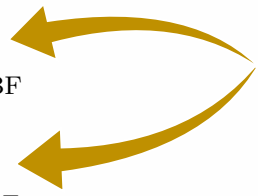
$\sigma_{1/2}$

 $\sigma_{3/2}$

$$A_{1/2} \sim \left\langle N^*, \lambda_R = +\frac{1}{2} \left| \epsilon_\mu^{(+)} J^\mu \right| N, \lambda_N = +\frac{1}{2} \right\rangle_{\text{BF}}$$

$$A_{3/2} \sim \left\langle N^*, \lambda_R = -\frac{3}{2} \left| \epsilon_\mu^{(-)} J^\mu \right| N, \lambda_N = +\frac{1}{2} \right\rangle_{\text{BF}}$$

$$S_{1/2} \sim \left\langle N^*, \lambda_R = -\frac{1}{2} \left| \epsilon_\mu^{(0)} J^\mu \right| N, \lambda_N = +\frac{1}{2} \right\rangle_{\text{BF}}$$



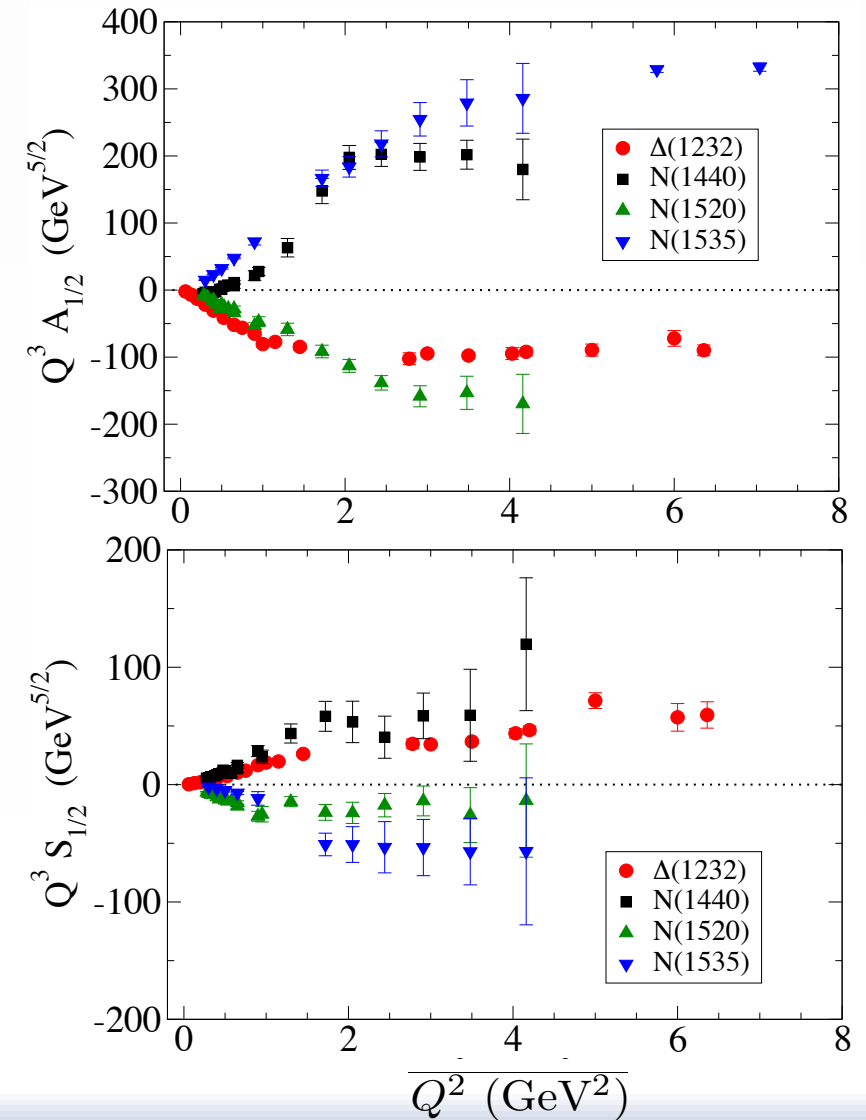
Transverse photons



Longitudinal photons

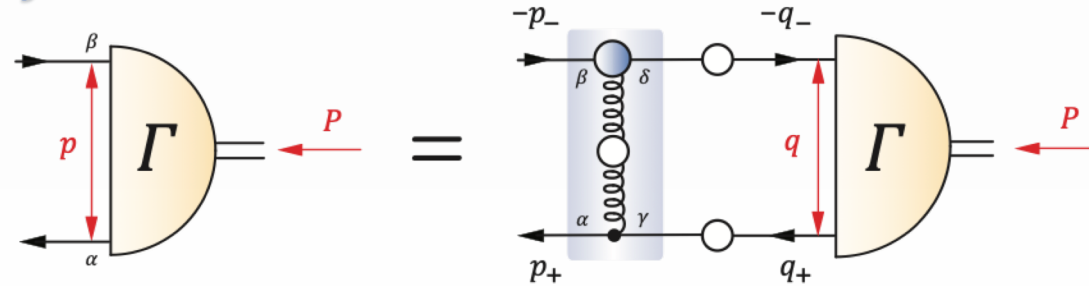
*Connection with TFFs depends on the baryons (J^P) involved.
Quark correlations become extremely important!*

Data from JLab/CLAS
and Jlab/Hall C



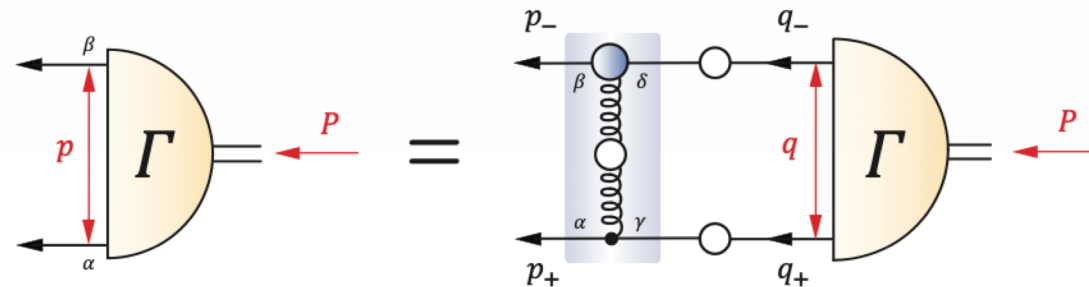
Bethe-Salpeter equation

Mesons J^{PC}



$$\Gamma_{f\bar{g}}(p, P) = -4\pi C_F \frac{\alpha_{IR}}{m_g^2} \int \frac{d^4 q}{(2\pi)^4} \gamma_\mu \mathcal{S}_f(q+P) \Gamma_{f\bar{g}}(q, P) \mathcal{S}_{\bar{g}}(q) \gamma_\mu$$

Diquarks $I(J^P)$



$$\Gamma_{fg}(p, P) = -\frac{4\pi}{2} C_F \frac{\alpha_{IR}}{m_g^2} \int \frac{d^4 q}{(2\pi)^4} \gamma_\mu \mathcal{S}_f(q+P) \Gamma_{fg}(q, P) \mathcal{C}^\dagger \mathcal{S}_g(q) \gamma_\mu$$

Non-exotic channels: J^P meson partners with J^{-P} diquark

$$J^{PC} = 0^{-+}, 1^{--}, 0^{++}, 1^{++}, 1^{+-}$$

$$I(J^P) = 0(0^+), 1(1^+), 0(0^-), 0(1^-), 1(1^-)$$

SCI forbids

BS Amplitudes

$$\Gamma^{0^{-+}}(P) = \gamma_5 \left[iE^{0^{-+}}(P) + \frac{\gamma \cdot P}{2M} F^{0^{-+}}(P) \right]$$

$$\Gamma^{0^{++}}(P) = \mathbb{1} E^{0^{++}}(P)$$

$$\Gamma_\mu^{1^{--}}(P) = \gamma_\mu^T E^{1^{--}}(P) + \frac{1}{2M} \sigma_{\mu\nu} P_\nu F^{1^{--}}(P)$$

$$\Gamma_\mu^{1^{++}}(P) = \gamma_5 \left[\gamma_\mu^T E^{1^{++}}(P) + \frac{1}{2M} \sigma_{\mu\nu} P_\nu F^{1^{++}}(P) \right]$$

Ground-state masses

Meson	Exp.	CI	Diquarks Mass
π	0.139	0.14	$(qq)_{0^+} = 0.78$
ρ	0.78	0.93	$(qq)_{1^+} = 1.06$
σ	1.2	1.22	$(qq)_{0^-} = 1.15$
a_1	1.260	1.37	$(qq)_{1^-} = 1.33$

N(940) - Elastic Form Factors

For a spin-1/2 nucleon, the electromagnetic current can be expressed in terms of Dirac (F_1) and Pauli (F_2) form factors

$$J_\mu(K, Q) = ie \bar{u}(P_f) \left(\gamma_\mu F_1(Q^2) + \frac{1}{2m_N} \sigma_{\mu\nu} Q_\nu F_2(Q^2) \right) u(P_i),$$

with $K = (P_i + P_f)/2$ and $Q = P_f - P_i$.

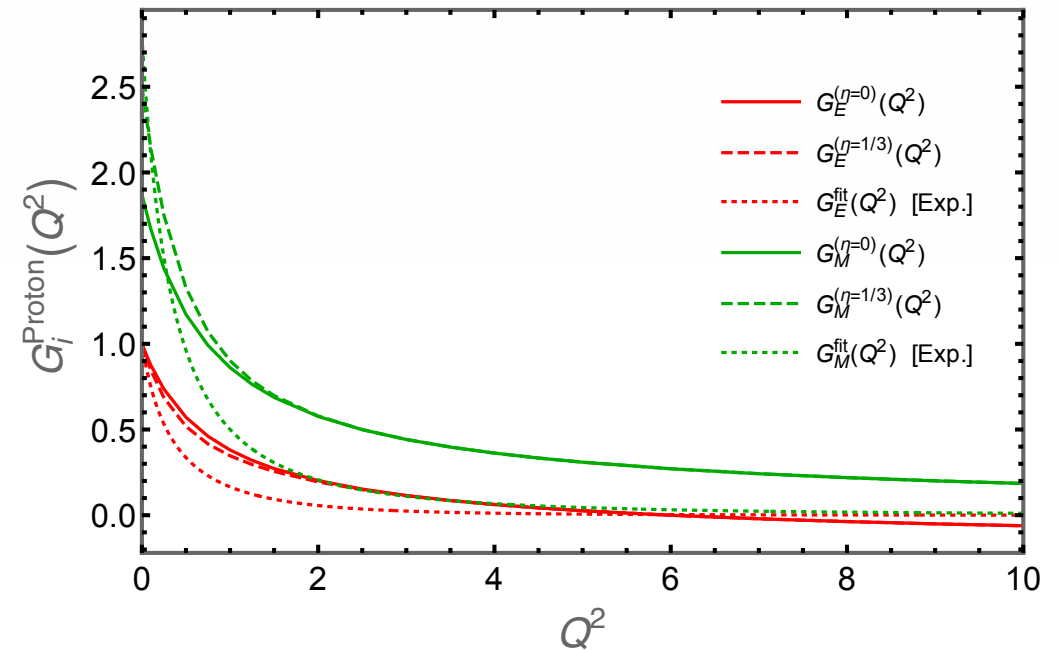
It is convenient to define the so-called Sachs form factors

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

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

The Sachs form factors admit a more direct physical interpretation in the Breit frame, where they are related to the spatial distributions of **charge** and **magnetization** inside the nucleon.

Proton's Sachs form factors



Fundamentals of QCD

$$\mathcal{L}_{QCD} = \sum_f \bar{q}_f (i\gamma^\mu D_\mu - m_f) q_f - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + g.f. + ghosts$$

Gauge covariance

$$D_\mu = \partial_\mu + ig_s \frac{\lambda_a}{2} A_\mu^a$$

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c$$

Emergent phenomena

Dynamical Chiral Symmetry Breaking (DCSB)
Confinement
Gluon mass generation (in pure Yang-Mills)
Strongly interacting bound states

Building blocks

q_f - Quark field: 6 flavours
 A_μ^a - Gluon field: 8 gauge bosons

Nucleons

Dominant mass of visible universe
 m_f - Spontaneous Symmetry Breaking
Higgs mechanism is not enough!

Strong QCD ~98% of M_p

$M_{p,n} \approx 940 \text{ MeV}$



Higgs ~2% of M_p
 $m_{u,d} \approx 5 - 10 \text{ MeV}$