A Relativistic Model for the Electromagnetic Structure of Baryons from the 3rd Resonance Region

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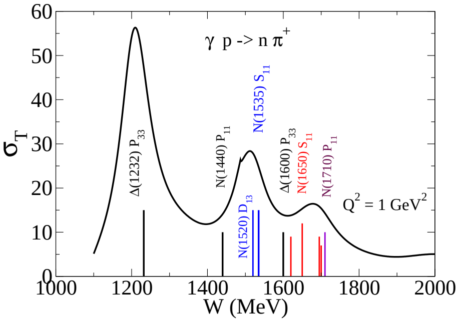
GR and K Tsushima, PRD 89, 073010 (2014); GR, PRD 90, 033010 (2014)

Collaborators: F. Gross (Jlab), M.T. Peña (Lisbon) and K. Tsushima (UCS/São Paulo)

Nucleon Resonances: From Photoproduction to
High Photon Virtualities
ECT*, Trento, Italy

October 15, 2015

Motivation



γ p -> n π+
Q2 = 1 GeV2
Δ(1232) P33
N(1440) P11
N(1520) D13
N(1535) S11
Δ(1600) P33
N(1650) S11
N(1710) P11
σT
W (MeV)
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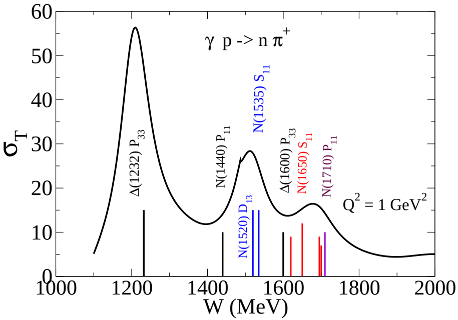

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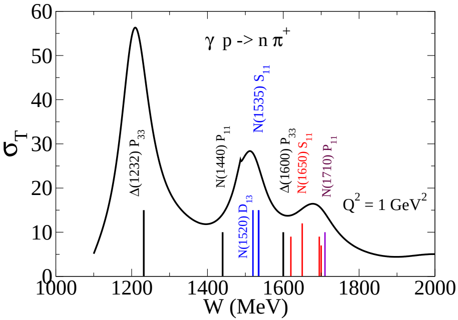

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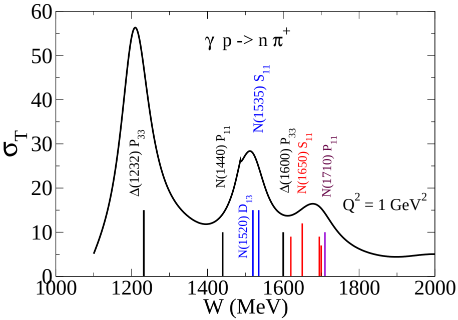

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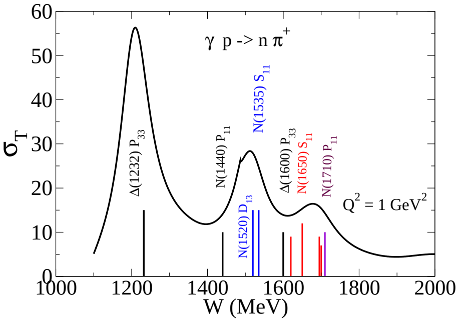

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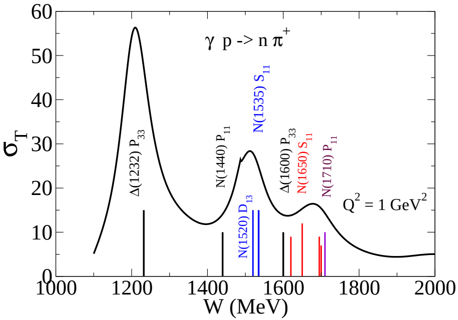

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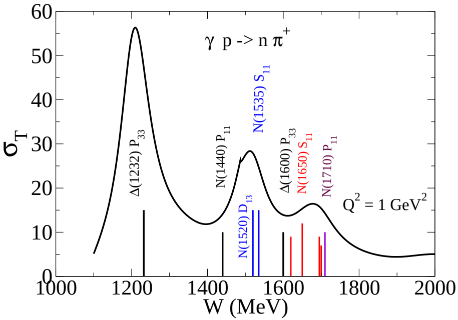

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- **Challenges:**
  - Interpret the data (theory/models)
  - Provide predictions (higher Q^2, higher W) **Jlab-12 GeV–upgrade**
- Improve description of the **3rd resonance region** & Extend calculations for higher Q^2

Plan of the talk

- **Study of $\gamma^* N \to N^*$ reactions**
- **Covariant Spectator Quark Model**
  Wave functions, quark current, transition current
- **Predictions for the** $N(1710)$ (2nd radial excitation of the nucleon)
- **Results for** $N(1535)$**,**$N(1520)$ ($S11$ and $D13$)
- **Single Quark Transition Model**
  Simple relation between the helicity transition amplitudes
  of the same $SU(6)$ supermultiplet
- **Application**:
  Input: amplitudes for the $N(1520)\frac{3}{2}^-$ and $N(1535)\frac{1}{2}^-$
  Output: amplitudes for $N(1650), N(1700), \Delta(1620), \Delta(1700)$

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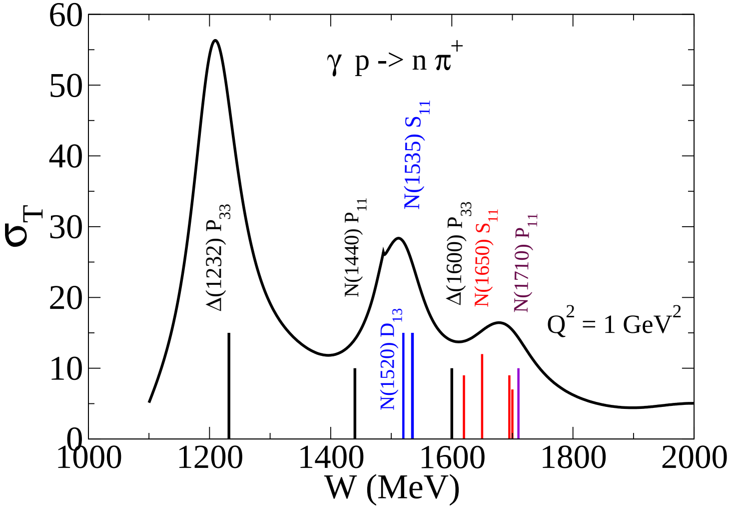
May fails for small Q^2 – meson cloud effects

SQTM has $SU_F(2)$; CSQM breaks $SU_F(2)$ $\Rightarrow$ **react. proton targets**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Methods

Methods to study the $\gamma^* N \to N^*$ reactions

- **QCD** (only practical at high Q^2)
- **Lattice QCD** (large m_π, euclidean space ...)
- **(Effective) Chiral Perturbation Theory**
  (baryons and mesons and degrees of freedom)
  small energy and momentum
- **Baryon-Meson coupled channel reaction models**
- **Dyson-Schwinger** (non-perturbative; quarks and gluons, euclidean)
- **Constituent quark models** and **chiral quark models**
  quarks with structure, quark-quark interaction
- **Covariant Spectator Quark Model** (Minkowski)
  Wave function determined phenomenologically (no dynamical eq.)
  Parametrization of the wave function by FF (M_B not predicted)

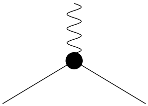
Covariant Spectator Quark Model – Applications †

F Gross, GR, MT Peña, K Tsushima, ...

Int. J. Mod. Phys. E **22**, 1330015 (2013)– (pages 89-92); arXiv:1008.0371 [hep-ph]

- Nucleon and Δ electromagnetic form factors
  PRC 77, 015202 (2008); PLB 678, 355 (2009); PLB 690, 183 (2010); JPG 36, 085004 (2009); PRD 86, 093022 (2012)
- Electromagnetic transition form factors $\gamma^* N \to N^*$
  $N^* = \Delta(1232), N^*(1440), N^*(1520), N^*(1535), \Delta(1600), N^*(1710), ...$
  EPJA 36, 329 (2008); PRD 78, 114017 (2008); PRD 82, 073007 (2010); PRD 81, 074020 (2010); PRD 84, 051301 (2011); PRD 89, 073010 (2014)
- Octet baryon and decuplet baryon e.m. form factors:
  physical regime, nuclear medium and **extension to lattice QCD**
  PRD, 033004 80 (2009); JPG 36, 115011 (2009); PRD 80, 013008 (2009); PRD 83, 054011 (2011); PRD 84, 054014 (2011); PRD 87, 093011 (2013); JPG 40, 015102 (2013)
- $\Delta(1232)$ mass distribution for the Dalitz decay: $\Delta \to N e^+ e^-$ $(pp \to e^+ e^- pp)$
  PRD 85, 113014 (2012) Timelike regime
- Nucleon – Deep Inelastic Scattering – PRC 77, 015202 (2008); PRD 85 093006 (2012)

Covariant Spectator Quark Model – Introduction



- Quarks with electromagnetic structure (**impulse approximation**)

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

  form factors $f_{i\pm}$ parametrized according with vector meson dominance
  simulate structure associated with $q\bar{q}$ and gluon dressing

- Use QM symmetries to represent the structure of the wave functions
- Shape (radial structure) determined phenomenologically
  by experimental data or lattice data of some ground state systems
- constraints from valence quark d.o.f. $\Rightarrow$ **Calibrate model**
- **Make predictions** for $\gamma^* N \to N^*$ form factors/helicity amplitudes

Spectator QM: Transition currents

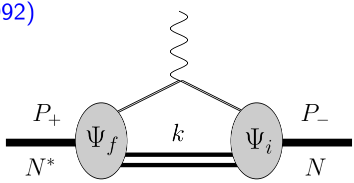
Quark current j_q^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

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

Relativistic impulse approximation:

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



integrate spectator q

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

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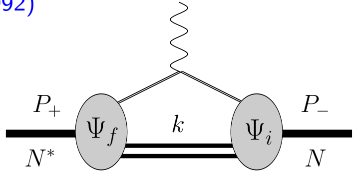

diquark on-shell

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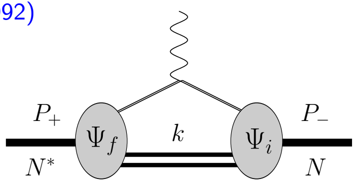

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If $q \cdot J \neq 0$: Landau prescription: $J^\mu \to J^\mu - \frac{q\cdot J}{q^2} q^\mu$

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

Spectator QM: Baryon wave functions (1)

- Baryon: 3 constituent quark system

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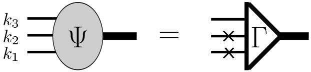
- Covariant Spectator Theory: wave function Ψ defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks



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

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

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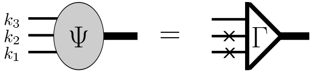

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- Ψ is **free** of singularities ($3q$ on-shell $\Gamma \equiv 0$) $\Rightarrow$ parametrize Ψ

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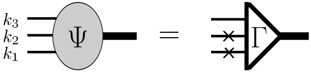

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- On-shell integration $(k_1, k_2) \Rightarrow$ $k = k_1 + k_2$, $r = \frac{1}{2}(k_1 - k_2)$
  $\Rightarrow$ integration in $\mathbf{k}$ and $s = (k_1 + k_2)^2$

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

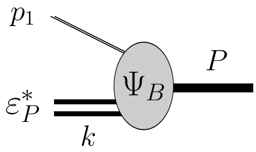
$$\int_{k_1}\int_{k_2} = \frac{\pi}{4}\int d\Omega_{\hat{\mathbf{r}}} \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s-4m_q^2}{s}} \int \frac{d^3\mathbf{k}}{2\sqrt{s+\mathbf{k}^2}} \to \int \frac{d^3\mathbf{k}}{2\sqrt{m_D^2+\mathbf{k}^2}}$$

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

Spectator QM: Baryon wave functions (2)

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

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



- Wave function Ψ_B expressed at the rest frame
- **Covariant** generalization of Ψ_B in terms **baryon** properties after *integration* on the diquark internal variables
- Phenomenology included on the quark-diquark radial wave function

$$\psi_N(\chi) = \frac{N_0}{m_D(\beta_1 + \chi)(\beta_2 + \chi)}, \qquad \chi = \frac{(M - m_D)^2 - (P-k)^2}{M m_D}$$

β_1, β_2: momentum scale parameters

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

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

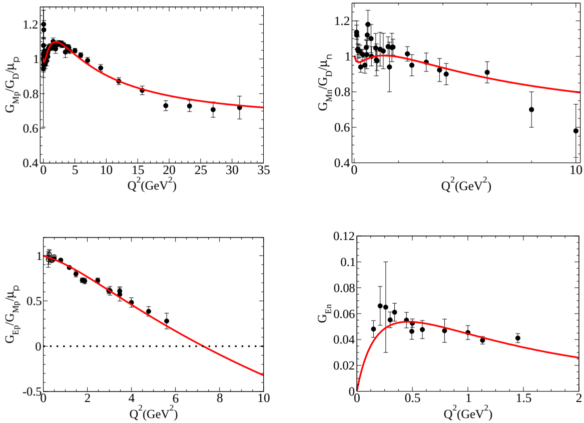
Isospin states: $\Phi_I^{0,1}$
Spin states: defined in terms of Nucleon-Dirac spinor $u(P)$; diquark polarization vector ε_λ

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

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

$\varepsilon_\lambda = \varepsilon_{\lambda P}$ function of nucleon momentum
F Gross, GR and MT Peña, PRC 77, 035203 (2008)

Nucleon form factors [F Gross, GR and MT Peña, PRC 77, 015202 (2008)]



- Model calibrated by Nucleon form factor data
- Quark current fix 4 parameters; Scalar wave function (2 parameters)
- No pion cloud (explicit);

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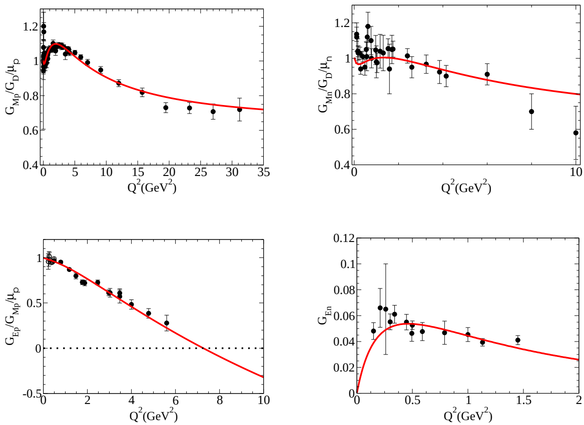


- Model calibrated by Nucleon form factor data
- Quark current fix 4 parameters; Scalar wave function (2 parameters)
- No pion cloud (explicit); can be extended to the lattice QCD regime

GR and MT Peña, JPG 36, 115011 (2009); PRD 80 (2009) 013008; GR, K Tsushima and AW Thomas, JPG 40 015102 (2013)

$\gamma^* N \to R$, $R =$ radial excitation of the nucleon

- $N0 =$Nucleon
  $N1 = N(1440) \equiv$ Roper, 1st radial excitation
  $N2 = N(1710) \approx$ 2nd radial excitation
  Same spin and isospin structure as the nucleon
- States distinguished by radial wave function:
  ψ_{N0}, ψ_{N1}, ψ_{N2} (and masses)
- Orthogonality given at $Q^2 = 0$ by

$$\int_k \psi_{N1}\psi_{N0} = 0, \quad \int_k \psi_{N2}\psi_{N0} = 0, \quad \int_k \psi_{N2}\psi_{N1} = 0,$$

- $\Rightarrow$ Define ψ_{N1}, ψ_{N2}, from ψ_{N0}
  with the same short-range structure: $\psi_{Nj} \propto \frac{1}{\beta_2 + \chi}$
- No adjustable parameters $\longrightarrow$ predictions

GR and K Tsushima, PRD 81, 074020 (2010); PRD 89 073010 (2014)

$\gamma^* N \to R$, $R =$ radial excitation of the nucleon (2)

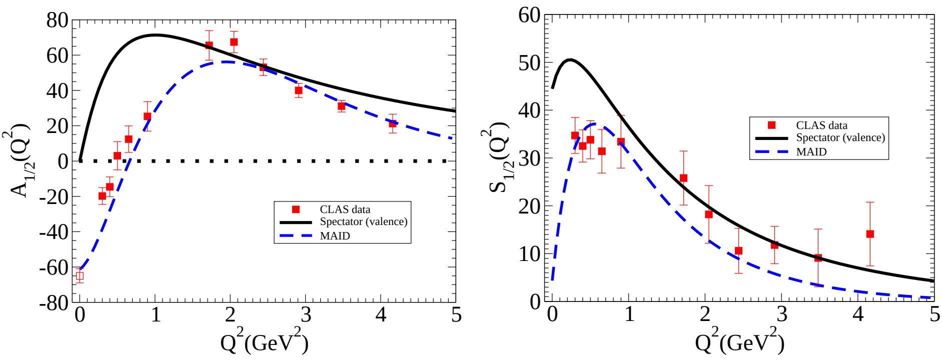
Radial wave functions $\beta_2 > \beta_1$ (β_2 – short range)

$$\psi_{N0}(\chi_{N0}) = N_0 \times \frac{1}{m_D(\beta_1 + \chi_N)(\beta_2 + \chi_N)}$$

$$\psi_{N1}(\chi_{N1}) = N_1 \frac{\beta_3 - \chi_{N1}}{\beta_1 + \chi_{N1}} \times \frac{1}{m_D(\beta_1 + \chi_{N1})(\beta_2 + \chi_{N1})}$$

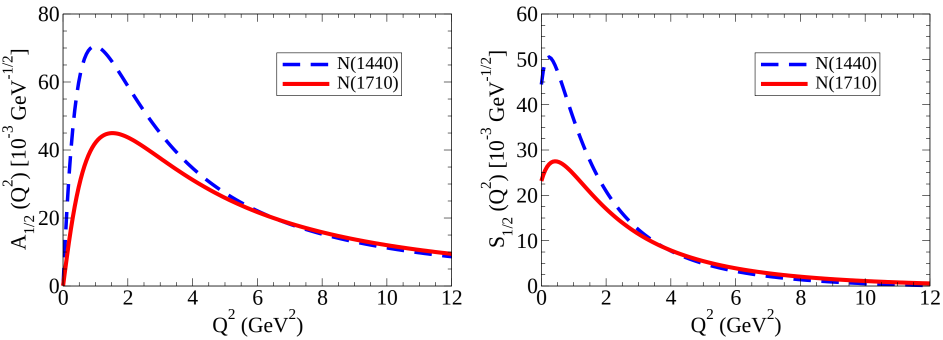
$$\psi_{N2}(\chi_{N2}) = N_2 \frac{\chi_{N2}^2 - \beta_4 \chi_{N2} + \beta_5}{(\beta_1 + \chi_{N2})^2} \times \frac{1}{m_D(\beta_1 + \chi_{N2})(\beta_2 + \chi_{N2})}$$

$\beta_3, \beta_4, \beta_5 \Leftarrow$ Orthogonality conditions

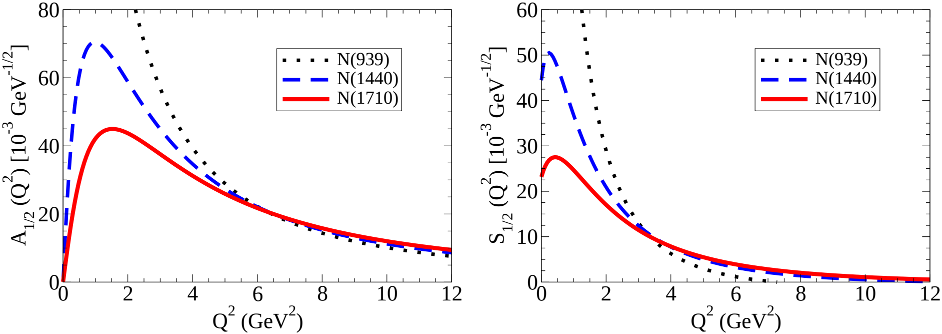


- CLAS data - Aznauryan et al PRC 80, 055203 (2009), MAID fit
- Good agreement for $Q^2 > 1.5$ GeV^2
- Difference for $Q^2 < 1.5$ GeV^2 –manifestation of meson cloud
- Good description also of lattice data Valence q d.o.f.

$\gamma^* N \to N(1710)$: Helicity amplitudes [PRD 89 073010 (2014)] (1)



- Prediction of $N(1710)$ compared with Roper amplitudes
- **Results similar with Roper for $Q^2 > 4$ GeV^2**
  Same short-range structure
- Low Q^2: no prediction – dominance of meson cloud

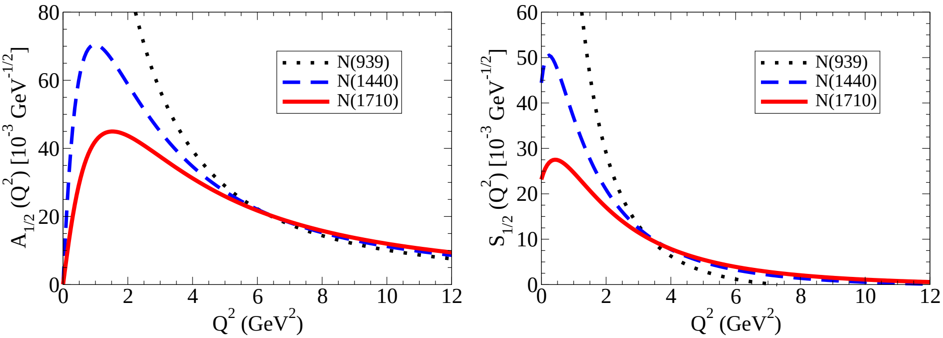


- Compare with nucleon form factors ($\mathcal{R}$- Roper)

  $\mathcal{R} = \frac{e}{2}\sqrt{\frac{(M_R - M)^2 + Q^2}{M_R M K}}$, $K = \frac{M_R^2 - M^2}{2M_R}$, $\tau \to \frac{Q^2}{4M^2}$

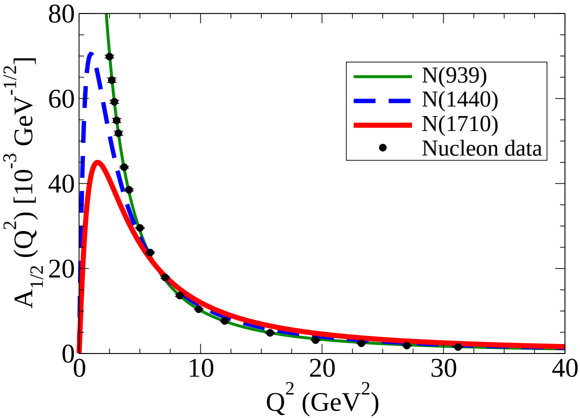
- *Equivalent* amplitudes (extra factor $\sqrt{2}$)

  $A_{1/2} \to \sqrt{2}\mathcal{R} G_M, \qquad S_{1/2} \to \sqrt{2}\frac{\mathcal{R}}{\sqrt{2}}\sqrt{\frac{1+\tau}{\tau}} G_E,$

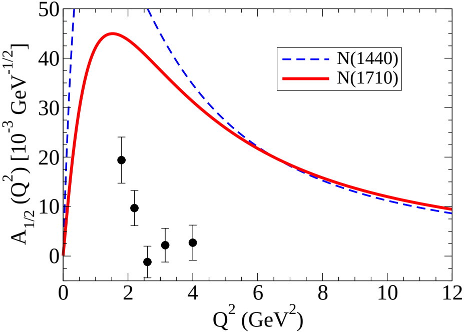


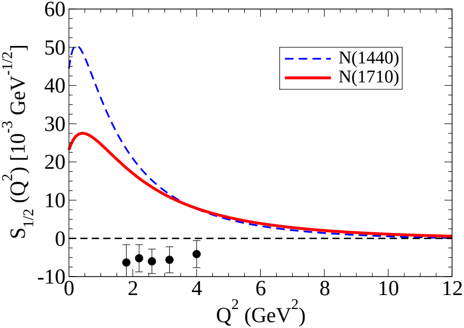
- Compare with nucleon form factors ($\mathcal{R}$- Roper)
  $\mathcal{R} = \frac{e}{2}\sqrt{\frac{(M_R - M)^2 + Q^2}{M_R M K}}$, $K = \frac{M_R^2 - M^2}{2M_R}$, $\tau \to \frac{Q^2}{4M^2}$
- *Equivalent* amplitudes (extra factor $\sqrt{2}$) Prediction
  $A_{1/2} \to \sqrt{2}\mathcal{R} G_M$, $S_{1/2} \to \sqrt{2}\frac{\mathcal{R}}{\sqrt{2}}\sqrt{\frac{1+\tau}{\tau}} G_E$,

Amplitude $A_{1/2}$: Roper, $N(1710) \approx G_M$(Nucleon)



Data: J. Arrington, W. Melnitchouk and J. A. Tjon, PRC **76**, 035205 (2007)

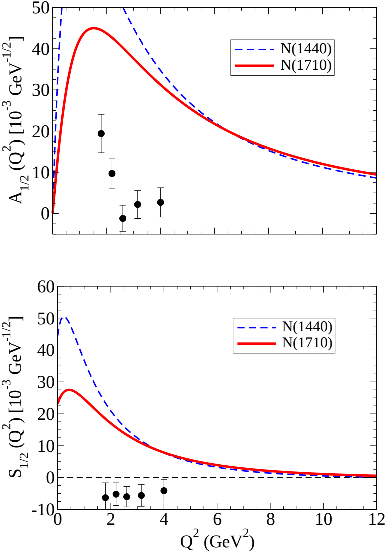




CLAS data: K Park et al, **PRC 91, 045203 (2015)**

— model predictions fail for intermediate Q^2

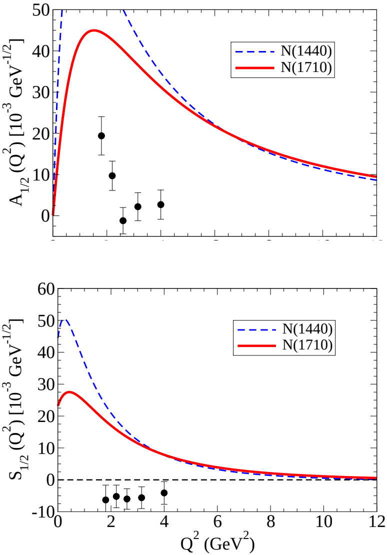
Amplitude $S_{1/2}$: difference of sign ...



Possible interpretations:

- Our results are valid only for larger Q^2
- $N(1710)$ it is not just a radial excitation
- There are mixture of (close) states
- $N(1710)$ is a dynamically generated resonance (EBAC): $N(1820)$
  N Suzuki *et al*, PRL 104, 042302 (2010)

$\gamma^* N \to N(1710)$: Helicity amplitudes [PRD 89 073010 (2014)] (5)



Discussion

- We can test the if there is a dominance of the **valence quark** effects: large Q^2:
  $A_{1/2} \propto \frac{1}{Q^3}$, $S_{1/2} \propto \frac{1}{Q^3}$
- Dominance of meson cloud $qqq - (q\bar{q})$: suppression $\propto 1/Q^4$ – stronger falloff
  Baryon-meson molecule
  (πN–$\pi\pi N$; πN–σN; $\sigma_v N$, gN, ...)
- *Most* quark models predict
  $A_{1/2} > 0$, $S_{1/2} > 0$
  T Melde *et al*, PRD 77 114002 (2008);
  M Ronniger *et al*, EPJA 49, 8 (2013)
- Hyperspherical QM predicts $S_{1/2} < 0$
  Santopinto and Giannini, PRC 86, 065202 (2012)
  good description of the data

Next ...

- Results for $N(1535)\frac{1}{2}^-, N(1520)\frac{3}{2}^-$
- Single Quark Transition Model
- Predictions for $N(1650)\frac{1}{2}^-, N(1700)\frac{3}{2}^-$, $\Delta(1620)\frac{1}{2}^-, \Delta(1700)\frac{1}{2}^-$

Wave functions $N(1520), N(1535)$ $[N^2 : s_q = 1/2;\ N^4 : s_q = 3/2]$ †

Using the $SU(6) \otimes O(3)$ structure; flavor wf: $\Phi_I^{0,1}$; spin wf: $X_{\lambda,\rho}^S$, $S = \frac{1}{2}, \frac{3}{2}$

$$\lambda = \text{symmetric} \qquad \rho = \text{anti} - \text{symmetric}$$

$$\left| N^2, \frac{1}{2}^- \right\rangle = N_{1/2} \left[\Phi_I^0 X_\rho^{1/2} + \Phi_I^1 X_\lambda^{1/2} \right] \psi_{S11}$$

$$\left| N^2, \frac{3}{2}^- \right\rangle = N_{3/2} \left[\Phi_I^0 X_\rho^{3/2} + \Phi_I^1 X_\lambda^{3/2} \right] \psi_{D13}$$

$$\left| N^4, S^- \right\rangle = ...$$

diquark: $k_\lambda = k_1 + k_2$, diquark internal momentum $k_\rho = \frac{1}{2}(k_1 - k_2)$,

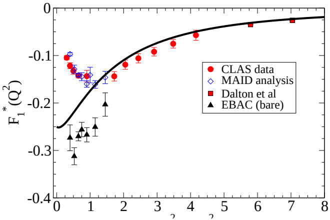
$$X_\rho^S(s) = \sum_{ms'} \langle 1 \tfrac{1}{2}; ms' | Ss \rangle \left[Y_{1m}(k_\rho) \left| s' \right\rangle_\lambda + Y_{1m}(k_\lambda) \left| s' \right\rangle_\rho \right]$$

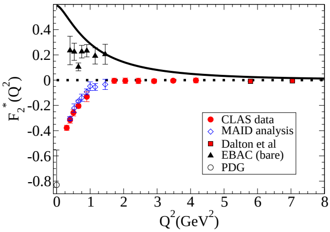
$$X_\lambda^S(s) = \sum_{ms'} \langle 1 \tfrac{1}{2}; ms' | Ss \rangle \left[Y_{1m}(k_\rho) \left| s' \right\rangle_\rho - Y_{1m}(k_\lambda) \left| s' \right\rangle_\lambda \right],$$

$\Longrightarrow$ covariant generalization: $\mathbf{k} \to k - \frac{k \cdot P}{P^2} P$; $Y_{lm}(k_\rho) \to \xi^m$; $\left| s' \right\rangle_{\rho,\lambda}$

$\gamma^* N \to N(1535)$ [GR and MT Peña, PRD 84, 033007 (2011)] $\frac{1}{2}^-$

- Spin 1/2 dominance
  $\cos\theta_S \simeq 0.85 \to 1$
  $|N(1535)\rangle \simeq \left| N^2, \frac{1}{2}^- \right\rangle$
- Pointlike diquark $Y_{10}(k_\rho) \to 0$
  $k_\rho = \frac{1}{2}(k_1 - k_2) \to 0$
- $\psi_{S11} \approx \psi_N$
  $\mathcal{I}_{S11}(Q^2) = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{S11} \psi_N$
- Approximated orthogonality
  $\mathcal{I}_{S11}(0) \neq 0$ ($\Rightarrow F_1^*(0) \neq 0$)
- F_1^* – good model for large Q^2
- F_2^* – model fails, ...
  describes EBAC data
  (quark core)
- Data ($Q^2 > 1.5$ GeV^2): $F_2^* \approx 0$





- Spin 1/2 dominance
  $\cos\theta_S \simeq 0.85 \to 1$
  $|N(1535)\rangle \simeq \left| N^2, \frac{1}{2}^- \right\rangle$
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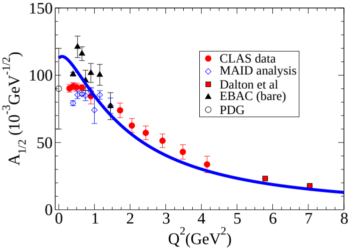
When $F_2^* = 0 \quad (A_{1/2} \propto F_1^*)$

$$A_{1/2} = -\frac{2}{3} F_S (f_{1+} + 2 f_{1-} \tau_3) \mathcal{I}_{S11}$$

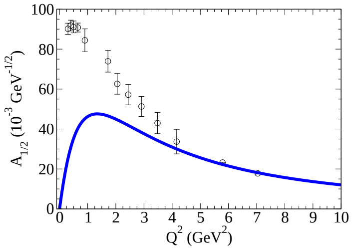


$\gamma^* N \to N(1535)$ – Updated model

- No pointlike diquark
  change normalization
- Orthogonality imposed
  $\mathcal{I}_{S11}(0) \equiv 0$
  Redefine ψ_{S11}
  (new parameter β_3)
- ψ_{S11} adjusted
  to high Q^2 data
- Then $F_1^*(0) = 0$
  But cannot
  describe low Q^2
  (meson cloud !!)

When $F_2^* = 0 \quad (A_{1/2} \propto F_1^*)$

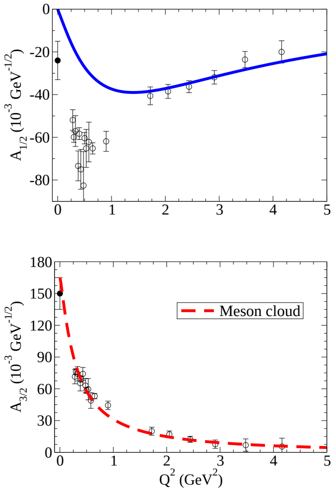
$$A_{1/2} = -\frac{\sqrt{2}}{3} F_S (f_{1+} + 2 f_{1-} \tau_3) \mathcal{I}_{S11}$$



- Spin 1/2 dominance ($\cos\theta_D \simeq 1$)
- Amplitudes:
  $\mathcal{I}_{D13} = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{D13} \psi_N$

$$A_{1/2} \propto (f_{1+} + 2 f_{1-} \tau_3) \mathcal{I}_{D13} + (f_{2+} + 2 f_{2-} \tau_3) \mathcal{I}_{D13}$$

(valence)

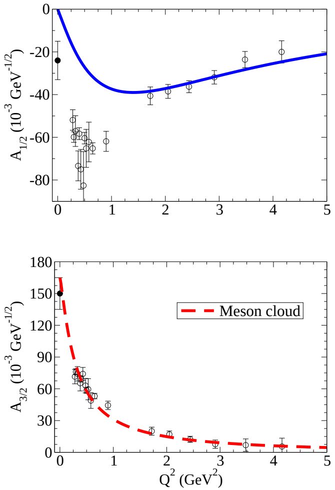


- ψ_{D13} fitted to high Q^2 data
- Orthogonality: $\mathcal{I}_{D13}(0) = 0$

- Spin 1/2 dominance ($\cos\theta_D \simeq 1$)
- Amplitudes:
  $\mathcal{I}_{D13} = \int_k \frac{k_z}{|\mathbf{k}|} \psi_{D13} \psi_N$

$$
\begin{aligned}
A_{1/2} &\propto (f_{1+} + 2 f_{1-} \tau_3) \mathcal{I}_{D13} \\
&+ (f_{2+} + 2 f_{2-} \tau_3) \mathcal{I}_{D13} \\
&\quad \text{(valence)} \\
A_{3/2} &= \frac{\sqrt{3}}{4} F_D G_4^\pi \\
&\quad \text{(meson cloud)}
\end{aligned}
$$

- ψ_{D13} fitted to high Q^2 data
- Orthogonality: $\mathcal{I}_{D13}(0) = 0$



N^* radial wave function (optional)

$$\psi_R(P,k) = \frac{N_R}{m_D(\beta_2+\chi)} \left\{ \frac{1}{\beta_1+\chi} - \frac{\lambda_R}{\beta_3+\chi} \right\}$$

New short range parameter β_3 – determined by large Q^2 data

Summary CSQM †

- Model for $N(1520)$, $N(1535)$ that include diquark structure
- Model describes the high Q^2 regime
  (adding a adjustable parameter β_i for resonance)
- For $N(1520)$ the amplitude $A_{3/2}$ is the consequence of meson cloud
  (zero contribution from valence quarks)
  $\Rightarrow$ $A_{3/2}$ phenomenological parametrization
- Small Q^2: failure of the model;
  no meson cloud effects included (except for $A_{3/2}^{D13}$)

Single Quark Transition Model

- Wave function given by $SU(6) \otimes O(3)$ group:
  supermultiplets $[SU(6), L^P]$ - $SU(6)$: number of particles (inc. spin proj.)
  Hey and Weyers, PL 48B, 69(1974); Cottingham and Dunbar, ZPC 2, 41 (1979);
  Burkert et al, PRC 67, 035204 (2003)
- Photon interaction with the quarks in **impulse approximation**
- Transverse current:

$$J^+ = AL^+ + B\sigma^+ L_z + C\sigma_z L^+ + D\sigma^- L^+ L^-$$

  A, B, C, D functions of Q^2 for the same $[SU(6), L^P]$
- supermultiplet $[70, 1^-]$ (negative parity):
  $N(1520), N(1535), N(1650), N(1700), \Delta(1620), \Delta(1700)$
  – only 3 independent coefficients: A, B, C
- $SU(6)$ breaking: $\theta_S \approx 31^\circ$, $\theta_D \approx 6^\circ$ ($1/2^- = S11$, $3/2^- = D13$)

$$|N(1535)\rangle = \cos\theta_S \overbrace{\left|N^2, \frac{1}{2}^-\right\rangle}^{s_q=1/2} - \sin\theta_S \overbrace{\left|N^4, \frac{1}{2}^-\right\rangle}^{s_q=3/2}, \quad |N(1520)\rangle = \cos\theta_D \overbrace{\left|N^2, \frac{3}{2}^-\right\rangle}^{s_q=1/2} - \sin\theta_D \overbrace{\left|N^4, \frac{3}{2}^-\right\rangle}^{s_q=3/2}$$

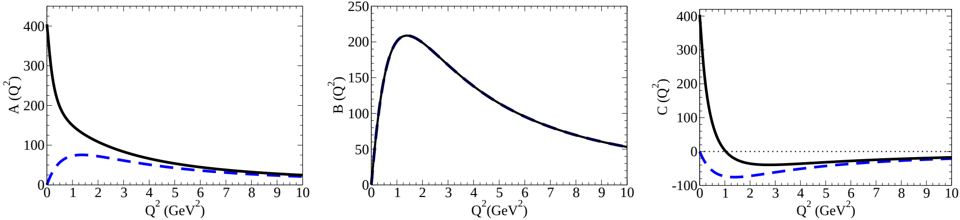
$$|N(1650)\rangle = \sin\theta_S \left|N^2, \tfrac{1}{2}^-\right\rangle + \cos\theta_S \left|N^4, \tfrac{1}{2}^-\right\rangle, \quad |N(1700)\rangle = \sin\theta_D \left|N^2, \frac{3}{2}^-\right\rangle + \cos\theta_D \left|N^4, \frac{3}{2}^-\right\rangle$$

SQTM: $[70, 1^-]$ amplitudes

State	Amplitude	
$S_{11}(1535)$	$A_{1/2}$	$\frac{1}{6}(A+B-C)\cos\theta_S$
$D_{13}(1520)$	$A_{1/2}$	$\frac{1}{6\sqrt{2}}(A-2B-C)\cos\theta_D$
	$A_{3/2}$	$\frac{1}{2\sqrt{6}}(A+C)\cos\theta_D$
$S_{11}(1650)$	$A_{1/2}$	$\frac{1}{6}(A+B-C)\sin\theta_S$
$S_{31}(1620)$	$A_{1/2}$	$\frac{1}{18}(3A-B+C)$
$D_{13}(1700)$	$A_{1/2}$	$\frac{1}{6\sqrt{2}}(A-2B-C)\sin\theta_D$
	$A_{3/2}$	$\frac{1}{2\sqrt{6}}(A+C)\sin\theta_D$
$D_{33}(1700)$	$A_{1/2}$	$\frac{1}{18\sqrt{2}}(3A+2B+C)$
	$A_{3/2}$	$\frac{1}{6\sqrt{6}}(3A-C)$

SQTM: Functions A, B and C

$$A = 2\frac{A_{1/2}^{S11}}{\cos\theta_S} + \sqrt{2}A_{1/2}^{D13} + \sqrt{6}A_{3/2}^{D13}, \quad B = 2\frac{A_{1/2}^{S11}}{\cos\theta_S} - 2\sqrt{2}A_{1/2}^{D13}, \quad C = -2\frac{A_{1/2}^{S11}}{\cos\theta_S} - \sqrt{2}A_{1/2}^{D13} + \sqrt{6}A_{3/2}^{D13}$$



- - - only valence quark contributions $(A + C = 0)$ – Model 1

—— include meson cloud $(A_{3/2}^{D13})$ – Model 2

Based in results for $S11$ and $D13$: $\Rightarrow$ predictions for $Q^2 > 2$ GeV^2

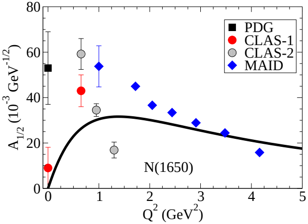
Data

Data:

- CLAS:
  I G Aznauryan, et al, PRC 72, 045201 (2005);
  M. Dugger et al. (CLAS Collaboration), PRC 79, 065206 (2009)
- CLAS-2: preliminary CLAS data
  V Mokeev et al, arXiv:1509.05460; V Mokeev, NSTAR 2015
- MAID:
  D. Drechsel et al EJPA, 34, 69 (2007); L. Tiator et al, Chin. Phys. C 33, 1069 (2009); Eur. Phys. J. Spec. Top. 198, 141 (2011)
  http://wwwkph.kph.unimainz.de/MAID//maid2007/data.html.
- NSTAR:
  V D Burkert et al PRC 67, 035204 (2003);
  V. Burkert, T.-S. H. Lee, R. Gothe, and V. Mokeev, Electromagnetic N-N* Transition Form Factors Workshop, Jlab, Newport News, 2008 (unpublished)

Results for $N(1650), N(1700)$

$A_{1/2}$



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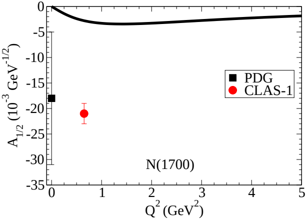
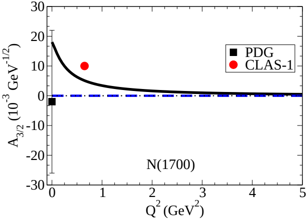
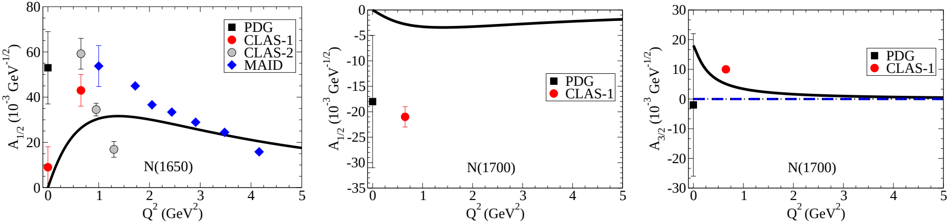


$A_{3/2}$



Data from CLAS, preliminary CLAS (CLAS-2), MAID and PDG

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

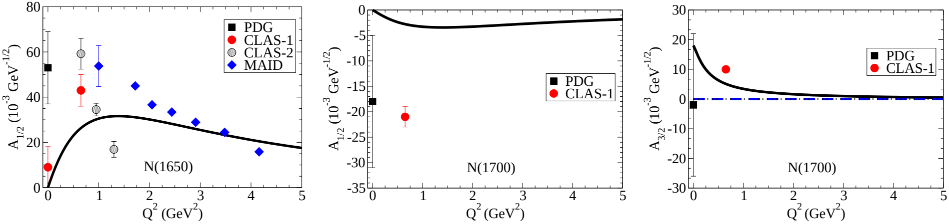


Data from CLAS, preliminary CLAS (CLAS-2), MAID and PDG

- Model 2: better for $A_{3/2} - N(1700)$

Results for $N(1650), N(1700)$

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

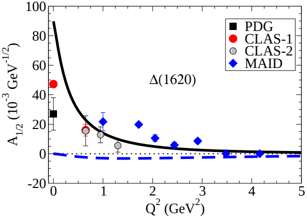


Data from CLAS, preliminary CLAS (CLAS-2), MAID and PDG

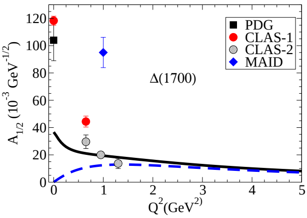
- Model 2: better for $A_{3/2}$ – $N(1700)$
- Both models: good for $N(1650)$: $Q^2 > 2$ GeV^2

Results for $\Delta(1620), \Delta(1700)$

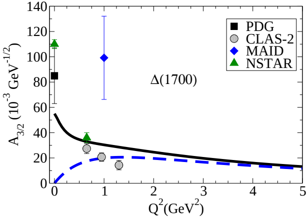
$A_{1/2}$



$A_{1/2}$



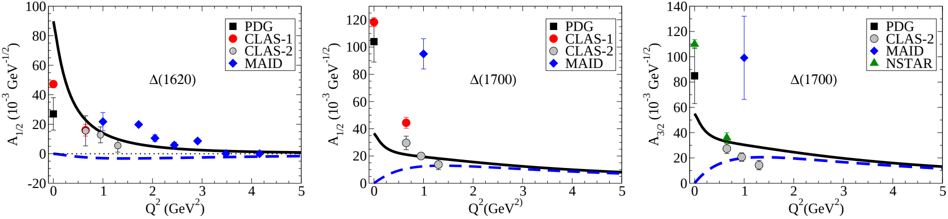
$A_{3/2}$



Data from CLAS, preliminary CLAS (CLAS-2), MAID, PDG and NSTAR (proceedings and conferences)

Results for $\Delta(1620), \Delta(1700)$

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

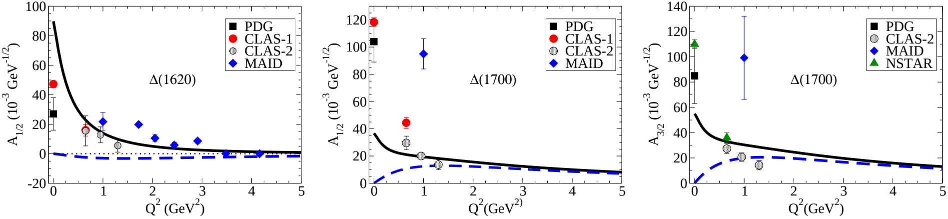


Data from CLAS, preliminary CLAS (CLAS-2), MAID, PDG and NSTAR (proceedings and conferences)

- $\Delta(1700)$: both models with similar results $Q^2 \gtrsim 1$ GeV^2

Results for $\Delta(1620), \Delta(1700)$

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



Data from CLAS, preliminary CLAS (CLAS-2), MAID, PDG and NSTAR (proceedings and conferences)

- $\Delta(1700)$: both models with similar results $Q^2 \gtrsim 1$ GeV^2
- $\Delta(1620)$: Model 2 –good for $Q^2 > 2$ GeV^2

Simple parametrization for large Q^2

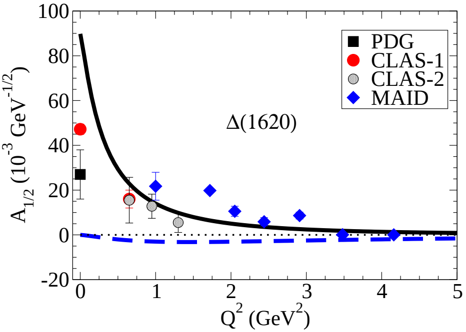
Facilitate comparison with future data – powers from pQCD

$$A_{1/2}(Q^2) = D\left(\frac{\Lambda^2}{\Lambda^2+Q^2}\right)^{3/2}, \qquad A_{3/2}(Q^2) = D\left(\frac{\Lambda^2}{\Lambda^2+Q^2}\right)^{5/2}$$

State	Amplitude	$D(10^{-3}\text{GeV}^{-1/2})$	$\Lambda^2(\text{GeV}^2)$
$S_{11}(1650)$	$A_{1/2}$	68.90	3.35
$S_{31}(1620)$	$A_{1/2}$	...	...
$D_{13}(1700)$	$A_{1/2}$	-8.51	2.82
	$A_{3/2}$	4.36	3.61
$D_{33}(1700)$	$A_{1/2}$	39.22	2.69
	$A_{3/2}$	42.15	8.42

$\gamma^* N \to \Delta(1620)$

$$A_{1/2}^{S31} \propto \left(2 \frac{A_{1/2}^{S11}}{\cos\theta_S} + 4\sqrt{2} A_{1/2}^{D13} + 4\sqrt{6} A_{3/2}^{D13} \right)$$

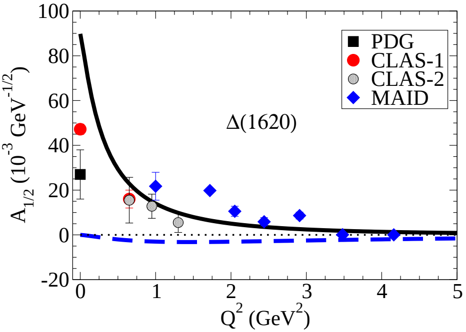


- - - only valence quark contributions

—— include meson cloud ($A_{3/2}^{D13}$)

$\gamma^* N \to \Delta(1620)$

$$A_{1/2}^{S31} \propto \left(2\frac{A_{1/2}^{S11}}{\cos\theta_S} + 4\sqrt{2}A_{1/2}^{D13} + 4\sqrt{6}A_{3/2}^{D13} \right) \not\propto \left(\frac{\Lambda^2}{\Lambda^2 + Q^2} \right)^{3/2}$$



- - - only valence quark contributions

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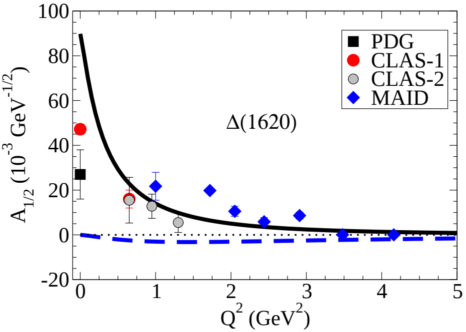
$\gamma^* N \to \Delta(1620)$

$$A_{1/2}^{S31} \propto \left(2\frac{A_{1/2}^{S11}}{\cos\theta_S} + 4\sqrt{2}A_{1/2}^{D13} + 4\sqrt{6}A_{3/2}^{D13} \right) \not\propto \left(\frac{\Lambda^2}{\Lambda^2+Q^2} \right)^{3/2}$$



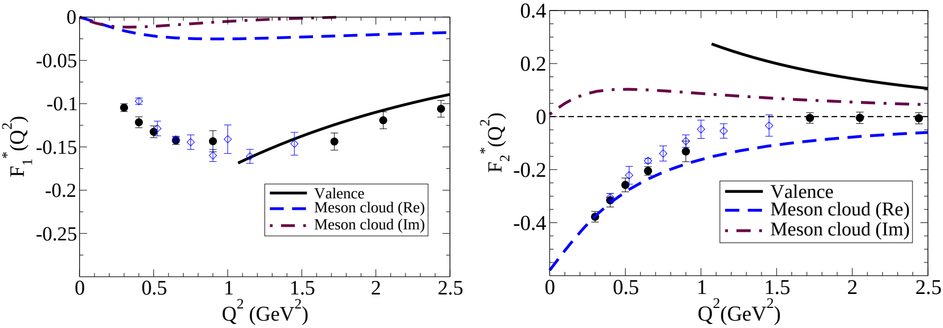
- - - only valence quark contributions

$$A_{1/2}^{S31} \propto \left(\frac{1}{1+\frac{Q^2}{1\mathrm{GeV}^2}} \right)^{5/2}$$

—— include meson cloud ($A_{3/2}^{D13}$)

$\gamma^* N \to N(1535)$: Meson cloud

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

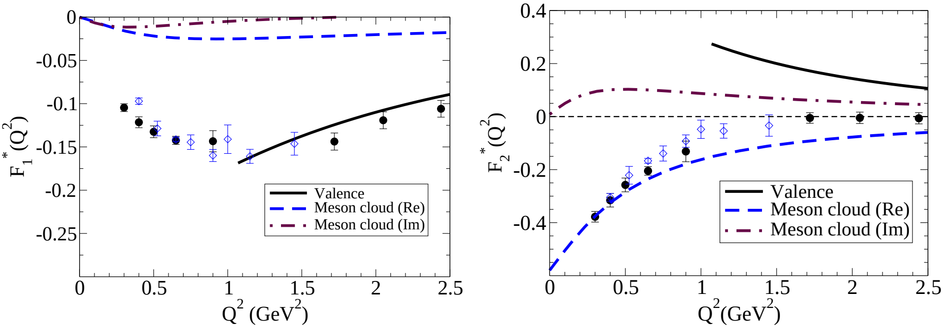


—— **Spectator quark model** $\longrightarrow$ Valence

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

Resonance dynamically generated $\longrightarrow$ Meson cloud

GR, D Jido and K Tsushima, PRD 85, 093014 (2012) $(F_2^*)^{mc} \approx -(F_2^*)^B$



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Implications of $F_2^* = 0$?

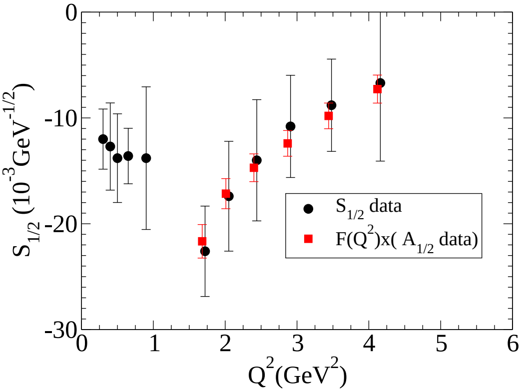
$\tau = \frac{Q^2}{(M_R+M)^2}$ $Q^2 > 1.5$ GeV^2

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

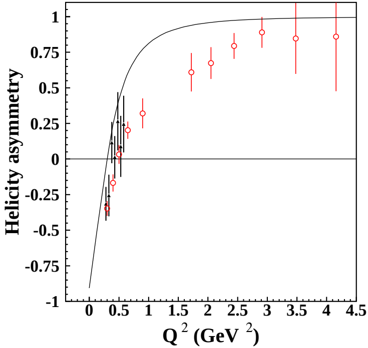
GR, K Tsushima
PRD 84, 051301 (2011)

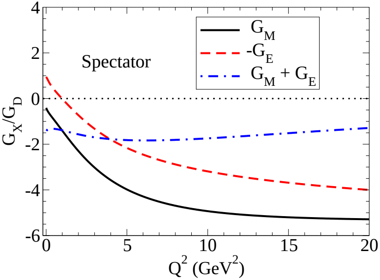
GR, D Jido, K Tsushima
PRD 85, 093014 (2012)

Cancellation between
valence and meson cloud



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

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Thank you

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