$N^*(1535)$ electroproduction at high Q^2

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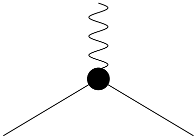
- Framework: covariant quark model (Spectator©) -Franz Gross

Spectator quark model –quark current

- Constituent quarks (quark form factors)

$$j_I^\mu = \left[\frac{1}{6}f_{1+} + \frac{1}{2}f_{1-}\tau_3\right]\left(\gamma^\mu - \frac{\not{q}q^\mu}{q^2}\right) + \left[\frac{1}{6}f_{2+} + \frac{1}{2}f_{2-}\tau_3\right]\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}$$

Quarks with anomalous magnetic moments κ_u, κ_d



quark-antiquark
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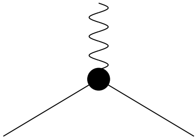

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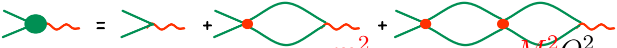
Quarks with anomalous magnetic moments κ_u, κ_d

- Vector meson dominance parameterization:

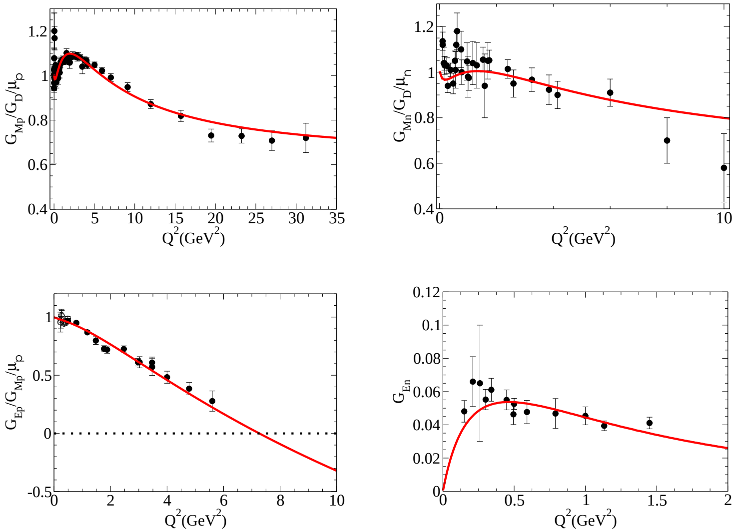


$$f_{1\pm} = \lambda_q + (1 - \lambda_q) \frac{m_v^2}{m_v^2 + Q^2} + c_\pm \frac{M_h^2 Q^2}{(M_h^2 + Q^2)^2}$$

$$f_{2\pm} = \kappa_\pm \left\{ d_\pm \frac{m_v^2}{m_v^2 + Q^2} + (1 - d_\pm) \frac{M_h^2}{M_h^2 + Q^2} \right\}$$

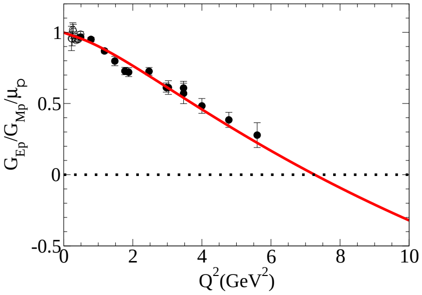
2 poles: $m_v = m_\rho$ and $M_h = 2M_N$; $\kappa_\pm \Leftarrow$ nucleon mag. mom.
5 parameters to be determined: λ_q,
mixture coefficients $c_\pm$ and $d_\pm$ with $d_+ = d_-$ [4 parameters]

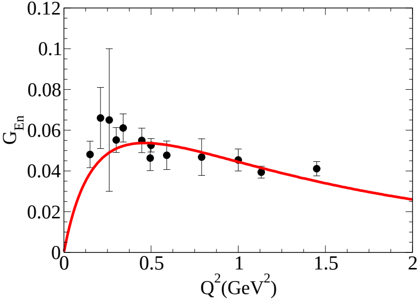
Results: Nucleon form factors (I)



Results: Nucleon form factors (II)

F Gross, GR and MT Peña, PRC 77, 015202 (2008) – model II



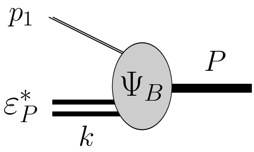


Quark current fixed [4 parameters]

Adjust 2 parameters in the nucleon wave function

No pion cloud (explicit) ... but VMD

- Wave functions: $B =$ quark $\oplus$ diquark



$$\Psi_B = \sum (\text{flavor}) \otimes (\text{spin}) \otimes (\text{orbital}) \otimes \overbrace{\psi_B(P,k)}^{\text{radial}}$$

Nucleon wave function: [PRC 77,015202 (2008)]

Simplest structure –S-state in quark-diquark system

$$\Psi_N(P,k) = \frac{1}{\sqrt{2}} \left[\Phi_I^0 \Phi_S^0 + \Phi_I^1 \Phi_S^1 \right] \psi_N(P,k)$$

S11 wave function:

$$\Psi_{S11}(P,k) = \frac{1}{\sqrt{2}} \gamma_5 \left[\Phi_I^0 X_\rho - \Phi_I^1 X_\lambda \right] \psi_{S11}(P,k)$$

Ψ_N, Ψ_{S11} **covariant**; ψ_N, ψ_{S11} scalar wave function

$\Phi_I^{0,1}$ isospin; $\Phi_S^{0,1}$, $X_{\rho,\lambda}$ spin – combination of **quark states**
$\Longrightarrow$ Ψ_B **written** in terms of **baryon** properties

Spectator quark model – S11 wave function

$SU(6) \otimes O(3)$ QM:

$$|N^*(1535)\rangle = \cos\theta \underbrace{|N\,{}^2P_{1/2}\rangle}_{S=1/2} - \sin\theta \underbrace{|N\,{}^4P_{1/2}\rangle}_{S=3/2}$$

Approximations:

- No mixture between states (pure $S = 1/2$ state)
- Pointlike diquark

$$k_\rho = \frac{1}{\sqrt{2}}(k_1 - k_2) \to 0$$

No diquark internal P-states

Spectator quark model – S11 wave function

Symmetry in the exchange of quarks 1 and 2 $\begin{cases} \rho = \text{anti-symmetric} \\ \lambda = \text{symmetric} \end{cases}$

Momentum: $k_\rho = \frac{1}{\sqrt{2}}(k_1 - k_2)$ $\quad k_\lambda = \frac{1}{\sqrt{6}}(k_1 + k_2 - 2k_3)$

Spin states:

$$|\tfrac{1}{2}, +\rangle_\rho = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)\uparrow \qquad |\tfrac{1}{2}, +\rangle_\lambda = \frac{1}{\sqrt{6}}\left[2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow\right]$$

Using SU(6)⊗O(3) quark model $[1 \oplus \frac{1}{2}]$:

$$X_\rho(+) = \sum_m \langle 1\, m; \tfrac{1}{2}, +\tfrac{1}{2} | \tfrac{1}{2}, +\tfrac{1}{2}\rangle Y_{1m}(\hat{k}_\lambda) |\frac{1}{2}, \tfrac{1}{2} - m\rangle_\rho + \sum_m (....) Y_{1m}(\hat{k}_\rho)$$

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Pointlike diquark approximation $k_\rho \to 0 \Rightarrow Y_{1m}(\hat{k}_\rho) \equiv 0$

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Spectator quark model – S11 wave function (II)

$k_{\lambda 0,\pm}$ spherical components of k_λ, $\quad N = 1/\sqrt{\mathbf{k^2}}$

$$X_\rho(+) = +N\left\{k_{\lambda 0}|+\rangle_\rho - \sqrt{2}k_{\lambda +}|-\rangle_\rho\right\}$$

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Relativistic generalization: ϵ_λ^α, $\tilde{k}$

Diquark polarization vector: ϵ_λ^α $(\lambda = 0, \pm)$ [Fixed-Axis base]

4-momentum $\tilde{k} = k - \frac{P\cdot k}{M_S^2}P$ [diquark 3-momentum in rest frame]

$$X_\rho(+) = -N\left[(\tilde{k}\cdot\epsilon_0)u_S(+) - \sqrt{2}(\tilde{k}\cdot\epsilon_+)u_S(-)\right]$$

$$X_\lambda(+) = +N\left[(\tilde{k}\cdot\epsilon_0)\epsilon_\alpha U_S^\alpha(+) - \sqrt{2}(\tilde{k}\cdot\epsilon_+)\epsilon_\alpha U_S^\alpha(-)\right]$$

$$N \to \frac{1}{\sqrt{-\tilde{k}^2}} \qquad U_S^\alpha(P,\pm) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma^\alpha - \frac{P^\alpha}{M_S}\right)u(P,\pm) \quad [1 \oplus \tfrac{1}{2} \to \tfrac{1}{2}]$$

Spectator quark model – Scalar wave functions

Scalar wave functions deppendent of $(P-k)^2$ = (quark momentum)^2

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D},$$

M_B = baryon mass; m_D = diquark mass

$$\psi_N(P,k) = N_0 \frac{1}{m_D(\beta_1+\chi_N)(\beta_2+\chi_N)}$$
$$\psi_{S11}(P,k) = N_S \frac{1}{m_D(\beta_1+\chi_{S11})(\beta_2+\chi_{S11})}$$

β_1 and and β_2: momentum range parameters

Same form for Nucleon and S11

No adjustable parameters

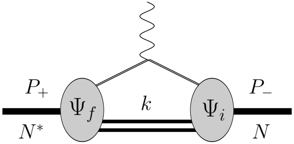
Spectator quark model –Electromagnetic transition current

Quark current j_I^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

- Spectator formalism: relativistic impulse approximation

$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+, k) j_I^\mu \Psi_i(P_-, k)$$

Franz Gross: PR186, 1448 (1969);
F Gross er al PRC 45, 2094 (1992)



diquark on-shell

$$J^\mu = \bar{u}_{S11}(P_+) \left\{ \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) F_1^*(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{M_S + M} F_2^*(Q^2) \right\} \gamma_5 u(P_-)$$

F_1^*, F_2^*: form factors

$\gamma N \to$ S11 form factors [arXiv:1105.2223 [hep-ph]]

$$F_1^*(Q^2) = +\frac{1}{2}(3j_1 + j_3)\mathcal{I}_0$$
$$F_2^*(Q^2) = -\frac{1}{2}(3j_2 - j_4)\frac{M_S + M}{2M}\mathcal{I}_0$$

Isospin coefficients – FG, GR and MTP, PRC 77, 015202 (2008)

$$j_1 = \tfrac{1}{6}f_{1+} + \tfrac{1}{2}f_{1-}\tau_3, \quad j_3 = \tfrac{1}{6}f_{1+} - \tfrac{1}{6}f_{1-}\tau_3$$
$$j_2 = \tfrac{1}{6}f_{2+} + \tfrac{1}{2}f_{2-}\tau_3, \quad j_4 = \tfrac{1}{6}f_{2+} - \tfrac{1}{6}f_{2-}\tau_3$$

Overlap integral (S11 rest frame):

$$\mathcal{I}_0(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|}\psi_{S11}(P_+, k)\psi_N(P_-, k),$$

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- If $M_S \neq M \Rightarrow \mathcal{I}_0(0) \neq 0$: **No** orthogonality
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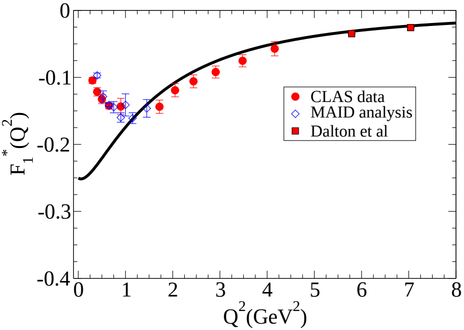
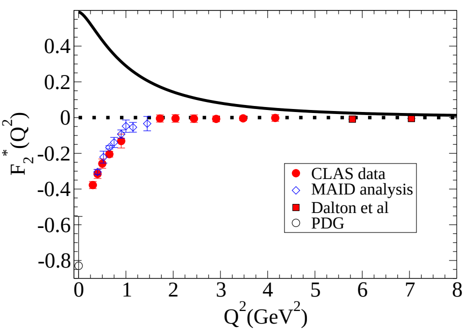
- Range of application of the model ? ($\mathcal{I}_0(0) \approx 0$)
  $|\mathbf{q}|_0$ defines the momentum scale
- If $Q^2 \gg |\mathbf{q}|_0^2 = 0.23$ GeV^2 $\Rightarrow \mathcal{I}_0(0) \approx 0$
  Model valid for $Q^2 > 2.3$ GeV^2

Results: $\gamma N \to N^*(1535)$ form factors





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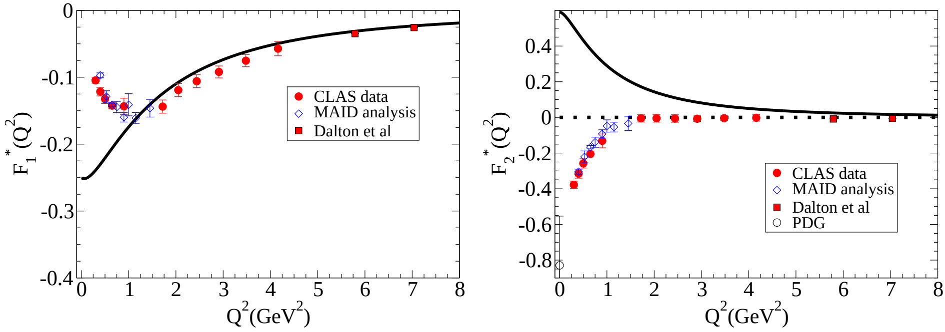

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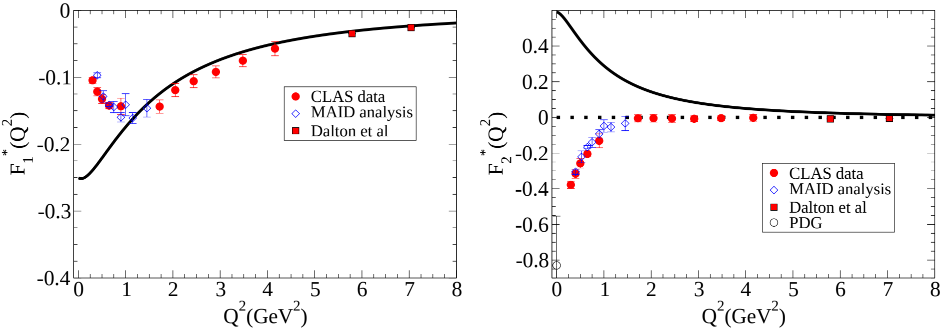

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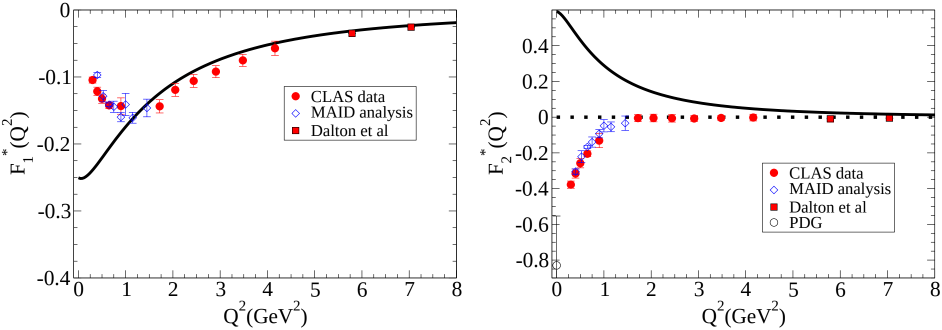

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- ... There is also estimates of **valence** contributions (EBAC)

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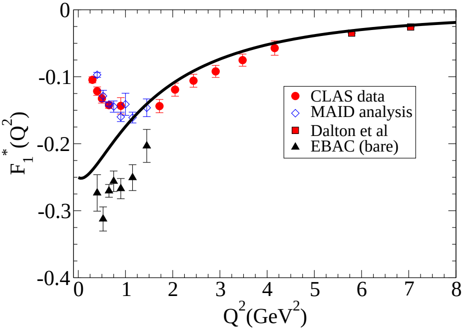

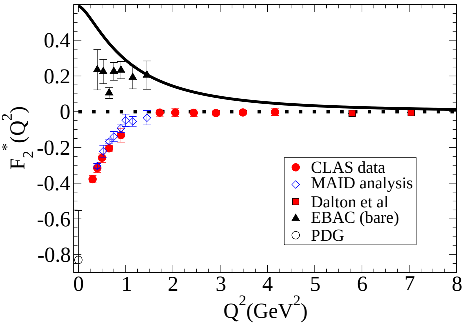

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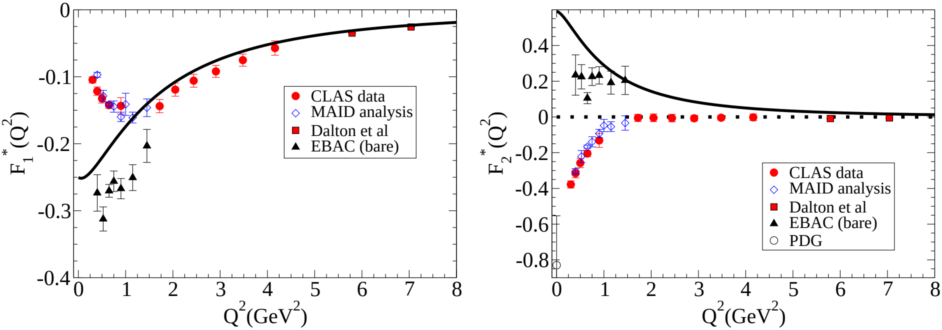

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- F_1^* close to EBAC (valence quark core) ($Q^2 < 2$ GeV^2)

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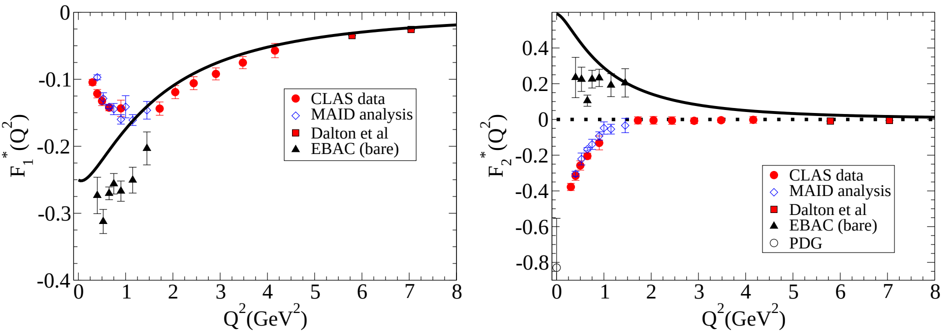

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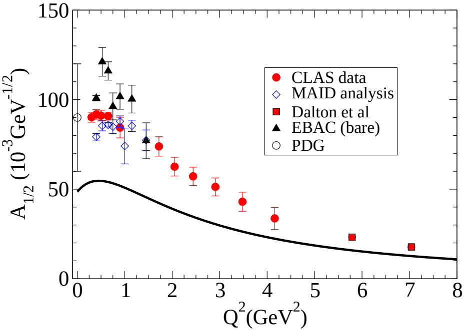
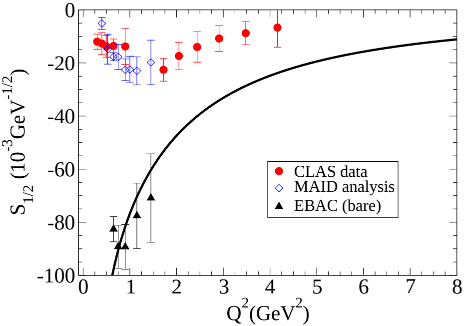
- F_1^* close to EBAC (valence quark core) ($Q^2 < 2$ GeV^2)
- F_2^* close to valence estimate ($Q^2 \approx 1$ GeV^2) $(F_2^*)^{Sp} \simeq (F_2^*)^{QM}$

Results: $\gamma N \to N^*(1535)$ helicity amplitudes





$$A_{1/2} = -2b \left[F_1^* + \frac{M_S - M}{M_S + M} F_2^* \right], \; S_{1/2} = \sqrt{2} b (M_S + M) \frac{|\mathbf{q}|}{Q^2} \left[\frac{M_S - M}{M_S + M} F_1^* - \tau F_2^* \right]$$

$$|\mathbf{q}| = \frac{\sqrt{[(M_S - M)^2 + Q^2][(M_S + M)^2 + Q^2]}}{2M_S}, \quad b = e \sqrt{\frac{(M_S - M)^2 + Q^2}{8M(M_S^2 - M^2)}}, \quad \tau = \frac{Q^2}{(M_S + M)^2}$$

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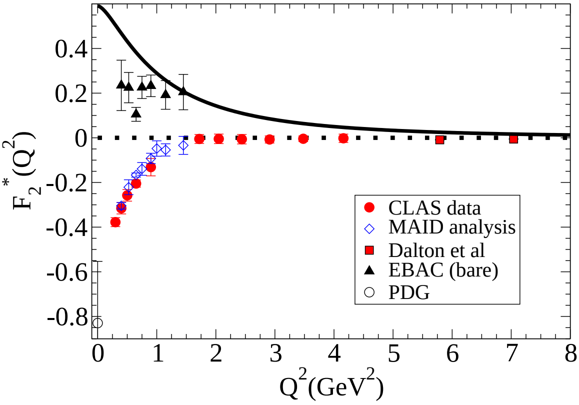
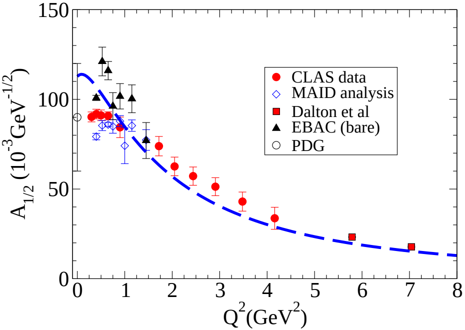
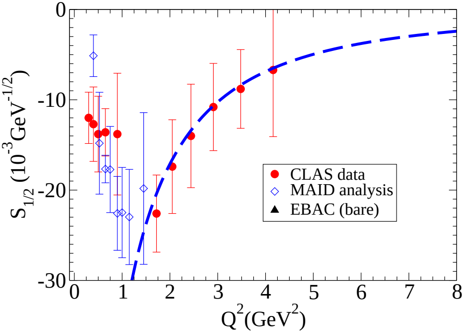


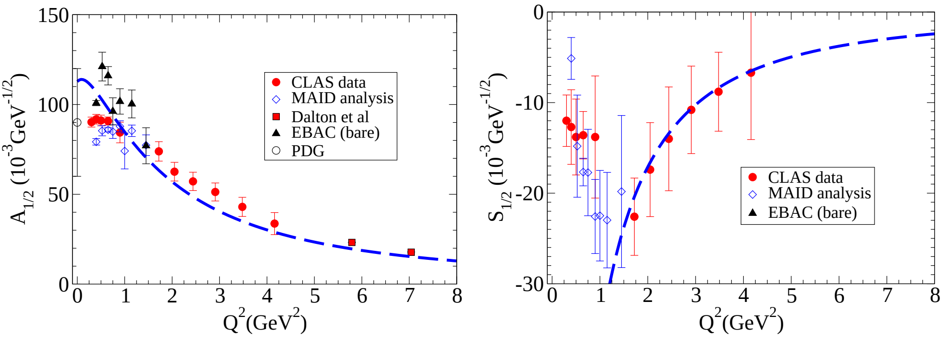
What if we use $F_2^* \approx 0$? ($Q^2 > 1.5$ GeV^2)





- $F_2^* = 0$ (data), F_1^* from Spectator model - - - - - -

Results: $\gamma N \to N^*(1535)$ helicity amplitudes



- $F_2^* = 0$ (data), F_1^* from Spectator model - - - - - -
- Good description of $A_{1/2}$ and $S_{1/2}$ for $Q^2 > 2.3$ GeV^2

Relation between $A_{1/2}$ and $S_{1/2}$ [arXiv:1105:2484 [hep-ph]]

Implications of $F_2^* = 0$? $(Q^2 > 1.5\ \text{GeV}^2)$

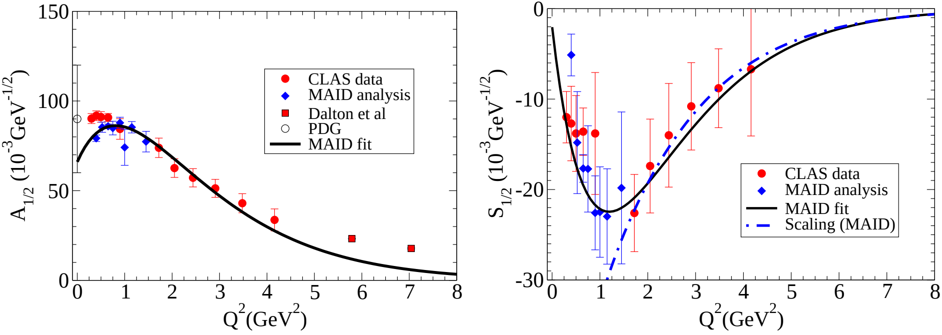
$$F_2^* = -\frac{M_S^2 - M^2}{(M_S - M)^2 + Q^2}\frac{1}{2b}\left[A_{1/2} + \sqrt{2}\frac{Q^2}{(_S - M)|\mathbf{q}|}S_{1/2}\right]$$

- Valence quark contribution for F_2^* must be canceled by other contributions
- Can it be the meson cloud? $\quad (F_2^*)^{QM} = -(F_2^*)^{mc}$
  $\Rightarrow$ Significant meson cloud
  $\gamma N \to \Delta$: pion cloud dominates G_C^*, G_E^* PRD 80, 013008 (2010)
- $F_2^* \simeq 0$: $$S_{1/2} \simeq -\frac{1}{\sqrt{2}}\frac{(M_S - M)|\mathbf{q}|}{Q^2}A_{1/2}$$

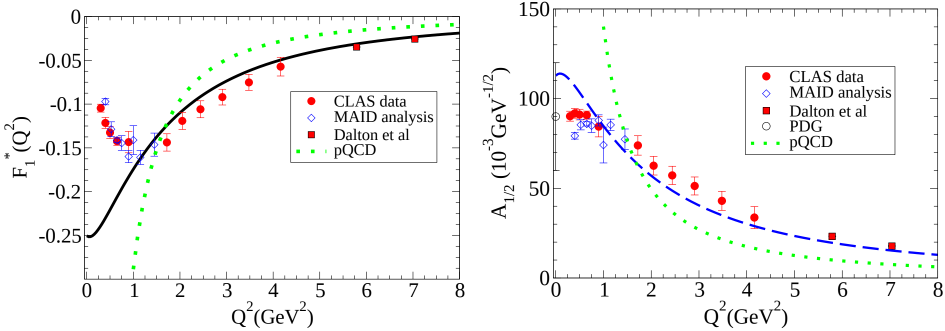
If $Q^2 > 1.8\ \text{GeV}^2$: $\quad [\ |\mathbf{q}| \simeq Q\sqrt{1+\tau}\ ]$

$$S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}}\frac{M_S^2 - M^2}{2M_S Q}A_{1/2}$$

Relation between $A_{1/2}$ and $S_{1/2}$ (MAID)



MAID parametrization $A_{1/2}$: $S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_S^2 - M^2}{2 M_S Q} A_{1/2}$



Comparing with pQCD, Carlson *et al.* PRL 81, 2646 (1998)

Model and Data overestimates pQCD result

$\gamma N \to N(1535)$: Conclusions

- $\gamma N \to N(1535)$ at high Q^2
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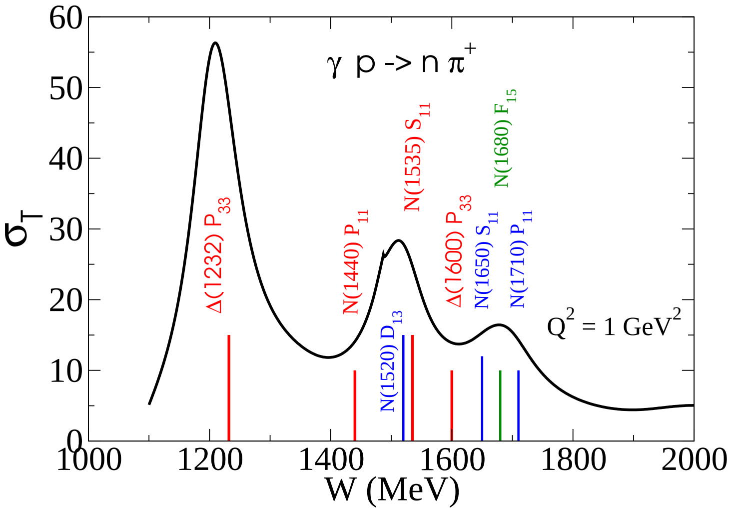
- Model applied to other resonances:
  $\Delta(1232), N(1440), \Delta(1600), \ldots$

Nucleon Resonances



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- **A simple relation between the $\gamma N \to N(1535)$ helicity amplitudes**
  G. Ramalho and K. Tsushima, [arXiv:1105.2484 [hep-ph]].