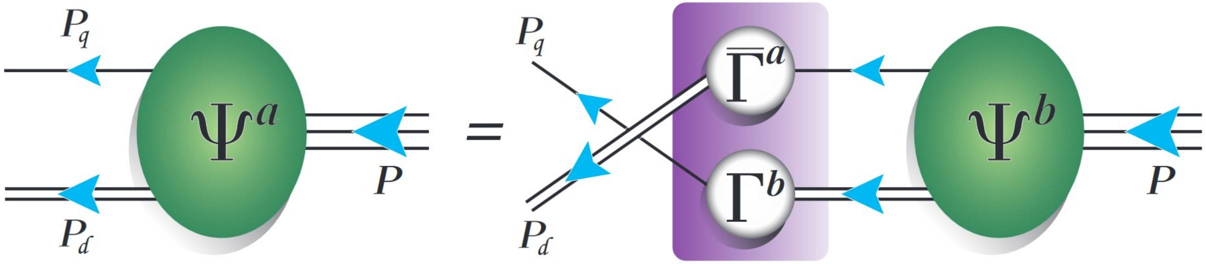
Nucleon electromagnetic transitions in a continuum approach

Khépani Raya Montaño

Bashir, Roberts, Segovia, etc..



Universidad de Huelva

NSTAR 2024

June 17 – 21, 2024. York (England)

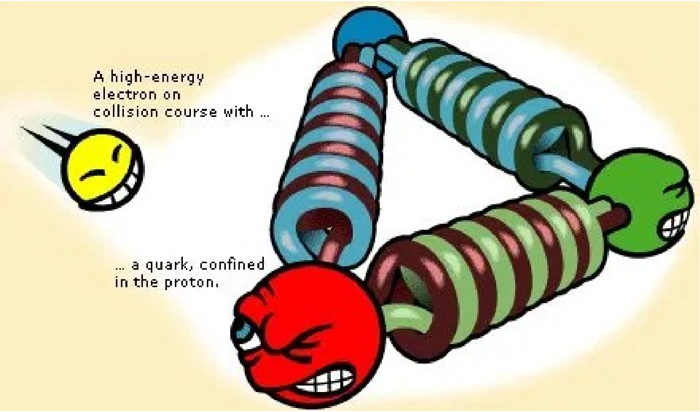
QCD: Basic Facts

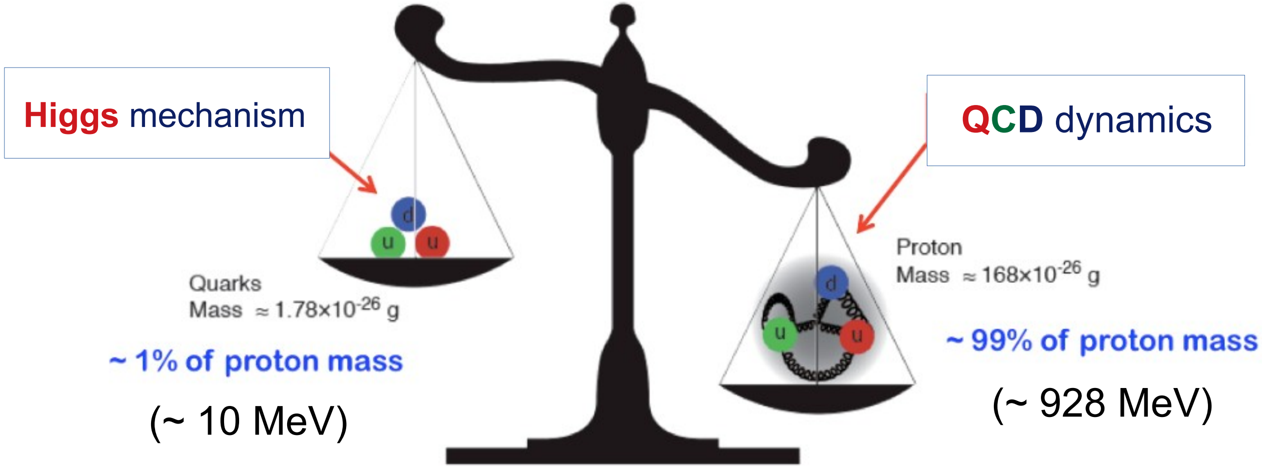
➢ **QCD** is characterized by two **emergent** phenomena: confinement and dynamical generation of mass (DGM).

$$\mathcal{L}_{\rm QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j[\gamma_\mu D_\mu + m_j]q_j + \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu},$$
$$D_\mu = \partial_\mu + ig\frac{1}{2}\lambda^a A^a_\mu\,,$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu + \partial_\nu A^a_\mu - \underline{g f^{abc} A^b_\mu A^c_\nu},$$

- Quarks and gluons not *isolated* in nature.
  - Formation of colorless bound states: "**Hadrons**"
  - **1-fm scale** size of hadrons?

- Emergence of hadron masses (EHM) from QCD **dynamics**





QCD: Basic Facts

➢ **QCD** is characterized by two **emergent** phenomena: confinement and dynamical generation of mass (DGM).

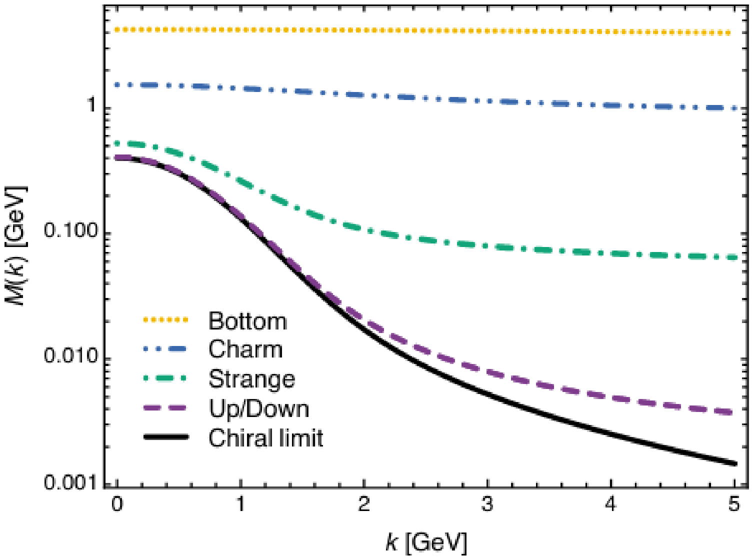
$$\mathcal{L}_{\rm QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j[\gamma_\mu D_\mu + m_j]q_j + \tfrac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu},$$
$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu\,,$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu + \partial_\nu A^a_\mu - \underline{g f^{abc} A^b_\mu A^c_\nu},$$

Can we trace them down to fundamental d.o.f?

- Emergence of hadron masses (EHM) from QCD **dynamics**

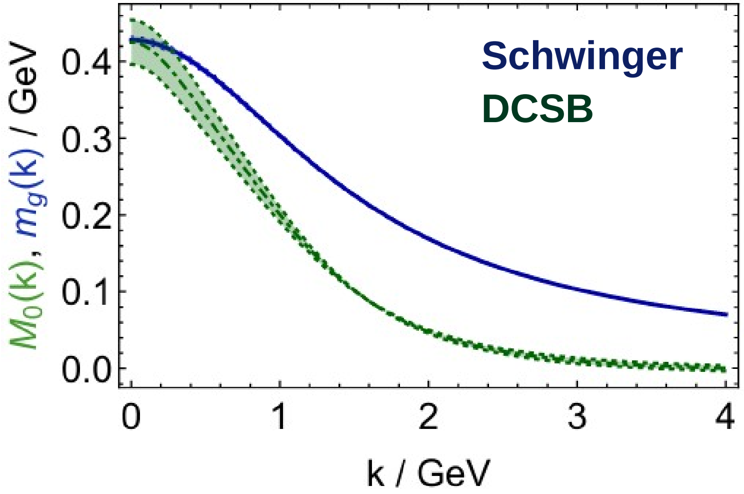
Dynamical masses

(**D**ynamical **C**hiral **S**ymmetry **B**reaking)



"Higgs" masses

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



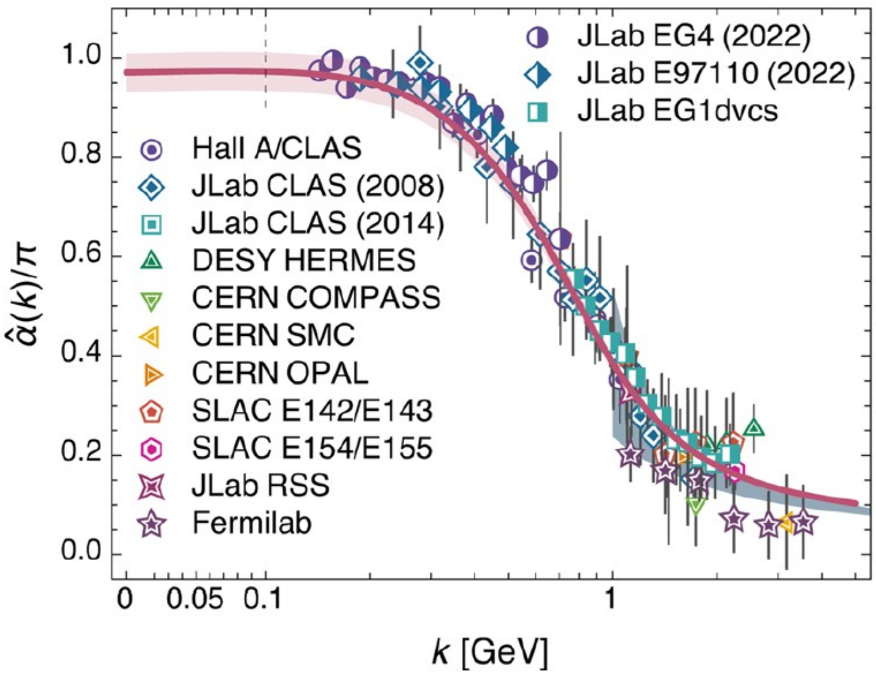
Gluon and quark *running masses*

QCD: Basic Facts

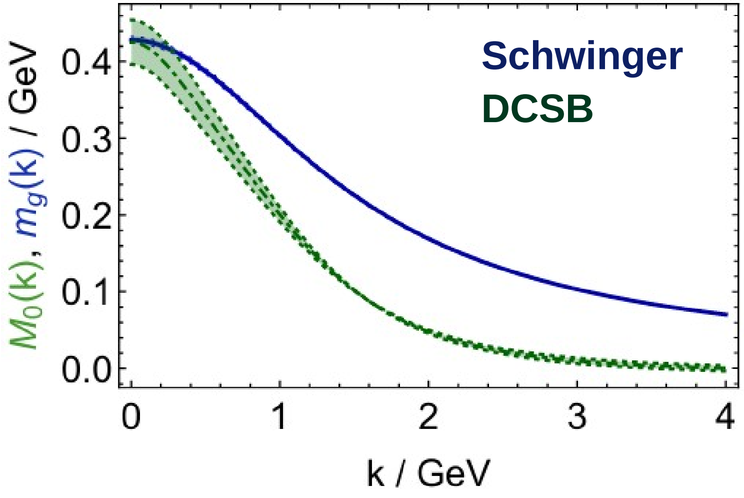
- **QCD** is characterized by two **emergent** phenomena: confinement and dynamical generation of mass (DGM).

$$\mathcal{L}_{\rm QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j[\gamma_\mu D_\mu + m_j]q_j + \tfrac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu},$$
$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu\,,$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu + \partial_\nu A^a_\mu - \underline{g f^{abc} A^b_\mu A^c_\nu},$$

Can we trace them down to fundamental d.o.f?



- Emergence of hadron masses (EHM) from QCD **dynamics**

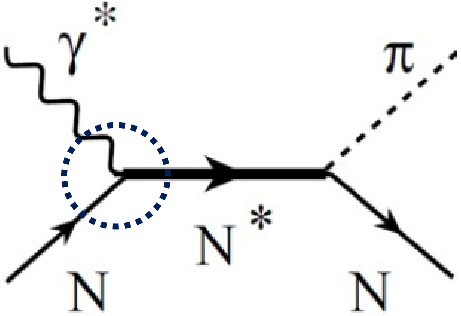


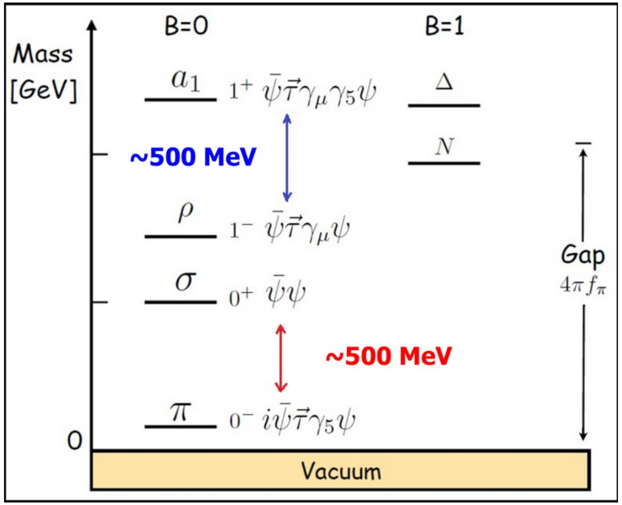
Gluon and quark *running masses*

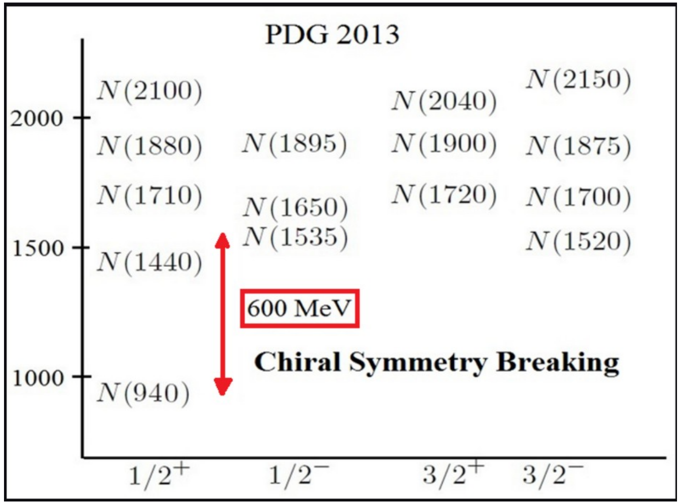
The proton: Understanding QCD

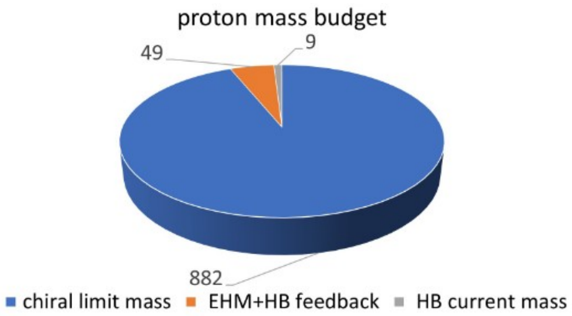
- Now, just as we learned from the **excited** states of the **hydrogen** **atom**, we should learn from the **excited** states of the **nucleon**.

- In particular, the role of **DCSB** could be well understood by analyzing **structural differences** of hadrons and their **parity partners**.

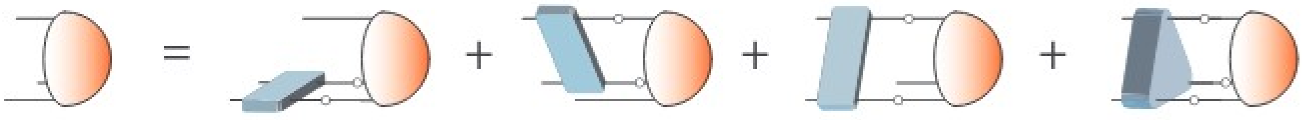


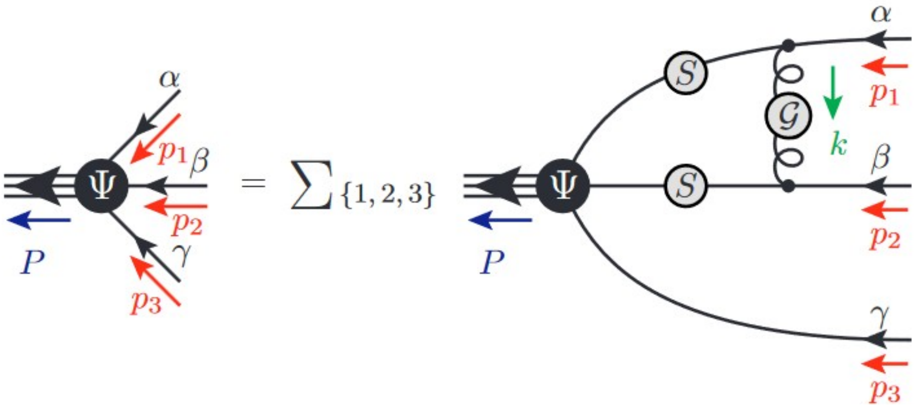






Baryon Faddeev equation





Eichmann:2016yit

Qin:2019hgk

Yao:2024uej

Baryons: Faddeev equation

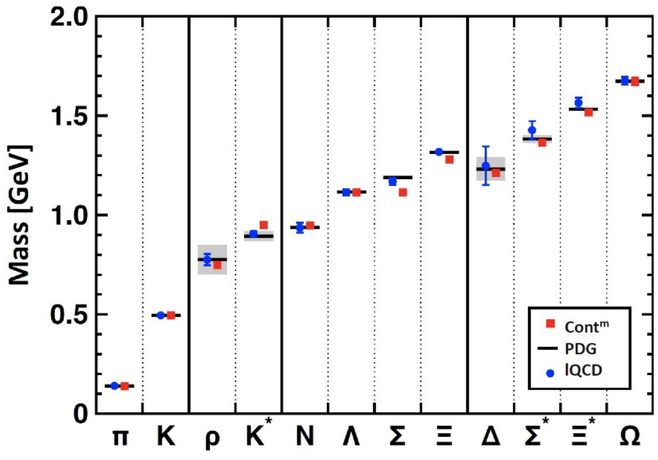
- A Poincaré-covariant **Faddeev equation** encodes all possible interactions/exchanges that could take place between the three dressed valence-quarks.

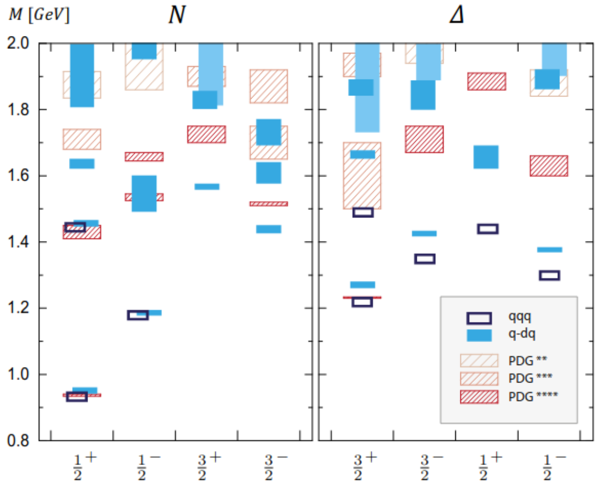
- By employing the **symmetry-preserving** **rainbow-ladder** truncation, this equation can be solved.

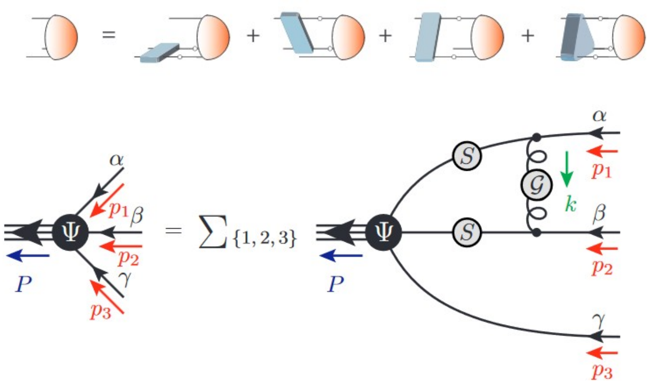
  (This implies, however, an outstanding challenge). Eichmann:2016yit Qin:2019hgk Yao:2024uej

- Exists now a plethora of results/predictions on the meson and baryon **mass spectrum**.

  (J = 1/2+ and 3/2+ baryons, first excitations, parity partners...)



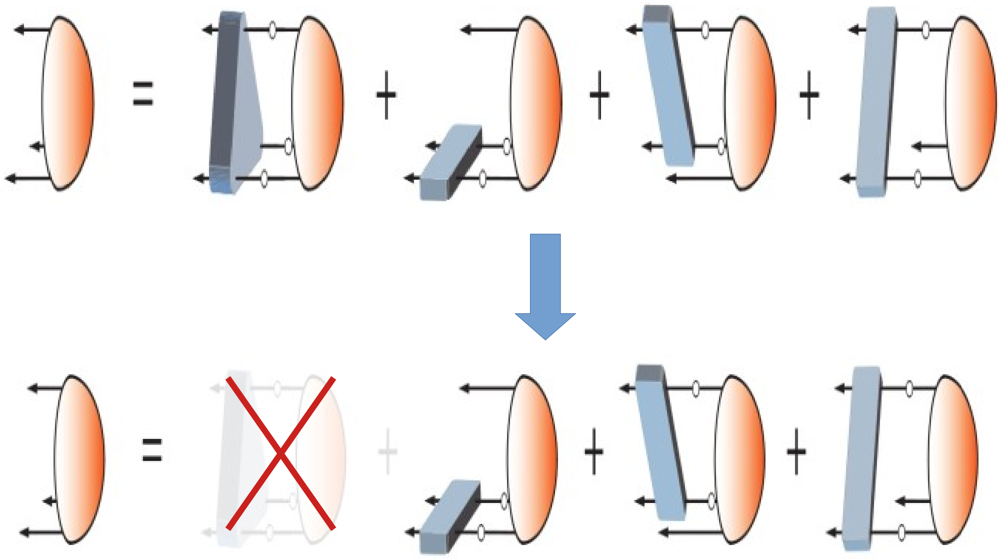




Baryons: Faddeev equation

- Strong evidence anticipates the formation of **dynamical** quark-quark correlations (**diquarks**) within **baryons,** for instance:
  - The **primary** **three-body** force **binding** the quarks within the baryon vanishes when projected onto the color singlet channel.

Eichmann:2016yit



i.e. a 3-gluon vertex attached to each quark once (and only once)

- The dominant 3-gluon contribution is the one attaching twice to a quark
- This produces a strengthening of quark-quark interactions

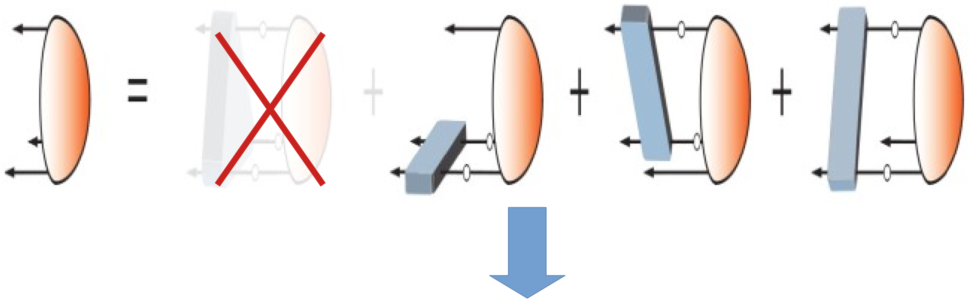
Barabanov:2020jvn

Baryons: Faddeev equation

- Strong evidence anticipates the formation of **dynamical** quark-quark correlations (**diquarks**) within **baryons,** for instance:

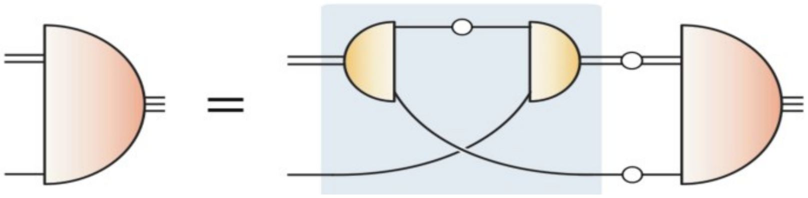
Barabanov:2020jvn

- The **primary** **three-body** force **binding** the quarks within the baryon vanishes when projected onto the color singlet channel.
- 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.



Non-pointlike diquarks:

- Color anti-triplet
- Fully interacting
- Origins related to **EHM** phenomena



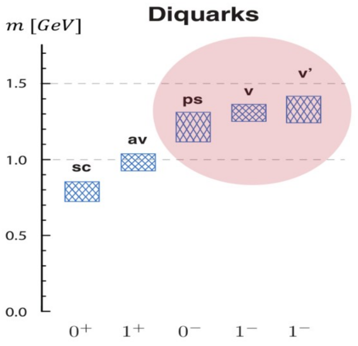
Dyamical Quark-diquark picture

Baryons: Quark-diquark picture

Barabanov:2020jvn

- 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.

- Due to charge conjugation properties, a ***J^P* diquark** partners with an analogous ***J^{-P}* meson**.
- We can thus establish a connection between the **meson** and **diquark** Bethe-Salpeter equations:



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

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

Less tightly 'bound'

Non-pointlike diquarks:
- Color anti-triplet
- Fully interacting
- Origins related to **EHM** phenomena

- Computed '**masses**' should be interpreted as correlation **lengths**:

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

- Stressing the fact that the **diquarks** have a **finite** size:

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

Contact Interaction model:
Some highlights

Contact Interaction

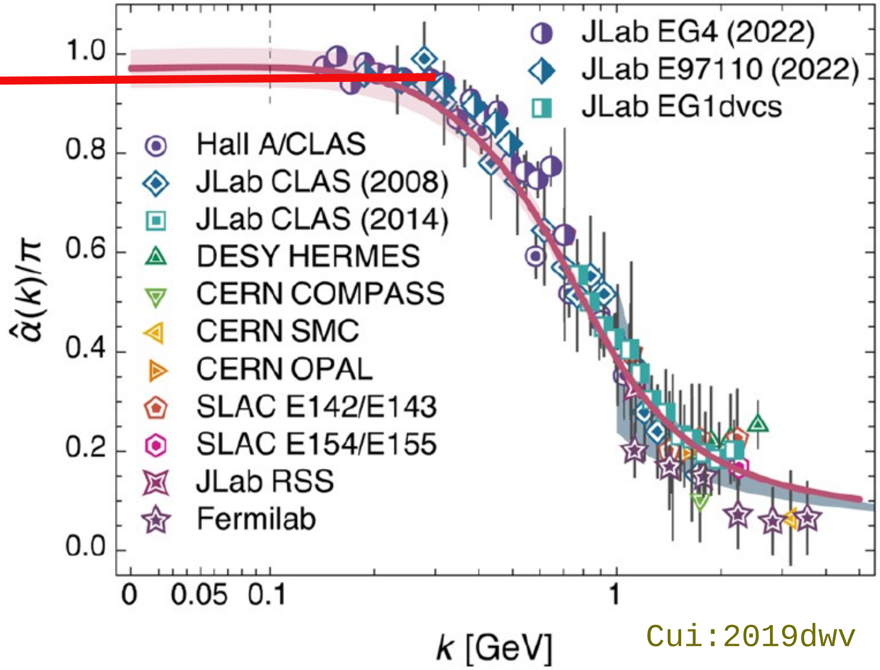
Roberts:2010rn
Gutierrez-Guerrero:2010waf

- The quark gap equation in a symmetry-preserving **contact interaction** model (**SCI**):

$$S^{-1}(p) = i\gamma\cdot p + m + \frac{16\pi}{3}\boxed{\frac{\alpha_{\rm IR}}{m_G^2}}\int\frac{d^4q}{(2\pi)^4}\,\gamma_\mu\, S(q)\,\gamma_\mu$$

Infrared strength $\alpha_{\rm IR} = 0.93\pi$

Compatible with modern computations.



Cui:2019dwv

> - **Recall** the quark **gap equation**:
>
> $$S_f^{-1}(p) = Z_2(i\gamma\cdot p + m_f^{\rm bm}) + \Sigma_f(p)\,,$$
>
> $$\Sigma_f(p) = \frac{4}{3}Z_1\int_{dq}^{\Lambda} g^2 D_{\mu\nu}(p-q)\gamma_\mu S_f(q)\Gamma_\nu^f(p,q)$$

- Namely, SCI kernel is essentially **RL** + **constant** gluon propagator

Contact Interaction

- The quark gap equation in a symmetry-preserving **contact interaction** model (**SCI**):

Roberts:2010rn
Gutierrez-Guerrero:2010waf

$$S^{-1}(p) = i\gamma\cdot p + m + \frac{16\pi}{3}\frac{\alpha_{\rm IR}}{m_G^2}\int\frac{d^4q}{(2\pi)^4}\,\gamma_\mu\,S(q)\,\gamma_\mu$$

- **Constant gluon propagator:**
  - ➔ Quark propagator, with **constant mass function**

$$S_f(p) = Z_f(p^2)(i\gamma\cdot p + M_f(p^2))^{-1} \;\Rightarrow\; S(p)^{-1} = i\gamma\cdot p + M$$

- ➔ **Non renormalizable**
- ➔ **Needs regularization scheme:**

$$\frac{1}{s+M_f^2} = \int_0^\infty d\tau e^{-\tau(s+M_f^2)} \to \int_{\tau_{uv}^2}^{\tau_{ir}^2} d\tau e^{-\tau(s+M_f^2)}$$

input: current masses				output: dressed masses			
m_0	m_u	m_s	m_s/m_u	M_0	M_u	M_s	M_s/M_u
0	0.007	0.17	24.3	0.36	0.37	0.53	1.43

$\tau_{ir} = 1/0.24\,\mathrm{GeV}^{-1}$: Ensures the absence of quark production thresholds (confinement)

$\tau_{uv} = 1/0.905\,\mathrm{GeV}^{-1}$: UV cutoff. Sets the scale of all dimensioned quantities.

Contact Interaction

- Let us now consider the quark gap equation in a symmetry-preserving **contact interaction** model (**SCI**)

$$S^{-1}(p) = i\gamma\cdot p + m + \frac{16\pi}{3}\frac{\alpha_{\rm IR}}{m_G^2}\int\frac{d^4q}{(2\pi)^4}\gamma_\mu S(q)\gamma_\mu$$

- Quark propagator, with **constant mass function**

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

- The **meson** Bethe-Salpeter equation:

$$\Gamma(k;P) = -\frac{16\pi}{3}\frac{\alpha_{\rm IR}}{m_G^2}\int\frac{d^4q}{(2\pi)^4}\gamma_\mu\chi(q;P)\gamma_\mu$$

- The **diquark** Bethe-Salpeter equation:

$$\Gamma_{qq}(k;P) = -\frac{8\pi}{3}\frac{\alpha_{\rm IR}}{m_G^2}\int\frac{d^4q}{(2\pi)^4}\gamma_\mu\chi_{qq}(q;P)\gamma_\mu$$

  - Recall a ***J^p* diquark** partners with an analogous ***J^{-p}* meson**.

- The interaction produces **momentum independent** BSAs:

$$\begin{aligned}
\Gamma_\pi(P) &= \gamma_5\left[iE_\pi(P) + \frac{\gamma\cdot P}{M}F_\pi(P)\right] \\
\Gamma_\sigma(P) &= \mathbb{1}E_\sigma(P)\,, \\
\Gamma_\rho(P) &= \gamma^T E_\rho(P)\,, \\
\Gamma_{a_1}(P) &= \gamma_5\gamma^T E_{a_1}(P)\,,
\end{aligned}$$

  - It is typical to reduce the RL strength in the scalar and axial-vector meson channels (and pseudoscalar and vector diquarks)

Contact **Interaction**

- The **quark-photon** vertex:

$$\Gamma_\mu^\gamma(Q) = \frac{Q_\mu Q_\nu}{Q^2}\gamma_\nu + \Gamma_\mu^{\rm T}(Q)$$

$$\Gamma_\mu^{\rm T}(Q) = P_{\rm T}(Q^2)\mathcal{P}_{\mu\nu}(Q)\gamma_\nu + \frac{\zeta}{2M_u}\sigma_{\mu\nu}Q_\nu \exp\left(-\frac{Q^2}{4M_u^2}\right)$$

Introduces a vector meson pole in the timelike axis.

Quark anomalous magnetic moment (AMM) term

$\zeta \sim 1/3$ sets its strength

- Might be generated automatically in **beyond RL** approaches.

Xing:2021dwe

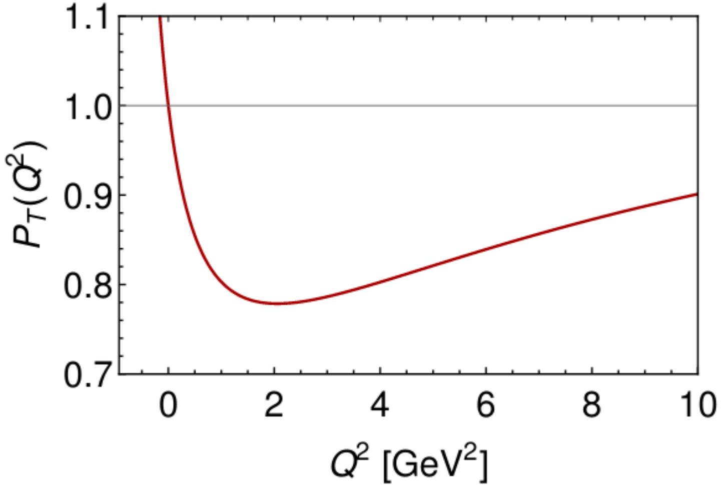
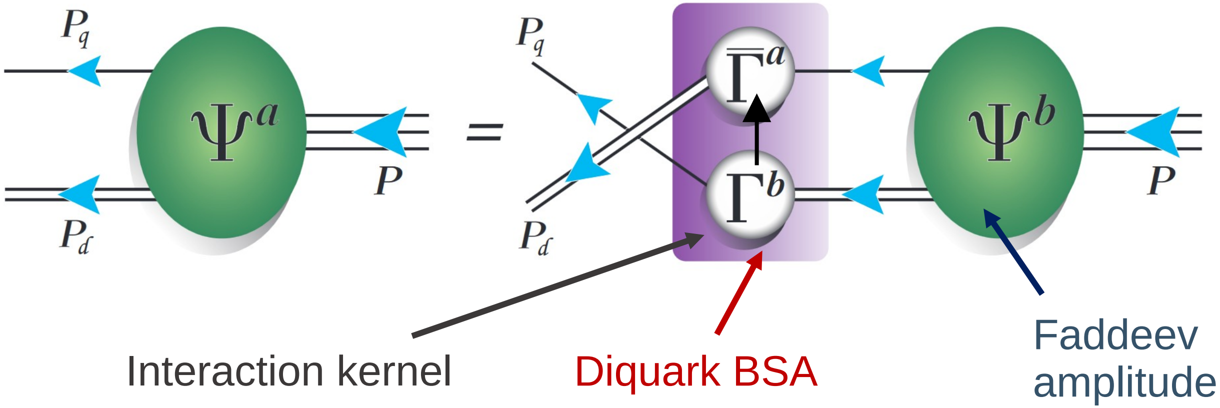


Fig. 9 Photon+quark vertex dressing function in Eq. (A.3). As in any symmetry preserving treatment of photon+quark interactions, $P_{\rm T}(Q^2)$ exhibits a pole at $Q^2 = -m_\rho^2$. Moreover, $P_{\rm T}(Q^2=0) = 1 = P_{\rm T}(Q^2 \to \infty)$.

Contact Interaction

- The **Faddeev** equation, in the **SCI** dynamical quark-diquark picture:



- Quarks inside baryons correlate into non-point-like diquarks.
- Breakup and reformation occurs via quark exchange.

- In the interaction kernel, the **exchanged quark** is represented in the **static approximation**:

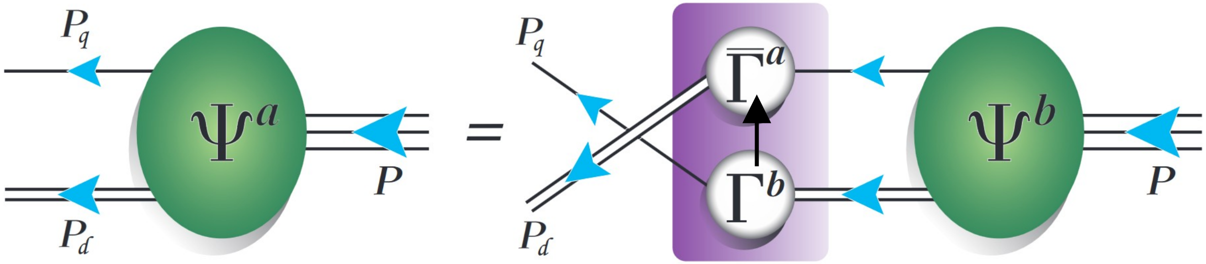
$$S^T(k) \to \frac{g_B^2}{M_u}$$

- The kernel penalizes the contribution of diquarks whose parity is opposite to that of the baryon, using a multiplicative factor **gDB = 0.1-0.3**

Yin:2019bxe
Yin:2021uom

Contact **Interaction**

- The **Faddeev** equation, in the dynamical quark-diquark picture:



- ➔ Quarks inside baryons correlate into non-point-like diquarks.
- ➔ Breakup and reformation occurs via quark exchange.

- Consider a **nucleon-like** J=1/2 baryon:

$$\psi^{\pm} u(P) = \Gamma^{1}_{0^+} \Delta^{0^+}(K)\, \mathcal{S}^{\pm}(P) u(P)$$ —— Scalar (0^+)

$$+ \sum_{f=1,2} \Gamma^{f}_{1^+\mu} \Delta^{1^+}_{\mu\nu}(K) \mathcal{A}^{\pm f}_{\nu}(P) u(P)$$ – Axial vector (1^+)

$$+ \Gamma^{1}_{0^-}(K) \Delta^{0^-}(K) \mathcal{P}^{\pm}(P)\, u(P)$$ —— Pseudoscalar (0^-)

$$+ \Gamma^{1}_{1^-\mu} \Delta^{1^-}_{\mu\nu}(K) \mathcal{V}^{\pm}_{\nu}(P) u(P)\,,$$ —— Vector (1^-)

$$\mathcal{S}^{\pm} = s^{\pm}\, \mathbf{I}_{\rm D}\, \mathcal{G}^{\pm}\,, \quad i\mathcal{P}^{\pm} = p^{\pm}\, \gamma_5\, \mathcal{G}^{\pm}\,,$$
$$i\mathcal{A}^{\pm f}_{\mu} = (a_1^{\pm f} \gamma_5 \gamma_\mu - i a_2^{\pm f} \gamma_5 \hat{P}_\mu) \mathcal{G}^{\pm}\,,$$
$$i\mathcal{V}^{\pm}_{\mu} = (v_1^{\pm} \gamma_\mu - i v_2^{\pm} \mathbf{I}_{\rm D} \hat{P}_\mu) \gamma_5 \mathcal{G}^{\pm}\,.$$

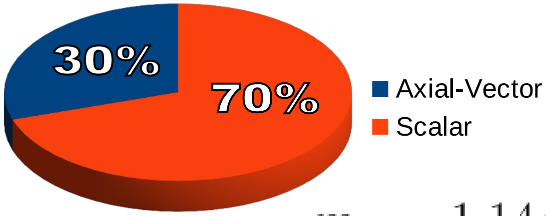
- ➔ We then arrive at an eigenvalue equation for:

$$(s^{\pm}, a_1^{\pm f}, a_2^{\pm f}, p^{\pm}, v_1^{\pm}, v_2^{\pm})$$

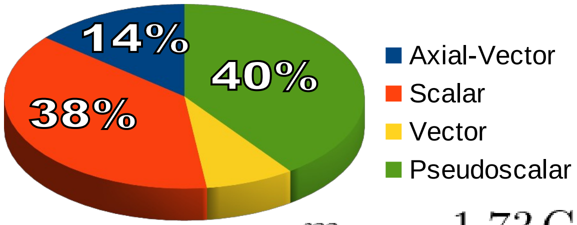
Lu:2017cln

N(940) and N(1535)

- The produced **masses** and **diquark content:**



$m_N = 1.14\,\text{GeV}$



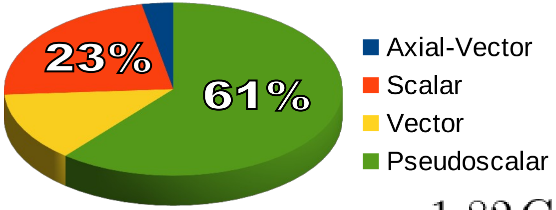
$m_{N^*} = 1.73\,\text{GeV}$

gDB = 0.2

- As expected, the **nucleon** is mostly composed by **scalar** diquarks, while also exhibiting a sizeable **axial-vector** diquark component.
- With the preferred value of **gDB=0.2**, the **nucleon parity partner** exhibits a similar contribution from **$0^+/0^-$** diquarks.

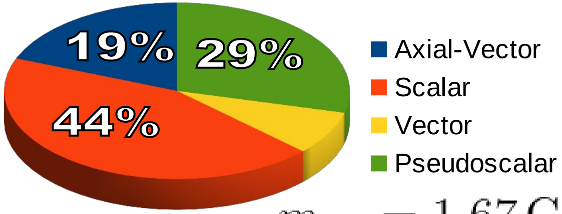
- The variation of **gDB** → **(1 ± 0.5) gDB** produces:

gDB = 0.1



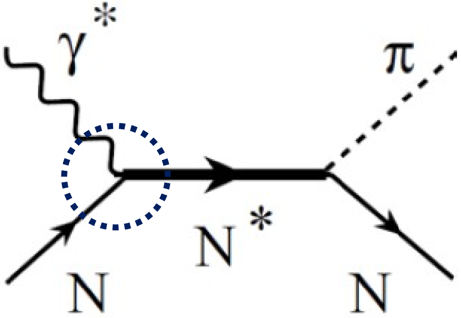
$m_{N^*} = 1.82\,\text{GeV}$

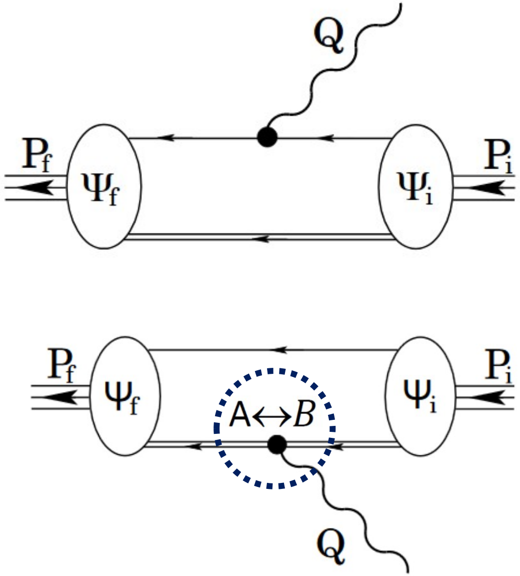
gDB = 0.3

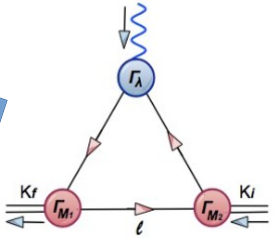


$m_{N^*} = 1.67\,\text{GeV}$

Nucleon TFFs: The approach

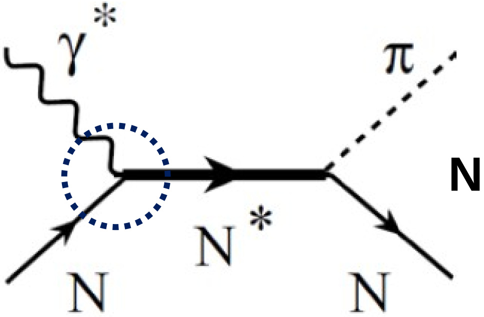






Nucleon transition form factors

- Let us consider the **electromagnetic transition**:



N→ N*

- In our approach, the **EM vertex** can be written:

$$\Gamma^{fi}_{\mu,\#}(P_f, P_i) = \sum_{I=S1,S2,S3}\int_\ell \Lambda^{\mathbf{p}_f}_{+,\#}(P_f)\,\mathcal{J}^{I}_{\mu,\#}(\ell; P_f, Pi)\,\Lambda^{\mathbf{p}_i}_{+,\#}(P_i)$$

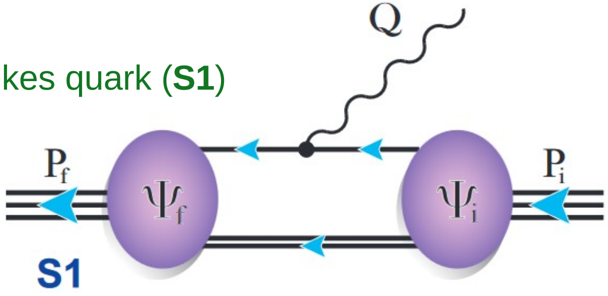
$$= \Lambda^{\mathbf{p}_f}_{+,\#}(P_f)\left[\sum_r \mathcal{Q}^{(j)}_{\mu,\#}(\ell; P_f, Pi) + \sum_{s,t}\mathcal{D}^{(s,t)}_{\mu,\#}(\ell; P_f, Pi)\right]\Lambda^{\mathbf{p}_i}_{+,\#}(P_i)$$

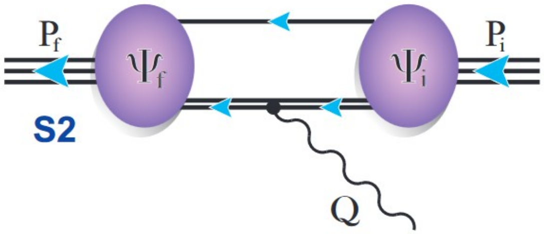
S1 diagrams

S2, S3 diagrams

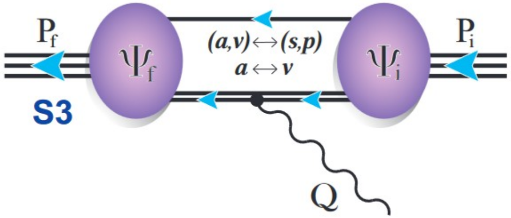
- In the **quark-diquark picture**, within the **SCI model**, the electromagnetic vertex can be splitted into 3 categories:

Photon strikes quark (**S1**)





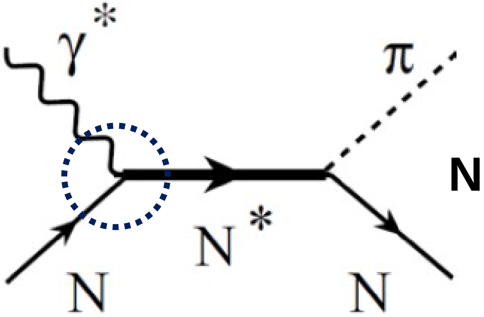
Photon strikes diquark, in an elastic scattering event (**S2**)



Photon strikes diquark, and a transition between different diquarks occurs (**S3**)

Nucleon **transition form factors**

- Let us consider the **electromagnetic transition**:

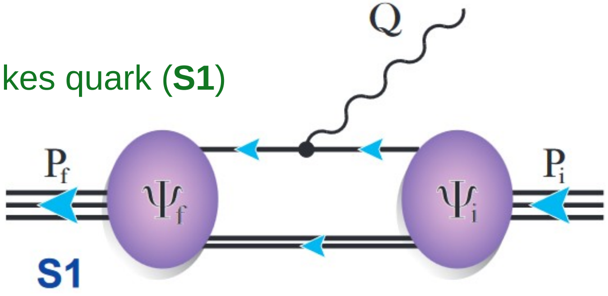


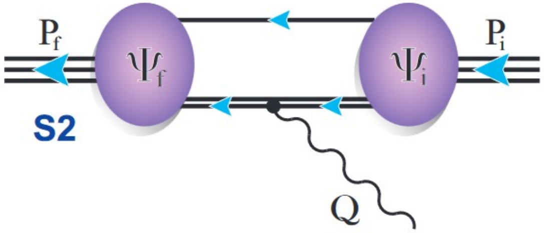
N→ N*

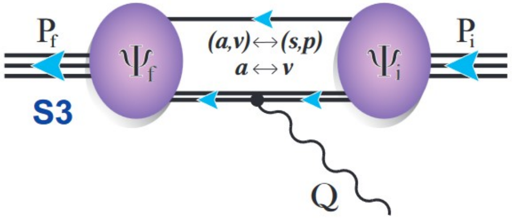
> ➔ Therefore, to evaluate the full electromagnetic vertex, we need, *in principle* to calculate **20 intermediate** contributions:
>
> - **4** from the photon strikes **quark** case (1 for each spectator diquark)
> - **4x4=16** from the photon strikes **diquark** cases.

- In the **quark-diquark picture**, within the **SCI model**, the electromagnetic vertex can be splitted into 3 categories:

Photon strikes quark (**S1**)







Photon strikes diquark, in an elastic scattering event (**S2**)

Photon strikes diquark, and a transition between different diquarks occurs (**S3**)

N → N(1535): Setting the stage

- The transition $\gamma^{(*)} p \to N(1535)\frac{1}{2}^-$ is characterized by the **EM vertex**:

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

Spin ½ initial and final states, but with opposite parity

Contributions from:

Photon hits quark

Spectator diquarks: $0^+,\ 0^-,\ 1^+,\ 1^-$

Photon hits diquark

Ini/Fin	0^+	0^-	1^+	1^-
0^+	$0^+ \to 0^+$	$0^+ \to 0^-$	$0^+ \to 1^+$	$0^+ \to 1^-$
0^-	$0^- \to 0^+$	$0^- \to 0^-$	$0^- \to 1^+$	$0^- \to 1^-$
1^+	$1^+ \to 0^+$	$1^+ \to 0^-$	$1^+ \to 1^+$	$1^+ \to 1^-$
1^-	$1^- \to 0^+$	$1^- \to 0^-$	$1^- \to 1^+$	$1^- \to 1^-$

→ To evaluate the full electromagnetic vertex, we need, *in principle* to calculate **20 intermediate** contributions:

N → N(1535): Setting the stage

- The transition $\gamma^{(*)} p \to N(1535)\frac{1}{2}^-$ is characterized by the **EM vertex**:

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

Spin ½ initial and final states,
but with opposite parity

Contributions from:

Photon hits quark

Spectator diquarks: 0^+, [redacted] 1^+ [redacted]

Photon hits diquark

Ini/Fin	0^+	0^-	1^+	1^-
0^+	$0^+ \to 0^+$	$0^+ \to 0^-$	$0^+ \to 1^+$	$0^+ \to 1^-$
[redacted]				
1^+	$1^+ \to 0^+$	$1^+ \to 0^-$	$1^+ \to 1^+$	$1^+ \to 1^-$
[redacted]				

- In this case, we can **anticipate** the number of **relevant** intermediate **transitions**:

  - The **0^-,1^- diquark** contributions to the nucleon wavefunction are **completely negligible**.

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

baryon	s	a^1_1	a^1_2	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

N → N(1535): Setting the stage

- The transition $\gamma^{(*)}p \rightarrow N(1535)\frac{1}{2}^-$ is characterized by the **EM vertex**:

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

Spin ½ initial and final states, but with opposite parity

Contributions from:

Photon hits quark

Spectator diquarks: 0^+, [redacted] 1^+, [redacted]

Photon hits diquark

Ini/Fin	0^+	0^-	1^+	1^-
0^+	$0^+ \rightarrow 0^+$	[redacted]	$0^+ \rightarrow 1^+$	$0^+ \rightarrow 1^-$
[redacted]				
1^+	$1^+ \rightarrow 0^+$	$1^+ \rightarrow 0^-$	$1^+ \rightarrow 1^+$	$1^+ \rightarrow 1^-$
[redacted]				

- In this case, we can **anticipate** the number of **relevant** intermediate **transitions**:

  - The **0^-,1^- diquark** contributions to the nucleon wavefunction are **completely negligible**.
  - The **$0^+ \rightarrow 0^-$ diquark** transition is trivially **zero**.

N → N(1535): Setting the stage

- The transition $\gamma^{(*)} p \rightarrow N(1535)\frac{1}{2}^-$ is characterized by the **EM vertex**:

$$\Gamma_\mu^*(P_f, P_i) = ie\,\Lambda_+^-(P_f)\left[\gamma_\mu^T F_1^*(Q^2) + \frac{1}{m_+ + m_-}\sigma_{\mu\nu}Q_\nu F_2^*(Q^2)\right]\Lambda_+^+(P_i)$$

Spin ½ initial and final states, but with opposite parity

Contributions from:

Photon hits quark

Spectator diquarks: 0^+, [redacted]

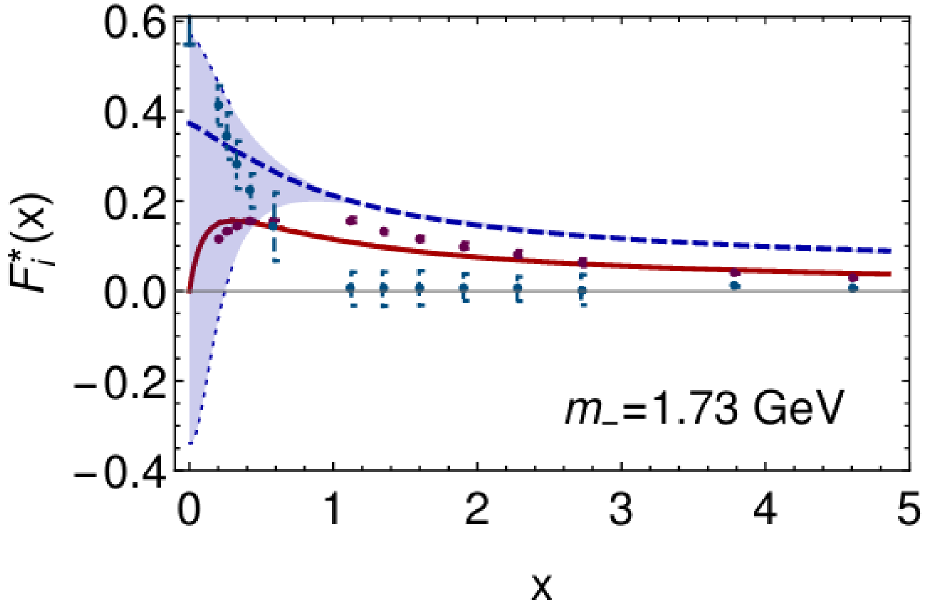
Photon hits diquark

Ini/Fin	0^+	0^-	1^+	1^-
0^+	$0^+ \rightarrow 0^+$	[redacted]	$0^+ \rightarrow 1^+$	$0^+ \rightarrow 1^-$
[redacted]				
1^+	$1^+ \rightarrow 0^+$	$1^+ \rightarrow 0^-$	$1^+ \rightarrow 1^+$	$1^+ \rightarrow 1^-$
[redacted]				

- In this case, we can **anticipate** the number of **relevant** intermediate **transitions**:
  - The **0^-,1^- diquark** contributions to the nucleon wavefunction are **completely negligible**.
  - The **$0^+ \rightarrow 0^-$ diquark** transition is trivially **zero**.
  - In the isospin symmetric limit, $m_u = m_d$, the total contribution of the **spectator 1^+** diquark **vanishes**.
    - → We are thus left with a total of **8 intermediate** transitions.

SCI Results:

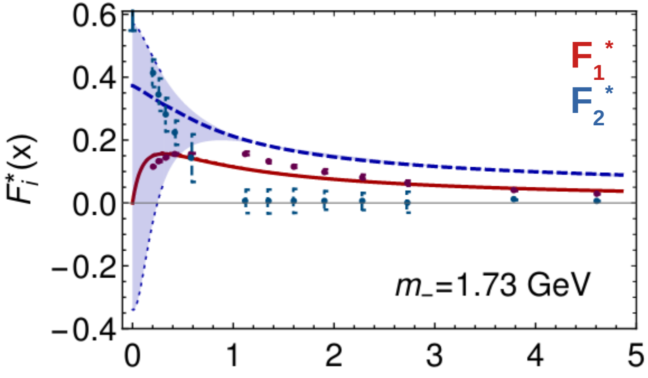
$\gamma^{(*)} p \to N(1535)\frac{1}{2}^{-}$ transition

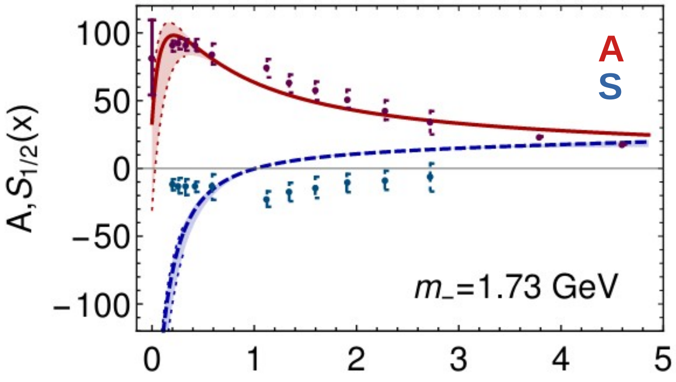


Raya:2021pyr

N → N(1535): **Numerical results**

- Transition **form factors** and **helicity amplitudes**:





Raya:2021pyr

$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$

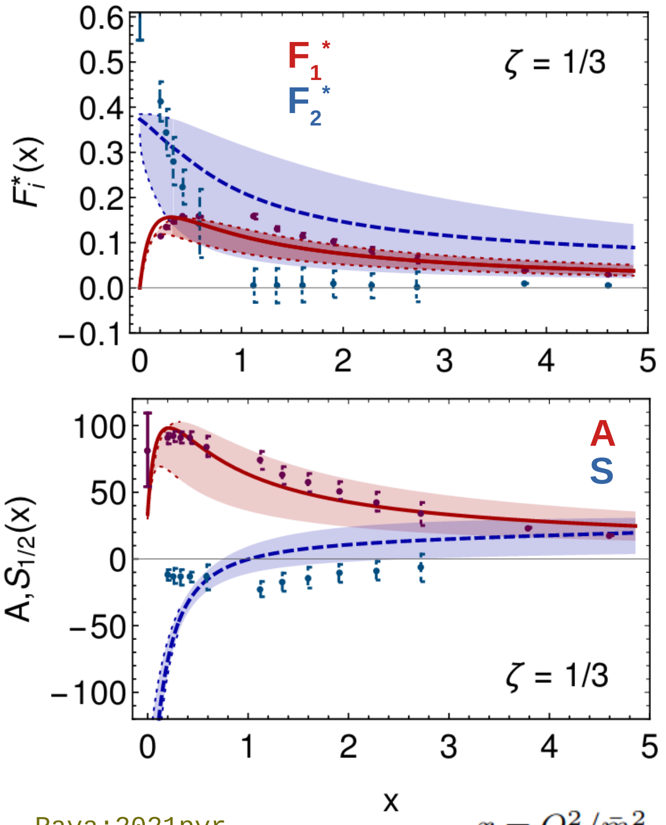
- The form factor ***F₁**** is **insensitive** to the quark **AMM**
  - Conversely, F_2^* is **rather sensitive** to it.
- F_1^* displays a **fair agreement** with CLAS data
- F_2^* becomes **too hard** as x increases, but it agrees in magnitude with data for ζ=1/3
- The transverse helicity amplitude **A** is **sensitive** to the **AMM**, but still in **agreement** with the experiment.
  - The longitudinal one, ***S***, 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

N → N(1535): Numerical results

- Transition **form factors** and **helicity amplitudes**:



Raya:2021pyr

$x = Q^2/\bar{m}^2$, $\bar{m} = (m_+ + m_-)/2$

- Both form factors and helicity amplitudes are quite **sensitive** to the value **gDB**, *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**.

If one varies $g_{DB} \to g_{DB}(1 \pm 0.5)$, then $m_{N(1535)} = (1.67, 1.82)$ GeV and

$N(1535)\frac{1}{2}^-$	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

N → N(1535): Numerical results

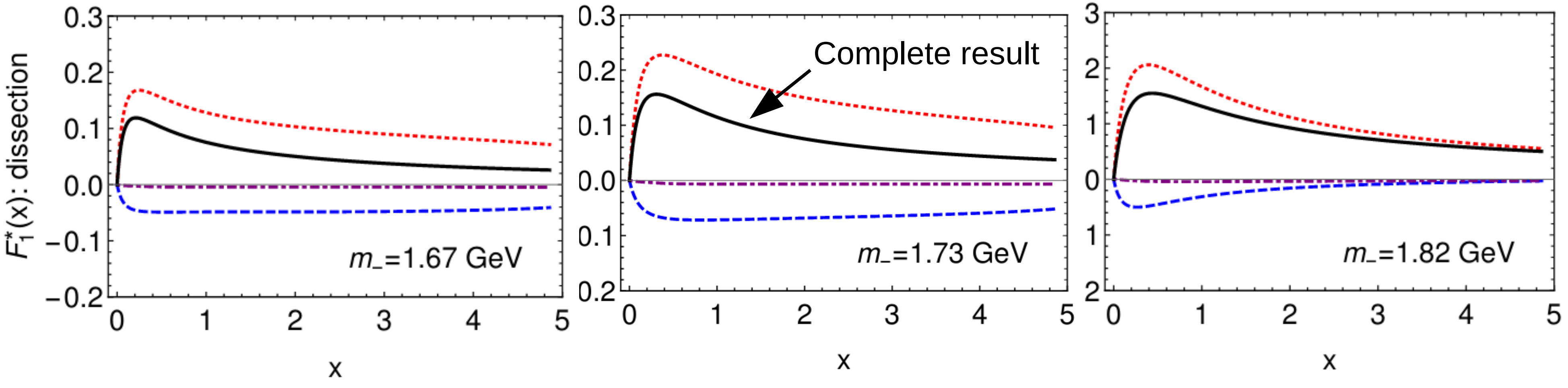
- **Dissection** of the form factors: F_1^*.

Red: Photon strikes quark Q^+Q^+

Blue: Photon strikes diquark, initial and final one have same parity D^+D^+

Purple: Photon strikes diquark, initial and final one have opposed parity D^-D^+

- The **parity-flip** contributions are practically **negligible**
- There is a **destructive interference** between the other two contributions, Q^+Q^+ D^+D^+
- In particular, the strength of Q^+Q^+, seems to be modulated by D^+D^+



N → N(1535): Numerical results

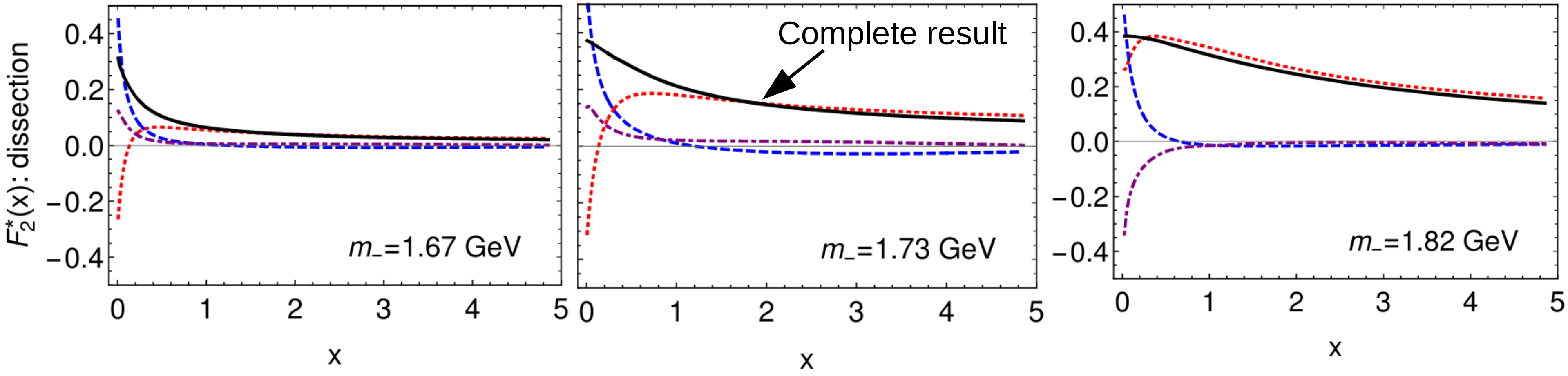
- **Dissection** of the form factors: F_2^*.

Red: Photon strikes quark Q^+Q^+

Blue: Photon strikes diquark, initial and final one have same parity D^+D^+

Purple: Photon strikes diquark, initial and final one have opposed parity D^-D^+

- The photon **strikes diquark** contribution interefere **constructively** in the light cases, but **destructively** in the heaviest case.
- This form factor is more **sensitive** to the quark **AMM**, specialy the photon **strikes quark** case.



A glimpse on

$$(\mathbf{I}, \mathbf{J}^{\mathbf{P}}) = \left(\frac{1}{2}, \frac{3}{2}^{-}\right) \;\&\; \left(\frac{3}{2}, \frac{3}{2}^{-}\right)$$

baryons...

$$\Delta(1700)\frac{3}{2}^{-} \qquad N(1520)\frac{3}{2}^{-}$$

Δ(1700), N(1520): Highlights

- In a momentum-dependent interaction, the **Δ(1700)** state is described by **16 amplitudes.**

Liu:2022nku

$$\mathcal{V}^1_{\lambda\rho}(k;Q) = \delta_{\lambda\rho}\mathbb{I}_{\rm D}\,, \quad (4a)$$
$$\mathcal{V}^2_{\lambda\rho}(k;Q) = \tfrac{i}{\sqrt{5}}[2\gamma^\perp_\lambda \hat{k}^\perp_\rho - 3\delta_{\lambda\rho}\gamma\cdot\hat{k}^\perp]\,, \quad (4b)$$
$$\mathcal{V}^3_{\lambda\rho}(k;Q) = -i\gamma^\perp_\lambda \hat{k}^\perp_\rho\,, \quad (4c)$$
$$\mathcal{V}^4_{\lambda\rho}(k;Q) = \sqrt{3}\hat{Q}_\lambda \hat{k}^\perp_\rho\,, \quad (4d)$$
$$\mathcal{V}^5_{\lambda\rho}(k;Q) = 3\hat{k}^\perp_\lambda \hat{k}^\perp_\rho - \delta_{\lambda\rho} - \gamma^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4e)$$
$$\mathcal{V}^6_{\lambda\rho}(k;Q) = \gamma^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4f)$$
$$\mathcal{V}^7_{\lambda\rho}(k;Q) = -i\sqrt{3}\hat{Q}_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4g)$$
$$\mathcal{V}^8_{\lambda\rho}(k;Q) = \tfrac{i}{\sqrt{5}}[\delta_{\lambda\rho}\gamma\cdot\hat{k}^\perp + \gamma^\perp_\lambda \hat{k}^\perp_\rho - 5\hat{k}^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp]\,.$$

- The **N(1520)** case is even more complicated **(20 amplitudes).**

Liu:2022ndb

+

$$\mathcal{X}^1_\rho(k;Q) = i\sqrt{3}\,\hat{k}^\perp_\rho \gamma_5\,,$$
$$\mathcal{X}^2_\rho(k;Q) = i\gamma\cdot\hat{k}^\perp\,\mathcal{X}^1_\rho(k;Q)\,,$$

(2 x 8) + (2 x 2) = **20**

Δ(1700), N(1520): Highlights

- In a momentum-dependent interaction, the **Δ(1700)** state is described by **16 amplitudes.**

Liu:2022nku

$$\mathcal{V}^1_{\lambda\rho}(k;Q) = \delta_{\lambda\rho}\mathbb{I}_{\rm D}\,, \quad (4a)$$

$$\mathcal{V}^2_{\lambda\rho}(k;Q) = \frac{i}{\sqrt{5}}[2\gamma^\perp_\lambda \hat{k}^\perp_\rho - 3\delta_{\lambda\rho}\gamma\cdot\hat{k}^\perp]\,, \quad (4b)$$

$$\mathcal{V}^3_{\lambda\rho}(k;Q) = -i\gamma^\perp_\lambda \hat{k}^\perp_\rho\,, \quad (4c)$$

$$\mathcal{V}^4_{\lambda\rho}(k;Q) = \sqrt{3}\hat{Q}_\lambda \hat{k}^\perp_\rho\,, \quad (4d)$$

$$\mathcal{V}^5_{\lambda\rho}(k;Q) = 3\hat{k}^\perp_\lambda \hat{k}^\perp_\rho - \delta_{\lambda\rho} - \gamma^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4e)$$

$$\mathcal{V}^6_{\lambda\rho}(k;Q) = \gamma^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4f)$$

$$\mathcal{V}^7_{\lambda\rho}(k;Q) = -i\sqrt{3}\hat{Q}_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp\,, \quad (4g)$$

$$\mathcal{V}^8_{\lambda\rho}(k;Q) = \frac{i}{\sqrt{5}}[\delta_{\lambda\rho}\gamma\cdot\hat{k}^\perp + \gamma^\perp_\lambda \hat{k}^\perp_\rho - 5\hat{k}^\perp_\lambda \hat{k}^\perp_\rho \gamma\cdot\hat{k}^\perp]\,.$$

- The **N(1520)** case is even more complicated **(20 amplitudes).**

Liu:2022ndb

$$+ \quad \mathcal{X}^1_\rho(k;Q) = i\sqrt{3}\,\hat{k}^\perp_\rho \gamma_5\,,$$
$$\mathcal{X}^2_\rho(k;Q) = i\gamma\cdot\hat{k}^\perp\,\mathcal{X}^1_\rho(k;Q)\,,$$

(2 x 8) + (2 x 2) = **20**

- But the **SCI kills them all**: Only survives one structure associated with the **$1^\pm$ correlations.**
- And then, the low masses of the **Δ(1700)** and **N(1520)** states leave out the **1^-**

Δ(1700), N(1520): Highlights

- Thus, the **Δ(1700)** and **N(1520)** states, in the **SCI**, are characterized by a single Faddeev amplitude, associated with the **1^+ diquark**.
  - Then they become indistinguishable, with mass **$m_\Delta = 2.08$ GeV**
  - We break this degeneracy by modifying the couplings in the Faddeev kernels, hence producing: **$m_{N^*}/m_\Delta = 0.85$**

Yin:2019bxe

Yin:2021uom

$\Delta(1700)$, N(1520): Highlights

- Thus, the **$\Delta(1700)$** and **N(1520)** states, in the **SCI**, are characterized by a single Faddeev amplitude, associated with the **1^+ diquark**.
  - Then they become indistinguishable, with mass **m_Δ = 2.08 GeV**
  - We break this degeneracy by modifying the couplings in the Faddeev kernels, hence producing: **m_{N^*}/m_Δ = 0.85**

Yin:2019bxe

Yin:2021uom

- In realistic interactions, however, this is the correlation that **contributes the most** to the normalization of the **wavefunction** and the **mass**.

Liu:2022nku Liu:2022ndb

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

mass %		amplitude %	
1^+	1^-	1^+	1^-
99.98	0.02	94.20	5.80

$N(1520)\frac{3}{2}^-$

B. mass %	$N(1520)\frac{3}{2}^-$
1^+	91.6
& 0^+	8.3
& 0^-	0.1
& 1^-	0.0

C. FA %	$N(1520)\frac{3}{2}^-$
1^+	70.1
0^+	20.3
0^-	6.2
1^-	3.4

$\Delta(1700)$, N(1520): Highlights

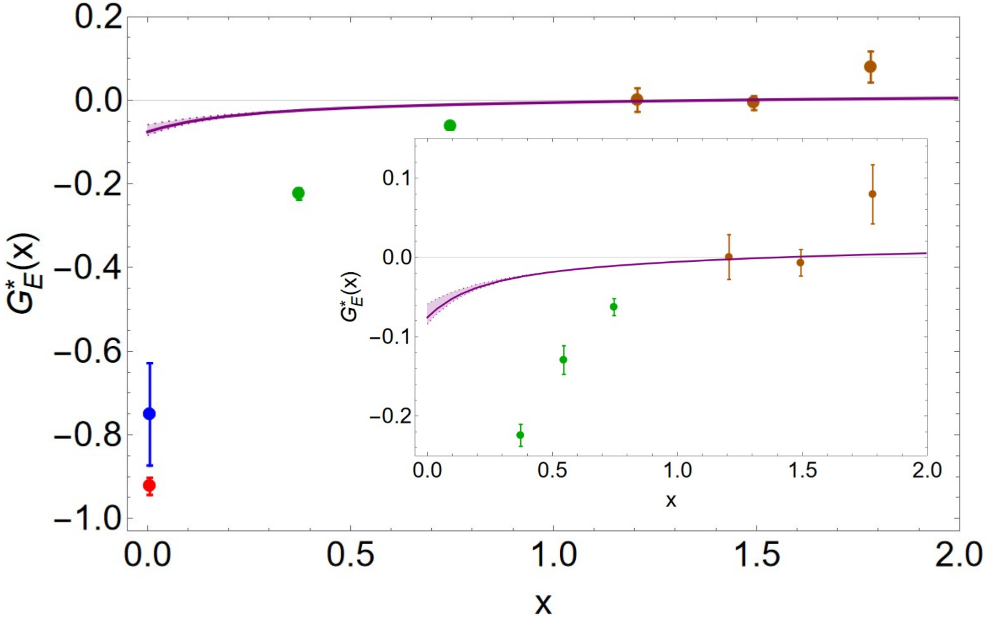
- Thus, the **$\Delta(1700)$** and **N(1520)** states, in the **SCI**, are characterized by a single Faddeev amplitude, associated with the **1^+ diquark**.
  - Then they become indistinguishable, with mass **$m_\Delta = 2.08$ GeV** Yin:2019bxe Yin:2021uom
  - We break this degeneracy by modifying the couplings in the Faddeev kernels, hence producing: **$m_{N^*}/m_\Delta = 0.85$**
- In realistic interactions, however, this is the correlation that **contributes the most** to the normalization of the **wavefunction** and the **mass**. Liu:2022nku Liu:2022ndb

> Can the **SCI** provide an **accurate** description of the **TFFs**?
>
> $$\gamma^* N \rightarrow \Delta^-(1700), N^*(1520)$$

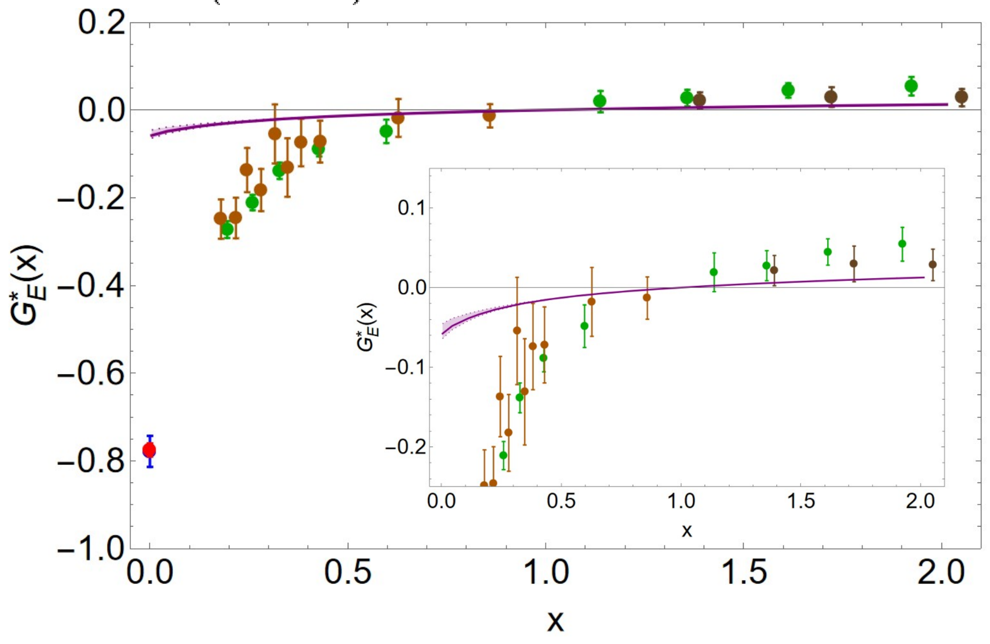
p → Δ(1700), N(1520): TFFs

- The G_E^* transition form factor:

$\Delta(1700)$



$N(1520)$



$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$:

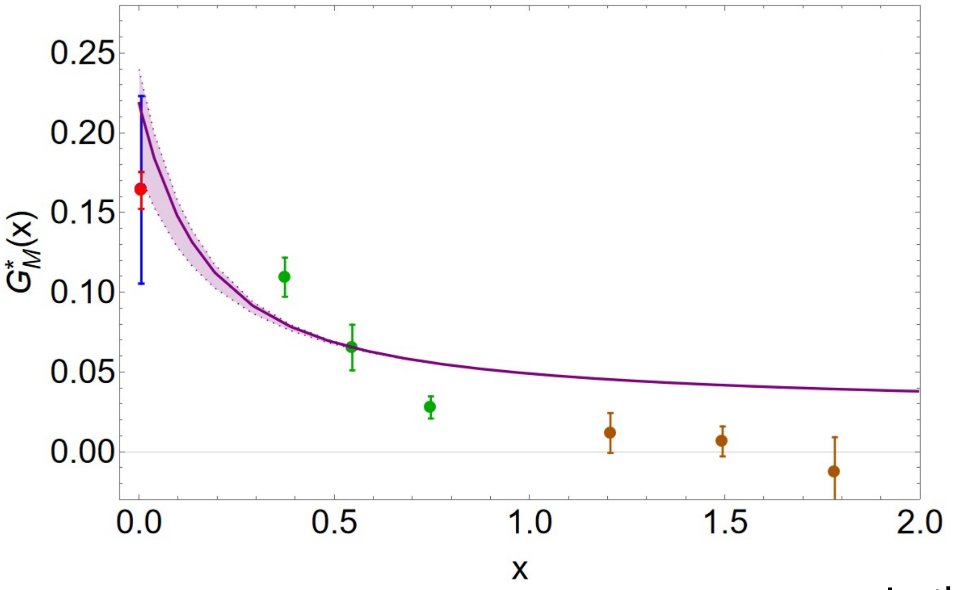
➔ The right patterns are captured, but not the fine **details**.

Data from: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

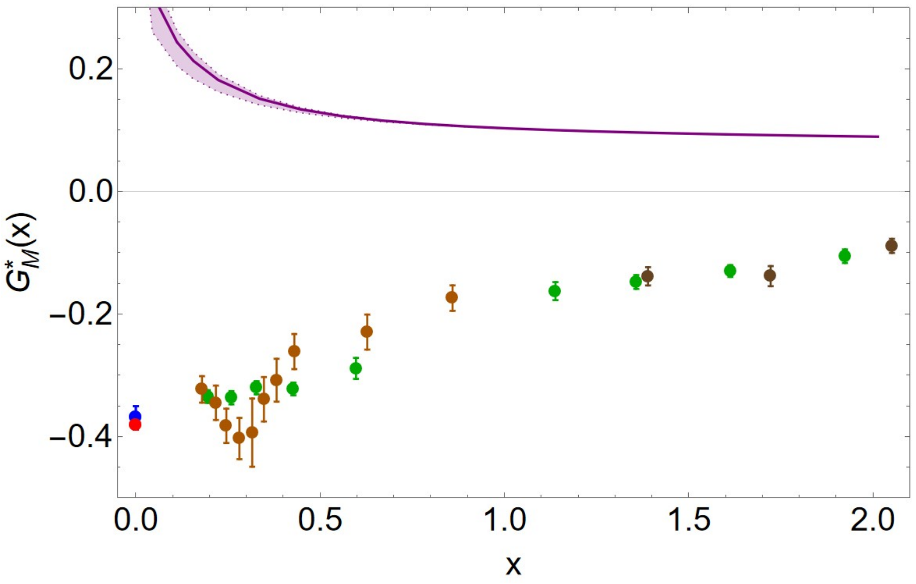
p → Δ(1700), N(1520): TFFs

- The G_M^* transition form factor:

$\Delta(1700)$



$N(1520)$



$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$:

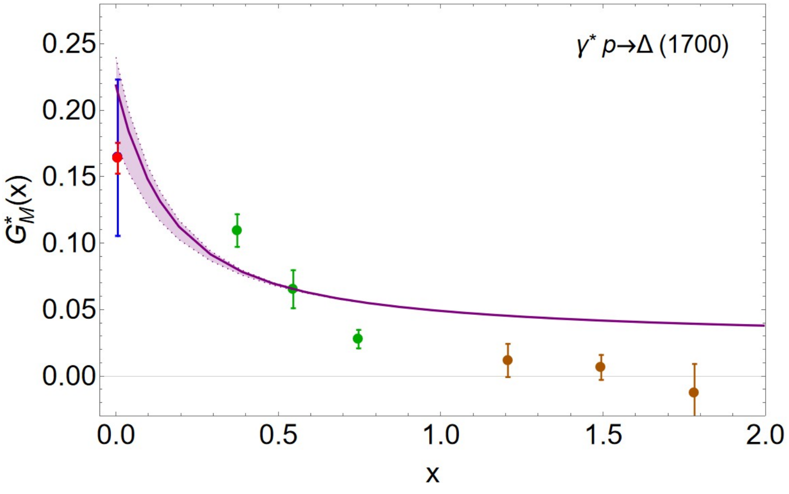
➔ In the **N(1520)** case, there is an apparent sign flip!

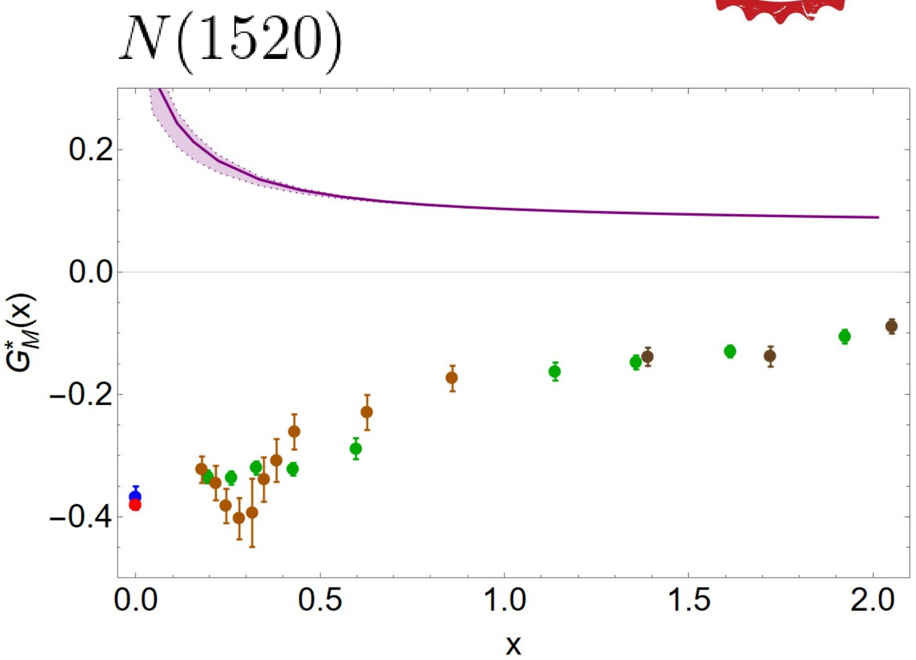
Data from: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

p → Δ(1700), N(1520): TFFs

PRELIMINARY

- The G_M^* transition form factor:



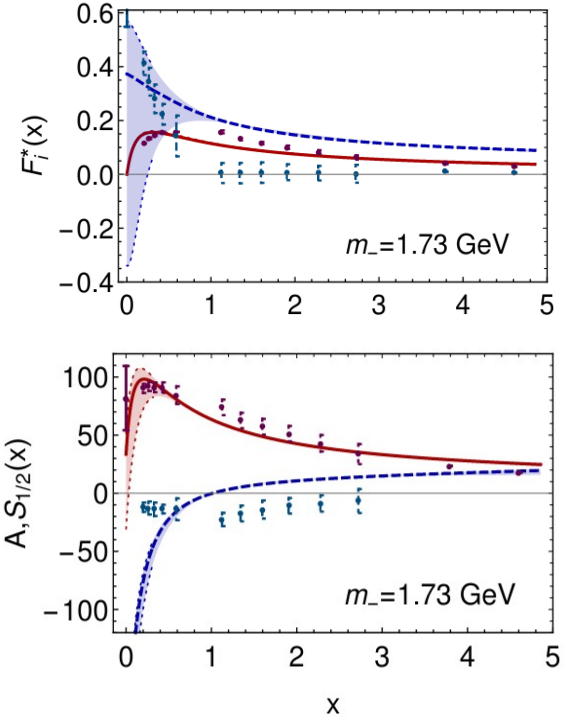


C. FA %	$N(1520)\frac{3}{2}^-$
1^+	70.1
0^+	20.3
0^-	6.2
1^-	3.4

- In the **N(1520)** case, there is an apparent sign flip!
  - Computed wavefunction is **lacking components**!

Data from: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

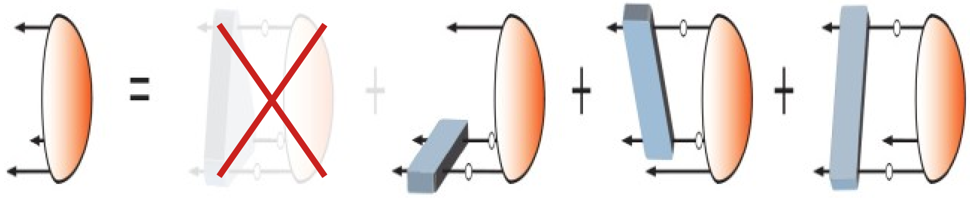
Summary

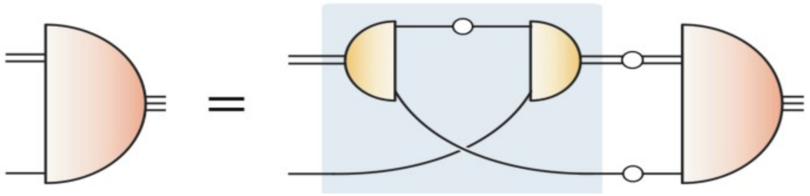

0.6
0.4
0.2
0.0
−0.2
−0.4
$F_i^*(x)$
m_-=1.73 GeV
0
1
2
3
4
5
100
50
0
−50
−100
$A, S_{1/2}(x)$
m_-=1.73 GeV
x


I just need the main ideas

Summary

- **Theoretical** evidence suggests the existence of **dynamical** **diquark** correlations:
  - The **3-body** **Faddeev** equation kernel self-arranges in blocks with spin-flavor structure of diquarks.
  - The **2-body** **BSE** reveal strong correlations in quark-quark scattering channels.
  - ➔ Consequently, the existence of non-point-like **diquarks** within baryons should be **connected** with EHM phenomena.

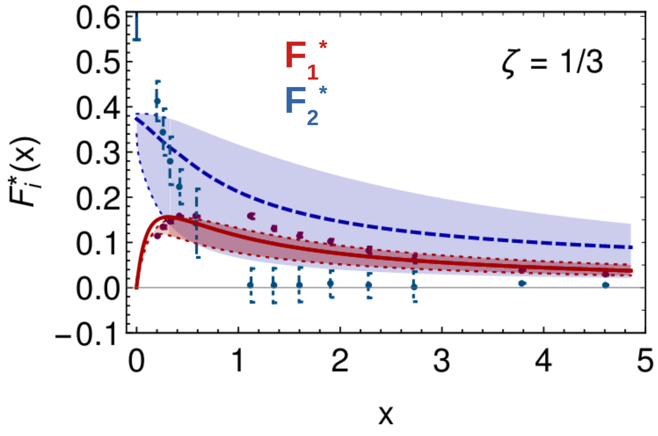




Summary

- **Theoretical** evidence suggests the existence of **dynamical** **diquark** correlations:
  - The **3-body** **Faddeev** equation kernel self-arranges in blocks with spin-flavor structure of diquarks.
  - The **2-body** **BSE** reveal strong correlations in quark-quark scattering channels.
  - → Consequently, the existence of non-point-like **diquarks** within baryons should be **connected** with EHM phenomena.

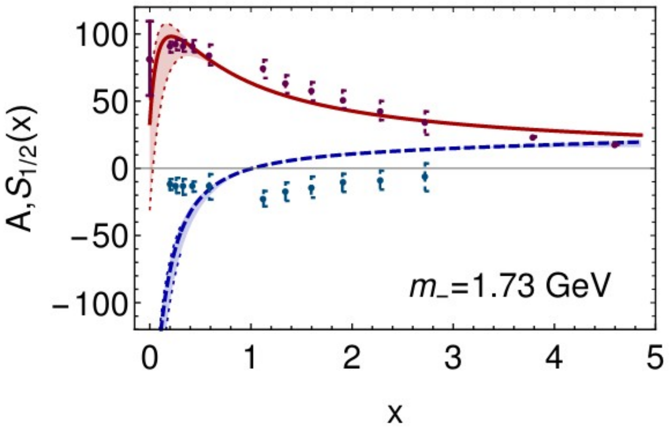
- Some **experimental** observables could yield to **unambiguous signals** of the presence of dynamical diquark correlations:
  - → Nucleon **transition form factors** and structure functions, spectroscopy of exotic hadrons, etc.
  - → The electromagnetic transitions are highly **sensitive** to the **baryon wavefunction**, and a path to better understand **DCSB**.



Summary

- **Theoretical** evidence suggests the existence of **dynamical** **diquark** correlations:
  - The **3-body** **Faddeev** equation kernel self-arranges in blocks with spin-flavor structure of diquarks.
  - The **2-body** **BSE** reveal strong correlations in quark-quark scattering channels.
  - Consequently, the existence of non-point-like **diquarks** within baryons should be **connected** with EHM phenomena.

- Some **experimental** observables could yield to **unambiguous signals** of the presence of dynamical diquark correlations:
  - Nucleon **transition form factors** and structure functions, spectroscopy of exotic hadrons, etc.
  - The electromagnetic transitions are highly **sensitive** to the **baryon wavefunction**, and a path to better understand **DCSB**.



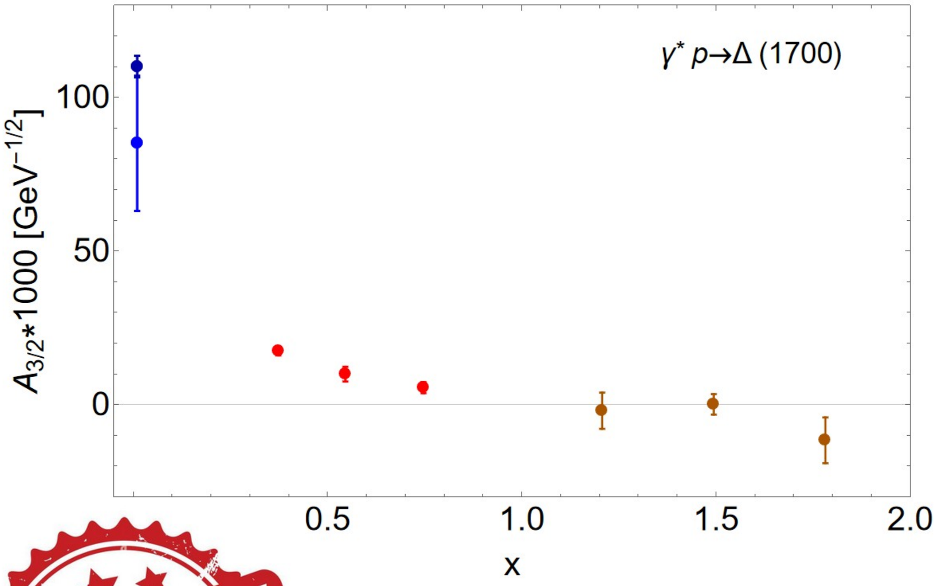
- Overall, the **SCI** exhibits a **fair agreement** with existing **data.** Then we anticipate sensible outcomes within more sophisticated approaches to **QCD**.

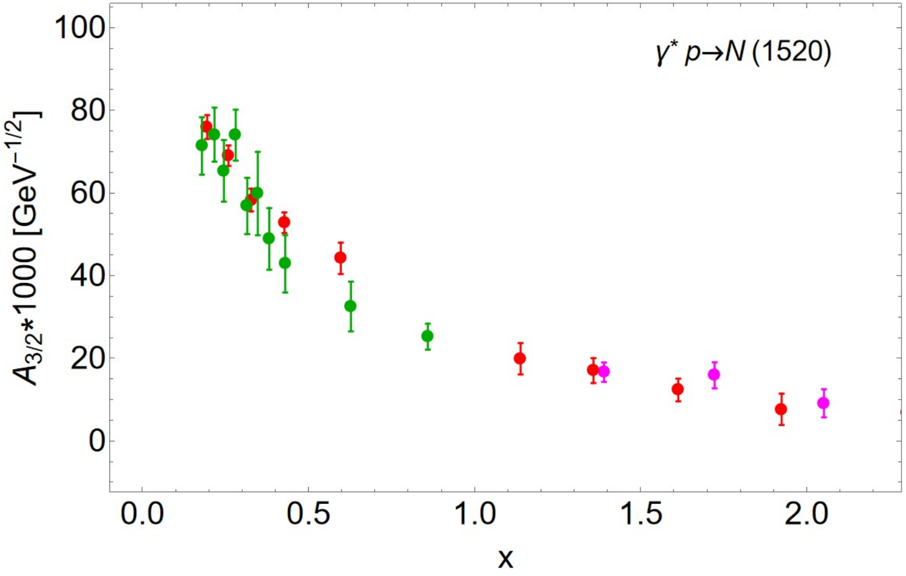
p → Δ(1700), N(1520): TFFs

$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$

- The $A_{3/2}$ helicity amplitude:

Data from: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/





→ In the **Δ(1700)** case, there is an apparent sign flip!
(recall, in this case, the $A_{1/2}$ helicity amplitude is positive)

Ramalho:2023hqd

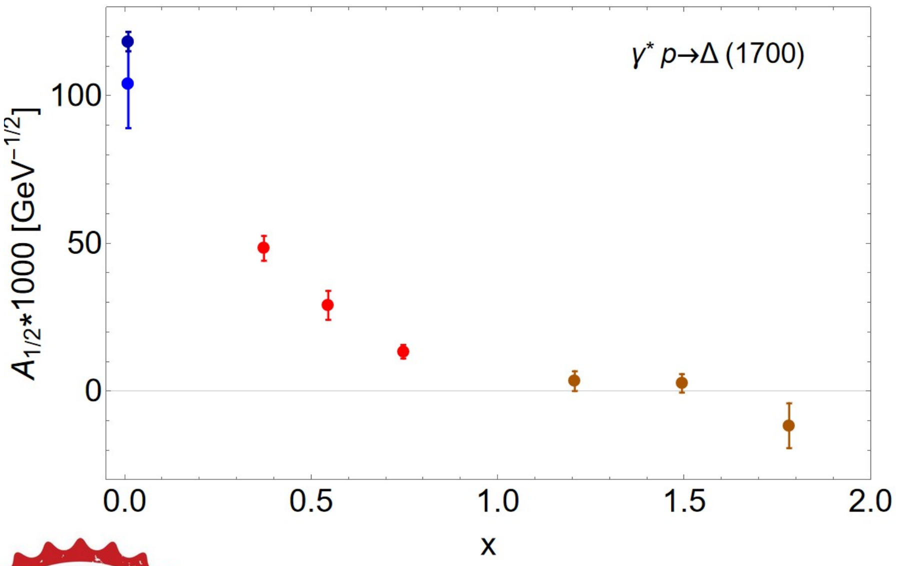
$$G_M(Q^2) = -F_{1-}\left(\frac{1}{\sqrt{3}}A_{3/2}(Q^2) - A_{1/2}(Q^2)\right)$$

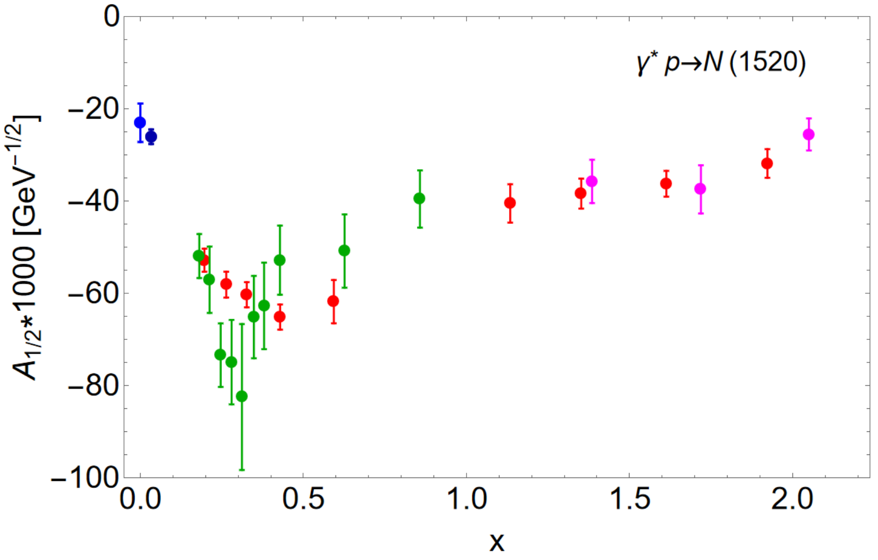
p → Δ(1700), N(1520): TFFs

$x = Q^2/\bar{m}^2$, $\bar{m} = (m_+ + m_-)/2$:

- The $A_{1/2}$ helicity amplitude:

Data from: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/





➔ In the **Δ(1700)** case, there is an apparent sign flip!
(recall, in this case, the $A_{1/2}$ helicity amplitude is positive)

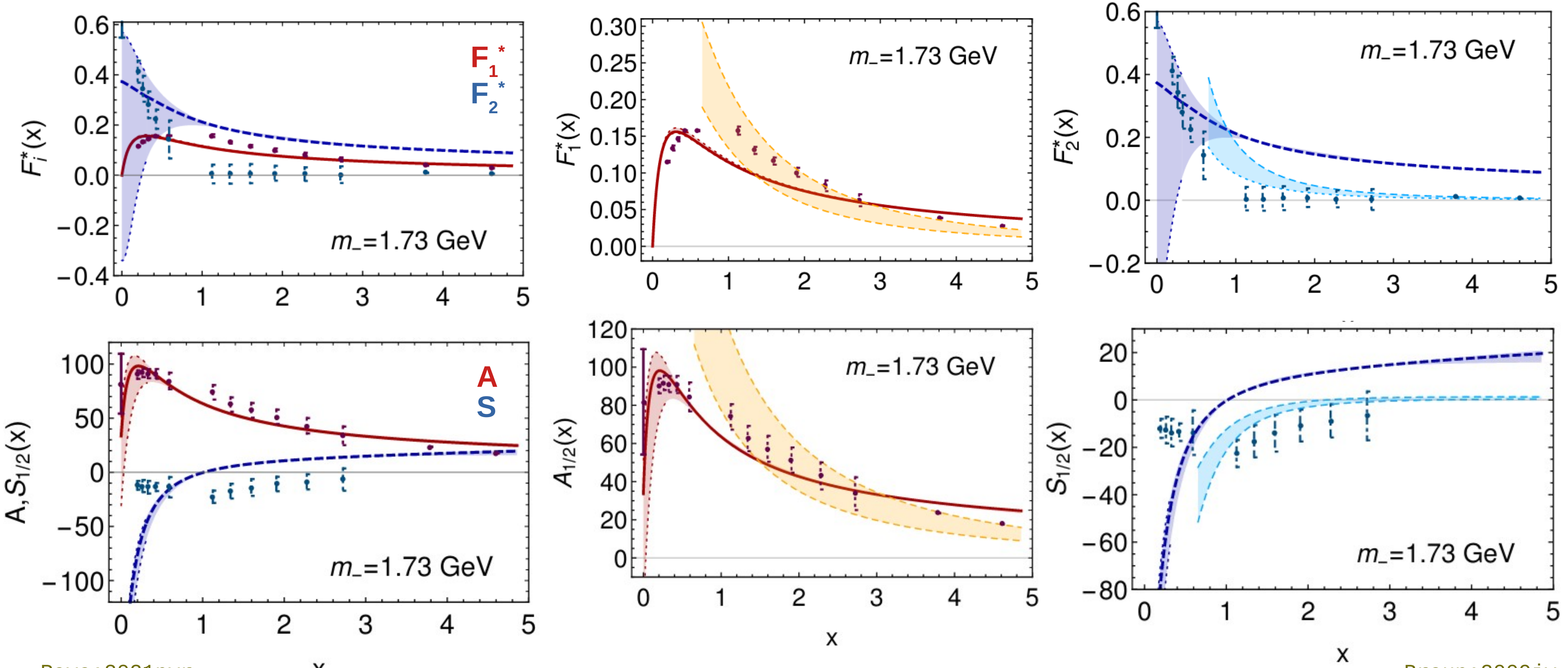
Ramalho:2023hqd

$$G_M(Q^2) = -F_{1-}\left(\frac{1}{\sqrt{3}}A_{3/2}(Q^2) - A_{1/2}(Q^2)\right)$$

N → N(1535): Numerical results

$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$

- Transition **form factors** and **helicity amplitudes**:



Raya:2021pyr CLAS:2009ces Braun:2009jy