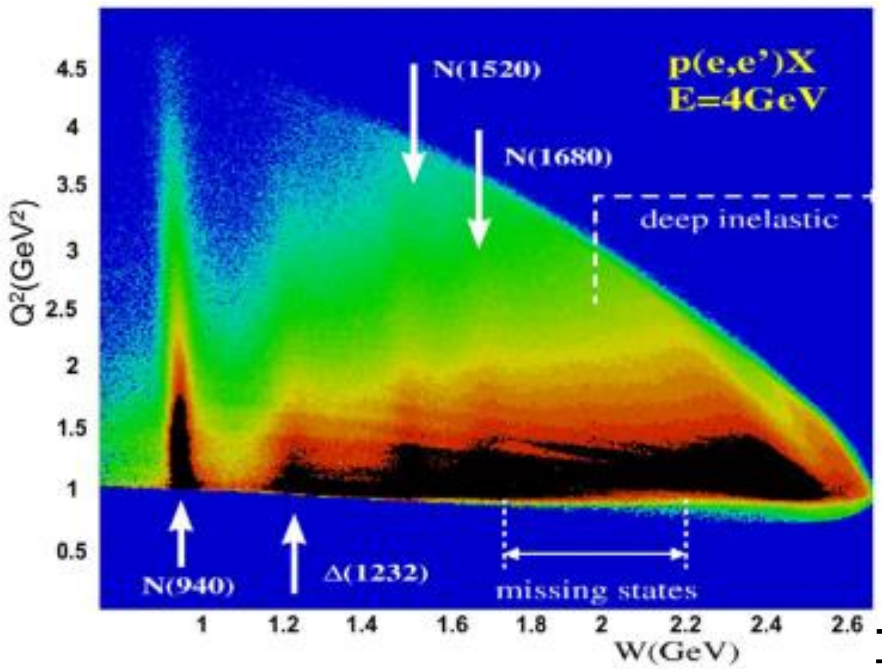
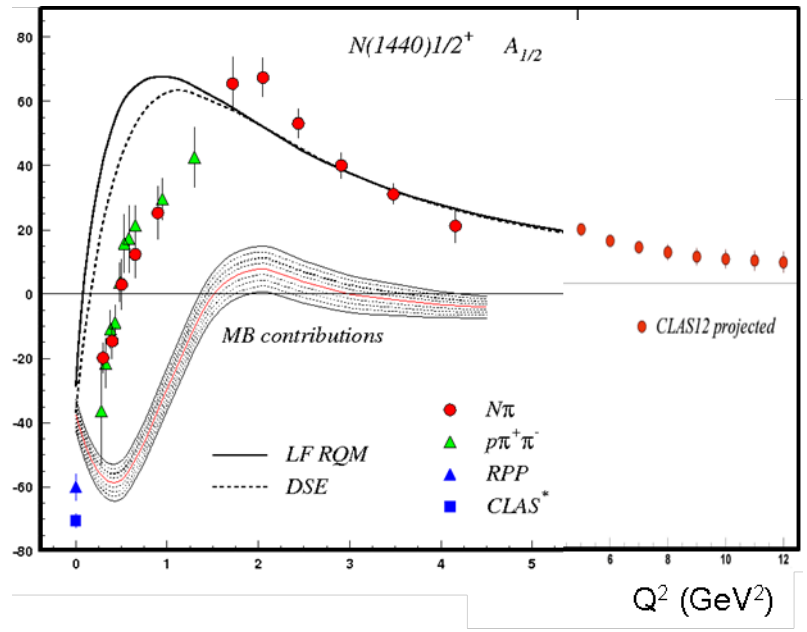
Excited Nucleon Structure and Strong QCD from Experiments with Electromagnetic Probes





V.I. Mokeev,
Jefferson Laboratory

Talk outline:

- N* electrocouplings as a window into strong QCD
- Extraction of $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction data
- From $\gamma_v pN^*$ electrocouplings to strong QCD dynamics
- Future prospects with CLAS12 and N*/DIS synergy

Office of Science

The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era, July 1-4, 2018, APCTP, Pohang, Korea

Major Directions in the Studies of N*-Structure with CLAS/CLAS12

The experimental program on the studies of N* structure in exclusive meson electroproduction with CLAS/CLAS12 seeks to determine:

- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from the CLAS data
- extend accessible Q^2 range up to 12 GeV^2 from the CLAS12 data and explore N* structure evolution in the transition from the strong and pQCD regimes
- search for hybrid baryons at 2.0 GeV < W < 2.5 GeV and Q^2<2.0 GeV^2; completion of the N*-spectrum exploration from exclusive meson photo- and electroproduction off proton data

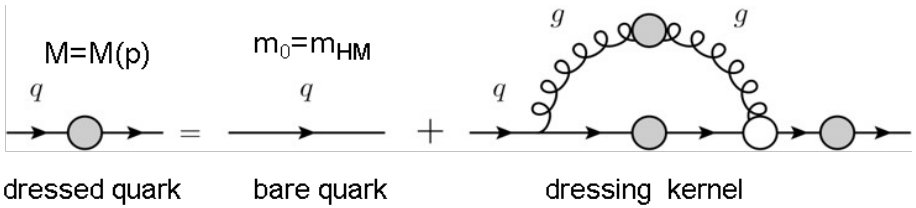
A unique source of information on many facets of strong QCD in generating different excited nucleon states

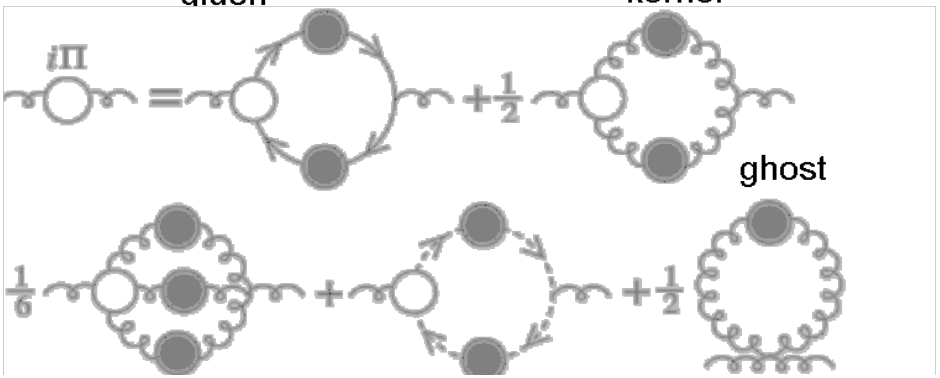
Review papers:

1. **I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).**
2. **I.G. Aznauryan et al., Int. J. Mod. Phys. E22,1330015 (2013).**
3. **V.D. Burkert, Few Body Syst. 59, 57 (2018).**
4. **C.D. Roberts, Few Body Syst. 59, 72 (2018).**

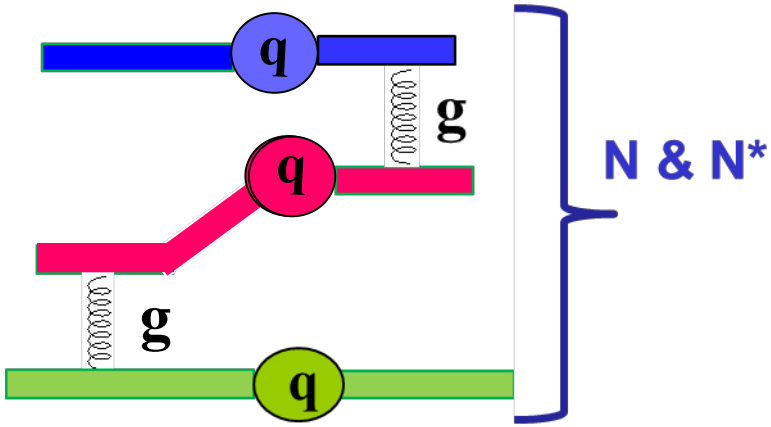
Excited Nucleon States and Insight into Strong QCD Dynamics

Emergence of Dressed Quarks and Gluons
D. Binosi et al, Phys. Rev. D95, 031501 (2017)

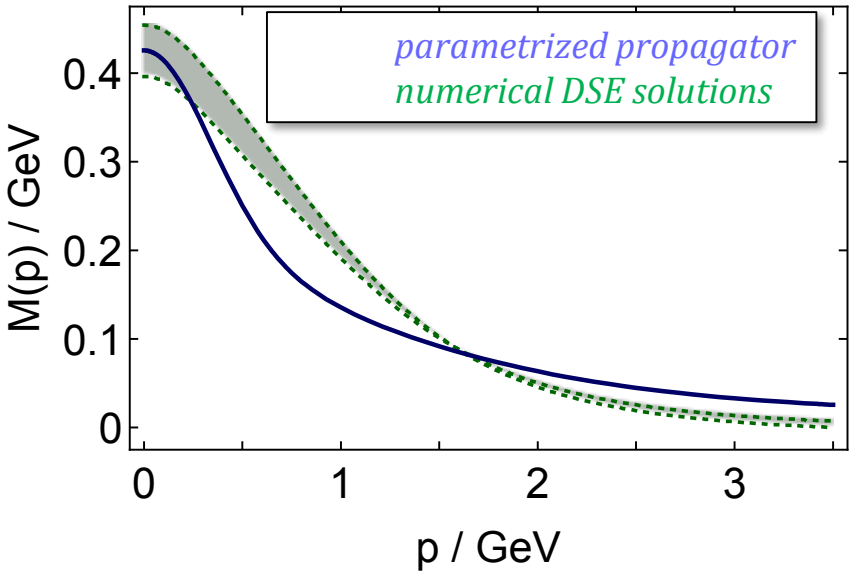




Dressed Quark Borromeo Binding in Baryons
Ch. Chen et al, Phys. Rev. D97, 034016 (2018)



Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)



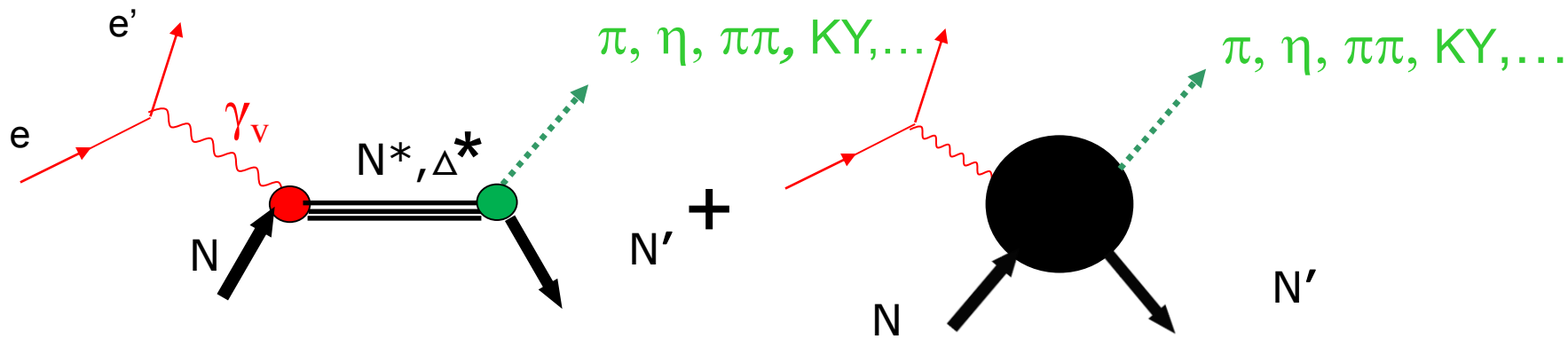
Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

N* structure studies address:

- **Nature of > 98% of hadron mass**
- **Confinement and color charge emergence from QCD**

Extraction of $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes **Non-resonant amplitudes**



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

- **Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$**

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

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

- **Consistent results on $\gamma_v pN^*$ electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.**

Summary of Published/Submitted 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'**
$\pi^+\pi^-p$	**1.3-1.60** **1.4-2.10** **1.4-2.00** **1.3-1.83**	**0.2-0.6** **0.5-1.5** **2.0-5.0** **0.4-1.0**	**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 asym-metries
- P^0, P' –recoil and transferred polarization of strange baryon

Over 140,000 data points!

Almost full coverage of the final hadron phase space

The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi.

Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings

Analyses of different meson electroproduction channels independently:

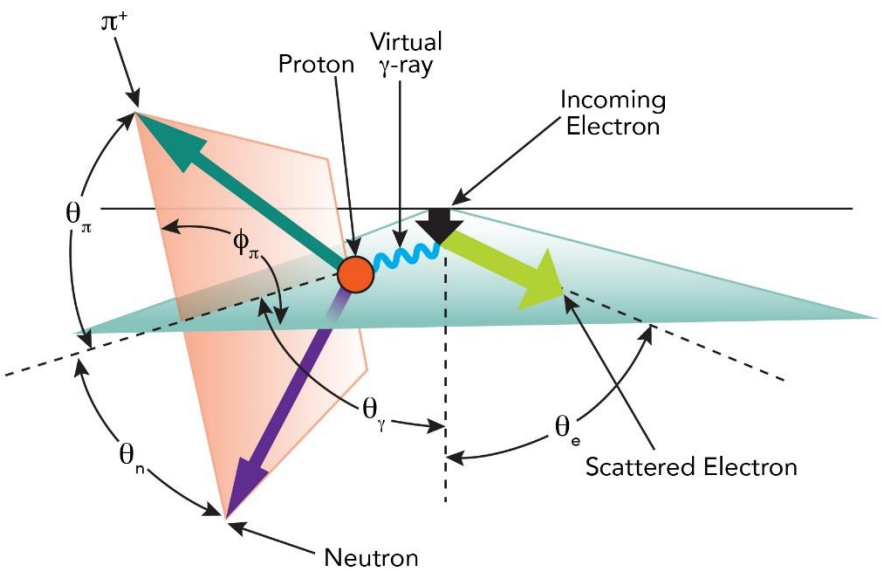
- **$\pi^+ n$ and $\pi^0 p$ channels:**
  Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)
  I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)
- **ηp channel:**
  Extension 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), 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), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)

Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018)
H. Kamano, JPS Conf. Proc. 13, 010012 (2017)

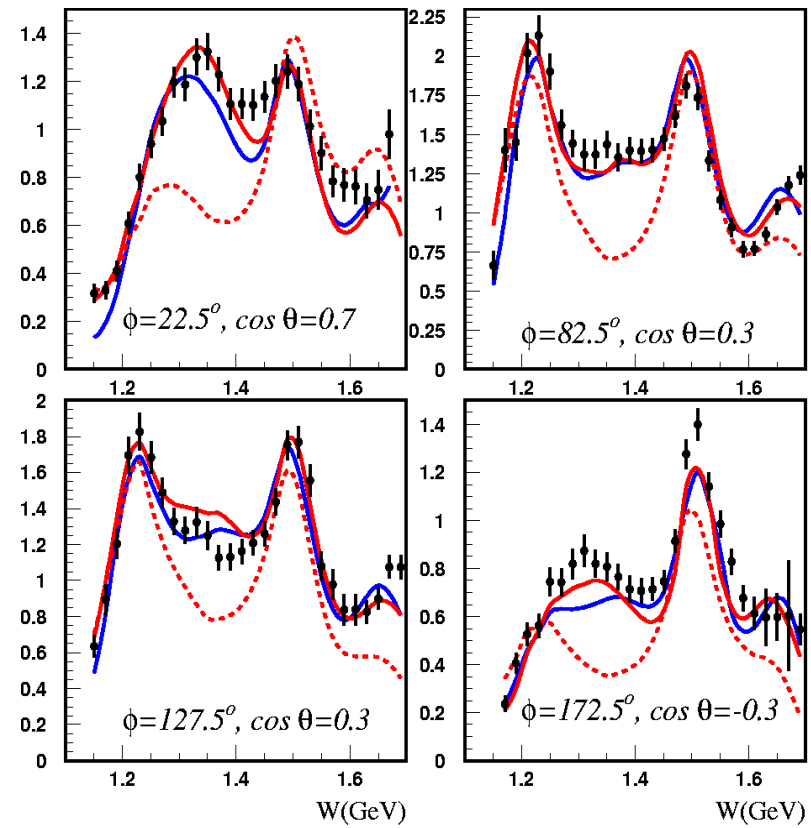
Accessing Resonance Electrocouplings from the π^+n Differential Electroproduction Cross Sections off Protons

Kinematics of exclusive π^+n electroproduction off protons (lab frame)



Q^2=2.05 GeV^2

DR
DR w/o P11
UIM

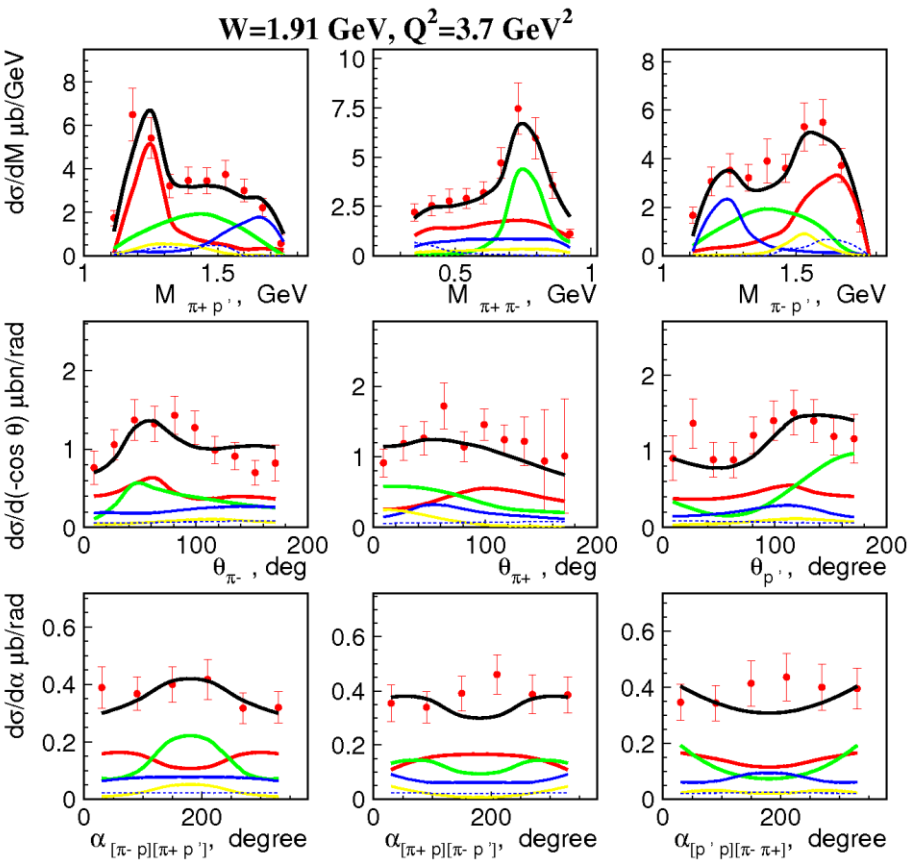


The final pion angles are in the CM-frame of the final hadrons

Accessing Resonance Electrocouplings from the $\pi^+\pi^-p$ Differential Electroproduction Cross Sections off Protons

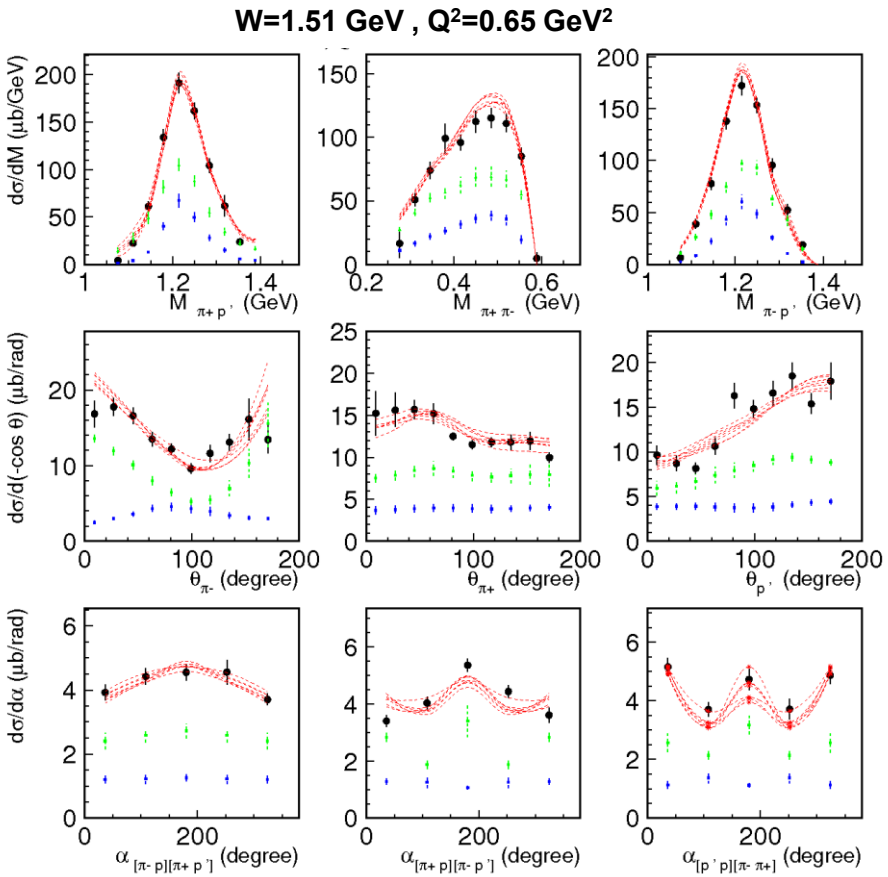
Contributing mechanisms seen in the data

E. Isupov et al. (CLAS), Phys. Rev. C96, 025209 (2017)



Resonant and non-resonant contributions

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



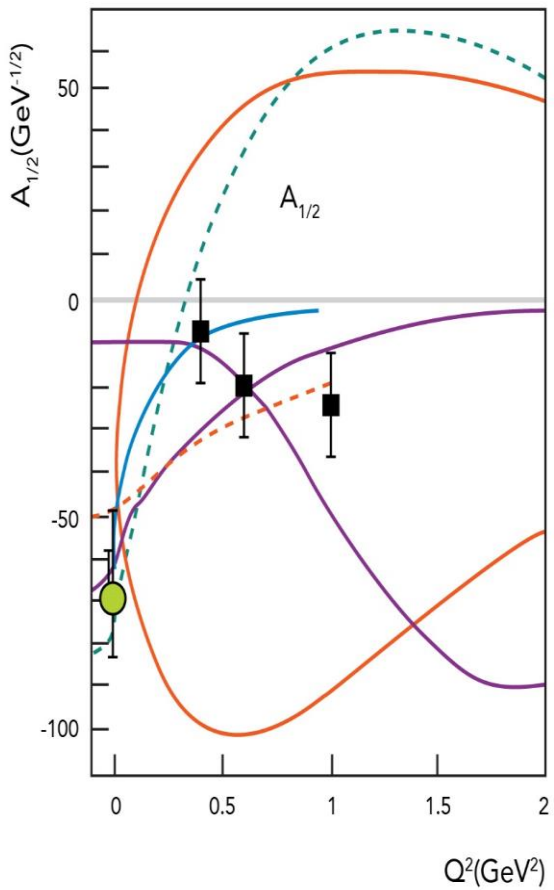
full JM — ρp — π^+ N(1520)3/2$^-$ — data fit within JM under variations of both resonant and background parameters

$\pi^-\Delta^{++}$ — $\pi^+\Delta^0$ — π^+ N(1680)5/2$^+$ — background cross sections

resonant cross sections

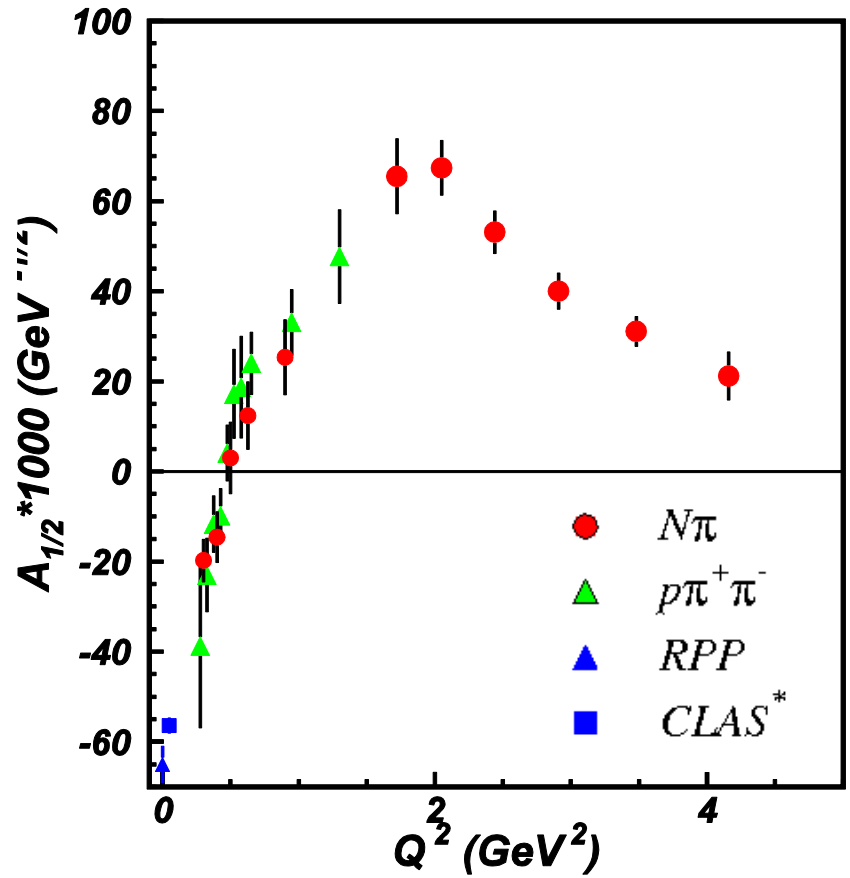
Roper Resonance in 2002 & 2018

2002



V. D. Burkert, Baryons 2002

2018



V. D. Burkert, Baryons 2016

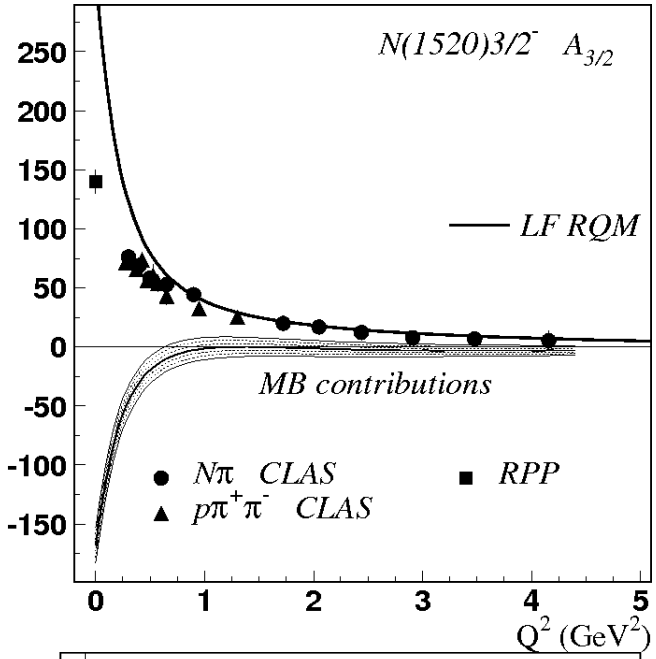
Summary of Results on $\gamma_v pN^*$ Electrocouplings from CLAS

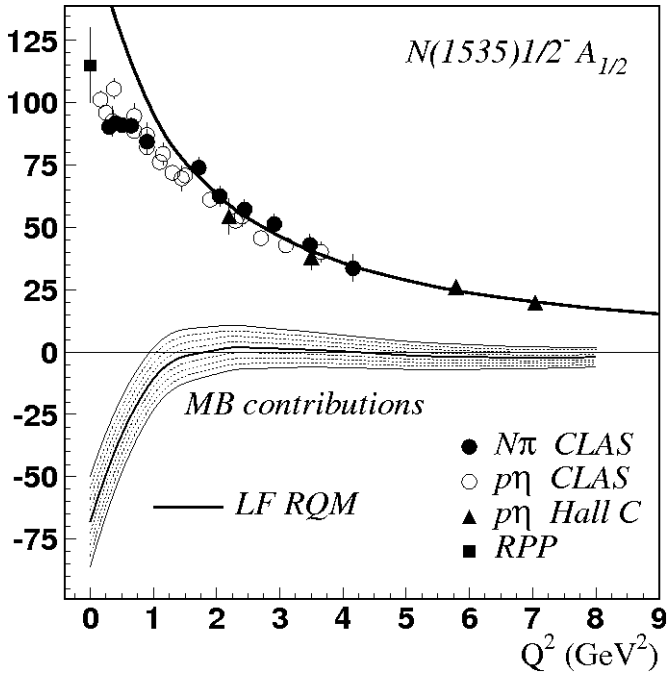
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5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

The website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

The interpolated/extra[polated CLAS results on $\gamma_v pN^*$ electrocouplings in the mass range <1.8 GeV and Q^2<5.0 GeV^2 :
userweb.jlab.org/~isupov/couplings/.

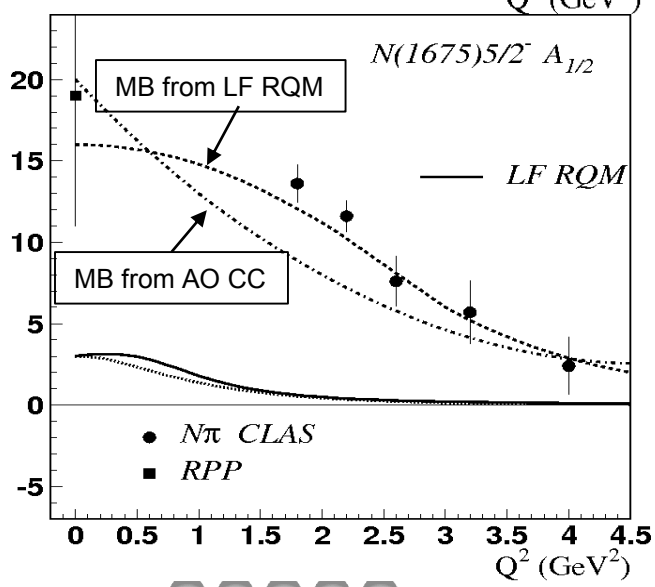
$\gamma_v pN^*$ Electrocouplings from $N\pi$, $N\eta$, and $\pi^+\pi^-p$ Electroproduction





CLAS data points from:
I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
K. Park et al., Phys. Rev. C91, 045203 (2015).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
V.I. Mokeev et al., Phys. Rev.. C93, 025206 (2016).

LF RQM:
I.G. Aznauryan and V.D. Burkert, Phys. Rev. C95, 065207 (2017).
AO CC:
B. Julia-Diaz et al., Phys. Rev. C77, 045205 (2008).



Consistent values of resonance electrocouplings from $N\pi$, $N\eta$, and $\pi^+\pi^-p$ electroproduction strongly support their reliable extraction

The structure of all resonances studied with CLAS represents a complex interplay between the inner quark core and external meson-baryon cloud.

Δ- Electrocouplings: Global Multi-Channel Analysis vs Nπ Electroproduction off Protons Analysis

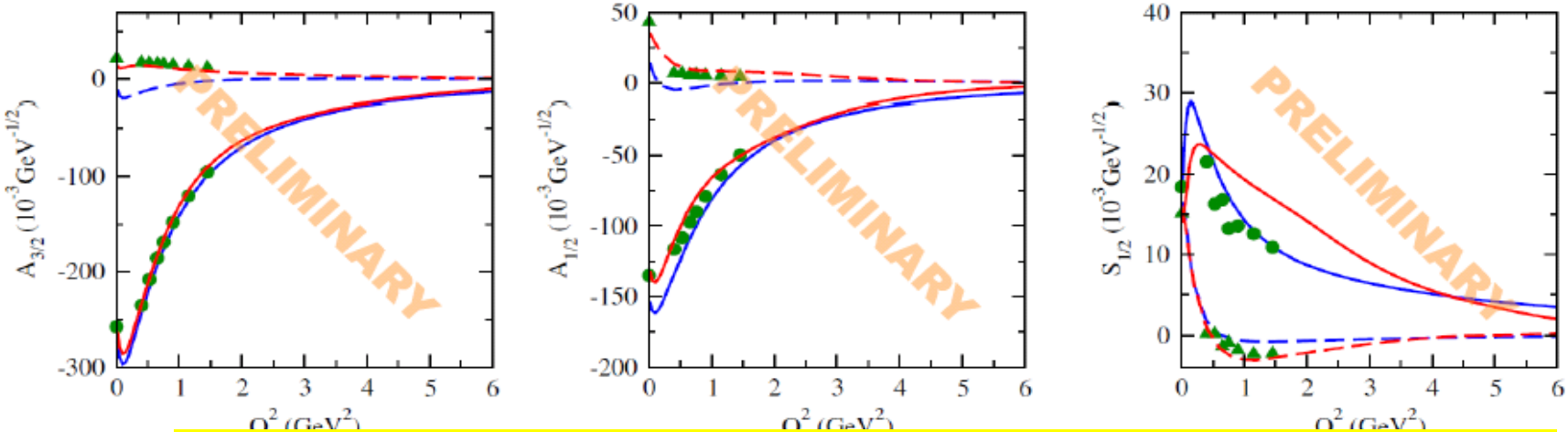
Re part

Im part

Other lines/symbols:
Previous AO analyses

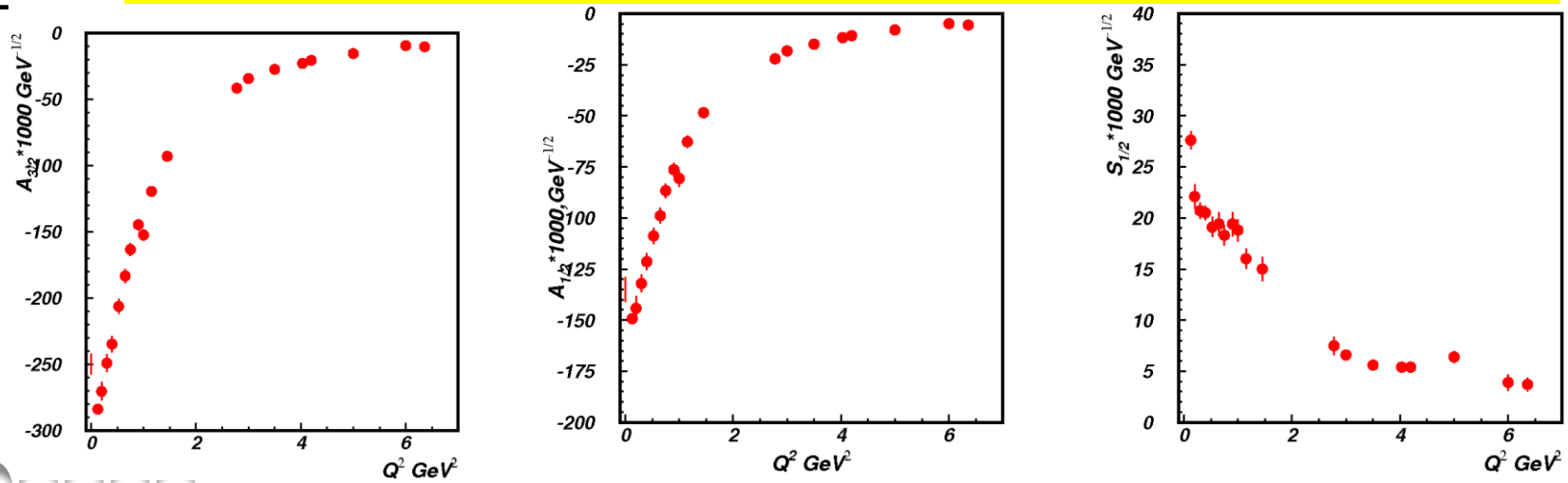
Argonne-Osaka (AO) eight-channel coupled channel approach. H.Kamano, Few Body Syst. 59, 24 (2018)

at the pole position



CLAS results at the resonant point (W=M_{N^*}) from analysis of Nπ electroproduction

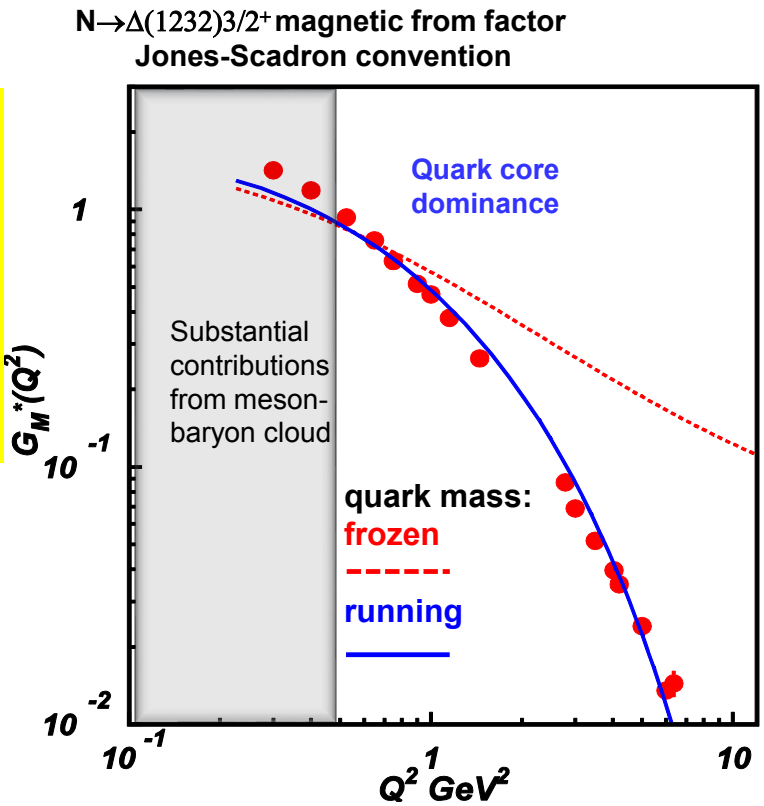
real electro-coupling values

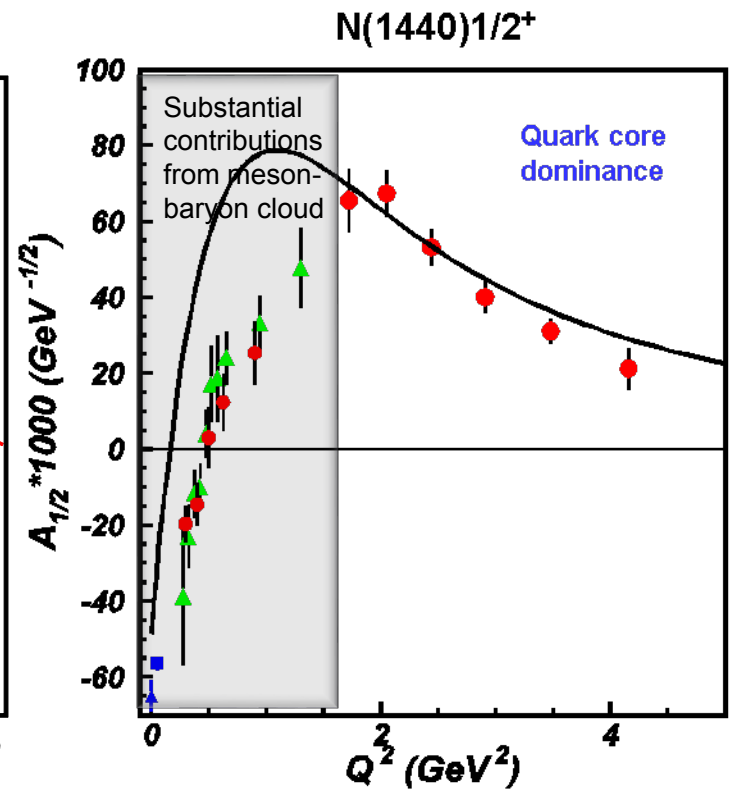


From Resonance Electrocouplings to Hadron Mass Generation

Dyson-Schwinger Equations (DSE):

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

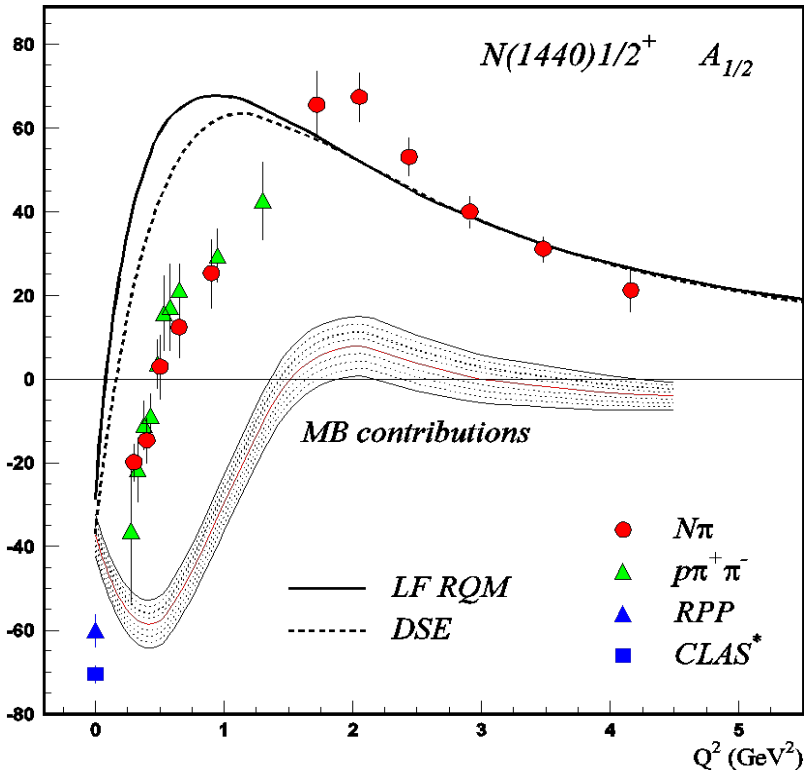




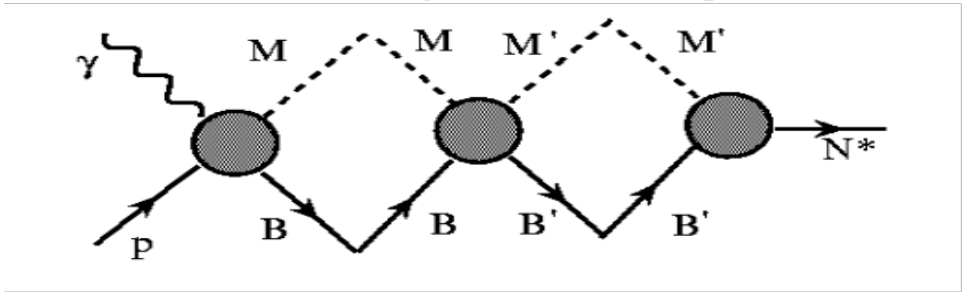
- *Dressed quark mass is running with momentum.*
- Good data description at Q^2>2.0 GeV^2 with <u>the same dressed quark mass function</u> for the ground and different excited nucleon states validate the DSE results on generation of dressed quarks as the relevant degree of freedom in the structure of the ground and excited nucleons.
- $\gamma_v pN^*$ electrocoupling data offer access to the strong QCD dynamics underlying the hadron mass generation.

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

Resolving Roper Puzzle



The mechanisms of the meson-baryon dressing



CLAS data in the range of Q^2<5.0 GeV^2 revealed the structure of N(1440)1/2$^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

LF RQM-Light Front relativistic quark model: V.D. Burkert, I.G. Aznauryan, Phys . Rev. C85, 055202 (2012); Phys. Rev. C95, 065207 (2017).

Quark core description within LF RQM and DSE is consistent

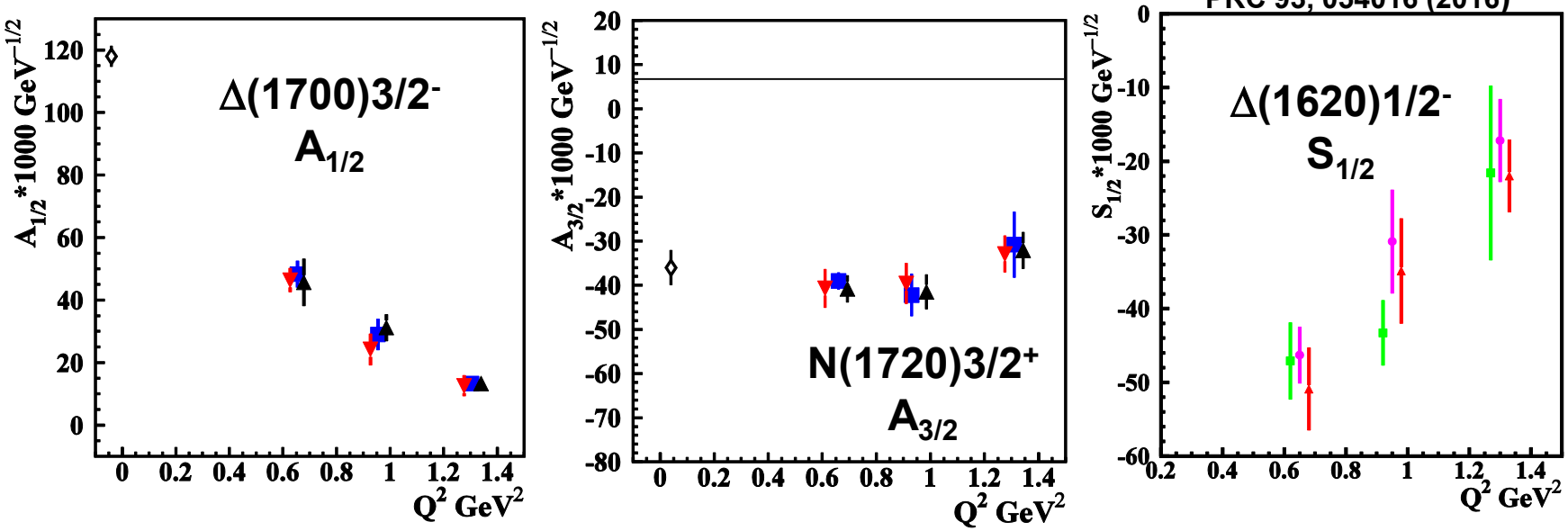
For more details on resolving Roper puzzle see:

V. D. Burkert and C.D. Roberts ``Roper resonance-solution to the fifty year puzzle", arXiv:1710.02549 [nucl-ex] .

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)

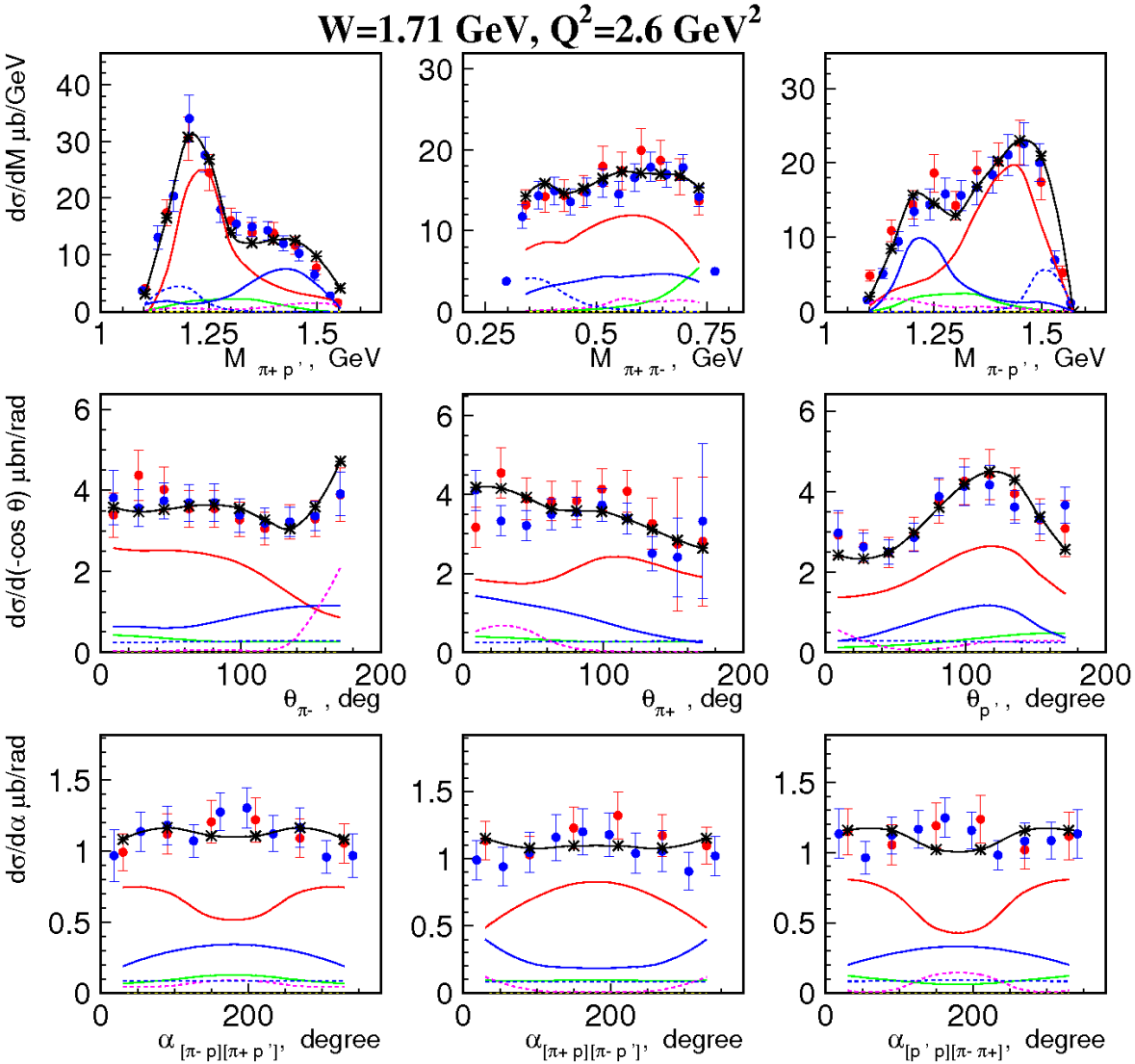


Independent fits in different W-intervals:

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 information on electrocouplings of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances that decay preferentially to the $N\pi\pi$ final states.

Extending the Kinematical Coverage of $\pi^+\pi^-p$ Electroproduction off Proton Data

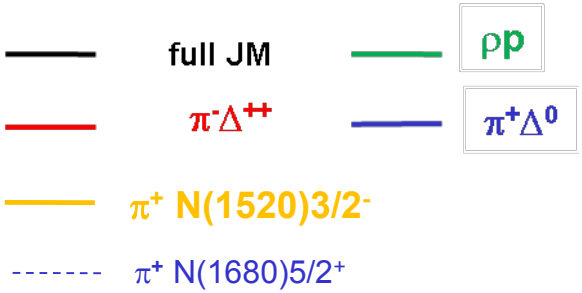


Two data sets at
1.40 GeV <W<2.0 GeV and
2.0 GeV² < Q² < 5.0 GeV² :

red - E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017).

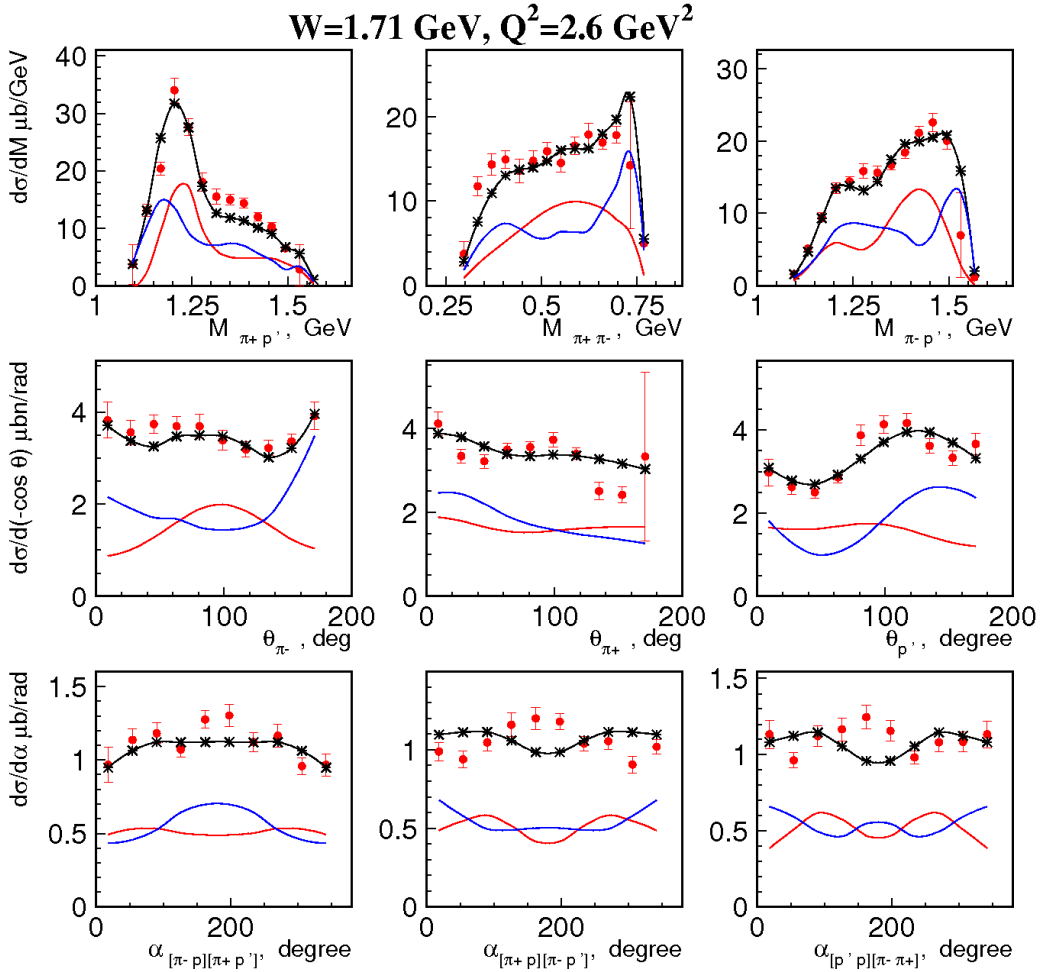
blue - preliminary, A.Trivedi, R.W. Gothe, USC.

JM18 results:



The JM18 model offers a good description of both $\pi^+\pi^-p$ electroproduction off protons data sets

Future Extension of the Results on $\gamma_v pN^*$ Electrocouplings



JM18 model version adjusted to the preliminary A.Trivedi & R.W. Gothe data

Resonant contributions

Non-resonant contributions

Significant resonant contributions and pronounced differences in behavior of the resonant /non-resonant contributions seen in all nine one-fold differential cross sections.

In the near term future electrocouplings of most excited nucleon states in the mass range up to 2.0 GeV will become available from these data sets at 2.0 GeV²<Q²<5.0 GeV²

Future Developments in the N* Structure Studies from the CLAS Data and Possible Connection to DIS Research

- **The $\gamma_v pN^*$ electrocouplings of most resonances in the mass range of W<2.0 GeV will become available in the near term future at Q^2<5.0 GeV^2 from the $N\pi$ and $\pi^+\pi^-p$ electro-production off protons data.**

- **Offer an excellent opportunity to map out dressed quark mass function at the distances corresponded strong QCD regime.**

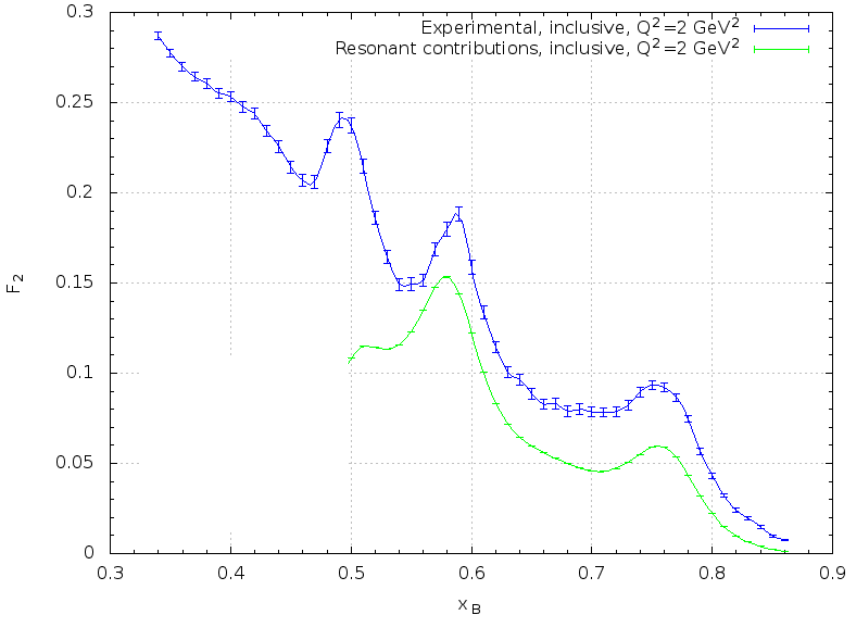
- **Theoretical framework for the combined studies of the N* and ground nucleon structure in one- and three-dimensions:**

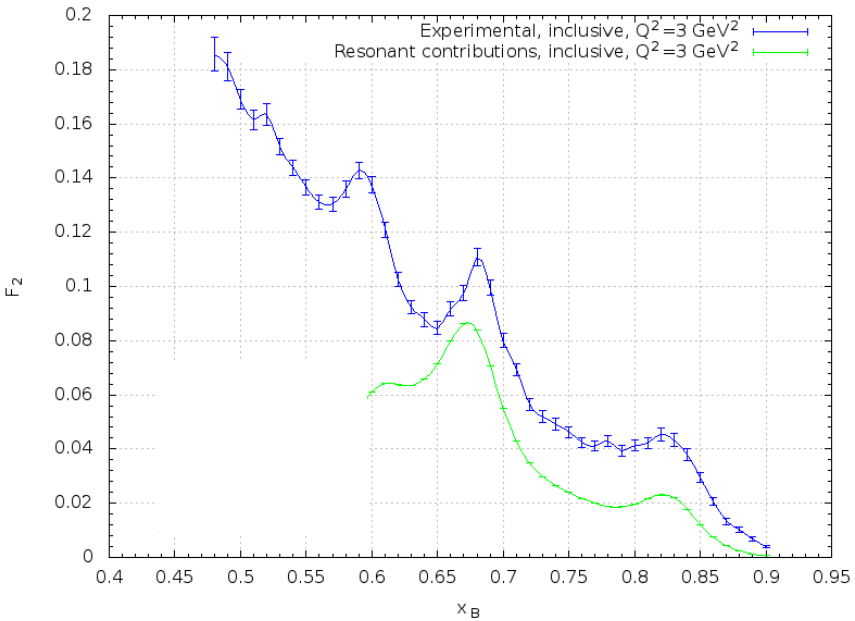
  common quark mass function for N/N*↔ light front ground nucleon wave function ↔ GPDs, TMDs

- **The JM model estimates of the $\gamma_v p \to \pi^- \Delta^{++}$, $\pi^+\Delta^0$, ρp cross sections and amplitudes are of potential interest for πX semi-inclusive studies, allowing us to account for the processes beyond those described within the factorization framework.**

- **Access to the ground nucleon parton distributions at large x_B in the resonance region.**

Accessing Parton Distributions in the Resonance Region





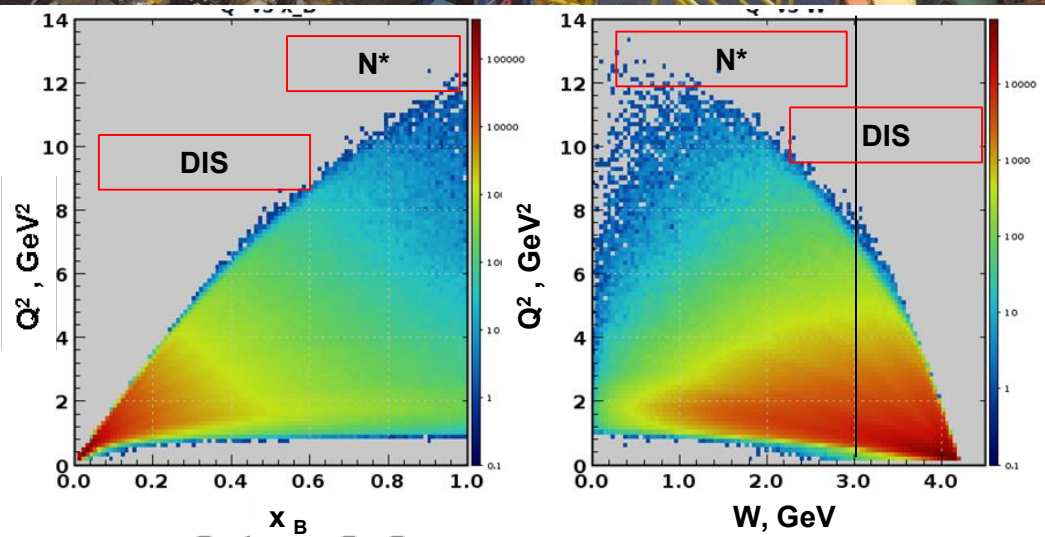
Interpolation of the CLAS data on $F_2(x,Q2)$ structure function, M.Osipenko et al. (CLAS Coll), Phys. Rev. D67, 092001 (2003).

Resonant contributions from the CLAS results on $\gamma_v pN^*$ electrocouplings stored in: userweb.jlab.org/~mokeev/resonance_electrocouplings, userweb.jlab.org/~isupov/couplings/

The CLAS results on electrocouplings of most N* in the mass range of W <1.8 GeV and at Q^2<5.0 GeV^2 makes it possible to evaluate the resonant contributions to the inclusive electron scattering offering access to the parton distributions at large x_B in the resonance region

See details in the talk: A.N. Hiller Blin ``Constraints from Finite-Energy Sum Rules on Inclusive Electron and Virtual Compton Scattering"

12 GeV Era with the CLAS12 Detector



Physics run started successfully in February 2018.

CLAS12 N* Program at High Q^2

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Gothe, Mokeev, Burkert, Cole, Joo, Stoler	*Carman, Gothe, Mokeev*

- 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. GeV, Q^2 = 3 → 12 GeV^2, W → 3.0 GeV with nearly 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 GeV^2.*

  CLAS12 is the only facility to map-out the N quark with minimal meson-baryon cloud contributions.*

The experiments already started in February 2018!

Emergence of Hadron Mass and Quark-Gluon Confinement

N* electroexcitation studies at JLab will address the critical open questions:

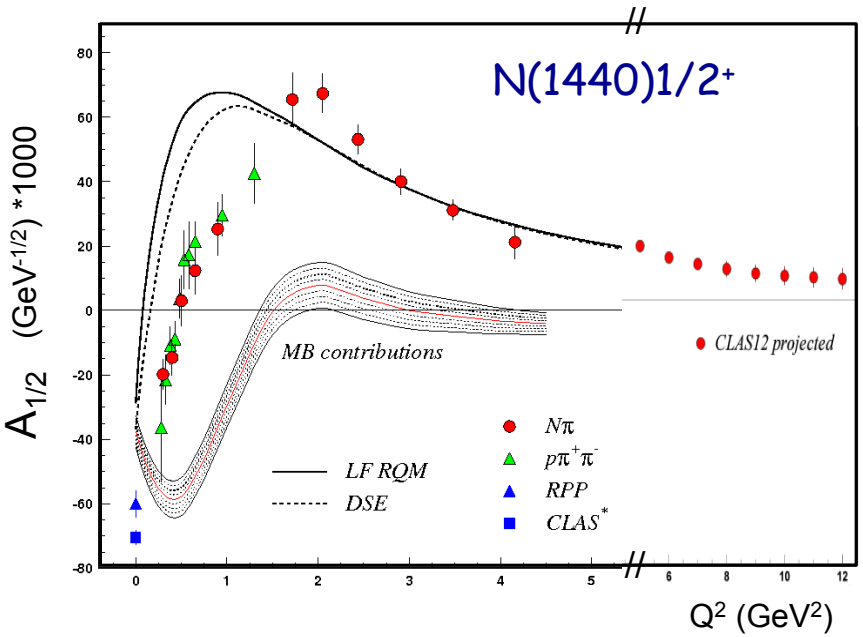
How is >98% of visible mass generated?

How does confinement emerge from QCD and how is it related to Dynamical Chiral Symmetry Breaking?

What is the behavior of QCD's running coupling at infrared momenta?

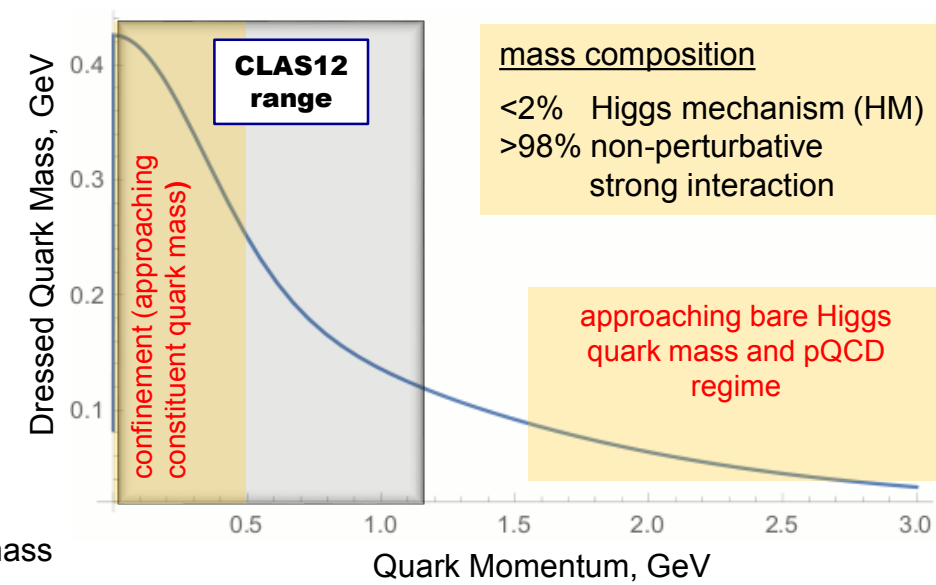
(D. Binosi et al., Phys. Rev. D96, 054026 (2017))

Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<12$ GeV^2 will allow us to explore the transition from strong QCD to pQCD regimes.



CLAS results versus theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



Conclusions and Outlook

- **High quality meson electroproduction data from CLAS have allowed us to determine the electrocouplings of most resonances in the mass range up to 1.8 GeV with consistent results from analyses of π^+n, π^0p, ηp, and $\pi^+\pi^-p$ electroproduction channels.**

- **Physics analyses of the $\gamma_v pN^*$ electroexcitation amplitudes have revealed the structure of excited nucleons as a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud.**

- **<u>Profound impact on the exploration of strong QCD dynamics:</u>**
  a) first DSE evaluations of $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes with a traceable connection to the QCD Lagrangian;
  b) synergistic efforts between the experimental studies of $\gamma_v pN^*$ electrocouplings in Hall B at JLab and the continuum QCD theory have demonstrated the capability for reliable access to the mechanisms underlying hadron mass generation.

- **Electrocouplings of most resonances in the mass range up to 2.0 GeV will become available at $Q^2<5.0$ GeV^2 from the new CLAS data on $N\pi$ and $\pi^+\pi^-p$ electroproduction in the near term future.**

- **Resonant contributions to the inclusive structure functions computed with $\gamma_v pN^*$ electrocouplings inferred from the CLAS exclusive meson electroproduction off protons data offer an opportunity to explore the ground nucleon parton distributions at large x_B in the resonance region.**

Conclusions and Outlook

- **CLAS12 is the only facility in the world capable of obtaining electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photon virtualities for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from measurements of Nπ, $\pi^+\pi^-$p, and KY electroproduction.**

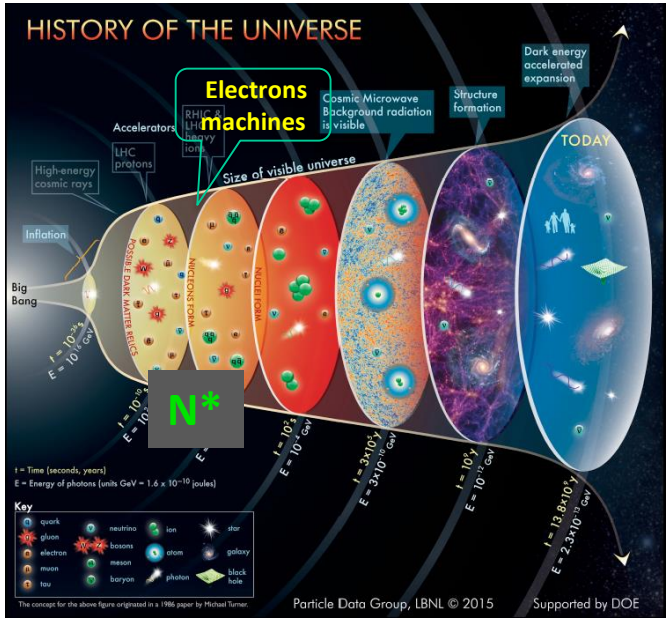
- **The expected results will allow us:**
  a) to search for hybrid-baryons and complete the N*-spectrum exploration;
  b) to map out the dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected, <u>addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.</u>

- **Success of the N* program will be very beneficial for the hadron physics community. Synergistic effort between experimentalists, phenomenologists, and theorists on the combined studies of γ_vpN* electrocouplings, elastic form factors, and the results on the 3D ground nucleon structure is required.**

- **The QCD-rooted theory framework for the unified description of the ground and excited nucleon state structure offering a <u>description and predictions</u> of the parameters extracted from experiment is of particular importance.**

Back up

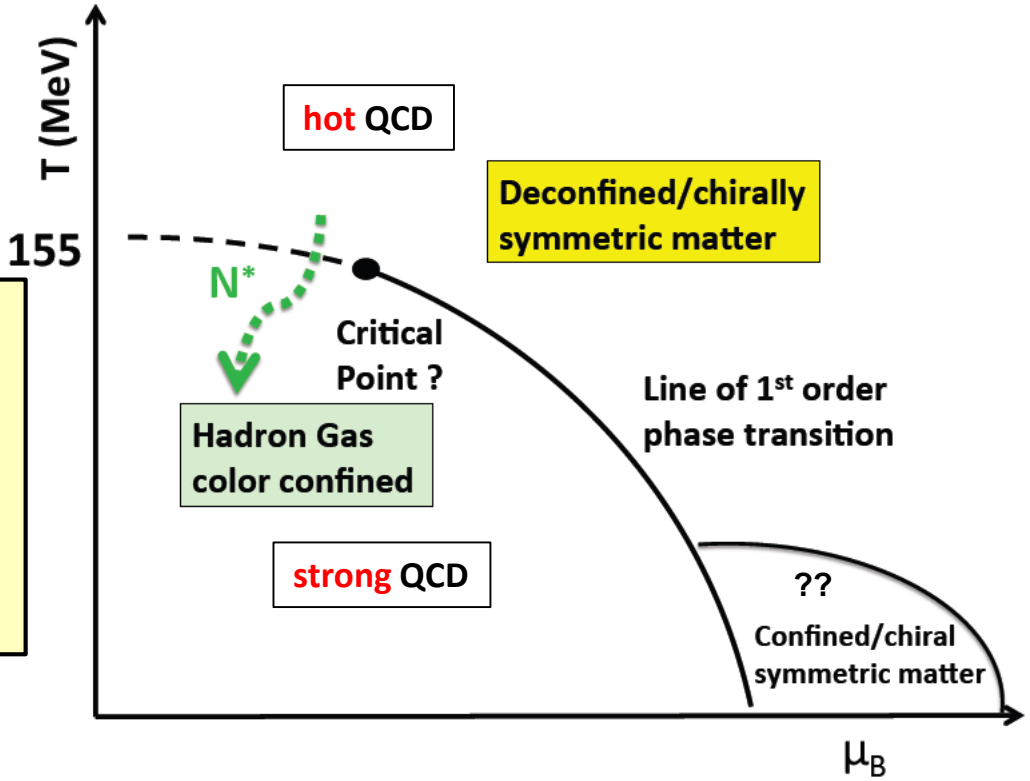
Nucleon Resonances in the History of the Universe



Dramatic events occur in the micro-second old universe during the transition from the QGP phase to hadron phase.

- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Quark-gluon confinement emerges

Full baryon spectrum shaped this transition



N* studies at 0.05 GeV^2 < Q^2 < 7.0 GeV^2 with CLAS12

Hybrid Baryons E12-16-010	Search for hybrid baryons (qqqg) focusing on 0.05 GeV^2 < Q^2 < 2.0 GeV^2 in mass range from 1.8 to 3 GeV in KΛ, Nππ, Nπ *(A. D'Angelo, et al.)*
KY Electroproduction E12-16-010A	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 GeV^2 *(D. Carman, et al.)*

Approved by PAC44

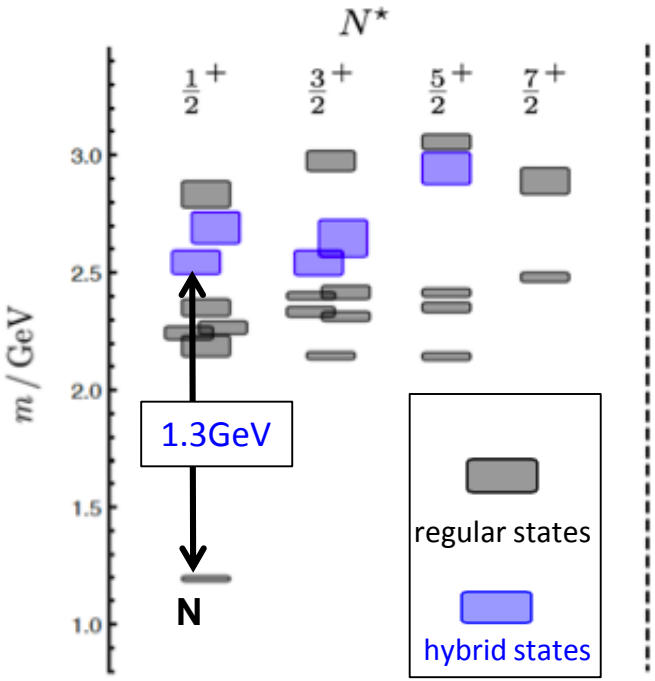
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- Polarized electrons, unpolarized LH_2 target
- L = 1x10^{35} cm^{-2}s^{-1}

Hunting for Glue in Excited Baryons with CLAS12

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

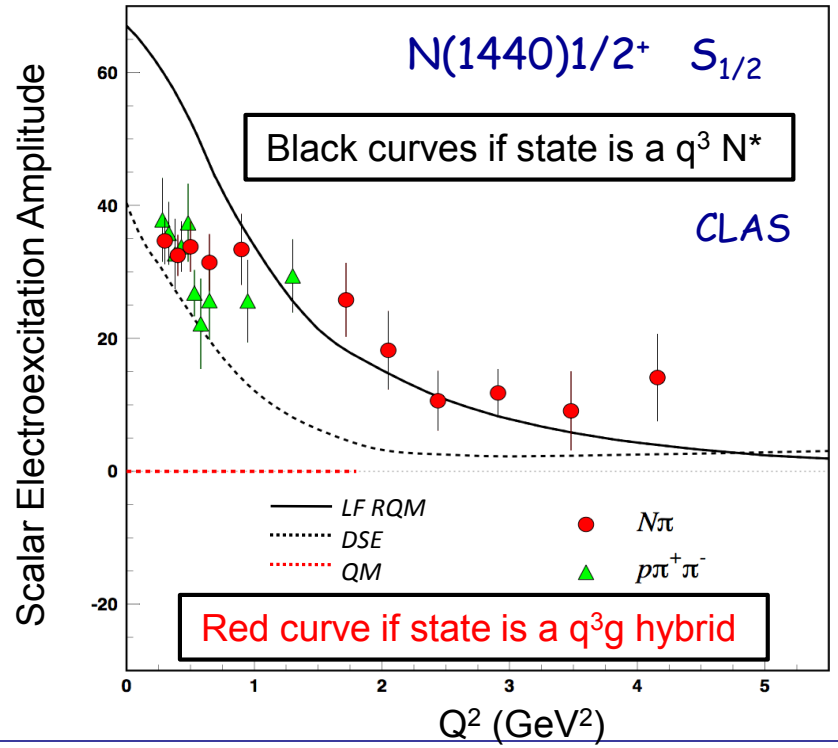
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



JLab LQCD group results

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

LQCD and/or QM predictions on Q^2 evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state



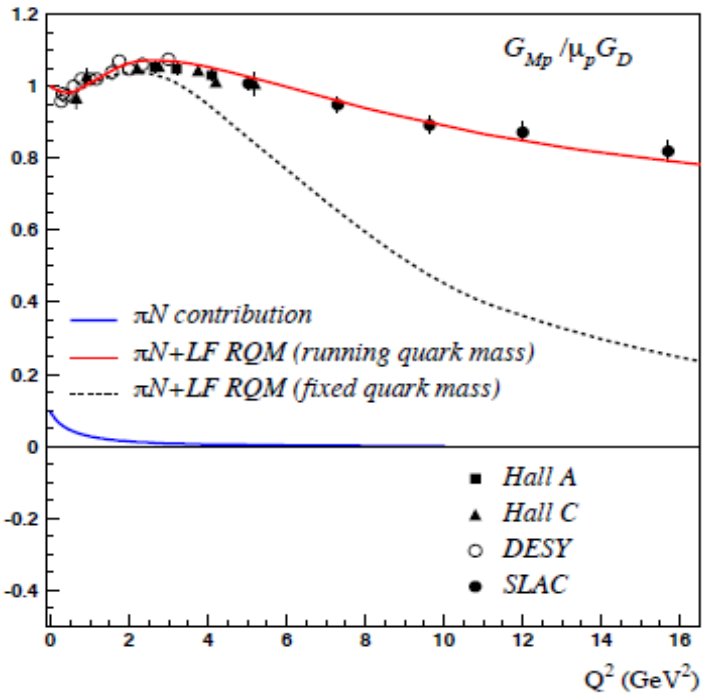
Quark Model with Input from QCD-based Approaches

Light Front QM by I.G. Aznauryan and V.D. Burkert: PRC 85, 055202 (2012).

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.

Proton Magnetic Form Factor



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

Implementation of momentum-dependent quark mass is needed in order to reproduce elastic magnetic form factor of proton at Q^2>3.0 GeV^2