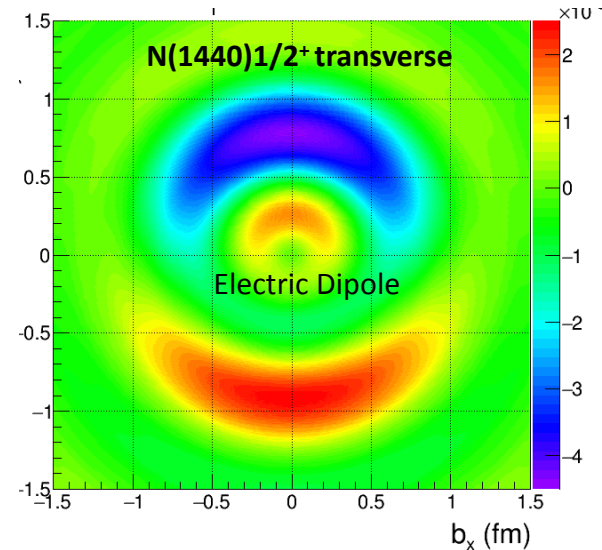
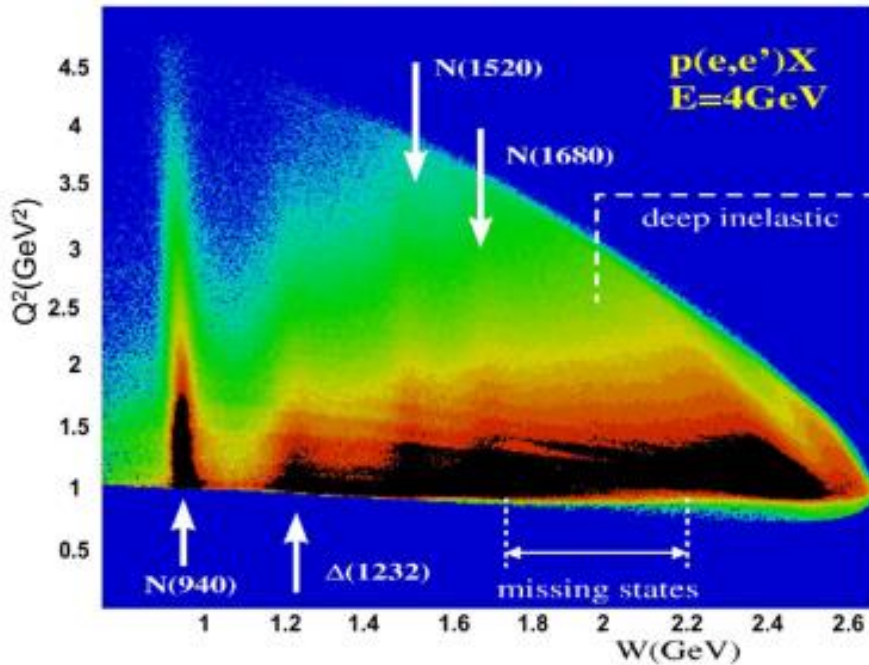


Two Pion Photo- and Electroproduction with CLAS



V.I. Mokeev
Jefferson Laboratory

Talk outline:

- N^* spectrum/structure as a window into strong QCD;
- Resonance photo-/electrocouplings from $\pi^+\pi^-p$ photo- and electroproduction off proton data;
- Insight into hadron mass generation;
- Evidence for the new $N'(1720)3/2^+$ state;
- Conclusion and outlook



**The 12th International Workshop on the Physics of Excited Nucleons,
 Bonn, Campus Poppelsdorf, 10-14 June 2019**



N* Spectrum and Structure in Experiments with CLAS/CLAS12

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

- N* spectrum with a focus on the new, so-called “missing” and hybrid resonance search
- $\gamma_V p N^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from 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
- explore the hadron mass emergence by mapping out dynamical quark mass in the transition from almost massless pQCD quark to fully dressed constituent quark

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

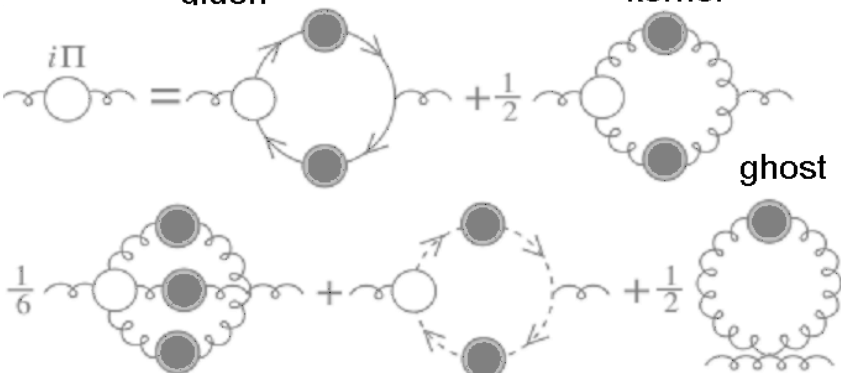
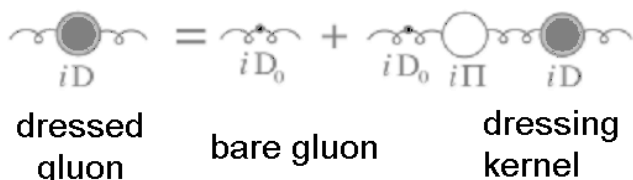
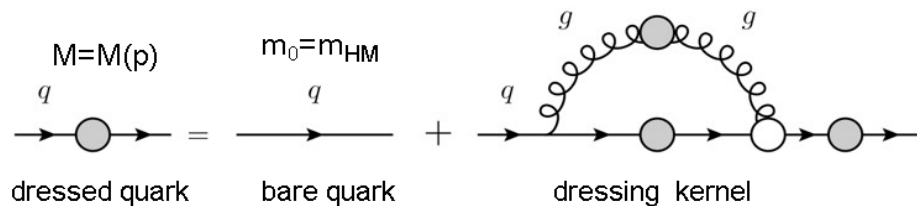
Review papers:

1. I.G. Aznauryan and V.D. Burkert, *Prog. Part. Nucl. Phys.* **67**, 1 (2012).
2. V.D. Burkert and C.D. Roberts, [arXiv:1710.02549 \[nucl-ex\]](https://arxiv.org/abs/1710.02549).
3. C.D. Roberts, *Few Body Syst.* **59**, 72 (2018).
4. V.I. Mokeev, *Few Body Syst.* **59**, 46 (2018).

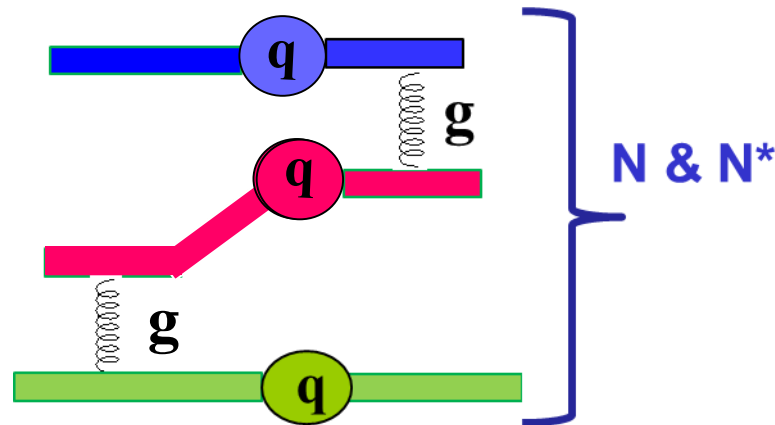


Excited Nucleon States and Insight into Strong QCD Dynamics

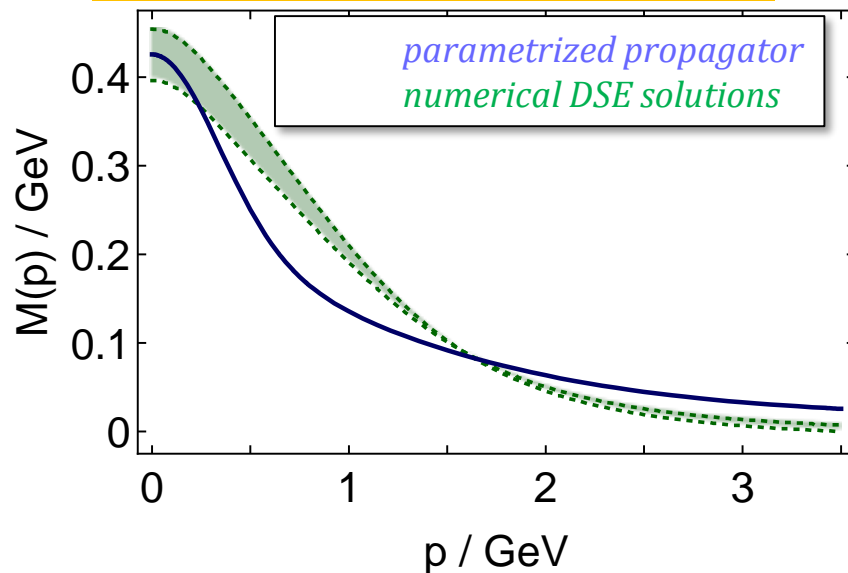
Emergence of Dressed Quarks and Gluons D. Binosi et al, Phys. Rev. D95, 031501 (2017)



Dressed Quark Borromean 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)



N* structure studies address:

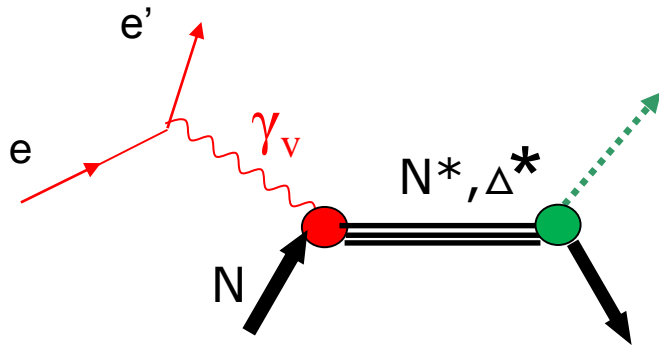
- Nature of > 98% of hadron mass
- Emergence of the ground nucleon parton distributions in 1D and 3D under studies in DIS



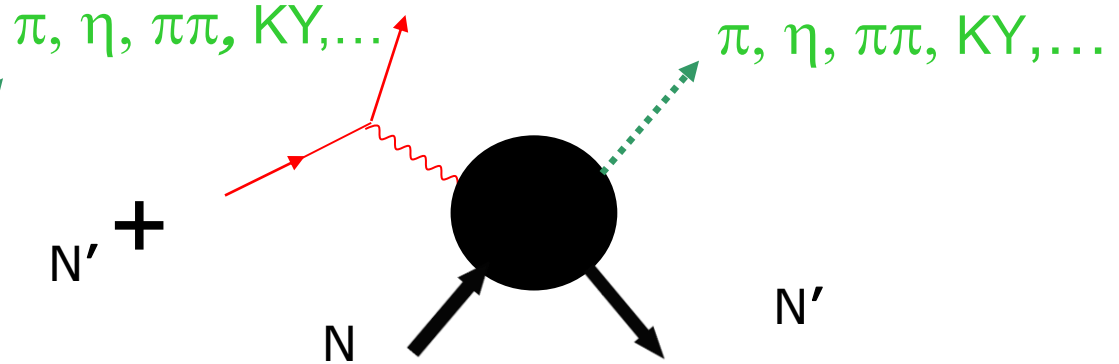
Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

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)

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

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

Summary of 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'
$\pi^+\pi^0p$	1.3-1.6 1.4-2.1 1.4-2.0	0.2-0.6 0.5-1.5 2.0-5.0	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 asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

Over 120,000 data points!

Almost full coverage of the final hadron phase space

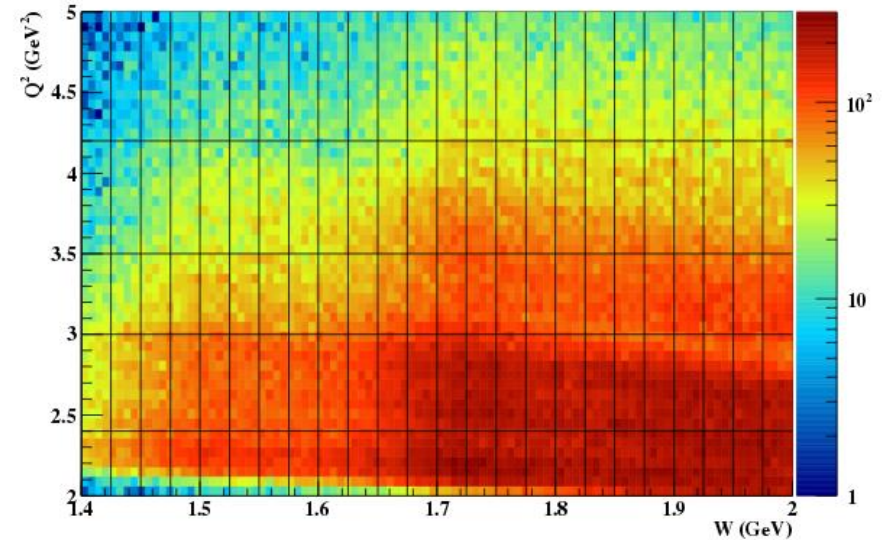
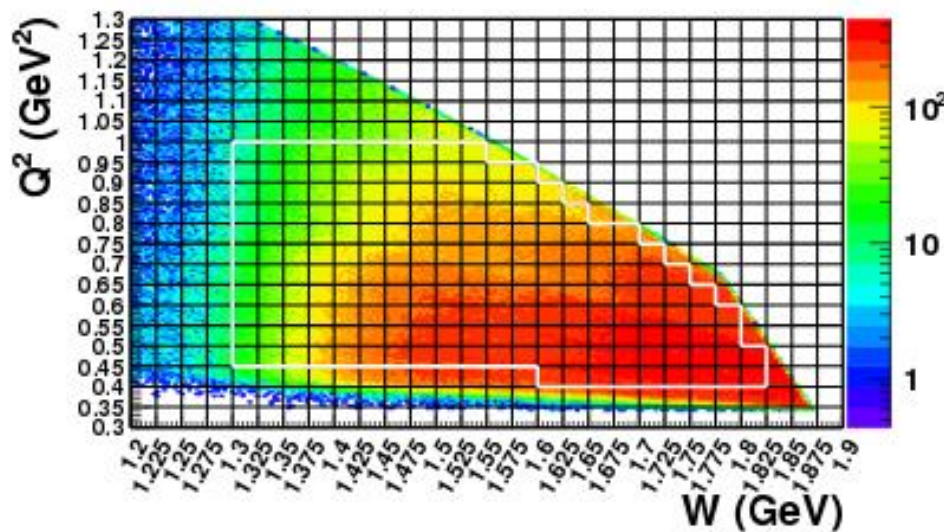
The measured observables from CLAS are stored in the **CLAS Physics Data Base** <http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi>



Kinematic Coverage and Approaches for Extraction of $\gamma_p p N^*$ Electrocouplings from $\pi^+\pi^-p$ Electroproduction off Proton Data

The CLAS detector has provided the only available data on nine independent one-fold differential $\pi^+\pi^-p$ photo-/electroproduction off proton cross sections at $1.40 \text{ GeV} < W < 2.0 \text{ GeV}$ and $0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$

Q^2 vs. W distributions of the $\pi^+\pi^-p$ events from CLAS data



➤ 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)

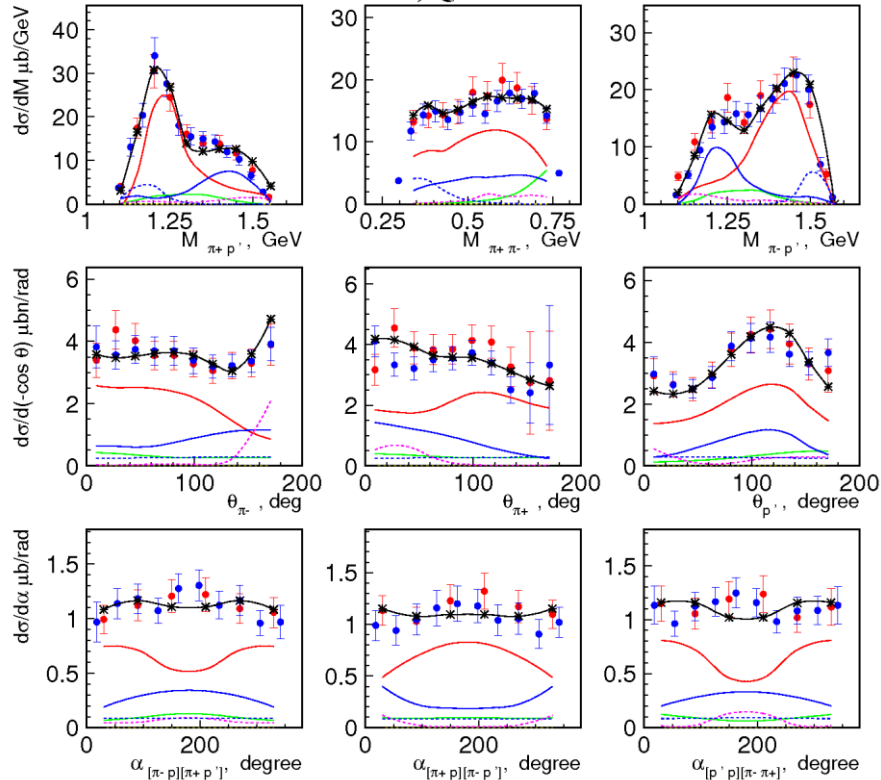
Accessing Resonance Electrocouplings from the $\pi^+\pi^-p$ Differential Electroproduction off Protons Cross Sections

Contributing mechanisms seen in the data

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

A.Trivedi, Few Body Syst. 60, 5 (2019)

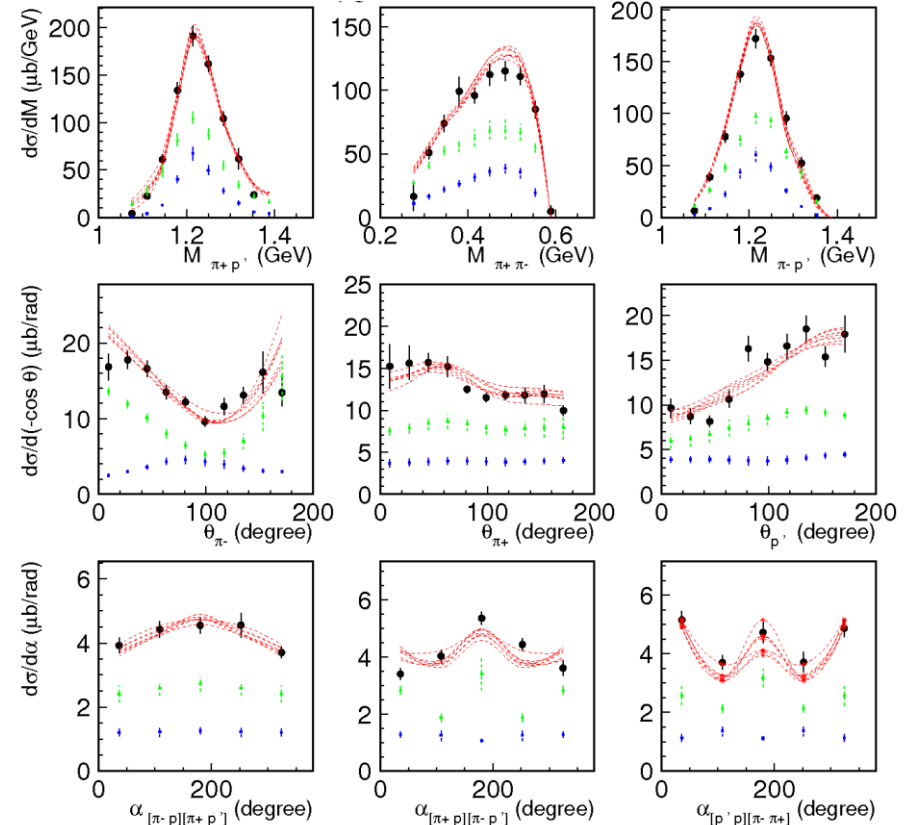
W=1.71 GeV, Q²=2.6 GeV²



Resonant and non-resonant contributions

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

W=1.51 GeV, Q²=0.65 GeV²



full JM

$\rho\rho$

$\pi^+ N(1520)3/2^-$

data fit within JM under variations of both resonant and background parameters

$\pi^- \Delta^{++}$

$\pi^+ \Delta^0$

$\pi^+ N(1680)5/2^+$

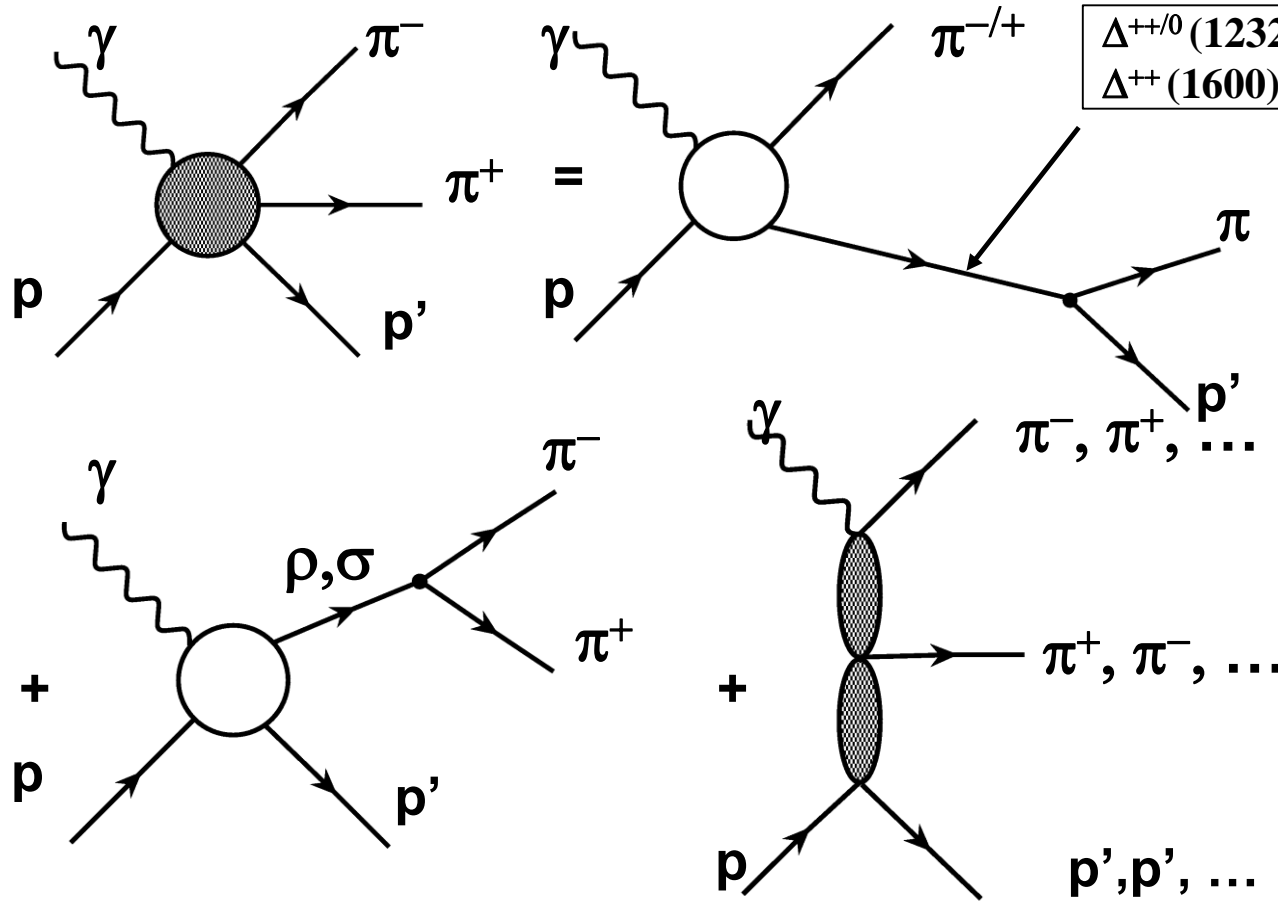
background cross sections

resonant cross sections



JM Model for Analysis of $\pi^+\pi^-p$ Photo-/Electroproduction

Major objectives: extraction of $\gamma_{r,v}pN^*$ photo-/electrocouplings and $\pi\Delta$, ρp decay widths



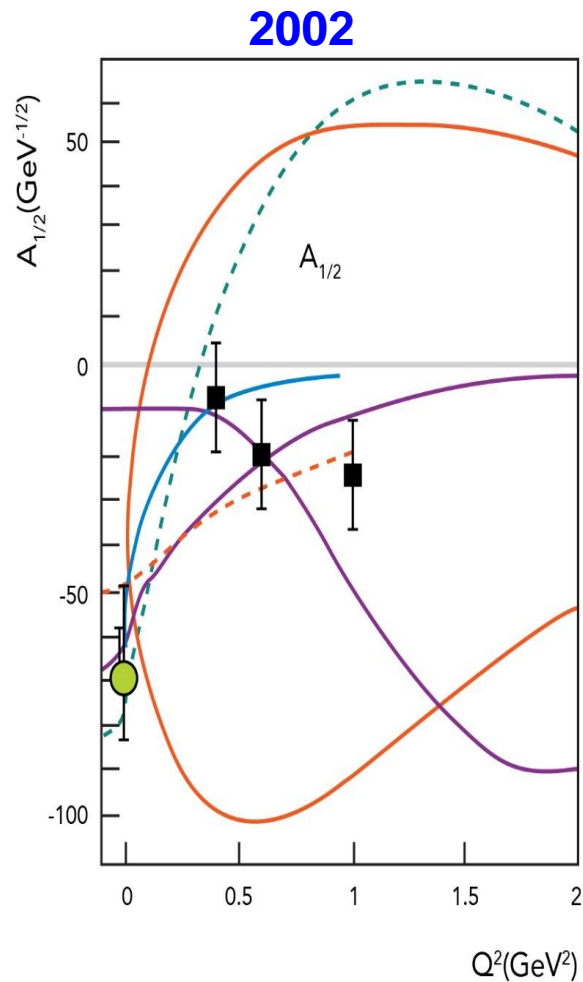
- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-p$ production;

- N^* contribute to $\pi\Delta$ and ρp channels only;

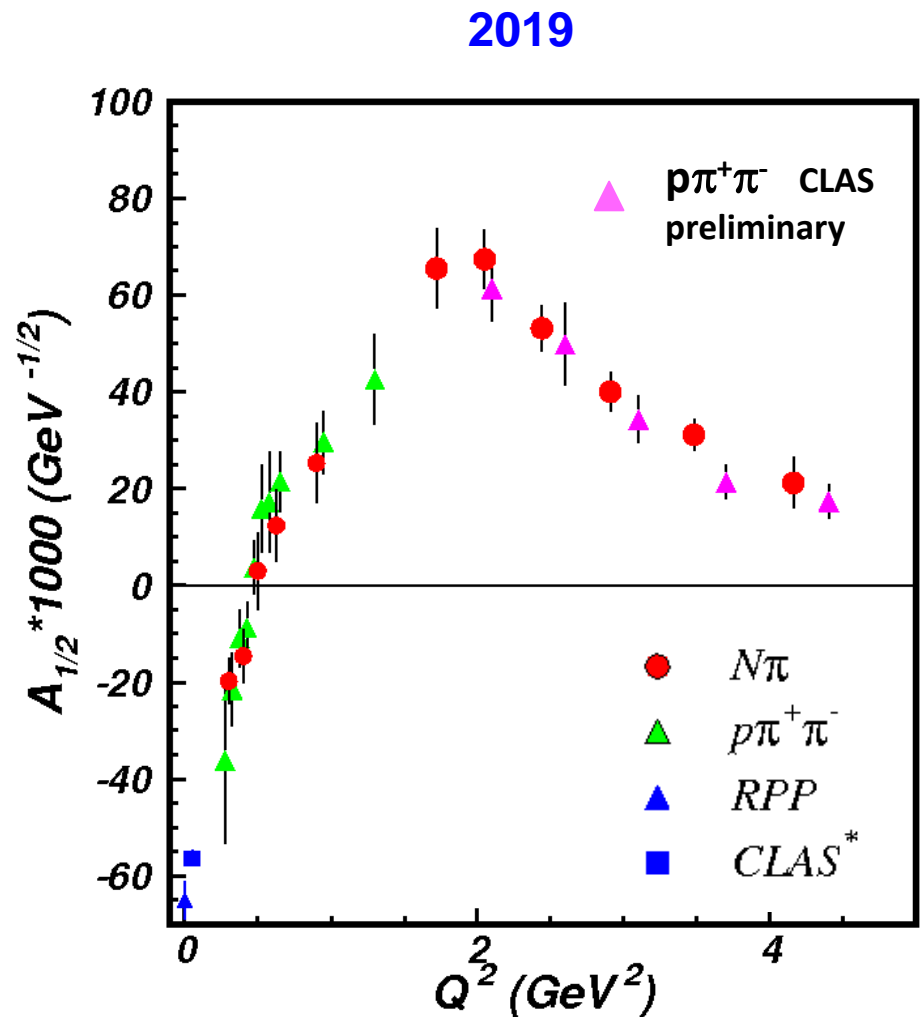
- unitarized Breit-Wigner ansatz for resonant amplitudes;

- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

Good description of $\pi^+\pi^-p$ photo-/electroproduction off protons cross sections at $1.4 \text{ GeV} < W < 2.0 \text{ GeV}$ and $0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$

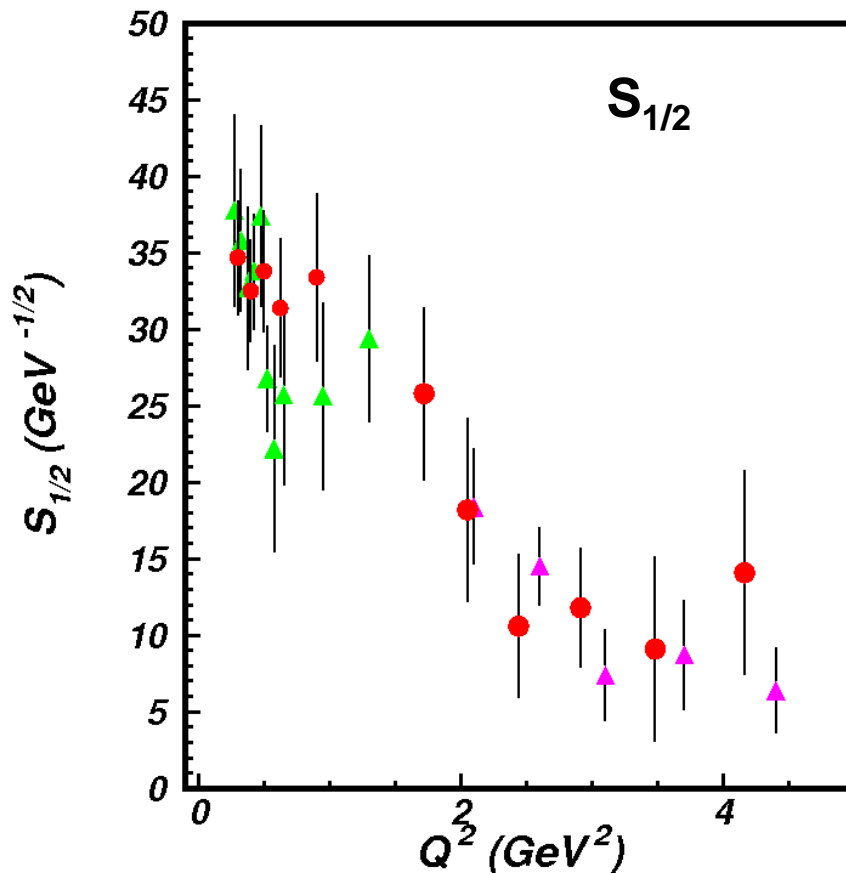
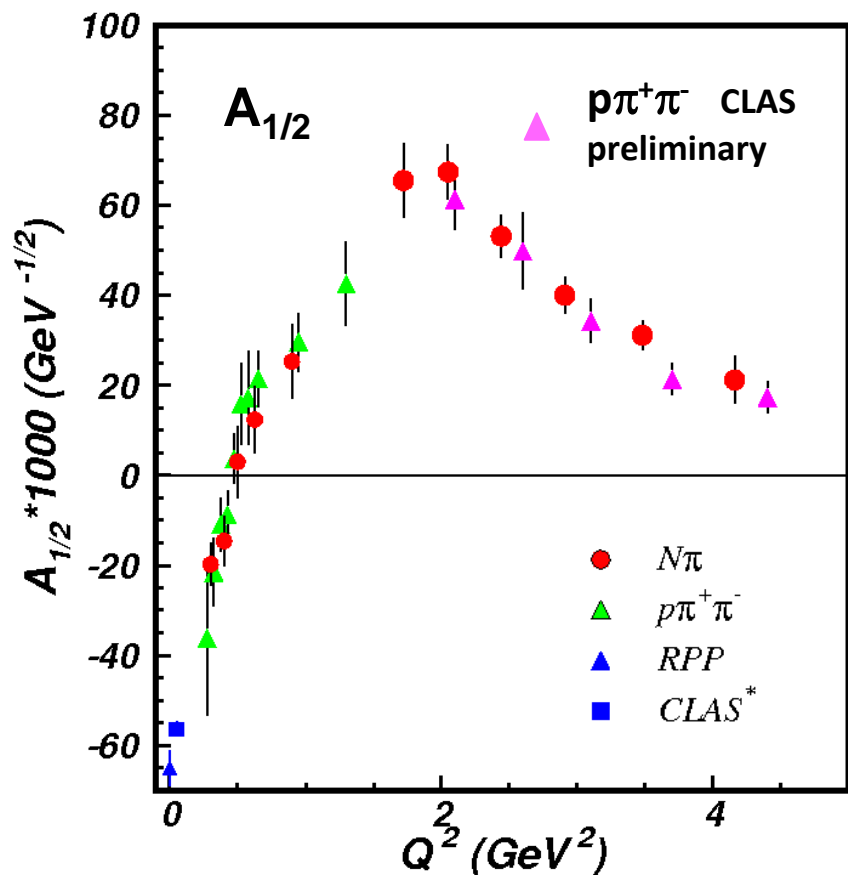


V. Burkert, *Baryons 2002*



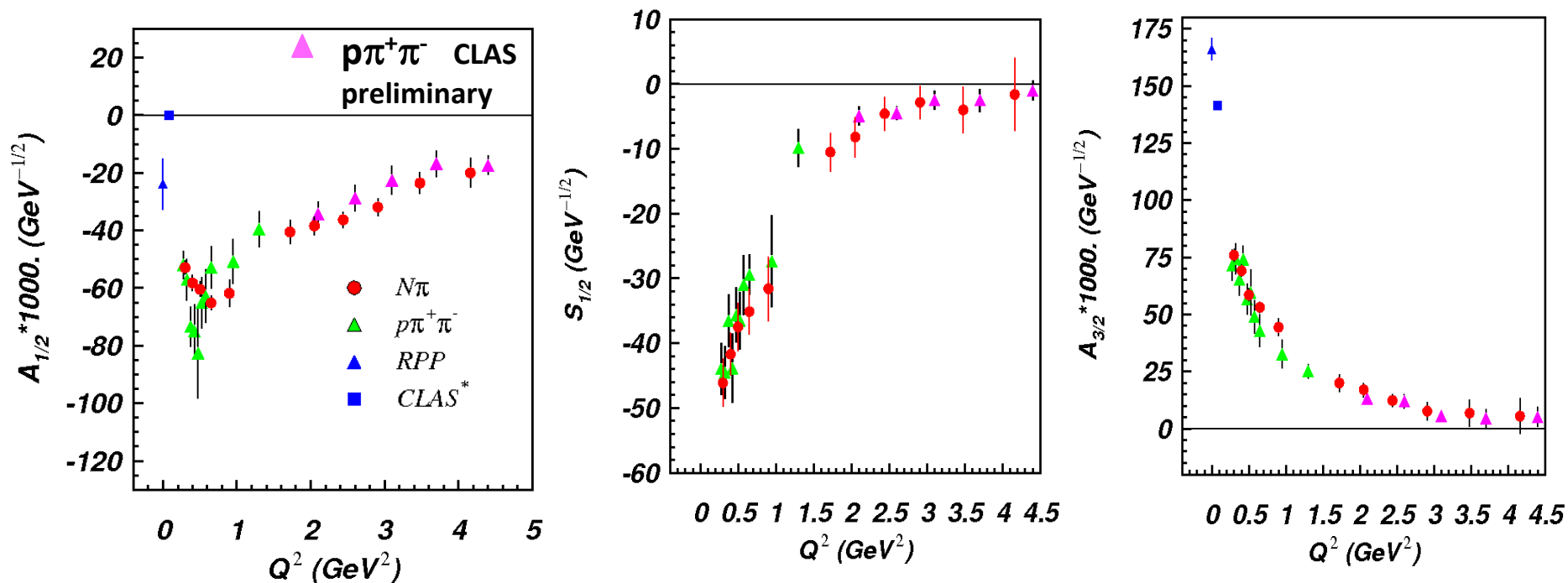
V. D. Burkert, *Baryons 2016* and the recent update from the CLAS $\pi^+\pi^-p$ electroproduction off protons data

Electrocouplings of $N(1440)1/2^+$ from $N\pi$ and $\pi^+\pi^-p$ Electroproduction off Proton Data



Consistent results on $N(1440)1/2^+$ electrocouplings from the independent studies of two major $N\pi$ and $\pi^+\pi^-p$ electroproduction off proton channels with different non-resonant contributions strongly support credible extraction of these quantities in a nearly model-independent way.

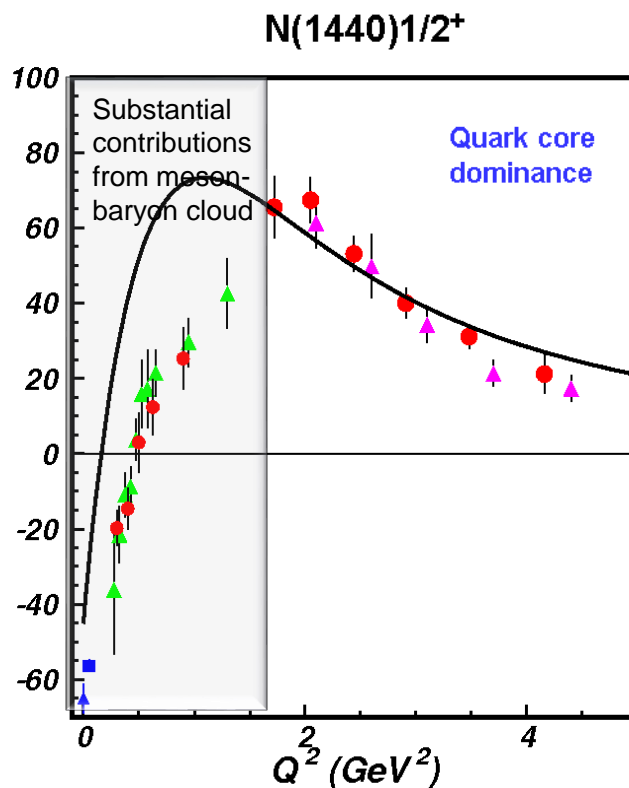
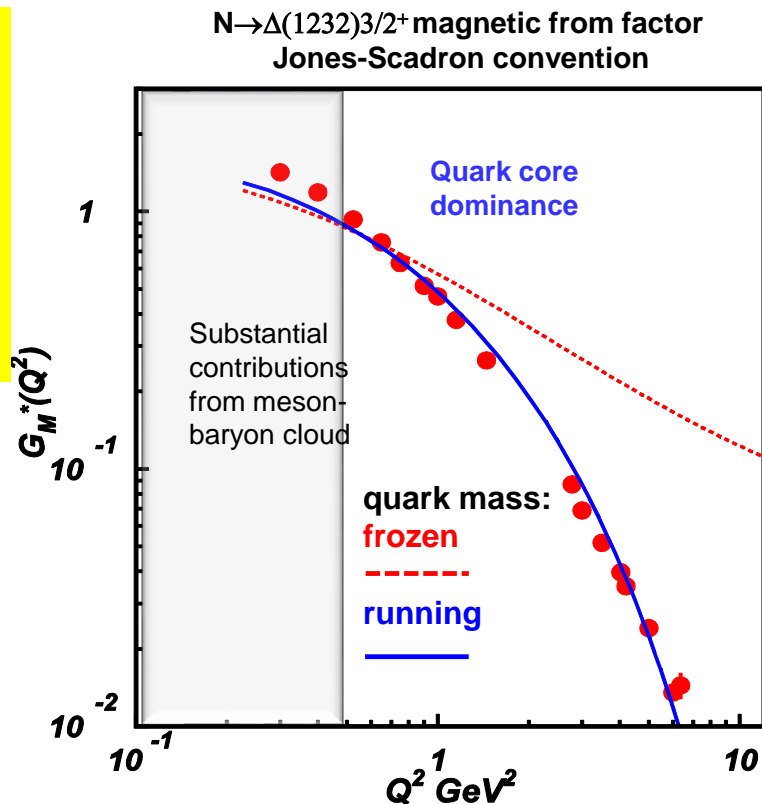
Electrocouplings of $N(1520)3/2^-$ from $N\pi$ and $\pi^+\pi^-p$ Electroproduction off Proton Data



Consistent results from $N\pi$ and $\pi^+\pi^-p$ electroproduction off proton data on electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ resonances with the biggest combined contribution into the resonant parts of both channels at $W < 1.55$ GeV strongly support the capabilities of the developed reaction models for credible extraction of resonance electrocouplings from independent analyses of both $N\pi$ and $\pi^+\pi^-p$ electroproduction.

Dyson-Schwinger Equations (DSE):

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



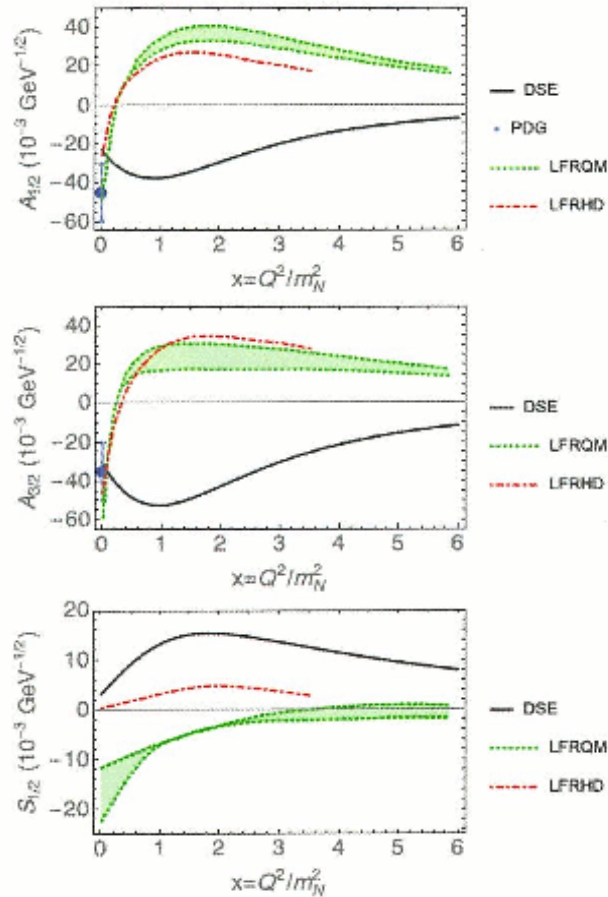
DSE analyses of the CLAS data on $\Delta(1232)3/2^+$ electroexcitation demonstrated that dressed quark mass is running with momentum.

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 **validate the DSE results on momentum dependence of dressed quark mass.** $\gamma_p N^*$ electrocoupling data offer access to the strong QCD dynamics underlying the hadron mass generation.

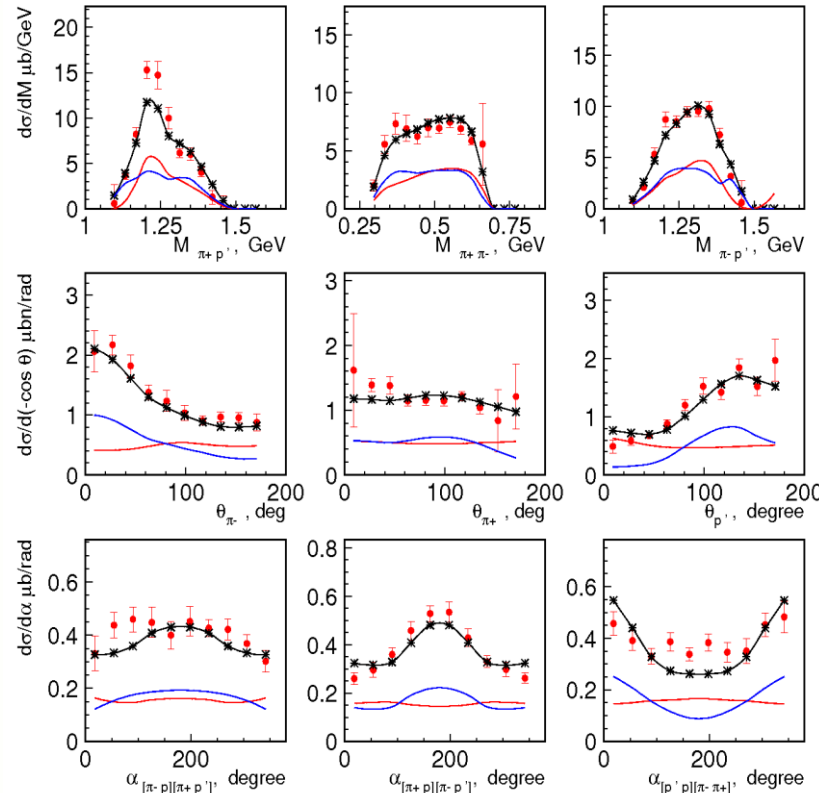
One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists and theorists.

Dressed Quark Mass Function from Electrocouplings of Radial Δ -Excitation

$\Delta(1600)3/2^+$



$W=1.61 \text{ GeV}, Q^2=3.2 \text{ GeV}^2$



$\pi^+\pi^-p$ data from CLAS
A.Trivedi Few Body
Syst. 60, 5 (2019)

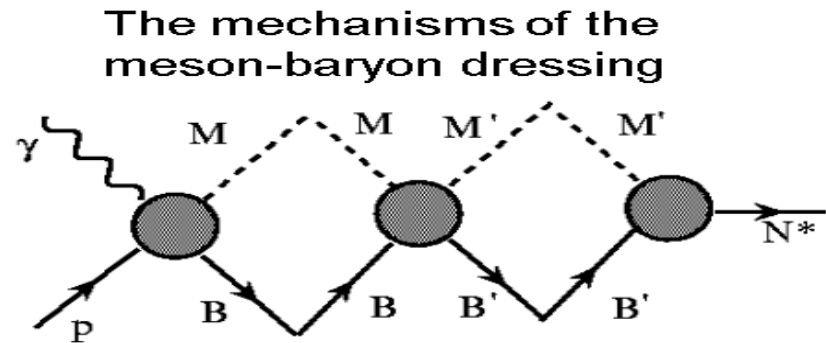
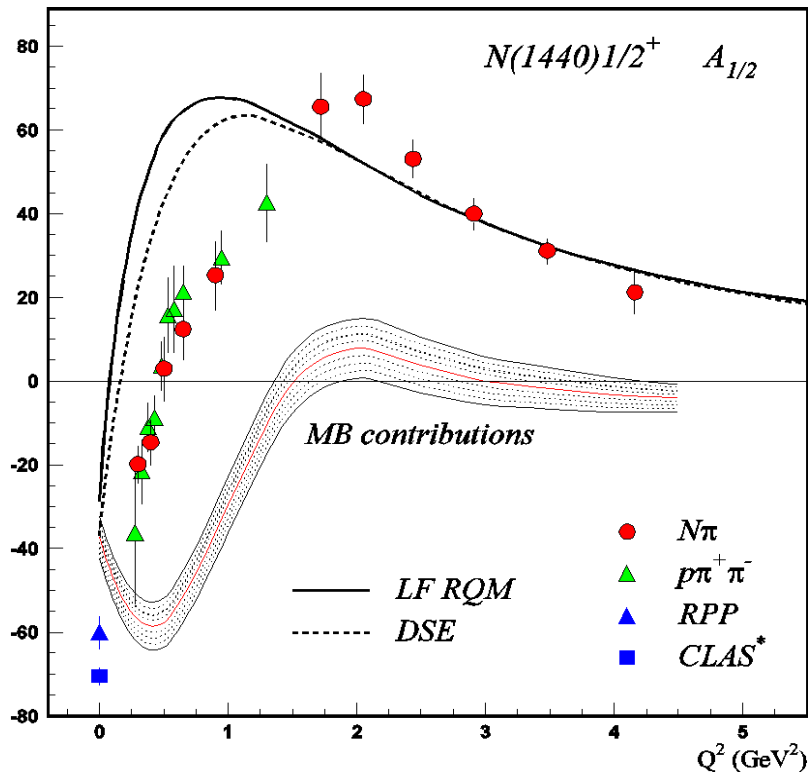
— N^*
— non-resonant contributions

Parameter free predictions for $N \rightarrow \Delta(1600)3/2^+$ e.m. transition form factors from DSEQCD
Ya Lu et al, arXiv:1904.03205 [nucl-th]

Good description of the CLAS $\pi^+\pi^-p$ electroproduction off protons data was achieved at $1.4 \text{ GeV} < W < 2.0 \text{ GeV}$ and $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$ within JM19 model.

- $\Delta(1600)3/2^+$ electrocouplings will be extracted soon.
- Confirmation of the DSE expectations will prove a relevance of dressed quark with running mass in the nucleon structure and radial nucleon and Δ excitations.
- Studies of $[70,1^-]$ orbital excitations is the next step.

Resolving Puzzle of the Roper Structure



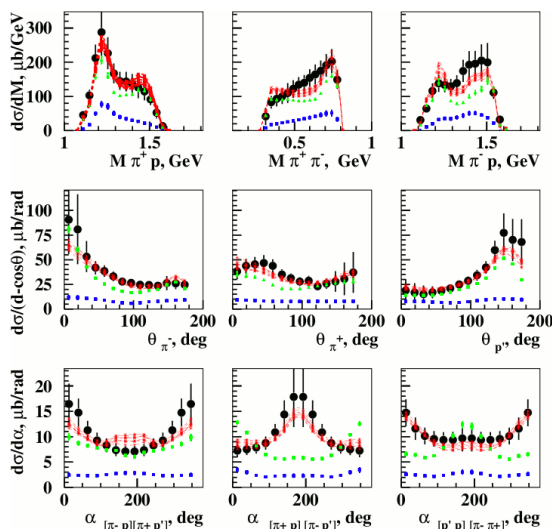
CLAS data in the range of $Q^2 < 5.0 \text{ GeV}^2$ revealed the structure of $N(1440)1/2^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baryon (MB) cloud

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

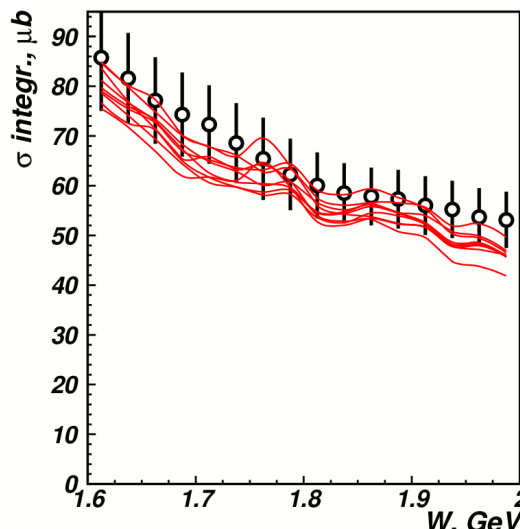
Quark core description within LF RQM and DSE is consistent

For more details on resolving Roper puzzle see:
V. D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019).

W=1.74 GeV



Fully integrated cross section



E.N. Golovach et al, CLAS Collaboration, Phys. Lett. B788, 371 (2019).

JM18 reaction model fit:

- Full
- Resonant contributions
- Non-resonant contributions

1.15 $\chi^2/d.p.$ < 1.30

Resonances	$A_{1/2} \times 10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{1/2} \times 10^3$ multichannel analysis [7] $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{3/2} \times 10^3$ multichannel analysis [7] $\text{GeV}^{-1/2}$
$\Delta(1620)1/2^-$	29.0 ± 6.2	30 – 60	55 ± 7			
$N(1650)1/2^-$	60.5 ± 7.7	35 – 55	32 ± 6			
$N(1680)5/2^+$	-27.8 ± 3.6	-18 – -5	-15 ± 2	128 ± 11	130 – 140	136 ± 5
$N(1720)3/2^+$	80.9 ± 11.5	80 – 120	115 ± 45	-34.0 ± 7.6	-48 – 135	135 ± 40
$\Delta(1700)3/2^-$	87.2 ± 18.9	100 – 160	165 ± 20	87.2 ± 16.4	90 – 170	170 ± 25
$\Delta(1905)5/2^+$	19.0 ± 7.6	17 – 27	25 ± 5	-43.2 ± 17.3	-55 – -35	-50 ± 5
$\Delta(1950)7/2^+$	-69.8 ± 14.1	-75 – -65	-67 ± 5	-118.1 ± 19.3	-100 – -80	-94 ± 4

In 2019 partial update of the Review of Particle Physics the entries on photocouplings and $N\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

Interpretation of the Structure at $W \sim 1.7$ GeV in $\pi^+\pi^-p$ Electroproduction

M. Ripani et al., CLAS Collaboration
 Phys. Rev. Lett. 91, 022002 (2003)

..... conventional states only, consistent with PDG 02
 — implementing $N'(1720)3/2^+$ candidate or only conventional states with different $N(1720)3/2^+$ $N\pi\pi$ decays than in PDG 02

Two equally successful ways for the data description:

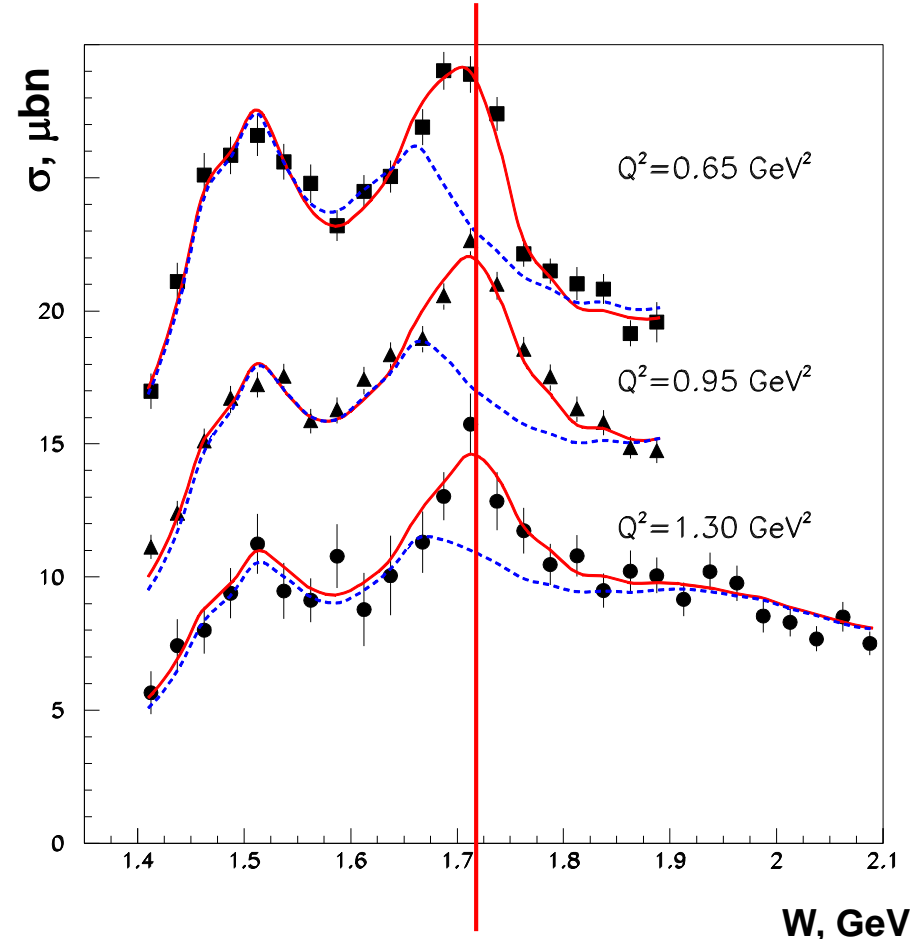
No new states, different than in PDG 02'

$N(1720)3/2^+$ $N\pi\pi$ hadronic decay widths:

	Γ_{tot} , MeV	BF($\pi\Delta$) %	BF($\rho\rho$) %
$N(1720)3/2^+$ decays fit to the CLAS $N\pi\pi$ data	126 ± 14	64-100	<5
$N(1720)3/2^+$ PDG 02'	150-300	<20	70-85

new $N'(1720)3/2^+$ and regular $N(1720)3/2^+$:

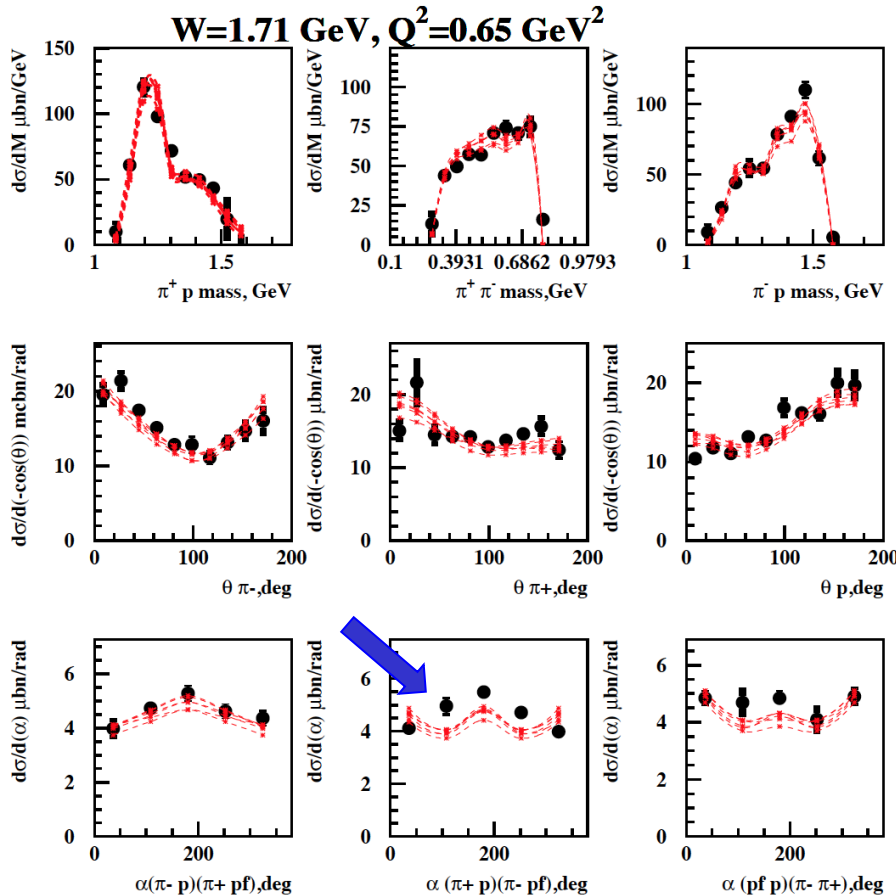
	Γ_{tot} , MeV	BF($\pi\Delta$) %	BF($\rho\rho$) %
$N'(1720)3/2^+$ New	119 ± 6	47-64	3-10.
$N(1720)3/2^+$ Conventional	112 ± 8	39-55	23-49



Analysis of the $ep \rightarrow e' \pi^+ \pi^- p$ CLAS data at $W \sim 1.7$ GeV in the JM model

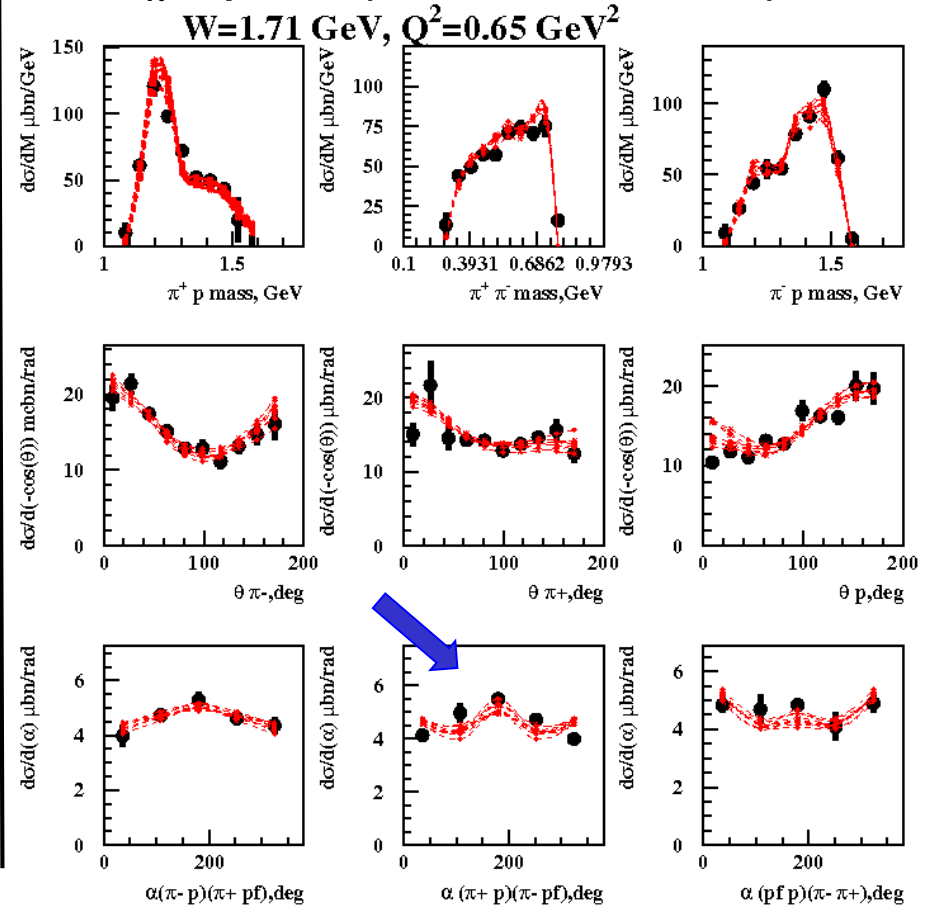
Conventional N^* -states with $\pi\Delta$, ρp couplings fit to the data

$2.85 < \chi^2/d.p. < 3.03$ ($1.66 \text{ GeV} < W < 1.76 \text{ GeV}$)



$N'(1720)3/2^+$ candidate state is included in the fit

$2.56 < \chi^2/d.p. < 2.80$ ($1.66 \text{ GeV} < W < 1.76 \text{ GeV}$)

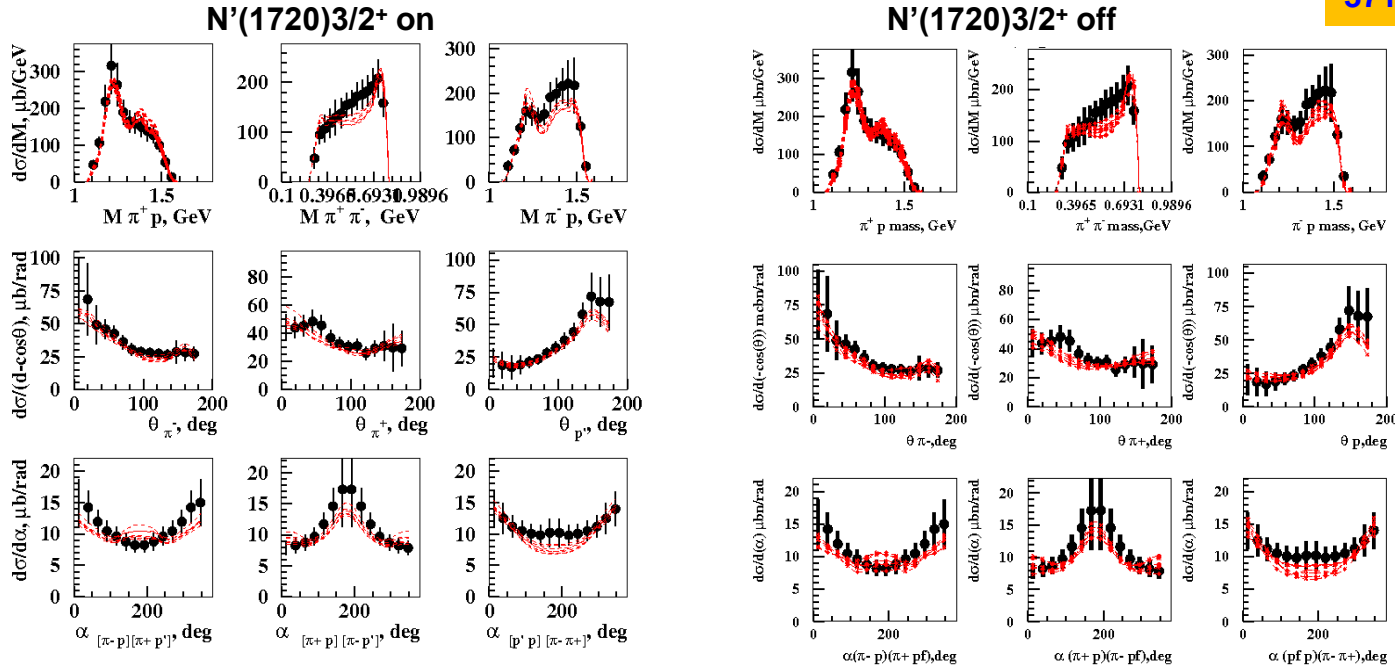


- Fit of θ_{π^-} , θ_{π^+} , θ_p angular distributions requires essential contribution(s) from the resonance(s) of $J^\pi=3/2^+$.
- Single state of $J^\pi=3/2^+$ should have major $\pi\Delta$ (>60%) and minor ρp (<5%) decays in order to reproduce pronounced Δ -peaks in $\pi^+ p$ and to avoid ρ -peak formation in the $\pi^+ \pi^-$ mass distributions.

Description of the CLAS $\pi^+\pi^-p$ Photoproduction off Protons Data with/without the New State $N'(1720)3/2^+$

E.N. Golovach et al., CLAS Collaboration, Phys. Lett. B 788, 371 (2019).

One-fold differential cross sections at $W=1.71$ GeV



Almost the same quality of the photoproduction data description was achieved with and without $N'(1720)3/2^+$ new state:

$N(1720)3/2^+$ and $N'(1720)3/2^+$ \implies $1.19 < \chi^2/\text{d.p.} < 1.28$
 $N(1720)3/2^+$ only \implies $1.08 < \chi^2/\text{d.p.} < 1.26$

Would it be possible to describe photo- and electroproduction data with Q^2 -independent resonance masses and total and partial hadron decay widths?



Evidence for the Existence of the New State $N'(1720)3/2^+$ from Combined $\pi^+\pi^-p$ Analyses in both Photo- and Electroproduction

$N(1720)3/2^+$ hadronic decays from the CLAS data fit with conventional resonances only

N^* hadronic decays from the data fit that incorporates the new $N'(1720)3/2^+$ state

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

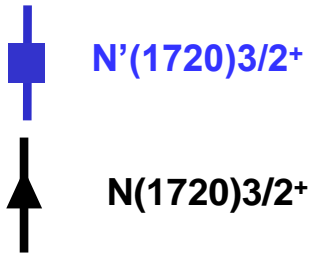
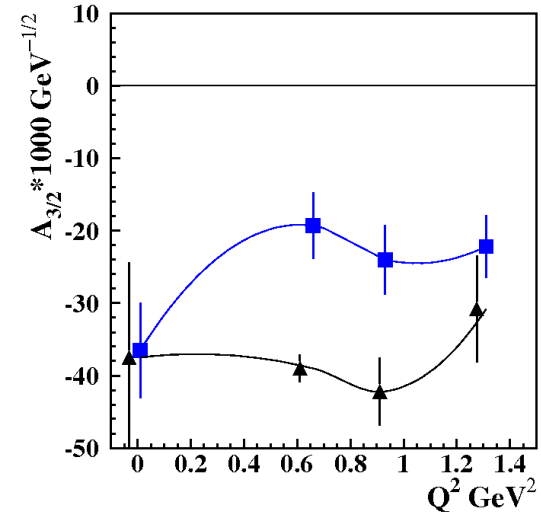
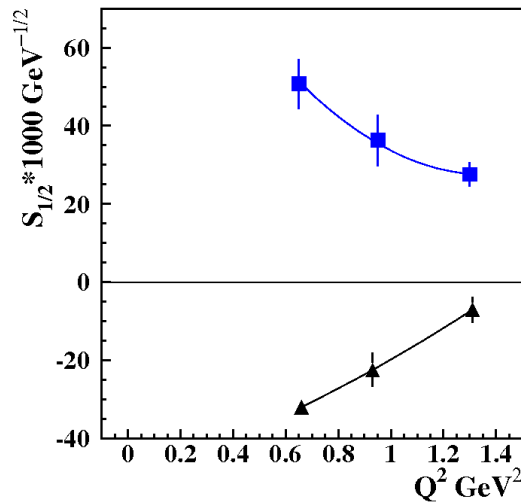
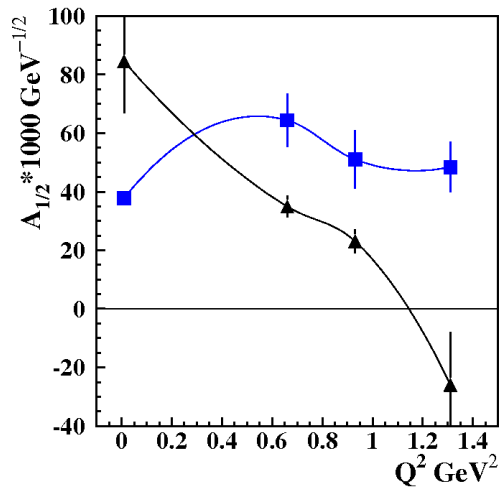
Resonance	BF($\pi\Delta$), %	BF(ρp), %
$N'(1720)3/2^+$ electroproduction	47-64	3-10
$N'(1720)3/2^+$ photoproduction	46-62	4-13
$N(1720)3/2^+$ electroproduction	39-55	23-49
$N(1720)3/2^+$ photoproduction	38-53	31-46
$\Delta(1700)3/2^-$ electroproduction	77-95	3-5
$\Delta(1700)3/2^-$ photoproduction	78-93	3-6

The contradictory BF values for $N(1720)3/2^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

The successful description of the $\pi^+\pi^-p$ photo- and electroproduction data achieved by implementing new $N'(1720)3/2^+$ state with Q^2 -independent hadronic decay widths of all resonances contributing at $W \sim 1.7$ GeV provides strong evidence for the existence of the new $N'(1720)3/2^+$ state.

The Parameters of the New $N'(1720)3/2^+$ State from the CLAS Data Fit

The photo-/electrocouplings of the $N'(1720)3/2^+$ and conventional $N(1720)3/2^+$ states

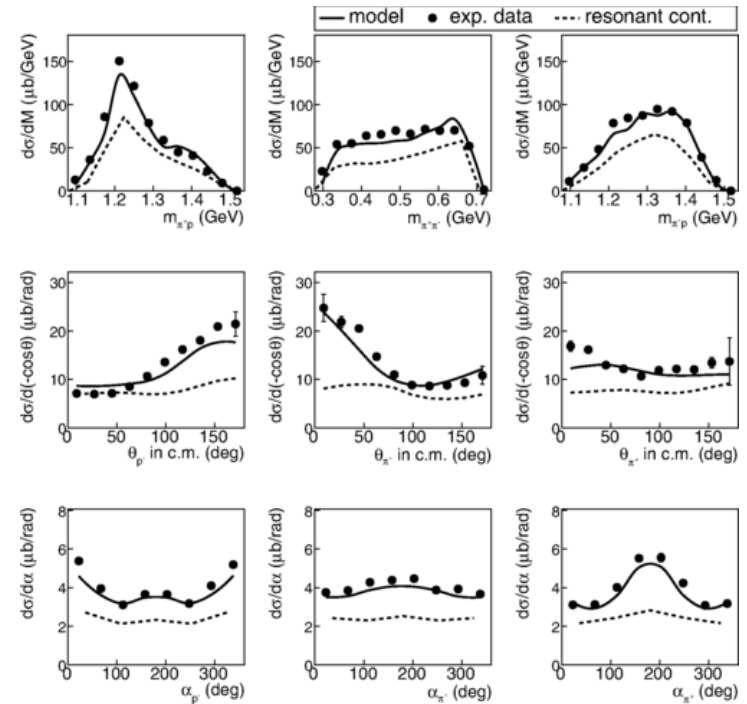
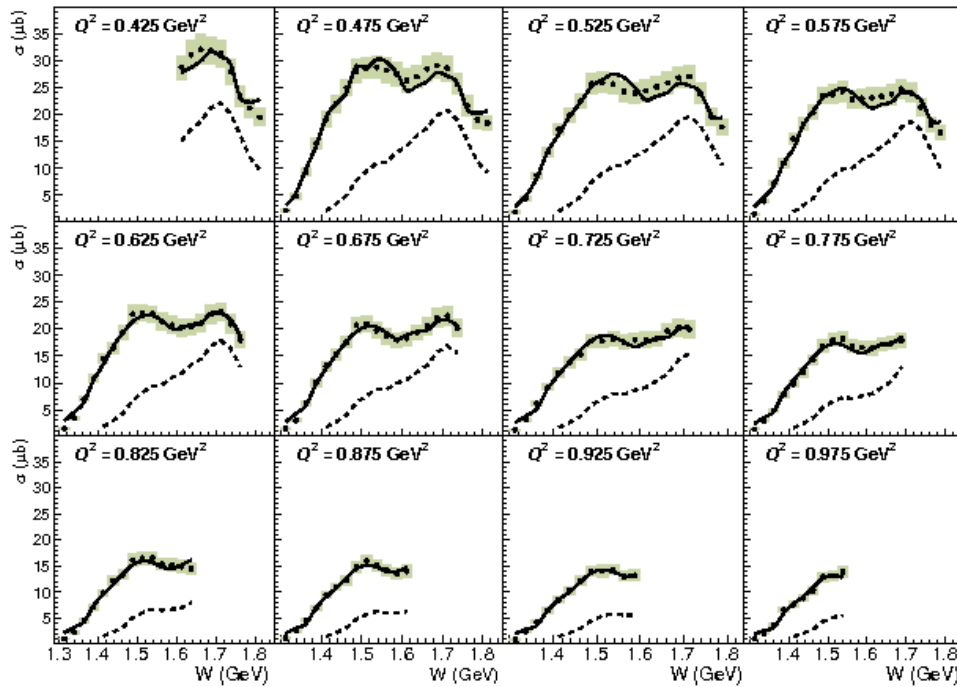


Resonance	Mass, GeV	Total width, MeV
$N'(1720)3/2^+$	1.715-1.735	120 ± 6
$N(1720)3/2^+$	1.743-1.753	112 ± 8

- $N'(1720)3/2^+$ is the only new resonance for which data on electroexcitation amplitudes have become available.
- Gaining insight into the “missing” resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.

Recent CLAS Data on $\pi^+\pi^-p$ Electroproduction off Protons at $0.4 < Q^2 < 1.0 \text{ GeV}^2$

G. V. Fedotov, Iu. A. Skorodumina et al., CLAS Collaboration, Phys. Rev. C98, 025203 (2018)



JM model/TWOPEG EG analysis:

--- resonant contribution
 — full cross section

9 one-fold differential cross sections at $W < 1.8 \text{ GeV}$ and $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$ of the best statistical and systematical accuracy obtained with minimal bin size over Q^2 ever achieved ($\Delta Q^2 = 0.05 \text{ GeV}^2$)

- Promising prospect to obtain 8 additional points on Q^2 -evolution of $N'(1720)3/2^+$ electrocouplings in the range of $0.4 \text{ GeV}^2 < Q^2 < 0.8 \text{ GeV}^2$

Conclusions and Outlook

- The CLAS detector has provided the only available data results on nine independent $\pi^+\pi^-p$ photo-/electroproduction off proton cross sections at $W < 2.0$ GeV and photon virtualities $0 < Q^2 < 5.0$ GeV².
- Photocouplings and $\pi\Delta$, ρp hadronic decay widths of most resonances in the mass range > 1.6 GeV have become available for the first time from $\pi^+\pi^-p$ photoproduction off proton data. The respective PDG entries for these excited states were updated accounting for the CLAS results.
- High quality $\pi^+\pi^-p$ electroproduction off proton 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.
- Profound impact on the exploration of strong QCD dynamics:
 - 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 $\gamma_\nu p N^*$ 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.

Conclusions and Outlook

- Combined studies of exclusive $\pi^+\pi^-p$ photo-/electroproduction off proton data have revealed convincing evidence for the existence of the new $N'(1720)3/2^+$ resonance. The first results on the Q^2 -evolution of the new baryon state electrocouplings have become available.
- Electrocouplings of most resonances in the mass range up to 2.0 GeV will be obtained at $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$ from the new CLAS data on $\pi^+\pi^-p$ electroproduction in the near term future.
- 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 $N\pi$, $\pi^+\pi^-p$, and KY electroproduction and **to address the most challenging problems in hadron physics on the nature of hadron mass and quark-gluon confinement**



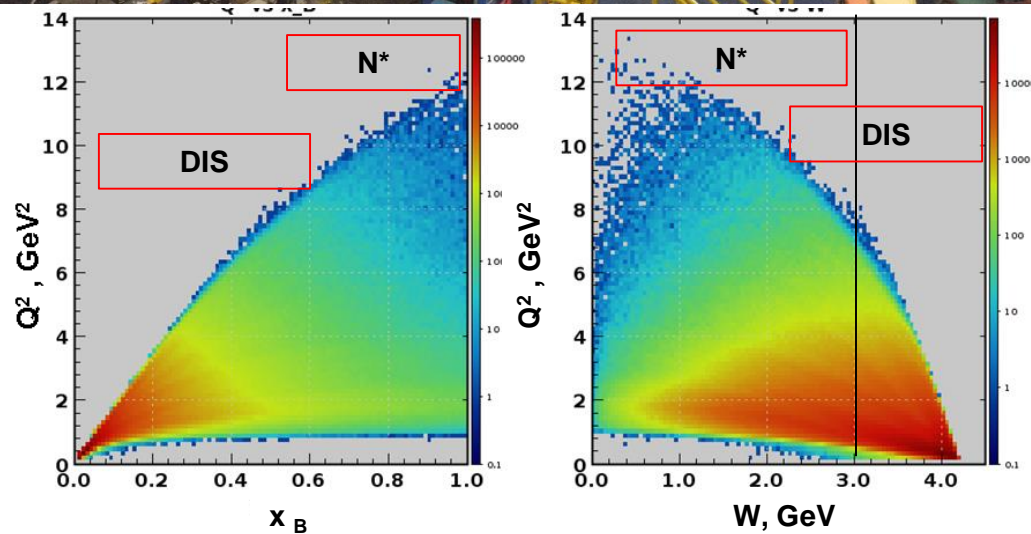
See the upcoming plenary talk by R.W. Gothe, Thursday, June 13, 9.35 a.m.

Back Up

12 GeV Era with the CLAS12 Detector



CLAS12 in Hall B



Physics run started successfully
in February 2018.

CLAS12 N* Program at High Q²

E12-09-003

Nucleon Resonance Studies with CLAS12

Gothe, Mokeev, Burkert, Cole, Joo, Stoler

E12-06-108A

KY Electroproduction with CLAS12

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:

$E_b = 11 \text{ GeV}$, $Q^2 = 3 \rightarrow 12 \text{ GeV}^2$, $W \rightarrow 3.0 \text{ GeV}$ 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 GeV².*

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

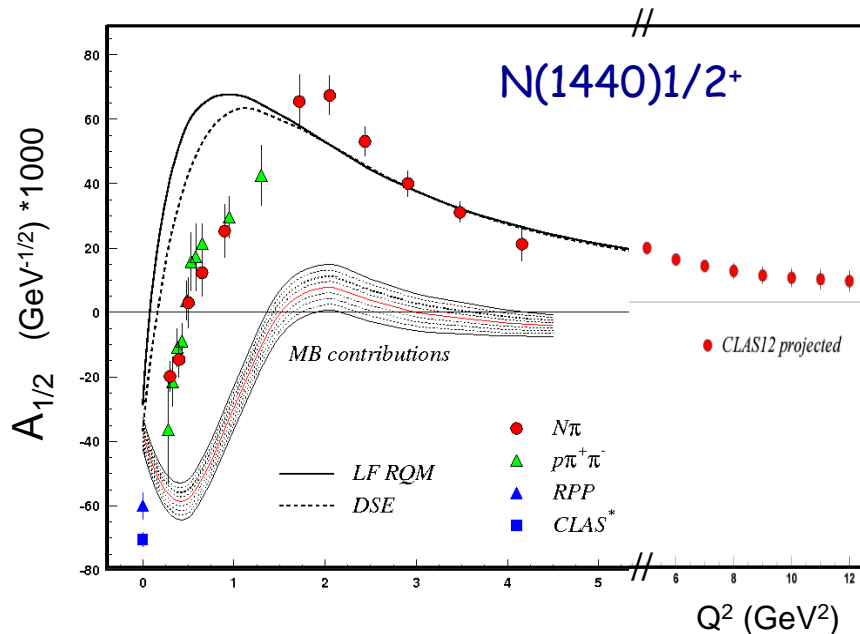
N* electroexcitation studies at JLab will address the critical open questions:

How is >98% of visible mass generated?

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

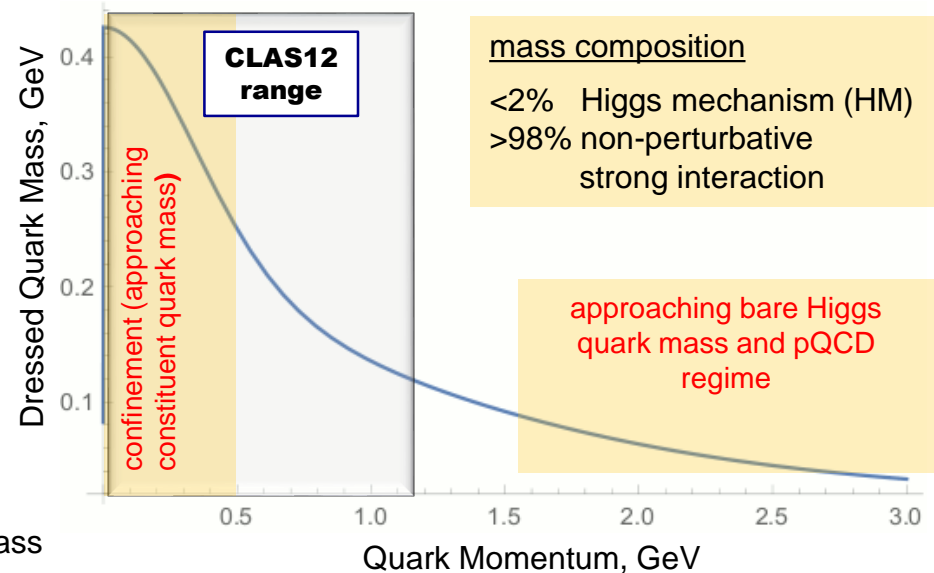
What is the behavior of QCD's running coupling at infrared momenta?

Mapping-out quark mass function from the CLAS12 results on $\gamma_V p N^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5 < Q^2 < 12 \text{ GeV}^2$ 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



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

Hybrid Baryons E12-16-010	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 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 $Q^2 < 7.0 \text{ GeV}^2$ (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

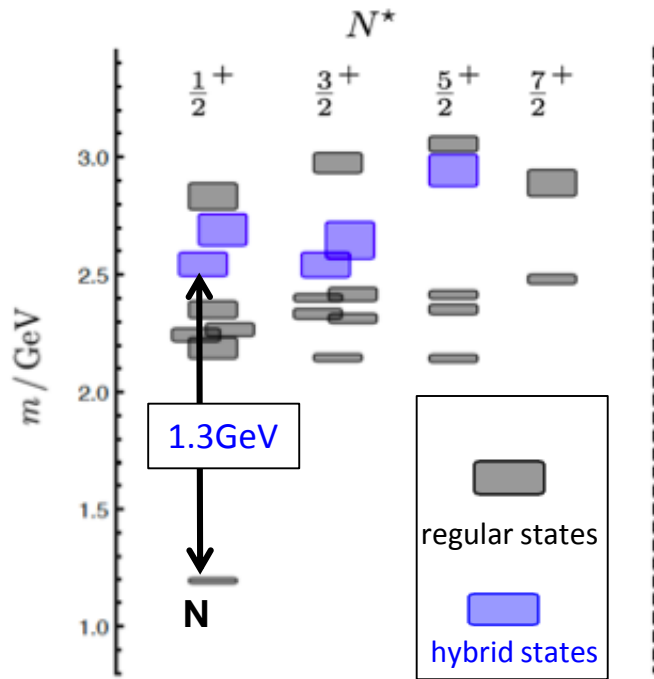
- Polarized electrons, unpolarized LH_2 target
- $L = 1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$



Hunting for Glue in Excited Baryons with CLAS12

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

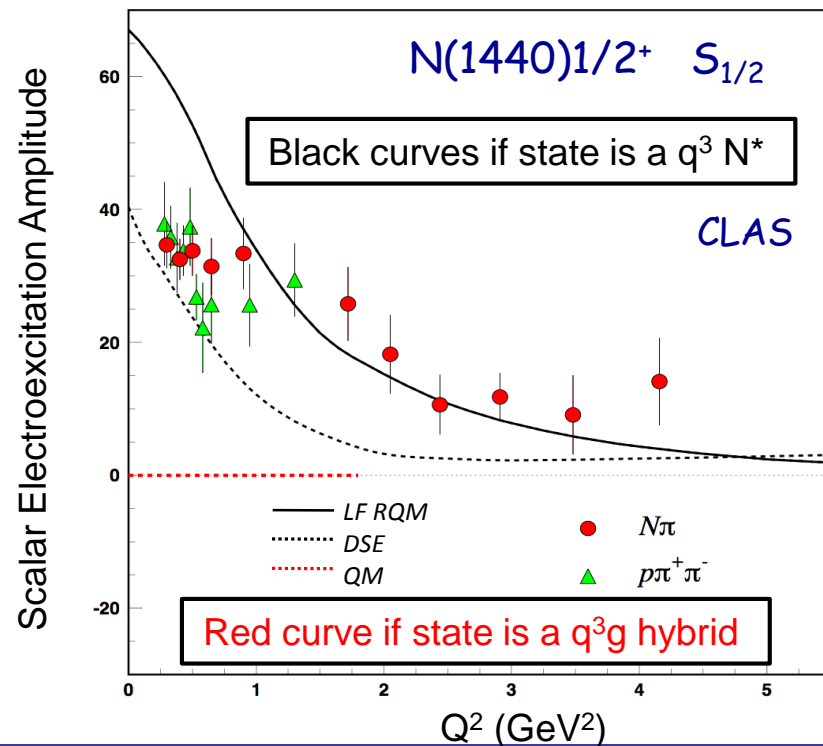
Predictions of the N^* spectrum from QCD show both regular q^3 and hybrid q^3g states



JLab LQCD group results

Search for hybrid baryons with CLAS12 in exclusive $K\gamma$ 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



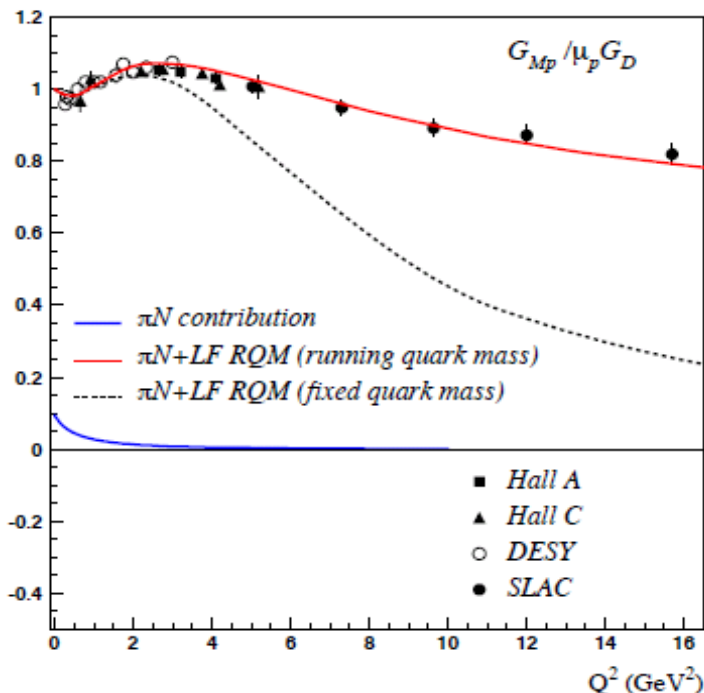
Quark Model with Input from QCD-based Approaches

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 $Q^2 > 3.0$ GeV²