A covariant formalism for the N^* electroproduction at high momentum transfer

Gilberto Ramalho

Instituto Superior Técnico, Lisbon

In collaboration with Franz Gross, M.T.Peña and K. Tsushima

4th Workshop on Exclusive Reactions
March 20, 2010

Motivation: frameworks

How to study the N^* electroproduction ?

- (Constituent) Quark Models ...
- Dynamical models [Coupled channels reaction models]
  Input: baryon core e. m. structure
  $\Rightarrow$ Dynamical dressing of baryons with
  meson-baryon interaction (non-perturbative)
  [EBAC, Sato-Lee, Mainz (DMT), Julich, ...]
- χ-Perturbation Theory, χEFT
  Degrees of freedom: baryons and pions
  Range: low Q^2; LEC $\rightarrow$ short range physics
  [Pascalutsa, Vanderhaeghen, Gail, Hemmert, ...]
- pQCD ... only for much higher Q^2
- Hybrid models (CBM, soliton, ...)

Motivation and goals $[\gamma^* N \to N^*]$

- Develop CQM for nucleon and nucleon excitations
  $\Rightarrow$ apply to low and high Q^2 regime [covariant formalism]
- Constituent quarks:
  quarks **dressed** by quark-antiquark effects and interaction with gluons
- Study the role of **valence quarks**
  Effects of angular momentum & radial excitations
  Large Q^2 regime: valence quark dominance
- Use experimental data and lattice data for a **precise** constraint of valence quark degrees of freedom
- $\Rightarrow$ estimate meson cloud contributions.

Spectator quark model- applications

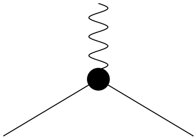
N^*electroproduction: $\gamma^* N \to N^*$

- Nucleon (elastic reaction)
  Valence quark wave function [No explicit pion cloud]
  But ... VMD parameterization of the quark current
  $\Rightarrow$ **fix quark current** [2+4 parameters]
- $\gamma N \to \Delta$
  Δ: Valence quarks wave function $\Rightarrow$ core contributions
  Pion cloud required
  Magnetic dipole: G_M^* – phenomenologic pion cloud
  Quadrupoles: G_E^*, G_C^* – large-N_c relations [4+2+2 parameters]
- $\gamma N \to P_{11}(1440)$ (Roper)
  Valence contribution from **orthogonality** with nucleon state
  No additional parameters required

Spectator quark model –quark current

- Constituent quarks (quark form factors)

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

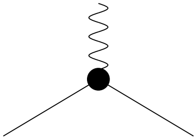


Quarks with anomalous magnetic moments κ_u, κ_d

Spectator quark model –quark current

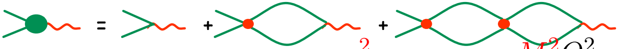
- Constituent quarks (quark form factors)

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



Quarks with anomalous magnetic moments κ_u, κ_d

- 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]

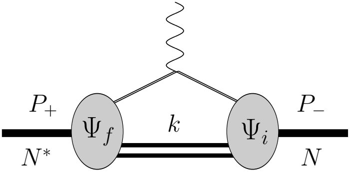
Quark current j_I^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

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

Relativistic impulse approximation:

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



diquark on-shell

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

Spectator quark model– Form factors

Nucleon:

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

$\gamma N \to \Delta$:

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

$$[G_4 = (M_\Delta + M_N)G_1 + \tfrac{1}{2}(M_\Delta^2 - M_N^2)G_2 - Q^2 G_3 \quad \Leftarrow \quad q_\mu J^\mu = 0]$$

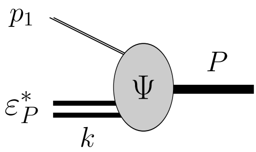
$\gamma N \to N^*$:

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

Form factors - exclusive functions of Q^2

Spectator quark model– Wave functions

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



$$\Psi_B = \sum (\text{flavor}) \otimes (\text{spin}) \otimes (\text{orbital}) \otimes (\text{radial})$$

- Write wave functions in terms of **diquark** (12) and single **quark** (3) states in the **rest frame** [SU(6) inspired]
- $\Longrightarrow$ Ψ_B in **covariant form** in terms baryon properties
- One can use Ψ_B in **any** frame and/or Q^2 regime

Baryon wave function -example: Nucleon (spin 1/2)

Simplest structure: S-state in quark-diquark
[Gross, GR and Peña, PRC 77,015202 (2008)]:

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

$\Phi_I^{0,1}$ - isospin; $\Phi_S^{0,1}$ - spin; $\psi_S(P,k)$ scalar wave function

Example $|p \uparrow\rangle$:

$$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \quad \chi_I = p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\uparrow = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \quad \chi_S = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Baryon wave function -example: Nucleon isospin

S-state in quark-diquark [PRC 77,015202 (2008)]:

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

Example $|p\uparrow\rangle$:

$$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix};\ \chi_{_I} = p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\Phi_I^0 = \frac{1}{\sqrt{2}}\left[ud - du\right]u \qquad \Phi_I^1 = \frac{1}{\sqrt{6}}\left[2uud - (ud+du)u\right]$$

$$\xi^s = \frac{1}{\sqrt{2}}\left[ud - du\right]$$

$$\xi^m = \begin{cases} uu & m=+1 \\ \frac{1}{\sqrt{2}}\left[ud+du\right] & m=0 \\ dd & m=-1 \end{cases}$$

$$\Phi_I^0 = \xi^s u \equiv \xi^s \chi_{_I}$$

$$\Phi_I^1 = -\frac{1}{\sqrt{3}}(\tau\cdot\xi)\,u \equiv -\frac{1}{\sqrt{3}}(\tau\cdot\xi)\,\chi_{_I}$$

Baryon wave function -example: Nucleon spin (I)

Example $|p\uparrow\rangle$: $\uparrow = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$; $\chi_S = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

Spin-0:

$$\Phi_S^0 = \overbrace{\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)}^{\varepsilon^s}\uparrow \quad = \quad \varepsilon^s \chi_S$$

Relativistic generalization $\rightarrow$ $\varepsilon^s \, u(P,\uparrow)$

Spin-1:

$$\Phi_S^1 = \frac{1}{\sqrt{6}}\left[2\uparrow\uparrow\downarrow - (\downarrow\uparrow + \downarrow\uparrow)\uparrow\right] \quad = \quad -\frac{1}{\sqrt{3}}\left(\sigma \cdot \varepsilon_P^*\right)\chi_S$$

Relativistic generalization $\rightarrow$ $-(\varepsilon_P^*)_\alpha U^\alpha(P,\uparrow)$

ε_P^*in **rest frame**: $\varepsilon_P^\alpha(0) = (0,0,0,1)$ $\quad \varepsilon_P^\alpha(\pm) = \mp\frac{1}{\sqrt{2}}(0,1,\pm i,0)$

$\Longrightarrow$ Fixed-axis polarization base

$\Phi_S^{0,1}$ in terms of baryon properties

Baryon wave function -example: Nucleon spin (II)

Covariant form to $U^\alpha(P,s)$

$$U^\alpha(P,s) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma^\alpha - \frac{P^\alpha}{M_N}\right)u(P,s) \xrightarrow{NR} -\frac{1}{\sqrt{3}}\left(\sigma\cdot\varepsilon_P^*\right)\chi_s$$

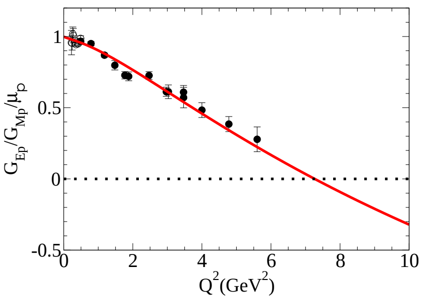
Fixed-axis polarization base [F Gross, GR and MT Peña, PRC 77, 015202 (2008)]

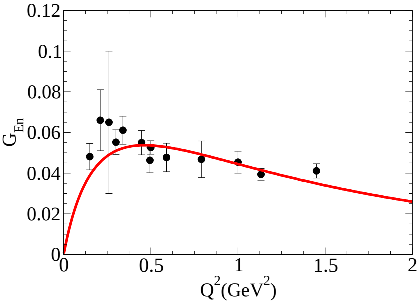
$$\varepsilon_P^\alpha(0) = \frac{1}{M_N}\left(P, 0, 0, \sqrt{M_N^2 + P^2}\right) \qquad \varepsilon_P^\alpha(\pm) = \mp\frac{1}{\sqrt{2}}\left(0, 1, \pm i, 0\right)$$

ε_P^α = function of baryon momentum

Pure angular momentum states; Covariant representation

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





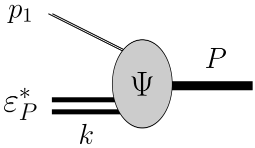
No pion cloud (explicit)

Quark current fixed [4 parameters]

Baryon wave function -example: more spin states

Direct product $1 \oplus \frac{1}{2} \Rightarrow S$ [Core spin: $S = S_d + S_q$]

$$S = \frac{1}{2}, \frac{3}{2}$$



Spin $\frac{1}{2}$: $$U^\alpha(P,s) = \sum_{\lambda\, s_1} \langle 1\lambda; \tfrac{1}{2} s_1 | \tfrac{1}{2} s_1 \rangle \varepsilon^\alpha_{\lambda P} u(P, s_1)$$

Spin $\frac{3}{2}$: $$w^\alpha(P,s) = \sum_{\lambda\, s_1} \langle 1\lambda; \tfrac{3}{2} s_1 | \tfrac{1}{2} s_1 \rangle \varepsilon^\alpha_{\lambda P} u(P, s_1)$$

$w^\alpha \equiv$ Rarita-Schwinger vector spin

Δ wave functions

Δ wave function as a mixture of **3 states** [2 mixture coefficients]

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

S-state:

$$\Psi_S(P,k) = -\psi_S(P,k)\bar{\phi}_I^1(\varepsilon_P^*)^\alpha w_\alpha(P)$$

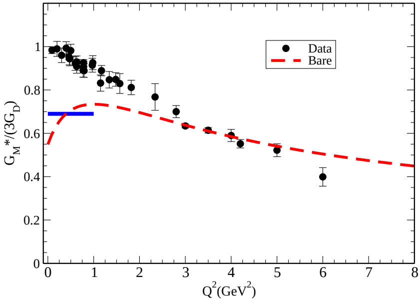
D-states: [GR, MT Peña and F Gross, PRD 78, 114017 (2008)]

- D-state operator $\mathcal{D}^{\alpha\beta}$
- create D-state $W = \mathcal{D} \cdot w$
  - projector $\mathcal{P}_{1/2}$: core **spin** $1/2$ (state D1)
  - projector $\mathcal{P}_{3/2}$: core **spin** $3/2$ (state D3)

$$\Psi_{Di}(P,k) = -3\psi_{Di}(P,k)\bar{\phi}_I^1(\varepsilon_P^*)_\alpha W_{Di}^\alpha(P,k)$$

Results for $\gamma N \to \Delta$ (only S-states)

Only $G_M^* \neq 0$, but $G_M^*(0) \leq 2.07$



Data from DESY, SLAC and CLAS (Jlab)

Valence quark contribution: GR, MT Peña and F Gross EPJA 38, 329 (2008)

$$G_M^*(Q^2) = 2\,\eta\, f_v \int_k \psi_\Delta \psi_N$$

$$\eta = \frac{4}{3\sqrt{3}} \frac{M_N}{M_N + M_\Delta}, \qquad f_v = f_{1-} + \frac{M_N + M_\Delta}{2M_N} f_{2-}$$

When $Q^2 = 0$: $\int_k \psi_\Delta \psi_N \le 1$

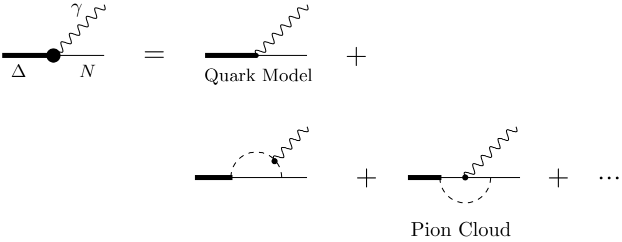
$$G_M^*(0) \le 2.07 < G_M^*(0)|_{exp} \simeq 3.02$$

Quark models $\Rightarrow$ upper limit to the valence contributions

$\Rightarrow$ Extra mechanisms have to be consider to explain the data

Results for $\gamma N \to \Delta$ (pion cloud effect)

Form factor = Bare + pion cloud



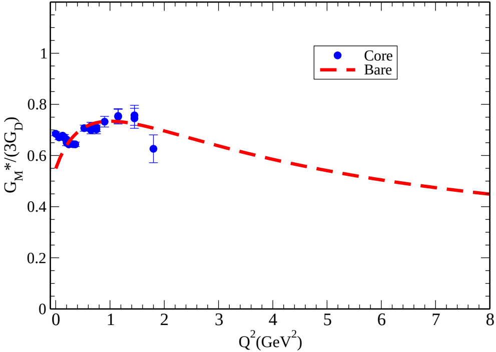
Form factors:

$$G_M^*(Q^2) = G_M^B(Q^2) + G_M^\pi(Q^2) \;\leftarrow\; \text{phenomenologic}$$

G_M^B compared with bare contributions

Results for $\gamma N \to \Delta$ (only S-states)

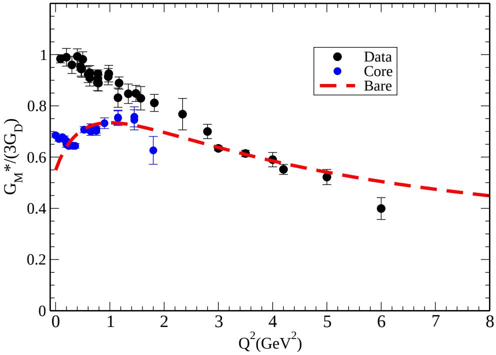
Compare G_M^B with core contributions



Core contributions extracted using Sato-Lee model
Diaz et al PRC 75, 015205 (2007)

Results for $\gamma N \to \Delta$ (only S-states)

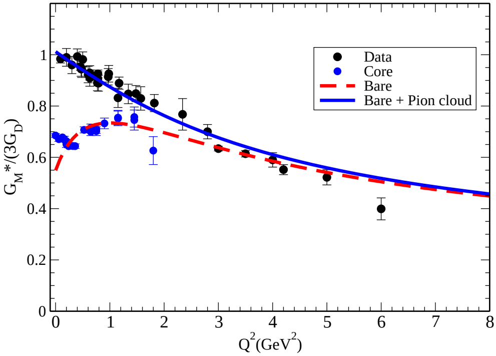
GR, MT Peña and F Gross EPJ A36, 329 (2008)



- Valence quark contributions $\Rightarrow$ fix 2 parameters [Sato-Lee model]
- ...

Results for $\gamma N \to \Delta$ (only S-states)

GR, MT Peña and F Gross EPJ A36, 329 (2008)



- Valence quark contributions $\Rightarrow$ fix 2 parameters [Sato-Lee model]
- Phenomenologic pion cloud

$\gamma N \to \Delta$ form factors

GR, MT Peña and F Gross PRD 78, 114017 (2008)

S-state	D3-state	D1-state
$G_M^* = 4N\eta f_v \mathcal{I}_S$	$-2aN\eta f_v \mathcal{I}_{D3}$	$+bN\eta f_v \mathcal{I}_{D1}$
$G_E^* =$	$-2aN\eta f_v \mathcal{I}_{D3}$	$-bN\eta f_v \mathcal{I}_{D1}$
$G_C^* =$		$+bN \frac{4M_N M_\Delta}{\sqrt{3}} f_C \frac{\mathcal{I}_{D1}}{Q^2}$

$$\mathcal{I}_S = \int_k \psi_S \psi_N \qquad \mathcal{I}_{D3} = \int_k b(\hat{k}) \psi_{D3} \psi_N \qquad \mathcal{I}_{D1} = \int_k b(\hat{k}) \psi_{D1} \psi_N$$

$$f_C = f_{1-} - \frac{Q^2}{2M_N(M_N+M_\Delta} f_{2-} \qquad b(\hat{k}) \approx Y_{20}(\hat{k}).$$

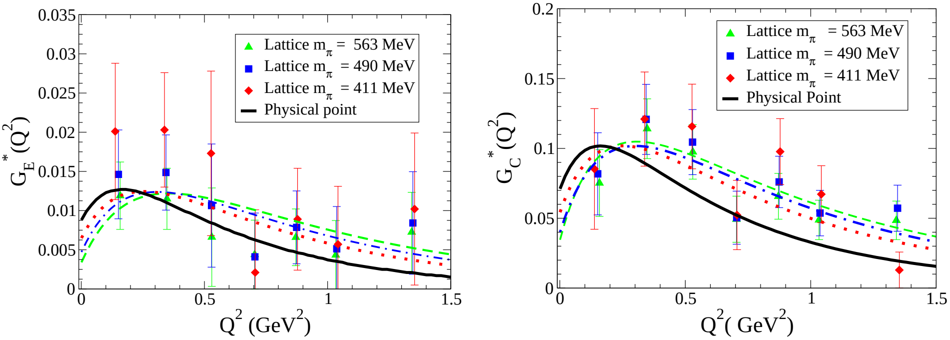
Valence quark phenomenology in the **scalar wave functions** (4 momentum scale parameters) $\oplus$ **mixture coefficients**

$\gamma N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ on lattice

Disentangling valence quark from pion cloud effects

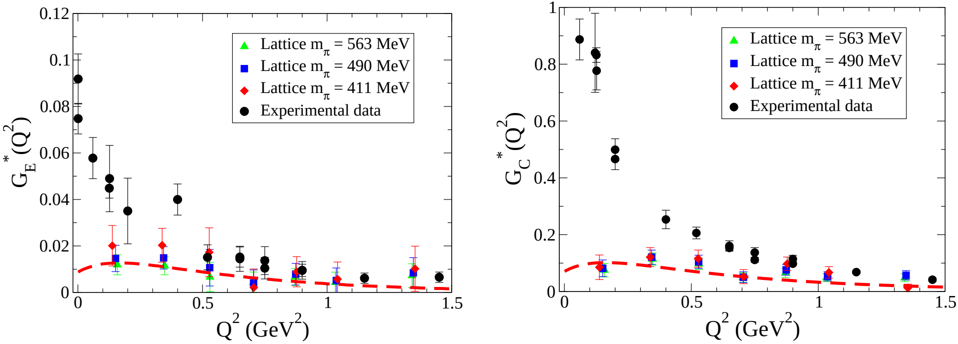
Quenched lattice data $\Rightarrow$ adjust valence contributions

Alexandrou et al



D3 state: 0.72%   D1 state: 0.72%

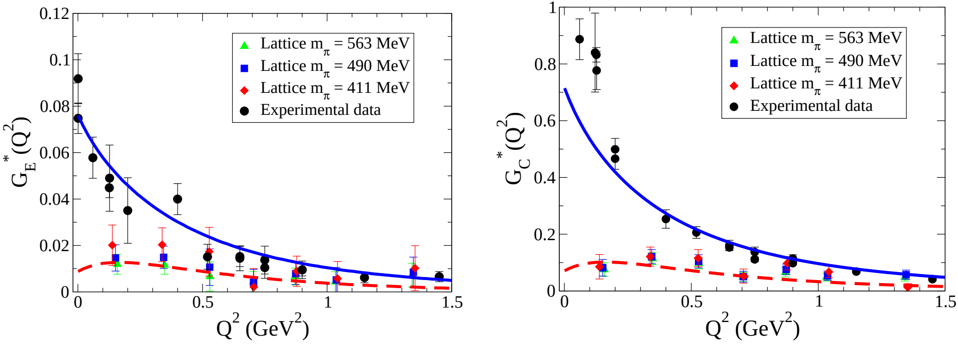
$\gamma N \to \Delta$- $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare)



GR, MT Peña PRD 80, 013008 (2009)

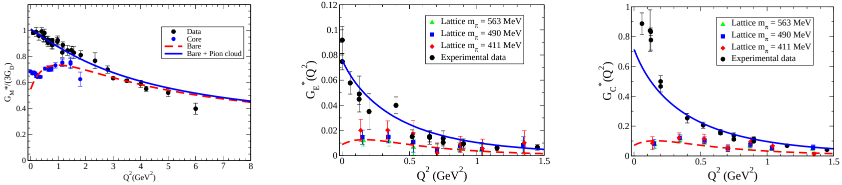
Small valence quark contributions

$\gamma N \to \Delta$ $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare + pc)



Pion cloud from large N_c relations [Buchmann $\oplus$ Pascalutsa-Vanderhaeghen]
(no additional parameters)

$\gamma N \to \Delta$ summary



- Decomposition: $G_X^* = G_X^B + G_X^\pi$
- Valence quark contributions:
  describes lattice data (G_M^B, G_E^B, G_C^B) and SL core contributions (G_M^*)
  $\to$ control of valence quark contributions
- Including pion cloud $\Rightarrow$ agreement with experimental data

$\gamma N \to$ Roper form factors

Roper wave function [same structure as the nucleon]
GR and K Tsushima, PRD 81, 074020 (2010):

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

Momentum dependence: $\chi_B = \frac{(M_B - m_s)^2 - (P-k)^2}{M_B m_s}$

$$\begin{aligned} \psi_N(P,k) &= N_0 \frac{1}{m_s(\beta_1 + \chi_N)(\beta_2 + \chi_N)} \\ \psi_R(P,k) &= N_R \frac{\beta_3 - \chi_R}{\beta_1 + \chi_R} \frac{1}{m_s(\beta_1 + \chi_R)(\beta_2 + \chi_R)} \end{aligned}$$

[β_1 = long range scale parameter]

Orthogonality: $\int_k \psi_R(P,k)\psi_N(P,k) \Big|_{Q^2=0} = 0$ fix β_3 [no parameters]

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

$$
\begin{aligned}
F_1^*(Q^2) &= \frac{3}{2} j_1 \mathcal{I} + \frac{1}{2}\frac{3(M_R+M)^2 - Q^2}{(M_R+M)^2+Q^2} j_3 \mathcal{I} \\
&\quad - \frac{M_R+M}{M}\frac{Q^2}{(M_R+M)^2+Q^2} j_4 \mathcal{I}, \\
F_2^*(Q^2) &= \frac{3}{4}\frac{M_R+M}{M} j_2 \mathcal{I} - \frac{(M_R+M)^2}{(M_R+M)^2+Q^2} j_3 \mathcal{I} \\
&\quad + \frac{M_R+M}{2M}\frac{(M_R+M)^2 - 3Q^2}{(M_R+M)^2+Q^2} j_4 \mathcal{I},
\end{aligned}
$$

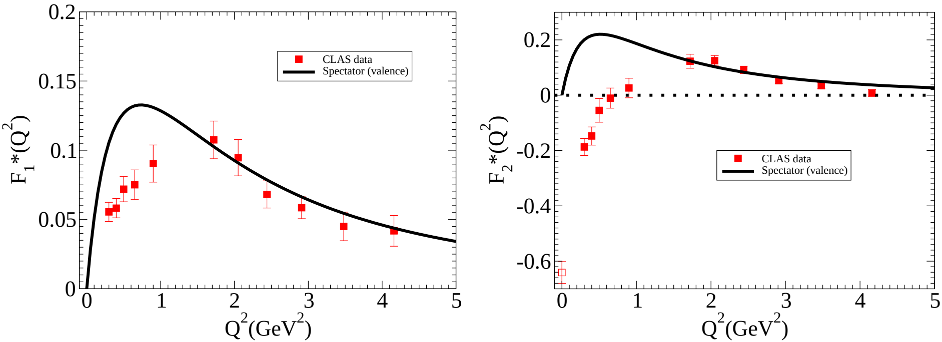
Overlap integral:

$$
\mathcal{I}(Q^2) = \int_k \psi_R(P_+, k)\psi_N(P_-, k),
$$

$$
\begin{aligned}
j_1 &= \tfrac{1}{6} f_{1+} + \tfrac{1}{2} f_{1-}\tau_3, & j_3 &= \tfrac{1}{6} f_{1+} - \tfrac{1}{6} f_{1-}\tau_3 \\
j_2 &= \tfrac{1}{6} f_{2+} + \tfrac{1}{2} f_{2-}\tau_3, & j_4 &= \tfrac{1}{6} f_{2+} - \tfrac{1}{6} f_{2-}\tau_3
\end{aligned}
$$

Nucleon quark currents– GR, MTP, and FG, PRC 77, 015202 (2008)

$\gamma N \to$ Roper form factors- results

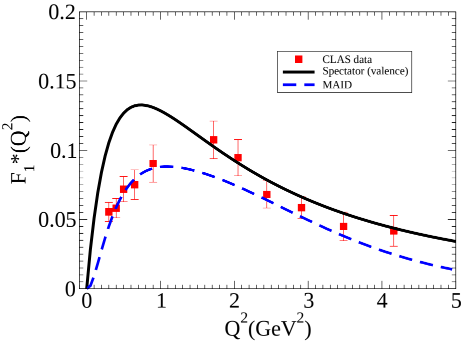


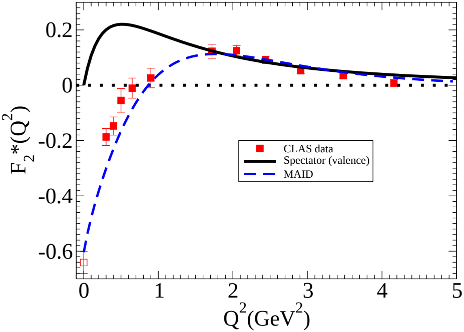
$\mathcal{I}(0) = 0 \Rightarrow F_1^*(0) = 0$ good; $\Rightarrow F_2^*(0) = 0$ bad

Underestimate data for $Q^2 < 1.5$ GeV^2

Explain data for $Q^2 > 1.5$ GeV^2

$\gamma N \rightarrow$ Roper form factors- results $\oplus$ MAID



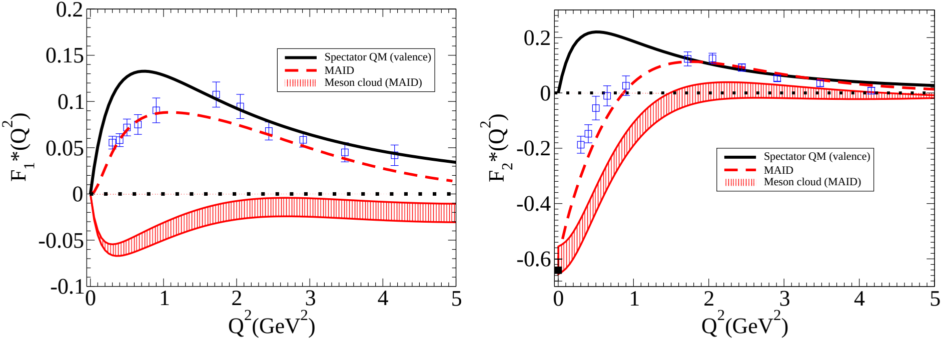


Use MAID fit to extract meson cloud contributions

Underestimate data for $Q^2 < 1.5$ GeV^2

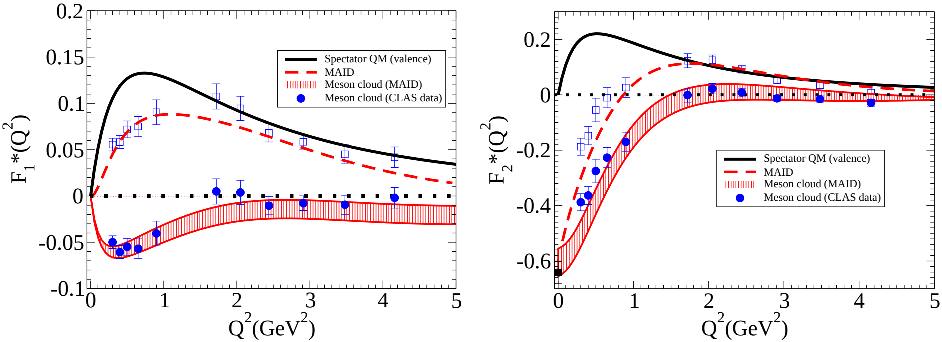
Explain data for $Q^2 > 1.5$ GeV^2

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

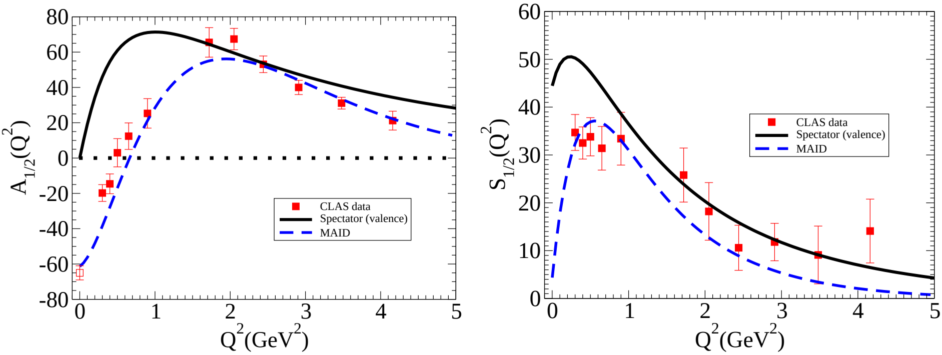


$$F_i^{mc}(Q^2) = F_i^*(Q^2) - F_i^{Spect}(Q^2) \qquad F_1^* \equiv F_1^{MAID}$$

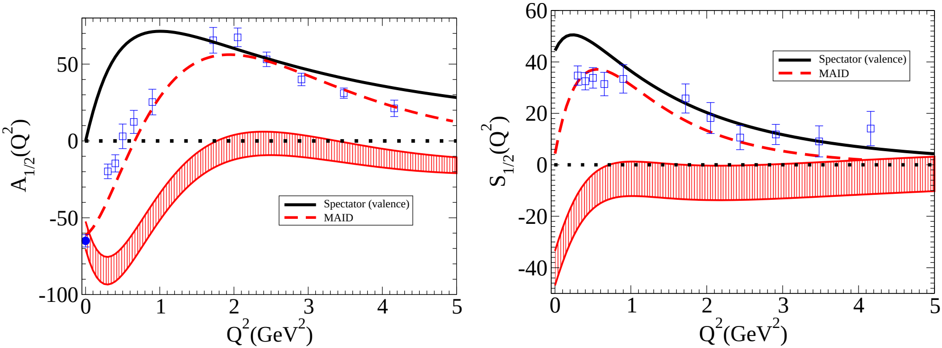
$\gamma N \rightarrow$ Roper –Meson cloud contributions- CLAS



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

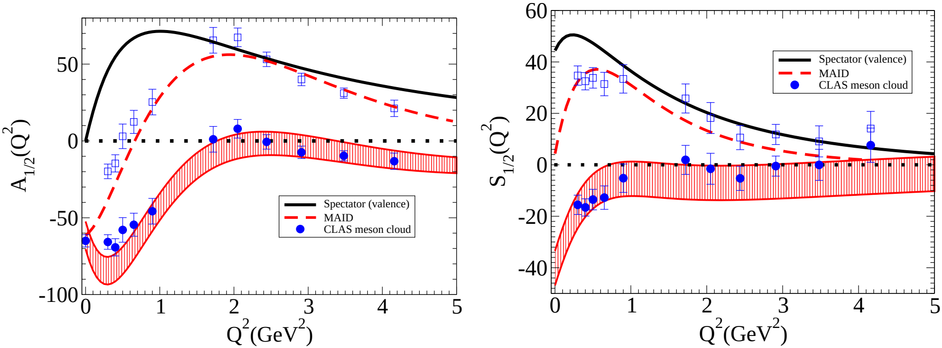

80
60
40
20
0
-20
-40
-60
-80
$A_{1/2}(Q^2)$
0
1
2
3
4
5
$Q^2(GeV^2)$
CLAS data
Spectator (valence)
MAID
60
50
40
30
20
10
0
$S_{1/2}(Q^2)$
0
1
2
3
4
5
$Q^2(GeV^2)$
CLAS data
Spectator (valence)
MAID

$\gamma N \to$ Roper – Helicity amplitudes- MAID meson cloud



$$A_i^{mc}(Q^2) = A_i(Q^2) - A_i^{Spect}(Q^2)$$

$\gamma N \rightarrow$ Roper – Helicity amplitudes- CLAS meson cloud



$$A_i^{mc}(Q^2) = A_i(Q^2) - A_i^{Spect}(Q^2)$$

Conclusions $[\gamma N \to N^*]$

- Nucleon elastic form factors
  Good description with NO explicit pion cloud contributions
- $\gamma N \to \Delta$
  Excellent description of lattice data $\oplus$ experimental data
- $\gamma N \to$ Roper
  Excellent description of high Q^2 data
  Use model to estimate meson cloud contributions
- More questions: ramalho@jlab.org
- Other applications
  - Ω^- form factors PRD**80**, 033004 (2009)
  - Δ form factors arXiv:1002.4170 [hep-ph], PLB 678, 355 (2009)
  - Octet magnetic moments (w/ pion cloud) arXiv:0910.2171 [hep-ph]
  - Nucleon form factors in lattice JPG**36**, 115011 (2009)

Bibliography (part 1)

- F. Gross, G. Ramalho and M. T. Peña, Phys. Rev. C **77**, 015202 (2008) [arXiv:nucl-th/0606029].
- F. Gross, G. Ramalho and M. T. Peña, Phys. Rev. C **77**, 035203 (2008).
- G. Ramalho, M. T. Peña and F. Gross, Eur. Phys. J. A **36**, 329 (2008) [arXiv:0803.3034 [hep-ph]].
- G. Ramalho, M. T. Peña and F. Gross, Phys. Rev. D **78**, 114017 (2008) [arXiv:0810.4126 [hep-ph]].
- G. Ramalho and M. T. Peña, Phys. Rev. D **80**, 013008 (2009) [arXiv:0901.4310 [hep-ph]].
- G. Ramalho and K. Tsushima, Phys. Rev. D **81**, 074020 (2010) [arXiv:1002.3386 [hep-ph]].

Bibliography (part 2)

- G. Ramalho and M. T. Peña, J. Phys. G **36**, 085004 (2009) [arXiv:0807.2922 [hep-ph]]
- G. Ramalho, K. Tsushima and F. Gross, Phys. Rev. D **80**, 033004 (2009) [arXiv:0907.1060 [hep-ph]].
- F. Gross, G. Ramalho and K. Tsushima, arXiv:0910.2171 [hep-ph] to appear in PLB
- G. Ramalho, M. T. Peña and F. Gross, Phys. Lett. B **678**, 355 (2009) [arXiv:0902.4212 [hep-ph]].
- G. Ramalho, M. T. Peña and Franz Gross, arXiv:1002.4170 [hep-ph]