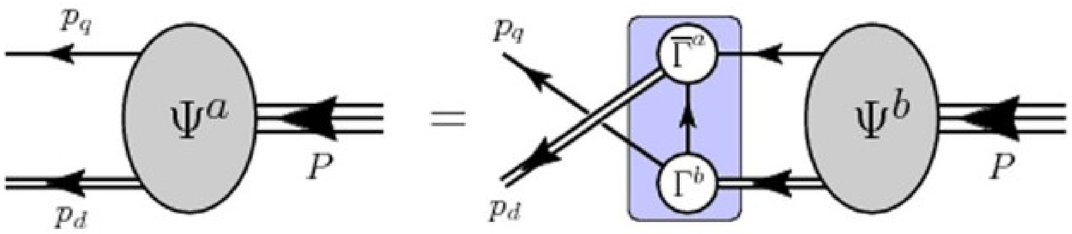
Dynamical diquarks in baryon transitions

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

Khépani Raya Montaño

Bashir, Roberts, Segovia, etc..



Universidad de Huelva

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QCD: Basic Facts

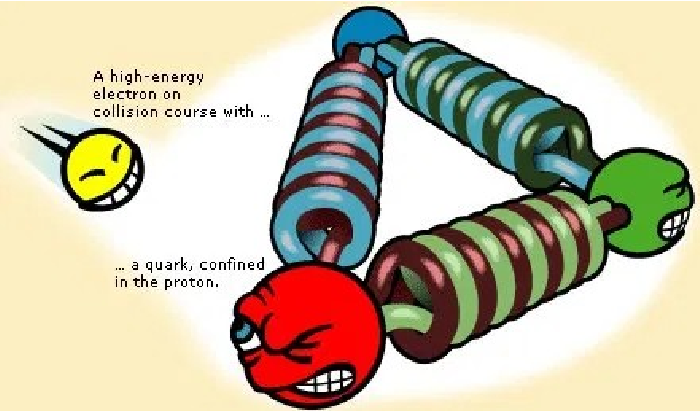
- QCD is characterized by two **emergent** phenomena: confinement and dynamical generation of mass (DGM).

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

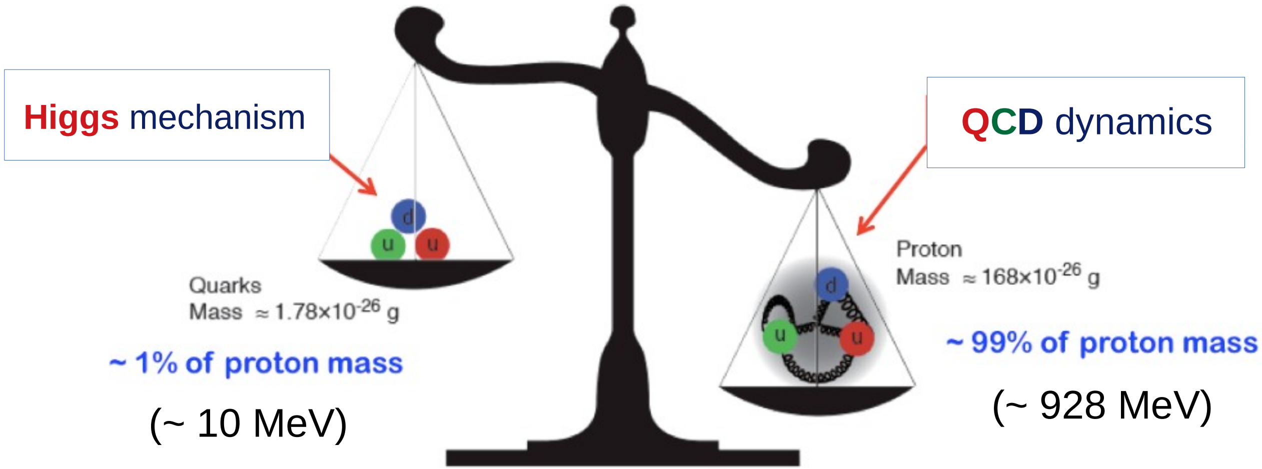
$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu\,,$$

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

- 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**



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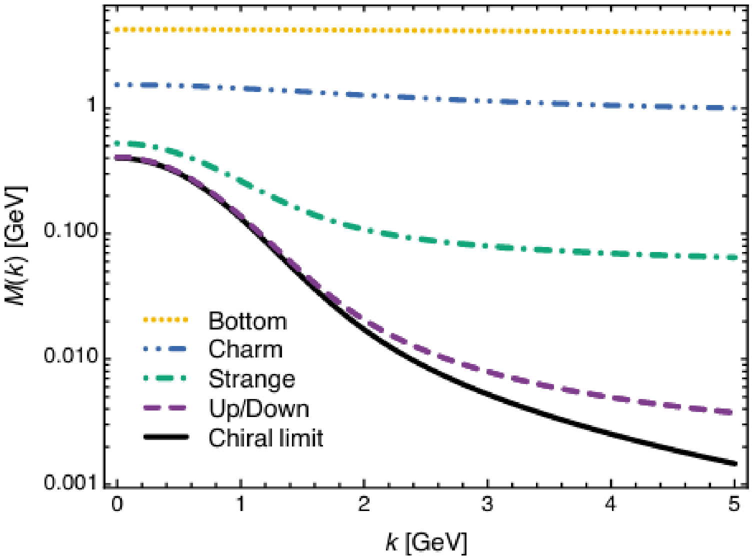
Can we trace them down to fundamental d.o.f?

Dynamical masses

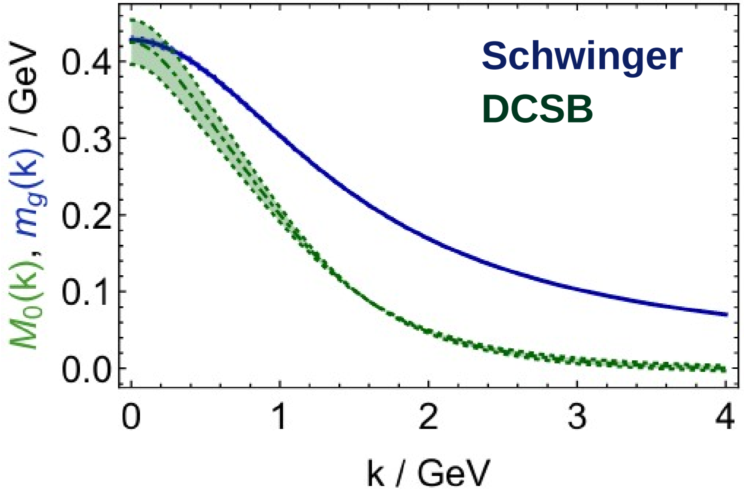
(Dynamical Chiral Symmetry Breaking)



"Higgs" masses

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

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



Gluon and quark *running masses*

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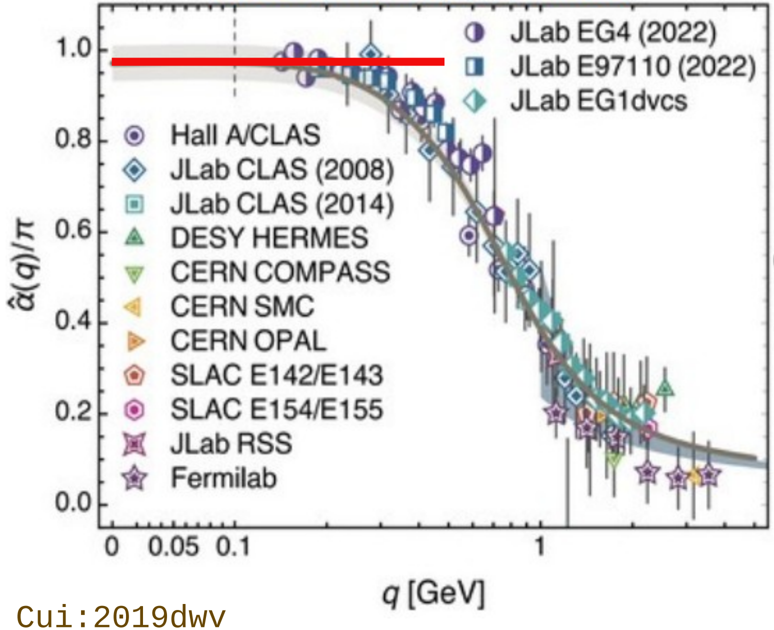
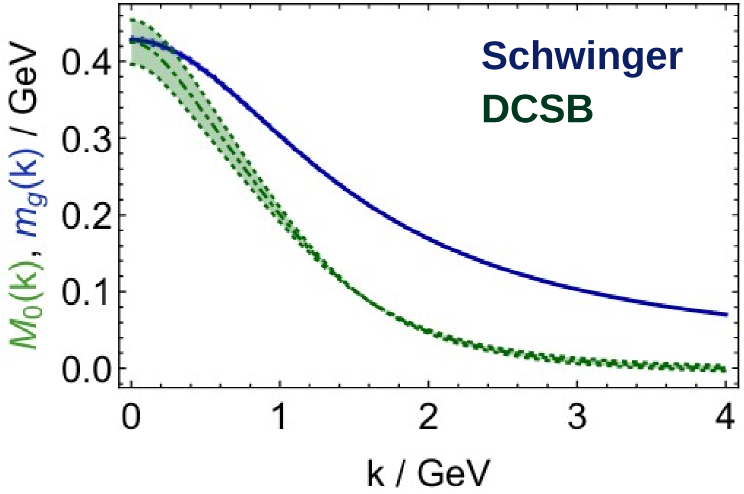
(figure: D. Binosi's courtesy!)



Cui:2019dwv

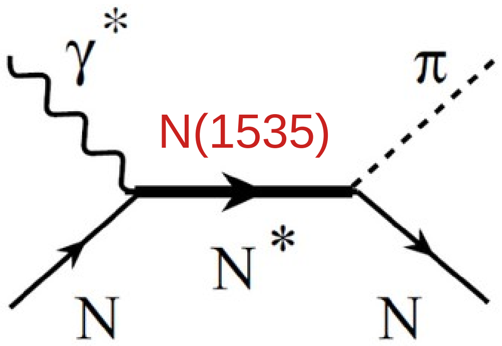
- Emergence of hadron masses (EHM) from QCD **dynamics**



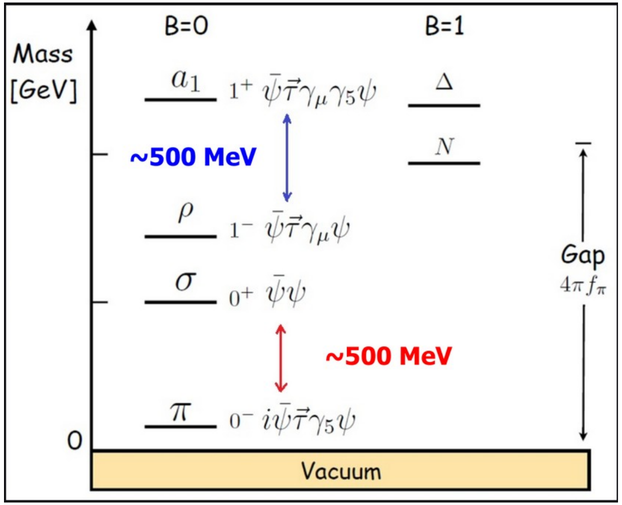
Gluon and quark *running masses*

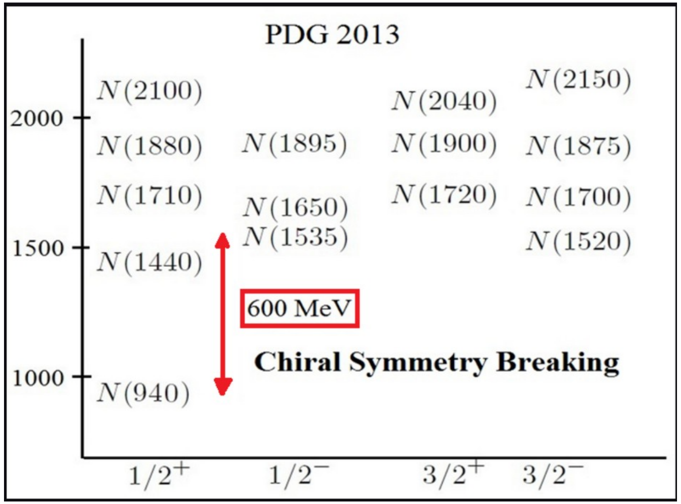
The proton: Understanding QCD

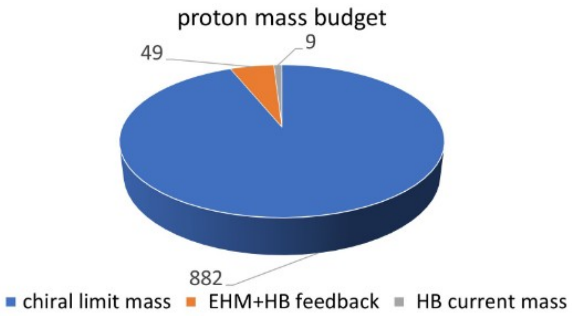
- Now, just as we learned from the **excited** states of the **hydrogen** **atom**, we should learn from the **excited** states of the **nucleon**.



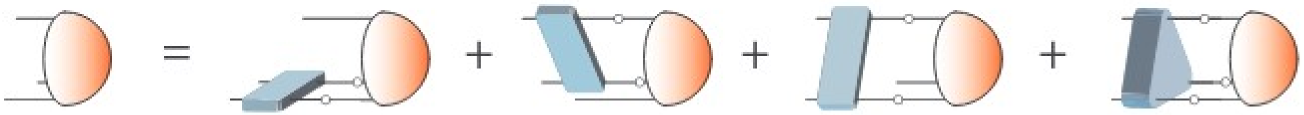
- In particular, the role of **DCSB** could be well understood by analyzing **structural differences** of hadrons and their **parity partners**.

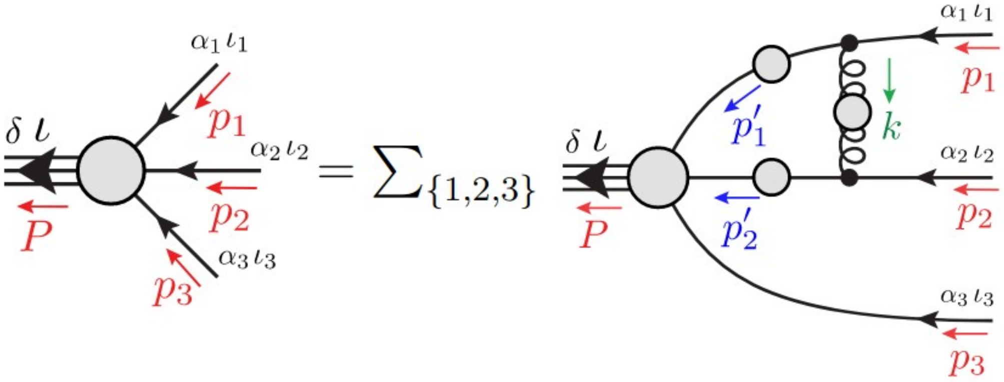






Baryon Faddeev equation





Eichmann:2016yit

Qin:2019hgk

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.

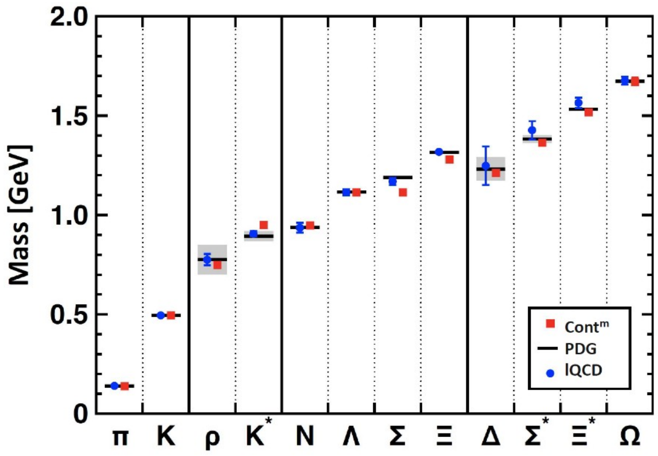
  (This implies, however, an outstanding challenge).

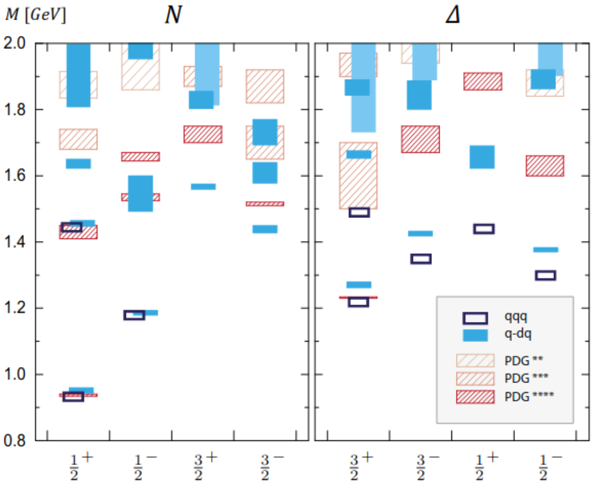
Eichmann:2016yit

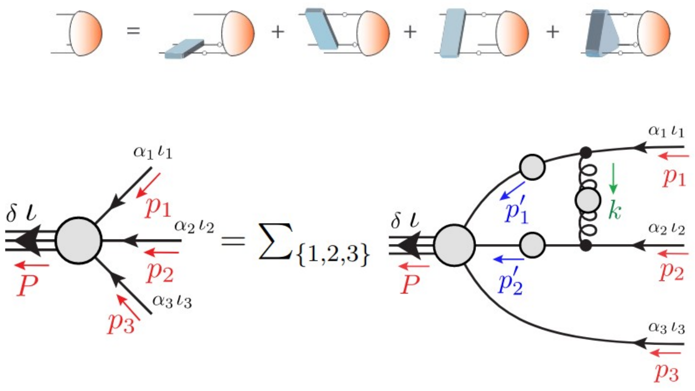
Qin:2019hgk

- 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

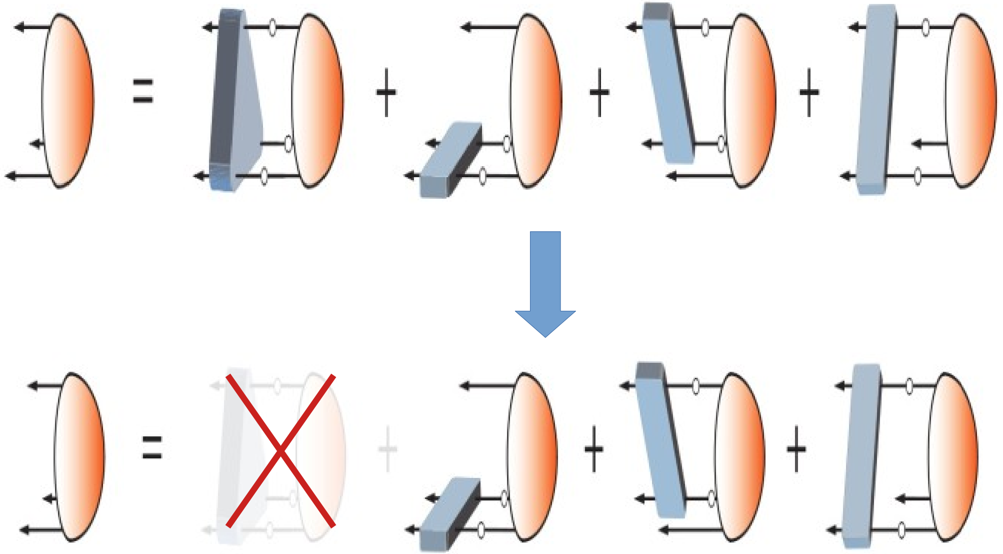
- Strong evidence anticipates the formation of **dynamical** quark-quark correlations (**diquarks**) within **baryons,** for instance:
  - The **primary three-body** force **binding** the quarks within the baryon vanishes when projected onto the color singlet channel.

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

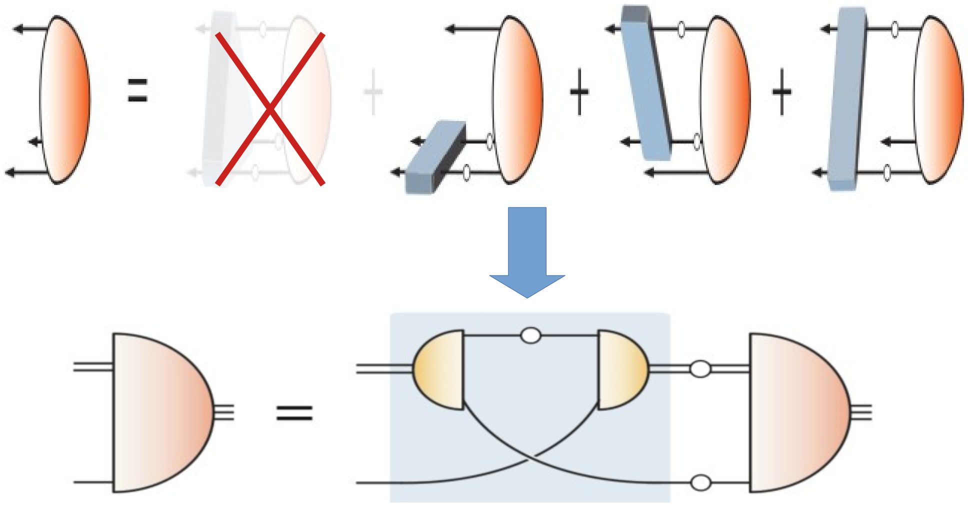


Baryons: Faddeev equation

- 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.



Dyamical Quark-diquark picture

Non-pointlike diquarks:

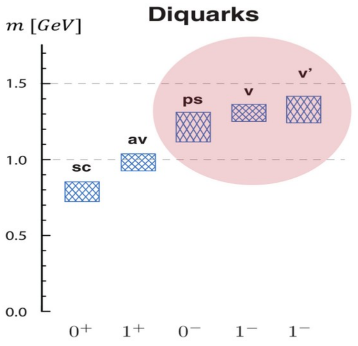
- Color anti-triplet
- Fully interacting
- Origins related to **EHM** phenomena

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**:

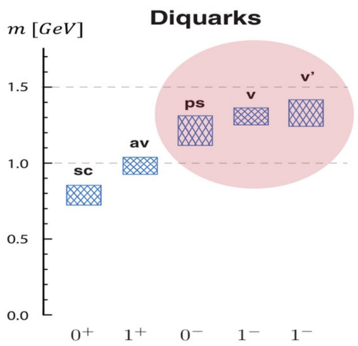
$$m_{[ud]_{0+}} = 0.7-0.8\,\text{GeV}, \quad m_{\{uu\}_{1+}} = 0.9-1.1\,\text{GeV}$$

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

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

Baryons: Quark-diquark picture

- When the comparison is possible, the dynamical **quark-diquark** picture turns out to be compatible with the **three-body** picture:



	N	Λ	Σ	Ξ	Δ	Σ*	Ξ*	Ω
Quark-diquark model [302]	$0.94^{(*)}$	1.13	1.14	1.32	$1.23^{(*)}$	1.38	1.52	1.67
Quark-diquark (RL) [305, 362]	0.94				1.28			
Three-quark (RL) [306, 316, 317]	0.94	1.07	1.07	1.24	1.22	1.33	1.47	1.65
Lattice [399]	$0.94^{(*)}$	1.12 (2)	1.17 (3)	1.32 (2)	1.30 (3)	1.46 (2)	1.56 (2)	1.67 (2)
Experiment (PDG)	0.938	1.116	1.193	1.318	1.232	1.384	1.530	1.672

Eichmann:2016yit

Non-pointlike diquarks:
- Color anti-triplet
- Fully interacting
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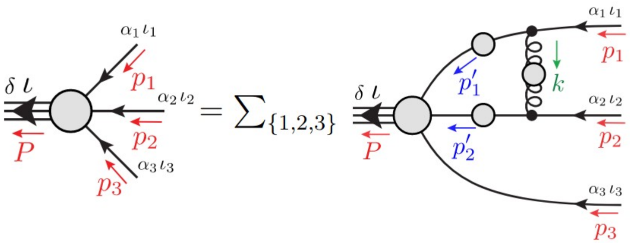
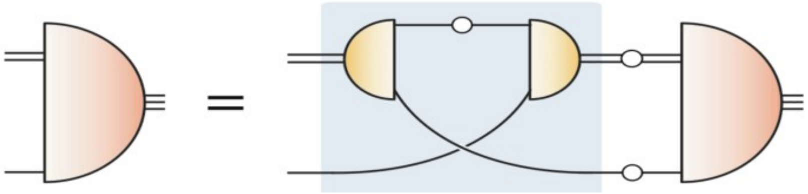


Three-body picture (**RL**)



Dyamical Quark-diquark picture

Contact Interaction model:
Some highlights

Contact **Interaction**

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

Roberts:2010rn

Gutierrez-Guerrero:2010waf

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

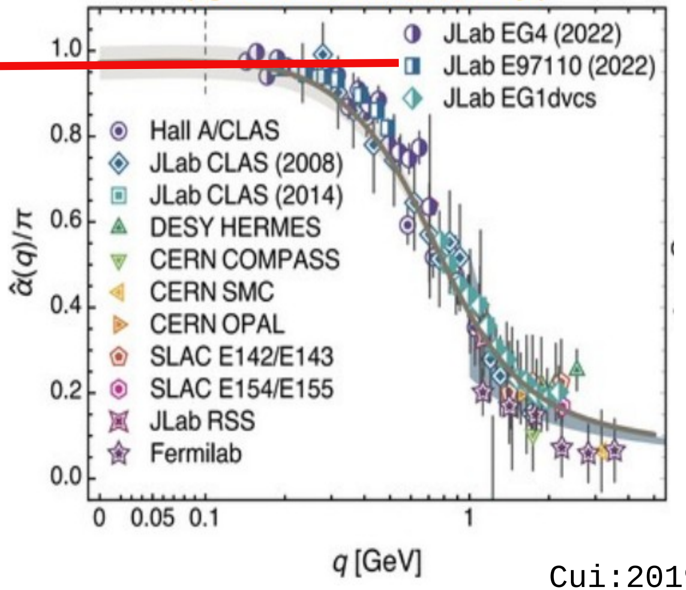
Infrared strength $\alpha_{\rm IR} = 0.93\pi$

Compatible with modern computations.

> **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

(figure: D. Binosi's courtesy!)



Cui:2019dwv

Contact Interaction

- Let us now consider 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:**

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

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

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

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

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

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

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

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

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

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

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

- 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**.

  - 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:

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

Introduces a vector meson pole in the timelike axis.

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

Quark anomalous magnetic moment (AMM) term

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

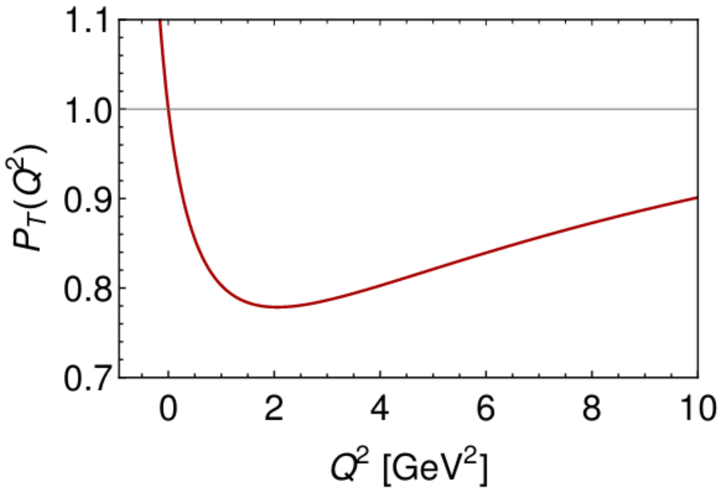
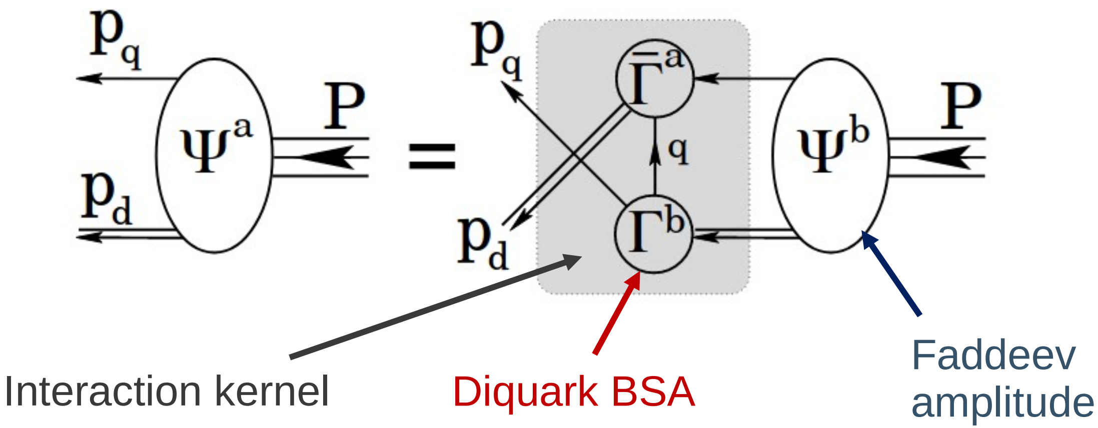


Fig. 9 Photon+quark vertex dressing function in Eq. (A.3). As in any symmetry preserving treatment of photon+quark interactions, $P_{\mathrm{T}}(Q^2)$ exhibits a pole at $Q^2 = -m_\rho^2$. Moreover, $P_{\mathrm{T}}(Q^2 = 0) = 1 = P_{\mathrm{T}}(Q^2 \to \infty)$.

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**:

$$S(k) \to \frac{g_8^2}{M_u} \qquad g_8 = 1.18$$

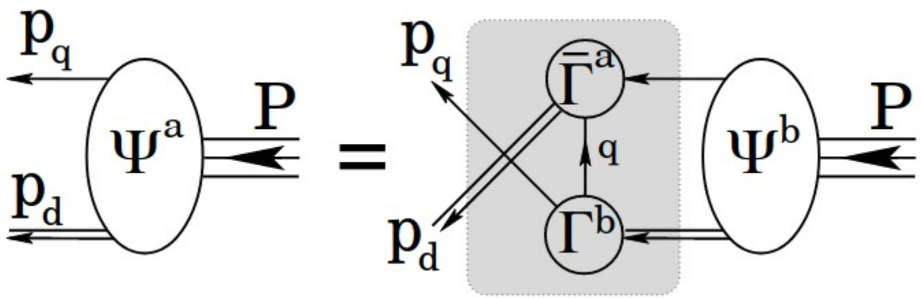
- The kernel penalizes the contribution of diquarks whose parity is opposite to that of the baryon, using a multiplicative factor **gDB = 0.2**

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.

- The **Faddeev** amplitude for the nucleon and its parity partner:

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

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

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

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

$$\begin{aligned}
\mathcal{S}^{\pm} &= s^{\pm}\,\mathbf{I}_{\rm D}\,\mathcal{G}^{\pm}\,, \quad i\mathcal{P}^{\pm} = p^{\pm}\,\gamma_5\,\mathcal{G}^{\pm}\,,\\
i\mathcal{A}^{\pm f}_{\mu} &= (a^{\pm f}_1\gamma_5\gamma_\mu - i a^{\pm f}_2\gamma_5\hat{P}_\mu)\,\mathcal{G}^{\pm}\,,\\
i\mathcal{V}^{\pm}_{\mu} &= (v^{\pm}_1\gamma_\mu - i v^{\pm}_2\mathbf{I}_{\rm D}\hat{P}_\mu)\gamma_5\,\mathcal{G}^{\pm}\,.
\end{aligned}$$

➔ We then arrive at an eigenvalue equation for:

$$(s^{\pm}, a^{\pm f}_1, a^{\pm f}_2, p^{\pm}, v^{\pm}_1, v^{\pm}_2)$$

Lu:2017cln

N(940) and N(1535)

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

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

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

gDB=0.2

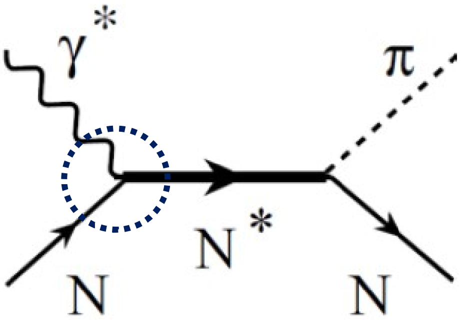
If one varies $g_{\rm DB} \to g_{\rm DB}(1 \pm 0.5)$, then $m_{N(1535)}$ $= (1.67, 1.82)$ GeV and

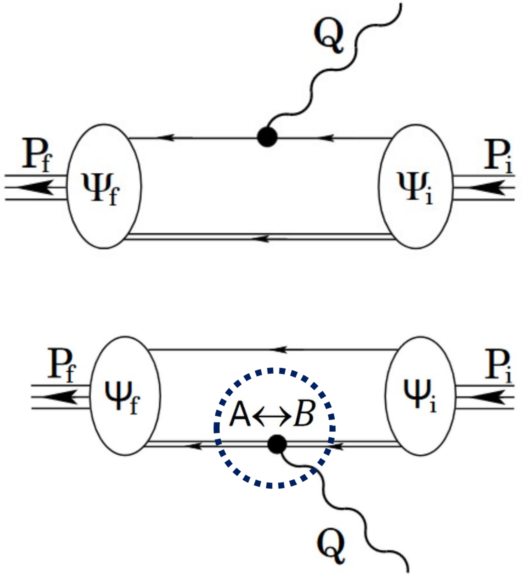
$N(1535)\frac{1}{2}^-$	s	a_1^1	a_2^1	p	v_1	v_2
$g_{\rm DB}$ 1.5	0.76	0.27	0.18	0.49	0.12	0.08
$g_{\rm DB}$ 1.0	0.66	0.20	0.14	0.68	0.11	0.09
$g_{\rm DB}$ 0.5	0.35	0.04	0.00	0.92	-0.05	0.18

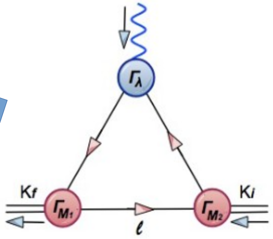
- As expected, the **nucleon** is mostly composed by **scalar** diquarks, while also exhibiting a sizeable **axial-vector** diquark component.
- With the preferred value of **gDB**, the **nucleon parity partner** exhibits an even distribution of **scalar-pseudoscalar** diquark contributions.
- The latter is in agreement with more sophisticated predictions, but should be confirmed in **beyond RL** calculations.

Chen:2019fzn

Nucleon TFFs: The approach

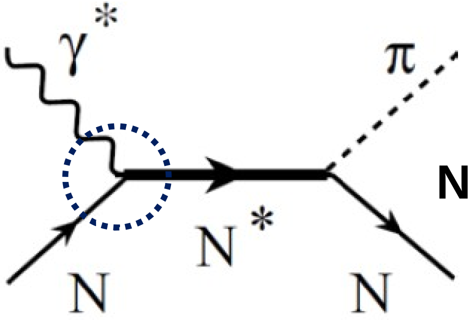






Nucleon **transition form factors**

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



N → N*

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

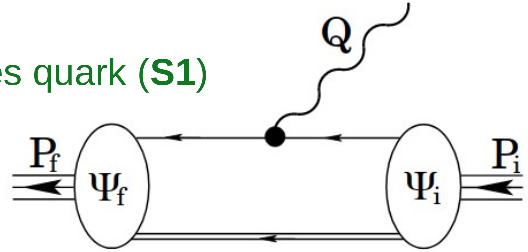
$$
\begin{aligned}
&\Gamma_\mu^{BA}(P_f, P_i) \\
&= \sum_{I=S1,S2,S3} \int_l \Lambda_+^B(P_f)\Lambda_\mu^I(l;P_f,P_i)\Lambda_+^A(P_i)\,, \\
&=: \int_l \Lambda_+^B(P_f)\left[\sum_r \mathcal{Q}_\mu^{(j)} + \sum_{s,t}\mathcal{D}_\mu^{(s,t)}\right]\Lambda_+^A(P_i)
\end{aligned}
$$

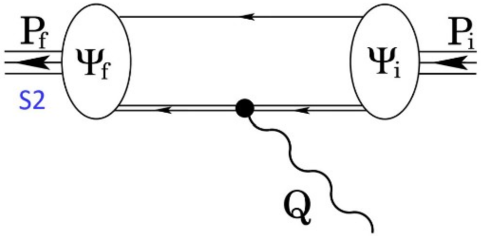
S1 diagrams

S2, S3 diagrams

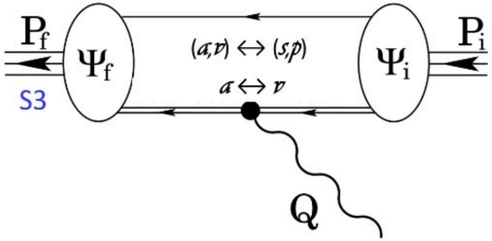
- In the **quark-diquark picture**, within the **SCI model**, the electromagnetic vertex can be splitted into 3 categories:

Photon strikes quark (**S1**)





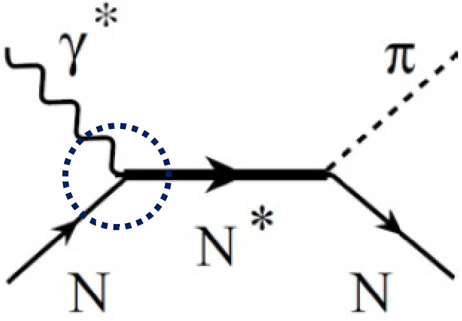
Photon strikes diquark, in an elastic scattering event (**S2**)



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

Nucleon transition form factors

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



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

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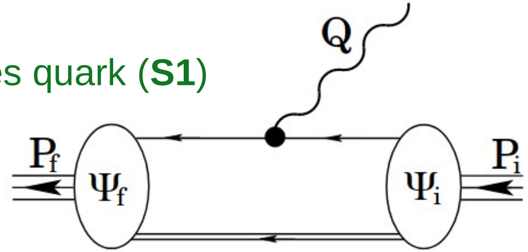
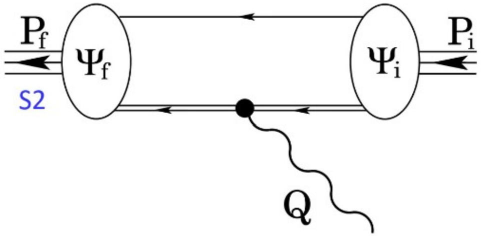


➔ Therefore, to evaluate the full electromagnetic vertex, we need, *in principle* to calculate **20 intermediate** contributions:

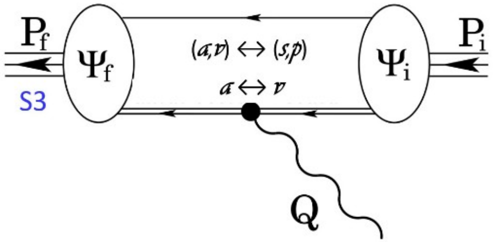
- **4** from the photon strikes **quark** case (1 for each spectator diquark)
- **4x4=16** from the photon strikes **diquark** cases.

S2



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

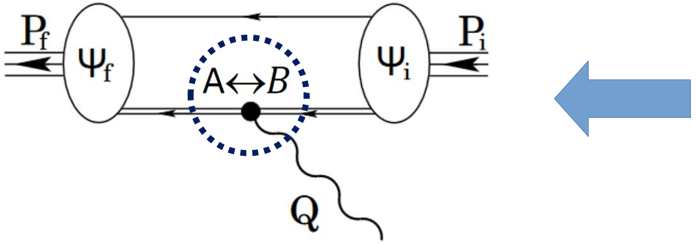
S3

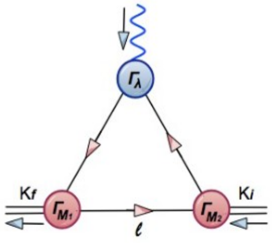


Photon strikes diquark, and a transition between different diquarks occurs (**S3**)

Diquark **transitions**

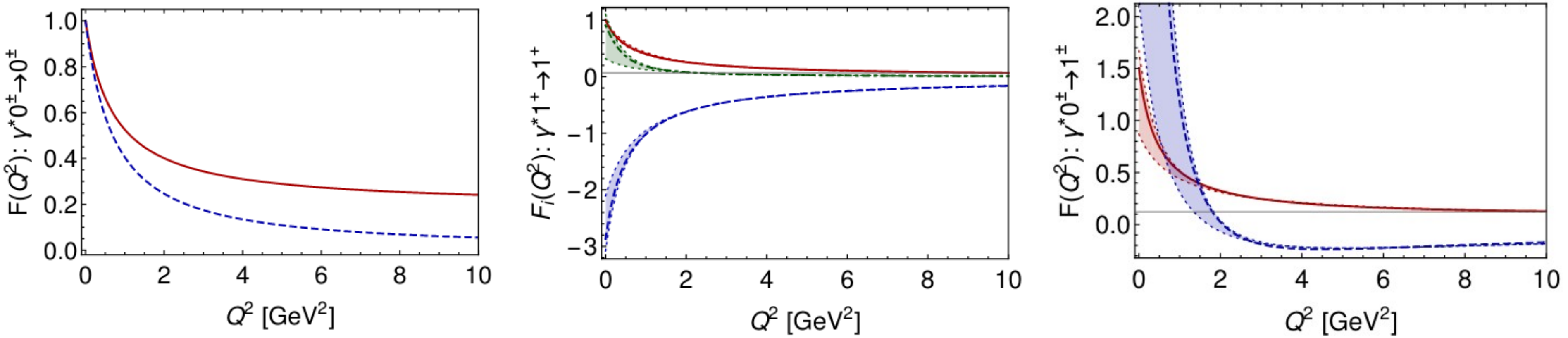
- The collection of ***"Photon strikes diquark"*** contributions require the evaluation of several **triangle diagrams** for different initial and final diquarks:





$$\Lambda_{\lambda(\mu\nu)}(p_i,p_f) \equiv \sum_{j=1}^{N_T} T^{(j)}_{\lambda(\mu\nu)}(p_f,p_i)F_j((p_f-p_i)^2) \qquad \text{(E1)}$$
$$= \int \frac{d^4q}{(2\pi)^4}\chi_\lambda(Q,q)\Gamma^{H_i}_{(\mu)}(p_i)S(q)\bar{\Gamma}^{H_f}_{(\nu)}(-p_f)\,.$$

- For example, some of relevance for the **N→ N(1535) transition**:



N $\rightarrow$ 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: $0^+,\ 0^-,\ 1^+,\ 1^-$

Photon hits diquark

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

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

N $\rightarrow$ 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^+	$0^+ \rightarrow 0^+$	$0^+ \rightarrow 0^-$	$0^+ \rightarrow 1^+$	$0^+ \rightarrow 1^-$
[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**.

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

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 $\rightarrow$ 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 $\rightarrow$ 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]

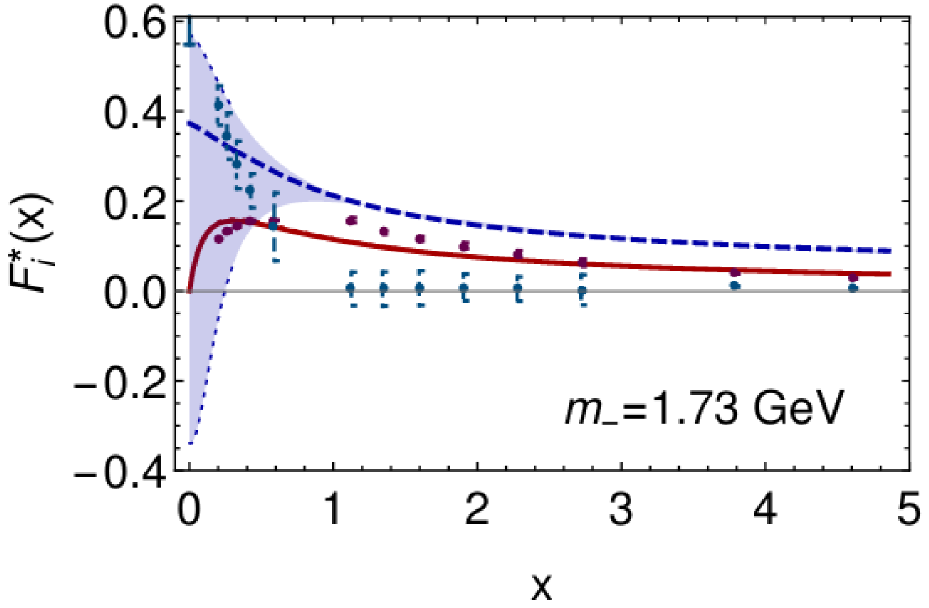
Photon hits diquark

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:

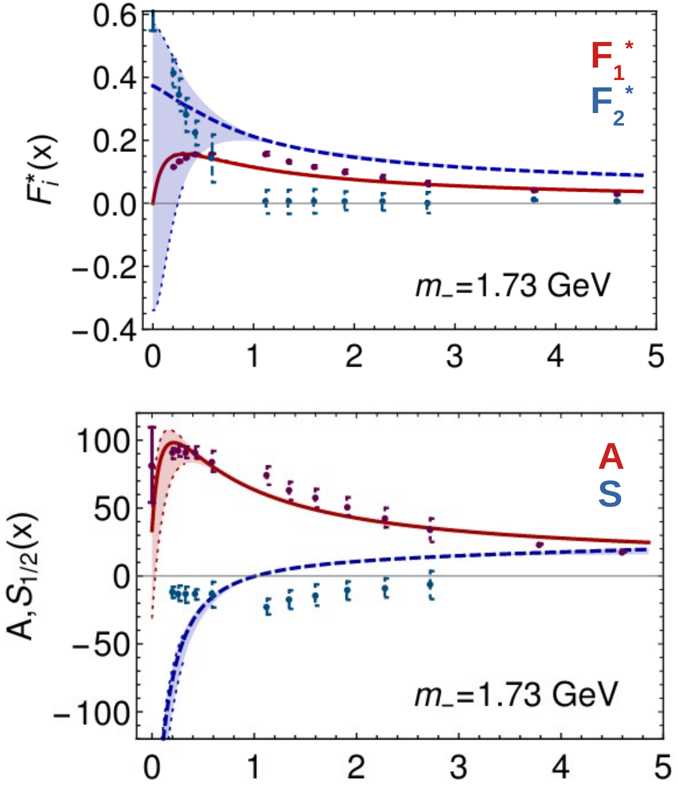
$\gamma^{(*)} p \rightarrow N(1535)\frac{1}{2}^{-}$ transition



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 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
- 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

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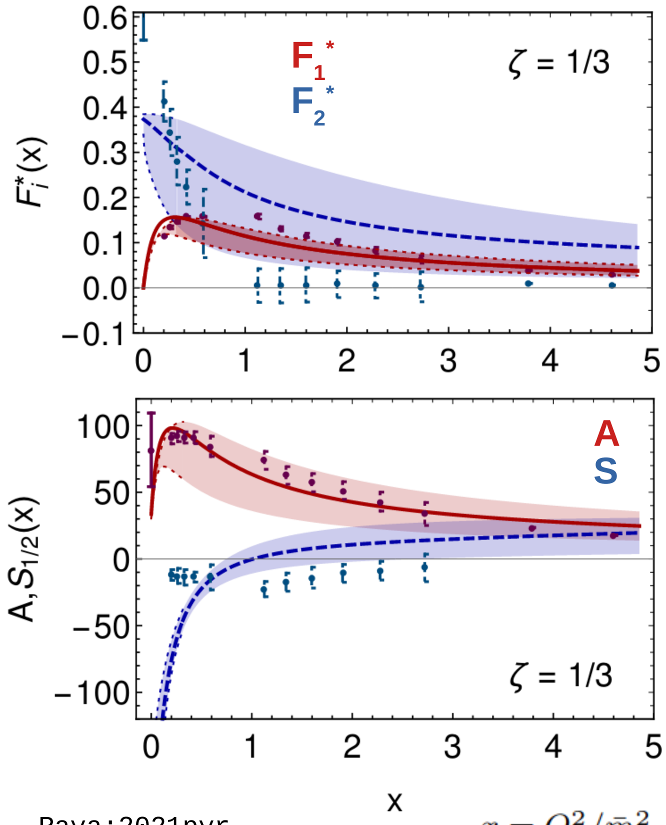


Raya:2021pyr

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

- 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 $g_{\rm DB} \to g_{\rm DB}(1 \pm 0.5)$, 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
$g_{\rm DB}$ 1.5	0.76	0.27	0.18	0.49	0.12	0.08
$g_{\rm DB}$ 1.0	0.66	0.20	0.14	0.68	0.11	0.09
$g_{\rm DB}$ 0.5	0.35	0.04	0.00	0.92	−0.05	0.18

N → N(1535): Numerical results

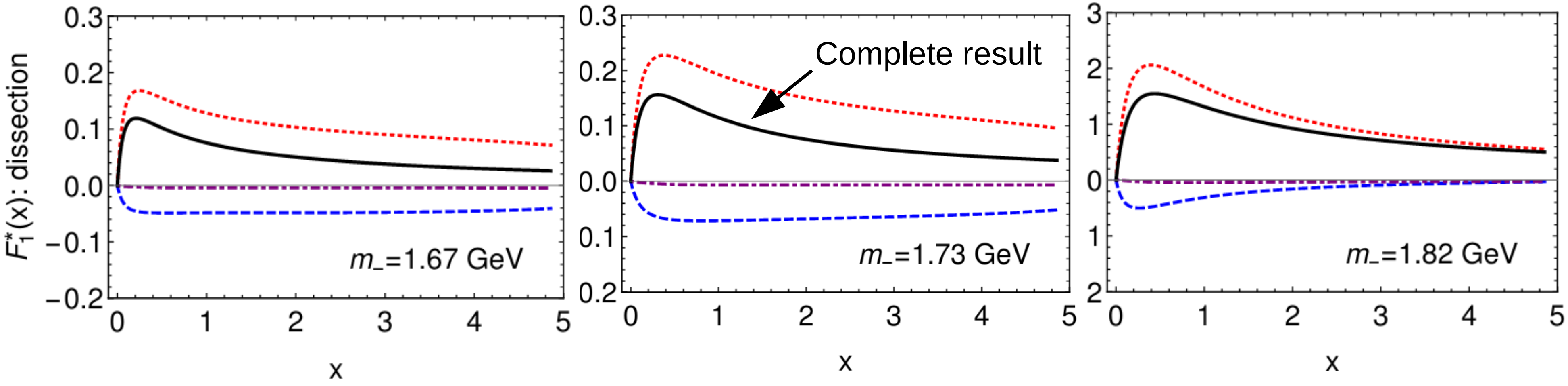
- **Dissection** of the form factors: F_1^*.

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^*.

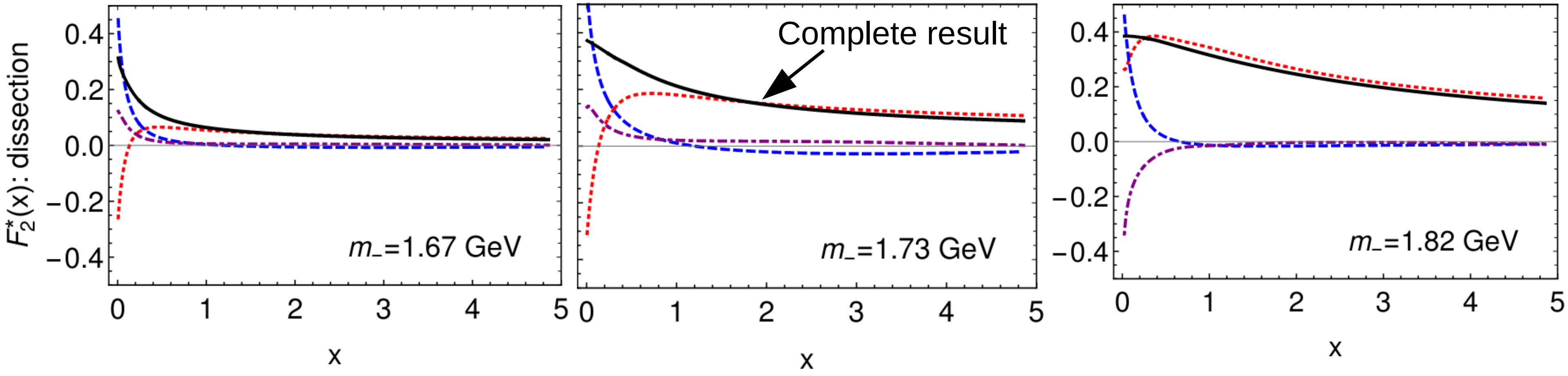
Red: Photon strikes quark Q^+Q^+

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

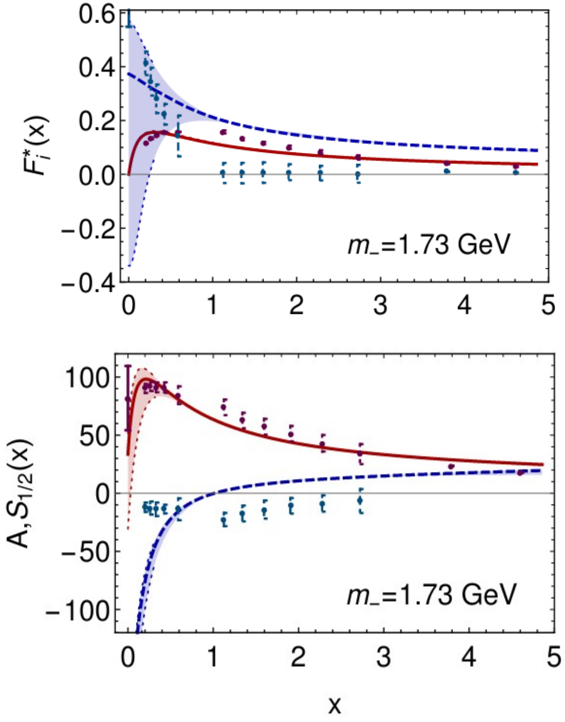
Purple: Photon strikes diquark, initial and final one have opposed parity D^-D^+

- 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.



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
0
1
2
3
4
5
x

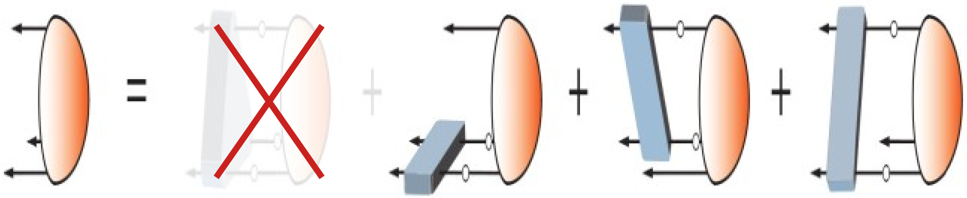

I just need
the main ideas

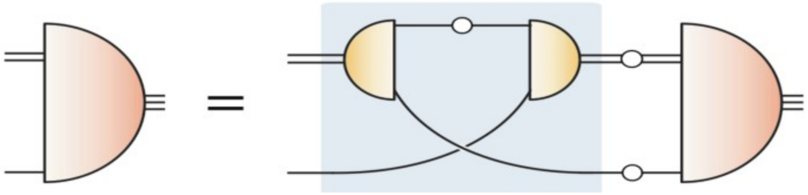
Summary

Barabanov:2020jvn

- **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.

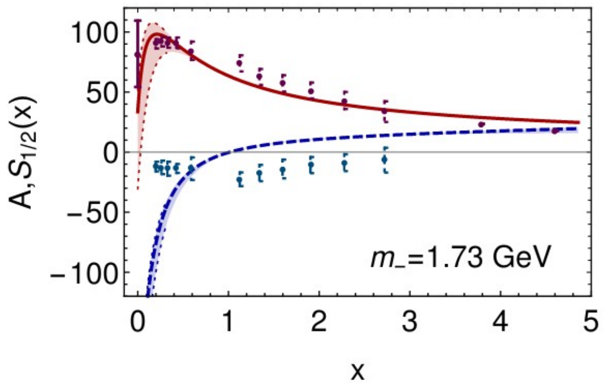




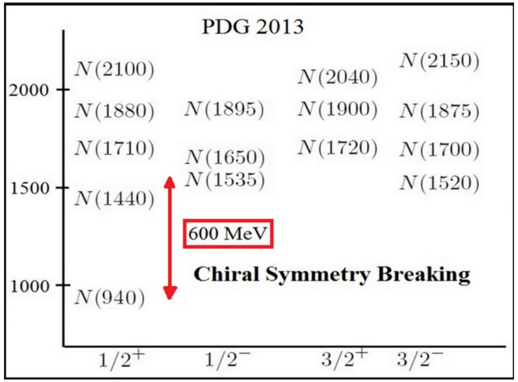
Summary

Raya:2021pyr

- **Theoretical** evidence suggests the existence of **dynamical diquark** correlations:
  - The formation of non-point-like **diquarks** within baryons should be **connected** with <u>EHM phenomena</u>.
- Some **experimental** observables could yield to **unambiguous signals** of their existence.



- The case of the **N→ N(1535)** electromagnetic transition is relevant because the **structural differences** between a hadron and its parity partner owe largely to **DCSB**.
- Our symmetry-preserving contact interaction computation revealed that such observable is highly **sensitive** to the baryon **wavefunction** and **mass**.
  - … which also happens to be interconnected
- Overall, the SCI exhibits a **fair agreement** with existing **data**. Then we anticipate sensible outcomes within more sophisticated approaches to QCD.



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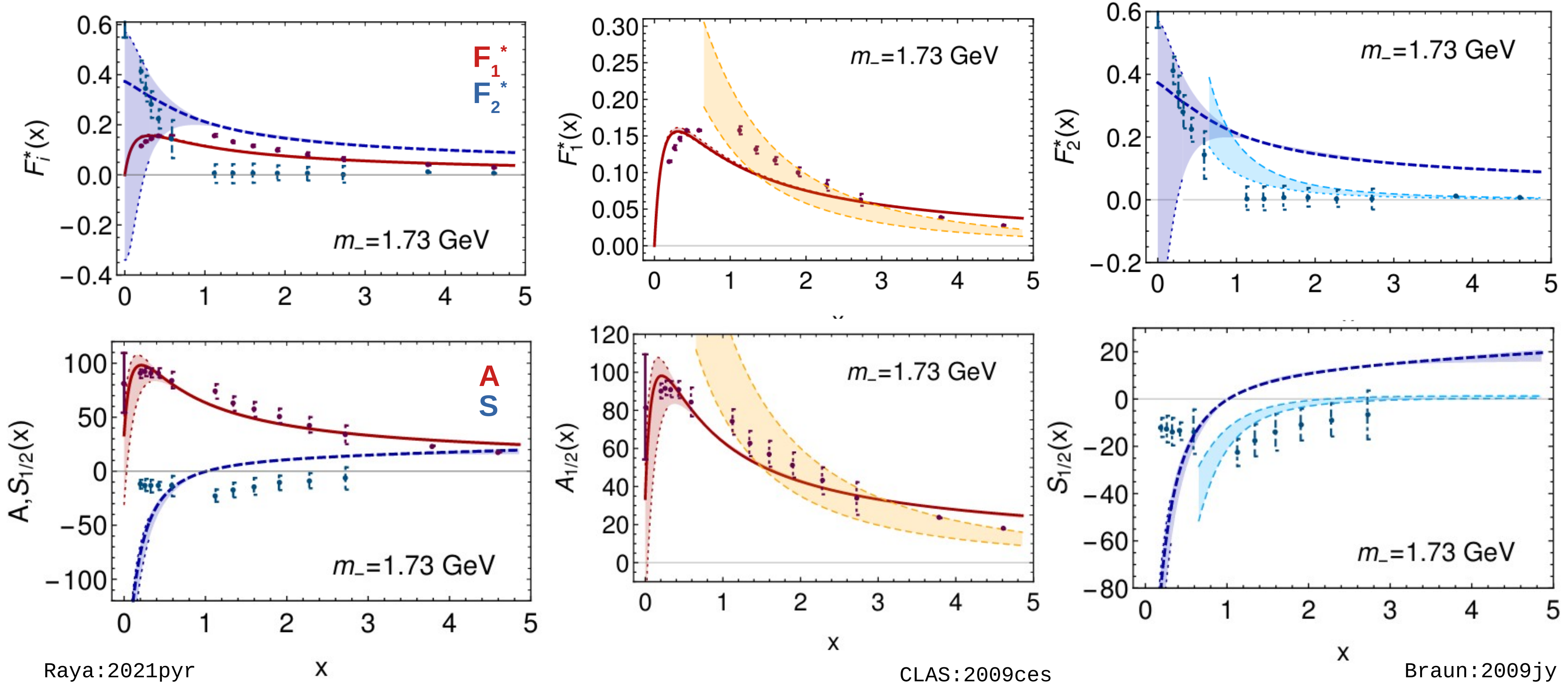
$x = Q^2/\bar{m}^2,\ \bar{m} = (m_+ + m_-)/2$



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