Resonance electrocouplings in a light-front model with running quark mass

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- Elastic Nucleon Form Factors
- Resonance transition Form Factors
- Conclusions

Foreword

The approach discussed here is purely phenomenological, and addresses a few topics that have some importance for the direction of the field, in particular:

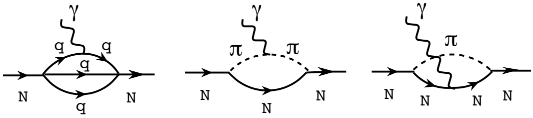
- obtain a better understanding of the expected meson-baryon contributions
- study the sensitivity of the resonance transition amplitudes to the running quark mass, which is a result of the DSE approach and of LQCD calculations.

Approach

The approach and its parameters are specified via description of nucleon electromagnetic form factors for $Q^2 \leq 20$ GeV^2. We therefore begin with the nucleon electromagnetic form factors.

- Nucleon electromagnetic form factors
  $\rightarrow q^3 + \pi N$ loops contributions in light-front dynamics
  $\rightarrow$ running quark mass
- Electroexcitation of $\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, and $N(1535)\frac{1}{2}^-$
  $\rightarrow q^3$ contribution in a LF RQM with running quark mass
  $\rightarrow$ inferred MB contributions

Model Ingredients



(a) (b) (c)

The contributions (a), (b), (c) have been found in Refs.:

- I. G. Aznauryan and V. D. Burkert, PR C85, 055202, 2012
- G. A. Miller, PR C66, 032201, 2002

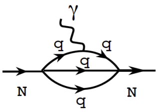
in the LF approach developed in:

- V. B. Berestetsky and Terent'ev, Sov.J.Nucl.Phys. 25,347,1977
- I. G. Aznauryan, A. S. Bagdasaryan, and N. L. Ter-Isaakyan, PL B112, 393, 1982; Yad.Fiz. 36, 1278 (1982).

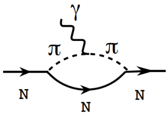
Parameters

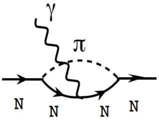
- **(a)** Here we have two parameters: $m_q(Q^2 = 0)$ and α_q. α_q determines the quark momentum distribution. These parameters are fixed by $G_{Mp}(0)$ and $G_{Mn}(0)$.

  We find $m_q(0) = 0.22$GeV - in agreement with value obtained from description of the baryon and meson masses in the relativized QM (S. Godfrey and N. Isgur, PR D21, 1868, 1980; S. Capstick and N. Isgur, PR D32, 189, 1985.)



- **(b,c)** Here we have two more parameters: $f_{\pi NN}$ and $\alpha_{\pi N}$. $f_{\pi NN}$ is known: $f^2_{\pi NN}/4\pi = 14.5$. $\alpha_{\pi N}$ determines the π and N momentum distribution in the loop; it is fixed by $G_{En}(Q^2)$, because the contribution of these diagrams is crucial for the description of $G_{En}(Q^2)$ at $Q^2 < 1.5$ GeV^2.





Renormalization of the $N(N^*) \to 3q$ vertices due to the presence of the MB loops

- The diagrams (b) and (c) give $\approx 10\%$ contribution to the charge of the proton: see plot for G_{Ep}. Therefore, to keep the charge of the proton $Q_p = 1$, we have to renormalize the vertex $N \to 3q$.

  In the absence of meson-baryon loops and with the $N \to 3q$ wave function normalized as: $\int |\Phi(\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3)|^2 d\Gamma = 1$, we have $|N> = |3q>$.

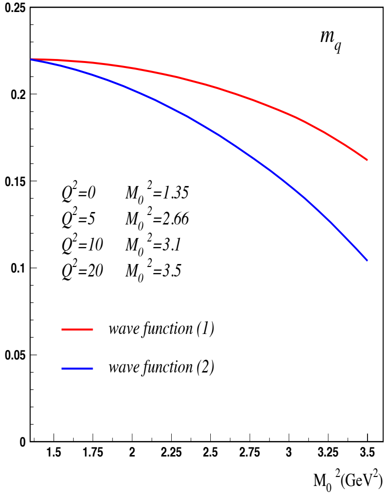
  With the πN loops included, we get: $|N> = 0.95|3q> + ...$.

- MB loops also contribute to the charge of resonances. Therefore, the vertices $N^* \to 3q$ should be renormalized: $|N^*> = c_{N^*}|3q> + ...$, $c_{N^*} < 1$.
- We find the coefficients c_{N^*} from experimental data on $\gamma^* N \to N^*$ assuming that at $Q^2 > 4$ GeV^2 these transitions are determined only by the $3q$ contributions.

Coefficients of q^3 resonance excitations

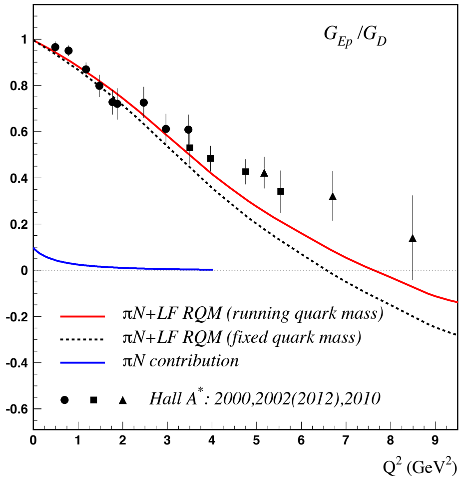
- $\Delta(1232)\frac{3}{2}^+$: $c_{N^*} = 0.88 \pm 0.04$
- $N(1440)\frac{1}{2}^+$: $c_{N^*} = 0.93 \pm 0.05$
- $N(1520)\frac{3}{2}^-$: $c_{N^*} = 0.80 \pm 0.06$
- $N(1535)\frac{1}{2}^-$: $c_{N^*} = 0.91 \pm 0.03$

Running quark mass



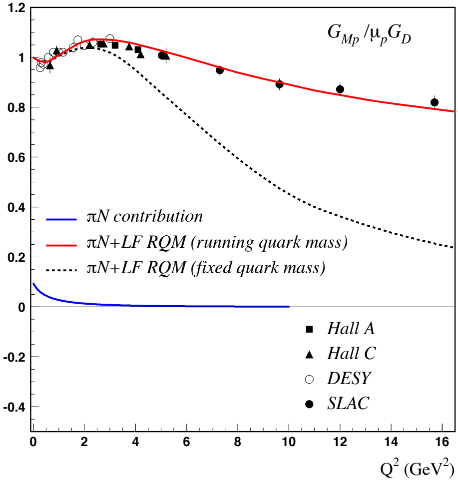
- With the fixed quark mass we obtain good description of all nucleon form factors up to $Q^2 = 2$ GeV^2.
- At $Q^2 > 2$ GeV^2, a constant value of the quark mass gives rise to rapidly decreasing form factors in discrepancy with experiment.
- Good description of the form factors up to $Q^2 = 20$ GeV^2 is obtained with running quark mass exploring two forms of wave functions:
- (1) $\Phi_1 \sim exp(-M_0^2/\alpha_1^2)$,
  (2) $\Phi_2 \sim exp[-(\mathbf{q}_1^2 + \mathbf{q}_2^2 + \mathbf{q}_3^2)/\alpha_2^2]$;
  M_0^2 in the plot is mean value of $M_0^2 = (q_1 + q_2 + q_3)^2$.
- In CQM, including LF RQM, quarks are on-mass-shell objects. In LF RQM, the virtuality of quarks is characterized by the invariant mass of the 3-quark system $M_0^2 = (q_1 + q_2 + q_3)^2$, which is increasing with increasing Q^2.
- In LQCD and DSE, we deal with off-mass-shell quarks, and the quark virtuality is determined by their four-momentum square.

Proton Electric Form Factor



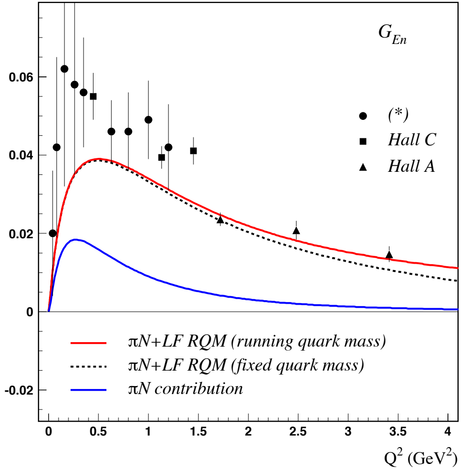
- Hall A* data are obtained from the data on $\mu_p G_{Ep}/G_{Mp}$ via multiplication by G_{Mp}/μ_p using parameterization of the data on G_{Mp}/μ_p found in E. J. Brash et al., PR C65, 051001, 2002
- Hall A, 2000: M. K. Jones et al., PRL 84, 1398, 2000
- Hall A, 2002: O. Gayou et al., PRL 88, 092301, 2002
- Hall A, 2012: A. J. R. Puckett et al., PR C85, 045203, 2012
- Hall A, 2010: A. J. R. Puckett et al., PRL 104, 242301, 2010

Proton Magnetic Form Factor



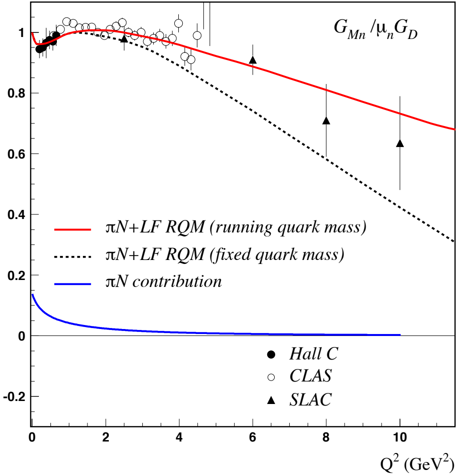
- Hall A: I. A. Qattan et al., PRL 94, 142301, 2005
- Hall C: M. E. Christy et al., PR C70, 015206, 2004
- DESY: W. Bartel et al., NP B58, 429, 1973
- SLAC: A. F. Sill et al., PR D48, 29, 1993

Neutron Electric Form Factor



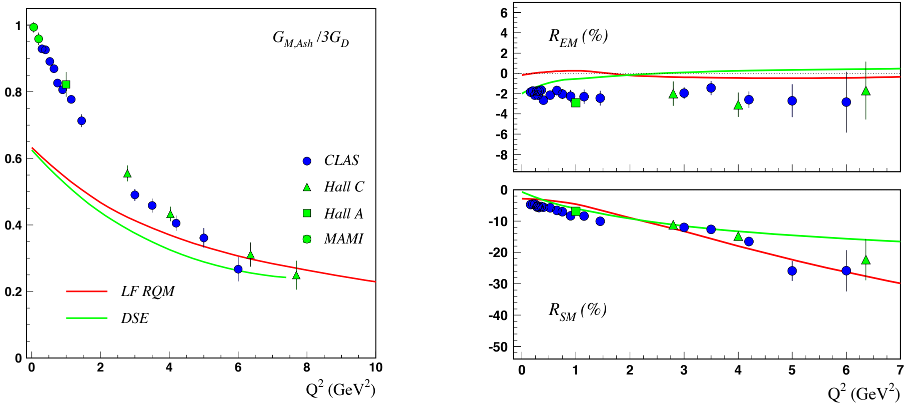
- (*): R. Schiavilla and I. Sick, PR C64, 041002, 2001
- Hall C: R. Madey et al., PRL 91,122002, 2003
- Hall A: S. Riordan et al., PRL 105, 262302, 2010

Neutron Magnetic Form Factor



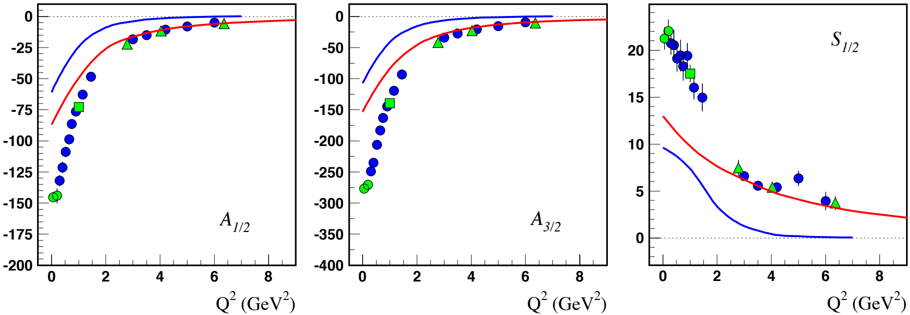
- Hall C: B. Anderson et al., PR C75, 043003, 2007
- CLAS: J. Lachniet et al., PRL 102,192001, 2009
- SLAC: S. Rock et al., PRL 49, 1139, 1982

$N\Delta(1232)$ Magnetic FF and Quadrupole ratios



- CLAS: from analysis I. G. Aznauryan et al., CLAS collaboration, PR C80,055203, 2009
- Hall C: V. V. Frolov et al., PRL 82, 45, 1999; A. N. Vilano et al., PR C80, 035203, 2009
- Hall A: J. J. Kelly et al., PR C75, 025201, 2007
- MAMI: N. F. Sparveris et al., PL B651, 102, 2007; S. Stave et al., PR C78, 025209, 2008

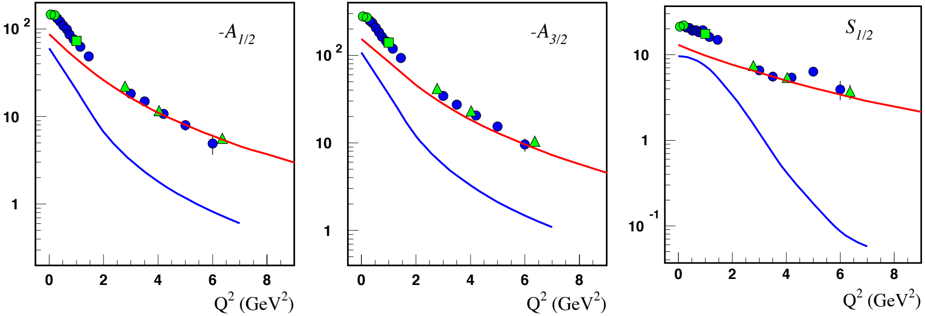
$N\Delta(1232)$ Helicity amplitudes $A_{1/2}$, $A_{3/2}$, $S_{1/2}$



Red curve: LF RQM I.G. Aznauryan and V.D. Burkert, PR C92, 035211, 2015; arXiv:1603.06692

Blue curves: inferred meson-baryon contributions.

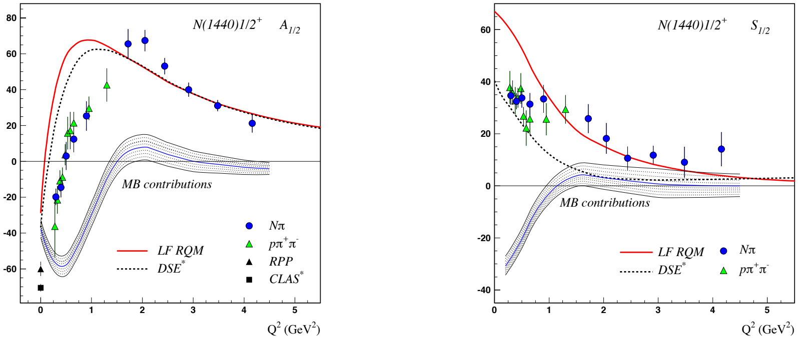
$N\Delta(1232)$ Helicity amplitudes in log scale



Red curve: LF RQM I.G. Aznauryan and V.D. Burkert, PR C92, 035211, 2015; arXiv:1603.06692

Blue curves: inferred meson-baryon contributions.

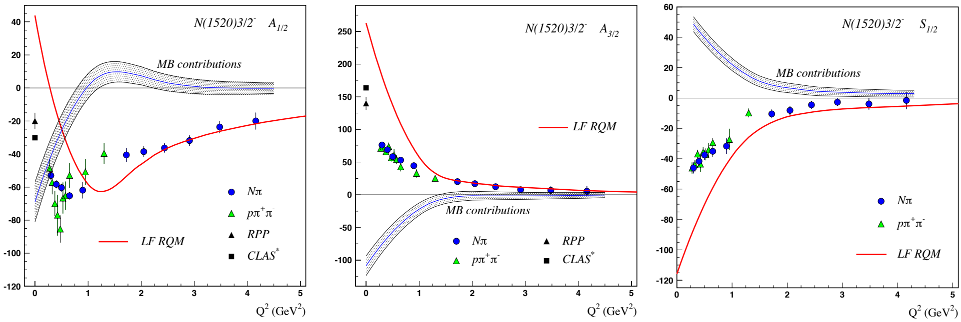
Roper $N(1440)\frac{1}{2}^{+}$ helicity amplitudes $A_{1/2}$, $S_{1/2}$



- LF RQM describes helicity amplitudes at $Q^2 > 1.5 - 2.5$ GeV^2.
- DSE curve is renormalized to account for MB contributions.

LF RQM: I.G. Aznauryan and V.D. Burkert, PR C92, 035211, 2015; arXiv:1603.06692
DSE*: C. D. Roberts and J. Segovia, arXiv: 1603.02722
Nπ: CLAS data from I. G. Aznauryan et al., PR C80,055203, 2009
p$\pi^+\pi^-$: CLAS data from V.I. Mokeev et al., PR C86, 035203, 2012; PR C93, 025206, 2016
CLAS*: M. Dugger et al., PR C79, 065206, 2009

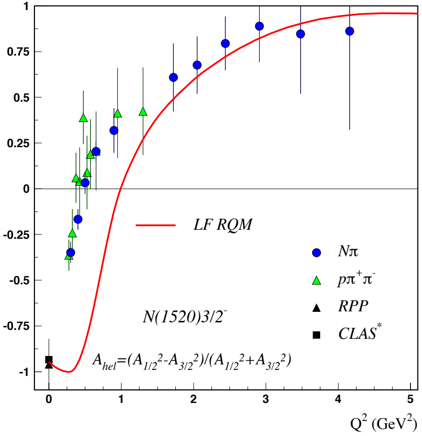
$N(1520)\frac{3}{2}^-$ Helicity amplitudes $A_{1/2}$, $A_{3/2}$, $S_{1/2}$



- LF RQM describes electrocouplings at $Q^2 > 1.5 - 2.5$ GeV^2.
- Non-quark contributions (MB) compete or dominate low Q^2 behavior.

LF RQM: I. G. Aznauryan and V. D. Burkert, PR C85, 055202, 2012
$N\pi$: CLAS data from I. G. Aznauryan et al., PR C80,055203, 2009
$p\pi^+\pi^-$: CLAS data from V.I. Mokeev et al., PR C86, 035203, 2012; PR C93, 025206, 2016
CLAS*: M. Dugger et al., PR C79, 065206, 2009

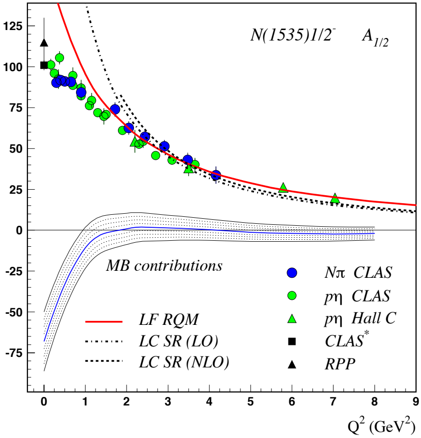
$N(1520)\frac{3}{2}^-$ Helicity asymmetry A_{hel}



$$A_{hel} = \frac{A^2_{1/2} - A^2_{3/2}}{A^2_{1/2} + A^2_{3/2}}$$

- The state exhibits a rapid change of its helicity structure from helicity $= \frac{3}{2}$ dominance at $Q^2 = 0$ to helicity $= \frac{1}{2}$ dominance at $Q^2 > 1.5$ GeV^2.
- The LF RQM agrees with data at $Q^2 > 1.5\text{GeV}^2$.

$N(1535)\frac{1}{2}^-$ Helicity amplitude $A_{1/2}$



- LF RQM (red curve) describes $A_{1/2}$ at $1.5 < Q^2 < 7.5$ GeV^2.

References to N(1535)

$N\pi$: CLAS data from I. G. Aznauryan et al., PR C80,055203, 2009

$p\eta$: CLAS data from R. Thompson et al., PRL 86, 1702, 2001; H. Denizli et al., PR C76, 015204, 2007

$p\eta$: Hall C data from C. S. Armstrong et al., PR D60, 052004, 2009; M. M. Dalton et al., PR C80, 015205, 2009

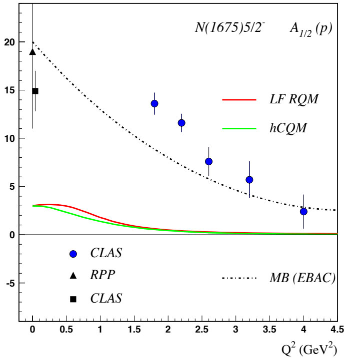
CLAS*: M. Dugger et al., PR C79, 065206, 2009

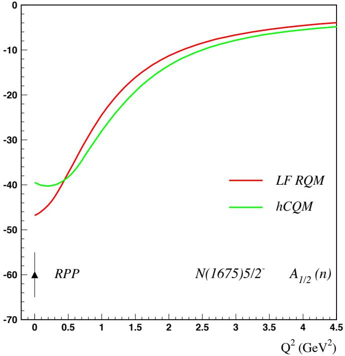
LF RQM: I. G. Aznauryan and V. D. Burkert, PR C85, 055202, 2012

LC SR (LO): V. M. Braun et al., PRL 103, 072001, 2009

LC SR (NLO): I. V. Anikin, V. M. Braun, and N. Offen, PR D92, 014018, 2015

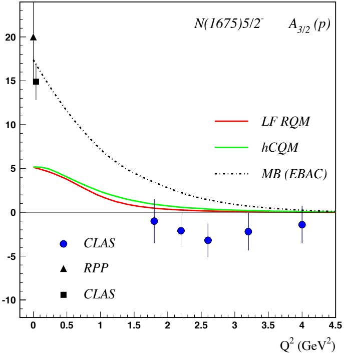
$N(1675)\frac{5}{2}^{-}$ Helicity amplitude $A^{p}_{1/2}$, $A^{n}_{1/2}$

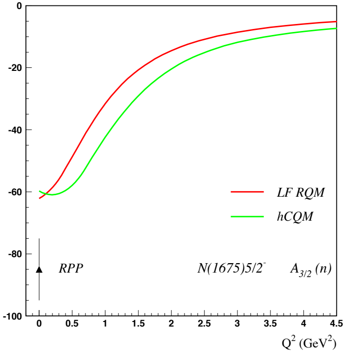




- $A^{p}_{1/2}$ consistent with dominance of MB contributions due to suppression of quark contributions for proton target.
- Quark core contribution to neutron $A^{n}_{1/2}$ are predicted order of magnitude larger than for proton.
- At the photon point MB contributions to protons and neutrons are of same order.

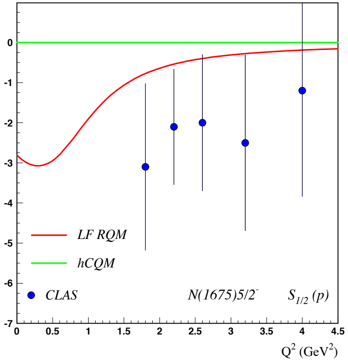
$N(1675)\frac{5}{2}^-$ Helicity amplitude $A^p_{3/2}$, $A^n_{3/2}$

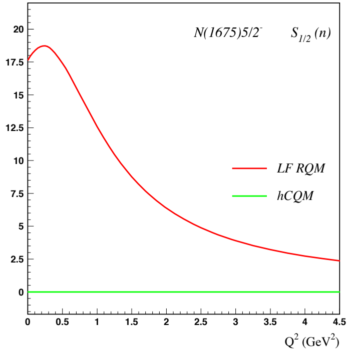




- $A^p_{3/2}(Q^2)$ consistent with suppression of quark core contributions.
- Quark core contribution to $A^n_{3/2}(Q^2)$ in LF RQM is predicted order of magnitude larger than for protons.
- At the photon point the MB contributions to the helicity amplitudes of protons and neutrons are of the same magnitude.

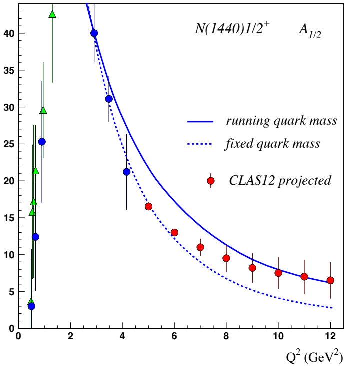
$N(1675)\frac{5}{2}^-$ Helicity amplitude $S^p_{1/2}$, $S^n_{1/2}$

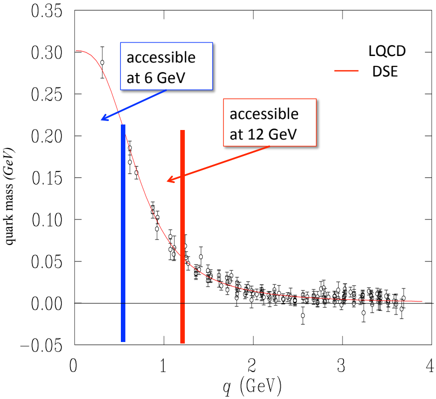




- In LF RQM the scalar electrocoupling for neutron transitions is predicted order of magnitude larger than for protons.

Running quark mass sensitivity





- Running quark mass predicted to have strong effects on $A^p_{1/2}(Q^2)$ of the Roper resonance at $Q^2 > 5\text{GeV}^2$.
- CLAS12 will test this in region where dressed quark mass expected to change significantly.

Conclusions & Outlook

- The LF RQM combined with πN loops and with running quark mass describes the elastic form factors of proton and neutron. At $Q^2 = 0$, pion loop contributions are of order 10% except for G_E^n where they can be up to 50%.
- The LF RQM describes all proton-resonance electrocouplings for $\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, $N(1535)\frac{1}{2}^-$ at $Q^2 > 1.5 - 2.5$ GeV^2 with the coefficient for the q^3 core contribution to these resonances of 0.8 - 0.9. In particular, $\Delta(1232)$ electrocouplings and $A_{1/2}$ amplitude for $N(1535)\frac{1}{2}^-$ are described at $Q^2 < 7.5$ GeV^2.
- Meson-baryon contributions are significant at $Q^2 < 1.5 - 2.5$ GeV^2 as inferred from the difference of LF RQM predictions and data. They show a similar behavior for all studied resonances.
- $N(1675)\frac{5}{2}^-$ helicity amplitudes on protons show a rapid drop with Q^2 consistent with the absence of significant quark core contributions.
- The MB contribution to $N(1675)\frac{5}{2}^-$ on proton and neutron are of similar magnitude while quark core contributions for proton an neutron are very different.
- The LF RQM projections indicate sensitivity to the running quark mass parametrization for the Roper resonance, especially at $Q^2 > 4$ GeV^2. This can be tested with the N* program at CLAS12.

CLAS12