Covariant models of Nucleon and Δ
$N - N^*$ Transition Form Factors Workshop

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MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

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2. Formalism
3. Spectator Quark Model
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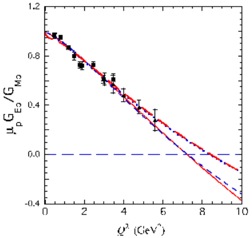
   - NΔ transition: S-state (Results)
4. NΔ transition
   - Delta D-states wave functions
   - NΔ transition (S+D) - Results
   - Comparing QM with DM
5. Conclusions

Motivation



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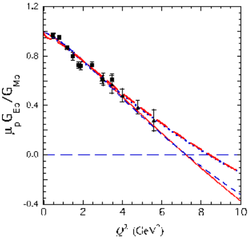

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  [simple $\equiv$ S-wave] Yes

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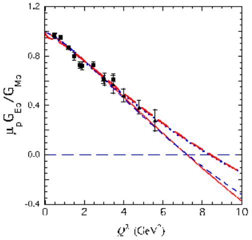

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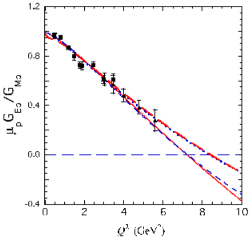

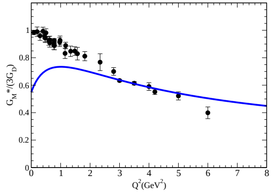

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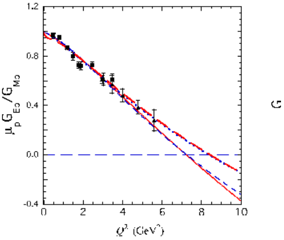
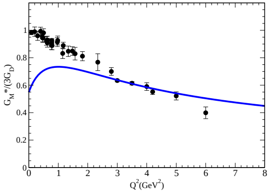
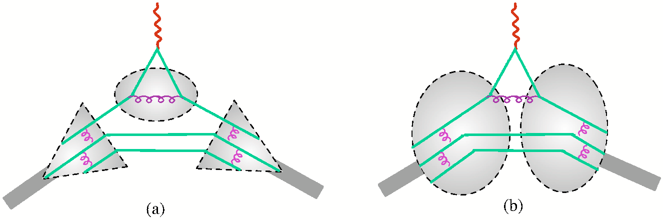




- Covariant quark model to work at high Q^2 regime
- Can we describe the Nucleon Elastic form factor data with a simple model ? [simple $\equiv$ S-wave] **Yes**
- Can we extend the model (S-wave) to heavier baryons (Δ) ? **Almost**
- Can we include systematically high angular momentum states ? ...

Formalism: CQM vs Light Front



Constituent Quark Model view

- Quark dressed by gluons and $q\bar{q}$ interactions
- Gluon interactions between $q\bar{q}$ $\Rightarrow$ quark form factors
- Quarks with anomalous magnetic moments κ_u, κ_d
- Nucleon FF can be explained without high angular momentum components

Light Front view

- Baryon states as a sum of Fock states:
  qqq, $qqqg$, $qqq(q\bar{q})$, ...
- Pointlike quarks
- No anomalous magnetic moments $\kappa_u, \kappa_d = 0$
- High angular momentum required to explain $\kappa_N \neq 0$

Formalism (Wave functions)

Construction of a baryon wave function:

Baryon $=$ quark $\oplus$ diquark

- Non Relativistic structure; baryon rest frame: $\mathbf{P} = 0$
  $\Rightarrow$ Relativistic form
- Consider a boost in the z-direction
  fixed-axis polarization states
- Initial and final state wave functions defined in a collinear frame
  diquark constraint
- Arbitrary Lorentz transformation Λ
  $\Rightarrow$ wave function defined in an arbitrary frame

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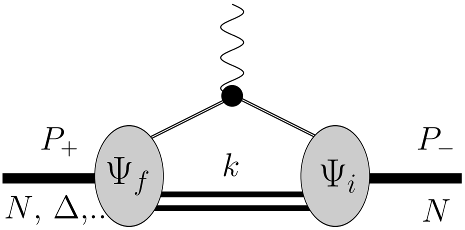
$\Rightarrow$ All states satisfies the Dirac equation

Spectator Quark Model



diquark on-mass-shell

Hadronic current

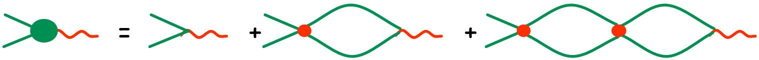
$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+, k) j_I^\mu \Psi_i(P_-, k)$$

Quark current

$$j_I^\mu = j_1 \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) + j_2 \frac{i \sigma^{\mu\nu} q_\nu}{2M}$$

$$j_i = \frac{1}{6} f_{i+} + \frac{1}{2} f_{i-} \tau_3$$

Vector Meson Dominance quark ff



Two poles: $\mathbf{m_V} = m_\rho$, $\mathbf{M_h} \sim 2M$ $\kappa_\pm$ fixed by $G_M(0)$,

3-4 parameter to adjust

Gross, GR and Peña, PRC 77, 015202 (2008).

S-state Wave Functions

- Nucleon $J = 1/2$: superposition of mixed symmetry states:

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

$\Phi_I^{I_z}$: isospin; $\phi_S^{S_z}$: spin; ψ_N scalar wave function [PRC 77, 015202 (2008)]

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- Delta $J = 3/2$: pure symmetric states

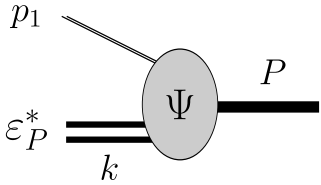
$$\Psi_\Delta = \bar{\Phi}_I^1 \bar{\Phi}_S^1 \psi_\Delta(P,k)$$

ψ_Δ: Δ scalar wave function [EPJ A36, 329 (2008)]

N and Δ spin wave functions

$$\{\Phi_s^1, \bar{\Phi}_s^1\} \Longrightarrow \Phi_S(\lambda, \lambda_s) \qquad S = 1/2, 3/2$$

λ = diquark polarization; λ_s = N or Δ spin projections



$$\Phi_{1/2}(\lambda, \lambda_s) = -(\varepsilon_{\lambda P}^*)_\alpha V_{1/2}^\alpha(P, \lambda_s)$$

$$\Phi_{3/2}(\lambda, \lambda_s) = -(\varepsilon_{\lambda P}^*)_\alpha V_{3/2}^\alpha(P, \lambda_s)[RS]$$

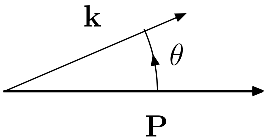
3-quark spin state given by ($B = N, \Delta$):

$$V_S^\alpha(P, \lambda_s) = \sum_\lambda \langle \frac{1}{2}\lambda; 1\lambda' | S\lambda_s \rangle \varepsilon_{\lambda' P}^\alpha u_B(P, \lambda)$$

$\varepsilon_{\lambda P}^\alpha$ = fixed-axis polarization states

Diquark polarization states

- Helicity states defined in terms of the $k = (E_k, k \sin\theta, 0, k\cos\theta)$



$\varepsilon_k(\lambda)$ dependent of θ

- Fixed-axis: vector particle is bound to a system with $P = (P_0, 0, 0, \mathrm{P})$:

$$\varepsilon(0) = \frac{1}{M}\begin{bmatrix} P \\ 0 \\ 0 \\ P_0 \end{bmatrix}, \qquad \varepsilon(\pm) = \mp\frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ 1 \\ \pm i \\ 0 \end{bmatrix}$$

$\Longrightarrow$ wave functions with No angular dependence;

F. Gross, GR and M.T. Peña, PRC 77, 035203 (2008).

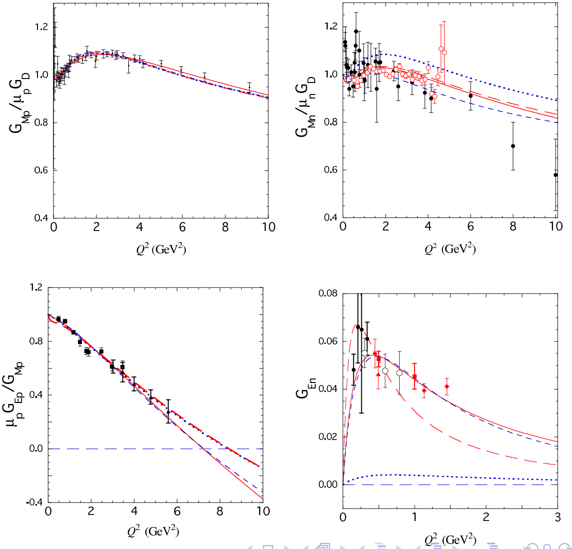
Nucleon Elastic Form Factors: Results

- Description of Elastic data with a S-wave [Rest frame]

$$\psi_N = \frac{N_0}{(\beta_1 + (P-k)^2)(\beta_2 + (P-k)^2)}$$

- Few parameters
  - - - Model II (3+2)

  No explicit pion cloud ...
  but VMD



NΔ transition: S-state

GR, M.T. Peña and F. Gross, EPJA A36, 329 (2008)

- S-states:

$$G_E^* = G_C^* = 0$$

$$G_M^*(Q^2) = \frac{4}{3\sqrt{3}} \frac{M}{M + M_\Delta} f_v \int \psi_\Delta \psi_N$$

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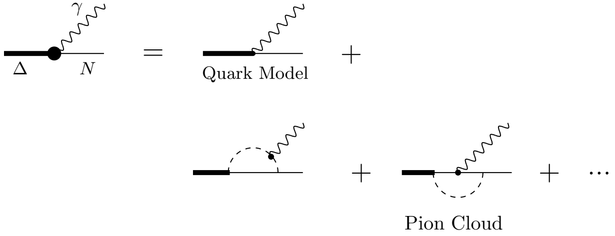
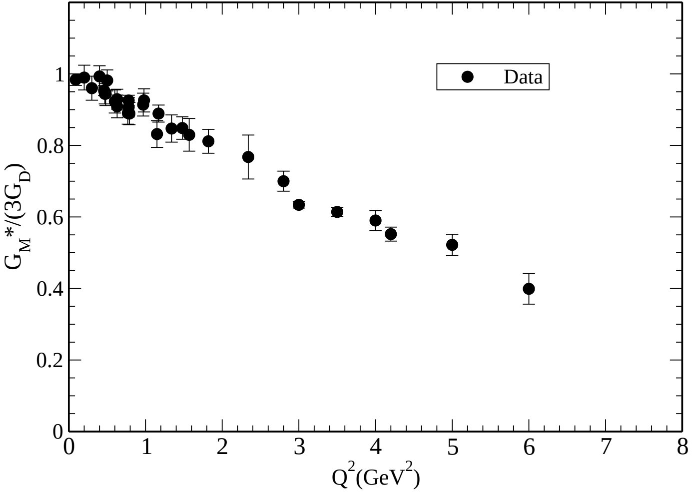
  Characteristic of Constituent Quark models
- $G_M^* = G_M^{Bare} + G_M^{\pi}$



- Quark Model $\Rightarrow G_M^{Bare}$ Dynamical Model $\Rightarrow G_M^{\pi}$ (Sato-Lee & DMT)

NΔ transition: G_M^* (Bare + Total)



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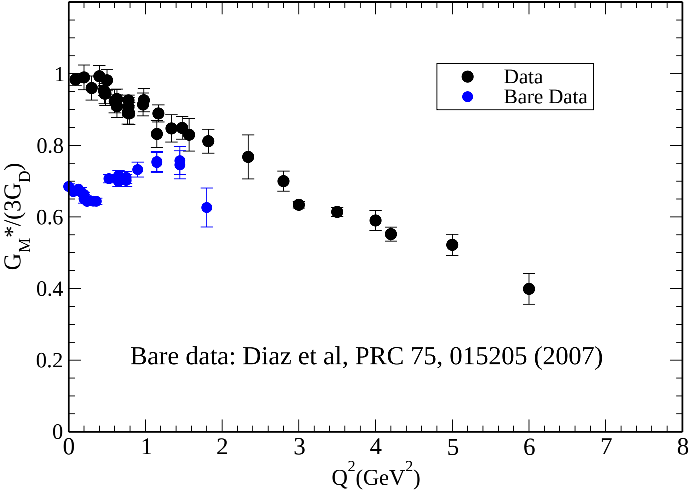
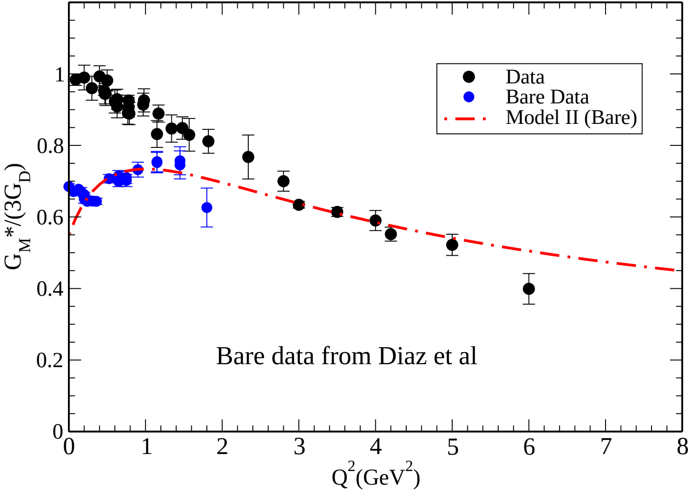
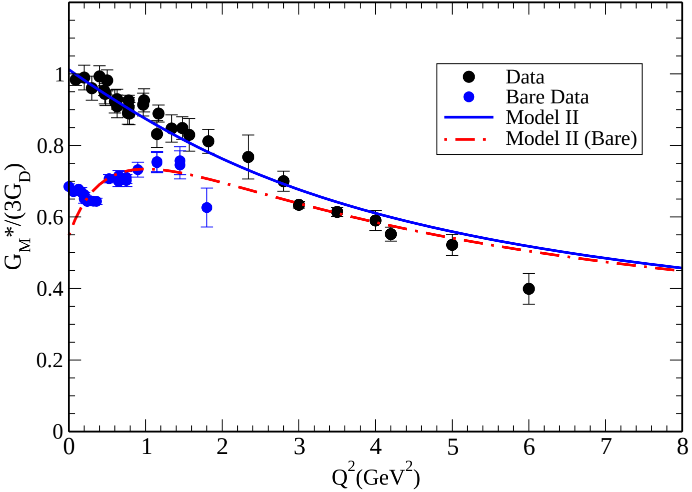


NΔ transition: G_M^* (Bare predictions)



NΔ transition: G_M^* (Full predictions)



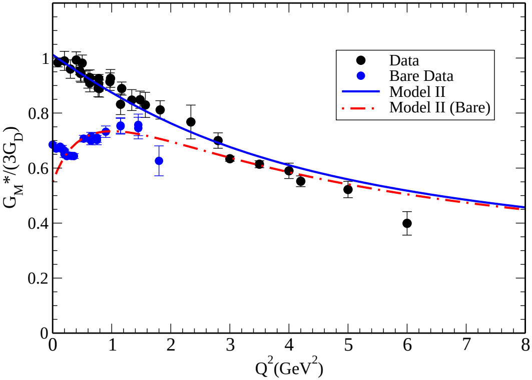
NΔ transition: S-state (Valence + Pion cloud)

- Valence Quarks (Bare): G_M^B set the scale

$$\psi_\Delta = \frac{N_\Delta}{(\alpha_1 + (P-k)^2)(\alpha_2 + (P-k)^2)^2}$$

- Sea quarks (Pion Cloud):

$$\frac{G_M^\pi}{3G_D} = \lambda_\pi \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 + Q^2} \right)^2$$



NΔ transition: High Angular Momentum States

Core spin= quark spin + diquark spin

$$\mathcal{S} = S_q + S_{dq} \Longrightarrow \begin{cases} V^{\alpha}_{1/2}(P, \lambda_s) \\ \\ V^{\alpha}_{3/2}(P, \lambda_s) \end{cases}$$

$$V^{\alpha}_{S}(P, \lambda_s) \equiv \sum_{\lambda} \langle \frac{1}{2}\lambda; 1\lambda' | S \lambda_s \rangle \varepsilon^{\alpha}_{\lambda' P} u_B(P, \lambda) \qquad \text{[S-states]}$$

Total angular momentum ($J = 3/2$):

$$J = L + \mathcal{S} \Longrightarrow \begin{cases} S & (0, \frac{3}{2}) \\ \\ D3 & (2, \frac{3}{2}) \\ \\ D1 & (2, \frac{1}{2}) \end{cases}$$

$N\Delta$ transition: D-states ($L = 2$)

D-state operator:

$$\mathcal{D}^{\alpha\beta} = \tilde{k}^\alpha \tilde{k}^\beta - \frac{\tilde{k}^2}{3}\left(g^{\alpha\beta} - \frac{P^\alpha P^\beta}{M_B^2}\right)$$

$$\approx Y_2^m \text{ (Rest frame)}$$

Core-spin projectors

$$\mathcal{P}_{1/2}^{\alpha\beta} + \mathcal{P}_{3/2}^{\alpha\beta} = g^{\alpha\beta} - \frac{P^\alpha P^\beta}{M_B^2} \xrightarrow{NR} -\delta^{ij}$$

[M. Benmerrouche et al PRC 39, 2339 (1989)]

D-state:

$$W_D^\alpha = \mathcal{D}^\alpha_\beta(P,k) V^\beta_{3/2}(P) \longleftarrow \text{S-state}$$

$$= \underbrace{(\mathcal{P}_{1/2})^\alpha_\beta {W_D}^\beta}_{D1-state} + \underbrace{(\mathcal{P}_{3/2})^\alpha_\beta {W_D}^\beta}_{D3-state}$$

NΔ transition: States vs Form Factors

Simple current

$$J^\mu = 3j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \gamma^\mu \Psi_N + 3j_2 \sum_\lambda \int_k \bar{\Psi}_\Delta \frac{i\sigma^{\mu\nu} q_\nu}{2M} \Psi_N$$

Modified current

$$J_R^\mu = 3j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) \Psi_N + 3j_2 \sum_\lambda \int_k \bar{\Psi}_\Delta \frac{i\sigma^{\mu\nu} q_\nu}{2M} \Psi_N$$

Equivalent prescriptions if $\sum_\lambda \int_k \bar{\Psi}_\Delta \Psi_N = 0 \quad (\text{all } Q^2)$

[orthogonal states]

Discuss S, D3 and D1 states

NΔ transition: States S and D3

States $(0,\frac{3}{2})$ and $(2,\frac{3}{2})$ are orthogonal to $(0,\frac{1}{2}) \equiv N$

Current:

$$J^\mu = 3j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \gamma^\mu \Psi_N + 3j_2 \sum_\lambda \int_k \bar{\Psi}_\Delta \frac{i\sigma^{\mu\nu} q_\nu}{2M} \Psi_N$$

Using the Dirac equation: [orthogonality]

$$q_\mu J^\mu = 3j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \not{q} \Psi_N = 3(M_\Delta - M) j_1 \underbrace{\sum_\lambda \int_k \bar{\Psi}_\Delta \Psi_N}_{=0}$$

Current conserved

It can also be shown that

$$q_\mu J^\mu \; \alpha \; G_C^*(Q^2)$$

Conclusion: S and D3 states $\Rightarrow G_C^* = 0$

State $(2, \frac{1}{2})$ is not orthogonal to $(0, \frac{1}{2})$

In principle:

$$q_\mu J^\mu = 3(M_\Delta - M) j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \Psi_N \neq 0.$$

There is a chance that $G_C^* \neq 0$; but $q_\mu J^\mu \neq 0$

Imposing current conservation

$$J_R^\mu = 3 j_1 \sum_\lambda \int_k \bar{\Psi}_\Delta \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) \Psi_N + 3 j_2 \sum_\lambda \int_k \bar{\Psi}_\Delta \frac{i\sigma^{\mu\nu} q_\nu}{2M} \Psi_N$$

$$q_\mu J_R^\mu = 0, \qquad G_C^* \; \alpha \; \frac{1}{Q^2} \sum_\lambda \int_k \bar{\Psi}_\Delta \Psi_N$$

To avoid divergence as $Q^2 \to 0$:

$$\sum_\lambda \int_k \bar{\Psi}_\Delta \Psi_N \sim Q^2 \qquad \text{[Orthogonality]}$$

Adding all angular momentum components:

Configuration: (L, S)

$$\Psi_N \to \Psi_\Delta \begin{cases} S & (0, \frac{3}{2}) & \to & G_M^* \\ D3 & (2, \frac{3}{2}) & \to & G_M^*, G_E^* \\ D1 & (2, \frac{1}{2}) & \to & \bar{G}_M^*, \bar{G}_E^*, G_C^* \end{cases}$$

$$\bar{G}_M^*, \bar{G}_E^* = 0 \quad \text{when} \quad Q^2 = 0$$

NΔ transition: S+D3+D1

S-state

$$G_M^S = 4\eta\mathcal{I}_S$$
$$G_E^S = 0$$
$$G_C^S = 0$$

$$\mathcal{I}_S = \int_k \phi_N \phi_S$$

$$\eta = \frac{2}{3\sqrt{3}}\frac{M}{M+M_\Delta} f_v$$

D3-state

$$G_M^{D3} = -2\eta\mathcal{I}_{D3}$$
$$G_E^{D3} = -2\eta\mathcal{I}_{D3}$$
$$G_C^{D3} = 0$$

$$\mathcal{I}_{D3} = \int_k b\phi_N \phi_{D3}$$

$$f_v = f_{1-} + \frac{2M}{M+M_\Delta} f_{2-}$$

D1-state

$$\mathbf{G_M^{D1}} = \eta\mathcal{I}_{\mathbf{D1}}$$
$$\mathbf{G_E^{D1}} = -\eta\mathcal{I}_{\mathbf{D1}}$$
$$\mathbf{G_C^{D1}} = \frac{4MM_\Delta}{\sqrt{3}} f_C \frac{\mathcal{I}_{\mathbf{D1}}}{Q^2}$$

$$\mathcal{I}_{\mathbf{D1}} = \int_{\mathbf{k}} \mathbf{b}\phi_{\mathbf{N}}\phi_{\mathbf{D1}}$$

$$b \approx \sqrt{\frac{4\pi}{5}}\mathbf{k}^2 Y_2^0(\hat{k})$$

$$f_C = f_{1-} - \frac{Q^2}{2M(M+M_\Delta)} f_{2-}$$

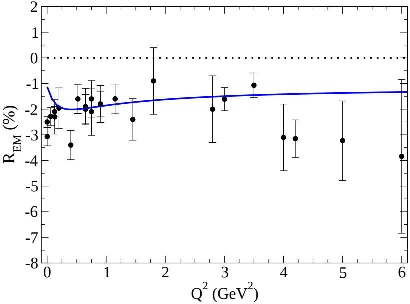
Orthogonality between Nucleon (S-state) and Δ D1 state:

$$\mathcal{I}_{D1} \sim Q^2 \text{ as } Q^2 \to 0$$

NΔ transition (S+D3+D1): Valence Quark + ...

Data from MAMI, LEGS, MIT-Bates and Jlab

$$R_{EM} = -\frac{G_E^*(Q^2)}{G_M^*(Q^2)}, \qquad R_{SM} = -\frac{|\mathbf{q}|_\Delta}{2M_\Delta}\frac{G_C^*(Q^2)}{G_M^*(Q^2)}$$



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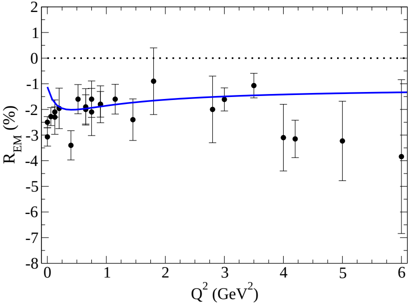

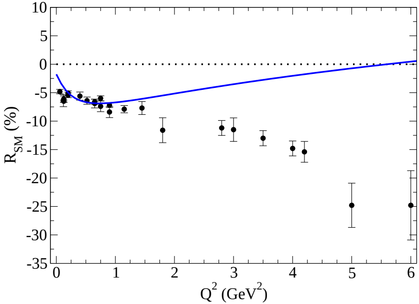

Valence Quark insufficient to explain G_C^* data

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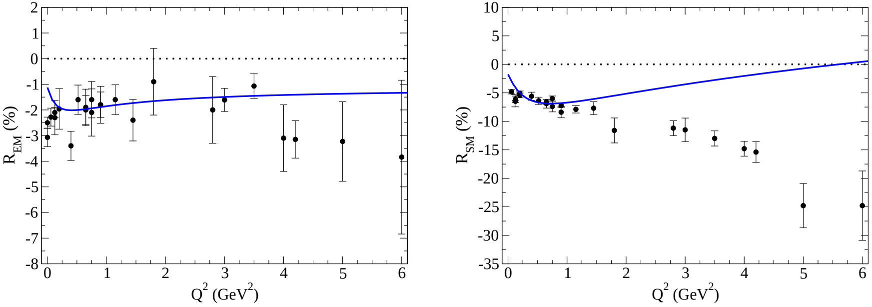


Valence Quark insufficient to explain G_C^* data

⇒ Include Sea Quark effects [Pion Cloud]

Pion Cloud effects in G_E^* and G_C^* ?

Large N_c limit, low Q^2:

$$G_C^\pi(Q^2) = \sqrt{\frac{2M}{M_\Delta}} M M_\Delta \frac{G_{En}(Q^2)}{Q^2}$$

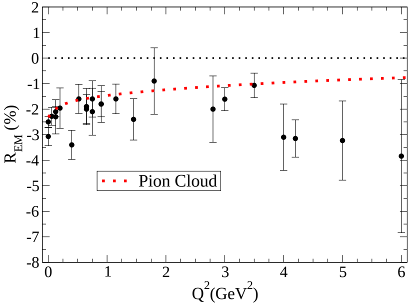
$$G_E^\pi(Q^2) = \left(\frac{M}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M^2}{2\sqrt{2}} \frac{G_{En}(Q^2)}{Q^2}$$

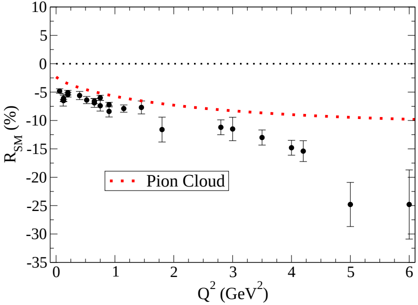
[Buchmann et al; Pascalutsa and Vanderhaeghen]

No adjustable parameters

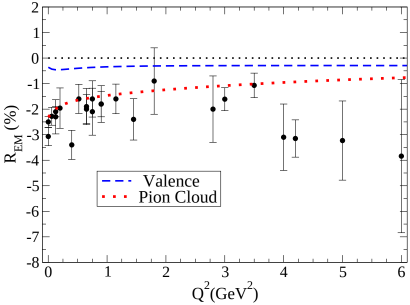
Nucleon: Pion Cloud $\Rightarrow G_{En} \neq 0$
$N\Delta$: $G_C^*, G_E^* \; \alpha \; G_{En}$: represents Pion Cloud

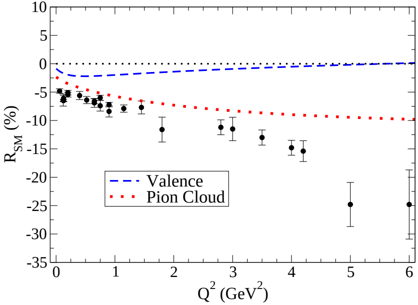
NΔ transition (S+D3+D1): Pion Cloud



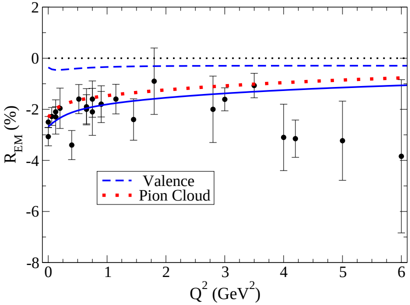


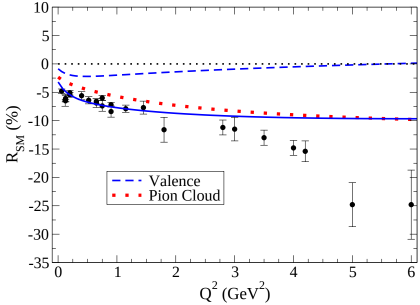
NΔ transition (S+D3+D1): Valence Quarks



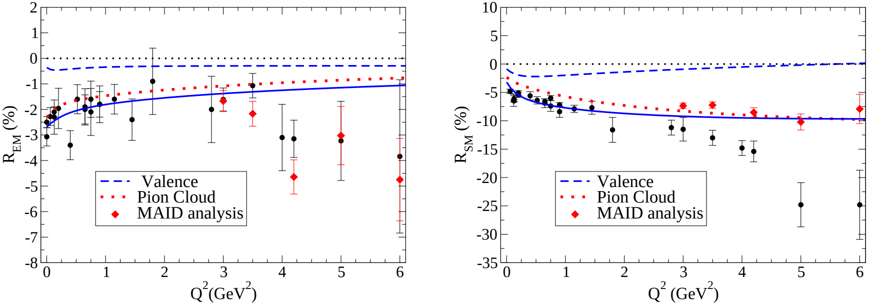


NΔ transition (S+D3+D1): Valence Q + Pion Cloud





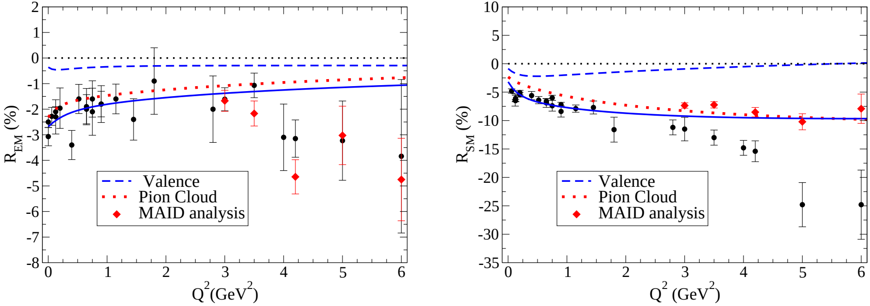
NΔ transition (S+D3+D1): Valence Q + Pion Cloud (2)



Model consistent with MAID analysis of CLAS data (Jlab)
Drechsel *et. al.*, EPJA 34, 69 (2007)

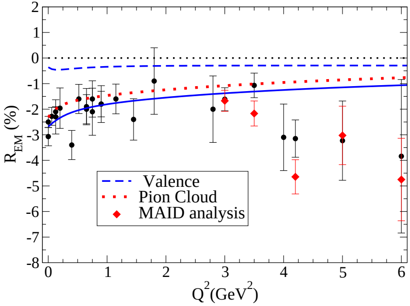
NΔ transition (S+D3+D1): Valence Q + Pion Cloud

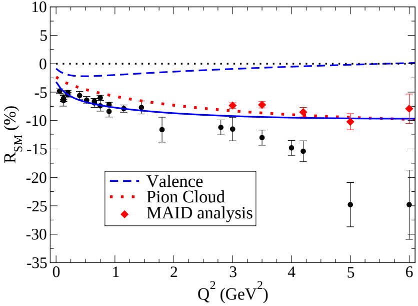
- Pion cloud dominant



NΔ transition (S+D3+D1): Valence Q + Pion Cloud

- Pion cloud dominant
- Small D-state mixture improves the description of the data (1% D3-state; 4% D1-state)





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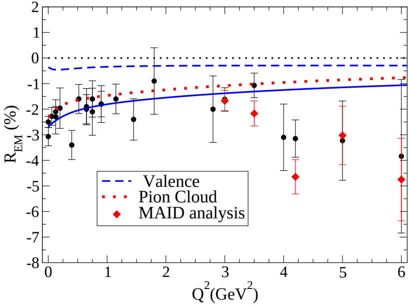
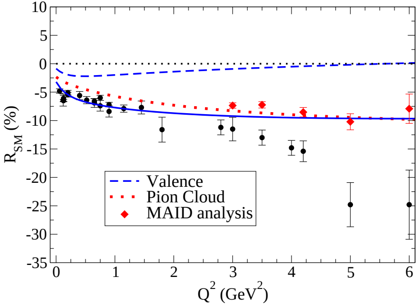
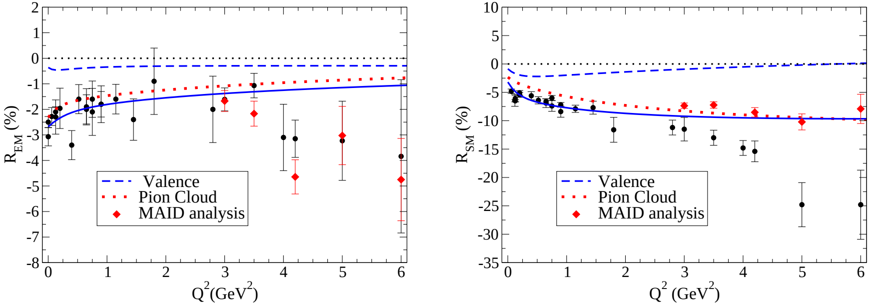




Limitations ?

NΔ transition (S+D3+D1): Pion Cloud parametrization

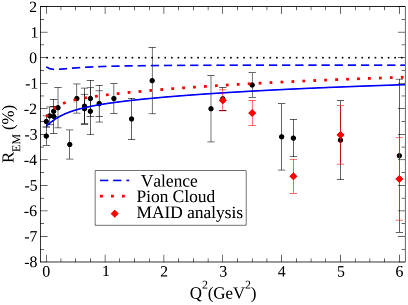
Does it make any sense to use
the pion cloud parametrization for $Q^2 \sim 3$ GeV^2 ?

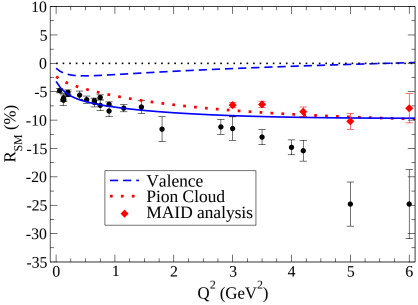


Conclusion:
We need to consider consistent description of the pion cloud

NΔ transition (S+D3+D1): Valence parametrization

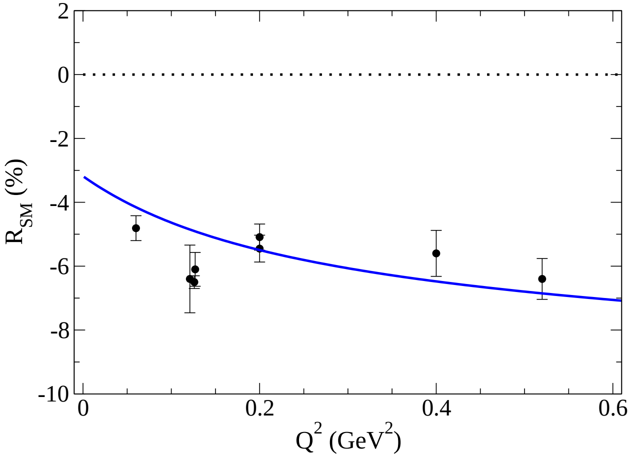
Is the valence quark model appropriated (for G_C^*) ?





The answer depends of the contribution of the pion cloud
But... valence QM calibrated by the data
Can we trust in the data ?

Is the Data consistent at low Q^2 ?



NΔ transition: Data analysis (low Q^2)

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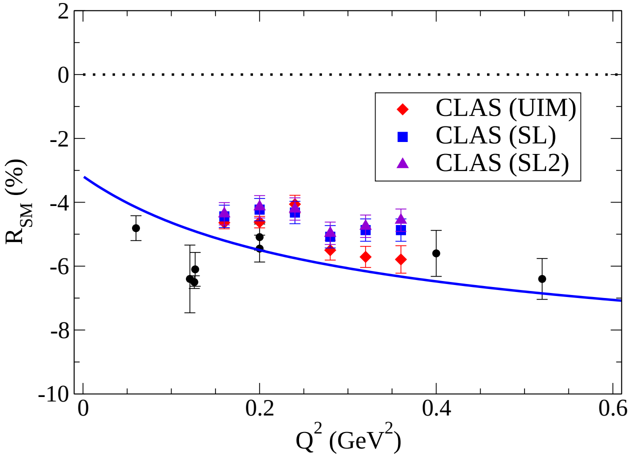
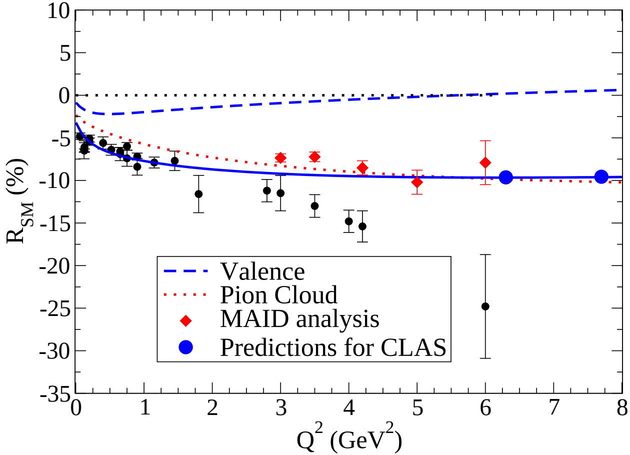


NΔ transition: Data analysis (high Q^2)

It is important to know the Q^2 dependence of the data for high Q^2



NΔ transition: comparing QM with DM

- Quark models
  - Consistent (correct normalization)
  - Incomplete (no pion cloud)

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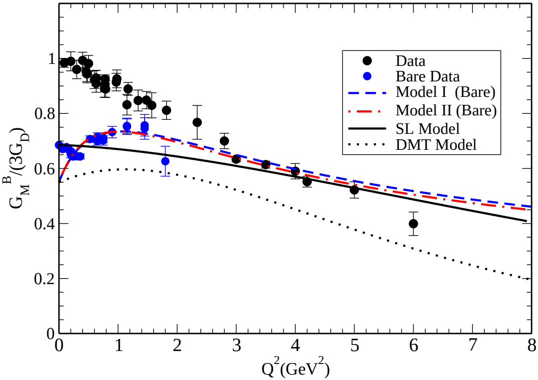

G_M^B dominates over G_M^π $\Rightarrow$ QM should be used as input

Conclusions

- Covariant spectator S-state wave functions for N and Δ
  - Explains Nucleon data
  - Main contribution of NΔ ($\sim$ 60% of G_M^*)
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