$N(1520)$, other nucleon resonances and more

Gilberto Ramalho

International Institute of Physics,
Federal University of Rio Grande do Norte, Brazil

In collaboration with M.T. Peña (IST, Lisbon) and K. Tsushima (UFRN, Brasil)

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Nucleon resonances

Covariant spectator quark model

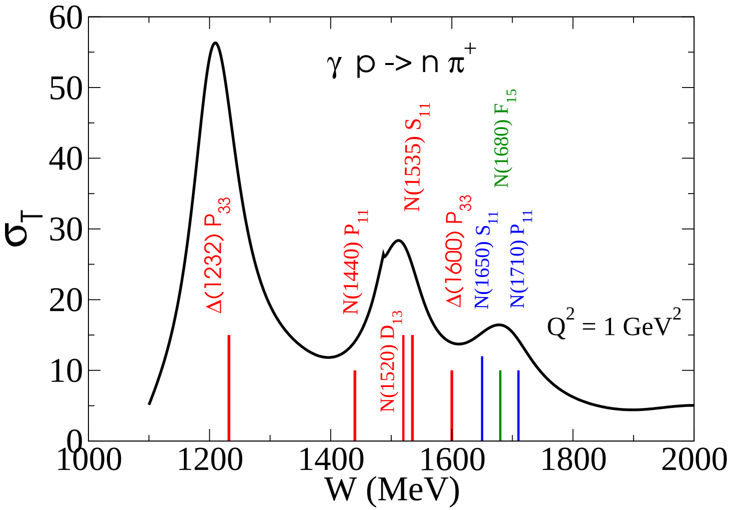
- Wave functions
- Quark current
- Transition current $\Rightarrow$ form factors/helicity amplitudes

$$F = F_{qqq} + \underbrace{F_{qqq(q\bar{q})}}_{\approx \frac{1}{Q^4} F_{qqq}}$$

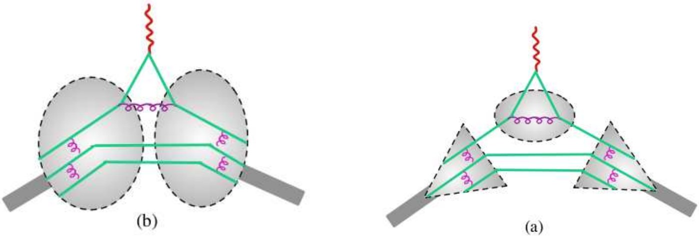
Form factors: quark core plus meson cloud (suppressed at high Q^2)

$\Longrightarrow$ Results for $\gamma^* N \to N^*$ form factors/helicity amplitudes
$N^* = N(939), N(1440), N(1520), N(1535), \Delta(1232), \Delta(1600)$

Nucleon Resonance Structure



Formalism (Light Front vs CSQM)



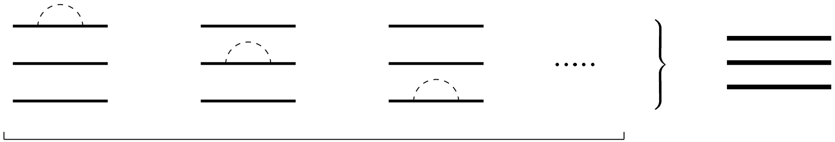
Light Front formalism

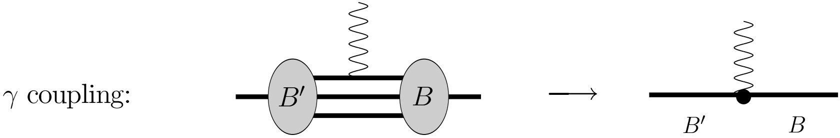
- Pointlike quarks
- Baryon states as a sum of Fock states: $qqq,\ qqqg,\ qqq(q\bar{q}), \ldots$
- **Light quarks** $\kappa_u, \kappa_d = 0$

Covariant Spectator QM formal.

- Gluon interactions between $q\bar{q}$ $\Rightarrow$ **quark form factors**
- **Baryon:** system of **dressed quarks** (gluons and $q\bar{q}$)
- Massive quarks with anomalous magnetic moments κ_u, κ_d

Quark structure and electromagnetic interaction (I) †





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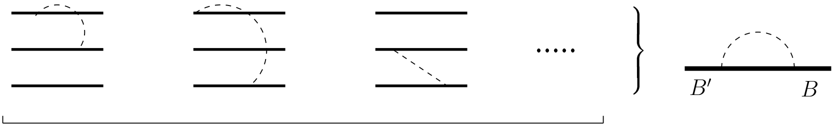
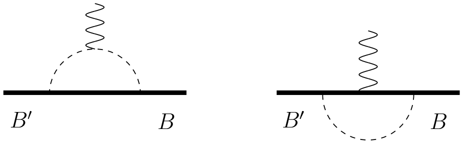


γ coupling:



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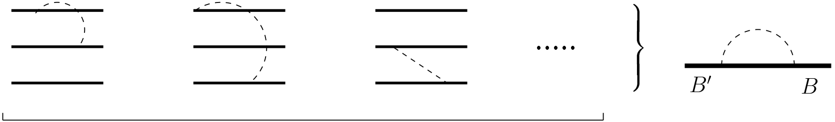

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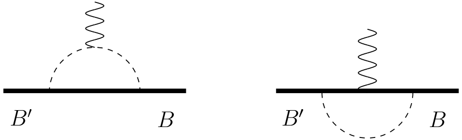

- Not important at high Q^2: pQCD: supression $1/Q^4$

  CE Carlson FBS Sup 11, 10 (1999): $F \propto \frac{1}{(Q^2)^{(N-1)}}$, $N = 3 + 2$

  Very important at low Q^2

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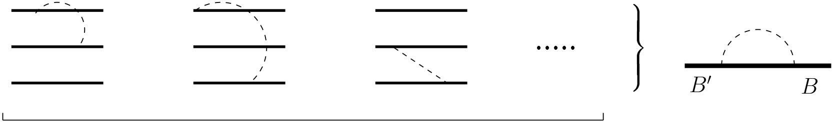

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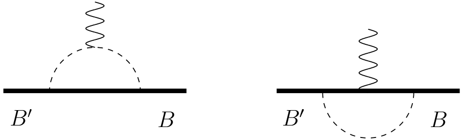

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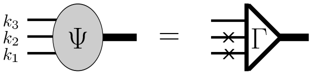
  Very important at low Q^2
- Assume NO interference with quark dressing processes

$$F = F^B + F^{mc}$$

(bare $\oplus$ meson cloud)

- Baryon: 3 constituent quark system
- Covariant Spectator Theory: wave function Ψ defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks



$$\Psi_\alpha(P,k_3) = \left(\frac{1}{m_q - \not{k}_3 - i\varepsilon}\right)_{\alpha\beta} \Gamma^\beta(P,k_1,k_2)$$

Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008)

- Ψ is **free** of singularities ($3q$ on-shell $\Gamma \equiv 0$) $\Rightarrow$ parametrize Ψ

Stadler, Gross and Frank PRC 56, 2396 (1998); Savkli and Gross PRC 63, 035208 (2001)

- On-shell integration $(k_1,k_2) \Rightarrow$ $k = k_1 + k_2$, $r = \frac{1}{2}(k_1 - k_2)$
  $\Rightarrow$ integration in $\mathbf{k}$ and $s = (k_1 + k_2)^2$

Gross, GR and Peña, PRC 77, 015202 (2008); PRD 85, 093005 (2012)

$$\int_{k_1}\int_{k_2} = \frac{\pi}{4}\int d\Omega_{\hat{\mathbf{r}}} \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s-4m_q^2}{s}} \int \frac{d^3\mathbf{k}}{2\sqrt{s+\mathbf{k}^2}} \to \int \frac{d^3\mathbf{k}}{2\sqrt{m_D^2+\mathbf{k}^2}}$$

Mean value theorem: $\sqrt{s} \to m_D$; cov. int. in diquark **on-shell** mom.

Spectator QM: Baryon wave functions (II)

Ψ_B not determined by a dynamical equation $\Leftarrow$ phenomenology $M_B = M_B^{\rm exp}$

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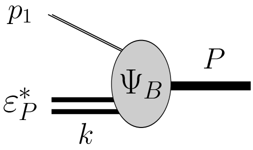
- Baryon wave functions: $B =$ **diquark** $\oplus$ **quark**
  Combination of **diquark** (12) and single **quark** (3) states, using $SU(6) \otimes O(3)$:

$$\Psi_B = \sum \text{(color)}\otimes\text{(flavor)}\otimes\text{(spin)} \otimes\text{(orbital)}\otimes \underbrace{\psi_B(P,k)}_{\text{radial}}$$



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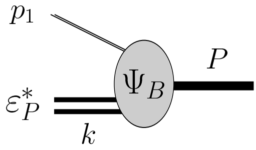

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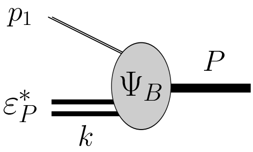

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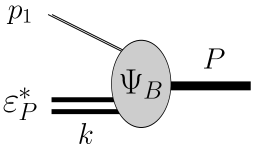

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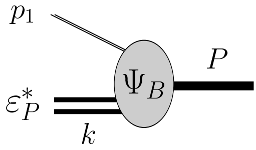

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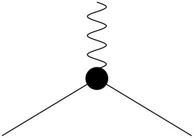
  - Ψ_B can be used on **any** frame and/or Q^2 regime
- Phenomenology in the **radial wf** (momentum scale parameters)

Spectator QM: Quark current (VMD at quark level) (I)

- Quark current [$f_{i\pm}$ quark form factors]

$$j_q^\mu = \left[\frac{1}{6} f_{1+} + \frac{1}{2} f_{1-} \tau_3\right] \gamma^\mu + \left[\frac{1}{6} f_{2+} + \frac{1}{2} f_{2-} \tau_3\right] \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$$



Quarks with anomalous magnetic moments κ_u, κ_d

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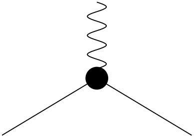

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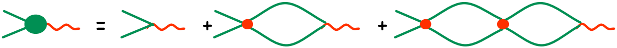
- Vector meson dominance parameterization:



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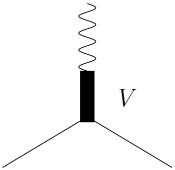

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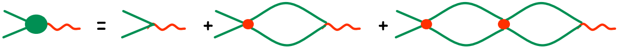
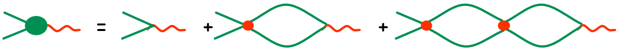


Spectator QM: Quark current (VMD at quark level) (II)

- Vector meson dominance parameterization: PRC77 015202 (2008)



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

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

2 poles:

- Light vector meson: $m_v \simeq m_\rho (\approx m_\omega)$
- Effective heavy meson: $M_h (= 2M_N) \leftarrow$ short range

Nucleon magnetic moments $\Rightarrow \kappa_\pm$

4 parameters: λ_q, $c_\pm, d_\pm$ (mixture coefficients) $\oplus$ $d_+ = d_-$

$\Uparrow$ **Fitted to nucleon form factors data**

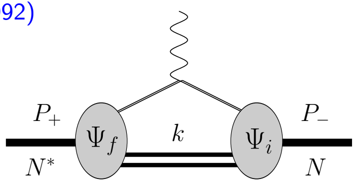
Quark current j_q^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

F Gross et al PR 186 (1969); PRC 45, 2094 (1992)

Relativistic impulse approximation:

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



diquark on-shell

$$q = P_+ - P_-, \qquad P = \tfrac{1}{2}(P_+ + P_-), \qquad Q^2 = -q^2$$

$q \cdot J \neq 0$: Landau prescription: $J^\mu \to J^\mu - \frac{q \cdot J}{q^2} q^\mu$

JJ Kelly, PRC 56, 2672 (1997); Z Batiz and F Gross, PRC 58, 2963 (1998)

Spin 1/2 resonances: transition currents †

Nucleon:

$$J^\mu = \bar{u}(P_+) \left[F_1 \gamma^\mu + F_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N} \right] u(P_-)$$

$\gamma N \to N(1440)$ (R): $J^P = \frac{1}{2}^+$

$$J^\mu = \bar{u}_R(P_+) \left[F_1^* \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) + F_2^* \frac{i\sigma^{\mu\nu} q_\nu}{M_R + M_N} \right] u(P_-)$$

$\gamma N \to N(1535)$ (S): $J^P = \frac{1}{2}^-$

$$J^\mu = \bar{u}_S(P_+) \left[F_1^* \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) + F_2^* \frac{i\sigma^{\mu\nu} q_\nu}{M_S + M_N} \right] \gamma_5 u(P_-)$$

Form factors $F_1^*, F_2^* \to A_{1/2}, S_{1/2}$ exclusive functions of Q^2

Spin 3/2 resonances: transition currents †

$\gamma N \to \Delta(1232), N^*(1520), \Delta(1600)$:

$$J^\mu = \bar{u}_\beta(P_+) \left[G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu} \right] \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix} u(P_-)$$

u_β Rarita-Schwinger spinor

Only 3 independent form factors:

$$q_\mu J^\mu = 0 \Rightarrow G_4 = (M_R \pm M_N) G_1 + \frac{1}{2}(M_R^2 - M_N^2) G_2 - Q^2 G_3$$

$$G_1, G_2, G_3 \Rightarrow G_M, G_E, G_C \text{ or } A_{1/2}, A_{3/2}, S_{1/2}$$

Definition of the helicity amplitudes $(\frac{1}{2} \to \frac{1}{2}, \frac{3}{2})$ ††

Resonance R rest frame

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{K}} \left\langle R, S'_z = +\tfrac{3}{2} \right| \epsilon_+ \cdot J \left| N, S_z = +\tfrac{1}{2} \right\rangle$$

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{K}} \left\langle R, S'_z = +\tfrac{1}{2} \right| \epsilon_+ \cdot J \left| N, S_z = -\tfrac{1}{2} \right\rangle$$

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

$$\alpha = \frac{e^2}{4\pi} \qquad\qquad K = \frac{M_R^2 - M^2}{2M_R}$$

Spectator QM: Nucleon wave function

Nucleon wave function: [PRC 77,015202 (2008); EPJA 36, 329 (2008)]
Simplest structure –S-state in quark-diquark system

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

Isospin states: $\Phi_I^{0,1}$
Spin states:

$$\Phi_S^0(s) \equiv u(P,s) \qquad \Phi_S^1(s) \equiv -(\varepsilon_\lambda^*)_\alpha U^\alpha(P,s)$$

$$U^\alpha(P,s) = \sum_{\lambda\, s'} \langle \frac{1}{2} s'; 1\lambda | \frac{1}{2} s\rangle \varepsilon_\lambda^\alpha u(P,s') \to \frac{1}{\sqrt{3}}\gamma_5 \left(\gamma^\alpha - \frac{P^\alpha}{M}\right) u(P,s)$$

$\varepsilon_\lambda = \varepsilon_{\lambda P}$ function of nucleon momentum
Fixed-Axis polarization states; PRC 77, 035203 (2008)
$\Longrightarrow$ Ψ_N pure S-state

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

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

M_B = baryon mass; m_D = diquark mass

Nucleon scalar wave function:

$$\psi_N(P,k) = \frac{N_0}{m_D}\frac{1}{(\beta_1+\chi_N)(\beta_2+\chi_N)} = \frac{N_0}{m_D}\frac{1}{\beta_2-\beta_1}\left[\frac{1}{\beta_1+\chi_N} - \frac{1}{\beta_2+\chi_N}\right]$$

$$\xrightarrow{NR} \frac{N_0}{m_D}\frac{1}{\beta_2-\beta_1}\left[\frac{1}{\beta_1+\frac{\mathbf{k}^2}{m_D^2}} - \frac{1}{\beta_2+\frac{\mathbf{k}^2}{m_D^2}}\right]$$

Position space:

$$\psi_N(P,k) \xrightarrow{FT} \frac{e^{-m_D\sqrt{\beta_1}r}}{r} - \frac{e^{-m_D\sqrt{\beta_2}r}}{r}$$

β_1, β_2 momentum range parameters; $\beta_2 > \beta_1$:
β_1 long spatial range; β_2 short spatial range

Nucleon form factors (I) ††

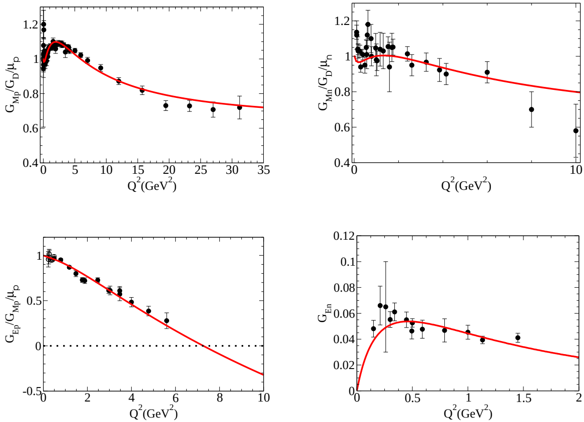
F Gross, GR and MT Peña, PRC 77, 015202 (2008)

Nucleon form factors: $G_E = F_1 - \tau F_2$, $G_M = F_1 + F_2$; $\tau = \frac{Q^2}{4M_N^2}$

$$G_E(Q^2) = \frac{1}{2}\left[(f_{1+} + f_{1-}\tau_3) - \tau(f_{1+} + f_{2-}\tau_3)\right] \int_k \psi_N(P_+, k)\psi_N(P_-, k)$$

$$G_M(Q^2) = \frac{1}{6}\left[(f_{1+} + 5f_{1-}\tau_3) + (f_{1+} + 5f_{2-}\tau_3)\right] \int_k \psi_N(P_+, k)\psi_N(P_-, k)$$

Nucleon form factors (II) [PRC 77, 015202 (2008)] - model II



- Quark current fix 4 parameters; Scalar wave function [2]

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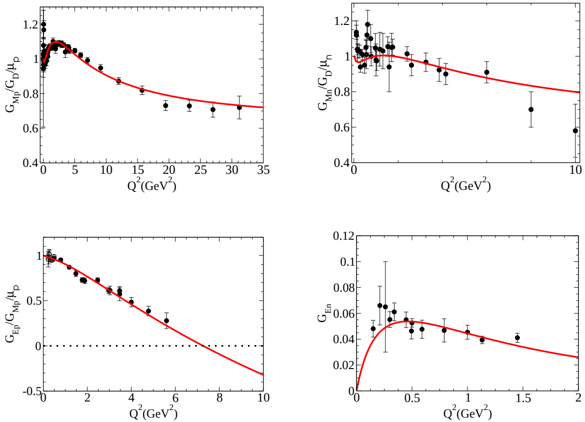

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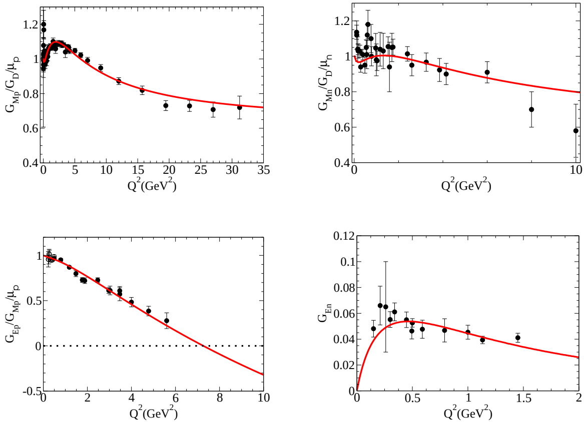

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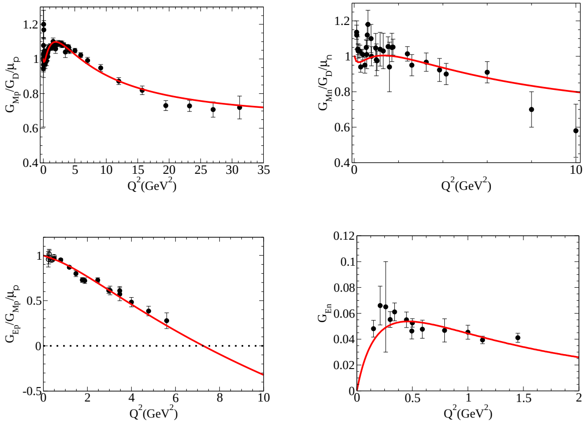


- Quark current fix 4 parameters; Scalar wave function [2]
- No pion cloud (explicit)
- How **can we** test the **valence quark** parametrization? Lattice

GR and MT Peña JPG 36, 115011 (2009)

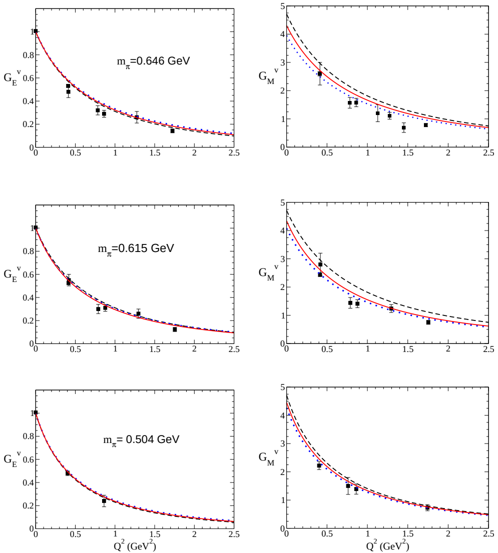
- Quark current (VMD): $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$
  Replace hadron masses by lattice masses $(M_N, m_\rho, M_h = 2M_N)$

  $j_q^\mu(M_N; m_\rho, M_h = 2M_N) \to j_q^\mu(M_N^{latt}; m_\rho^{latt}, 2M_N^{latt})$
- Wave functions:
  $\Psi_B(\{M_B\}) \to \Psi_B(\{M_B^{latt}\})$

$\Rightarrow$ Form factors $G_X(m_\pi^{latt}, Q^2)$

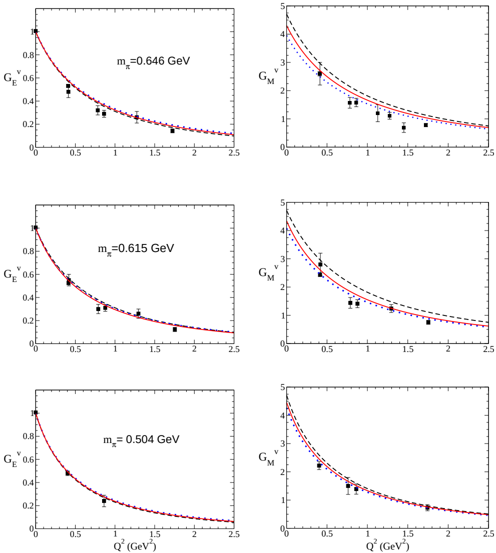
If meson cloud are supressed: $G_X \equiv G_X^B$
Compare G_X^B-model with lattice data

Nucleon form factors on lattice [JPG 36, 115011 (2009)] G_X^{p-n}



Data from Gockeler at al, PRD 71, 034508 (2005) - - - Model II

Nucleon form factors on lattice [JPG 36, 115011 (2009)] G_X^{p-n}



Describes physical and lattice QCD regimes - - - Model II

$\gamma N \to N(1440)$ [PRD 81, 074020 (2010), GR and K Tsushima]

- $N(1440)$ is the 1st radial excitation of the nucleon
  Same spin and isospin structure as the nucleon; $\psi_R \neq \psi_N$
- Ψ_R orthogonal to Ψ_N
  Orthogonality given by scalar wave functions

$$\int_k \psi_R(P_+, k)\psi_N(P_-, k)\Big|_{Q^2=0} = 0$$

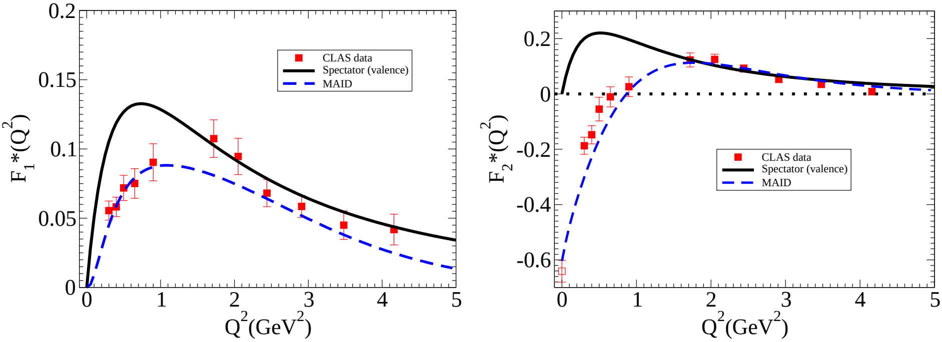
Wave function:

$$\psi_R(\chi_R) = N_1 \frac{\overbrace{\beta_3 - \chi_R}^{\text{radial excitation}}}{\beta_1 + \chi_R} \psi_N(\chi_R)$$

β_1 fixed by ψ_N; β_3 determined by the orthogonality condition

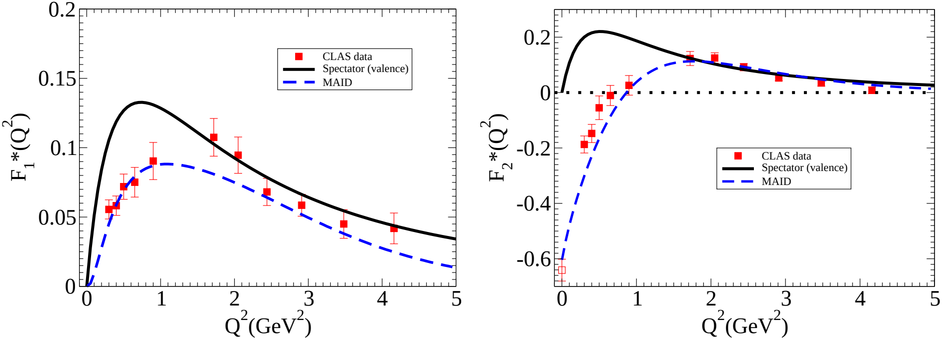
No adjustable parameters $\to$ predictions

$\gamma N \to N(1440)$ form factors [PRD 81, 074020 (2010)]



- CLAS data - Aznauryan et al PRC 80, 055203 (2009), MAID fit
- Good agreement for $Q^2 > 1.5$ GeV^2
- Difference for $Q^2 < 1.5$ GeV^2 –manifestation of meson cloud
- Good description also of lattice data (H.W. Lin et al)

$\gamma N \to N(1440)$ form factors [PRD 81, 074020 (2010)]



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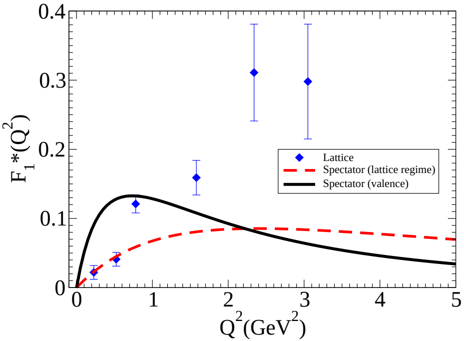
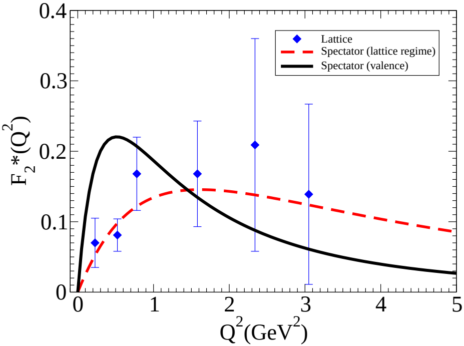
$\gamma N \to N(1440)$ on lattice [PRD 81, 074020 (2010)] ††



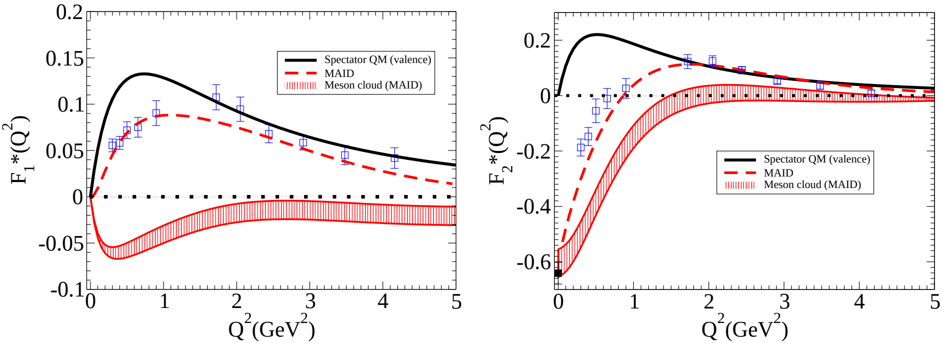


Data: H.W. Lin et al PRD 78, 114508 (2008)

Good agreement with Lattice data

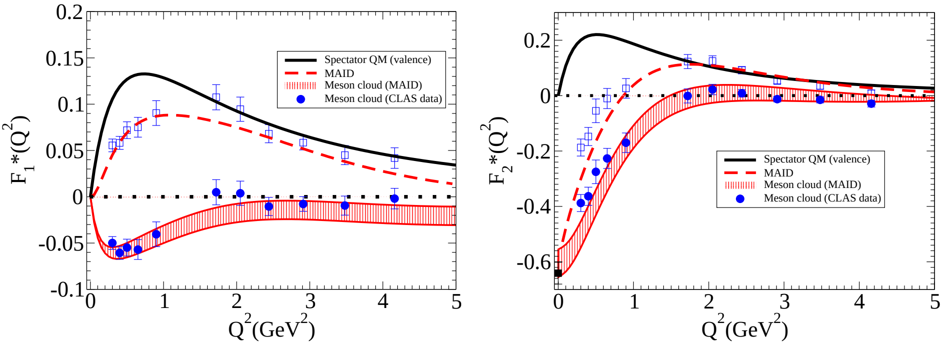
GR and K Tsushima, PRD 81, 074020 (2010)

$\gamma N \to$ Roper –Meson cloud contributions- MAID fit



$$F_i^{mc}(Q^2) = F_i^*(Q^2) - F_i^{val}(Q^2) \qquad F_1^* \equiv F_1^{MAID}$$

$\gamma N \to$ Roper –Meson cloud contributions- CLAS



$$F_i^{mc}(Q^2) = F_i^*(Q^2) - F_i^{val}(Q^2) \qquad F_1^* \equiv F_1^{CLAS}$$

$\gamma N \to N(1535)$ [PRD 84, 051301 (2011), GR and MT Peña]

- Pointlike diquark $k_1 - k_2 = 0$ [no diquark w/ P-states] $J^P = \frac{1}{2}^-$
- Pure spin 1/2 core: [Karl-Isgur model: $\cos\theta_S \approx 0.85$]

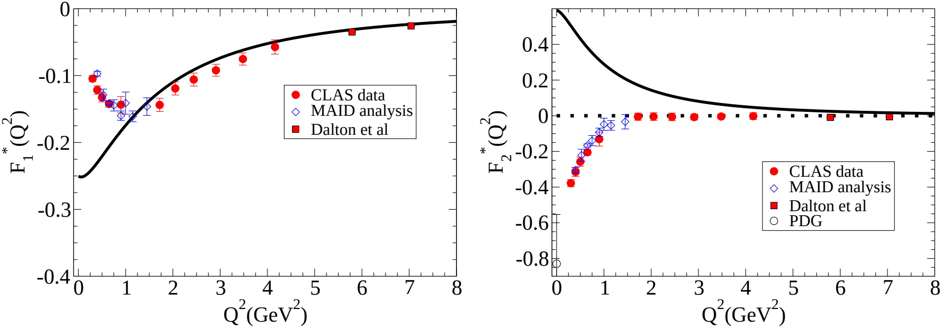
$$\begin{aligned} |N(1535)\rangle &= \cos\theta_S |S = 1/2\rangle - \sin\theta_S |S = 3/2\rangle \\ &\to |S = 1/2\rangle \end{aligned}$$

- Radial wave function: $\psi_{S11}(\chi_{S11}) \equiv \psi_N(\chi_{S11})$
- Form factors: ($\mathcal{I}$ = overlap integral - S11 rest frame)

$$F_i^* \propto \mathcal{I}(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{S11}(P_{S11}, k)\, \psi_N(P_N, k)$$

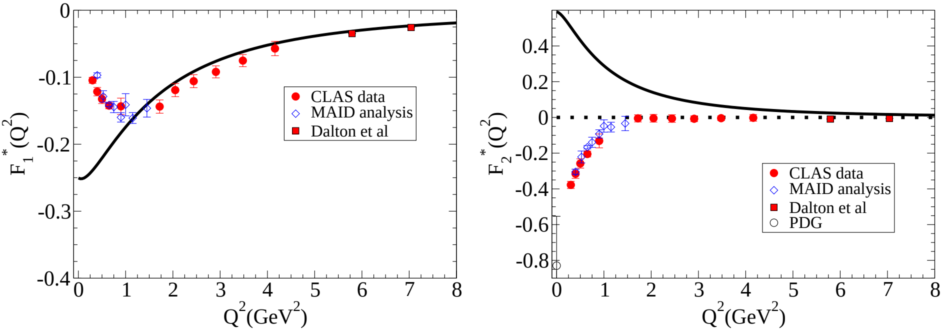
- At $Q^2 = 0$: $\mathcal{I}(0) \propto |\mathbf{q}|_0 = \frac{M_R^2 - M^2}{2M_R} \neq 0$
- No exact orthogonality ($\mathcal{I}(0) \neq 0$)
  Approximated orthogonality $Q^2 \gg |\mathbf{q}|_0^2 \approx 0.23$ GeV^2
  Model valid for $Q^2 > 1.2$ GeV^2

$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]



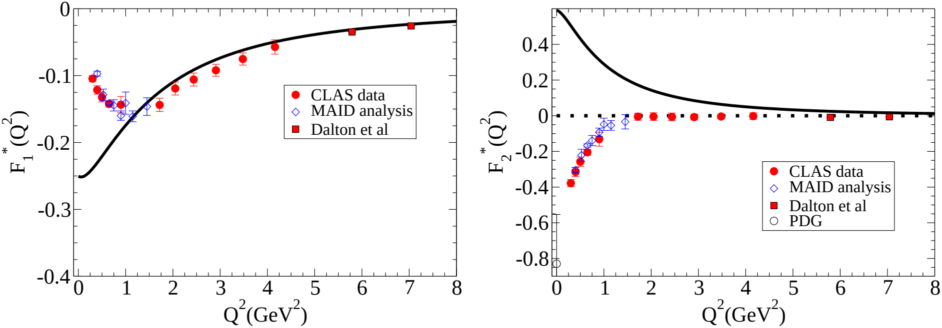
- Model compared with CLAS and MAID data

$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]



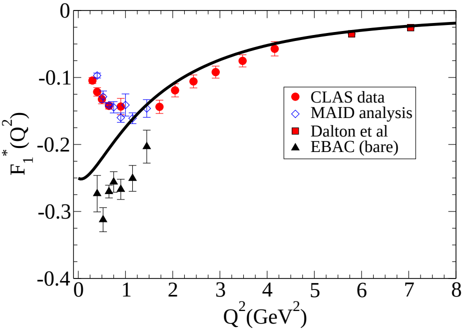
- Model compared with CLAS and MAID data
- F_1^* OK; F_2^* wrong sign

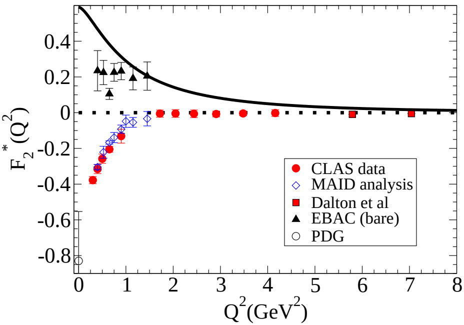
$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]



- Model compared with CLAS and MAID data
- F_1^* OK; F_2^* wrong sign
- F_2^* close to EBAC ▲ (core estimate: mc removed)
- ...

$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]





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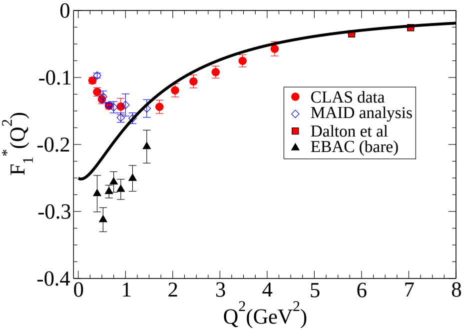
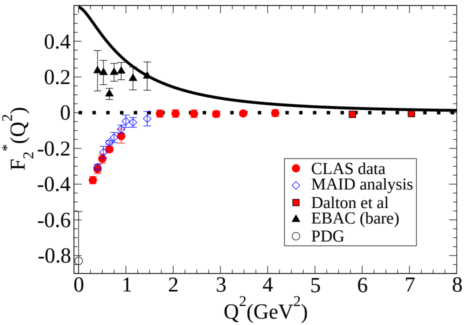
$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]





- Model compared with CLAS and MAID data
- F_1^* OK; F_2^* wrong sign
- F_2^* close to EBAC ▲ (core estimate: mc removed)
- Valence quark effects under control

Implications of $F_2^* = 0$?

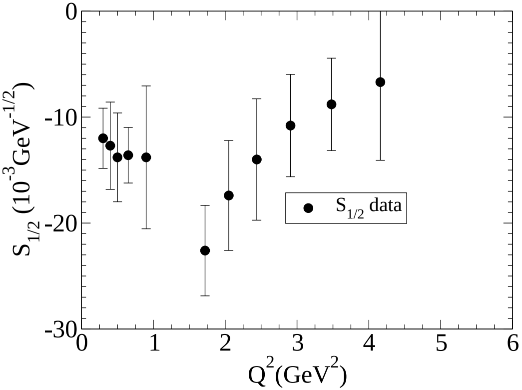
Cancellation between valence and meson cloud

GR, K Tsushima
PRD 84, 051301 (2011)

GR, D Jido, K Tsushima
PRD 85, 093014 (2012)

$\tau = \frac{Q^2}{(M_R+M)^2}$ $Q^2 > 1.5$ GeV^2

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



$\gamma^* N \to N^*(1535)$: relation between $A_{1/2}$ and $S_{1/2}$ †

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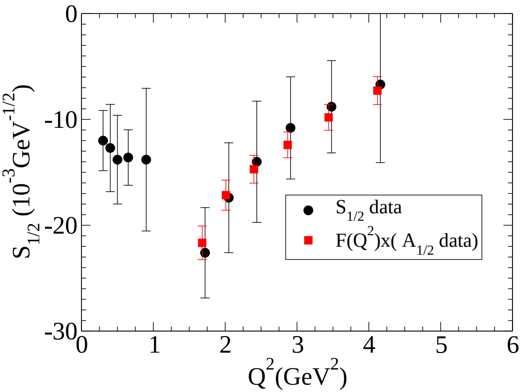

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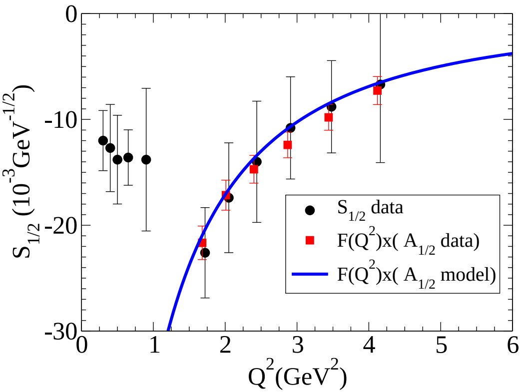
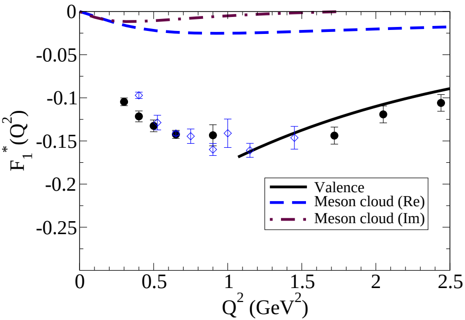
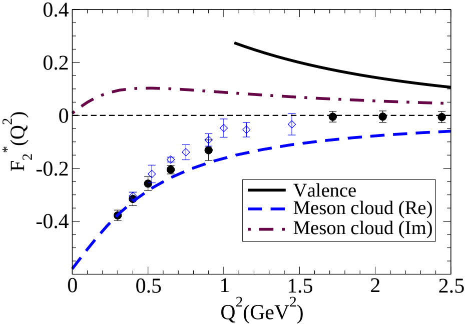


$\gamma^* N \to N^*(1535)$ form factors [PRD 84, 051301 (2011)]





—— **GR, D Jido and K Tsushima, PRD 85, 093014 (2012)**

– – – D Jido, M Doring and E Oset, PRC 77, 065207 (2008) - χ Unitary Model

Spin 3/2 resonances: $\Delta(1232)$ wave functions

- Δ wave function: EPJA 36, 329 (2008); PRD 78, 114017 (2008); PRD 80, 013008 (2009)

$$\Psi_\Delta = N \left[\Psi_S + a\Psi_{D3} + b\Psi_{D1} \right]$$

$$S = 0 \oplus \frac{3}{2}, \quad D3 = 2 \oplus \frac{3}{2}, \quad D1 = 2 \oplus \frac{1}{2}$$

- Wave functions fitted to form factor data $[G_M^*, G_E^*, G_C^*]$
(Radial wave functions: $\alpha_S, \alpha_{D3}, \alpha_{D1}, \alpha'_{D1}$)
- S-state model: $\Rightarrow G_M^*$

$$G_M^B(0) = \frac{8}{3\sqrt{3}} \frac{M}{M+M_\Delta} f_v \int_k \psi_\Delta \psi_N \Big|_{Q^2=0} \qquad f_v = 1 + \frac{M+M_\Delta}{2M}\kappa_-$$

$$= 2.07 \int_k \psi_\Delta \psi_N \Big|_{Q^2=0} \leq 2.07$$

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- With D-states: small effect

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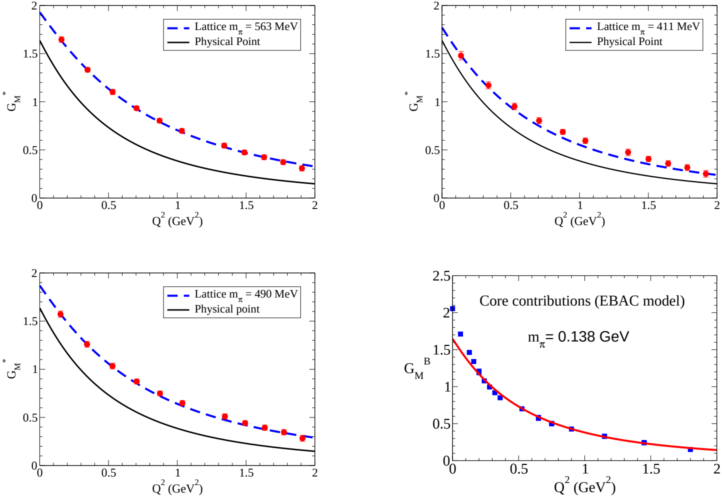
- With D-states: small effect

$$G_E^*, G_C^* \Leftarrow \textbf{Fit}\ \text{lattice QCD data (bare contribution)} \oplus \overbrace{\text{Pion cloud}}^{\text{Large } N_C}$$

$\gamma N \to \Delta$: $G_M^*(Q^2)$ on lattice [PRD 80, 013008 (2009)]

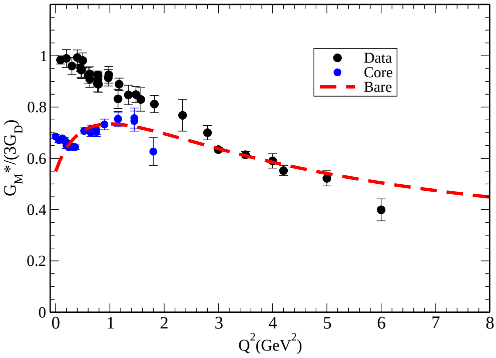


EBAC: J. Diaz et al, PRC 75, 015205 (2007) $\oplus$

Lattice: Alexandrou et al, PRD 77, 085012 (2008)

$\gamma N \to \Delta$: $G_M^*(Q^2)$ (valence)

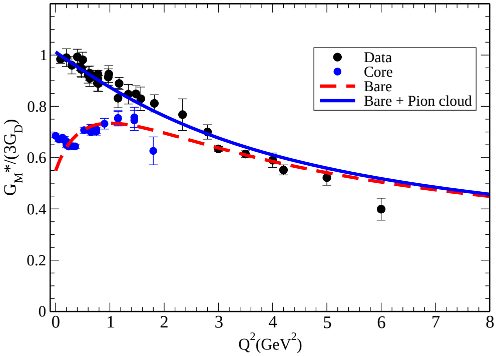
GR and MT Peña PRD 80, 013008 (2009) $\quad G_D = 1/\left(1 + Q^2/0.71\right)^2$



- Bare ≈ EBAC model

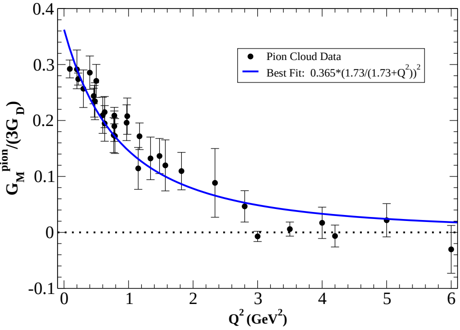
$\gamma N \to \Delta$: $G_M^*(Q^2)$ (valence + pion cloud [phenomenological])

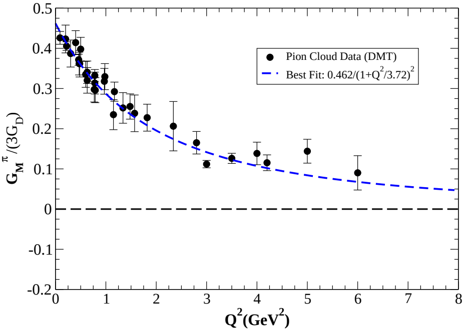
GR and MT Peña PRD 80, 013008 (2009) $G_D = 1/\left(1 + Q^2/0.71\right)^2$



- Bare ≈ EBAC model ⊕ $G_M^\pi = \lambda_\pi \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 + Q^2}\right)^2 (3G_D)$ $\frac{G_M^B(0)}{3G_D} \leq 0.7$

$\gamma N \to \Delta$: $G_M^*(Q^2)$ - Meson cloud

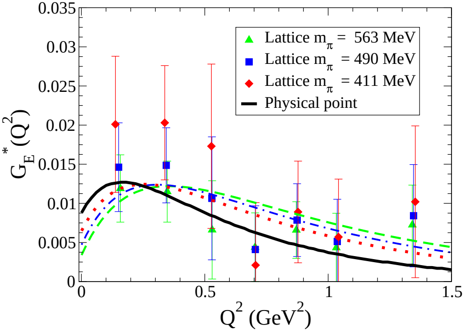


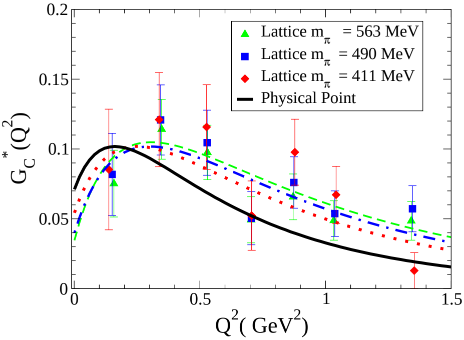


Sato-Lee model

Dubna-Maintz-Tapai model

Fit to lattice QCD data (bare contribution)
Alexandrou et al, PRD, 77, 085012 (2008)

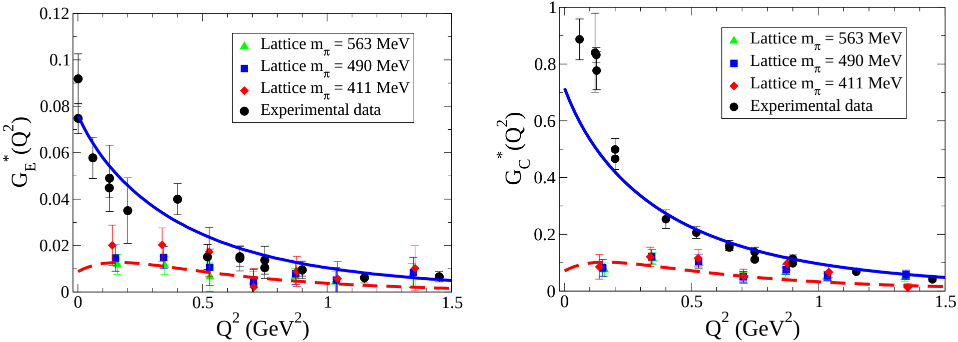




D3 state: 0.72%

D1 state: 0.72%

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare + pion cloud) ††



– – – – Lattice extrapolation → Physical regime

$\oplus$ Pion cloud [Large N_c; no additional parameters]

AJ Buchmann et al, PRD 66, 056002 (2002); V Pascalutsa and M Vanderhaeghen, PRD 76, 111501 (2007)

Pion cloud dominant; Good global description ($Q^2 < 1.5$ GeV^2)

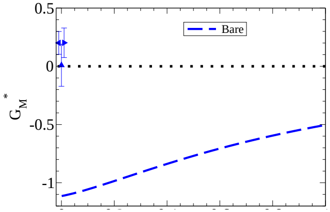
$\gamma N \to \Delta(1600)$ [PRD 82, 073007 (2010), GR and K Tsushima]

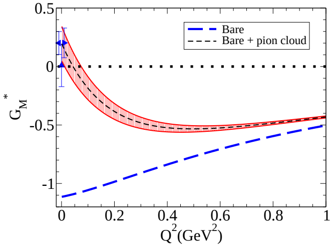
$\Delta(1600)$ as the 1st radial excitation of $\Delta(1232)$ EPJA, 36, 329 (2008) [S-state]
$G_E^* \equiv 0$, $G_C^* \equiv 0$

$$\text{Bare}: \quad G_M^B(0) = -1.113$$

$SU(3)$ symmetry $\Rightarrow$ π cloud effects

Decay	BR
$\Delta(1600) \to \pi N$	0.153±0.019
$\Delta(1600) \to \pi\Delta$	0.590±0.100
$\Delta(1600) \to \pi N(1440)$	0.130±0.040





$\gamma^* N \to N(1520)$: GR and MT Peña, arXiv:1309.0730

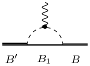
- More general case (no pointlike diquark limit) $\quad J^P = \frac{3}{2}^-$
- Orthogonality assured by radial wave function ψ_R

$$\int_k \frac{k_z}{|\mathbf{k}|} \psi_R(P_R, k) \psi_N(P_N, k) \Big|_{Q^2=0} = 0 \qquad (R \text{ rest frame})$$

One parameter to fit to high Q^2 data: β_4 (small mc effects)

$$\psi_R \approx \frac{1}{m_D(\beta_2 + \chi)} \left\{ \frac{1}{\beta_1 + \chi} - \frac{\lambda_R}{\beta_4 + \chi} \right\}$$

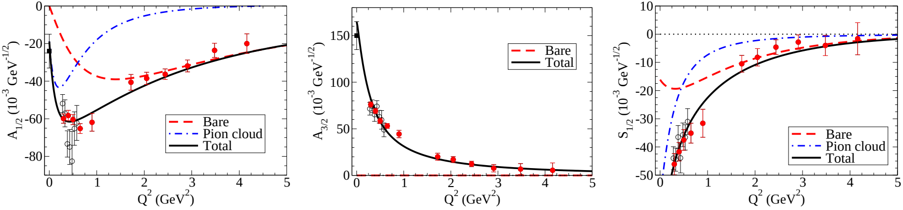
- Valence quarks **are not** sufficient to explain the data $(A_{3/2} \neq 0)$: exclusive of CSQM



- $\Rightarrow$ Include phenomenological parametrizations of the meson cloud at low Q^2

$\gamma^* N \to N(1520)$ form factors [arXiv:1309.0730]

$A_{1/2}$ $\qquad$ $A_{3/2}$ $\qquad$ $S_{1/2}$



– – – – – Bare; ——— Bare plus meson cloud

$A_{1/2}, S_{1/2}$: Valence quarks $\Rightarrow$ good description for $Q^2 > 1.5$ GeV^2

$A_{3/2} \Leftarrow$ Meson cloud

Conclusions

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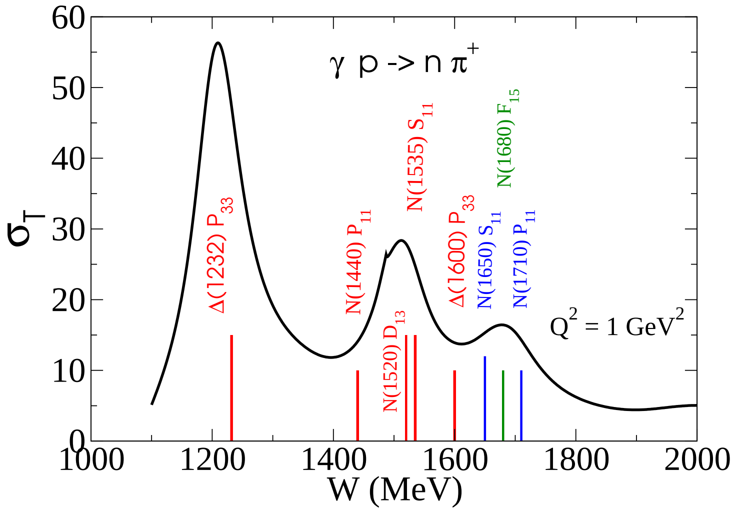
Thank you

Nucleon Resonance Structure



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- **A Covariant model for the nucleon and the Δ**,
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- **D-state effects in the electromagnetic $N\Delta$ transition**,
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Selected bibliography (part 3)

- **Valence quark contributions for the $\gamma N \to P_{11}(1440)$ form factors**, G. Ramalho and K. Tsushima, Phys. Rev. D **81**, 074020 (2010) [arXiv:1002.3386 [hep-ph]].
- **A model for the $\Delta(1600)$ resonance and $\gamma N \to \Delta(1600)$ transition**, G. Ramalho and K. Tsushima, Phys. Rev. D **82**, 073007 (2010) [arXiv:1008.3822 [hep-ph]].
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- **A simple relation between the $\gamma N \to N(1535)$ helicity amplitudes**, G. Ramalho and K. Tsushima, Phys. Rev. D **84**, 051301 (2011) [arXiv:1105.2484 [hep-ph]].
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$N^*(1520)$ in spacelike

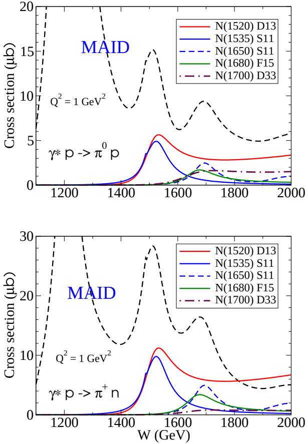
Plan of the talk

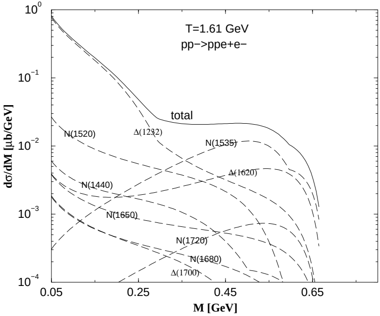
- **Introduction and motivation**
- **Framework: Covariant spectator quark model**
- **Valence quark effects**
- **Parametrization of meson cloud effects**

Why is the $N^*(1520)D_{13}$ an interesting resonance ?

- Dominante resonance from 2nd resonance region (**spacelike** and timelike)
- Interesting features of helicity amplitudes $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ (first data in 2009)
- Understand the role of the valence quark effects (baryon core) and the meson cloud effects
- Derive parametrization that can be extended to the **timelike** region

Introduction– Motivation (II)





Timelike

Faessler et al, JPG 29, 603 (2003)

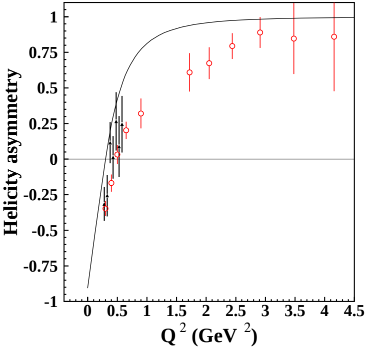
Spacelike

MAID 2007, Drechsel et al, EPJA 34, 69 (2007)

Introduction – Literature †

Previous studies of the $\gamma^* N \to N^*(1520)$ reaction

- First models (non relativistic):
  Close and Gilman PLB 38, 541 (1972); Koniuk and Isgur PRD 21, 1868 (1981)
- Relativistic models: Warns et al PRD 42, 2215 (1990); Capstick et al PRD 51, 3598 (1995); Merten et al EPJA 14, 477 (2002); Ronniger et al EPJA 48, 8 (2012); Aznauryan et al PRC 85, 055202 (2012)
- Hypercentral constituent quark model
  Aiello et al JPG 24, 753 (1998); Santopinto et al PRC 86, 065202 (2012)
- Collective model of baryons
  Bijker et al PRC 54, 1935 (1996)
- Meson cloud dressing:
  EBAC: J.-Diaz et al, PRC 77, 045205 (2008);
  CBM: Golli and Sirca, EPJA 49, 111 (2013)
- **Accurate CLAS data** $(\pi N;\, \pi\pi N)$
  Aznauryan et al, PRC 80, 055203 (2009); Mokeev et al, PRC 86, 045203 (2012)
- MAID analysis: EPJ ST 198, 41 (2011); EPJA 34, 69 (2007)
- **Review:** Aznauryan and Burkert, Prog. Part. NP 67, 1 (2012)



$$A_h = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

CLAS: Aznauryan et al PRC 80, 055203 (2009) (πN); Mokeev et al PRC 86, 035203 (2012) ($\pi\pi N$)

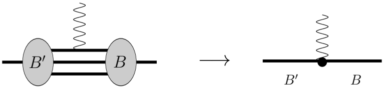
- $A_{1/2}$ dominates at large Q^2
- $A_{3/2}$ is large for small Q^2; falls off very fast
- Meson cloud effects are very important at small Q^2 (mainly to $A_{3/2}$, but also $A_{1/2}$) EBAC $\oplus$ valence quark models
- pQCD:
  $A_{1/2} \propto 1/Q^3$
  $A_{3/2} \propto 1/Q^5$
  $S_{1/2} \propto 1/Q^3$
  Carlson and Mukhopadhyay

  PRD 41, 2343 (1990)

Covariant Spectator Quark Model

Covariant Spectator Quark Model

- Quarks have internal electromagnetic structure (constituents) [dressed by gluon and quark-antiquark effects] ⇒ Bare
- ...

Bare 

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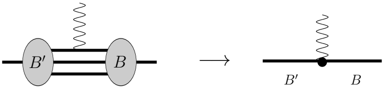
- Quarks have internal electromagnetic structure (constituents) [dressed by gluon and quark-antiquark effects] ⇒ Bare
- ...but there are processes that cannot be represented as quark dressing effects

Bare



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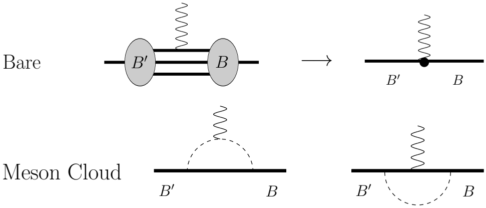

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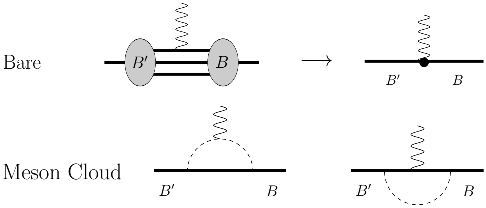


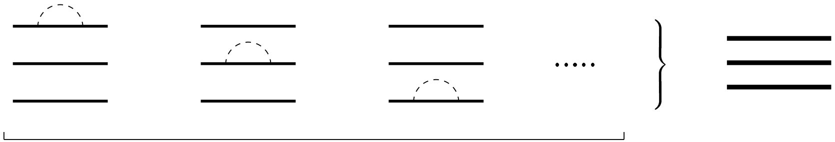
- Form factors

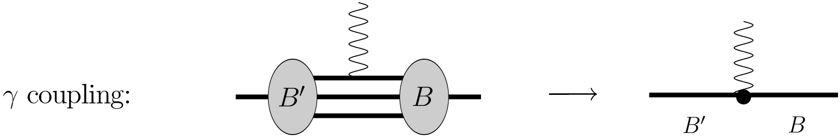
$$F = F^B + F^{MC}$$

MC: Not important at high Q^2; Very important at low Q^2

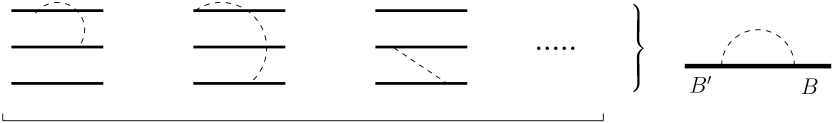
Quark structure and electromagnetic interaction (I) ††

Covariant Spectator QM: quarks with structure (constituents)

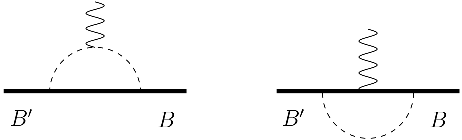




Quark structure and electromagnetic interaction (II) ††



γ coupling:



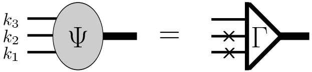
- Not important at high Q^2: pQCD – supression $1/Q^4$
  Very important at low Q^2
- Combining the 2 processes

$$F = F^B + F^{mc}$$

(bare ⊕ meson cloud)

Spectator QM: Baryon wave functions (I)

- Baryon: 3 constituent quark system
- Covariant Spectator Theory: wave function Ψ defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks



$$\Psi_\alpha(P,k_3) = \left(\frac{1}{m_q - \not{k}_3 - i\varepsilon} \right)_{\alpha\beta} \Gamma^\beta(P,k_1,k_2)$$

Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008)

- Ψ is **free** of singularities $\Rightarrow$ parametrize Ψ

Stadler, Gross and Frank PRC 56, 2396 (1998); Savkli and Gross PRC 63, 035208 (2001)

- On-shell integration $(k_1,k_2) \Rightarrow$ $k = k_1 + k_2$, $r = \frac{1}{2}(k_1 - k_2)$

Gross, GR and Peña PRC 77, 015202 (2008); PRD 85, 093005 (2012)

$$\int_{k_1}\int_{k_2} = \frac{\pi}{4}\int d\Omega_{\hat{\mathbf{r}}} \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s-4m_q^2}{s}} \int \frac{d^3\mathbf{k}}{2\sqrt{s+\mathbf{k}^2}} \to \int \frac{d^3\mathbf{k}}{2\sqrt{m_D^2+\mathbf{k}^2}}$$

$\Rightarrow$ integration in $\mathbf{k} \oplus s = (k_1+k_2)^2 \to m_D^2$ (Mean value theorem)

$\Rightarrow$ covariant integration in diquark **on-shell** momentum

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Ψ_B not determined by a dynamical equation $\Leftarrow$ phenomenology $M_B = M_B^{\rm exp}$

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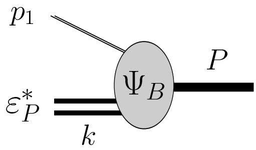
  Combination of **diquark** (12) and single **quark** (3) states, using $SU(6) \otimes O(3)$:

$$\Psi_B = \sum \text{(color)} \otimes \text{(flavor)} \otimes \text{(spin)} \otimes \text{(orbital)} \otimes \underbrace{\psi_B(P,k)}_{\text{radial}}$$



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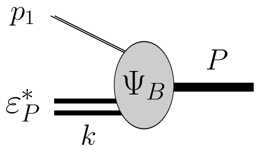

  - Ψ_B in **rest frame** using quark states
  - **Covariant** generalization of Ψ_B in terms **baryon** properties

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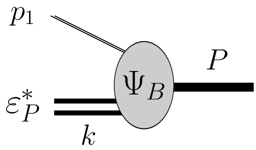
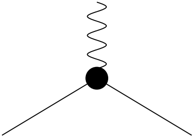


  - Ψ_B in **rest frame** using quark states
  - **Covariant** generalization of Ψ_B in terms **baryon** properties
- Phenomenology in the **radial wf** (momentum scale parameters)

Spectator QM: Quark current (VMD at quark level) (I)

- Quark current [$f_{i\pm}$ quark form factors]

$$j_q^\mu = \left[\frac{1}{6} f_{1+} + \frac{1}{2} f_{1-} \tau_3\right] \gamma^\mu + \left[\frac{1}{6} f_{2+} + \frac{1}{2} f_{2-} \tau_3\right] \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$$



Quarks with anomalous magnetic moments κ_u, κ_d

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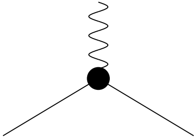
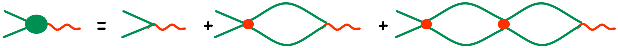


Quarks with anomalous magnetic moments κ_u, κ_d

- Vector meson dominance parameterization:



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$$
\begin{aligned}
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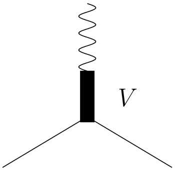
& \left[\frac{1}{6} f_{2+} + \frac{1}{2} f_{2-}\tau_3\right]\frac{i\sigma^{\mu\nu} q_\nu}{2M_N}
\end{aligned}
$$



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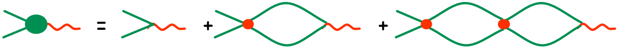
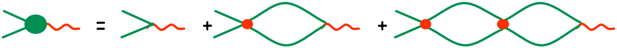


- Vector meson dominance parameterization: PRC77 015202 (2008)



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

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

2 poles:

- Light vector meson: $m_v \simeq m_\rho (\approx m_\omega)$
- Effective heavy meson: $M_h (= 2M_N)$ $\leftarrow$ short range

Nucleon magnetic moments $\Rightarrow \kappa_\pm$

4 parameters: λ_q, $c_\pm$, $d_+ = d_-$ (mixture coefficients)

$\Uparrow$ **Fitted to nucleon form factors data**

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

Spectator QM: Transition currents ($\gamma N \to N^*$)

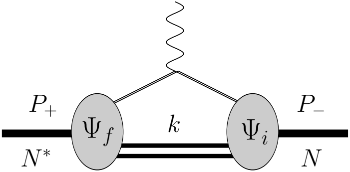
Quark current $j_q^\mu \bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

F Gross et al PR 186 (1969); PRC 45, 2094 (1992)

Relativistic impulse approximation:

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



diquark on-shell

$$q = P_+ - P_-, \qquad P = \tfrac{1}{2}(P_+ + P_-), \qquad Q^2 = -q^2$$

$q \cdot J \neq 0$: Landau prescription: $J^\mu \to J^\mu - \frac{q\cdot J}{q^2} q^\mu$

JJ Kelly, PRC 56, 2672 (1997); Z Batiz and F Gross, PRC 58, 2963 (1998)

$\gamma^* N \to N^*(1520)$ transition (I)

$$J^\mu = \bar{u}_\beta(P_R)\left\{G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu}\right\} u(P_N)$$

$$q = P_R - P_N \qquad P = \frac{1}{2}(P_R + P_N)$$

Current conservation $q \cdot J = 0$:

$$G_4 = (M_R + M) G_1 + \frac{1}{2}(M_R^2 - M^2) G_2 - Q^2 G_3$$

Additional function

$$g_C = 4 M_R G_1 + (3M_R^2 + M^2 + Q^2) G_2 + 2(M_R^2 - M^2 - Q^2) G_3$$

$$(G_1, G_2, G_3) \Longleftrightarrow (G_1, G_4, g_C)$$

$\gamma^* N \to N^*(1520)$ transition (II)

Amplitudes and multipole form factors (base G_1, G_4, g_C)

$$A_{1/2} = 2\mathcal{A}\left\{G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R}\right\}$$

$$A_{3/2} = 2\sqrt{3}\mathcal{A}G_4$$

$$S_{1/2} = -\frac{1}{\sqrt{2}}\frac{|\mathbf{q}|}{M_R}\mathcal{A}g_C$$

$$G_M = -F\left(\frac{1}{\sqrt{3}}A_{3/2} - A_{1/2}\right) = -\mathcal{R}[(M_R - M)^2 + Q^2]\frac{G_1}{M_R}$$

$$G_E = F\left(\sqrt{3}A_{3/2} + A_{1/2}\right) = -\mathcal{R}\left\{2G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R}\right\}$$

$$G_C = 2\sqrt{2}\frac{M_R}{|\mathbf{q}|}FS_{1/2} = -\mathcal{R}g_C$$

$$\mathcal{A} = \frac{e}{4}\sqrt{\frac{(M_R + M)^2 + Q^2}{6MM_RK}}, \quad F = \frac{1}{e}\frac{M}{|\mathbf{q}|}\sqrt{\frac{MK}{M_R}\frac{(M_R - M)^2 + Q^2}{(M_R - M)^2}}, \quad \mathcal{R} = 2\mathcal{A}F, \quad K = \frac{M_R^2 - M^2}{2M_R}$$

$\gamma^* N \to N^*(1520)$ transition (II)

Amplitudes and multipole form factors (base G_1, G_4, g_C)

$$A_{1/2} = 2\mathcal{A}\left\{ G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \right\}$$

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$$\begin{aligned} G_M &= -F\left(\frac{1}{\sqrt{3}}A_{3/2} - A_{1/2}\right) \\ &= -\mathcal{R}[(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \\ G_E &= F\left(\sqrt{3}A_{3/2} + A_{1/2}\right) \\ &= -\mathcal{R}\left\{ 2G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \right\} \\ G_C &= 2\sqrt{2}\frac{M_R}{|\mathbf{q}|}FS_{1/2} = -\mathcal{R}g_C \end{aligned}$$

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$$A_{1/2} = +\frac{1}{4F}(3G_M - G_E)$$

$$A_{3/2} = -\frac{\sqrt{3}}{4F}(G_M + G_E)$$

$\gamma^* N \to N^*(1520)$ transition (II)

Amplitudes and multipole form factors (base G_1, G_4, g_C)

$$A_{1/2} = 2\mathcal{A}\left\{ G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \right\}$$

$$A_{3/2} = 2\sqrt{3}\mathcal{A} G_4$$

$$S_{1/2} = -\frac{1}{\sqrt{2}}\frac{|\mathbf{q}|}{M_R}\mathcal{A} g_C$$

$$2\mathcal{R} G_4 = -(G_M + G_E) \to G_4'$$

$$\begin{aligned} G_M &= -F\left(\frac{1}{\sqrt{3}}A_{3/2} - A_{1/2}\right) \\ &= -\mathcal{R}[(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \\ G_E &= F\left(\sqrt{3}A_{3/2} + A_{1/2}\right) \\ &= -\mathcal{R}\left\{ 2G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \right\} \\ G_C &= 2\sqrt{2}\frac{M_R}{|\mathbf{q}|} F S_{1/2} = -\mathcal{R} g_C \end{aligned}$$

$$\mathcal{A} = \frac{e}{4}\sqrt{\frac{(M_R+M)^2 + Q^2}{6 M M_R K}}, \quad F = \frac{1}{e}\frac{M}{|\mathbf{q}|}\sqrt{\frac{MK}{M_R}\frac{(M_R - M)^2 + Q^2}{(M_R - M)^2}}, \quad \mathcal{R} = 2\mathcal{A}F, \quad K = \frac{M_R^2 - M^2}{2M_R}$$

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$\gamma^* N \to N^*(1520)$ transition (II)

Amplitudes and multipole form factors (base G_M, G_4', g_C)

$$A_{1/2} = 2\mathcal{A}\left\{ G_4 - [(M_R - M)^2 + Q^2]\frac{G_1}{M_R} \right\}$$

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$$\mathcal{A} = \frac{e}{4}\sqrt{\frac{(M_R + M)^2 + Q^2}{6MM_RK}}, \quad F = \frac{1}{e}\frac{M}{|\mathbf{q}|}\sqrt{\frac{MK}{M_R}\frac{(M_R - M)^2 + Q^2}{(M_R - M)^2}}, \quad \mathcal{R} = 2\mathcal{A}F, \quad K = \frac{M_R^2 - M^2}{2M_R}$$

$$A_{1/2} = +\frac{1}{4F}(3G_M - G_E) \qquad A_{1/2} = \frac{1}{F}G_M + \frac{1}{4F}G_4'$$

$$A_{3/2} = -\frac{\sqrt{3}}{4F}(G_M + G_E) \qquad A_{3/2} = \frac{\sqrt{3}}{4F}G_4'$$

$N^*(1520)$ wave function

$\Psi_R = \cos\theta_D \Psi_{P1} - \sin\theta_D \Psi_{P3}, \qquad \Psi_P = N_P \left[\phi_I^0 X_\rho + \phi_I^1 X_\lambda\right] \tilde{\psi}_P(r,k)$

- Nonrelativistic form (CM): $k_\rho \to r = \frac{1}{2}(k_1 - k_2)$, $k_\lambda \to k = k_1 + k_2$

  S Capstick and W Roberts, Prog. Part. Nucl. Phys. **45** S241 (2000) $\rho \to A$, $\lambda \to S$

Case $S = 1/2$

$X_\rho(s) = \sum_{ms'} \left\langle 1 \tfrac{1}{2}; ms' | \tfrac{3}{2} s \right\rangle \left[Y_{1m}(r) \left| s' \right\rangle_\lambda + Y_{1m}(k) \left| s' \right\rangle_\rho \right]$

$X_\lambda(s) = \sum_{ms'} \left\langle 1 \tfrac{1}{2}; ms' | \tfrac{3}{2} s \right\rangle \left[Y_{1m}(r) \left| s' \right\rangle_\rho + Y_{1m}(k) \left| s' \right\rangle_\lambda \right]$

Case $S = 3/2$

$X_\rho(s) = \sum_{ms'} \left\langle 1 \tfrac{1}{2}; ms' | \tfrac{3}{2} s \right\rangle Y_{1m}(r) \chi^S_{s'}$

$X_\lambda(s) = \sum_{ms'} \left\langle 1 \tfrac{1}{2}; ms' | \tfrac{3}{2} s \right\rangle Y_{1m}(k) \chi^S_{s'}$

- Relativistic generalization: $U_R^\alpha(P,s) = \frac{1}{\sqrt{3}} \gamma_5 \left(\gamma^\alpha - \frac{P^\alpha}{M_R} \right) u_R(P,s)$, $u_\beta(P,s)$

  spin states represented in a covariant form

  $k \to \tilde{k} = k - \frac{P \cdot k}{M_R^2} P \qquad \left| s \right\rangle_\rho \to u_R(P,s)$

  $Y_{1m}(k) \to -\frac{1}{\sqrt{-\tilde{k}^2}} (\varepsilon_{mP} \cdot \tilde{k}) \qquad \left| s \right\rangle_\lambda \to -(\varepsilon^*_{\Lambda P})_\alpha U_R^\alpha(P,s)$

  $Y_{1m}(r) \to \zeta^\nu_m \qquad \chi^S_s \to -(\varepsilon^*_{\Lambda P})^\beta u_\beta(P,s)$

  GR and MT Peña PRD 84, 033007 (2011); arXiv:1309.0730

- $\Rightarrow$ Reduction to quark-diquark system $\tilde{\psi}_P(r,k) \to \psi_P(P,k)$

$\gamma^* N \to N^*(1520)$ transition – quark model

$$\Psi_R = \cos\theta_D \Psi_{P1} - \sin\theta_D \Psi_{P3}$$

$\sin\theta_D \approx 0.1$: Ψ_{P3} effect very small

$$G_M \propto I_z^{P1}, \qquad G_4' = 0, \qquad G_C \propto \frac{I_z^{P1}}{Q^2}$$

$$A_{1/2} = \frac{1}{F} G_M, \qquad A_{3/2} \equiv 0, \qquad S_{1/2} \propto G_C$$

$$I_z^{P1}(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{P1}(P_R, k) \psi_N(P_N, k) \qquad (R \text{ rest frame})$$

Note: pQCD limit $G_4' \approx A_{3/2} \approx 0$ $\quad [G_M + G_E \approx 0]$

$\gamma^* N \to N^*(1520)$ - radial wave functions

$P_B^2 = M_B^2$, $k^2 = m_D^2$:
Radial wave function dependent of $(P_B - k)^2$, $\chi = \chi_B$

$$\chi = \frac{(M_B - m_D)^2 - (P_B - k)^2}{M_B m_D}$$

Nucleon radial wave function ($\beta_2 > \beta_1$; $\beta_1 \to$ long range)

$$\psi_N = \frac{N_0}{m_D} \frac{1}{(\beta_2 + \chi)} \frac{1}{(\beta_1 + \chi)}$$

$P1$ radial wave function (β_3 new short range parameter) $\to$ fit to the data

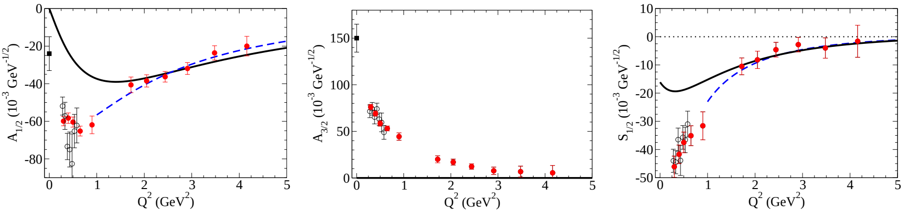
$$\psi_{P1} = \frac{N_1}{m_D} \frac{1}{(\beta_2 + \chi)} \left\{ \frac{1}{(\beta_1 + \chi)} - \frac{\lambda_{P1}}{(\beta_3 + \chi)} \right\}$$

Orthogonality between state (R rest frame): fixes λ_{P1}

$$I_z^{P1}(0) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{P1}(P_R, k) \psi_N(P_N, k) \bigg|_{Q^2=0} = 0$$

$\gamma^* N \to N(1520)$ amplitudes – Results (I)

$A_{1/2}$ $\qquad$ $A_{3/2}$ $\qquad$ $S_{1/2}$

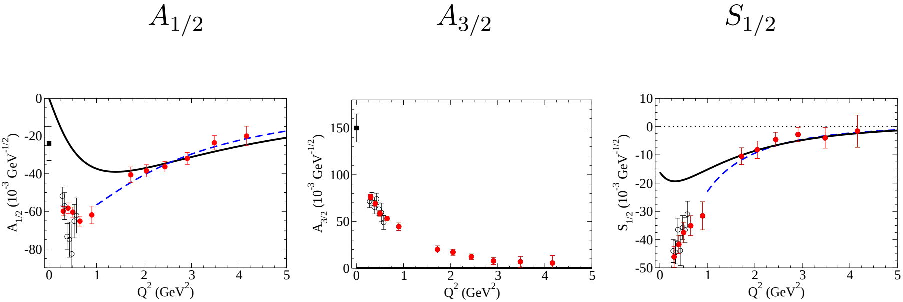


- - - - - Model $\psi_R \equiv \psi_N$ (no orthogonality)

——— $\psi_R = \psi_R(\beta_3)$ fit to $Q^2 > 1.5$ GeV^2 CLAS data

$A_{1/2}, S_{1/2}$: Valence quarks $\Rightarrow$ good description of large Q^2 data

$\gamma^* N \to N(1520)$ amplitudes – Results (I)



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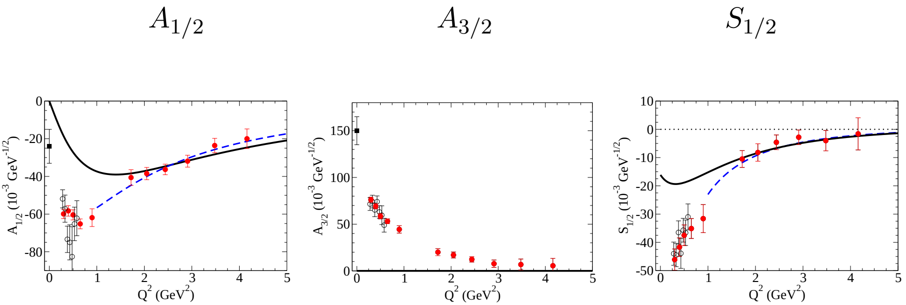
How to explain the $A_{3/2}$ data ?

$\gamma^* N \to N(1520)$ amplitudes – Results (I)



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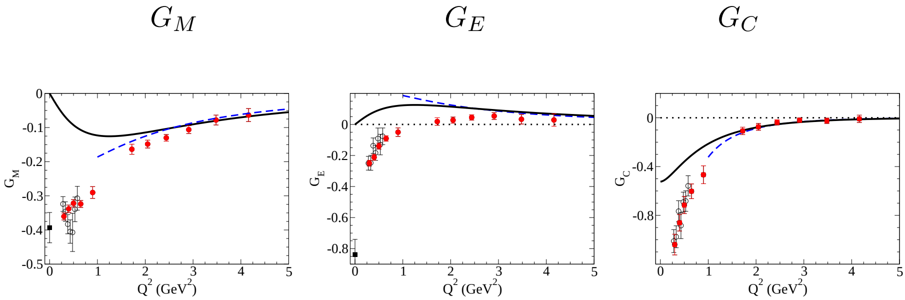
$A_{1/2}, S_{1/2}$: Valence quarks $\Rightarrow$ good description of large Q^2 data

How to explain the $A_{3/2}$ data ? Meson cloud

$\gamma^* N \to N(1520)$ form factors – Results (I) †



- - - - - Model $\psi_R \equiv \psi_N$ (no orthogonality)

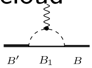
——— $\psi_R = \psi_R(\beta_3)$ fit to $Q^2 > 1.5$ GeV^2 CLAS data

G_M, G_E: Valence quarks $\Rightarrow$ not so good description ($A_{3/2} \equiv 0$)

How to explain the data ? Meson cloud

$\gamma^* N \to N(1520)$ – Meson cloud

πN (60%); $\pi\pi N$ (40%); simple assumption: dominance of pion cloud



$G_M = G_M^B + G_M^\pi$, $\quad G_4 = G_4^\pi$, $\quad G_C = G_C^B + G_C^\pi$,

pQCD: N constituents: $F \propto \frac{1}{(Q^2)^{(N-1)}}$ CE Carlson, FBS Sup 11, 10 (1999)

$$G_X^\pi \approx \frac{1}{Q^4} G_X^B, \qquad \frac{1}{Q^4} \to F_\rho = \frac{m_\rho^2}{m_\rho^2 + Q^2 + \frac{1}{\pi}\frac{\Gamma_\rho^0}{m_\pi} Q^2 \log \frac{Q^2}{m_\pi^2}}$$

$$G_M^\pi = \lambda_\pi^M (1 + a_M Q^2) \left(\frac{\Lambda_M^2}{\Lambda_M^2 + Q^2} \right)^3 F_\rho \, \tau_3$$

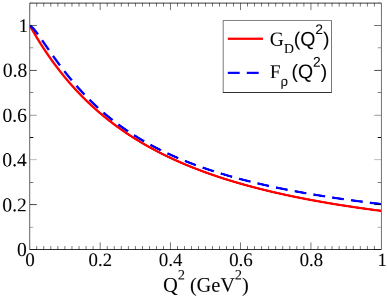
$$G_4^\pi = \lambda_\pi^{(4)} \left(\frac{\Lambda_4^2}{\Lambda_4^2 + Q^2} \right)^3 F_\rho \, \tau_3$$

$$G_C^\pi = \lambda_\pi^C \left(\frac{\Lambda_C^2}{\Lambda_C^2 + Q^2} \right)^3 F_\rho \, \tau_3$$

$\lambda_\pi^M, \lambda_\pi^{(4)}, \lambda_\pi^C, a_M, \Lambda_M^2, \Lambda_4^2, \Lambda_C^2 \Rightarrow$ fit to the data

$\gamma^* N \to N(1520)$ – Meson cloud

Motivation to use F_ρ, instead of $G_D = \left(1 + Q^2/0.71\right)^{-2} \approx 1/Q^4$

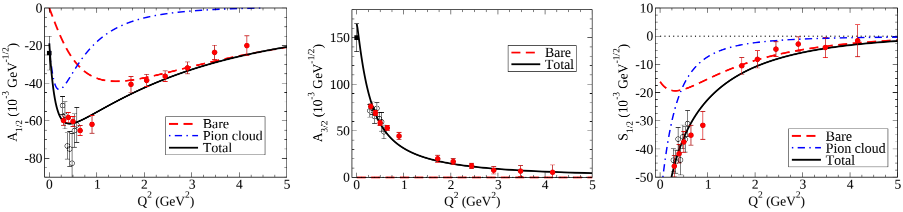


F_ρ simulates pion cloud dressing

F Iachello, A D Jackson, and A Lande, PLB 43, 191 (1973)

$\gamma^* N \to N(1520)$ amplitudes – Results (II)

$A_{1/2}$ $A_{3/2}$ $S_{1/2}$



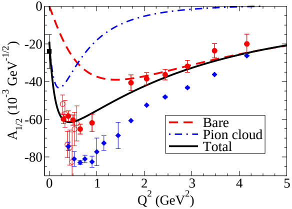
– – – – – Bare; ——— Bare plus meson cloud

$A_{1/2}, S_{1/2}$: good description

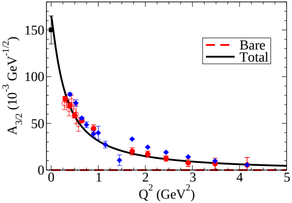
Meson cloud ⇒ good description of $A_{3/2}$

$\gamma^* N \to N(1520)$ amplitudes – Results (II) MAID

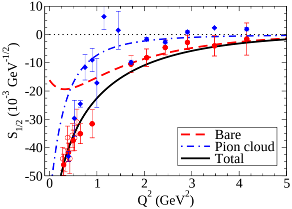
$A_{1/2}$



$A_{3/2}$



$S_{1/2}$

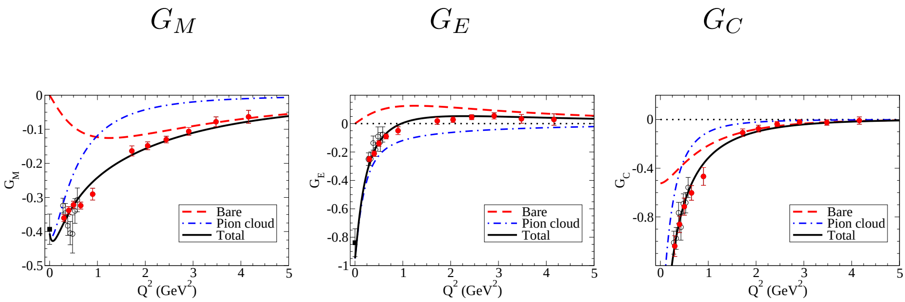


– – – – – Bare; ——— Bare plus meson cloud

$A_{1/2}, S_{1/2}, A_{3/2}$: good description

Discrepance between CLAS and MAID analysis

$\gamma^* N \to N(1520)$ form factors – Results (II) ††

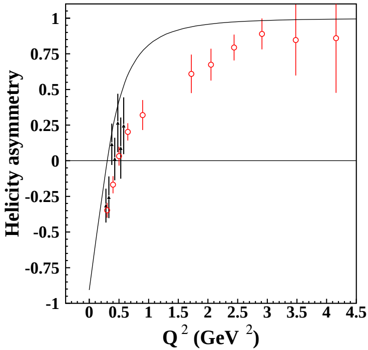


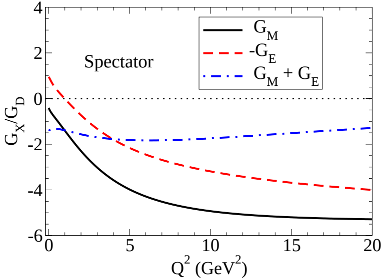
$- - - - -$ Bare; ——— Bare plus meson cloud

G_M, G_E, G_C: good description

Discrepance between CLAS and MAID analysis

$\gamma^* N \to N(1520)$ form factors – large Q^2





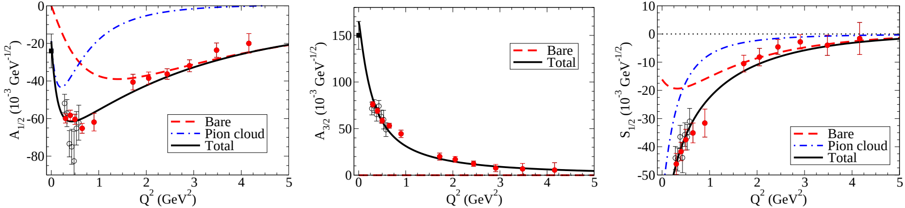
$$A_h = 1 - \frac{3(G_M + G_E)^2}{2(3G_M^2 + G_E^2)}$$

$$A_h = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

$G_M + G_E \to 0$ very slowly

$\gamma^* N \rightarrow N(1520)$ – Conclusions

$A_{1/2}$ $A_{3/2}$ $S_{1/2}$

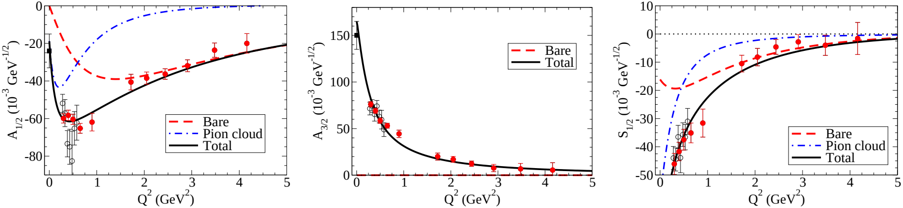


Covariant Spectator Quark Model

Good description of high Q^2 data: $A_{1/2}, S_{1/2}$ (fit 1 parameter)

$\gamma^* N \rightarrow N(1520)$ – Conclusions

$A_{1/2}$ $A_{3/2}$ $S_{1/2}$



Covariant Spectator Quark Model

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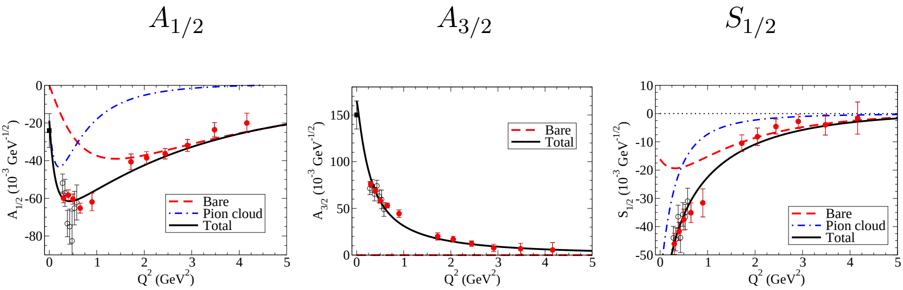
Meson cloud parametrization $\Rightarrow$ Low Q^2 $\oplus$ $A_{3/2}$ data

$\gamma^* N \to N(1520)$ – Conclusions



Covariant Spectator Quark Model

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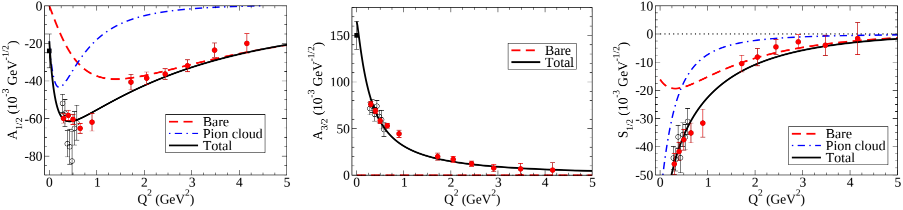
Meson cloud parametrization $\Rightarrow$ Low Q^2 $\oplus$ $A_{3/2}$ data

MC parametrization extendable for **timelike** $F_\rho(q^2) = \frac{m_\rho^2}{m_\rho^2 - q^2 + \ldots + i\frac{\Gamma_\rho^0}{m_\pi}q^2}$

$\gamma^* N \to N(1520)$ – Conclusions

$A_{1/2}$ $A_{3/2}$ $S_{1/2}$



Covariant Spectator Quark Model

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Thank you

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Selected bibliography (part 4)

- **Valence quark and meson cloud contributions for the $\gamma^* \Lambda \to \Lambda^*$ and $\gamma^* \Sigma^0 \to \Lambda^*$ reactions**, G. Ramalho, D. Jido and K. Tsushima, Phys. Rev. D **85**, 093014 (2012) [arXiv:1202.2299 [hep-ph]].
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More

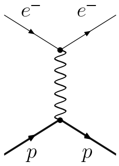
Other applications:

- **Octet Baryon Electromagnetic form Factors in Nuclear Medium**
  GR, K Tsushima, AW Thomas J. Phys. G40 (2013) 015102
  (extrapolation of VMD to the medium
  $m_X \to m_X^*$; medium modifications of coupling constants)
- **Nucleon *unphysical* form factors**
  in discussion

Nucleon form factors (2)

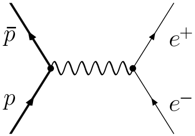
$$J^\mu = F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Spacelike



$q^2 \leq 0$

Timelike

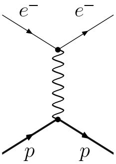


$q^2 \geq 4M^2$

Nucleon form factors (2)

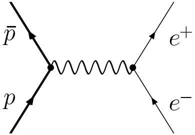
$$J^\mu = F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Spacelike



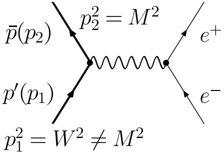
$q^2 \leq 0$

Timelike



$q^2 \geq 4M^2$

Unphysical



$4m_e^2 \leq q^2 \leq 4M^2$

Nucleon form factors in timelike region $[0 < q^2 < 4M^2]$

Unphysical form factors: $4m_e^2 < q^2 < 4M^2$ can be accessed by:

- $\gamma N \to e^+e^- N$, $\pi N \to e^+e^- N$
  Schäfer, Dönges and Mosel, PLB 342, 13 (1995);
  Dieperink and Nagorny, PLB 397, 20 (1997)
- $NN \to e^+e^- NN$
  Schäfer, Dönges, Engel and Mosel, NPA 575, 429 (1994)
- $\bar{N}N \to e^+e^- \pi$
  Gakh, Gustafsson, Dbeyssi and Gakh, PRC 86, 025204 (2012)

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Comments:

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Comments:

- It is necessary to define **off-shell** form factors (extra parameters ...)

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Comments:

- It is necessary to define **off-shell** form factors (extra parameters ...)
- Nucleon form factors contributions are mixed with other processes
  (Bethe-Heitler mechanism, Virtual Compton Scattering, higher resonances, ...)

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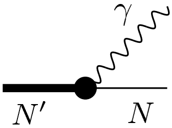
- $\bar{N}N \to e^+e^-\, \pi$
  Gakh, Gustafsson, Dbeyssi and Gakh, PRC 86, 025204 (2012)

Comments:

- It is necessary to define **off-shell** form factors (extra parameters ...)
- Nucleon form factors contributions are mixed with other processes
  (Bethe-Heitler mechanism, Virtual Compton Scattering, higher resonances, ...)
- Two-photon exchange effects negleted in 1st approximation

Alternative Model:

- N' **as a** qqq **system with mass** W **(on-shell)**



$$0 \leq q^2 \leq (M - W)^2$$

analytical continuation of **baryon wave functions** and **quark currents** (follow extension to lattice regime)

- **Calculate of form factors:**
  $G_E(Q^2; W)$, $G_M(Q^2; W)$ for the region $0 \leq q^2 \leq (M - W)^2$