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

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Outline

- Foreword
- Strategy
- Model description
- Elastic Nucleon Form Factors
- Resonance transition Form Factors
- Conclusions
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.
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**
  - $q^3 + \pi N$ loops contributions in light-front dynamics
  - running quark mass

- **Electroexcitation of $\Delta(1232)^{3/2^+}$, $N(1440)^{1/2^+}$, $N(1520)^{3/2^-}$, and $N(1535)^{1/2^-}$**
  - $q^3$ contribution in a LF RQM with running quark mass
  - inferred $MB$ contributions
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:

Parameters

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

We find $m_q(0) = 0.22\text{GeV}$ - 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 $\pi$ 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 $Q^2 < 1.5 \text{ GeV}^2$. 
Renormalization of the $N(N^*) \rightarrow 3q$ 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 $N \rightarrow 3q$.

In the absence of meson-baryon loops and with the $N \rightarrow 3q$ wave function normalized as: $\int |\Phi(q_1, q_2, q_3)|^2 d\Gamma = 1$, we have $|N >= |3q>$. With the $\pi N$ loops included, we get: $|N >= 0.95|3q> + ...$.

- MB loops also contribute to the charge of resonances. Therefore, the vertices $N^* \rightarrow 3q$ should be renormalized: $|N^* >= c_{N^*}|3q> + ...$, $c_{N^*} < 1$.

- We find the coefficients $c_{N^*}$ from experimental data on $\gamma^* N \rightarrow N^*$ assuming that at $Q^2 > 4$ GeV$^2$ these transitions are determined only by the $3q$ contributions.
Coefficients of $q^3$ resonance excitations

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

- With the fixed quark mass we obtain good description of all nucleon form factors up to $Q^2 = 2 \text{ GeV}^2$.
- At $Q^2 > 2 \text{ GeV}^2$, 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 $Q^2 = 20 \text{ GeV}^2$ is obtained with running quark mass exploring two forms of wave functions:
  1. $\Phi_1 \sim \exp(-M_0^2/\alpha_1^2)$,
  2. $\Phi_2 \sim \exp[-(q_1^2 + q_2^2 + q_3^2)/\alpha_2^2]$;

- $M_0^2$ 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 $G_{Mp}/\mu_p$ using parameterization of the data on $G_{Mp}/\mu_p$ found in E. J. Brash et al., PR C65, 051001, 2002
Proton Magnetic Form Factor

\[ G_{Mp}/\mu_p G_D \]

- **πN contribution**
- **πN+LF RQM (running quark mass)**
- **πN+LF RQM (fixed quark mass)**

- **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

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Neutron Electric Form Factor

\[ G_{En} \]

- \( (*) \): 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

\( Q^2 \) (GeV\(^2\))
Neutron Magnetic Form Factor

$G_{Mn}/\mu_n G_D$

- $\pi N+LF$ RQM (running quark mass)
- $\pi N+LF$ RQM (fixed quark mass)
- $\pi N$ contribution

- 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

$G_{M,Ash}/3G_D$

- $CLAS$
- $Hall~C$
- $Hall~A$
- $MAMI$

$R_{EM} (\%)$

$R_{SM} (\%)$

- 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 \( A_{1/2}, A_{3/2}, S_{1/2} \)


Blue curves: inferred meson-baryon contributions.
$N\Delta(1232)$ Helicity amplitudes in log scale


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.

$N\pi$: 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
$N(1520)^{3/2}^-_3$ 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
$N(1520)^{3/2}_-\text{ Helicity asymmetry } A_{hel}$

\[ A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2} \]

- 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 $Q^2 > 1.5 \text{ GeV}^2$.

- The LF RQM agrees with data at $Q^2 > 1.5\text{ GeV}^2$. 

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Resonance electrocouplings in a light-front model with running quark mass
\(N(1535)_{1/2}^-\) 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

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

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

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Resonance electrocouplings in a light-front model with running quark mass
\( N(1675)^{\frac{5}{2}}^- \) Helicity amplitude \( A_{3/2}^p, A_{3/2}^n \)

\[ N(1675)^{5/2} \quad A_{3/2} (p) \]

- \( A_{3/2}^p (Q^2) \) consistent with suppression of quark core contributions.
- Quark core contribution to \( A_{3/2}^n (Q^2) \) 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.
In LF RQM the scalar electrocoupling for neutron transitions is predicted order of magnitude larger than for protons.
Running quark mass predicted to have strong effects on $A_{1/2}^{p}(Q^2)$ 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 $\pi N$ 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 $G_n^E$ where they can be up to 50%.

- The LF RQM describes all proton-resonance electrocouplings for $\Delta(1232)^3_{\frac{3}{2}^+}$, $N(1440)^{1\frac{1}{2}^+}$, $N(1520)^{3\frac{1}{2}^-}$, $N(1535)^{1\frac{1}{2}^-}$ 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 $N(1535)^{1\frac{1}{2}^-}$ 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.

- $N(1675)^5_{\frac{3}{2}^-}$ helicity amplitudes on protons show a rapid drop with $Q^2$ consistent with the absence of significant quark core contributions.

- The MB contribution to $N(1675)^5_{\frac{3}{2}^-}$ 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.
Resonance electrocouplings in a light-front model with running quark mass