Preliminary Exploration into the N* Structure

Gustavo Paredes Torres

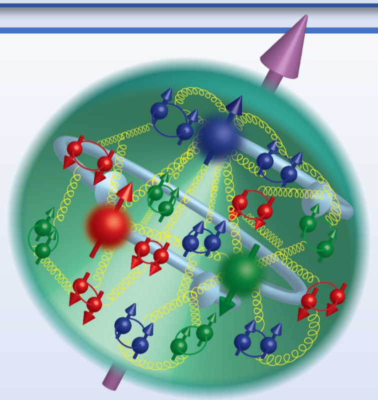
Non-Perturbative Physics: Tools and Applications

4-8 septiembre 2023
Instituto de Física y Matemáticas. Universidad Michoacana de San Nicolás de Hidalgo
America/Mexico_City timezone

CONTENT

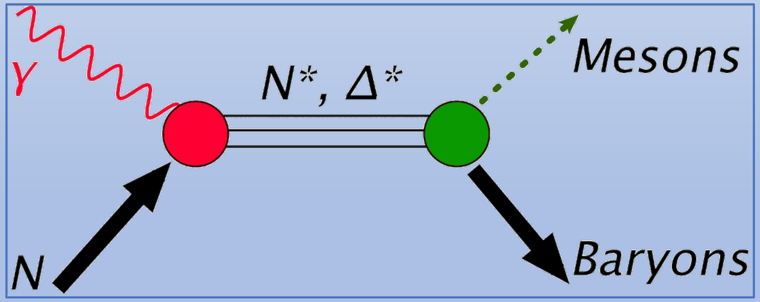
- Introduction
- SCI Model
- Schwinger – Dyson and Bethe – Salpeter equations
- Faddeev equation
- Some results for N’s and Δ’s
- Conclusions

Introduction



- It has been known since the 1970s that the nucleon is a bound state of three valence quarks surrounded by an in- finite sea of gluons and quark-antiquark pairs.

- An implication of this understanding is that when energy is dumped into the nucleon ground states, they are excited, and can lose their energies only by emitting colorless states, mostly mesons. Many excited states or nucleon resonances, referred to generically as N^*'s and $\Delta^{*\prime}s$, have been observed.

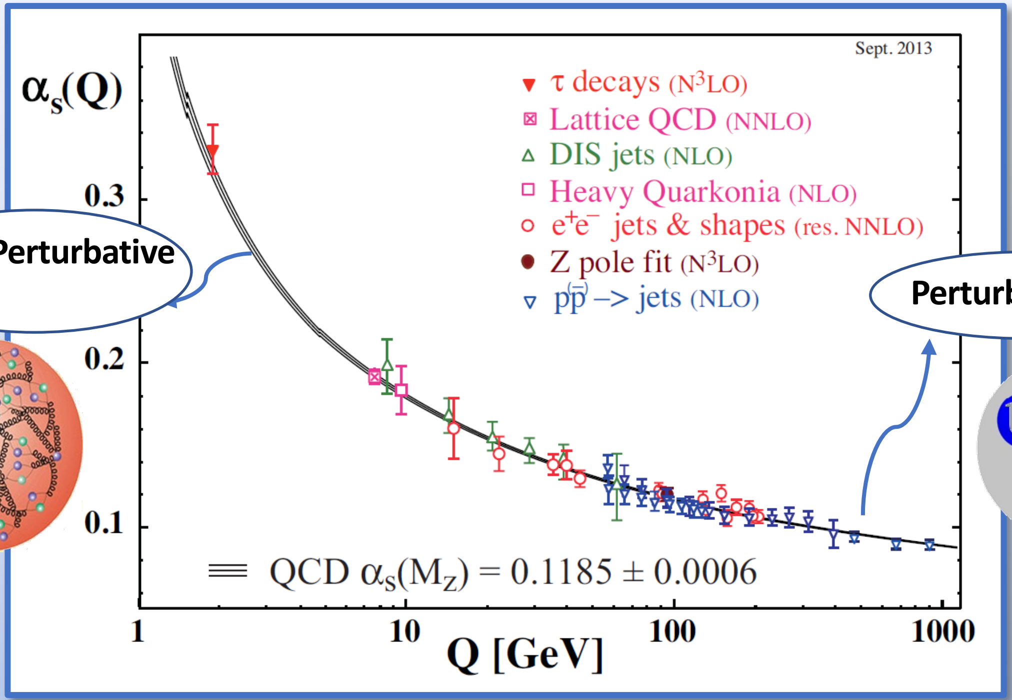


- The spectrum of these excited states

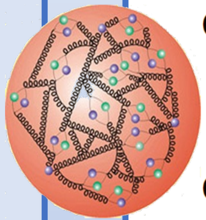
I	S	$J^P = \frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\frac{1}{2}$	0	**N(940)** **N(1440)** N(1710) N(1880)	**N(1720)** N(1900)	**N(1680)** N(1860)	**N(1535)** **N(1650)** N(1895)	**N(1520)** N(1700) N(1875)	**N(1675)**
$\frac{3}{2}$	0	**Δ(1910)**	**Δ(1232)** Δ(1600) Δ(1920)	**Δ(1905)**	**Δ(1620)** Δ(1900)	**Δ(1700)** Δ(1940)	Δ(1930)
0	−1	**Λ(1115)** Λ(1600) Λ(1810)	**Λ(1890)**	**Λ(1820)**	**Λ(1405)** **Λ(1670)** Λ(1800)	**Λ(1520)** **Λ(1690)**	**Λ(1830)**
1	−1	**Σ(1190)** Σ(1660) Σ(1880)	**Σ(1385)**	**Σ(1915)**	Σ(1750)	**Σ(1670)** Σ(1940)	**Σ(1775)**
$\frac{1}{2}$	−2	**Ξ(1320)**	**Ξ(1530)**			Ξ(1820)	
0	−3		**Ω(1672)**				

Introduction

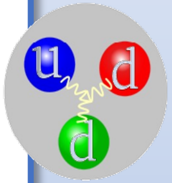
- Asymptotic freedom



Non Perturbative QCD

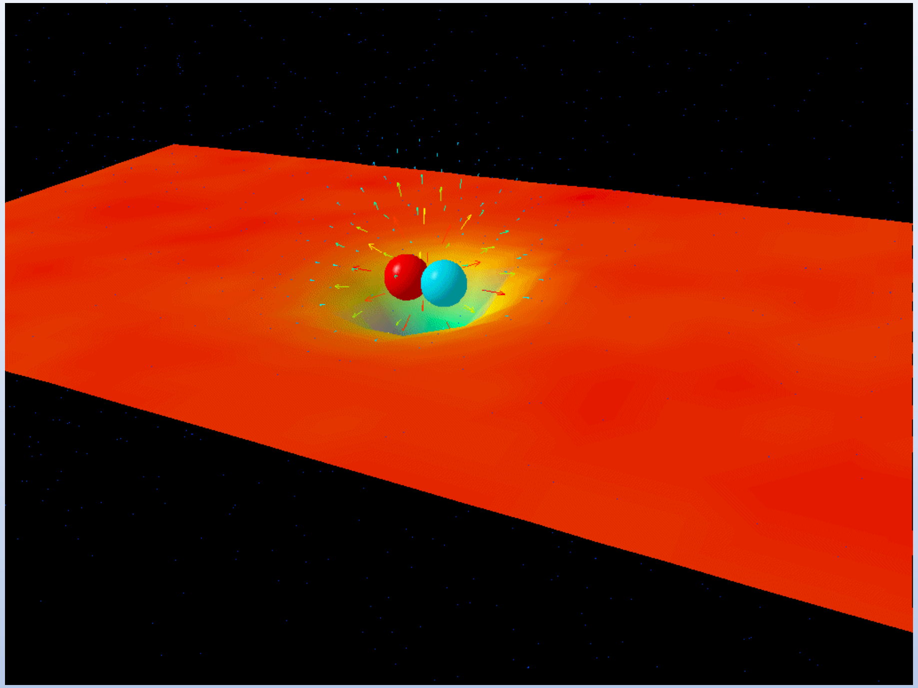


Perturbative QCD



- q and g interactions form a color field that prevents quarks from separating.
- The intensity of interactions decreases at high energies (short distances).

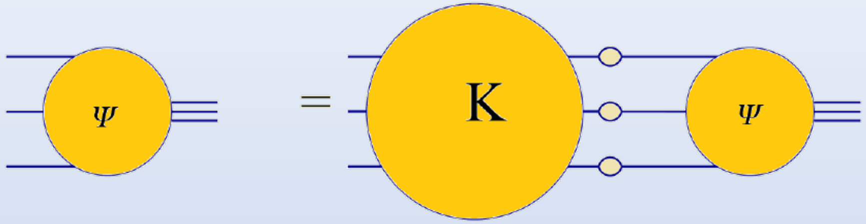
- Confinement



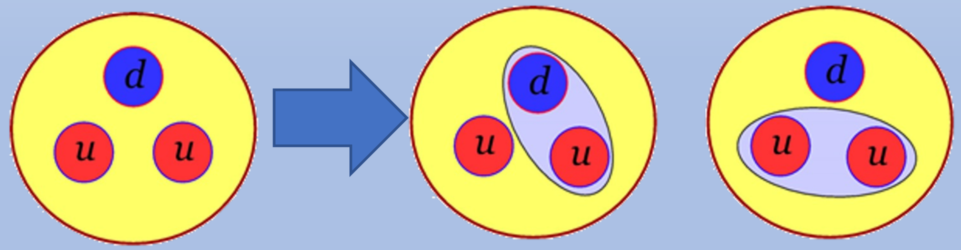
- By increasing the coupling confinement appears and it is necessary to use non-pertrbative theories to study this regime.

Formalism

- We use a continuous nonperturbative formalism to solve QCD.
- The Faddeev equation has 64 Dirac structures: G. Eichmann, Phys. Rev. D84, 014014 (2011).



- In the quark-diquark model that describes the baryons, there is a quark and a diquark that are constantly exchanged, so we have 8 Dirac structures. Such approach reproduces the nucleon mass with a 5% error:



Formalism

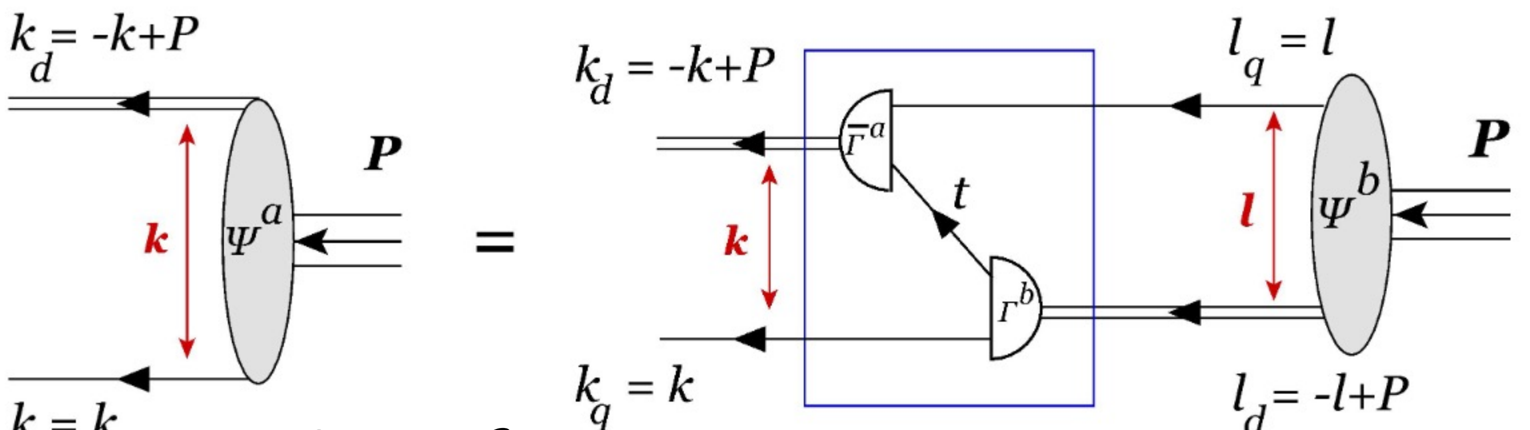
- **The Faddeev amplitude Ψ for Baryons**:

$$\begin{aligned}\Psi(P) = \psi(P)^{\pm}u(P) = {} & \Gamma^{0^+}\ \Delta^{0^+}(K)\ \mathcal{S}^{\pm}(P)u(P) \\ & + \sum_{f=1,2} \Gamma^{1^+}_{\mu}\ \Delta^{1^+}_{\mu\nu}(K)\ \mathcal{A}^{\pm f}_{\nu}(P)u(P) \\ & + \Gamma^{0^-}\ \Delta^{0^-}(K)\ \mathcal{P}^{\pm}(P)u(P) \\ & + \Gamma^{1^-}_{\mu}\ \Delta^{1^-}_{\mu\nu}(K)\ \mathcal{V}^{\pm}_{\nu}(P)u(P),\end{aligned}$$

- Scalar
- Axial vector
- Pseudoscalar
- Vectorial

$$S^{-1}(p,\mu) = \frac{i\gamma\cdot p + M(p^2,\mu^2)}{Z(p^2,\mu^2)}$$

$$\Delta^{1^\pm}_{\mu\nu}(K) = \left[\delta_{\mu\nu} + \frac{K_\mu K_\nu}{m^2_{1^\pm}}\right]\frac{1}{K^2+m^2_{1^\pm}},$$



$$P^2 = -M_B^2$$

$$\Delta^{0^\pm}(K) = \frac{1}{K^2+m^2_{0^\pm}},$$

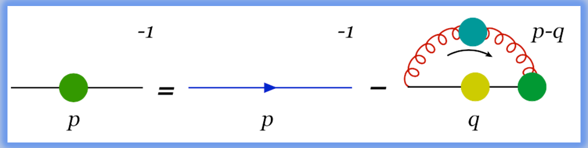
$$\Psi_{(fg)h}(P) = g^{P_BP_d}_{DB}\ \Gamma_{(gh)}(l_{gh})\ S^T_g\ \bar{g}^{P_BP_d}_{DB}\ \bar{\Gamma}_{(fg)}(-k_{fg})\ S_f(l_f)\ \Delta_{(gh)}(l_{gh})\ \Psi_{(gh)f}(P)$$

$$\begin{aligned}\Gamma^{0^+}(K) &= \gamma_5\left[iE^{0^+}(K) + \frac{1}{M_R}\gamma\cdot KF^{0^+}(K)\right],\\ \Gamma^{0^-}(K) &= \mathbb{1}_D E^{0^-}(K),\\ \Gamma^{1^+}_\mu(K) &= \gamma^\perp_\mu E^{1^+}(K),\\ \Gamma^{1^-}_\mu(K) &= \gamma_5\gamma^\perp_\mu E^{1^-}(K),\end{aligned}$$

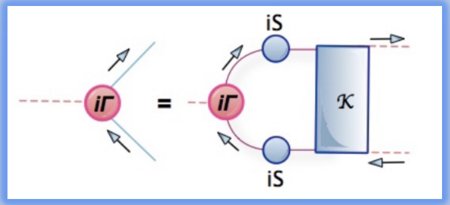
Formalisim

- We use a Symmetry preserving Contact Interaction (SCI) treatment of the gluon interaction in the QCD Schwinger - Dyson equations (SDE)
  - Simple to use
  - Good approximation at small Q^2 , especially for ground states
  - We can calculate the form factors of nucleons and its first radial excitations
- We use the Bethe – Salpeter equation (BSE) to solve a 2-body bound state problem like mesons and diquark
- Next we use the quark – diquark model to solve the Faddeev equation (FE)
- We can insert a node into the integrand of BSE and FE to produce an radial excited state

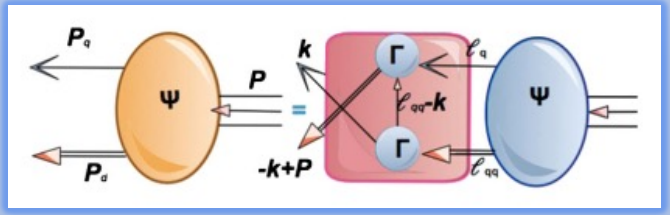
SDE
q



BSE
$q\bar{q} \leftrightarrow qq$

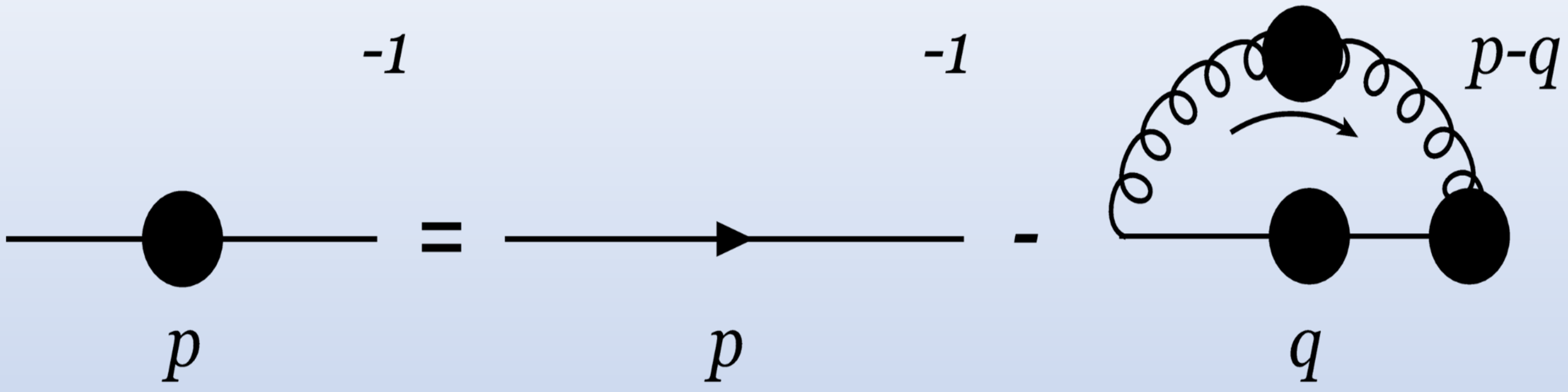


FE
$q - qq$



Schwinger – Dyson Equations

- **Ideal for studying non-perturbative phenomena as no assumptions are made about the value of the coupling :**



$$\underbrace{\underbrace{S^{-1}(p,\mu)}_{\textit{Complete Propagator, dressed}} = \underbrace{Z_{2F}S_0^{-1}(p)}_{\textit{Bare propagator, tree level}}}_{\textbf{Gap equation}} + \underbrace{Z_{1F}\int\frac{d^4p}{(2\pi)^4}g^2\underbrace{D_{\rho\nu}(p-q;\mu)}_{\textit{Dressed gluon propagator}}\frac{\lambda^a}{2}\gamma_\rho S(q;\mu)\underbrace{\Gamma^a_\nu(q,p;\mu)}_{\textit{Dressed quark-gluon vertex}}.}_{\Sigma(\mathrm{p})\ \textbf{Self-energy}}$$

Symmetry preserving Contact Interaction Model

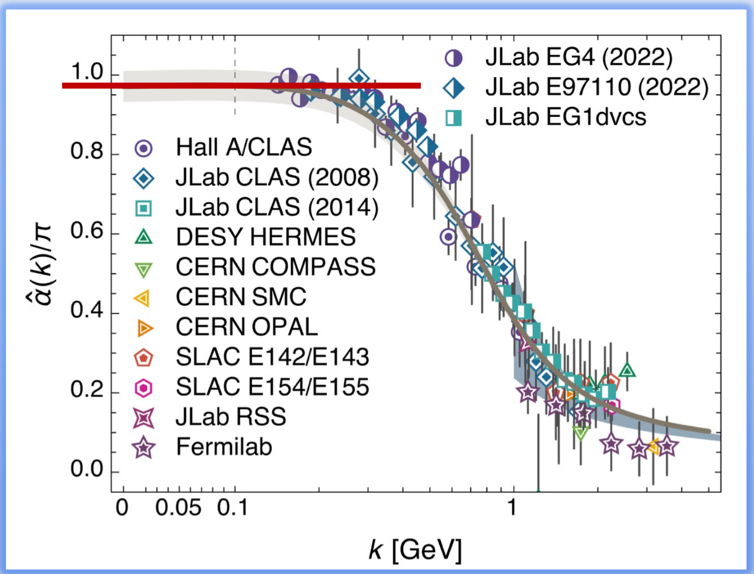
- **Simplified QCD model, where UV divergences are regularized to preserve QCD symmetries, compatible with confinement and DCSB**

- **The effective gluon mass in the IR from motives this truncation that replace the full gluon propagator by a constant in the infrared**

Interaction strength in infrared $\alpha_{IR} = 0.93\pi$ compatible with modern computations

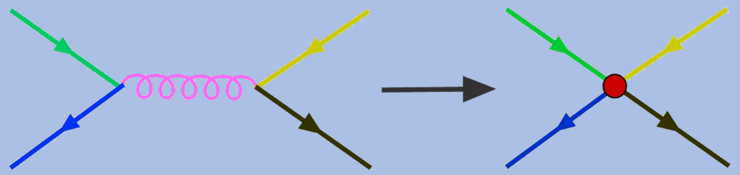
$$g^2 D_{\mu\nu}(k) = g^2\left[g_{\mu\nu} - (1-\xi)\frac{k_\mu k_\nu}{k^2}\right]\frac{1}{k^2} \to \frac{4\pi\alpha_{IR}}{m_g^2}\delta_{\mu\nu} \equiv \delta_{\mu\nu}\frac{1}{m_G^2},$$

Gluon mass scale 500 MeV



[Ding:2022ows]

- **Feynman diagram for $q\bar{q}$ scattering:**



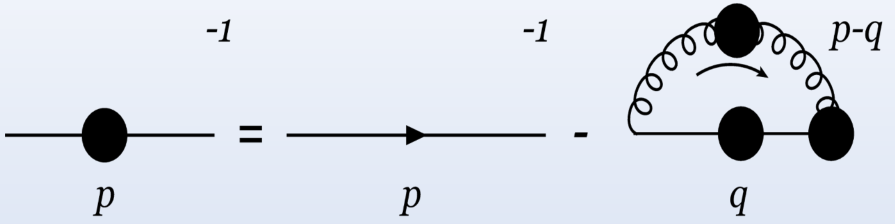
[Gutierrez-Guerrero:2010waf Roberts:2010rn]

SDE in SCI

- The gap equation

$$S_f^{-1}(p) = Z_{2F}\left(i\gamma\cdot p + m_f^{bm}\right) + \Sigma_f(p)$$

$$S_{f_1}^{-1}(p) = i\gamma\cdot p + m_{f_1} + \int \frac{d^4q}{(2\pi)^4}\, g^2\, D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S_{f_1}(q)\Gamma_\nu(p,q),$$



- **Truncation scheme:** Rainbow-Ladder

$$\Gamma_\nu^a(p,q;\mu) \to \frac{\lambda^a}{2}\gamma_\nu.$$

- In SCI SDE becomes

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

- Non renormalizable

$$S_f^{-1}(p) = Z_{2F}\left(i\gamma\cdot p + m_f^{bm}\right) + \Sigma_f(p) \Rightarrow S_f^{-1}(p) = i\gamma\cdot p + M$$

- Momentum independet
- Simplifies or remove loop integrations
- Simplifies tensor contractions
- All mass functions constants

Current masses	$m_0 = 0$	$m_{u/d} = 0.007$	$m_s = 0.17$	$m_c = 1.08$	$m_b = 3.92$
Dressed masses	$M_0 = 0.357$	$M_{u/d} = 0.367$	$M_s = 0.53$	$M_c = 1.52$	$M_b = 4.68$

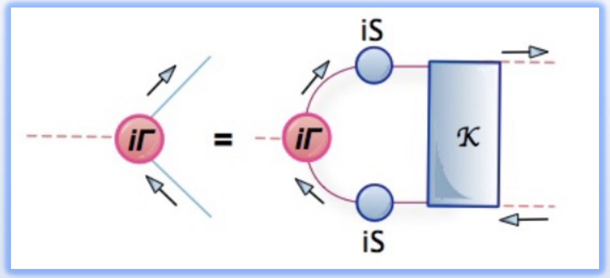
- This is a startingh point for a more advanced treactment

[Gutierrez-Guerrero:2021rsx]

Bethe – Salpeter Equations in SCI

- The interaction Implies momentum independent BSAs

$$
\begin{aligned}
\Gamma_{\sigma}^{0^{++}}(P) &= \mathbb{1} E_{\sigma}^{0^{++}}(P), \\
\Gamma_{\pi}^{0^{-+}}(P) &= \gamma_5 \left[i E_{\pi}^{0^{-+}}(P) + \frac{\gamma \cdot P}{2M_R} F_{\pi}^{0^{-+}}(P) \right], \\
\Gamma_{\mu,\,\rho}^{1^{--}}(P) &= \gamma_{\mu}^{T} E_{\rho}^{1^{--}}(P) + \frac{1}{2M_R} \sigma_{\mu\nu} P_{\nu} F_{\rho}^{1^{--}}(P), \\
\Gamma_{\mu,\,a_1}^{1^{++}}(P) &= \gamma_5 \left[\gamma_{\mu}^{T} E_{a_1}^{1^{++}}(P) + \frac{1}{2M_R} \sigma_{\mu\nu} P_{\nu} F_{a_1}^{1^{++}}(P) \right],
\end{aligned}
$$



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	$(qq)_{1^-} = 1.33$

- The BSE takes the next form for mesons and diquarks with the factor ½:

$$
\Gamma_{q\bar{q}}(k,P) = -\frac{4}{3}\frac{1}{m_G^2}\int \frac{d^4q}{(2\pi)^4}\gamma_\mu S_{f_1}(q+P)\Gamma_{q\bar{q}}(q,P)S_{\bar{f}_2}(q)\gamma_\mu
$$

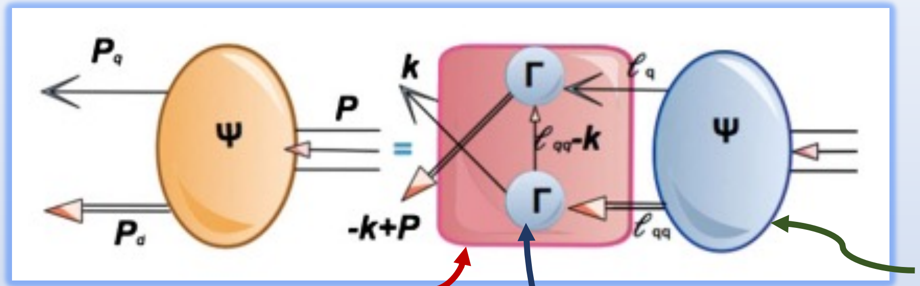
$$
\Gamma_{qq}(K,P)C^{\dagger} = -\frac{1}{2}\frac{4}{3}\frac{1}{m_G^2}\int \frac{d^4q}{(2\pi)^4}\gamma_\mu S_{f_1}(q+P)\Gamma_{qq}(q,P)\,C^{\dagger}S_{\bar{f}_2}(q)\gamma_\mu
$$

[Roberts:2011cf, Roberts:2011wy, Yin:2019bxe, Chen:2012qr, Gutierrez-Guerrero:2019uwa, Gutierrez-Guerrero:2021rsx, Yin:2021uom]

- Less tightly bound.

Faddeev in SCI and quark-diquark model

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



Interaction Kernel

BAS for the diquark

Faddeev amplitud

$$\begin{bmatrix} \mathcal{S}^P(l;P) \\ \mathcal{A}^{P\,f}_\mu(l;P) \\ \mathcal{P}^P(l;P) \\ \mathcal{V}^P_\mu(l;P) \end{bmatrix} u_\rho = 4\int \frac{d^4 l}{(2\pi)^4} \mathcal{M}^{fg}_{\mu\nu}(k,l,P) \begin{bmatrix} \mathcal{S}^P(l;P) \\ \mathcal{A}^{P\,g}_\nu(l;P) \\ \mathcal{P}^P(l;P) \\ \mathcal{V}^P_\nu(l;P) \end{bmatrix} u_\rho,$$

$$\mathcal{M}^{fg}_{[q_1q_3][q_1q_2]} = t^{q_1\,T} t^{[q_1q_2]} t^{[q_1q_3]^T} t^{q_3} \left[g^{P_BP_d}_{DB}\, \Gamma^g_{[q_1q_2]}(l_{q_1q_2})\, S^T_{q_1}\, \bar{g}^{P_BP_d}_{DB}\, \bar{\Gamma}^f_{[q_1q_3]}(-k_{q_1q_3})\, S_{q_3}(l_{q_3})\, \Delta^g_{[q_1q_2]}(l_{q_1q_2}) \right]$$

Static aproximation

$$S^T_{q_1} = \frac{g_8}{M_{q_1}} = \frac{1.18}{M_{q_1}}$$

- Quarks inside baryons correlate into non-point-like diquarks.
- Breakup and reformation occurs via quark exchange.
- The kernel penalizes the contribution of diquarks whose parity is opposite to that of the baryon, using a multiplicative factor $g^{P_BP_d}_{DB}$

[Gutierrez-Guerrero:2019uwa, Yin:2019bxe, Yin:2021oum]

Baryons $\left(\frac{1}{2},\frac{1}{2}^{\pm}\right)$

- The Faddeev amplitude for Baryons:

$$\begin{aligned}\Psi(P) = \psi(P)^{\pm}u(P) = \Gamma^{0^+}\ \Delta^{0^+}(K)\ \mathcal{S}^{\pm}(P)u(P) \\ + \sum_{f=1,2}\Gamma^{1^+}_{\mu}\ \Delta^{1^+}_{\mu\nu}(K)\ \mathcal{A}^{\pm f}_{\nu}(P)u(P) \\ + \Gamma^{0^-}\ \Delta^{0^-}(K)\ \mathcal{P}^{\pm}(P)u(P) \\ + \Gamma^{1^-}_{\mu}\ \Delta^{1^-}_{\mu\nu}(K)\ \mathcal{V}^{\pm}_{\nu}(P)u(P),\end{aligned}$$

- Scalar
- Axial vector
- Pseudoscalar
- Vectorial

$$\begin{aligned}\mathcal{S}^{\pm} &= (s^{\pm}\ \mathbb{1}_D)\mathcal{G}^{\pm} \\ i\,\mathcal{A}^{\pm f}_{\mu} &= \left(a_1^{\pm f}\ \gamma_5\,\gamma_\mu - i\,a_2^{\pm f}\gamma_5\ \hat{P}_\mu\right)\mathcal{G}^{\pm} \\ i\,\mathcal{P}^{\pm} &= (p^{\pm}\ \gamma_5)\mathcal{G}^{\pm} \\ i\,\mathcal{V}^{\pm}_{\mu} &= \left(v_1^{\pm}\ \gamma_\mu - i\,v_2^{\pm}\mathbb{1}_D\hat{P}_\mu\right)\mathcal{G}^{\pm}\end{aligned}$$

- The vector in terms of diquarks and Dirac structure is:

$$\begin{bmatrix} r_1\ u[ud]_{0^+} \\ r_2\ d\{uu\}_{1^+} \\ r_3\ u\{ud\}_{1^+} \\ r_4\ u[ud]_{0^-} \\ r_5\ u[ud]_{1^-} \end{bmatrix}$$

$$\begin{bmatrix} s\ \mathbb{1}_D \\ -a_1^1\ i\,\gamma_5\gamma_\mu \\ -a_1^2\ i\,\gamma_5\gamma_\mu \\ -a_2^1\ \gamma_5\hat{P}_\mu \\ -a_2^2\ \gamma_5\hat{P}_\mu \\ -p\ i\,\gamma_5\mathbb{1}_D \\ -v_1\ i\,\gamma_\mu \\ -v_2\ \hat{P}_\mu \end{bmatrix}\mathcal{G}^{\pm}$$

- We then arrive at an eigenvalue equation for:

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

Baryons $\left(\frac{1}{2},\frac{3}{2}^{\pm}\right)$

- The Faddeev amplitude for Baryons:

$$\begin{aligned}\psi(P)^{\pm}_{\mu\nu}u_\nu(P) = {}& \Gamma^{0^+}\ \Delta^{0+}(K)\ \mathcal{S}^{\pm}(P)u_\nu(P)\\ &+ \sum_{f=1,2}\Gamma^{1^+}_{\mu}\ \Delta^{1^+}_{\mu\nu}(K)\ \mathcal{A}^{\pm f}_{\nu}(P)u_\nu(P)\\ &+ \Gamma^{0^-}\ \Delta^{0^-}(K)\ \mathcal{P}^{\pm}(P)u_\nu(P)\\ &+ \Gamma^{1^-}_{\mu}\ \Delta^{1^-}_{\mu\nu}(K)\ \mathcal{V}^{\pm}_{\nu}(P)u_\nu(P),\end{aligned}$$

- Scalar
- Axial vector
- Pseudoscalar
- Vectorial

- In SCI becomes:

$$\psi_{\mu\nu}(P)u_\nu = \Gamma_{qq_{1^+}\mu}\Delta^{1^+}_{\mu\nu,qq}(\ell_{qq})\mathcal{D}_{\nu\rho}(P)u_\rho(P)$$

- with:

$$\mathcal{D}_{\nu\rho}(\ell;P) = \mathcal{S}(\ell;P)\delta_{\nu\rho} + \gamma_5\mathcal{A}_\nu(\ell;P)\ell^{\perp}_{\rho}$$

- For Baryon type (qqq):

$$\mathcal{D}_{\nu\rho}(\ell,P)\ u^B_\rho(P) = f^B(P)\mathbb{1}_D u^B_\nu(P)$$

$$1 = \frac{g_B^2}{Mq}\frac{E^2_{\{qq\}_{1^+}}}{m^2_{\{qq\}_{1^+}}}\frac{1}{2\pi^2}\int_0^1\left(\alpha M_B + M_q\right)\left(m^2_{\{qq\}_{1^+}} + (1-\alpha)^2M_B^2\right)\overline{C}'(\sigma_q^{\{qq\}_{1^+}}(\alpha))\,d\alpha$$

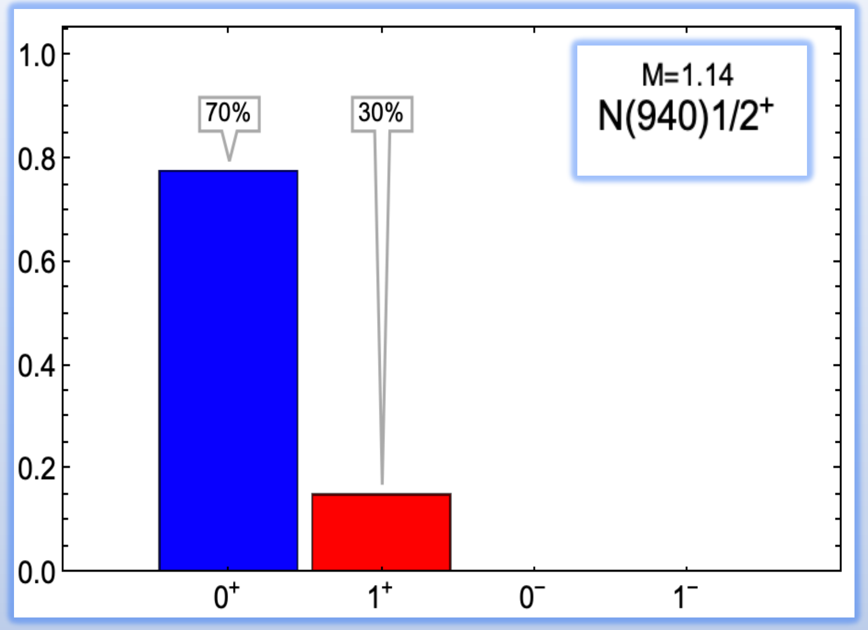
- If we do not use isospin symmetry:

$$\mathcal{D}_{\nu\rho}(\ell,P)\ u^B_\rho(P) = \sum_{i=\{uu\},\{ud\}} d^B_i(P)\ \delta_{\nu\alpha}\ u^B_\alpha(P)$$

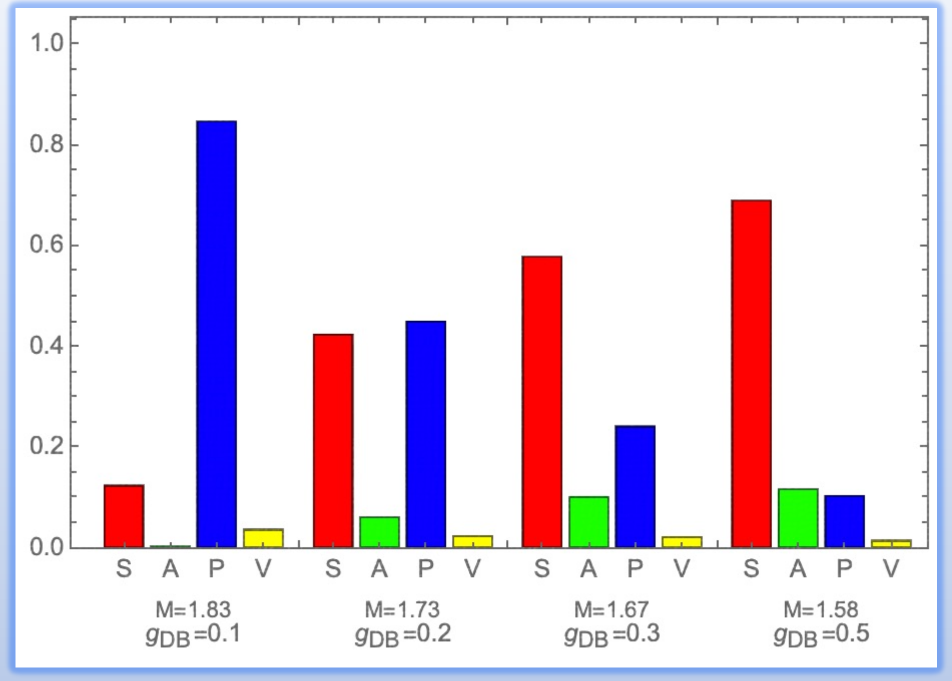
$$\begin{bmatrix} d^{\{uu\}}\\ d^{\{ud\}}\end{bmatrix} u^B_\mu(P) = -4\int\frac{d^4l}{(2\pi)^4}\begin{bmatrix} M^{\{uu\},\{uu\}}_{\mu\nu}(l,P) & M^{\{uu\},\{ud\}}_{\mu\nu}(l,P),\\ M^{\{ud\},\{uu\}}_{\mu\nu}(l,P) & M^{\{ud\},\{ud\}}_{\mu\nu}(l,P)\end{bmatrix}\begin{bmatrix} d^{\{uu\}}\\ d^{\{ud\}}\end{bmatrix} u^B_\nu(P).$$

N(940) and N(1535)

- The produced masses and diquark content:



- The variation of $g_{DB} \rightarrow (1 \pm 0.5) g_{DB}$ produces:



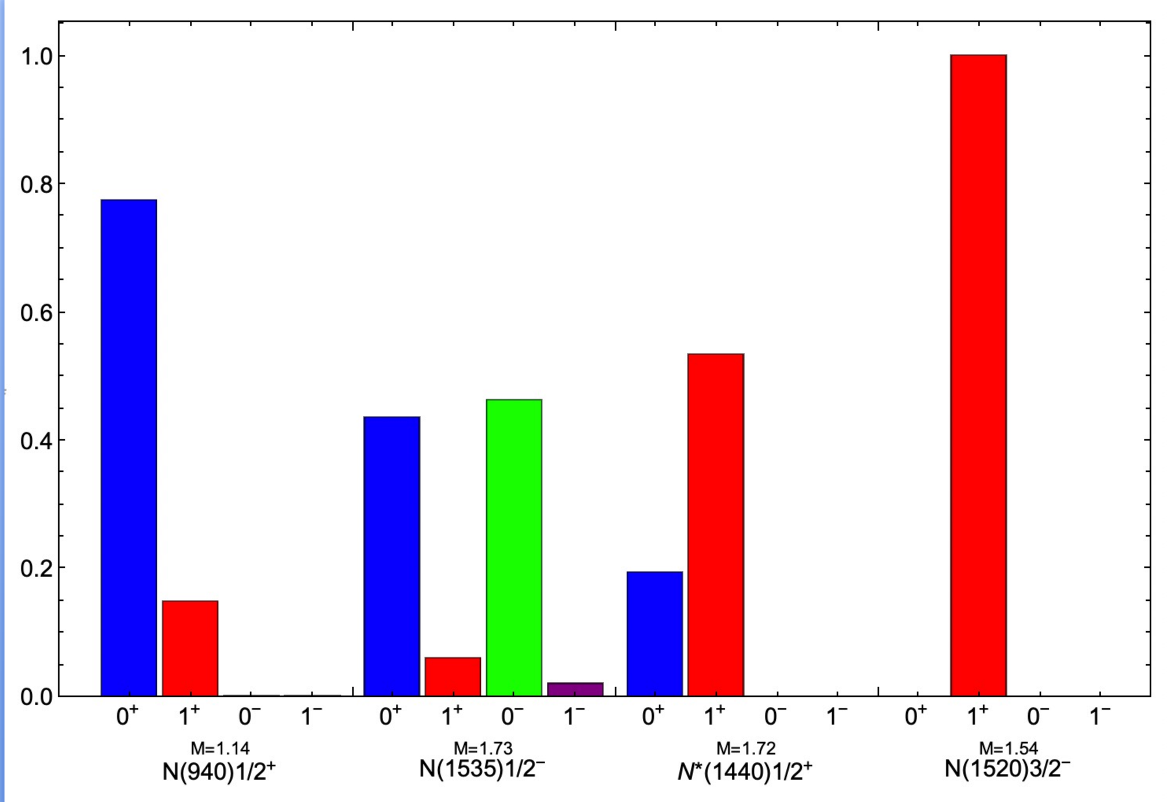
- As expected, the nucleon is mostly composed by scalar diquarks, while also exhibiting a sizeable axial- vector diquark component.

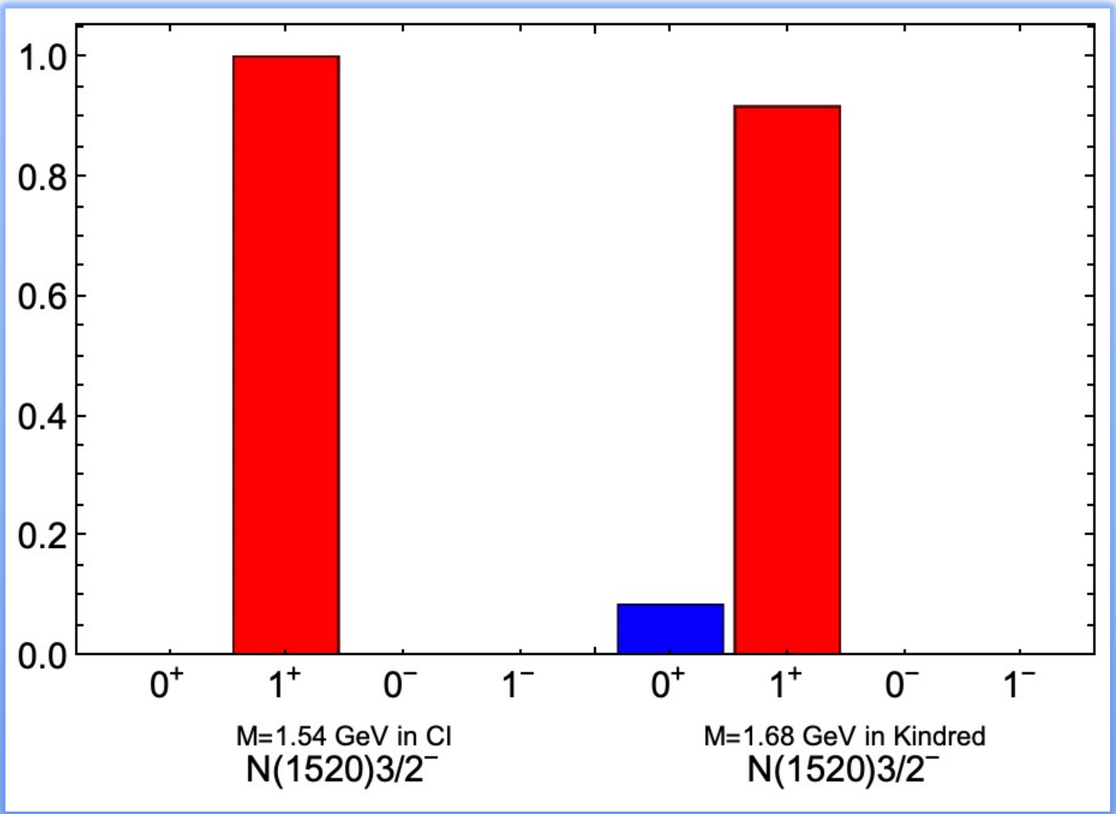
- With the preferred value of g_{DB}, the nucleon $N(1535)$ exhibits a similar contribution from $0^+|0^-$ diquarks.

[Lu:2017cln, Raya:2021pyr]

Towards "Results" for N^*

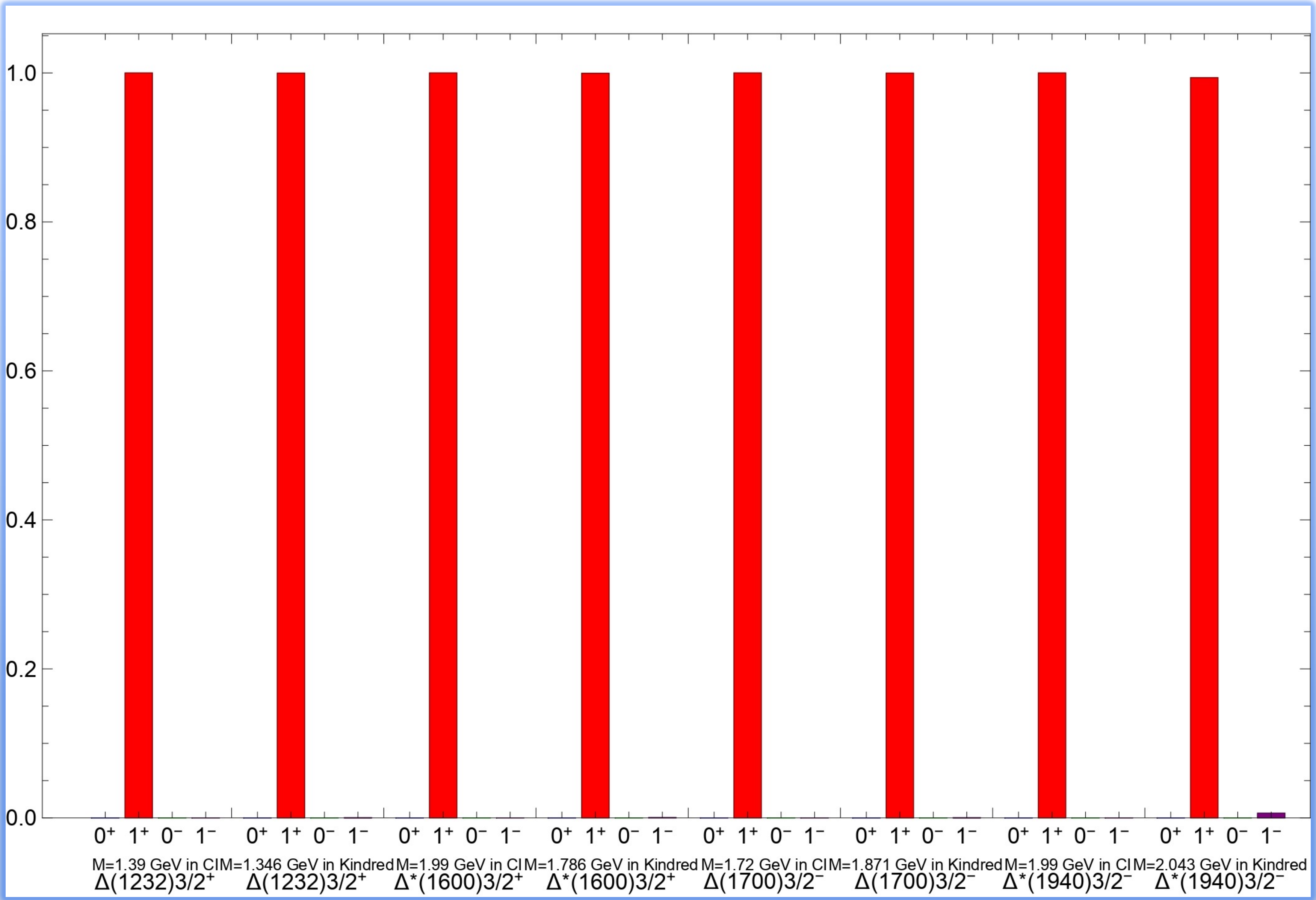
- In collaboration with K. Raya and A. Bashir





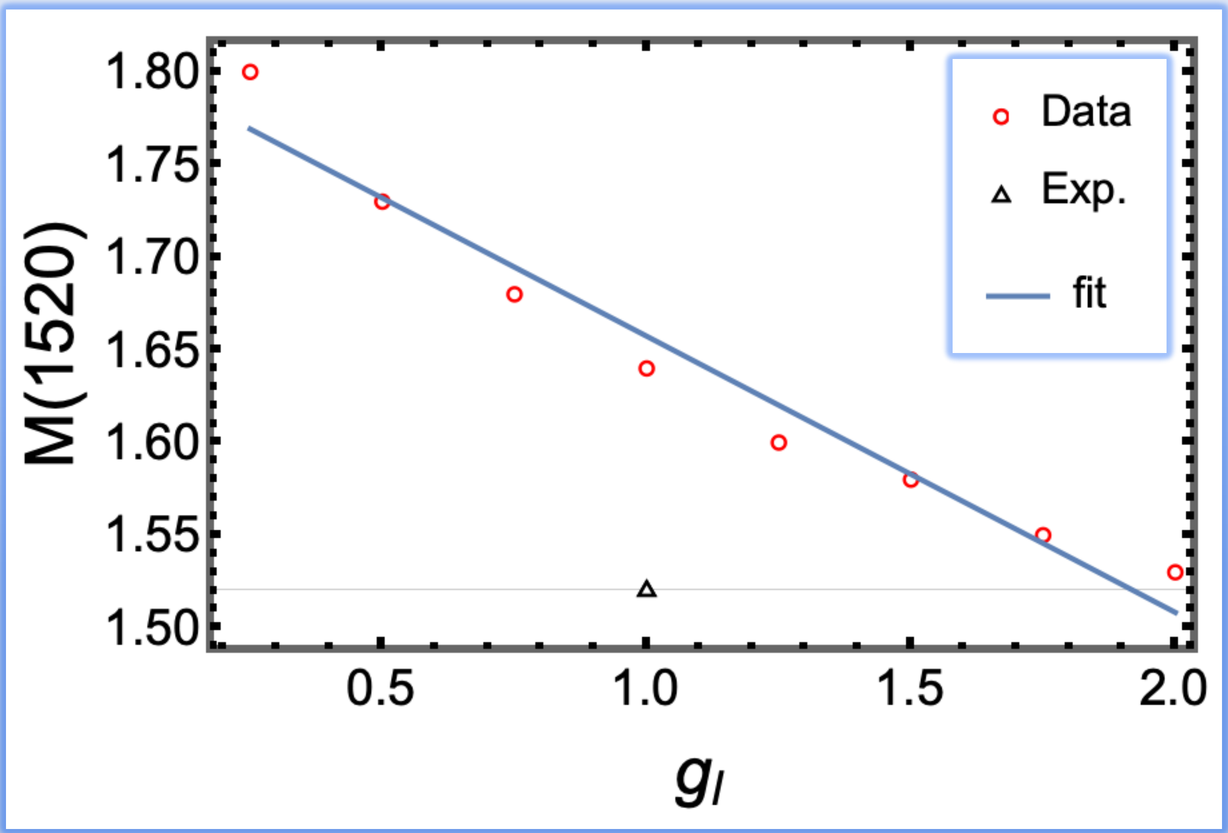
[Liu:2022nku]

Results for Δ



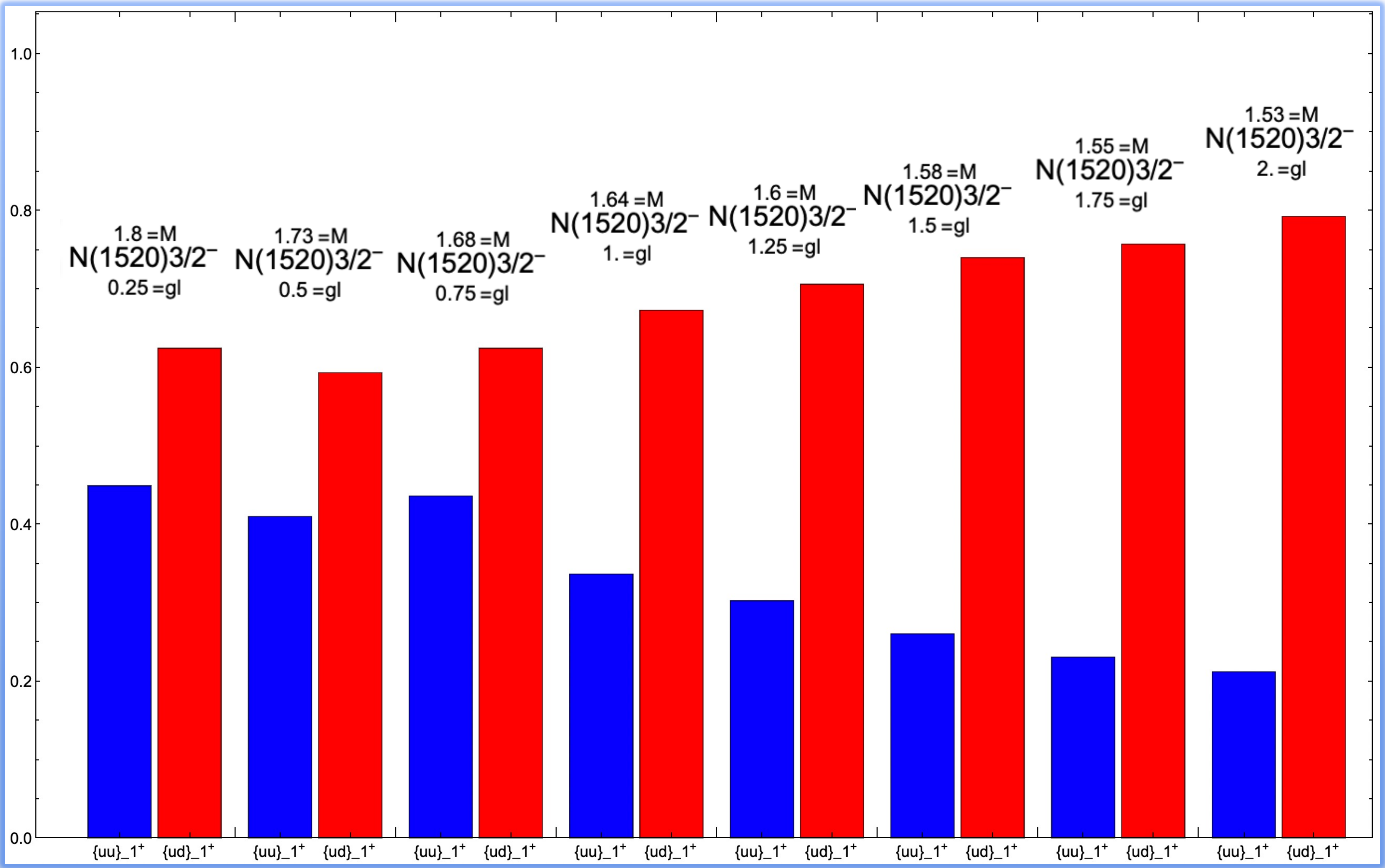
N(1520)

- Due the Faddeev's equation for $\Delta(1700)\frac{3}{2}^-$ is equal for $\mathrm{N}(1520)\frac{3}{2}^-$ and the only difference is g_B, $g_N = 1.18$ and $g_\Delta = 1.56$.
- This difference is caused by the orbital angular momentum.
- In order to restores the effect of orbital angular momentum we introduce the parameter g_l



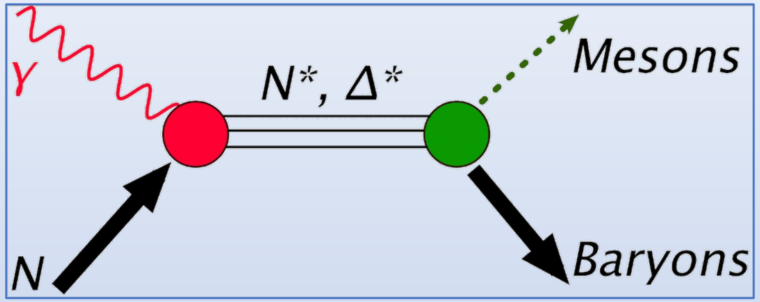
- In collaboration with K. Raya and A. Bashir

N(1520) with $\{uu\}_{1^+}$ and $\{ud\}_{1^+}$

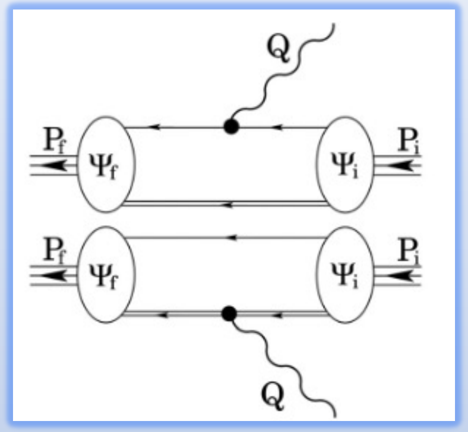


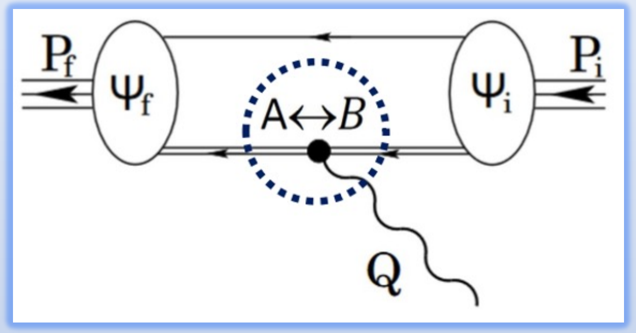
$N \rightarrow N^*, \Delta^*$ Transition Form Factors

- Considering the electromagnetic transition:



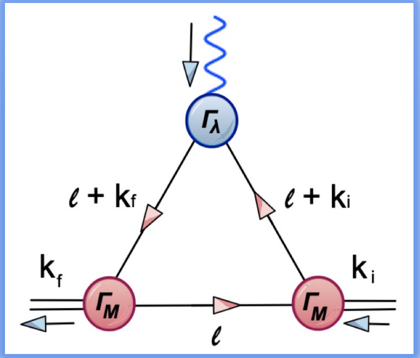
- the quark-diquark picture within the SCI model, the electromagnetic vertex can be described as:





- We need to consider if the photon hits the quark and the diquarks is an espectator (4 contributions), and if the photon hits the diquarks (16 contributions):

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^-	$1^- \to 0^+$	$1^- \to 0^-$	$1^- \to 1^+$	$1^- \to 1^-$



[Raya:2021pyr]

$N \to N^*, \Delta^*$ Elastic Form Factors

- We are interested in the nucleon's electric and magnetic form factors, the delta's multipole form factor and the magnetic-dipole, $N\ and\ \Delta$ elastic form factors.
- Electric quadrupole and Coulomb quadrupole from $\gamma + N \to \Delta$ transition form factors

[Segovia:2014aza, Nicmorus:2010sd]

- The current for N EFF:

$$J_\mu(K,Q) = ie\,\Lambda_+(P_f)\,\Gamma_\mu(K,Q)\,\Lambda_+(P_i)$$

- The vertex:

$$\Gamma_\mu(K,Q) = \gamma_\mu F_1(Q^2) + \frac{1}{2m_N}\sigma_{\mu\nu}Q_\nu F_2(Q^2)$$

- Momentum space distribution of N's charge nd ,agnetization:

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

- The current for Δ EFF:

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

- The vertex:

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

- The multipole form factors G in terms of F's:

$$G_{E0}(Q^2) = \left(1 + \frac{2\tau_\Delta}{3}\right)(F_1^* - \tau_\Delta F_2^*) - \frac{\tau_\Delta}{3}(1+\tau_\Delta)(F_3^* - \tau_\Delta F_4^*)\,,$$
$$G_{M1}(Q^2) = \left(1 + \frac{4\tau_\Delta}{5}\right)(F_1^* + F_2^*) - \frac{2\tau_\Delta}{5}(1+\tau_\Delta)(F_3^* + F_4^*)\,,$$
$$G_{E2}(Q^2) = (F_1^* - \tau_\Delta F_2^*) - \frac{1}{2}(1+\tau_\Delta)(F_3^* - \tau_\Delta F_4^*)\,,$$
$$G_{M3}(Q^2) = (F_1^* + F_2^*) - \frac{1}{2}(1+\tau_\Delta)(F_3^* + F_4^*)\,,$$

$N \to \Delta^*$ Transition Form Factors

- The current:

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

- The vertex:

$$\Gamma_{\alpha\mu}(K,Q) = k \left[\frac{\lambda_m}{2\lambda_+} (G_M^* - G_E^*) \gamma_5 \varepsilon_{\alpha\mu\gamma\delta} \check{K}_\gamma \check{Q}_\delta - G_E^* \mathcal{T}^Q_{\alpha\gamma} \mathcal{T}^K_{\gamma\mu} - \frac{i\varsigma}{\lambda_m} G_C^* \check{Q}_\alpha \check{K}^\perp_\mu \right]$$

- The the Jones-Scadron form factors:

$$g_1 = b \, \frac{\sqrt{1+2\delta}\,\sqrt{\tau}}{2\lambda_+} \, (G_M^\star - G_E^\star)\,,$$

$$g_2 = b \left[\frac{\omega}{2\lambda_+} (G_M^\star - G_E^\star) - \frac{\tau\, G_C^\star + (\delta - \tau)\, G_E^\star}{\omega} \right]$$

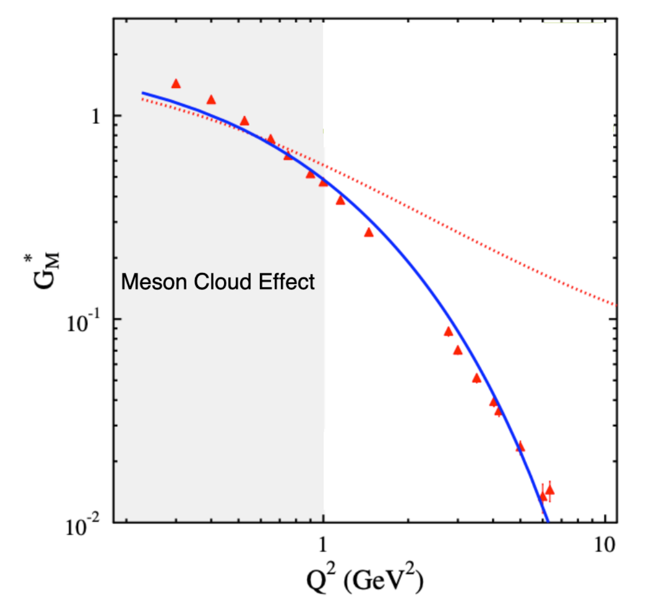
$$g_3 = b\, \frac{G_M^\star + G_E^\star}{2}\,,$$

- G_M^* Magnetic dipole
- G_E^* Electric quadrupole
- G_C^* Coulomb quadrupole

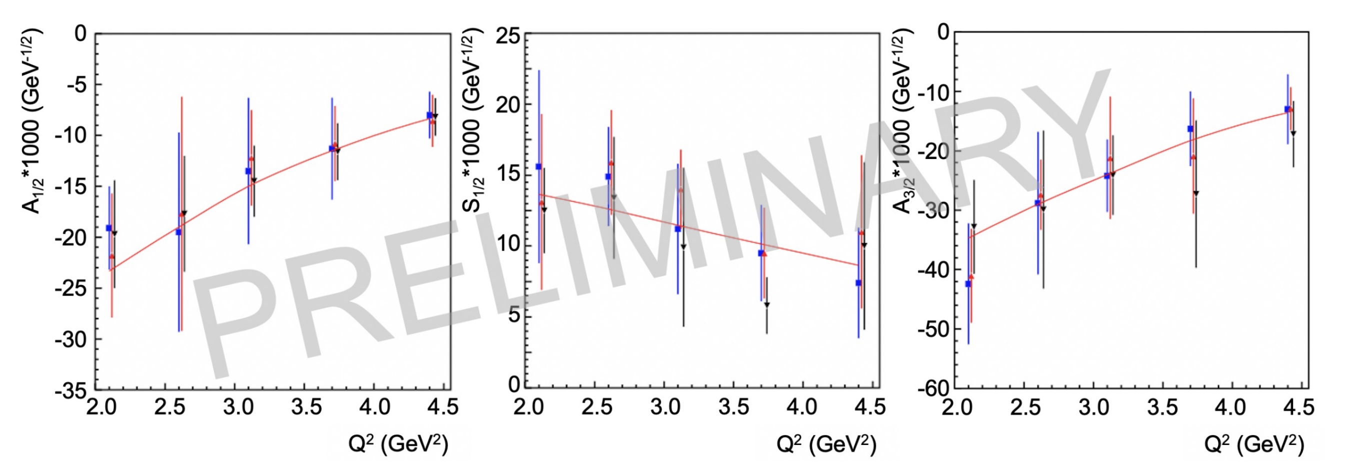
$N \to \Delta(1232), \Delta(1600)$ Transition Form Factors

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

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



Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

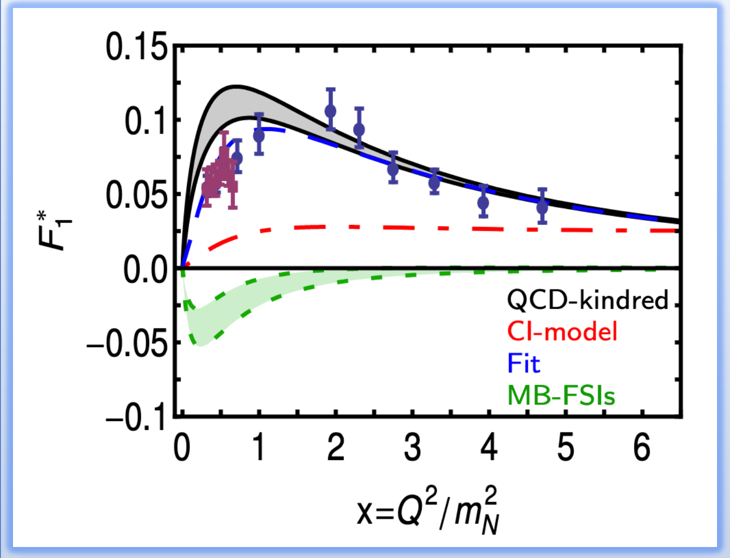


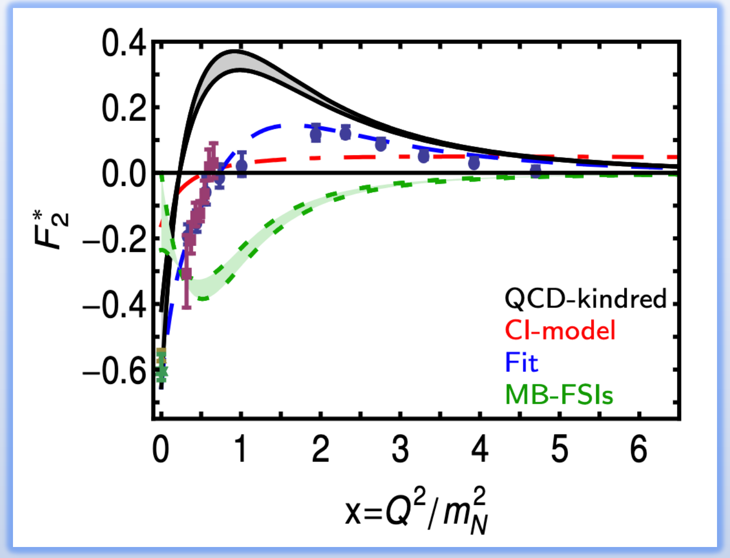
- CLAS results on Δ(1600)3/2+ electrocouplings confirmed the CSM prediction based on QCD kindred calculation.

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

$N \to N(1440)$ Transition Form Factors

- CSM computation of Dirac and Pauli transition form factors:





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

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

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

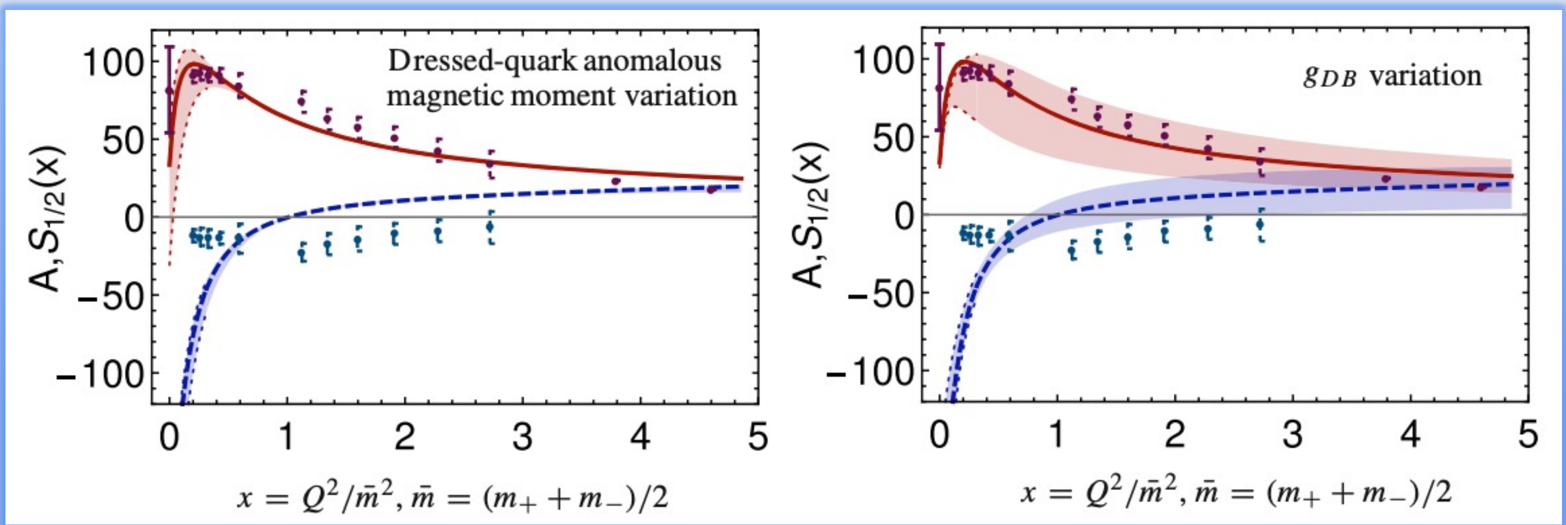
- The mismatch between the CSM prediction and the data on the domain $x \lesssim 2$ is attributed to the meson cloud contribution.

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

$N \to N(1535)1/2^{-}$ and $N \to N(1520)3/2^{-}$

- The computation of nucleon transition form factors to Δ(1232)3/2⁺, N(1440)1/2⁺, Δ(1600)3/2⁺ in QCD kindred models is available.
- Similar results for $N \to N(1535)1/2^{-}$ and $N \to N(1520)3/2^{-}$ are not yet available.

- An insightful starting point can be provide the symmetry preserving contact interaction (SCI).
- An SCI treatment of $N \to N(1535)1/2^{-}$ transition amplitudes and form factors provides first results providing us insight into its relative diquark content.



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

Summary and Scope

- A satisfactory description of the nucleon transition form factors to $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $\Delta(1600)3/2^+$ in QCD kindred models is already available in the literature.

- A SCI treatment of $N \to N(1535)$ transition amplitudes and form factors provides first results emphasizing its significant dependence on its structure and relative diquark content.

- The defining features of the SCI are the infrared enhanced coupling strength, gluon mass scale and dressed quark mass.

- A similar analysis for N(1520) and other transitions is required. We have made a start with SCI.

- It will take us another step closer towards explaining mesons, diquarks and nucleons, their ground and excited states, electromagnetic and transition form factors and amplitudes through a unified treatment within continuum QCD.

- Thank you.