Electromagnetic form factors of the Nucleon and the Delta

MTP and Gilberto Ramalho, CFTP

Franz Gross, JLAB

Delta

1 Has main role in Nπ scattering and NN interaction

2 Led to the introduction of the quantum number color

3 Still largely unknown (e.g. electric radius?)

It is unstable $\tau \sim 10^{-24}$ s

Δ^{++} μ [3.7,7.5]μ_N PDB

Δ^{+} [$2.7_{-1.0}^{+1.3} \pm 1.5 \pm 3.0$]μ_N M. Kotulla et. al PRL 89, 27, 2002

4 LQCD (quenched and unquenched) **gives unique information Alexandrou et al., Boinepalli et al.**

Study of Baryon Structure

Tool: Electromagnetic probing

“For everything that exists there are 3 instruments by which the knowledge of it is necessarily imparted (...)

The first is the name, the second the definition, the third the image.” ***Plato, Epistle VII***

Form Factors

Nucleon

$$J^\mu = \bar{u}(P_+)\Gamma^\mu(P,q)u(P_-)$$

2: $G_{E0}(Q^2)$ $G_{M1}(Q2)$

Nucleon-Delta

$$J^\mu = \bar{w}_\alpha(P_+)\Gamma^{\alpha\mu}(P,q)u(P_-)$$

3: $G^*_{M1}(Q2)$ $G^*_{E2}(Q^2)$

$G^*_{C2}(Q2)$

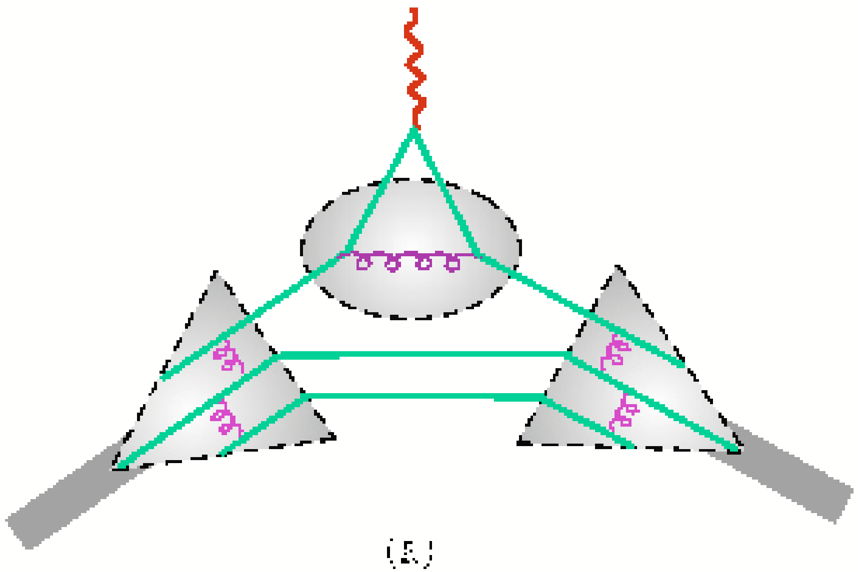
Delta

$$J^\mu = \bar{w}_\alpha(P_+)\Gamma^{\alpha\beta\mu}(P,q)w(P_-)_\beta(P_+)$$

4: $G_{E0}(Q^2)$ $G_{M1}(Q2)$

$G_{E2}(Q2)$ $G_{M3}(Q2)$

PRC77 015202 (2008); PRD78 114017(2008); JPG36 085004 (2009)

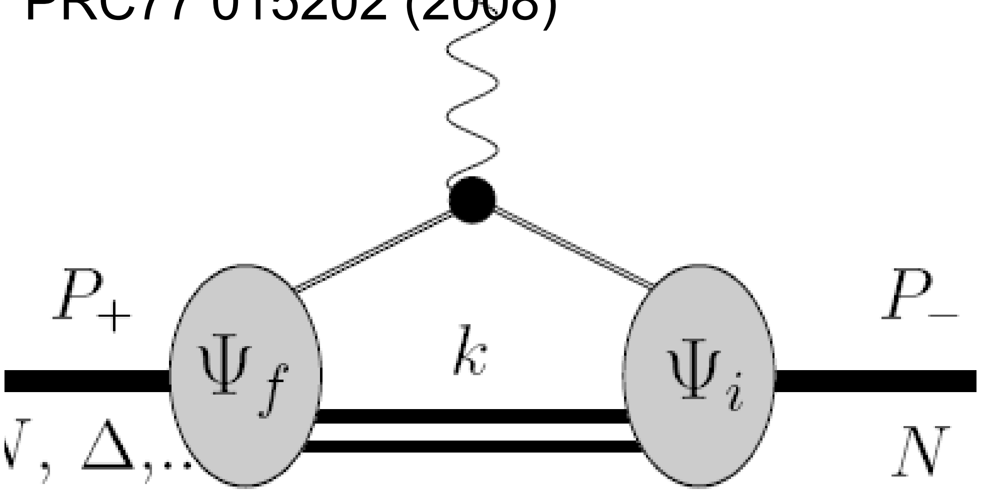


Constituent Quark Model view

- Quark dressed by gluons and $q\bar{q}$ interactions
- Gluon interactions between $q\bar{q}$ $\Rightarrow$ quark form factors
- Quarks with anomalous moments κ_u, κ_d

Spectator Quark Model

PRC77 015202 (2008)



diquark on-mass-shell

Hadronic current

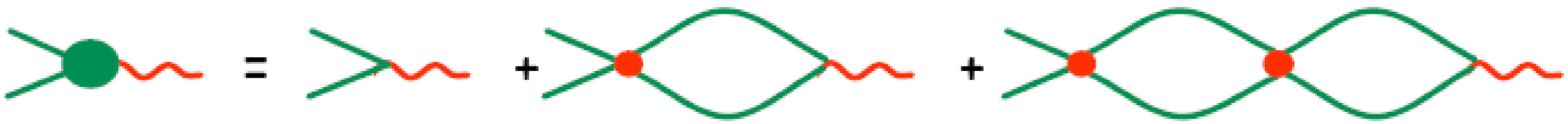
$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+, k) j_I^\mu \Psi_i(P_-, k)$$

Quark current

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

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

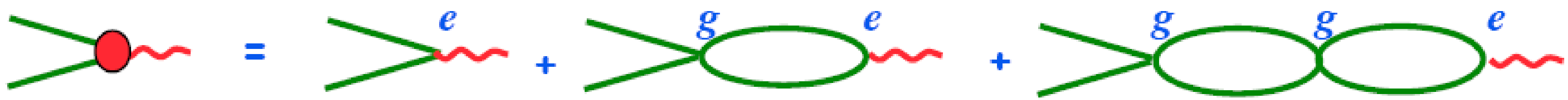
Vector Meson Dominance quark ff



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

3-4 parameter to adjust

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



$$f_{1\pm}(Q^2) = \lambda + \frac{(1-\lambda)}{1+Q_0^2/m_v^2} + \frac{c_\pm Q_0^2/M_h^2}{(1+Q_0^2/M_h^2)^2}$$

$$f_{2\pm}(Q^2) = \kappa_\pm \left\{ \frac{d_\pm}{1+Q_0^2/m_v^2} + \frac{(1-d_\pm)}{1+Q_0^2/M_h^2} \right\}$$

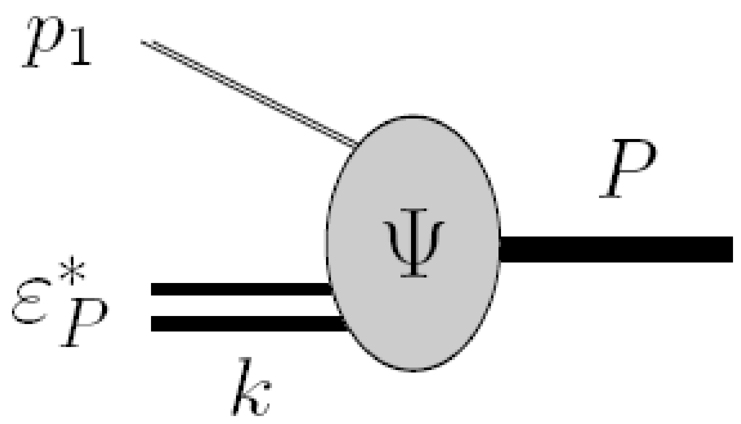
Low-energy behavior encodes high-energy behavior:

Scale enters in the problem!

DIS used to fixed λ and diquark mass

m_s=0.87m_n (see talk Diana Nicmorus)

Baryon = quark $\oplus$ diquark



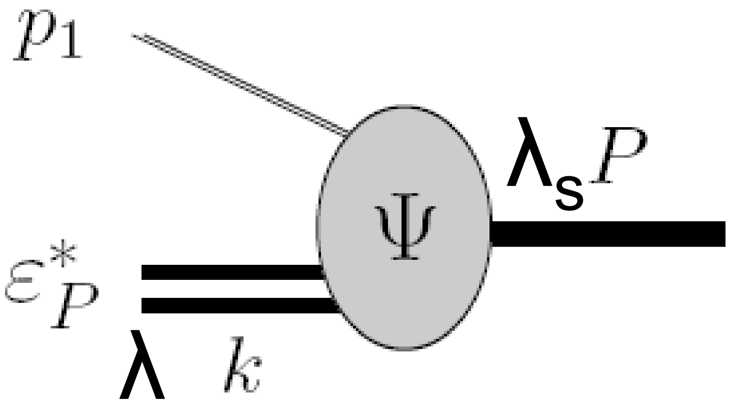
$$\Psi(P,k) = (m_q - \not{p}_1)^{-1} \langle k|\,\Gamma\,|P\rangle$$

Confinement: No pole contribution

$\langle k|\,\Gamma\,|P\rangle$ **develops a zero** symmetries

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

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

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 (S+ D states)

Adding all angular momentum components:

Configuration: (L, S)

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

Pining down deformation

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

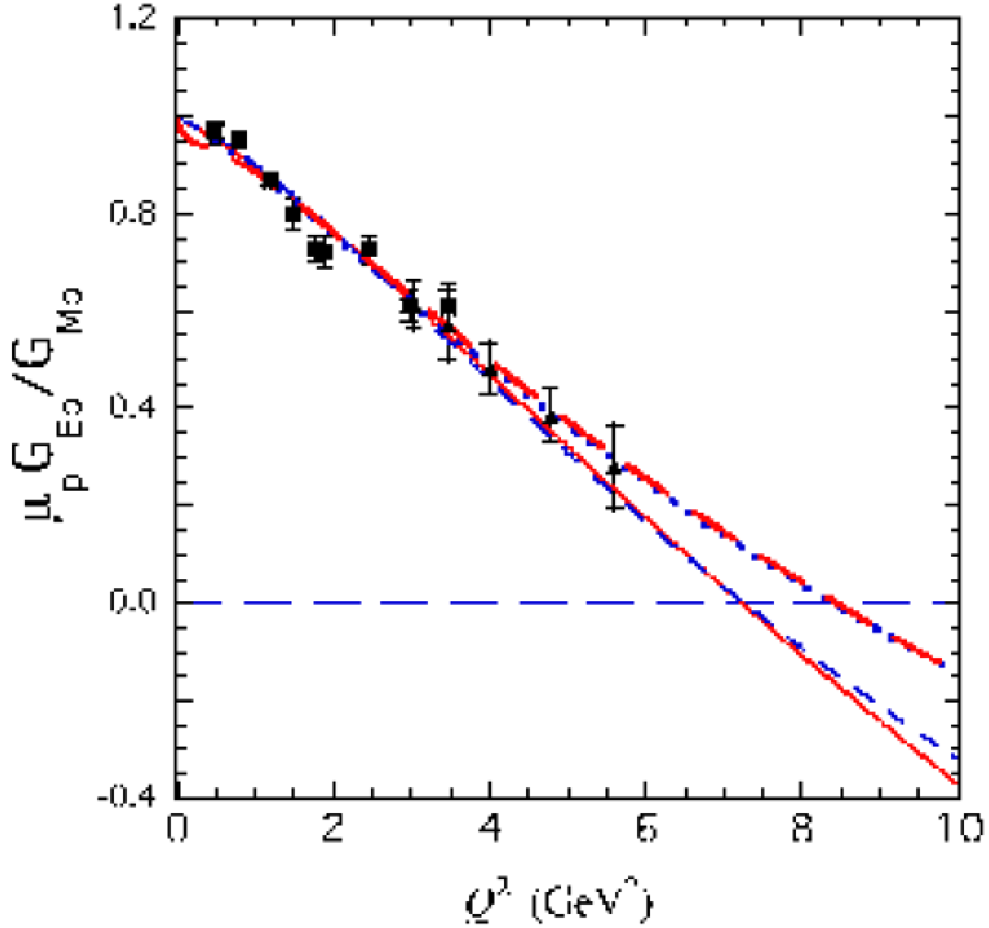
Spec 1

Pining down deformation in the Delta

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

Pining down deformation

How **small** **are** a and b?



Charge extends to a larger region than magnetism

Is this due to distorted shape?

5 parameters, χ^2= 1.36

Data

VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

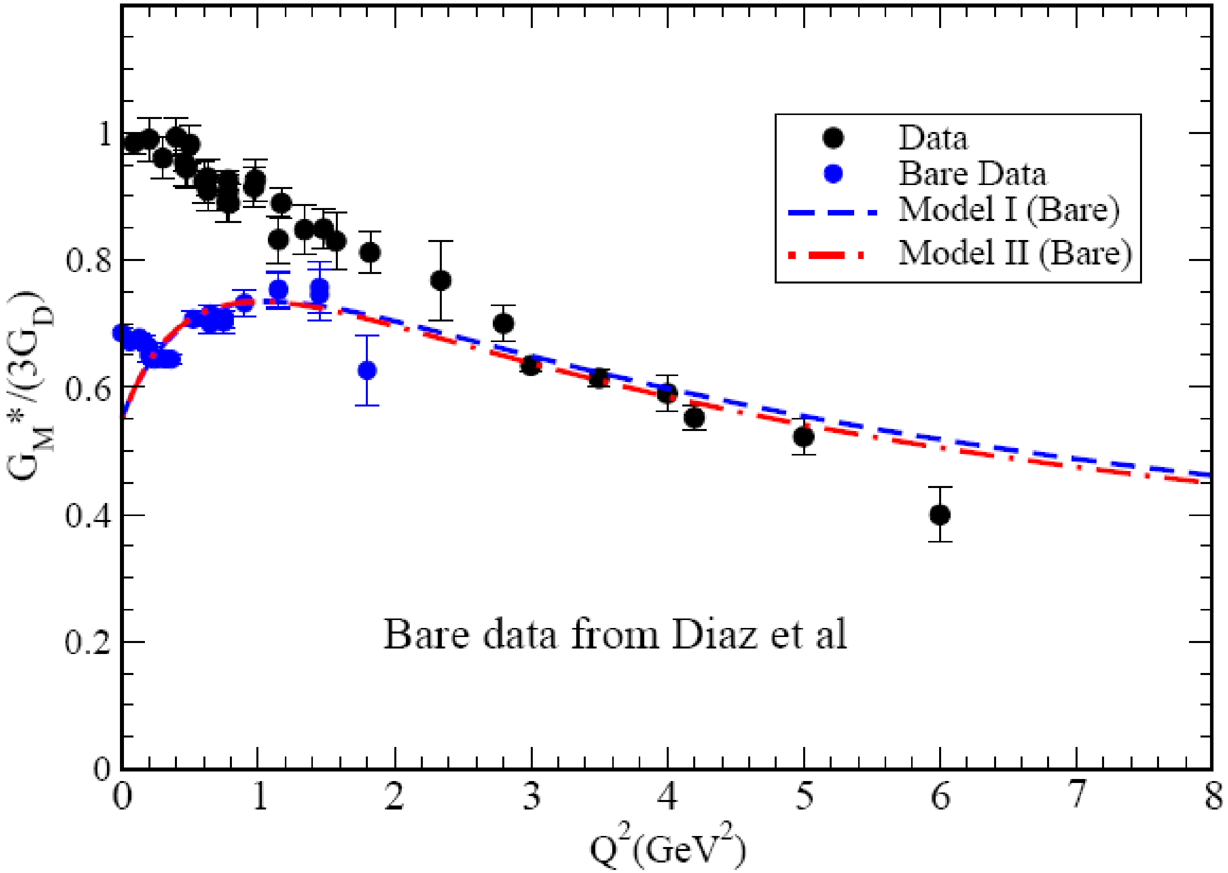
Measurement of G_{E_p}/G_{M_p} in $\vec{e}p \rightarrow e\vec{p}$ to $Q^2 = 5.6$ GeV^2

NDelta transition mixes quark and explicit pion degrees of freedom

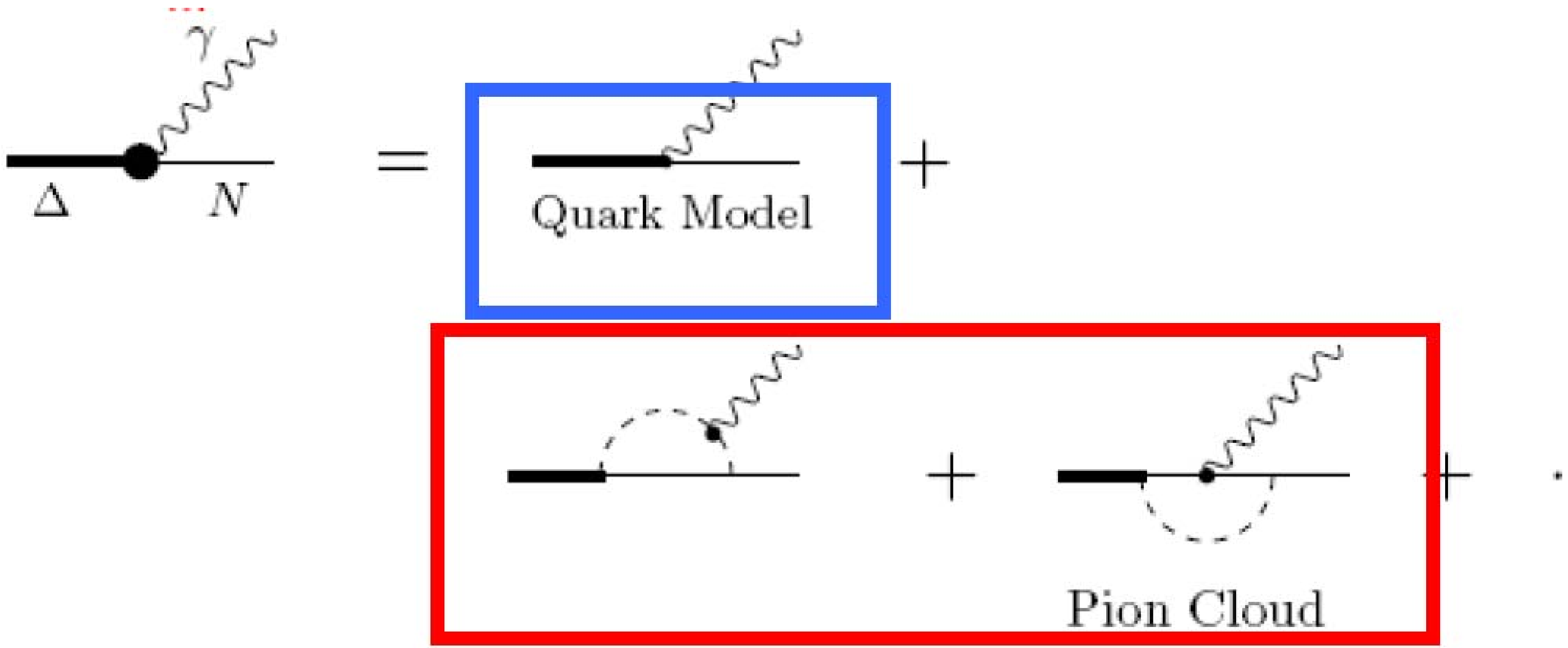
Diaz et al PRC75 015205 2007

N-Δ transition: G_M^* form factor -Bare results

EPJ A 36 329 2008



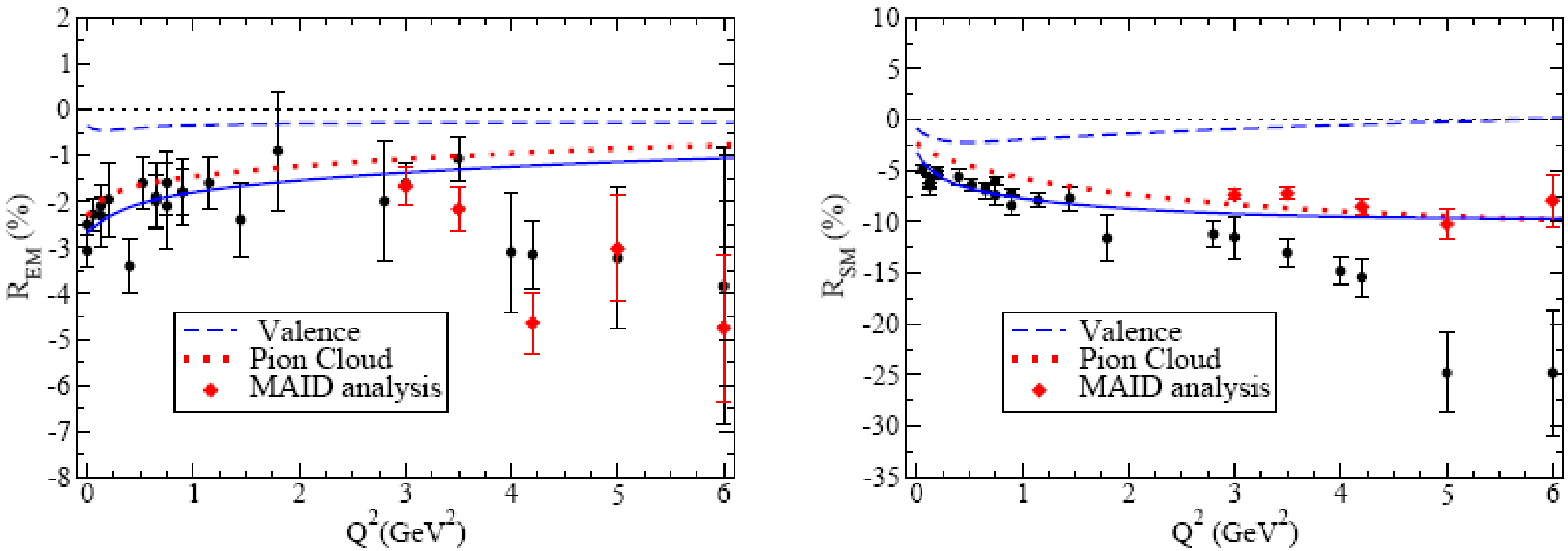
$$G = G_B + G_\pi$$



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

D3 1% and D1 4% of the wavefunction

PRD78 114017(2008)



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

Can one do better?

Spec 2

Finer information on D-states from LQCD NDelta data

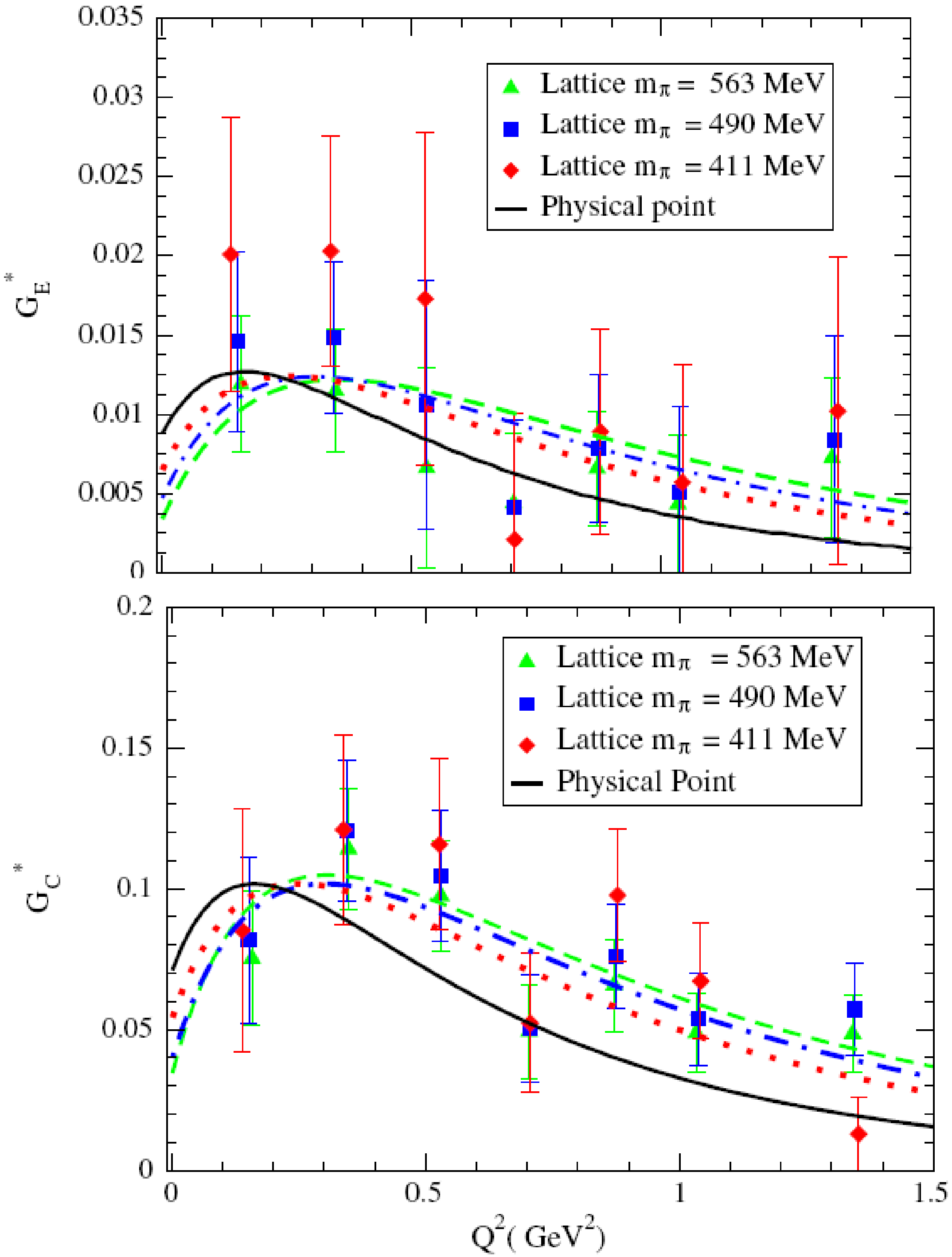
PRD80 013008 (2009)

Constraining

the D-states

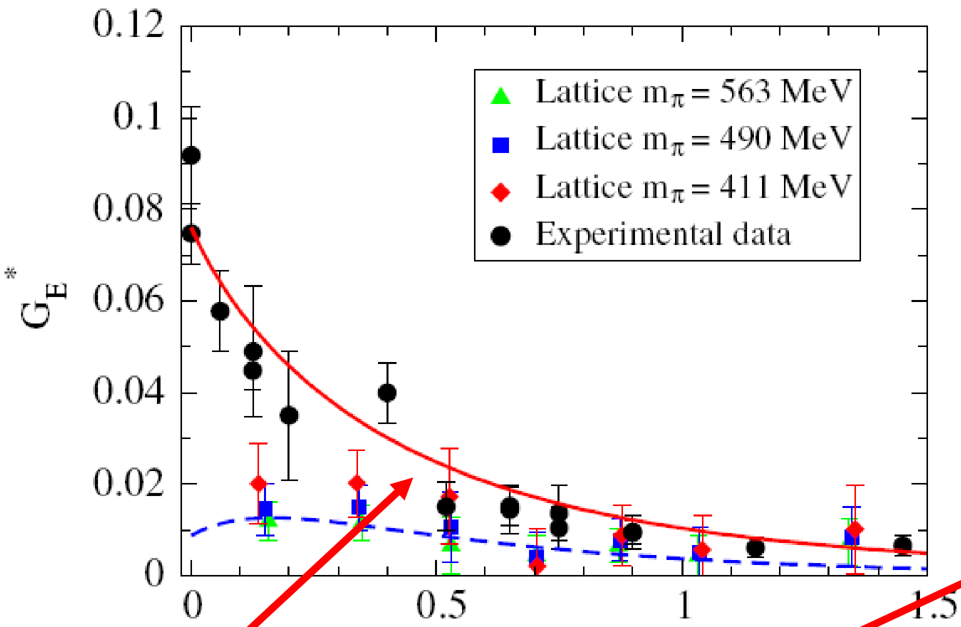
by the lattice data

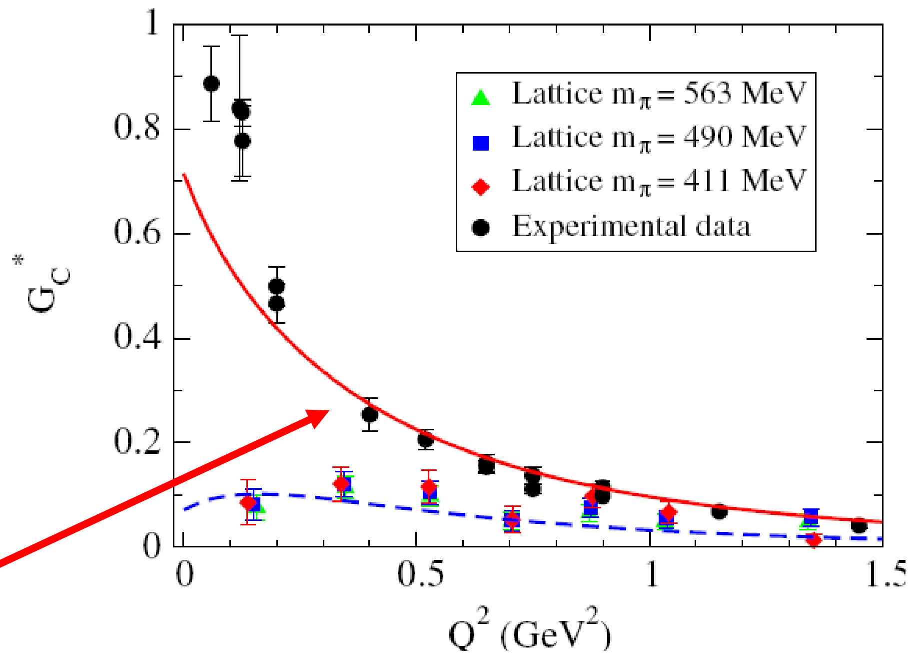
PRD80 013008 (2009)



NDelta

D3 0.72% and D1 0.72 % of the wavefunction





+ pion cloud

Large N_C limit

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

PRD80 013008 (2009)

$$G_C^\pi(Q^2) = \sqrt{\frac{2m_N}{m_\Delta}} m_N m_\Delta \frac{G_{En}(Q^2)}{Q^2}.$$

Predictions for the Delta

PLB 678 (2009) 355

Delta

a and **b** small

$$G_{E0}(Q^2) = N^2 \tilde{g}_\Delta \mathcal{I}_S$$

$$G_{M1}(Q^2) = N^2 \tilde{f}_\Delta \left[\mathcal{I}_S + \frac{4}{5} a \mathcal{I}_{D3} - \frac{2}{5} b \mathcal{I}_{D1}\right]$$

$$G_{E2}(Q^2) = 3(aN^2)\tilde{g}_\Delta \frac{\mathcal{I}_{D3}}{\tau}$$

$$G_{M3}(Q^2) = \tilde{f}_\Delta N^2 \left[a \frac{\mathcal{I}_{D3}}{\tau} + 2b \frac{\mathcal{I}_{D1}}{\tau}\right]$$

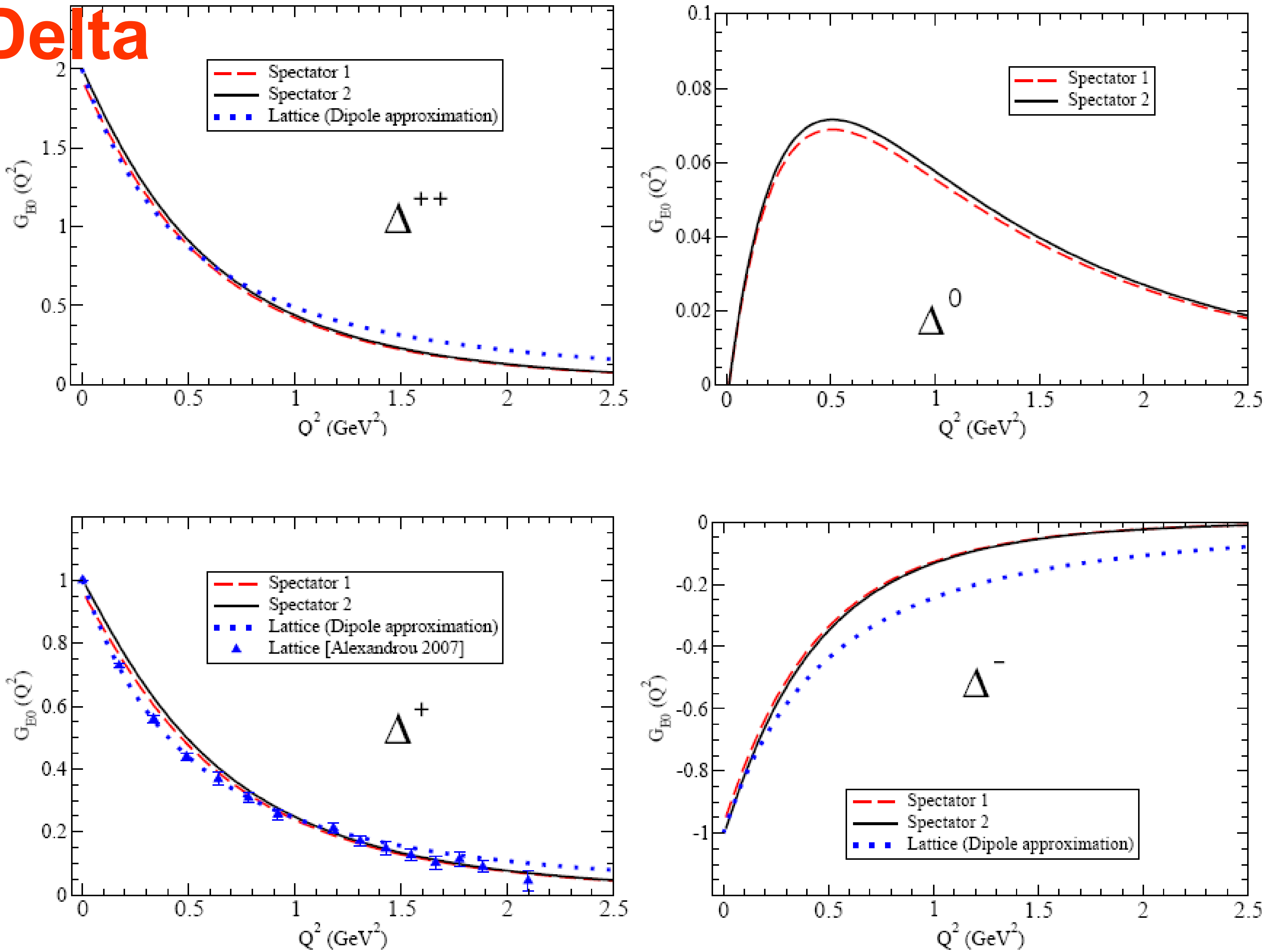
D state corrections

from overlap

Integrals between

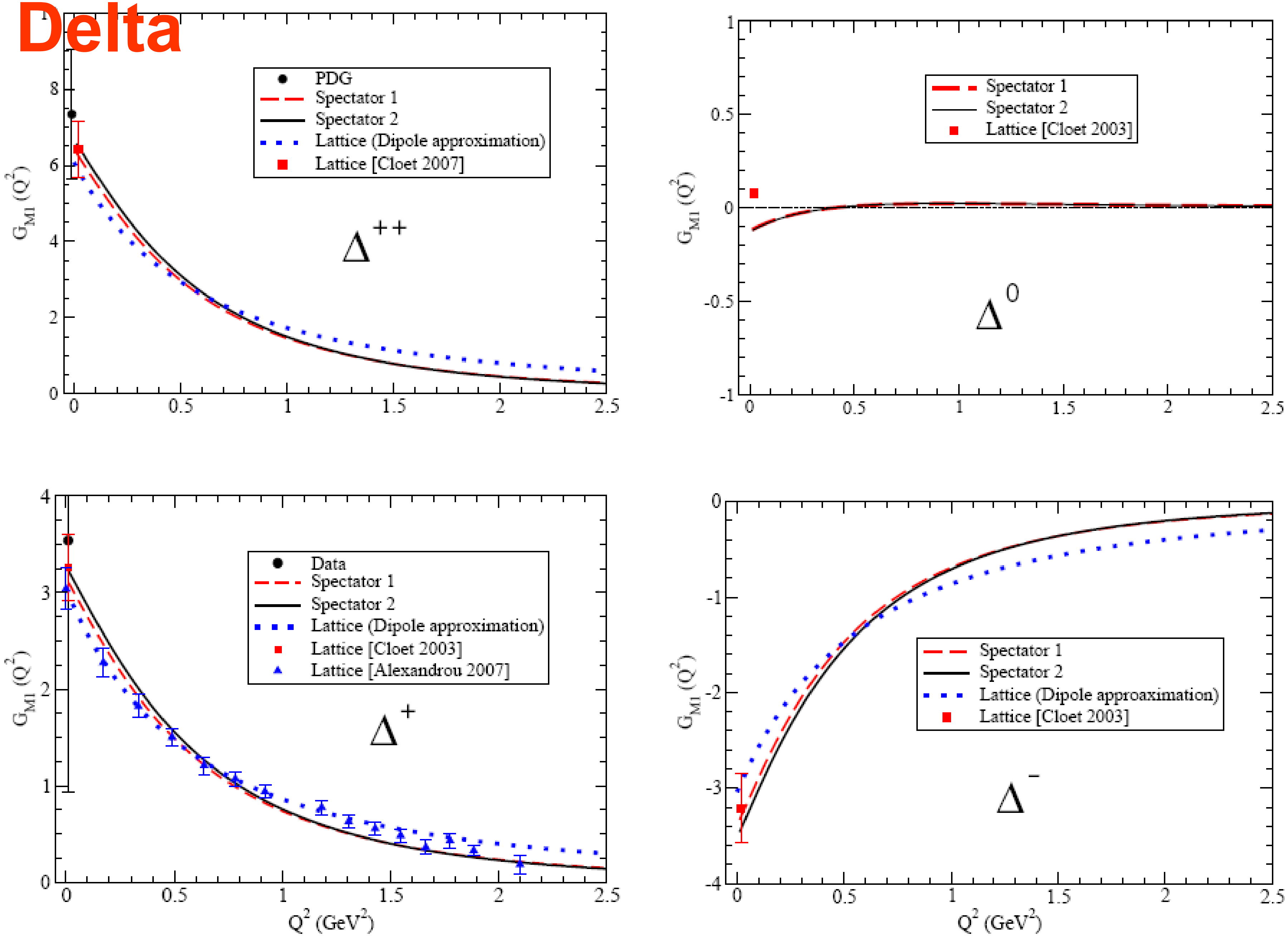
S and D states

Delta



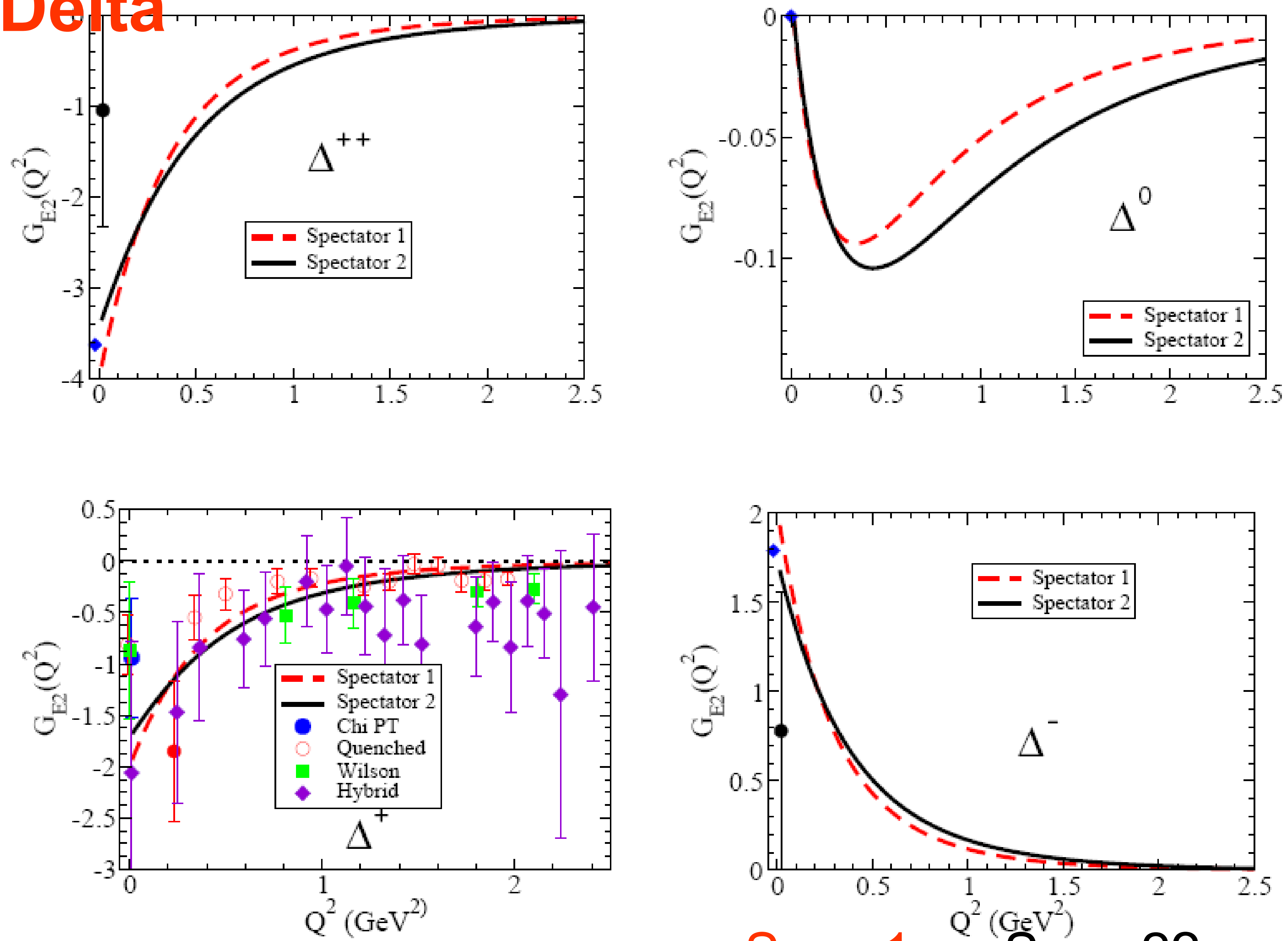
Spec 1 or Spec 2?

Delta



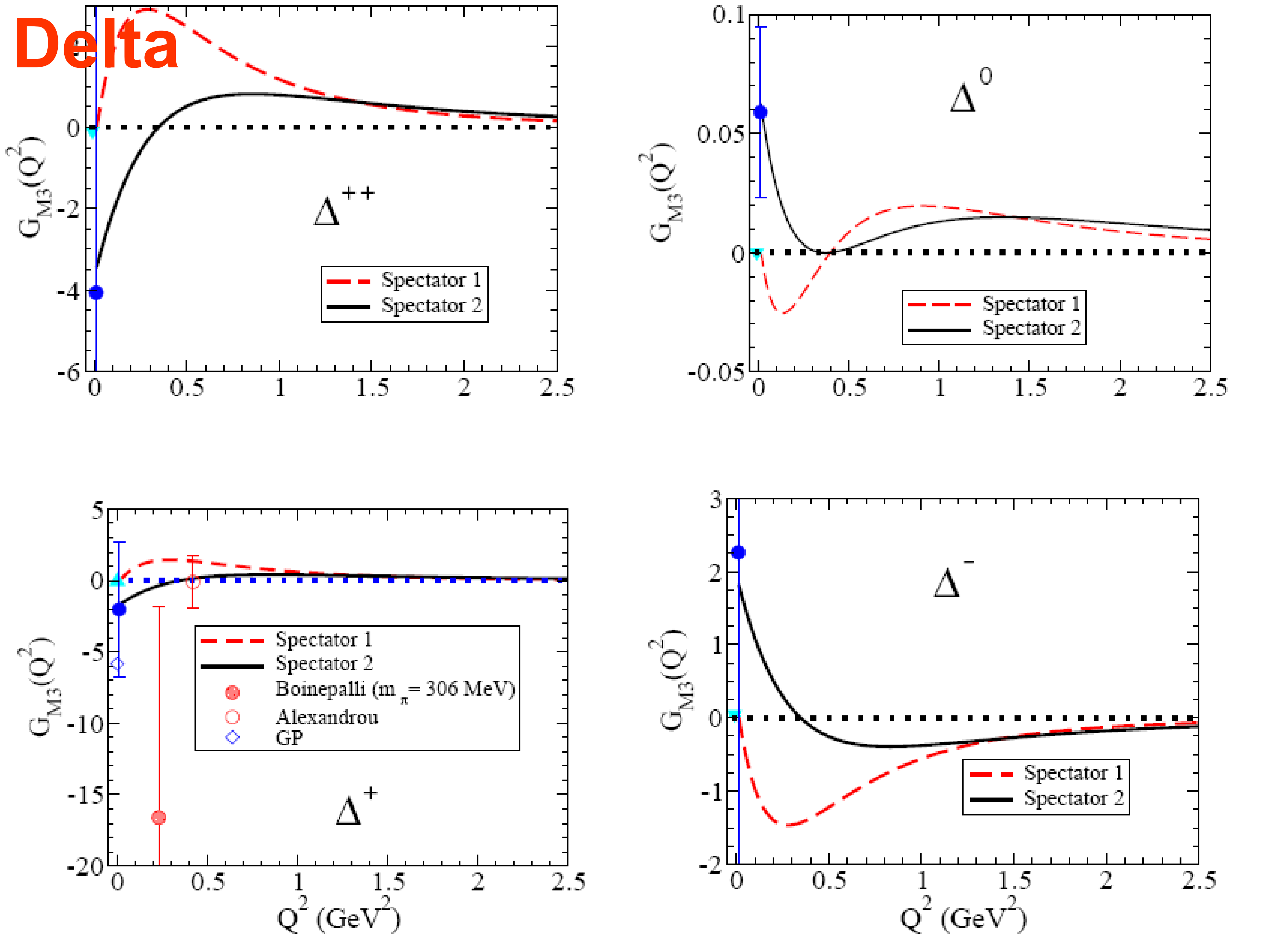
Spec 1 or Spec 2?

Delta



Spec 1 or Spec 2?

Delta



Spec 1 ≠ Spec 2

Summary

To desintangle orbital motion and pion cloud effects: Constituent quark models **better constrained** when extended to the unphysical world of the NDelta **LQCD** calculations.

Predictions for the Delta:

$r^2_{\Delta+}$ =0.3fm^2 $\mu_{\Delta++}$ =5.01μ_N $\mu_{\Delta+}$ =2.45 μ_N

$Q_{\Delta+}$ =-0.043efm^2 $O_{\Delta+}$=-0.0035 efm^3

More LQCD data welcome

1 Good agreement between LQCD and SPec1 Spec2

2 Dominance of S-states for GE0 and GM1

(special good agreement of Spec1,2 with LQCD)

3 Results for **GE2 consistent with unquenched LQCD** data -> Pion cloud important for NDelta but not dominant for Delta

4 Only **GM3 sensitive to D-state** parametrization;

5 Predictions: $Q_{\Delta+}$ =-0.043efm^2 $O_{\Delta+}$=-0.0035 efm^3

More LQCD data welcome.

Redo calculations with consistent introduction of Pion cloud

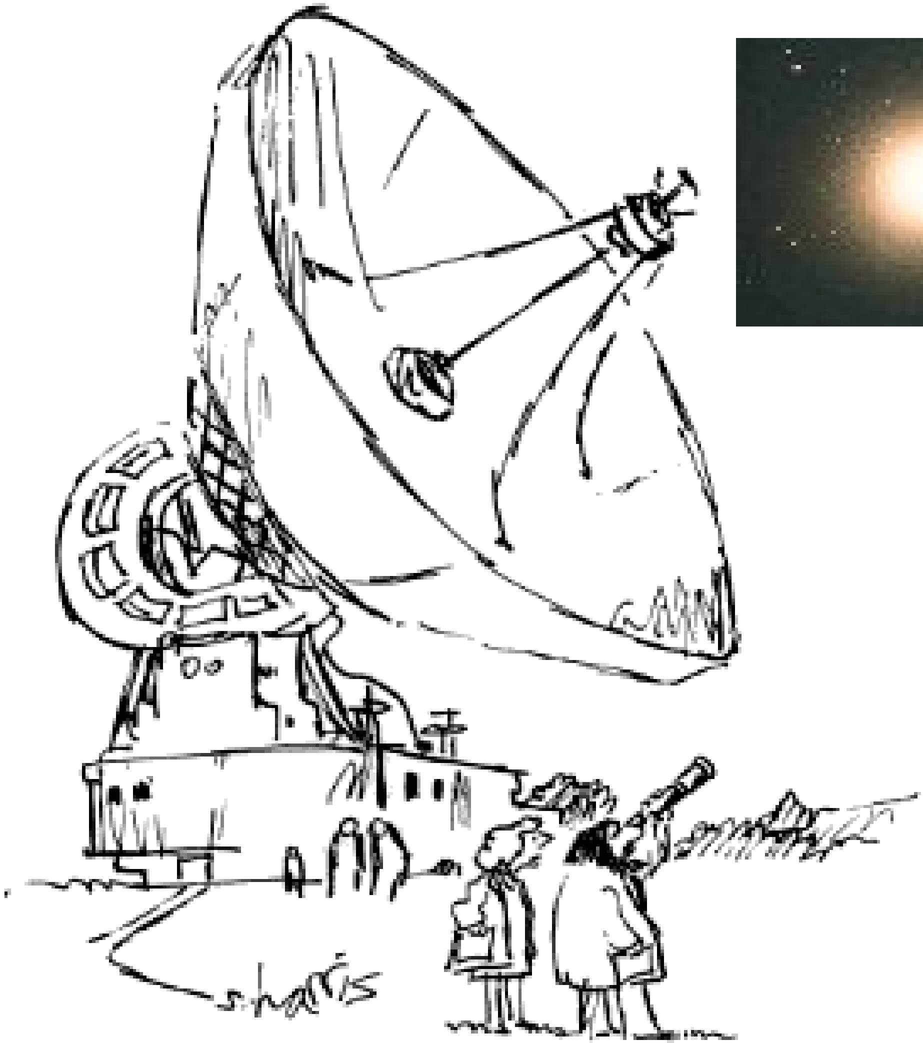
$Q_{\Delta+}$ =-0.043efm^2 $O_{\Delta+}$=-0.0035 efm^3

Oblate charge and magnetic distributions?

Oblate, accordingly to “classical” definition

Open issue:

Discussion in progress



"Just checking."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