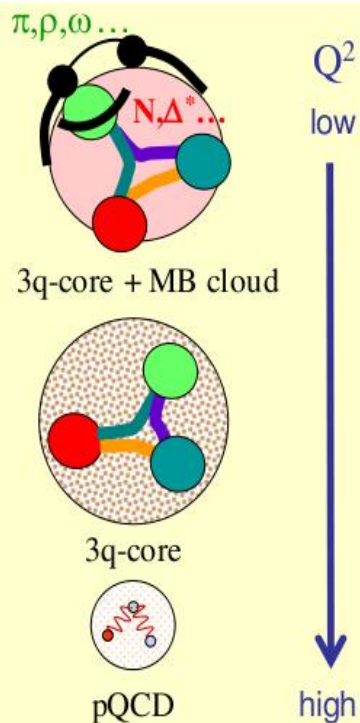
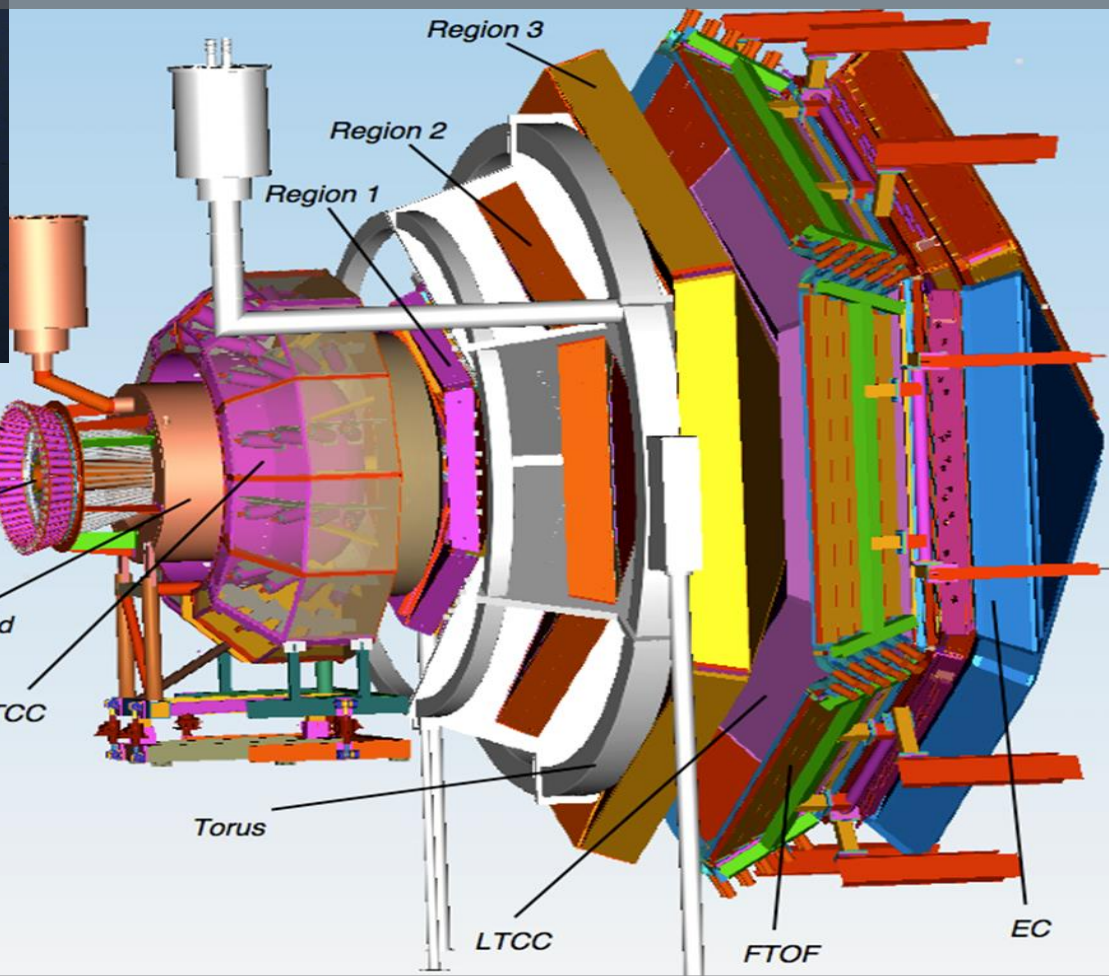


New results on N^* spectrum/structure with CLAS and preparation for the CLAS12 era



V.I. Mokeev,
Jefferson Laboratory

INT Workshop "Spectrum and Structure of Excited Nucleons from Exclusive Electroproduction", Seattle, November 14-18 2016, USA

Major Directions in the Studies of N^* -Spectrum and Structure with CLAS

The experimental program on the studies of N^* spectrum/structure in exclusive meson photo-/electroproduction with CLAS seeks to determine:

- $\gamma_V NN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels
- extend knowledge on N^* -spectrum and on resonance hadronic decays from the data for photo- and electroproduction reactions, in particular, for $\pi^+\pi^-p$ and KY final states

A unique source of information on different manifestations of the non-perturbative strong interaction in generating different excited nucleon states.

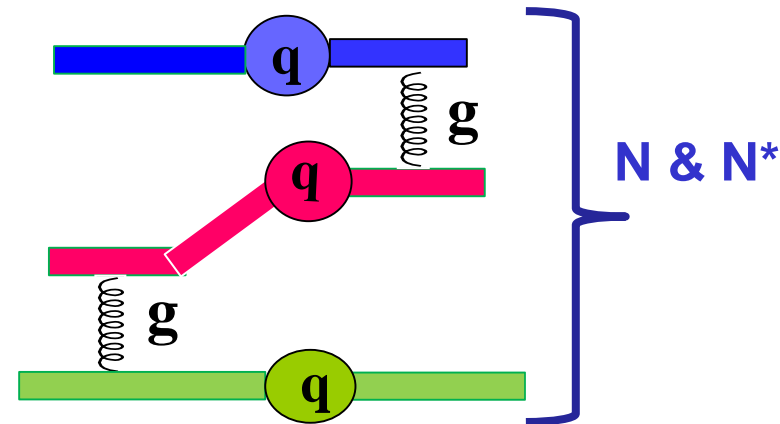
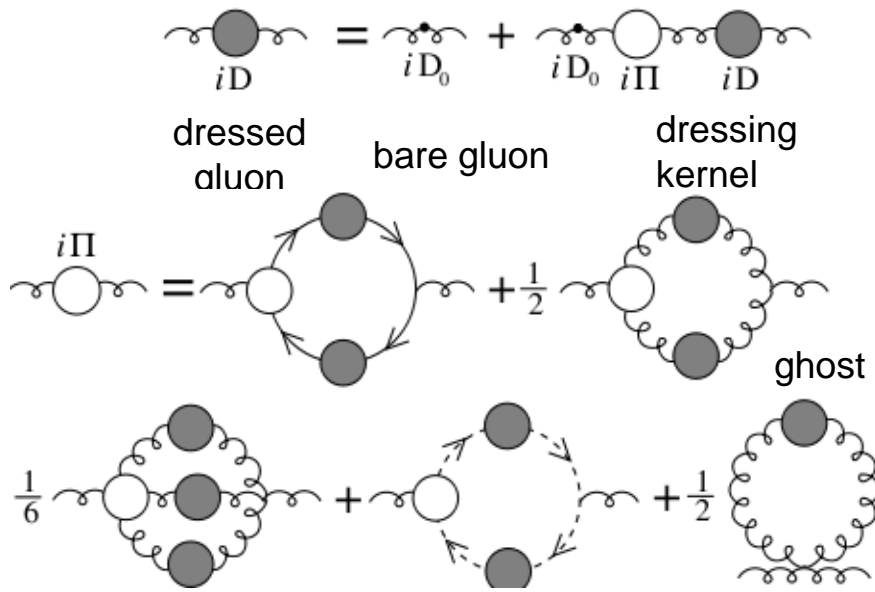
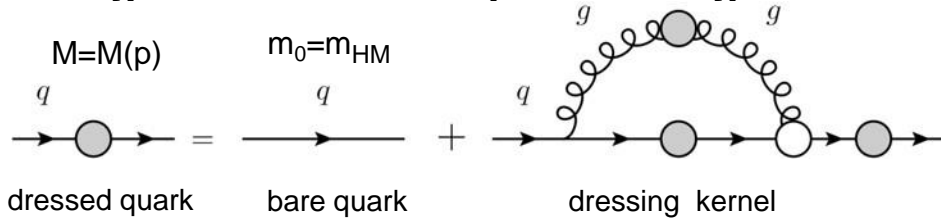
Review papers:

1. I.G. Aznauryan and V.D. Burkert, *Prog. Part. Nucl. Phys.* **67**, 1 (2012).
2. V.D. Burkert, *Few Body Syst.* **57**, 873 (2016).
3. C.D. Roberts, *J. Phys. Conf. Ser.* **706**, 022003 (2016).

Excited Nucleon States and Insight to Non-Perturbative Strong Interaction

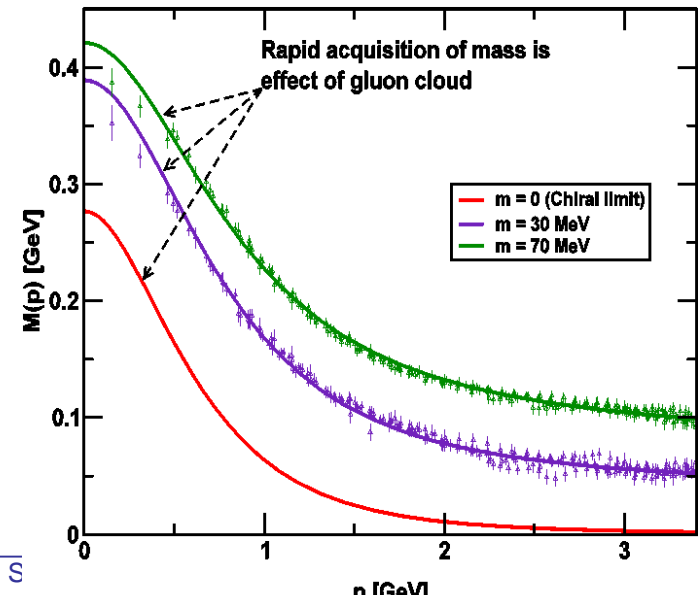
Studies of N^* spectrum/structure suggest that ground and excited nucleon states consist of three dressed (constituent) quarks bound by the quark exchange between the di-quark pairs correlated through dressed gluon exchange

Emergence of dressed quarks and gluons

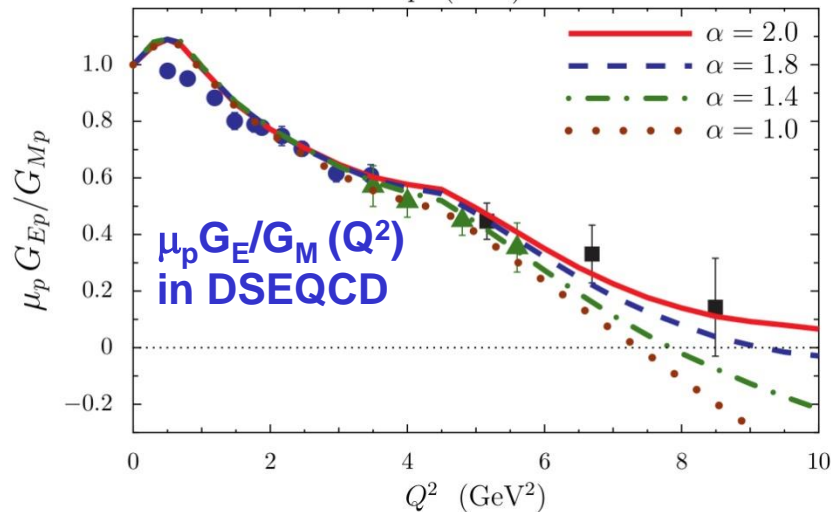
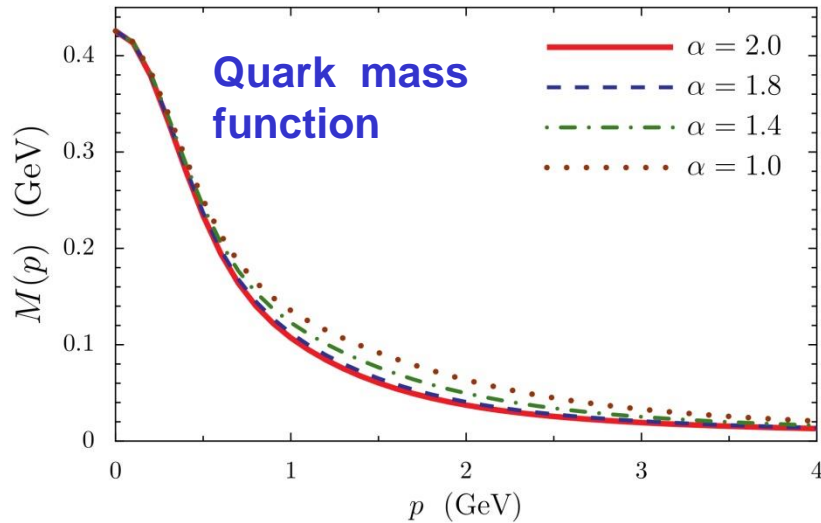


Dynamical dressed quark mass:

- Account for >98 % of hadron mass.
- Fully define the hadron spectrum and structure.



Mapping –out Quark Mass Function



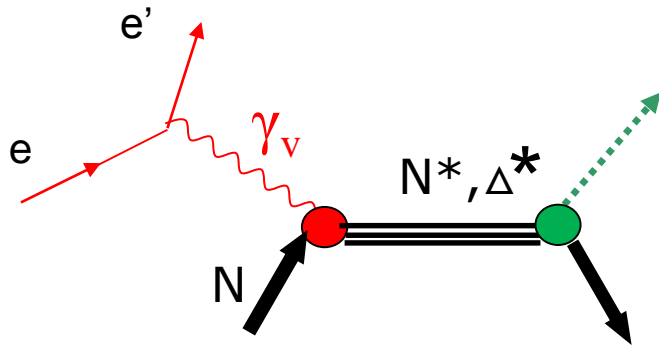
I.C.Cloët, C.D.Roberts, A.W.Thomas,
Phys. Rev. Lett. 111, 101803 (2013).

- elastic form factors are sensitive to momentum dependence of quark mass function.
- mass function should be the same for dressed quarks in the ground and excited nucleon states.
- consistent results on dressed quark mass function determined from the data on elastic form factors and transition $\gamma_v NN^*$ electrocouplings are critical to prove a credible access to these quantities.

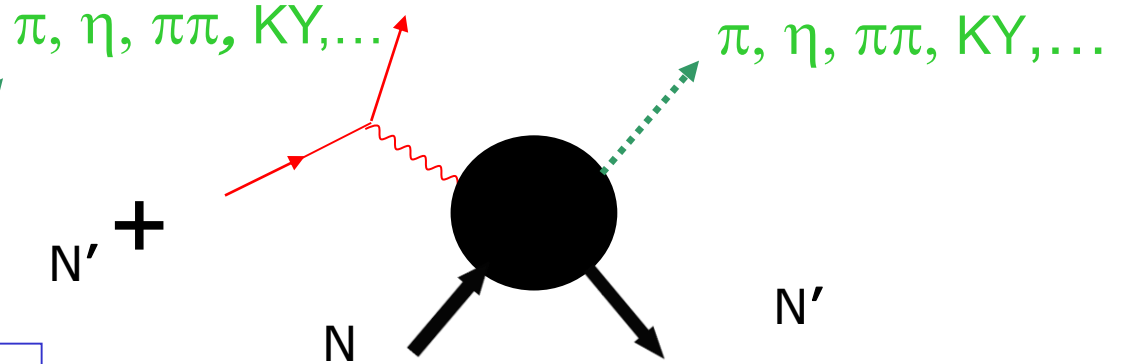
Studies of elastic and transition $N \rightarrow N^*$ form factors ($\gamma_v NN^*$ electrocouplings) represents the central direction in the exploration of strong interaction in non-perturbative regime.

Extraction of $\gamma_\nu NN^*$ Electrocouplings from the Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes



Non-resonant amplitudes



- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
or
- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$
or
- $G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$

I.G. Aznauryan and V.D. Burkert,
Prog. Part. Nucl. Phys. 67, 1
(2012).

Definition of N^* photo-/electrocouplings employed in the CLAS data analyses:

$$\Gamma_\gamma = \frac{q_\gamma^2}{\pi (2J_r + 1) M_{N^*}} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

Γ_γ stands for N^* electromagnetic decay widths at the photon point ($Q^2=0$) and $W=M_{N^*}$ on the real energy axis.

- Consistent results on $\gamma_\nu NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of these quantities.

Summary of the Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q ² -range, GeV ²	Measured observables
π^+n	1.1-1.38 1.1-1.55 1.1-1.7 1.6-2.0	0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega, A_b$ $d\sigma/d\Omega$
π^0p	1.1-1.38 1.1-1.68 1.1-1.39	0.16-0.36 0.4-1.8 3.0-6.0	$d\sigma/d\Omega$ $d\sigma/d\Omega, A_b, A_t, A_{bt}$ $d\sigma/d\Omega$
ηp	1.5-2.3	0.2-3.1	$d\sigma/d\Omega$
$K^+\Lambda$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/d\Omega$ P^0, P'
$K^+\Sigma^0$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/d\Omega$ P'
$\pi^+\pi^+p$	1.3-1.6 1.4-2.1	0.2-0.6 0.5-1.5	Nine 1-fold differential cross sections

- $d\sigma/d\Omega$ –CM angular distributions
- A_b, A_t, A_{bt} -longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

Almost full coverage of the final hadron phase space in $\pi N, \pi^+\pi^+p, \eta p, KY$ electroproduction

The measured with the CLAS observables of exclusive electroproduction for all listed final states are stored in the [CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi](http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi).

Approaches for Extraction of $\gamma_{\nu}NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

- **Analyses of different pion electroproduction channels independently:**

- π^+n and π^0p channels:

- Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)**

- I.G. Aznauryan, Phys. Rev. C67, 015209 (2003).

- I.G. Aznauryan et al., CLAS Coll., Phys Rev. C80, 055203 (2009).

- I.G. Aznauryan et al., CLAS Coll., Phys. Rev. C91, 045203 (2015).

- Reggeized background employing DR & Finite Energy Sum Rules: under development by JPAC**

- ηp channel:

- Extension of UIM and DR**

- I.G. Aznauryan, Phys. Rev. C68, 065204 (2003).

- Data fit at $W < 1.6$ GeV, assuming $N(1535)1/2^-$ dominance**

- H. Denizli et al., CLAS Coll., Phys. Rev. C76, 015204 (2007).

- $\pi^+\pi^-p$ channel:

- Data driven JLAB-MSU meson-baryon model (JM)**

- V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009).

- V.I. Mokeev et al., CLAS Coll., Phys. Rev. C86, 035203 (2012).

- V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).

- B_5 Veneziano model for 3-body background: under development by JPAC**

- Global coupled-channel analyses of the CLAS/world data of $\gamma_{r,\nu}N$, πN , ηN , $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:**

- T.-S. H. Lee, AIP Conf. Proc. 1560, 413 (2013).

- H. Kamano et al., Phys. Rev. C88, 035209 (2013).

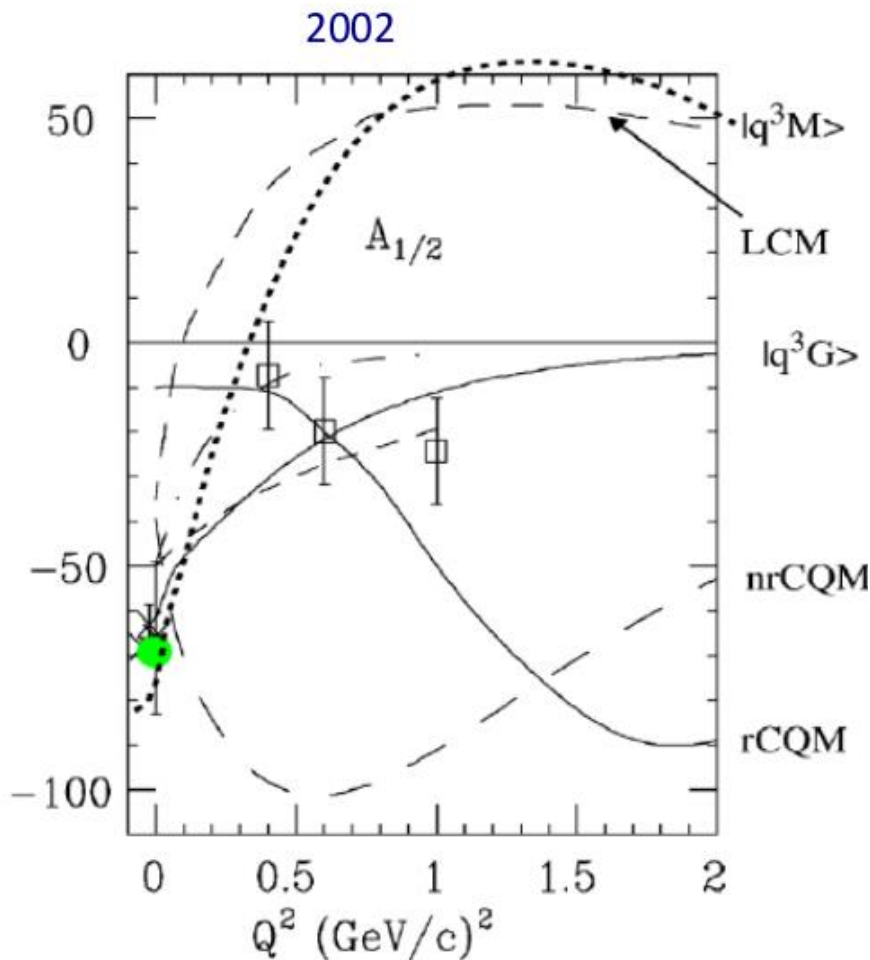
Summary of the Results on $\gamma_V p N^*$ Electrocouplings from CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2 -ranges for extracted $\gamma_V NN^*$ electrocouplings, GeV^2
$\pi^0 p, \pi^+ n$	$\Delta(1232)3/2^+$	0.16-6.0
	$N(1440)1/2^+, N(1520)3/2^-, N(1535)1/2^-$	0.30-4.16
$\pi^+ n$	$N(1675)5/2^-, N(1680)5/2^+, N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+ \pi^- p$	$N(1440)1/2^+, N(1520)3/2^-$	0.25-1.50
	$\Delta(1620)1/2^-, N(1650)1/2^-, N(1680)5/2^+, \Delta(1700)3/2^-, N(1720)3/2^+, N'(1720)3/2^+$	0.5-1.5

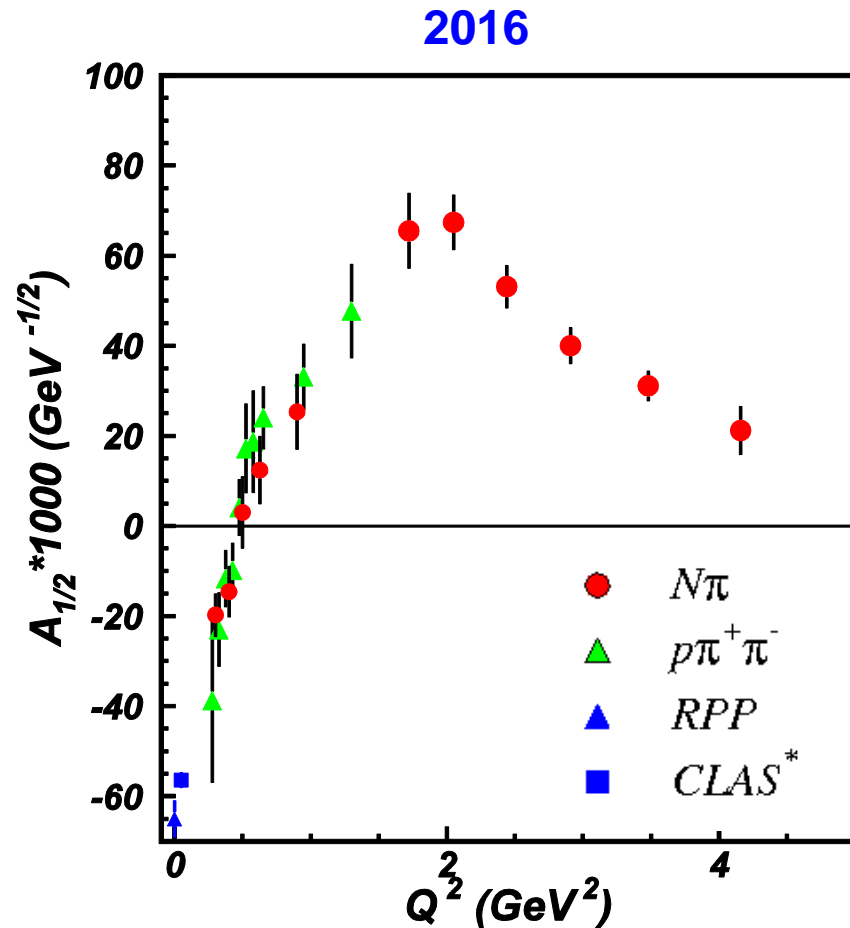
The values of resonance electrocouplings can be found in:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

The CLAS results on $\gamma_V p N^*$ electrocouplings for the excited states in mass range up to 1.8 GeV were interpolated/extrapolated in Q^2 -range up to 5.0 GeV^2 . The Fortran code for computation of $\gamma_V p N^*$ electrocoupling values is available in: userweb.jlab.org/~isupov/couplings/.

Roper resonance in 2002 & 2016



V. Burkert, *Baryons 2002*



V. D. Burkert, *Baryons 2016*

Electrocouplings of $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, $N(1710)1/2^+$ were published in the recent edition of the PDG, *Chin. Phys. C*40, 100001 (2016).

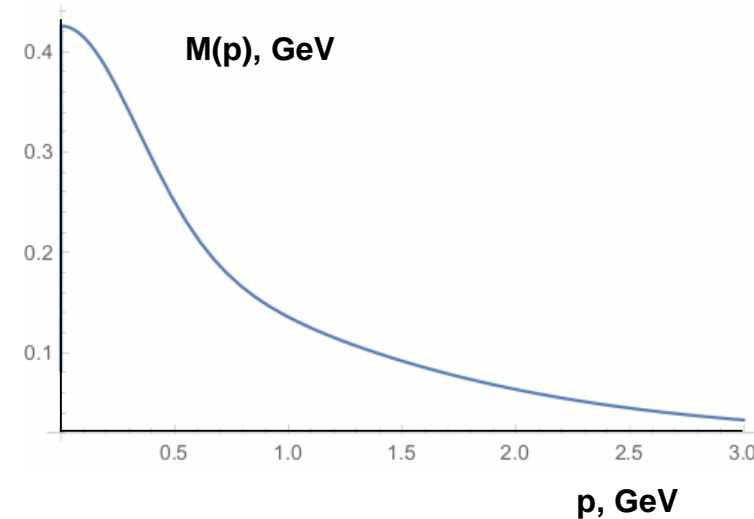
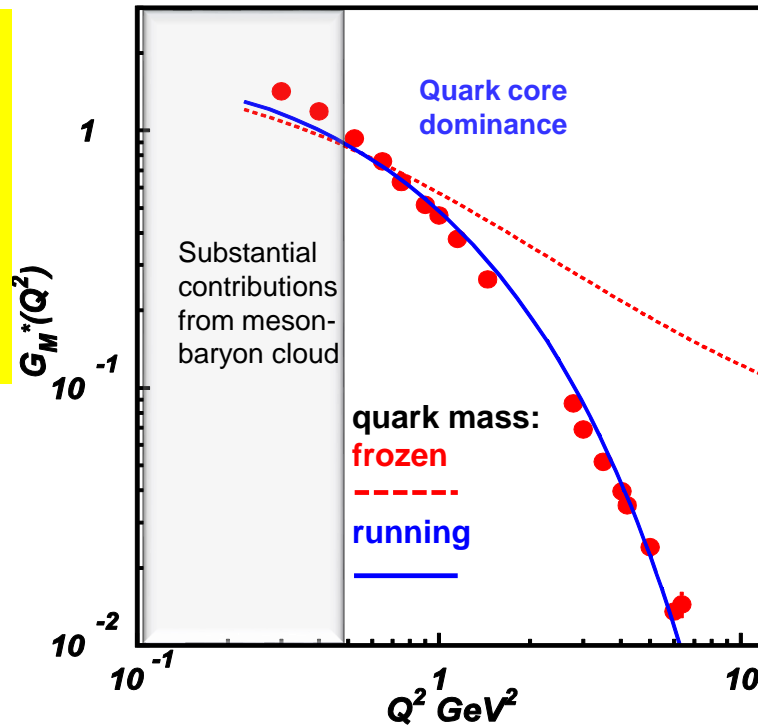
Evidence from Experiment for Running Dressed Quark Mass

$N \rightarrow \Delta(1232)3/2^+$ magnetic form factor
Jones-Scadron convention

Dyson-Schwinger Equations (DSE):

(DSE):

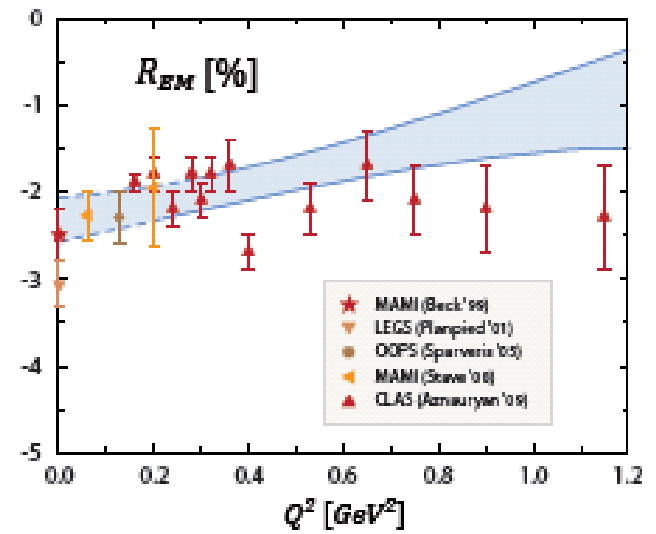
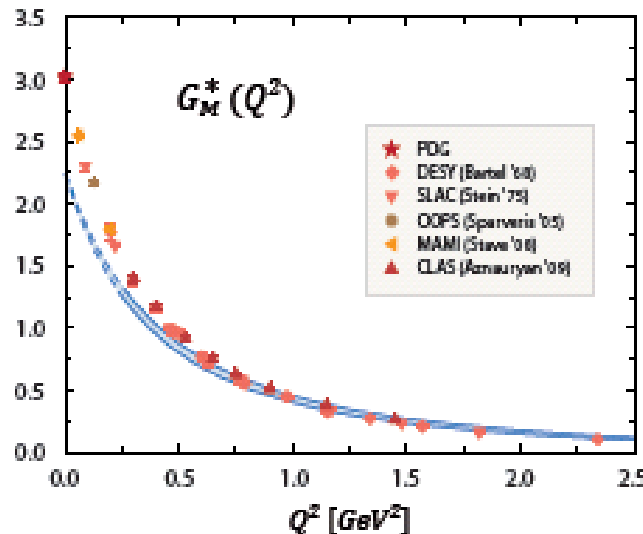
- J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).



Data on $\Delta(1232)3/2^+$ electroexcitation from CLAS for the first time demonstrated that dressed quark mass is running with momentum.

Successful f.f. description with running quark mass in independent DSE studies :

G.Eichmann et al., Phys. Rev D85, 093004 (2012) over narrower range of Q^2 , with simplified RL quark-gluon vertex.

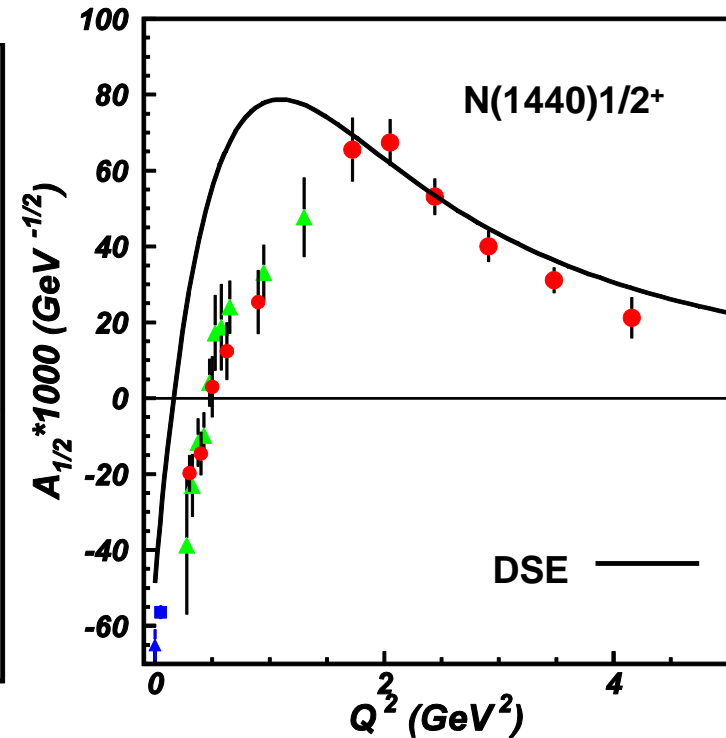
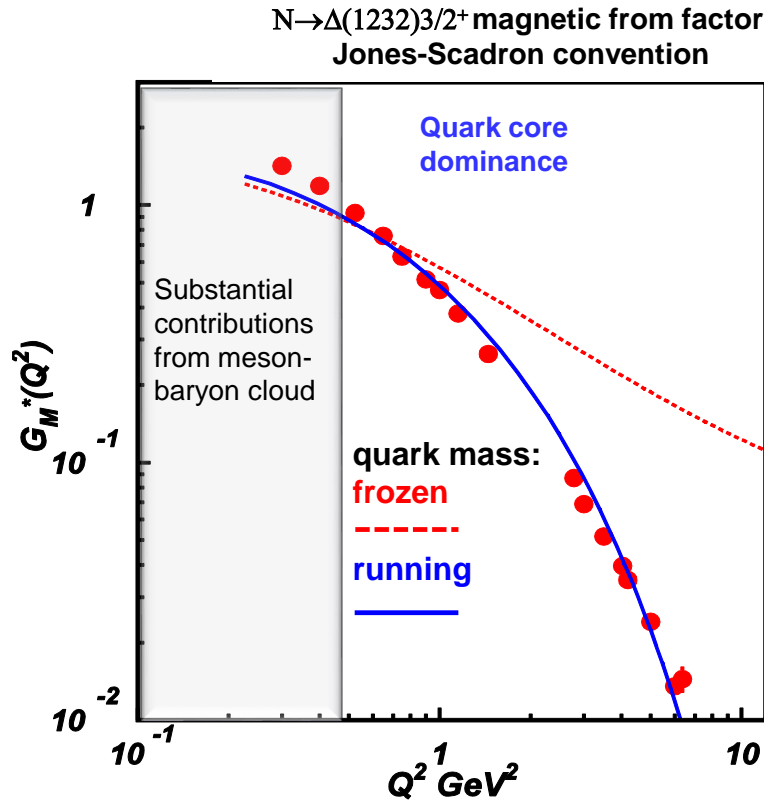


Validating the Access to the Quark Mass Function

Dyson-Schwinger Equations (DSE):

(DSE):

- J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).



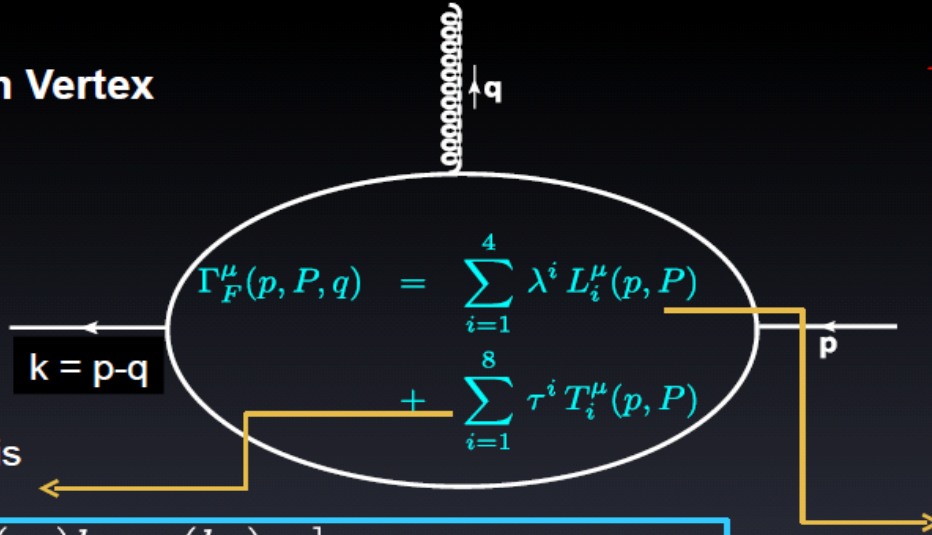
Good data description at $Q^2 > 2.0 \text{ GeV}^2$ achieved with the same dressed quark mass function for the ground and excited nucleon states of distinctively different structure provides strong evidence for:

- the relevance of dressed quarks with dynamically generated mass and structure;
- access to quark mass function from the data on elastic and $N \rightarrow N^*$ transition form factors.

One of the most important achievement in hadron physics of the last decade obtained in synergistic efforts between experimentalists and theorists.

Orbital Excited N* and Quark-Gluon Vertex

Quark Gluon Vertex



$$P = k + p$$

$$q = k - p$$

Simplest rainbow-ladder (RL) truncation:
All structures $L_{i\mu}$ are equal to zero except $L_{1\mu}$.

Far from reality, but a reasonable approximation for the states with orbital momentum of quarks $L=0$.

Dressing of quark-gluon vertex beyond RL-truncation produces nonzero quark orbital angular momenta.

Talks by: D.Binosi, A.Kizilerzu, J. Papavasiliou, G.Eichmann at NPQCD16
Workshop: www.uhu.es/gem/meeting/QCDNP2016/program-LP.php

Transverse Basis

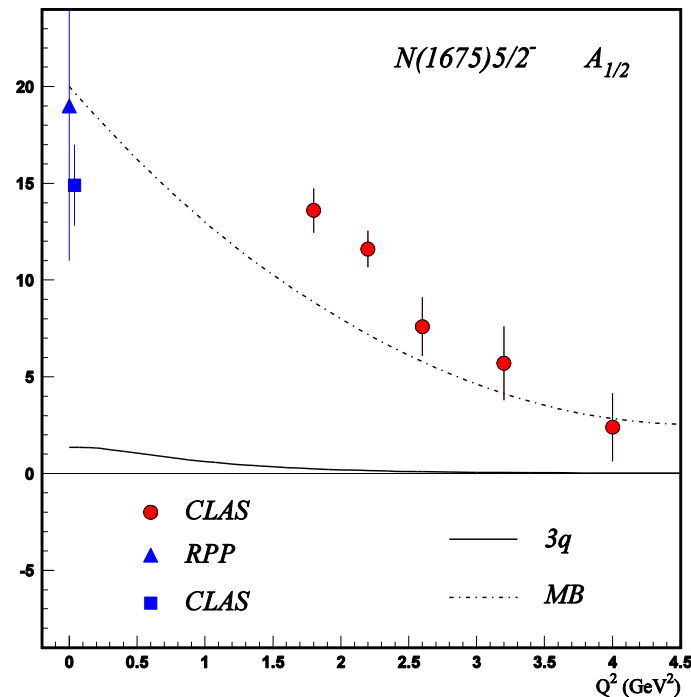
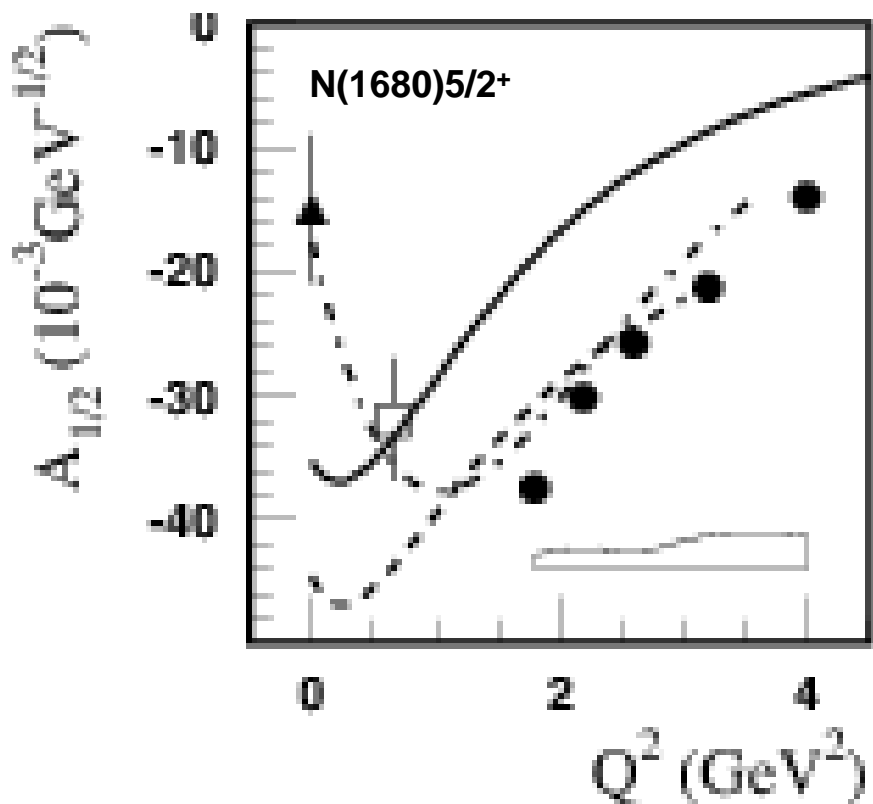
$$\begin{aligned} T_{1\mu} &= -i [(pq)k_\mu - (kq)p_\mu] \\ T_{2\mu} &= -\not{P} [(pq)k_\mu - (kq)p_\mu] \\ T_{3\mu} &= \not{q} q_\mu - q^2 \gamma_\mu \\ T_{4\mu} &= -i [q^2 \sigma_{\mu\nu} P_\nu + 2q_\mu \sigma_{\nu\lambda} p_\nu k_\lambda] \\ T_{5\mu} &= -i \sigma_{\mu\nu} q_\nu \\ T_{6\mu} &= (qP) \gamma_\mu - \not{q} P_\mu \\ T_{7\mu} &= -\frac{i}{2} (qP) \sigma_{\mu\nu} P_\nu - i P_\mu \sigma_{\nu\lambda} p_\nu k_\lambda \\ T_{8\mu} &= -\gamma_\mu \sigma_{\nu\lambda} p_\nu k_\lambda - \not{p} k_\mu + \not{k} p_\mu \end{aligned}$$

Longitudinal Basis

$$\begin{aligned} L_{1\mu} &= \gamma_\mu \\ L_{2\mu} &= -\not{P} P_\mu \\ L_{3\mu} &= -i P_\mu \\ L_{4\mu} &= -i \sigma_{\mu\nu} P_\nu \end{aligned}$$

Electrocouplings of N* states with nonzero quark orbital angular momentum extend the capabilities for access to the complexity of quark-gluon vertex dressing beyond the simplest rainbow-ladder truncation.

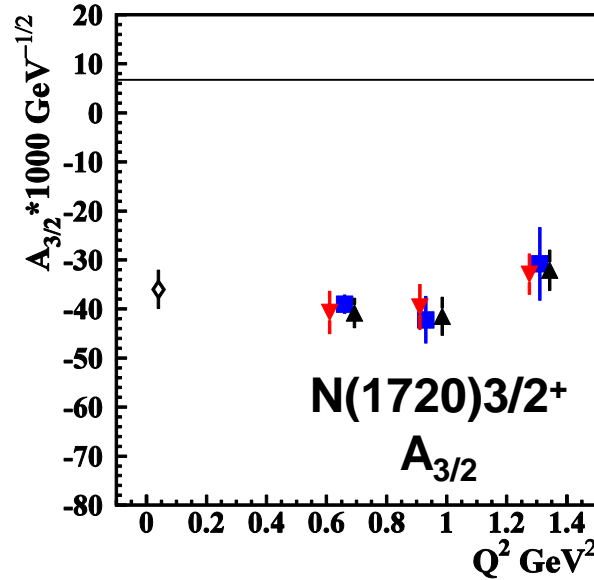
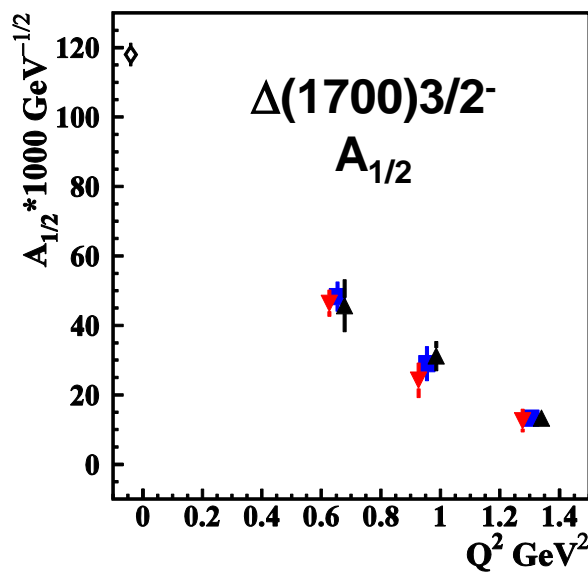
Electrocouplings of orbital-excited N^* in the 3-rd resonance region from π^+n electroproduction



New results from $N\pi$ channels, including those which cover $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$, will be presented in the talks by K.Park, M.Ungaro, N.Markov.

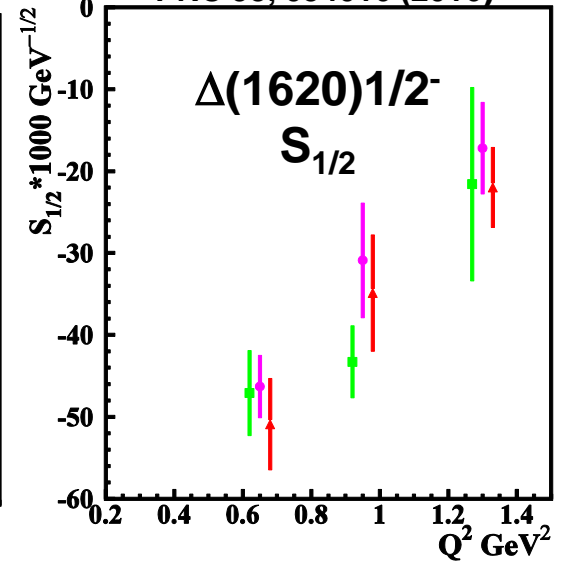
Electrocouplings of the Orbital Excited Resonances from the CLAS $\pi^+\pi^-p$ Electroproduction Data

V.I. Mokeev and I.G. Aznauryan., Int. J. Mod. Phys. Conf. Ser. 26. 146080 (2014)



V.I. Mokeev et al.,

PRC 93, 054016 (2016)



Independent fits in different W-intervals:

green: $1.51 < W < 1.61$ GeV red: $1.61 < W < 1.71$ GeV black: $1.71 < W < 1.81$ GeV
magenta: $1.56 < W < 1.66$ GeV blue: $1.66 < W < 1.76$ GeV

The $\pi^+\pi^-p$ electroproduction is the major source of the information on electrocouplings of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances which decay preferentially to the $N\pi\pi$ final states.

Extension of the Experimental Results on $\gamma_{\nu}pN^*$ Electrocouplings and Request for the Theory Support

- $\gamma_{\nu}pN^*$ electrocouplings of all prominent nucleon resonances in mass range $M_{N^*} < 2.0$ GeV and at $0.3 < Q^2 < 5.0$ GeV² will be determined from independent analyses of $N\pi$, $N\pi\pi$, channels measured with the CLAS in the near term future.
- In addition, high mass resonance electro-couplings ($M_{N^*} > 1.6$ GeV) will become available from KY electroproduction. ➡ [see talks by K.Park, M.Ungaro, N.Markov](#)
- DSE evaluations of the electrocouplings for the resonances of $[70,1^-]$ $SU_{sf}(6)$ -multiplet with $L=1$ in order to address:
 - a) environmental sensitivity of the quark mass function to orbital excitations of three dressed quarks;
 - b) complexity quark-gluon vertex dressing beyond the simplest rainbow-ladder truncation
 - c) access to pseudoscalar and vector di-quark correlations. ➡ [DSE talks Tuesday & Wednesday](#)
- Shed light on DCSB and its evolution with distance from electrocouplings of chiral partners:
 $\Delta(1232)3/2^+/\Delta(1700)3/2^-$, $N(1520)3/2^-/N(1720)3/2^+$, $N(1675)5/2^-/N(1680)5/2^+$
- Further development of the quark models (hCQM, LFQM, AdS/CFT) for description of orbital excited N^* by:
 - implementing input from DSE ➡ [see V.D.Burkert talk, Friday morning](#)
 - updating the model ingredients based on the description of the CLAS results on their electrocouplings ➡ [talks by E. Santopinto, I.Obukhovsky, V.Lyubovotsky](#)
- LQCD efforts for the N^* electrocouplings evaluation ➡ [see talks by D.G. Richards and R.Briceno](#)

N* at $0.05 \text{ GeV}^2 < Q^2 < 7.0 \text{ GeV}^2$ with the CLAS12

Hybrid Baryons PR12-16-010	Search for hybrid baryons (qqqq) focusing on $0.05 \text{ GeV}^2 < Q^2 < 2.0 \text{ GeV}^2$ in mass range from 1.8 to 3 GeV in $K\Lambda$, $N\pi\pi$, $N\pi$ (A. D'Angelo, et al.)
KY Electroproduction PR12-16-010A	Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield Q^2 evolution of electrocoupling amplitudes at $Q^2 < 7.0 \text{ GeV}^2$ (D. Carman, et al.)

Approved by PAC44

Run Group conditions:

$E_b = 6.6 \text{ GeV}$, 50 days

$E_b = 8.8 \text{ GeV}$, 50 days

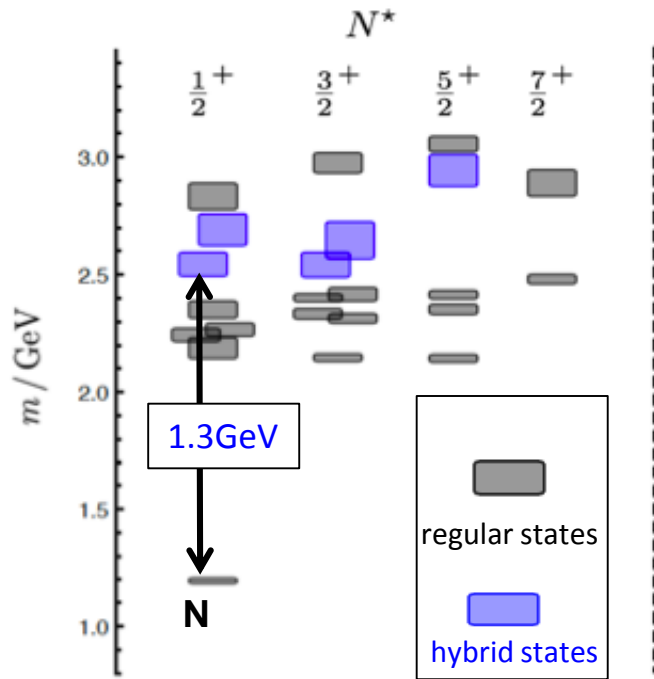
- Polarized electrons, unpolarized LH_2 target
- $L = 1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Hunting for Glue in Excited Baryons with CLAS12

Can glue be a structural component to generate hybrid q^3g baryon states?

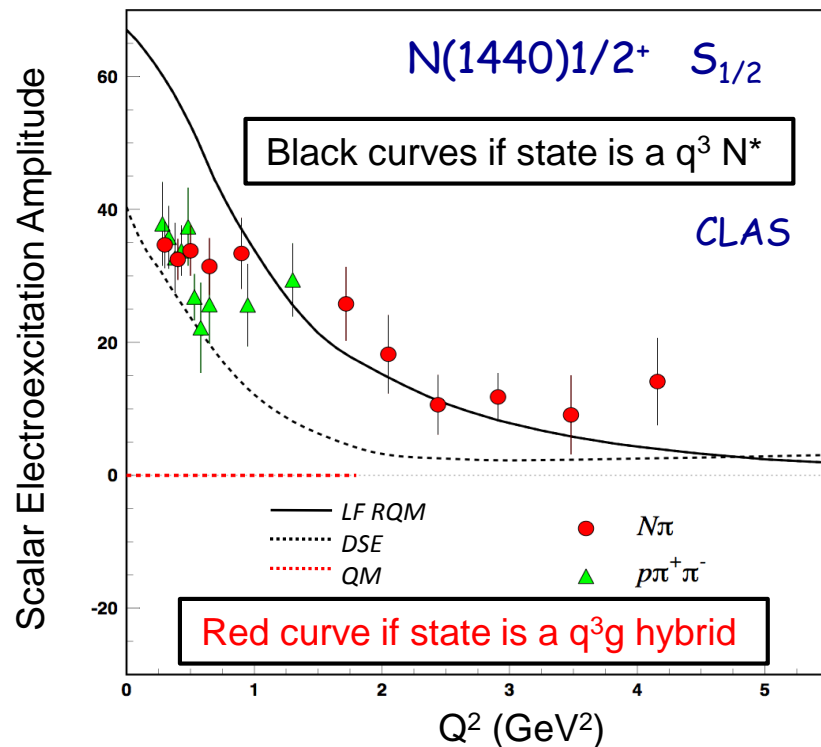
Predictions of the N^* spectrum from QCD show both regular q^3 and hybrid q^3g states

The only way to establish the nature of a baryon state as q^3 or q^3g is from the Q^2 evolution of its electroexcitation amplitude



JLab LQCD group results

Search for hybrid baryons with CLAS12 in exclusive $K\gamma$ and $\pi^+\pi^-p$ electroproduction



Request for the Theory Support on Hybrid Baryon Search

- Extension of Bonn-Gatchina multi-channel approach for extraction of resonance electrocouplings from exclusive meson electroproduction data at low and intermediate Q^2 , at least.
- Quark model predictions on Q^2 -evolution of electrocouplings for the N^* states with masses from 2.0 GeV to 2.5 GeV, spin-parities $J^P = 1/2^+, 3/2^+$ assuming: a) the contribution from $3q$ only, b) $qqqG$ hybrid nature.
- Evaluation of the contributions from meson-baryon cloud to the structure of the aforementioned resonances employing both reaction and structural models.
- Full spectrum of the nucleon resonances with $J^P = 1/2^+, 3/2^+$ from DSE identifying regular qqq and hybrid $qqqG$ states.
- If feasible, LQCD predictions on electrocouplings of low lying hybrid

E12-09-003

Nucleon Resonance Studies with CLAS12

Burkert, Mokeev, Stoler, Joo, Gothe, Cole

E12-06-108A

KY Electroproduction with CLAS12

Carman, Mokeev, Gothe

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

$E_b = 11 \text{ GeV}$, $Q^2 = 3 \rightarrow 12 \text{ GeV}^2$, $W \rightarrow 3.0 \text{ GeV}$ with the almost complete coverage of the final state phase space

- Key Motivation

Study the structure of all prominent N^ states in the mass range up to 2.0 GeV vs. Q^2 up to 12 GeV².*

CLAS12 is the only facility foreseen in the world capable to map-out N^ quark core under almost negligible contributions from meson-baryon cloud*

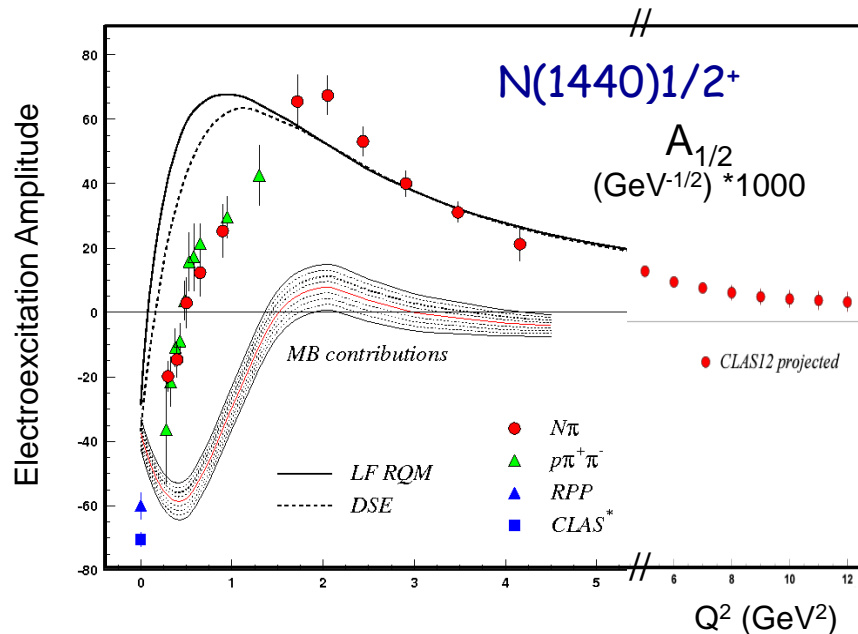
The experiments will start in the first year of running with the CLAS12 detector.

Emergence of Hadron Mass and Quark-Gluon Confinement

N* electroexcitation studies with CLAS12 in Hall B at JLab will address the critical open questions:

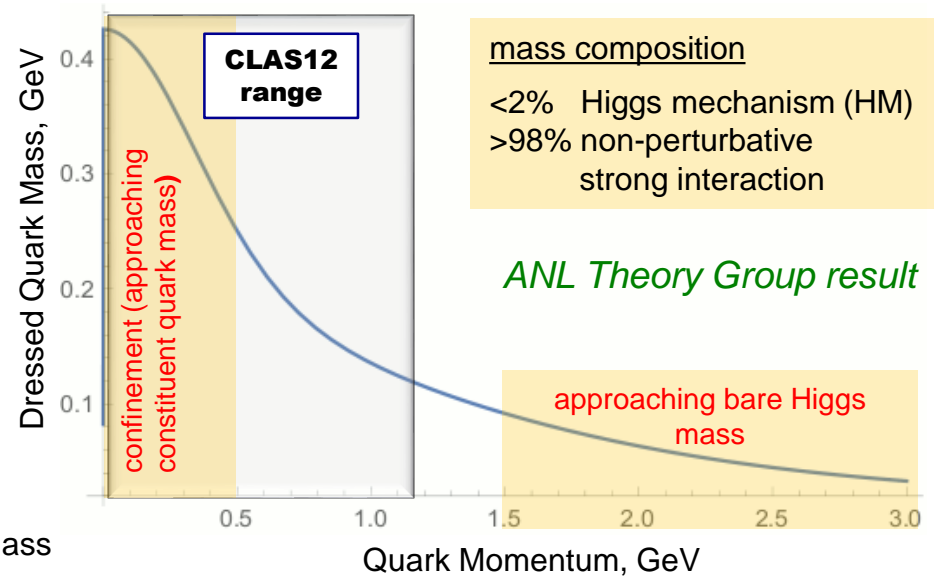
How is >98% of visible mass generated,?

How confinement emerges from QCD and how it is related to DCSB?



CLAS results versus theory expectations with running quark mass

Exploration of dressed quark mass function from the data on resonance electrocouplings



Conclusions and Outlook

- High quality meson electroproduction data from CLAS allowed us to determine the electrocouplings of most well-established resonances in mass range up to 1.8 GeV from analyses of π^+n , π^0p , ηp and $\pi^+\pi^-p$ electroproduction channels.
- Strong impact of the N^* studies on the QCD-based hadron structure theory:
 - a) first DSE evaluations of $\Delta(1232)3/2^+$ and $N(1440)1/2^-$ electroexcitation amplitudes starting from the QCD Lagrangian;
 - b) synergistic efforts between ANL Theory group and the Hall-B at JLAB conclusively demonstrated the feasibility to explore dressed quark mass function from the experimental results on elastic and transition $N \rightarrow N^*$ form factors.
- Electrocouplings of most resonances in the mass range up to 2.0 GeV will become available at $Q^2 < 5.0 \text{ GeV}^2$ from independent analyses of the new CLAS data on $N\pi$ and $\pi^+\pi^-p$ electroproduction in the near term future.
- Future analyses the CLAS results on electrocouplings of orbital-excited resonances within the QCD-based framework will provide new insight to non-perturbative strong interaction dynamics addressing:
 - a) the environmental sensitivity of dressed quark mass function,
 - b) complexity of the dressed quark-gluon vertex and di-quark correlation,
 - c) shed light on the DCSB manifestation in the structure of chiral partner resonances.



Conclusions and Outlook

- After 12 GeV Upgrade, CLAS12 will be only available worldwide facility capable to obtain electrocouplings of all prominent N^* states at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photo virtualities ever achieved for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from the measurements of exclusive $N\pi, \pi^+\pi^-p$, and KY electroproduction.
- The expected results will allow us:
 - a) search for hybrid-baryons and other new states of baryon matter;
 - b) fully explore the transition to quark-core dominance and emergence of MB-cloud;
 - c) to map out the dressed quark mass function at the distance scales where the transition from quark-gluon confinement to pQCD regime is expected, addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and quark-gluon confinement.
- Success of N^* Program with the CLAS12 detector at Jefferson Lab will be very beneficial for hadron physics community . It requires close collaborative efforts between experiment, phenomenology and the QCD-based hadron structure theory.

