Electromagnetic Transition Form Factors of Baryon Resonances

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In collaboration with:
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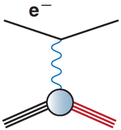
[1] **OMEG**: **O**rigin of **M**atter and **E**volution of **G**alaxies

Plan of the talk

Electromagnetic Transition Form Factors of Baryon Resonances,
Progress in Particle and Nuclear Physics, 136, 104097 (2024)

- Electromagnetic form factors of baryons:
  Hyperons and nucleon resonances (N^*)
- Structure functions for the study of $\gamma^* N \to N^*$ transitions
- Present knowledge of the $\gamma N \to N^*$ transition Amplitudes/ Form Factors

Spacelike and timelike reactions – elastic/inelastic cases †

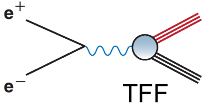


TFF
JLab/CLAS:
most world data

Spacelike reactions:
$e^- N \to e^- N^*$ $(e^- B \to e^- B')$

Amplitudes/FF are real functions

- Rosenbluth separation method
  $\frac{d\sigma}{d\Omega} \propto (\tau G_M^2 + \epsilon G_E^2 + ...)$, $(\tau = \frac{Q^2}{4M^2}$, $\epsilon^{-1} \propto \tan^2 \frac{\theta}{2} + ...)$
- Most data for $\gamma^* N \to N^*$ transitions
- Almost no data for Hyperons for $Q^2 > 0$



BES III, BELLE II

Timelike reactions: $e^- e^+ \to \gamma^* \to B\bar{B}$, $B\bar{B}'$

Form factotrs are complex functions

- Differential cross-section: $|G_E|$, $|G_M|$, $\Delta\Phi =$ rel. phase
- Integrated cross-section $(\tau = \frac{q^2}{4M^2})$
  $\sigma(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$
  [...] define effective form factor
- Available method: EM structure of Hyperons; $q^2 > 4M_B^2$

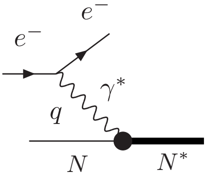
PART 1 – $\gamma^* N \to N^*$: formalism

- Structure functions for the study of $\gamma^* N \to N^*$ transitions
- Helicity Amplitudes; Multipole form factors
  Review formalism: adjust phases; fix coefficients $(J > \frac{3}{2})$
- Discuss properties at low-Q^2 and large-Q^2

Structural functions $\gamma^* N \to N^*$

Electron-Nucleon scattering

Vertex: $\gamma^* N \to N^* \;\Rightarrow J^\mu$



Diferential cross sections $\Rightarrow$ Structure functions $F(Q^2)$, $Q^2 = -q^2 > 0$

Spin-Parity J^P; M = nucleon mass; M_R = mass of the resonance N^*

- Independent KSF form factors: G_1, G_2, G_3
  KSF = kinematic-singularity-free Devenish et al, PRD 14, 3063 (1976)
  Defined by the gauge-invariant structure of the current
- Helicity amplitudes: $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ † – experiments
  Aznauryan and Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)
- Multipole form factors: G_M, G_E, G_C † – experiments
  Bjorken and Walecka, Annals Phys. 38, 35 (1966); Jones and Scadron, Annals Phys. 81, 1 (1973); Devenish et al, PRD 14, 3063 (1976)
- Breit frame Amplitudes: G_+, G_0, G_- Carlson et al, PRD 58, 094029 (1998) †

† defined in terms of G_i

Helicity amplitudes – N^* rest frame – state J^P $Q = \sqrt{Q^2}$

$N^*(S'_z)$, $N(S_z)$, photon $(\epsilon_{+,0})$ $\quad K = \frac{M_R^2 - M^2}{2M_R}$, $\quad \alpha = \frac{e^2}{4\pi}$, $\quad Q_\pm^2 = (M_R \pm M)^2 + Q^2$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{K}} \langle N^*, S'_z = +\tfrac{3}{2} | \epsilon_+ \cdot J | N, S_z = +\tfrac{1}{2} \rangle \qquad \rightarrow \qquad \longrightarrow$$

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{K}} \langle N^*, S'_z = +\tfrac{1}{2} | \epsilon_+ \cdot J | N, S_z = -\tfrac{1}{2} \rangle \qquad \leftarrow \qquad \rightarrow$$

$$S_{1/2} = \sqrt{\frac{2\pi\alpha}{K}} \langle N^*, S'_z = +\tfrac{1}{2} | \epsilon_0 \cdot J | N, S_z = +\tfrac{1}{2} \rangle \frac{|\mathbf{q}|}{Q} \qquad \rightarrow \qquad \rightarrow$$

N^* rest frame $\quad$ $\mathbf{q}$= photon 3-momentum $\quad$ $\omega = M_R - E$ $\quad$ $\epsilon_0 \cdot J \frac{|\mathbf{q}|}{Q} = J^0$

$$p = (E, 0, 0, -|\mathbf{q}|), \qquad p_R = (M_R, 0, 0, 0), \qquad q = (\omega, 0, 0, |\mathbf{q}|)$$

$$|\mathbf{q}| = \frac{\sqrt{Q_+^2 Q_-^2}}{2M_R}, \qquad E = \frac{M_R^2 + M^2 + Q^2}{2M_R}, \qquad \omega = \frac{M_R^2 - M^2 - Q^2}{2M_R}$$

- In the limit $|\mathbf{q}| = 0$, (pseudothreshold limit) $Q^2 = -(M_R - M)^2$: Amps are correlated
  Long wavelength theorem (Siegert's theorem): $S \propto E|\mathbf{q}|$, Siegert, PR 52, 787 (1937); Forest, Adv. Phys. 15, 1 (1966); Amaldi et al, Tracts Mod. Phys. 83, 1 (1979); Buchmann et al, PRC 58, 2478 (1998)
- The correlations cannot be ignored in the analysis of the results ...
  and need to be taken into account in parametrizations of the data GR PRD 100, 114014 (2019)

Helicity amplitudes vs Breit frame amplitudes

Breit frame amplitudes $(m = +, 0, -)$: $\mathbf{p}_R = -\mathbf{p}$

$$G_m = \left\langle N^*, \lambda_R = m - \frac{1}{2} \right| \epsilon^{(m)} \cdot J \left| N, \lambda_N = +\frac{1}{2} \right\rangle$$

Appropriated to study properties at **large** Q^2**:** $q \simeq (\frac{M_R^2 - M^2}{Q}, 0, 0, Q)$

$J^P = \frac{1}{2}^{\mp}, \frac{3}{2}^{\pm}, \frac{7}{2}^{\mp}, \ldots$

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{K}} G_+, \quad S_{1/2} = \mp \frac{|\mathbf{q}|}{Q} \sqrt{\frac{2\pi\alpha}{K}} G_0, \quad A_{3/2} = \mp \sqrt{\frac{2\pi\alpha}{K}} G_-$$

Breit frame amplitudes equivalent to Helicity amplitudes

pQCD/quark counting rules: Carlson et al, PRD 58, 094029 (1998)

Large Q^2**:** $A_{1/2} \propto \frac{1}{Q^3}, \quad S_{1/2} \propto \frac{|\mathbf{q}|}{Q} \frac{1}{Q^4} \propto \frac{1}{Q^3}, \quad A_{3/2} \propto \frac{1}{Q^5}$

Amplitudes and FF: transition currents

Notation: $\mathbb{1}_P = \begin{pmatrix} \gamma_5 \\ \mathbb{1} \end{pmatrix}$, G_i independent KSF form factors; $J = l + \frac{1}{2}$

Up: upper parity index; Down: lower parity index

Devenish et al, PRD 14, 3063 (1976); Aznauryan and Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

- $J^P = \frac{1}{2}^{\mp}$

$$J^\mu = F_1 \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) \mathbf{1}_P + F_2 \frac{i\sigma^{\mu\nu} q_\nu}{M_R + M_N} \mathbf{1}_P, \qquad \langle N^* | J^\mu | N \rangle = \bar{u}_R(p') J^\mu \, u(p)$$

Alternative representation use $F_1 = Q^2 G_1$ and $F_2 = -\frac{1}{2}(M_R \mp M)(M_R + M) G_2$

- $J^P = \frac{3}{2}^{\pm}, \frac{5}{2}^{\mp}, \frac{7}{2}^{\pm}, \ldots \; (l = 1, 2, 3, \ldots)$

$$\Gamma^{\alpha\mu}(q) = G_1 \left(q^\alpha \gamma^\mu - \not{q} g^{\alpha\mu} \right) \mathbf{1}_P + G_2 \left(q^\alpha P^\mu - P \cdot q g^{\alpha\mu} \right) \mathbf{1}_P + G_3 \left(q^\alpha q^\mu - q^2 g^{\alpha\mu} \right) \mathbf{1}_P$$

$$\langle N^* | \, J^\mu \, | N \rangle = \bar{u}_{\alpha_1 \alpha_2 \ldots \alpha_{l-1} \alpha}(p') \, \underbrace{q^{\alpha_1} \, q^{\alpha_2} \cdots q^{\alpha_{l-1}}}_{l-1 \text{ indices}} \Gamma^{\alpha\mu}(q) \, u(p),$$

Cases $J > \frac{3}{2}$: similar to $J = \frac{3}{2}$ (RS spinor J has $l = J - \frac{1}{2}$ indices)

Amplitudes and FF: $J^P = \frac{1}{2}^{\pm}$

upper/lower convention

Devenish et al, PRD 14, 3063 (1976); (F_i)

Aznauryan and Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012) ($A_{1/2}, S_{1/2}$)

$$A_{1/2} = e\mathcal{B}_{\mp}\left[F_1 + \frac{M_R \pm M}{M_R + M} F_2\right], \qquad \mathcal{B}_{\mp} = \sqrt{\frac{Q_{\mp}^2}{4MM_RK}}$$

$$S_{1/2} = \pm \frac{e}{\sqrt{2}}\mathcal{B}_{\mp}\frac{(M_R + M)|\mathbf{q}|}{Q^2}\left[\frac{M_R \pm M}{M_R + M} F_1 - \frac{Q^2}{(M_R + M)^2} F_2\right]$$

$$\mathcal{B}_{-} = \sqrt{\frac{M_R}{MKQ_{+}^2}}|\mathbf{q}| \qquad \mathcal{B}_{+} = \sqrt{\frac{Q_{+}^2}{4MM_RK}}$$

Inverse relations

$$F_1 = \frac{1}{e\mathcal{B}_{\mp}}\frac{Q^2}{Q_{\pm}^2}\left[A_{1/2} \pm \sqrt{2}\frac{M_R \pm M}{|\mathbf{q}|} S_{1/2}\right]$$

$$F_2 = \frac{1}{e\mathcal{B}_{\mp}}\frac{(M_R + M)(M_R \pm M)}{Q_{\pm}^2}\left[A_{1/2} \mp \sqrt{2}\frac{Q^2}{(M_R \pm M)|\mathbf{q}|} S_{1/2}\right]$$

Amplitudes and FF: $J^P = \frac{1}{2}^{\pm}$

upper/lower convention

Devenish et al, PRD 14, 3063 (1976); (F_i)

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$$S_{1/2} = \pm\frac{e}{\sqrt{2}}\mathcal{B}_{\mp}\frac{(M_R+M)|\mathbf{q}|}{Q^2}\left[\frac{M_R \pm M}{M_R + M}F_1 - \frac{Q^2}{(M_R+M)^2}F_2\right]$$

$$\mathcal{B}_{-} = \sqrt{\frac{M_R}{MKQ_+^2}}|\mathbf{q}| \qquad \mathcal{B}_{+} = \sqrt{\frac{Q_+^2}{4MM_RK}}$$

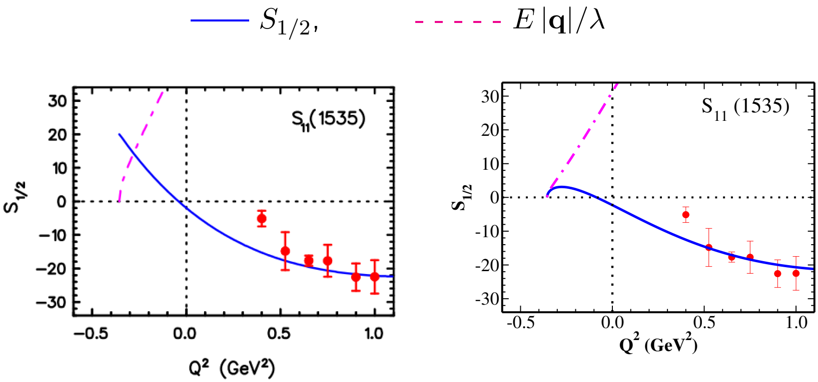
Interesting case: $J^P = \frac{1}{2}^{-}$ ($S \propto E|\mathbf{q}|, \quad E \equiv A_{1/2}$)

$$A_{1/2} \propto |\mathbf{q}|^0, \quad S_{1/2} \propto |\mathbf{q}|, \quad A_{1/2} = \sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|}$$

F_1, F_2 uncorrelated; Amplitudes are correlated;

Parametrizations of the data: amplitudes **must** be correlated when $|\mathbf{q}| \to 0$

$J^P = \frac{1}{2}^-$: constraints at PT; ST: $A_{1/2} = \lambda\, S_{1/2}/|\mathbf{q}|$



Left: MAID – uncorrelated amplitudes; $S_{1/2} \propto |\mathbf{q}|^0$ **MAID data**

Tiator, FBS 57, 1087 (2016); Drechsel *et al.*, EPJA 34, 69 (2007)

Right: parametrize F_i, correlated amplitudes; $S_{1/2} \propto |\mathbf{q}|$ $\oplus$ satisfy ST

MAID-type GR, PLB 759, 126 (2016); GR, PRD 100, 114014 (2019)

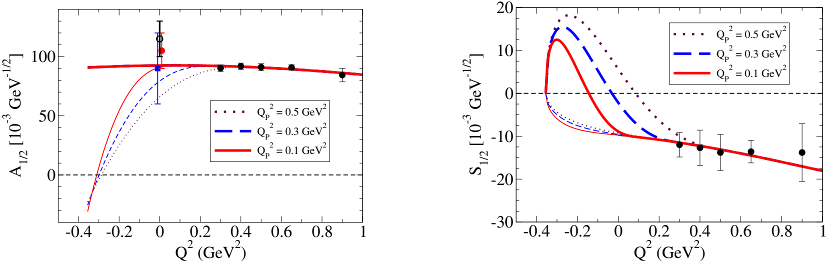
$A_{1/2}$ data > 0; turning point on $S_{1/2}$: $\Rightarrow$ $S_{1/2} > 0$ near PT

$J^P = \frac{1}{2}^-$: constraints at PT: $\gamma^* N \to N(1535)$

$S_{1/2}$ **unknown** near $Q^2 = 0$ **CLAS/JLab data**

Imposing **Siegert's theorem:** Mod. parametrizations Low Q^2: $A_{1/2} = \sqrt{2}(M_R - M_N)\frac{S_{1/2}}{|\mathbf{q}|}$

Devenish et al, PRD 14, 3063 (1976); GR, PRD 100, 114014 (2019); GR, PLB 759, 126 (2016); Devenish et al, PRD 14, 3063 (1976); GR and M.T. Peña PRD 101, 114008 (2020)



Data: PDG 2012, **PDG 2016**, PDG 2020

- Case 1 (**Thick lines**): $A_{1/2}$ smooth: $A_{1/2} > 0 \Rightarrow S_{1/2}$ **must** change sign
- Case 2 (Thin lines): $S_{1/2}$ smooth: $S_{1/2} < 0 \Rightarrow A_{1/2}$ **must** change sign

$J^P = \frac{1}{2}^-$: constraints at PT: $\gamma^* N \to N(1535)$

$S_{1/2}$ **unknown** near $Q^2 = 0$ **CLAS/JLab data**

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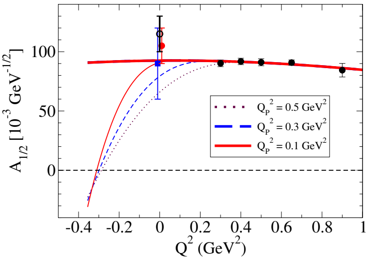
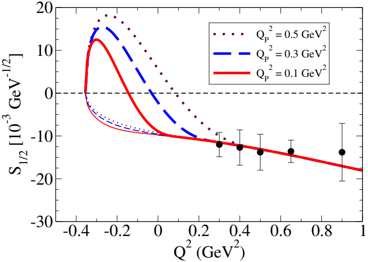




Data: PDG 2012, **PDG 2016**, PDG 2020 **Data needed below 0.25 GeV^2**

- Case 1 (**Thick lines**): $A_{1/2}$ smooth: $A_{1/2} > 0 \Rightarrow S_{1/2}$ **must** change sign
- Case 2 (Thin lines): $S_{1/2}$ smooth: $S_{1/2} < 0 \Rightarrow A_{1/2}$ **must** change sign

Amplitudes and FF: $J \geq \frac{3}{2}$: Amplitudes

$J^P = \frac{3}{2}^\pm, \frac{5}{2}^\mp, \frac{7}{2}^\pm, \ldots$ upper/lower convention $l = J - \frac{1}{2}$

Devenish et al, PRD 14, 3063 (1976); (G_i, h_i, G_α)

Aznauryan and Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012) $(A_{1/2}, A_{3/2}, S_{1/2})$

Helicity form factors/auxiliar functions h_i

$$h_1 = 4M_R G_1 + 4M_R^2 G_2 + 2(M_R^2 - M^2 - Q^2) G_3$$
$$h_2 = -2(M_R \pm M) G_1 - (M_R^2 - M^2 - Q^2) G_2 + 2Q^2 G_3$$
$$h_3 = -\frac{2}{M_R}\left[Q^2 + M(M \pm M_R)\right] G_1 + (M_R^2 - M^2 - Q^2) G_2 - 2Q^2 G_3$$

Calculate Helicity Amplitudes Factor C_l important: $A_{3/2}$

$$A_{1/2} = (-1)^{l+1} \mathcal{A}_{l\mp} h_3, \quad A_{3/2} = \pm(-1)^{l+1} \mathcal{A}_{l\mp} \frac{C_l}{l} h_2 \quad S_{1/2} = \pm(-1)^{l+1} \mathcal{A}_{l\mp} \frac{|\mathbf{q}|}{2M_R} h_1$$

$$\mathcal{A}_{l-} = \frac{1}{2\sqrt{2}} \frac{1}{\sqrt{z_{l+1}}} \sqrt{\frac{2\pi\alpha}{K}} \sqrt{\frac{M_R}{MQ_+^2}} |\mathbf{q}|^l, \qquad z_l = \frac{(2l)!}{2^l[(l)!]^2},$$

$$\mathcal{A}_{l+} = \frac{1}{2\sqrt{2}} \frac{1}{\sqrt{z_{l+1}}} \sqrt{\frac{2\pi\alpha}{K}} \sqrt{\frac{Q_+^2}{4MM_R}} |\mathbf{q}|^{l-1}, \qquad C_l = \sqrt{l(l+2)}$$

Amplitudes and FF – Multipole FF: $J^P = \frac{3}{2}^+, \frac{5}{2}^-, ...$

$$J^P = \tfrac{3}{2}^+, \tfrac{5}{2}^-, ..., \qquad l = J - \tfrac{1}{2}, \qquad F_{l+} = \sqrt{\tfrac{3}{2}} \frac{M}{6(M_R - M)} \frac{1}{\mathcal{A}_{l-}} \propto \frac{1}{|\mathbf{q}|^l}$$

G_M, G_E, G_C: linear combinations of G_i (h_i)

$$G_M = -F_{l+} \left(\frac{l+2}{C_l} A_{3/2} + A_{1/2} \right) \frac{2l}{l+1} (-1)^{l+1}$$

$$G_E = -F_{l+} \left(\frac{l}{C_l} A_{3/2} - A_{1/2} \right) \frac{2}{l+1} (-1)^{l+1}$$

$$G_C = \sqrt{2} F_{l+} \frac{2M_R}{|\mathbf{q}|} S_{1/2} (-1)^{l+1}$$

Constraint at PT: $A_{1/2} \propto |\mathbf{q}|^l$, $A_{3/2} \propto |\mathbf{q}|^l$, $S_{1/2} \propto |\mathbf{q}|^{l+1}$

$$\left(A_{1/2} - \frac{1}{C_l} A_{3/2} \right) \frac{1}{|\mathbf{q}|^l} = \frac{l+1}{2} \sqrt{2} (M_R - M) \frac{S_{1/2}}{|\mathbf{q}|^{l+1}}, \qquad G_E = \frac{M_R - M}{2M_R} G_C$$

Correlations between amplitudes and form factors

Cases $J^P = \frac{3}{2}^-, \frac{5}{2}^+, ...$: $G_M \leftrightarrow G_E$, $G_C \to -G_C$ and $F_{l+} \to F_{l-}$

Amplitudes and FF – Multipole FF $J^P = \frac{3}{2}^-, \frac{5}{2}^+, ...$

$J^P = \frac{3}{2}^-, \frac{5}{2}^+, ...,$ $\quad l = J - \frac{1}{2},$ $\quad F_{l-} = \sqrt{\frac{3}{2}} \frac{M}{6(M_R+M)} \frac{1}{\mathcal{A}_{l+}} \propto \frac{1}{|\mathbf{q}|^{l-1}}$

G_M, G_E, G_C: linear combinations of G_i (h_i) – expressed in terms of $A_{1/2}$, $A_{3/2}$, $S_{1/2}$

$$G_M = -F_{l-}\left(\frac{l}{C_l}A_{3/2} - A_{1/2}\right)\frac{2}{l+1}(-1)^{l+1}$$

$$G_E = -F_{l-}\left(\frac{l+2}{C_l}A_{3/2} + A_{1/2}\right)\frac{2l}{l+1}(-1)^{l+1}$$

$$G_C = -\sqrt{2}F_{l-}\frac{2M_R}{|\mathbf{q}|}S_{1/2}(-1)^{l+1}$$

Constraint at PT: $A_{1/2} \propto |\mathbf{q}|^{l-1}$, $A_{3/2} \propto |\mathbf{q}|^{l-1}$, $S_{1/2} \propto |\mathbf{q}|^{l}$

$$\left(A_{1/2} + \tfrac{l+2}{C_l}A_{3/2}\right)\frac{1}{|\mathbf{q}|^l} = \tfrac{l+1}{l}\sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|^{l+1}}, \qquad G_E = -\frac{M_R - M}{M_R}G_C$$

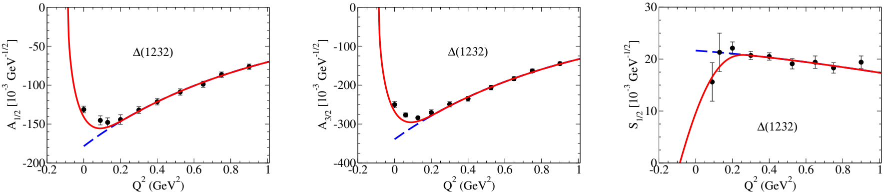
$$A_{1/2} = \tfrac{1}{C_l}A_{3/2}, \qquad G_M \propto |\mathbf{q}|^2$$

Correlations between amplitudes and form factors

Cases $J^P = \frac{3}{2}^+, \frac{5}{2}^-, ...$: $G_M \leftrightarrow G_E$, $G_C \to -G_C$ and $F_{l-} \to F_{l+}$

$J^P = \frac{3}{2}^+$: constraints at PT, $\gamma^* N \to \Delta(1232)$ – Amps

We can use the analytic form to redefine parametrizations at low Q^2



– – – – JLab parametrization: Rational functions; Blin et al, PRC 100, 035201 (2019), https://userweb.jlab.org/~isupov/couplings/ $Q^2 > 0.5$ GeV^2

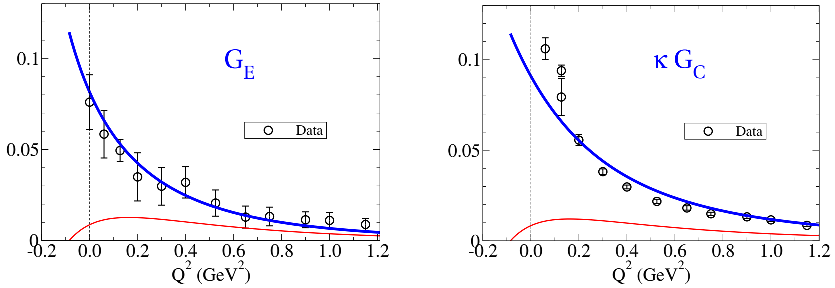
——— Analytic extension for $Q^2 < 0.3$ GeV^2; GR, PRD 100, 114014 (2019)

Turning points – Signature of PT constraints

$J^P = \frac{3}{2}^+$: constraints at PT, $\gamma^* N \to \Delta(1232)$ – FF

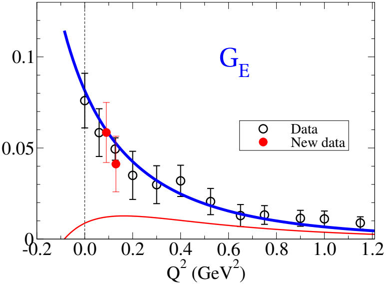
Jones and Scadron, Annals Phys. 81, 1 (1973); Devenish et al, PRD 14, 3063 (1976)

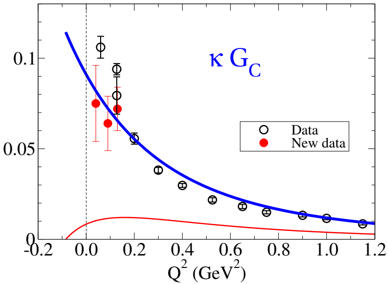
$E = \sqrt{2}(M_R - M) S_{1/2}/|\mathbf{q}|$ or $G_E = \frac{M_R - M}{2M_R} G_C$ Talk MT Peña



- Naive parametrizations fail to describe $G_E = \kappa G_C$; MAID: Drechsel *et al.*, EPJA 34, 69 (2007); Tiator, FBS 57, 1087 (2016) JLab: Blin et al, PRC 100, 035201 (2019) $\kappa = \frac{M_R - M}{2M_R}$
- Models constistent with ST: Pascalutsa and Vanderhaeghen, PRD 76, 111501 (2007); Buchmann, PRD 66, 056002 (2002) π-cloud contribution from Large-N_c ($G_E, G_C \propto G_{En}$ – neutron)
  Quark Model $\oplus$ Large-N_c pion cloud $\Rightarrow$ Underestimate G_C
  GR, PRD 94, 114001 (2016); GR, EPJA 54, 75 (2018)

$J^P = \frac{3}{2}^+$: constraints at PT, $\gamma^* N \to \Delta(1232)$ – FF





- Data: JLab/CLAS, MAMI, MIT, PDG – New data: JLab/Hall A Blomberg et al, PLB 760, 267 (2016): $Q^2 = 0.04, 0.09, 0.13$ GeV^2
- Combination of QM (small component) GR, MT Peña, PRD 80, 013008 (2009) with **Large-N_c relations** – consistent with Siegert's theorem GR, EPJA 54, 75 (2018)
- **Good** description of the data & **consistent** representation of G_E, G_C

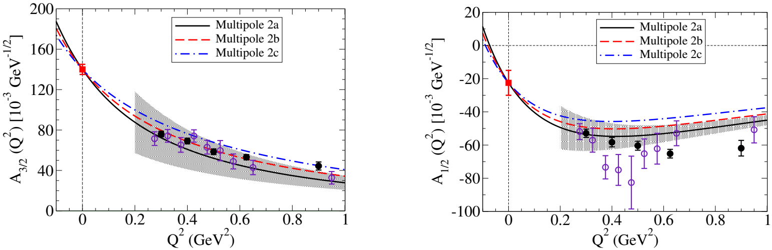
$J^P = \frac{3}{2}^-$: constraints at PT, $\gamma^* N \to N(1520)$ †

Interesting case: $|A_{3/2}(0)| \gg |A_{1/2}(0)|$ – **GR, PRD 109, 074021 (2024)**

Large $A_{1/2}$; Small $A_{1/2}$: $G_2(0) \simeq -\frac{2M}{M_R(M+M_R)} G_1(0)$ **Data: PDG, JLab/CLAS**

Test if we can describe low-Q^2 using parametrization:

$G_1(Q^2) = G_1(0) / \left(1 + \frac{Q^2}{\Lambda_3^2}\right)^3$, $G_{2,3}(Q^2) = G_{2,3}(0) / \left(1 + \frac{Q^2}{\Lambda_4^2}\right)^4$ determine scale Λ_n^2



Natural scale: $\left(1 + \frac{Q^2}{\Lambda_n^2}\right)^{-n} \simeq \left(1 + \frac{Q^2}{\Lambda_D^2}\right)^{-2}$, Λ_D nucleon dipole cutoff

Good descr.: $S_{1/2}(0) = -(75 - 85) \times 10^{-3}$ GeV$^{-1/2}$ (Mult. 2a – 2b) **Solution** $\Leftarrow G_{1,2}(0)$ **and** Λ_D^2

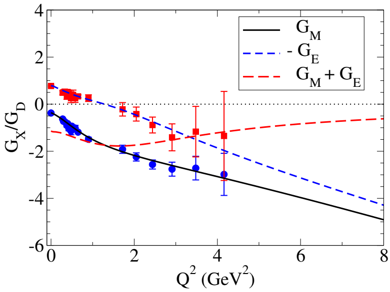
Large Q^2: $J \geq \frac{3}{2}$ $\quad l = J - \frac{1}{2}$

$A_{1/2} \propto \frac{1}{Q^3}$, $A_{3/2} \propto \frac{1}{Q^5}$: $\quad G_E \propto \frac{1}{Q^{2l+2}}$, $G_M \propto \frac{1}{Q^{2l+2}}$

$J^P = \frac{3}{2}^+, \frac{5}{2}^-, \ldots$: $G_M \simeq -l G_E$, $\qquad J^P = \frac{3}{2}^-, \frac{5}{2}^+, \ldots$: $G_M \simeq -\frac{1}{l} G_E$

$\Delta(1232)\frac{3}{2}^+$: no sign of convergence $G_E/G_M \simeq 0.1$

$N(1520)\frac{3}{2}^-$: very slow convergence: $G_E + G_M \propto \frac{1}{Q^6}$



Part 1 – Summary

- Helicity Amplitudes and Multipole form factors are expressed in terms of Kinematic-Singularity-Free Form Factors
- At low-Q^2 (near the pseudothreshold) **there are correlations** between Helicity Amplitudes/Mutipole Form Factors that afect **the shape** of the Amplitudes/Form Factors: $\Delta(1232)$, $N(1535)$ (light N^* states)
- These correlations cannot be ignored in the analysis of the results ... and need to be taken into account in parametrizations of the data
- Accurate low-Q^2 data: **necessary** to determine the **shape** of the amplitudes Important to study of the timelike region $N^* \to \gamma^* N \to \ell^- \ell^+ N$ (N^* Dalitz decay/di-lepton decays, HADES/GSI)

Electromagnetic Transition Form Factors of Baryon Resonances,

Progress in Particle and Nuclear Physics, 136, 104097 (2024)

Correlations between helicity amplitudes (multipole FF) ††

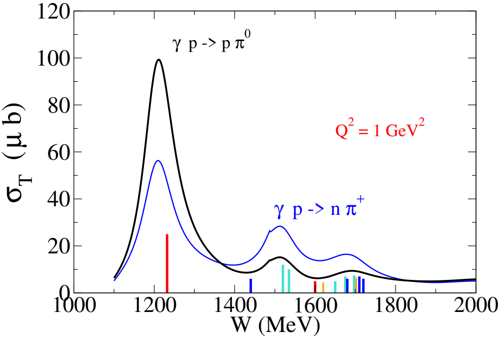
Relations between helicity amplitudes and transition form factors near the pseudothreshold

$A, S \propto |\mathbf{q}|^n$; Relations between amplitudes; Relations between FF

$\frac{1}{2}^+$	$A_{1/2} \propto |\mathbf{q}|$,	$S_{1/2} \propto |\mathbf{q}|^2$		
$\frac{1}{2}^-$	$A_{1/2} \propto 1$,	$S_{1/2} \propto |\mathbf{q}|$	$A_{1/2} = \sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|}$	$G_E = 2\frac{M_R - M}{M_R} G_C$
$\frac{3}{2}^+$	$A_{1/2} \propto |\mathbf{q}|$, $A_{3/2} \propto |\mathbf{q}|$	$S_{1/2} \propto |\mathbf{q}|^2$	$\left(A_{1/2} - \frac{1}{\sqrt{3}} A_{3/2}\right)\frac{1}{|\mathbf{q}|} = \sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|^2}$	$G_E = \frac{M_R - M}{2M_R} G_C$
$\frac{3}{2}^-$	$A_{1/2} \propto 1$, $A_{3/2} \propto 1$	$S_{1/2} \propto |\mathbf{q}|$	$A_{1/2} + \sqrt{3}A_{3/2} = -2\sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|}$ $A_{1/2} = \frac{1}{\sqrt{3}} A_{3/2}$	$G_E = -\frac{M_R - M}{M_R} G_C$ $G_M \propto |\mathbf{q}|^2$
$\frac{5}{2}^-, \frac{7}{2}^+, ...$	$A_{1/2} \propto |\mathbf{q}|^l$, $A_{3/2} \propto |\mathbf{q}|^l$	$S_{1/2} \propto |\mathbf{q}|^{l+1}$	$\left(A_{1/2} - \frac{l}{C_l} A_{3/2}\right)\frac{1}{|\mathbf{q}|^l} = \frac{l+1}{2}\sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|^{l+1}}$	$G_E = \frac{M_R - M}{2M_R} G_C$
$\frac{5}{2}^+, \frac{7}{2}^-, ...$[2]	$A_{1/2} \propto |\mathbf{q}|^{l-1}$, $A_{3/2} \propto |\mathbf{q}|^{l-1}$	$S_{1/2} \propto |\mathbf{q}|^l$	$\left(A_{1/2} + \frac{l+2}{C_l} A_{3/2}\right)\frac{1}{|\mathbf{q}|^{l-1}} = -\frac{l+1}{l}\sqrt{2}(M_R - M)\frac{S_{1/2}}{|\mathbf{q}|^l}$ $A_{1/2} = \frac{l}{C_l} A_{3/2}$	$G_E = -\frac{M_R - M}{M_R} G_C$ $G_M \propto |\mathbf{q}|^2$

[2] Condition $A_{1/2} - \frac{l}{C_l} A_{3/2} \propto |\mathbf{q}|^{l+1}$

Part 2 – Electromagnetic structure of nucleon resonances



Focus on: **Most data from JLab**

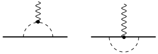
$\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, $N(1535)\frac{1}{2}^-$, ..., $\Delta(1600)\frac{3}{2}^+$

$\Delta(1232)$ decays: **BR**(e^+e^-p): 1.4×10^{-5} (HADES) – 1st N^* Dalitz decay

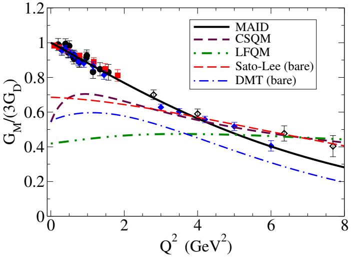
HADES: PRC 95, 065205 (2017); GR, Peña, Weil, Hess, Mosel, PRD 93, 033004 (2016), Talk Izabela Ciepal

$\Delta(1232)\frac{3}{2}^+$ resonance

- $J = \frac{3}{2}$, Isospin $I = \frac{3}{2}$; $\Delta \to \pi N$ (99.4%)
- Dominated by magnetic dipole FF: G_M
  G_E, G_C: small components; $G_M(0) \simeq 3$
- QM underestimate G_M ($\sim$ 35%)
  $SU(6)$: $G_M(0) = 2.3$
- Additional d.o.f.: pion cloud dressing:
  Dynamical M. : Burkert, Lee. IJMP E13, 1035 (2004)



  Sato-Lee/EBAC; Sato, Lee et al. PRC 54, 2660 (1996); PRC 76, 065201 (2007); Dubna-Mainz-Taipei: Kamalov et al. PRC, 032201 (2001)
- Covariant Spectator QM ($f_{i\pm}$ quark FF):
  $G_M^B \propto \left[f_{1-} + \frac{M_\Delta + M}{2M} f_{2-} \right] \int \psi_\Delta \psi_N \leq 2.03$
  Describe data including effective π cloud ($\sim$ SL, DMT)
  Bare contribution can be tested by lattice QCD data (C Alexandrou et al, PRD 77, 085012 (2008))
- Similar (bare) estimates in Dyson-Schwinger Eqs
  Dynamic mass generation (DCSB) $m_q(Q^2)$



$G_M(0) = 1.65$–2.3

	$G_M(0)$
Data	3.02
$SU(6)$ symmetry	2.3
SL (bare) [223,226]	2.0
DMT (bare) [206]	1.65
Non relativistic QM [31,33]	2.2
Relativistic QM [484]	2.3
Hypercentral QM [54]	2.0
QM+ MEC [485]	2.2
MIT [486]	2.2

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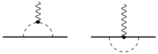

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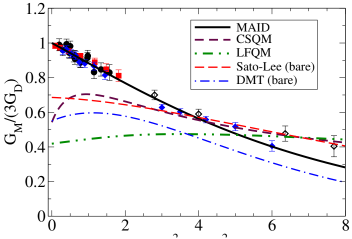

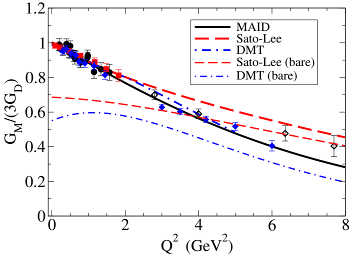

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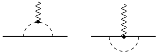

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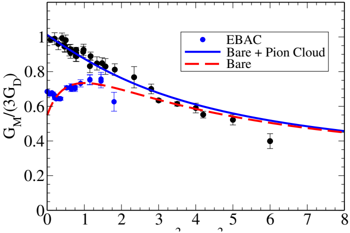

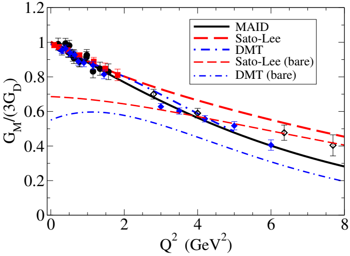

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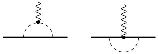

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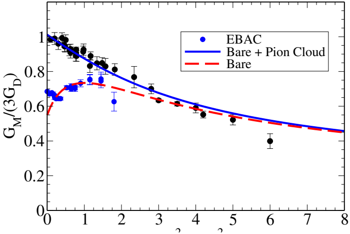

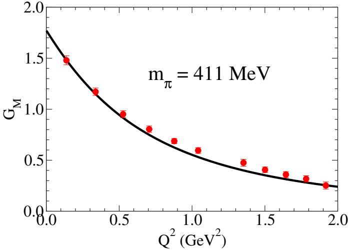

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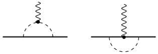

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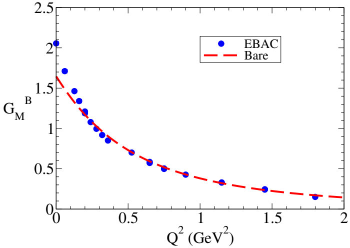
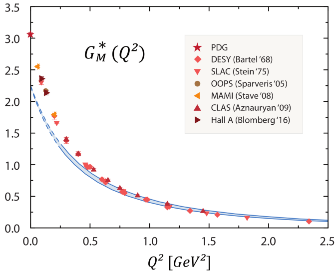
  G Eichmann et al, PRD 85, 093004 (2012); PPNP 91, 1 (2016); Segovia, Yu et al, FBS 55, 1 (2014); PRD 100, 034001 (2019)



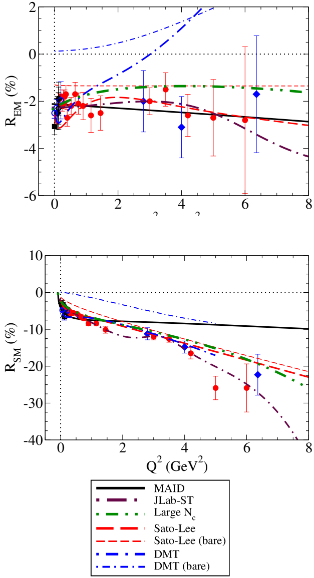


$\Delta(1232)\frac{3}{2}^{+}$ resonance (2) ††

- Electric and Coulomb quadrupole FF: small contributions – measure deformation
  $R_{EM} = -\frac{G_E}{G_M}$, $R_{SM} = -\frac{|\mathbf{q}|}{2M_\Delta}\frac{G_C}{G_M}$
- EFT: low Q^2 region:
  Small number of parameters
  Connect Physical data with lattice QCD data
  Pascalutsa, Vanderhaeghen, Yang, PR 125, 437 (2007)

  EFT based on old R_{SM} data:
  GH: Gail, Hemert, EPJA 28, 91 (2006)
  PV: Pascalutsa, Vanderhaeg., PRL 95, 232001 (2005)
  New data may require **recalibration of LECs**

  EFT based on **new data**:
  Mainz: Hilt et al, PRC 97, 035205 (2018)
- New results consistent with **Large** N_c:
  Pascalutsa, Vanderhaeghen: $R_{EM}(0) = R_{SM}(0)$



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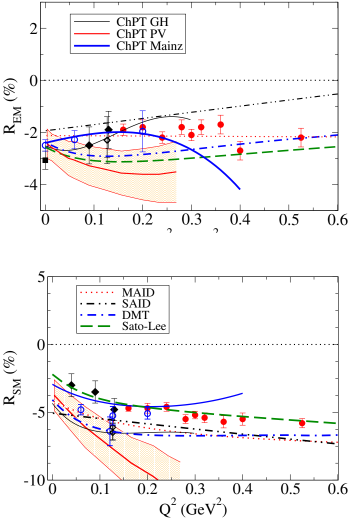

New data: smaller $|R_{SM}|$

JLab/Hall A, PLB 760, 267 (2016)

$\Delta(1232)\frac{3}{2}^+$ resonance (2) ††

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  $R_{EM} = -\frac{G_E}{G_M}$, $R_{SM} = -\frac{|\mathbf{q}|}{2M_\Delta}\frac{G_C}{G_M}$
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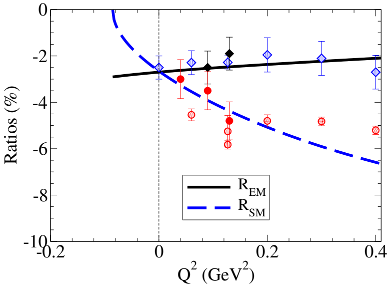
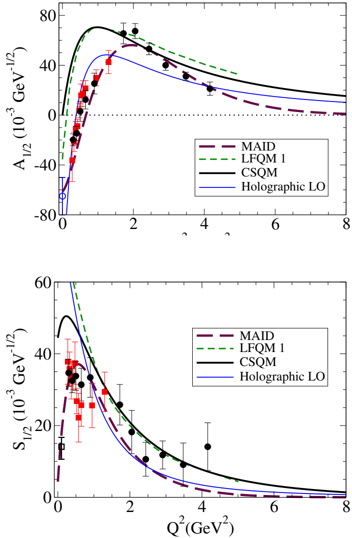


GR, EPJA 54, 75 (2018)

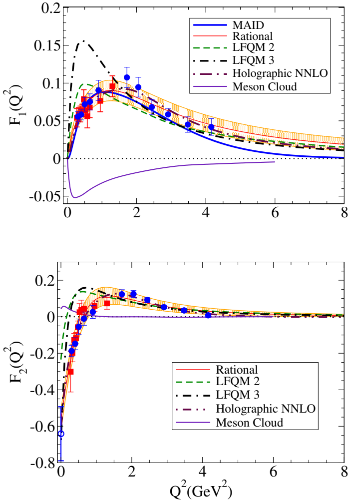
$N(1440)\frac{1}{2}^+$ resonance (Roper)

- Discussed in detail this workshop
  Review: VD Burkert, CD Roberts, RMP 91, 011003 (2019)
  Correct order in spectrum:
  Lattice QCD, Dyson-Schwinger (DSE)
- Consistence of πN and $\pi\pi N$ data (CLAS)
  PRC 80, 055203 (2009); PRC 86, 035203 (2012);
  PRC 93, 025206 (2016)
  $S_{1/2}$ unknown near $Q^2 = 0$
- **Present status:**
  • qqq excitation:
  compatible with large Q^2 data
  • Low Q^2: significant contributions of meson-baryon states (σN, $\pi\pi N$)
  • Hybrid: ANL-Osaka Dynamical model
  $M_{\rm bare} = 1.7$ GeV; Roper mass is reduced by dressing of bare state   N Suzuki et al PRL 104, 042302 (2010)
  • **Lattice/Lücher method** - phase shifts
  Hamiltonean EFT – Strong interference between MB channels – qqq small effect – Talk D. Lineweber

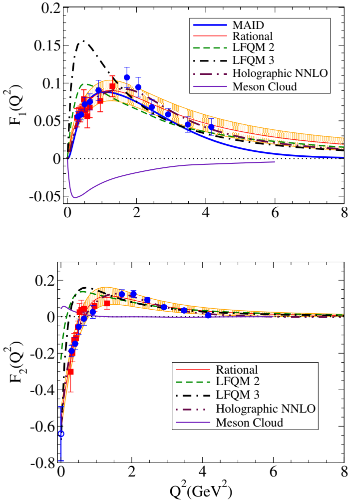


$N(1440)\frac{1}{2}^+$ resonance (Roper) F_1, F_2

- **Large Q^2: dominance of qqq (QM)**
  LFQM 1: Aznauryan, PRC 76, 025212 (2007);
  CSQM: GR, Tsushima, PRD 81, 074020 (2010); Holography
  - **Light Front Quark Models**
    combined with **meson-baryon** states
    LFQM 2: Aznauryan, Burkert, PRC 85, 055202 (2012) $m_q(Q^2)$
    LFQM 3: Obukhovsky et al, PRD 100, 094013 (2019)
  - Also DSE –mass evolution $m_q(Q^2)$
    DJ Wilson et al, PRC 85, 025205 (2012);
    J Segovia et al, PRL 115, 171801 (2015)
- **Meson Cloud**
  ANL-Osaka Dynamical Model: Sato, FBS 57, 949 (2016); Nakamura et al, PRD 92, 074024 (2015)
- Holographic QCD: Brodsky/Teramond – analytic form; Phys. Rep. 584, 1 (2015); Gutsche et al, PRD 86, 036007 (2012); PRD 97, 054011 (2018); GR, PRD 96, 034037 (2017); GR and Melnikov, PRD 97, 073002 (2018)
  Good description of **bare core** with a small number of parameters



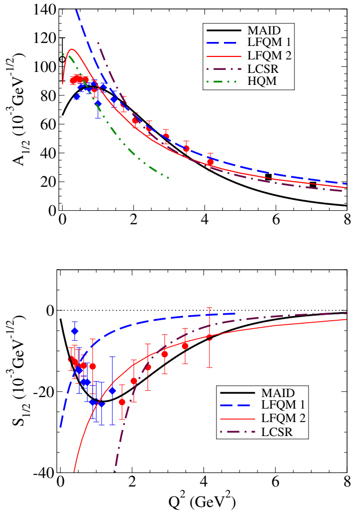
$N(1440)\frac{1}{2}^+$ resonance (Roper) – Summary



- **Summary:**
  - Quark Models/LFQM/DSE: Describe well the large Q^2 region: qqq picture
  - Low Q^2: baryon-meson states play an important rule

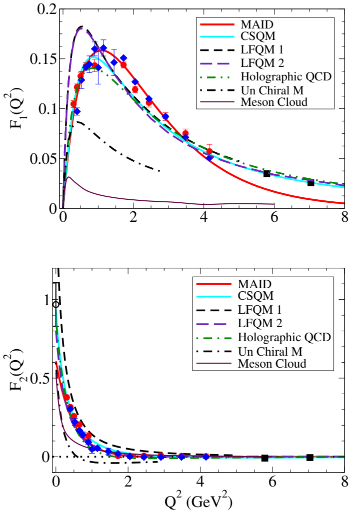
$N(1535)\frac{1}{2}^-$ resonance

- Dominated by πN and ηN decays ($\sim 50\%$)
  JLab/Hall C: Armstrong, PRD 60, 052004 (1999); Dalton, PRC 80, 015205 (2009) $A_{1/2}$; JLab/CLAS: Aznauryan, PRC 80, 055203 (2009) $A_{1/2}$, $S_{1/2}$; MAID: https://maid.kph.uni-mainz.de/maid2007/data.html
- **No model describe the data in the full range**
- Quark Models: w/ P-states
  LFQM 1: Aznauryan, Burkert, PRC 95, 065207 (2017) (MC)
  LFQM 2: Obukhovsky et al, PRD 100, 094013 (2019) (MC)
  HQM: Aiello, Giannini, Santopinto, JPG 24, 753 (1998)
- Lith Cone SR: $Q^2 > 2$ GeV^2 – lattice QCD data
  Anikin, Braun, Offen PRD 92, 014018 (2015) quark p-states
- Models based on quark d.o.f.: OK $Q^2 > 2$ GeV^2
- **CSQM discussed by MT Peña for timelike**



$N(1535)\frac{1}{2}^-$ resonance F_1, F_2

- Compare results with Form Factors F_1, F_2
  – different prespective
  CSQM: GR and MT Peña, PRD 101, 114008 (2020)
  Holography: Gutsche et al, PRD 101, 034026 (2020), LFQMs
  Still dominance of qqq states for large Q^2
- Hamiltonean EFT: ZW Liu et al, PRL 116, 082004 (2016)
  $N(1535)$ dominated by qqq components
- Models with **baryon-meson** contributions:
  - Unitary Chiral Model: generated dynamicaly
    Jido, Döring, Oset, PTC 77, 065207 (2008) ⇒ $A_{1/2}$, F_i
  - ANL-Osaka model - Meson cloud F_1, F_2
    Nakamura, Kamano, Sato, PRD 92, 074024 (2015)
- Form factor F_2: $F_2(Q^2) \simeq 0$, $Q^2 > 2$ GeV^2:
  $S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_R^2 - M^2}{2 M_R Q} A_{1/2}$, $\tau = \frac{Q^2}{(M_R+M)^2}$
  GR and Tsushima, PRD 84, 051301 (2011)
  ■ prediction for $S_{1/2}$



$N(1535)\frac{1}{2}^{-}$ resonance F_1, F_2

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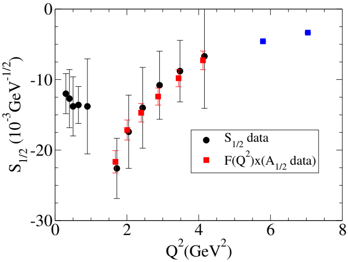

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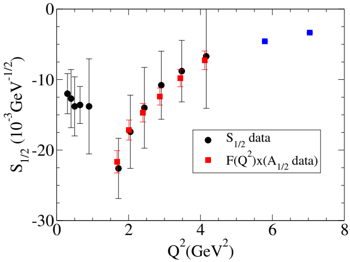
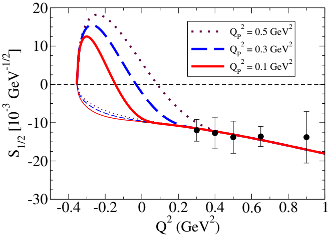
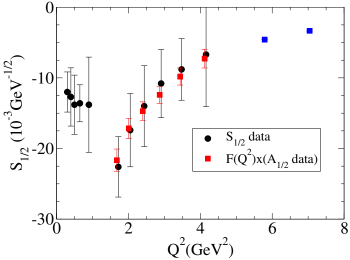
  ■ prediction for $S_{1/2}$ awaiting for new data



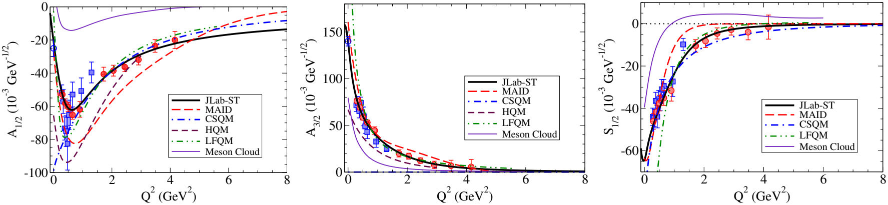
$N(1535)\frac{1}{2}^-$ resonance – Summary



- **No model describe the data in the full range**
- Models based on quark d.o.f. w/ P-states:
  Describe well the large Q^2 region ($Q^2 > 2$ GeV^2)
- **Baryon-meson contributions** are **important** at low Q^2 ($A_{1/2}$, F_1)
- Shape of amplitudes $A_{1/2}$, $S_{1/2}$
  unknown below $Q^2 = 0.25$ GeV^2
  Region important for timelike studies
- **Large Q^2:** correlation of amplitudes:
  $S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_R^2 - M^2}{2 M_R Q} A_{1/2}$

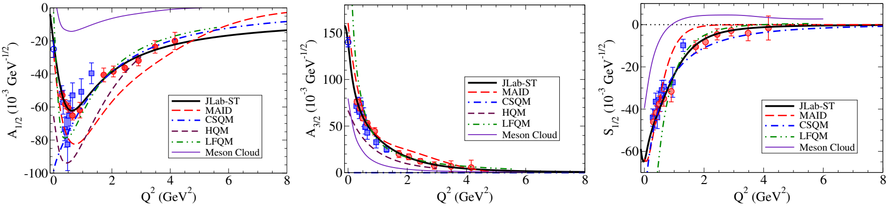


$N(1520)\frac{3}{2}^-$ resonance



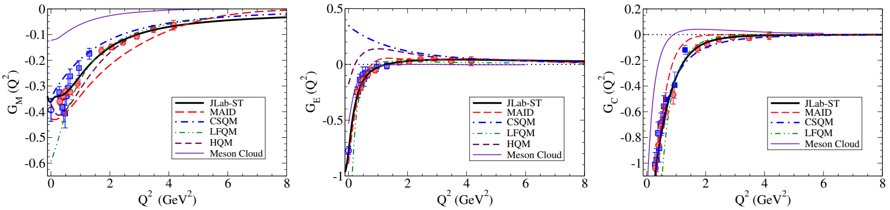
- Negative parity resonance: Decays dominated by πN (60%) and $\pi\pi N$ (40%)
  JLab/CLAS: Aznauryan et al., PRC 80, 055203 (2009)
  JLab/CLAS: Mokeev et al., PRC 93, 025206 (2016)
  Different results from MAID - - - -
- **Discussed by MT Peña (TL/SL) and I. Ciepal (timelike)**
- Quark models describe well $A_{1/2}$, $S_{1/2}$: only 1/2 or 1/3 of $A_{3/2}$ near $Q^2 = 0$
- Meson cloud contributions (low Q^2): significant effect on $A_{3/2}$
- **Large Q^2:** $G_M \simeq -G_E$

$N(1520)\frac{3}{2}^-$ resonance †



- $A_{3/2}$ dominate at Low Q^2: $A_{3/2} \simeq 150 \gg |A_{1/2}|$
  Large Q^2: $|A_{1/2}| \gg |A_{3/2}|$ – dominance of $A_{1/2}$ – helicity conservation
- Quark models (P-states):
  good description of large Q^2: $A_{1/2}$, $S_{1/2}$; small QM contributions $A_{3/2}$
  CSQM: GR, PRD 95, 054008 (2017); Hypercentral QM: Aiello, Giannini, Santopinto, JPG 24, 753 (1998);
  LFQM: Aznauryan, Burkert, PRC 95, 065207 (2017) $m_q(Q^2)$
- Meson cloud – ANL-Osaka model – Important to $A_{3/2}$ ($S_{1/2}$)
  S Nakamura, H Kamano, T Sato, PRD 92, 074024 (2015)
- Low Q^2: Effective parametrization $G_1(0)$, $G_2(0)$, Λ_D^2 ($G_3(0)$)
- Large Q^2: $A_{3/2} \propto (G_M + G_E) \propto \frac{1}{Q^5} \Rightarrow G_M \simeq -G_E$
  GR, MT Peña, PRD 98, 094016 (2014); PRD 95, 014003 (2017)

$N(1520)\frac{3}{2}^-$ resonance † – G_E, G_M



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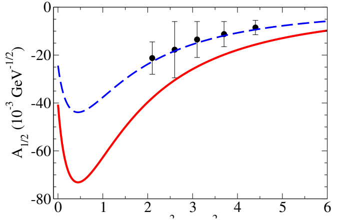
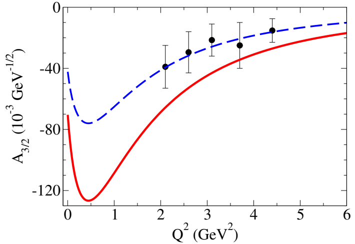
$\Delta(1600)\frac{3}{2}^+$ resonance

- $\Delta(1600)$: radial excitation of the $\Delta(1232)$
- Amplitudes measured for the first time 2023
  CLAS: V. Mokeev et al PRC 108, 025204 (2023)
- Calculated in different frameworks
  LFQM: Capstick, Keister, PRD 51, 3598 (1995)
- Recent calculations:
  DSE/CSM: Y Lu et al, PPD 100, 034001 (2019)
  good description of the data
  LFQM: Aznauryan and Burkert, PRC 82, 035211 (2015)
  CSQM: GR and Tsushima, PRD 82, 073007 (2010)
  Assume $A_{1/2}, A_{3/2} > 0$; MC eff: $|G_M^\pi(0)| = 0..1.3$
- Update of CSQM (asuming $S-$state)
  Estimate based on new information
  Adjusting signs of $A_{1/2}, A_{3/2}$, $|G_M^\pi(0)| = 0.65$
  —- $A_\alpha \Rightarrow ZA_\alpha$, where $Z \simeq 0.5$ - - -
  • Convert Amps to G_M, G_E
  Dominance of magnetic dipole FF: $G_E \simeq 0$
- $\Delta(1600)$ **consistent with radial excitation**
  • Baryon-meson contributions important to explain the data





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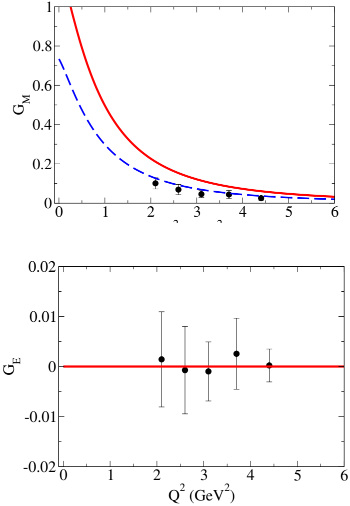

Part 2 – Outlook and Conclusions

- We reviewed the experimental and theoretical status of the most well-known nucleon resonances ... $\Delta(1600)$
- The main properties: mass, decay widths, falloff of helicity amplitudes
  Large Q^2: baryons as systems of pointlike quarks (core)
  Low Q^2: meson-baryon structure emerge (peripheral region)
- Experimental results **are expected** JLab, JLab-12 GeV:
  $N(1650)\frac{1}{2}^-$, $N(1675)\frac{5}{2}^-$, $N(1680)\frac{5}{2}^+$, $N(1700)\frac{3}{2}^-$, $N(1710)\frac{1}{2}^+$, $N(1880)\frac{1}{2}^+$, $N(1720)\frac{3}{2}^+$, $N'(1720)\frac{3}{2}^+$, $\Delta(1620)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$
- Accurate Low-Q^2 data ($Q^2 = 0$–0.25 GeV^2) are necessary to determine the shape of the amplitudes of some N^* states ($N(1535)$, ...)
  Important for timelike studies ($N^* \to e^+e^-N$, HADES)
  Information about neutron targets also important – Talks I. Ciepal, MT Peña
- Range $W = 1.7$–1.9 GeV: amplitudes analysis need to include $\pi\pi N$ and meson-hyperon channels (Talk U. Thoma, V. Mokeev, D. Carman ...)

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Thank you

More questions: gilberto.ramalho2013@gmail.com

Backup slides

Amplitudes and FF – Multipole FF $J^P = \frac{3}{2}^+, \frac{5}{2}^-, ...$

$$J^P = \tfrac{3}{2}^+, \tfrac{5}{2}^-, ..., \qquad l = J - \tfrac{1}{2}, \qquad F_{l+} = \sqrt{\tfrac{3}{2} \tfrac{M}{6(M_R - M)} \tfrac{1}{\mathcal{A}_{l-}}} \propto \tfrac{1}{|\mathbf{q}|^l}$$

G_M, G_E, G_C: linear combinations of G_i (h_i)

$$G_M = -F_{l+}\left(\frac{l+2}{C_l} A_{3/2} + A_{1/2}\right)\frac{2l}{l+1}(-1)^{l+1}$$

$$G_E = -F_{l+}\left(\frac{l}{C_l} A_{3/2} - A_{1/2}\right)\frac{2}{l+1}(-1)^{l+1}$$

$$G_C = \sqrt{2} F_{l+} \frac{2M_R}{|\mathbf{q}|} S_{1/2}(-1)^{l+1}$$

Inverse relations

$$A_{1/2} = -\frac{1}{4F_{l+}}\left[G_M - (l+2)G_E\right](-1)^{l+1}, \qquad S_{1/2} = \frac{1}{\sqrt{2}F_{l+}}\frac{|\mathbf{q}|}{2M_R} G_C (-1)^{l+1}$$

$$A_{3/2} = -\frac{C_l}{4F_{l+}}\left[\frac{1}{l} G_M + G_E\right](-1)^{l+1}$$

Cases $J^P = \frac{3}{2}^-, \frac{5}{2}^+, ...$: $G_M \leftrightarrow G_E$, $G_C \to -G_C$ and $F_{l+} \to F_{l-}$

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G_M, G_E, G_C: linear combinations of G_i (h_i)

$$G_M = -F_{l-}\left(\frac{l}{C_l} A_{3/2} - A_{1/2}\right)\frac{2}{l+1}(-1)^{l+1}$$

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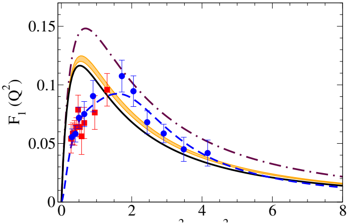
Cases $J^P = \frac{3}{2}^+, \frac{5}{2}^-, ...$: $G_M \leftrightarrow G_E$, $G_C \to -G_C$ and $F_{l-} \to F_{l+}$

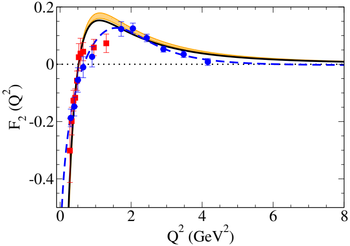
$N(1440)\frac{1}{2}^+$ resonance (Roper) F_1, F_2

- **Large Q^2: dominance of qqq (QM)**
  LFQM 1: Aznauryan, PRC 76, 025212 (2007);
  CSQM: GR, Tsushima, PRD 81, 074020 (2010); Holography
  • Also DSE –mass evolution $m_q(Q^2)$
  DJ Wilson et al, PRC 85, 025205 (2012);
  J Segovia et al, PRL 115, 171801 (2015)
  • **Light Front Quark Models** (F_1, F_2)
  combined with meson-baryon state
  LFQM 2: Aznauryan, Burkert, PRC 85, 055202 (2012) $m_q(Q^2)$
  LFQM 3: Obukhovsky et al, PRD 100, 094013 (2019)

- **Low Q^2:**
  • Meson Cloud ANL-Osaka Sato, FBS 57, 949 (2016);
  Nakamura et al, PRD 92, 074024 (2015)
  • EFT- Mainz, PRC 90, 015201 (2014): $Q^2 < 0.6$ GeV^2
  • Lattice/Lücher method - phase shifts
  Hamiltonean EFT – Strong interference between channels:
  qqq small effect ZW Liu et al, PRL 116, 082004 (2016); CB Lang et al, PRD 95, 014510 (2017); JJ Wu et al, PRD 97, 09450 (2018)

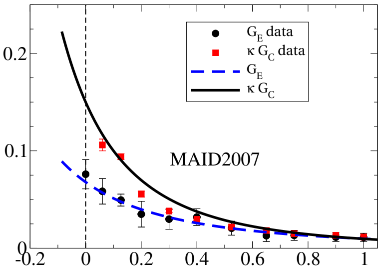
- Holographic QCD: Brodsky/Teramond – analytic form; Phys. Rep. 584, 1 (2015); Gutsche et al, PRD 86, 036007 (2012); PRD 97, 054011 (2018); GR, PRD 96, 034037 (2017); GR and Melnikov, PRD 97, 073002 (2018)





$J^P = \frac{3}{2}^+$: constraints at PT, $\gamma^* N \to \Delta\left(\frac{3}{2}^+\right)$

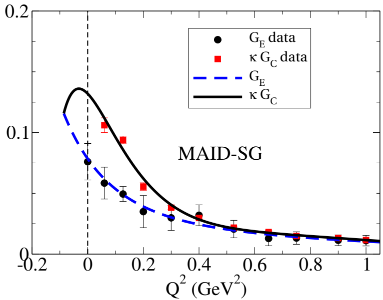
$$\sqrt{2}(M_R - M)S_{1/2} = E|\mathbf{q}| \text{ or } G_E = \frac{M_R - M}{2M_R} G_C$$



Bad parametrization

Uncorrelated form factores

Drechsel, Kamalov and Tiator, EPJ. A34, 69 (2007)



Good parametrization

Correlated form factores

GR PLB 759, 126 (2016); PRD, 113012 (2016)

Siegert's theorem constrain shapes of form factors/helicity amplitudes at low Q^2

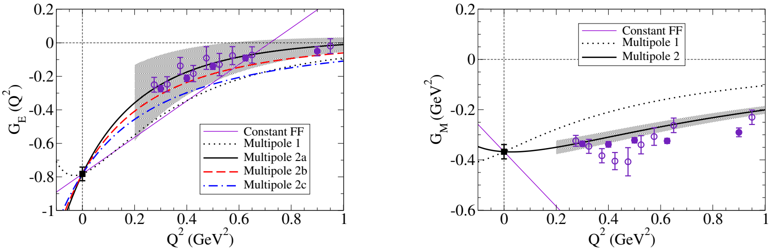
$J^P = \frac{3}{2}^-$: constraints at PT, $\gamma^* N \to N(1520)$; G_E, G_M

GR, PRD 109, 074021 (2024) Interesting case: $|A_{3/2}(0)| \gg |A_{1/2}(0)|$

Large $A_{1/2}$; Very small $A_{1/2}$: $G_2(0) \simeq -\frac{2M}{M_R(M+M_R)} G_1(0)$

Test if we can describe the low-Q^2 using parametrization: **Data: PDG, JLab/CLAS**

$G_1(Q^2) = G_1(0) / \left(1 + \frac{Q^2}{\Lambda_3^2}\right)^3$, $G_{2,3}(Q^2) = G_{2,3}(0) / \left(1 + \frac{Q^2}{\Lambda_4^2}\right)^4$ determine scale Λ_n^2



Natural scale: $\left(1 + \frac{Q^2}{\Lambda_n^2}\right)^{-n} \simeq \left(1 + \frac{Q^2}{\Lambda_D^2}\right)^{-2}$, Λ_D nucleon dipole cutoff; $G_M \propto |\mathbf{q}|^2$

Good descr.: $S_{1/2}(0) = -(75 - 85) \times 10^{-3}$ GeV$^{-1/2}$ (Mult. 2a – 2b) **Solution** $\Leftarrow G_{1,2}(0)$ **and** Λ_D^2