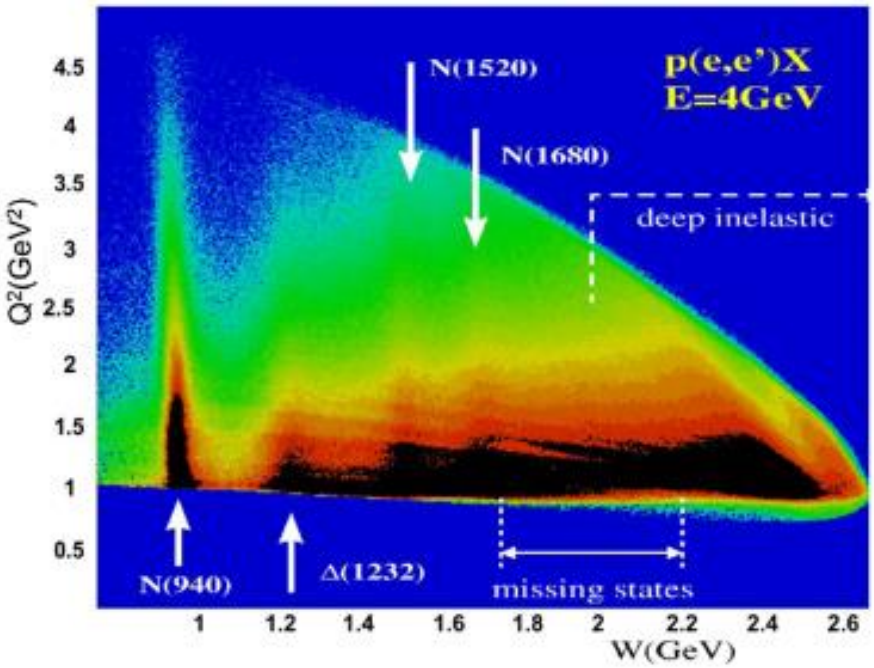
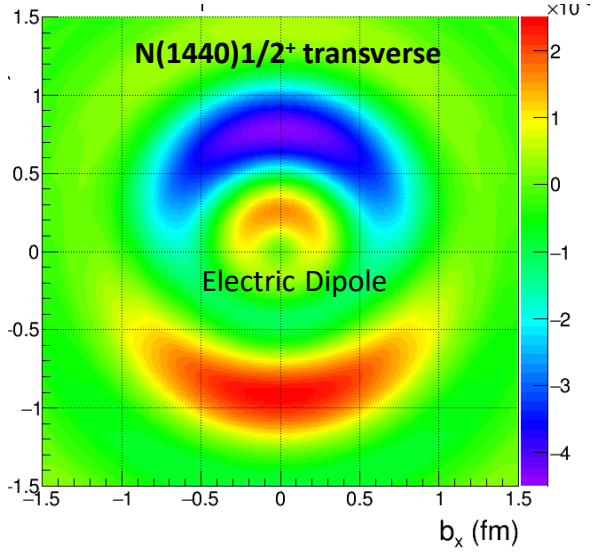
# Two Pion Photo- and Electroproduction with CLAS





**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

Office of Science

**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
- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 $GeV^2$ for most of the excited proton states through analyzing major meson electroproduction channels from 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

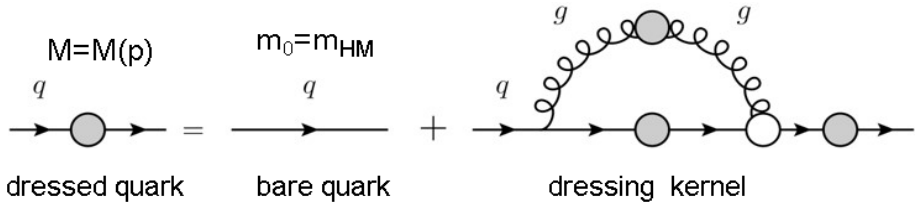
**A unique source of information on many facets of strong QCD in generating excited nucleon states with different structural features**

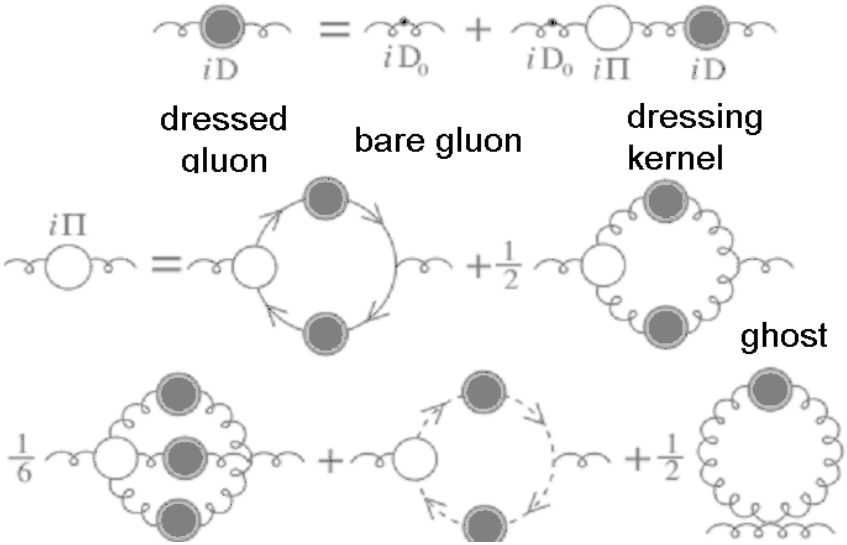
**Review papers:**


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].
3. C.D. Roberts, Few Body Syst. 59, 72 (2018).
4. V.I. Mokeev, Few Body Syst. 59, 46 (2018).

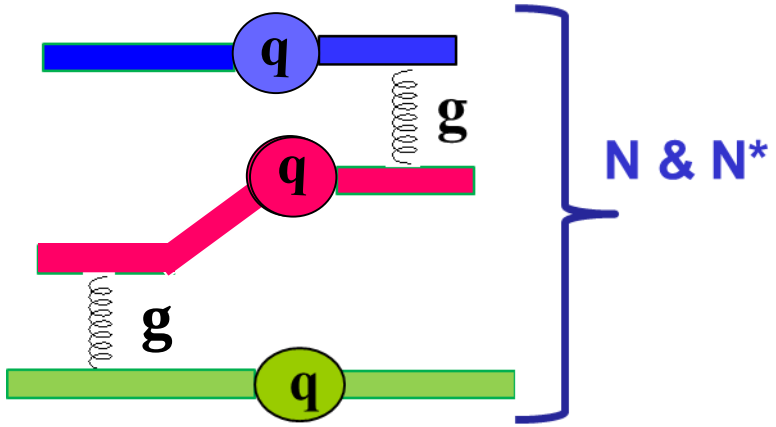
# Excited Nucleon States and Insight into Strong QCD Dynamics

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

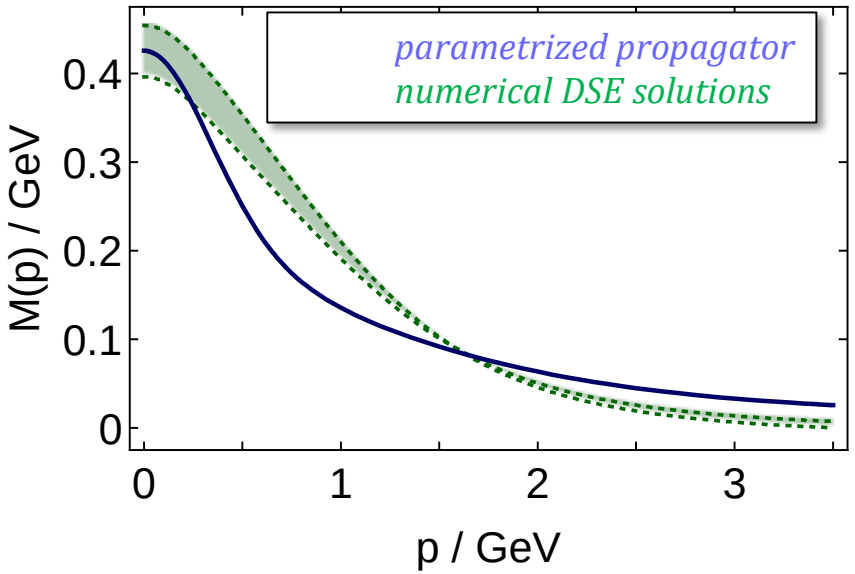



**Dressed Quark Borromeo Binding in Baryons**
**Ch. Chen et al, Phys. Rev. D97, 034016 (2018)**




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



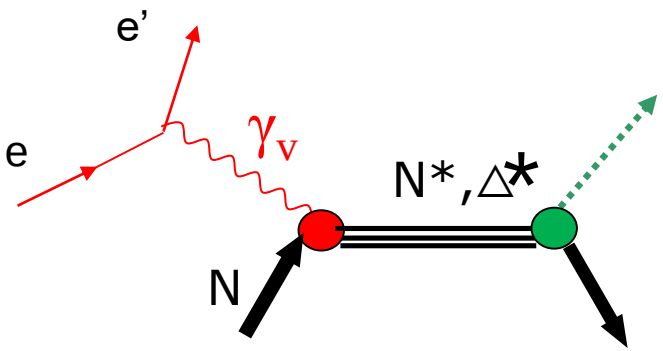

**Inferred from QCD Lagrangian with only the $\Lambda_{QCD}$ parameter**

**N* structure studies address:**

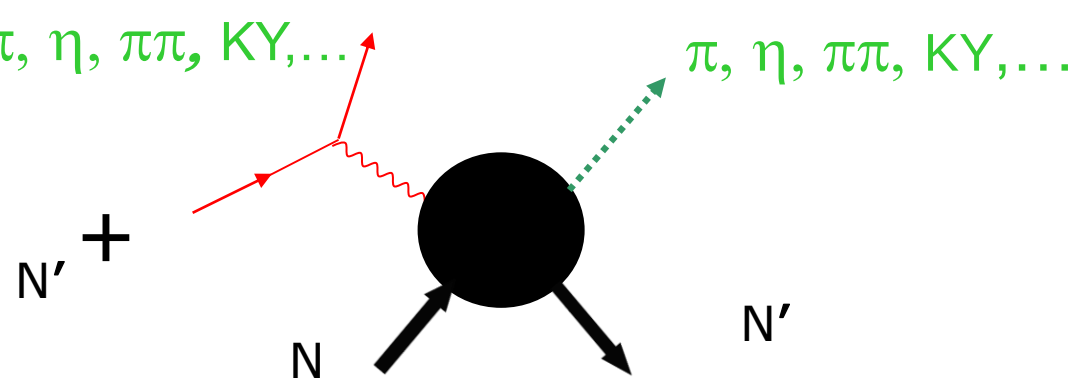
- **Nature of > 98% of hadron mass**
- **Emergence of the ground nucleon parton distributions in 1D and 3D under studies in DIS**

# 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 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 |
|---|---|---|---|
| $\pi^+n$ | **1.1-1.38**<br>**1.1-1.55**<br>**1.1-1.7**<br>**1.6-2.0** | **0.16-0.36**<br>**0.3-0.6**<br>**1.7-4.5**<br>**1.8-4.5** | **$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$, $A_b$**<br>**$d\sigma/d\Omega$** |
| $\pi^0p$ | **1.1-1.38**<br>**1.1-1.68**<br>**1.1-1.39** | **0.16-0.36**<br>**0.4-1.8**<br>**3.0-6.0** | **$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$, $A_b$,$A_t$,$A_{bt}$**<br>**$d\sigma/d\Omega$** |
| $\eta p$ | **1.5-2.3** | **0.2-3.1** | **$d\sigma/d\Omega$** |
| $K^+\Lambda$ | **thresh-2.6** | **1.40-3.90**<br>**0.70-5.40** | **$d\sigma/d\Omega$**<br>**$P^0$, P'** |
| $K^+\Sigma^0$ | **thresh-2.6** | **1.40-3.90**<br>**0.70-5.40** | **$d\sigma/d\Omega$**<br>**P'** |
| $\pi^+\pi^-p$ | **1.3-1.6**<br>**1.4-2.1**<br>**1.4-2.0** | **0.2-0.6**<br>**0.5-1.5**<br>**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!**

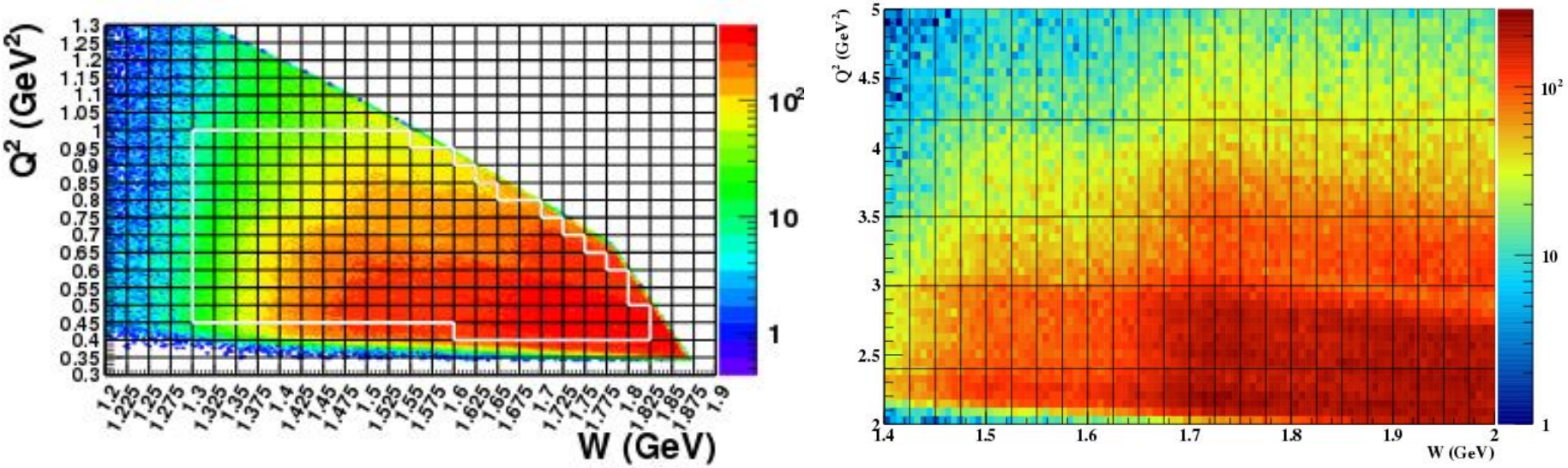
**Almost full coverage of the final hadron phase space**

**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 $\gamma_v pN^*$ 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 GeV < W < 2.0 GeV and 0 GeV$^2$ < Q$^2$ < 5.0 GeV$^2$**

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



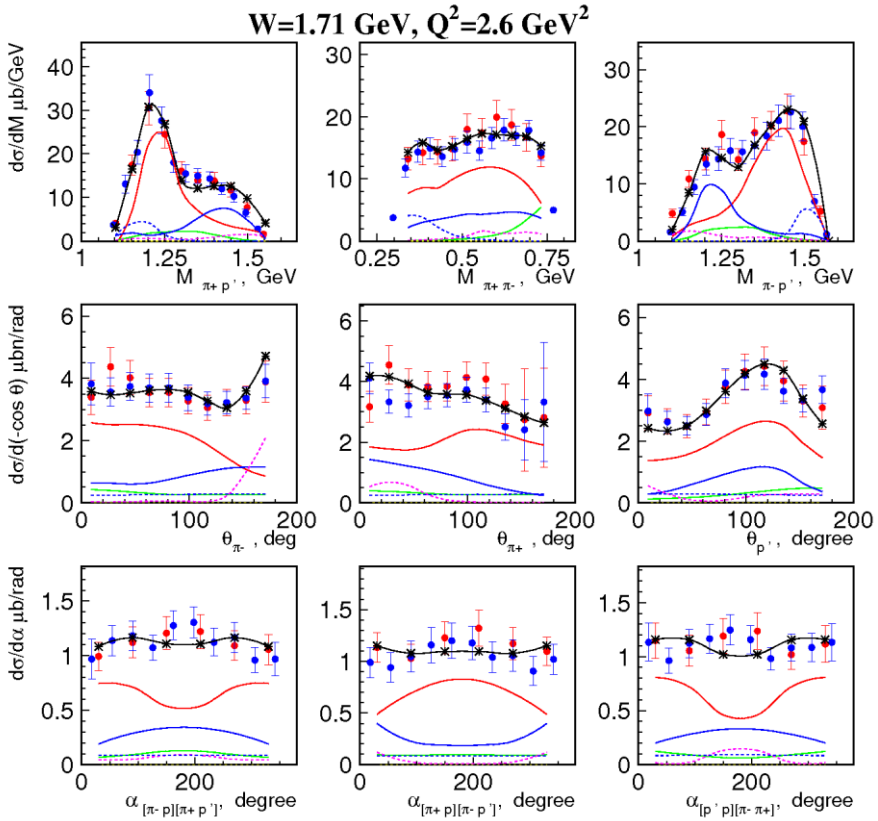

- **Data driven JLab-MSU meson-baryon model (JM)**

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

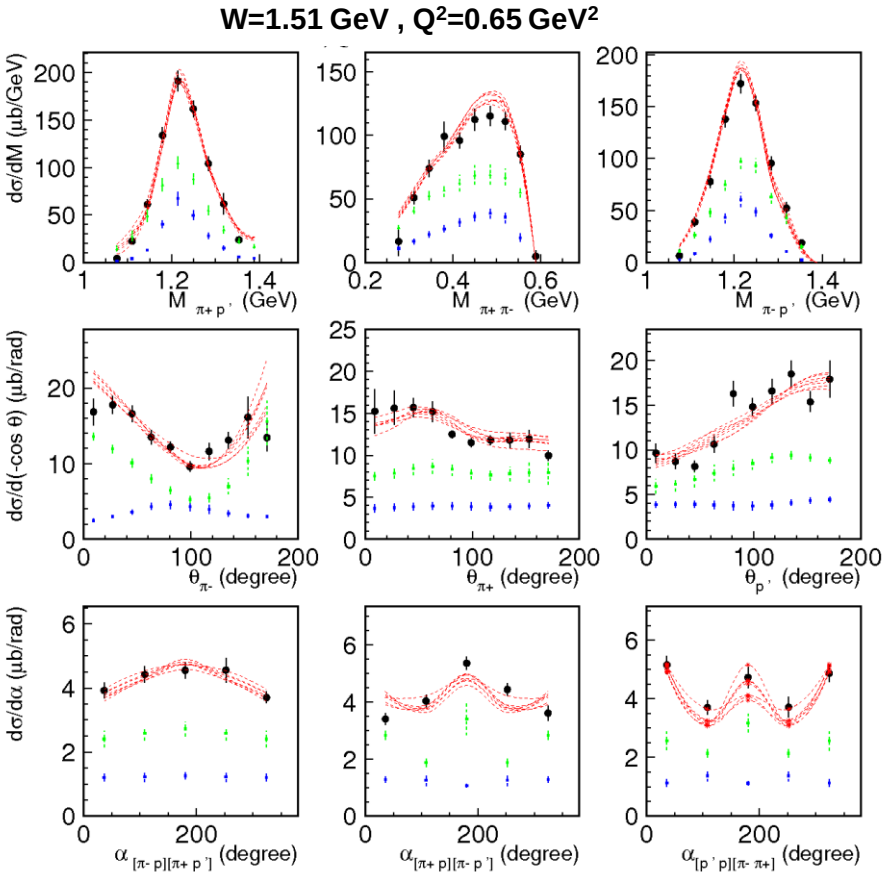
## Contributing mechanisms seen in the data

E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)
A.Trivedi, Few Body Syst. 60, 5 (2019)




## Resonant and non-resonant contributions

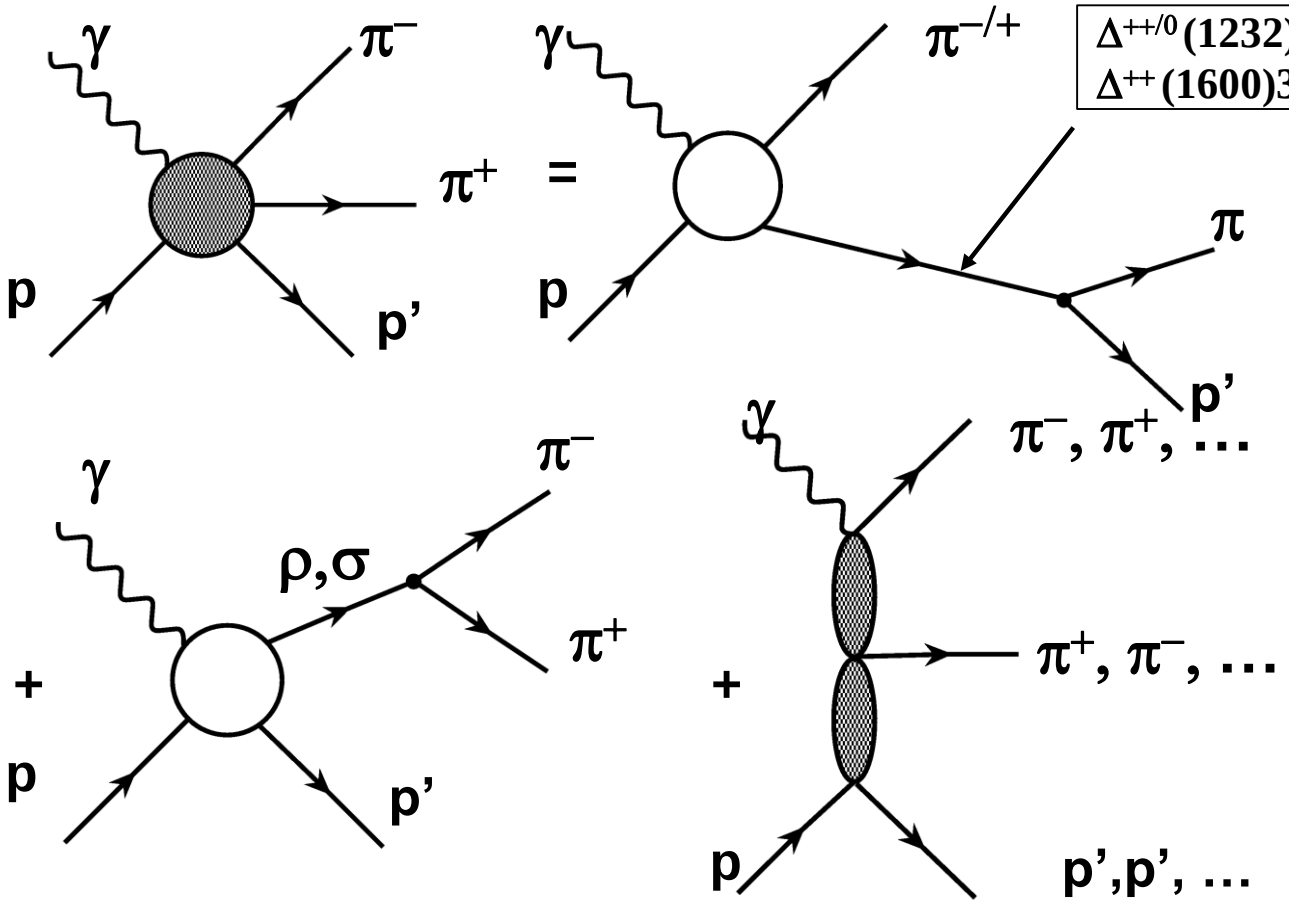
V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).




full JM
ρp
$\pi^+$ 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 $\pi\Delta$, $\rho$p decay widths**

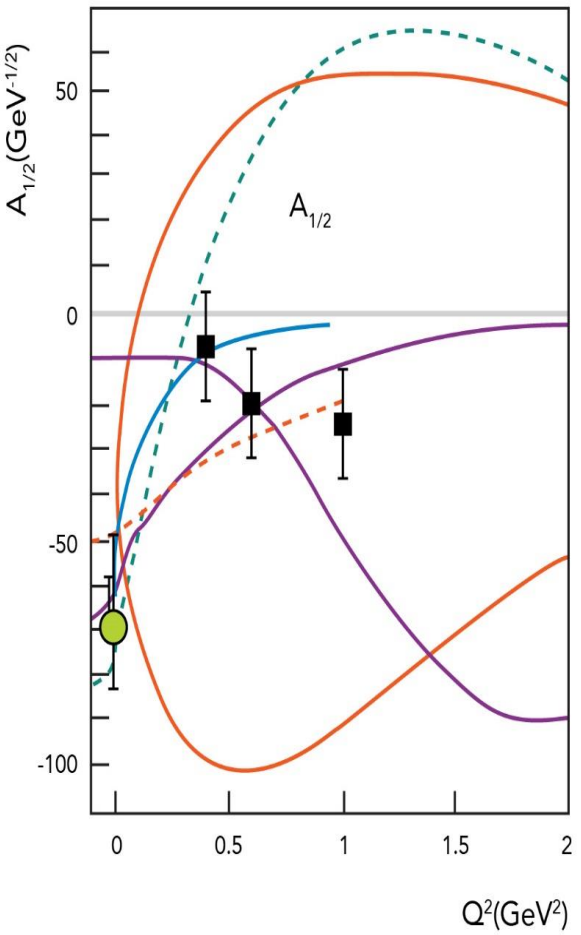



- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-$p production;
- N* contribute to $\pi\Delta$ and $\rho$p channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

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

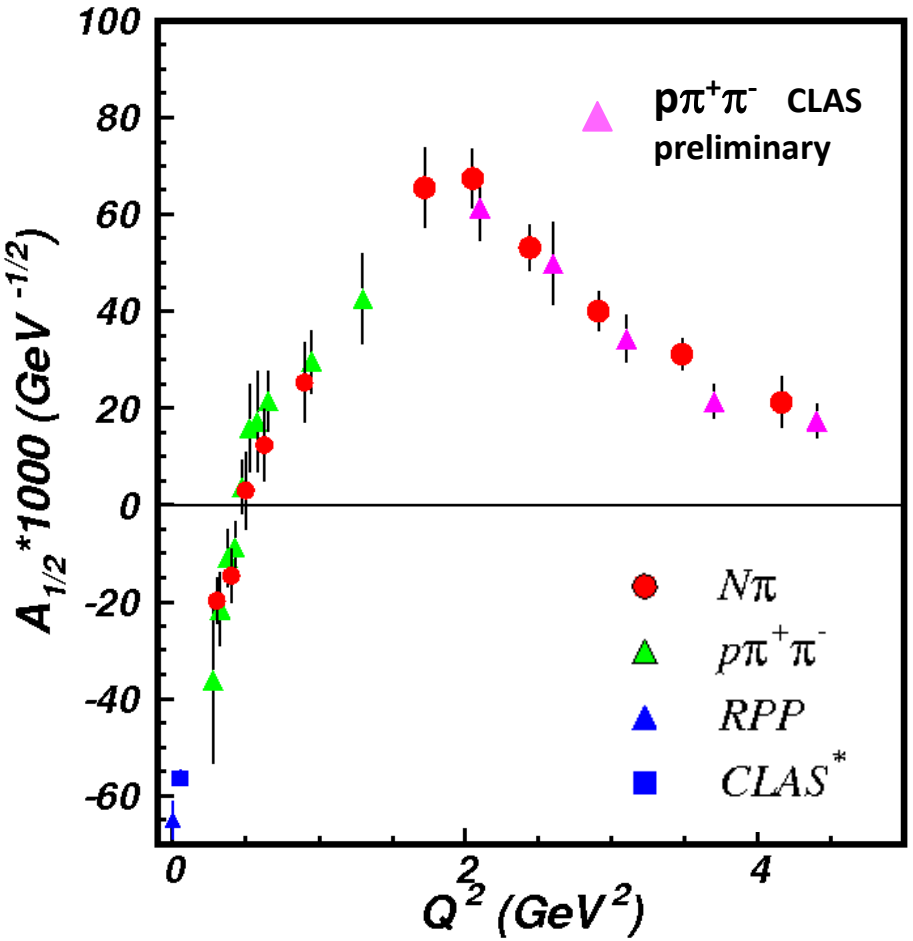
# Roper Resonance in 2002 & 2019

## 2002



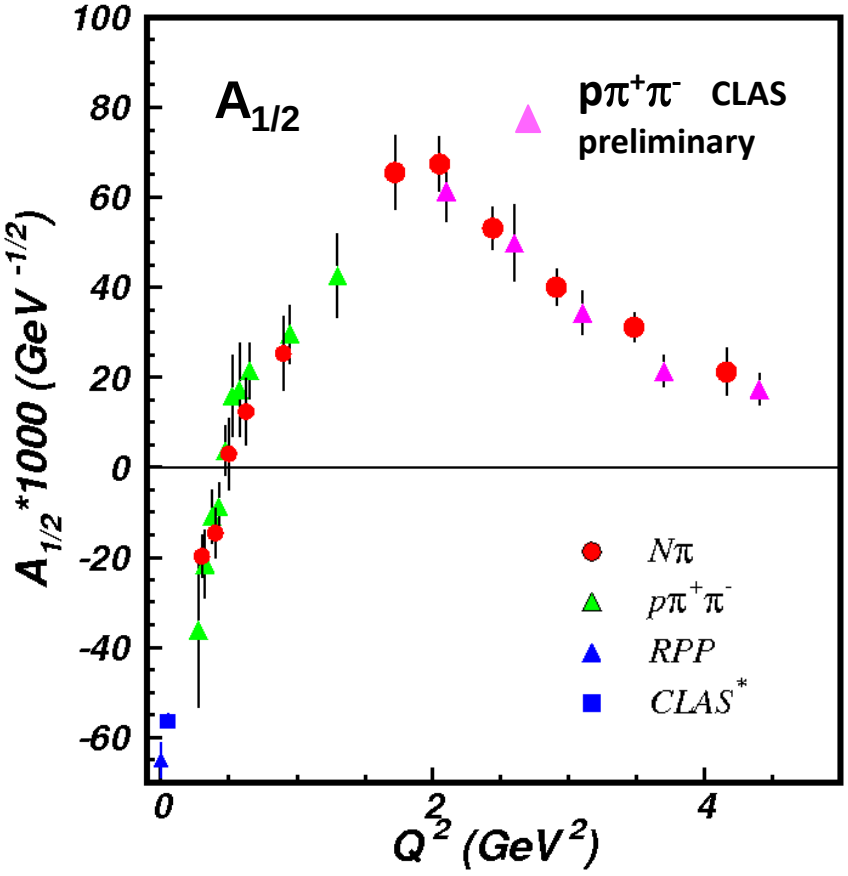

*V. Burkert, Baryons 2002*

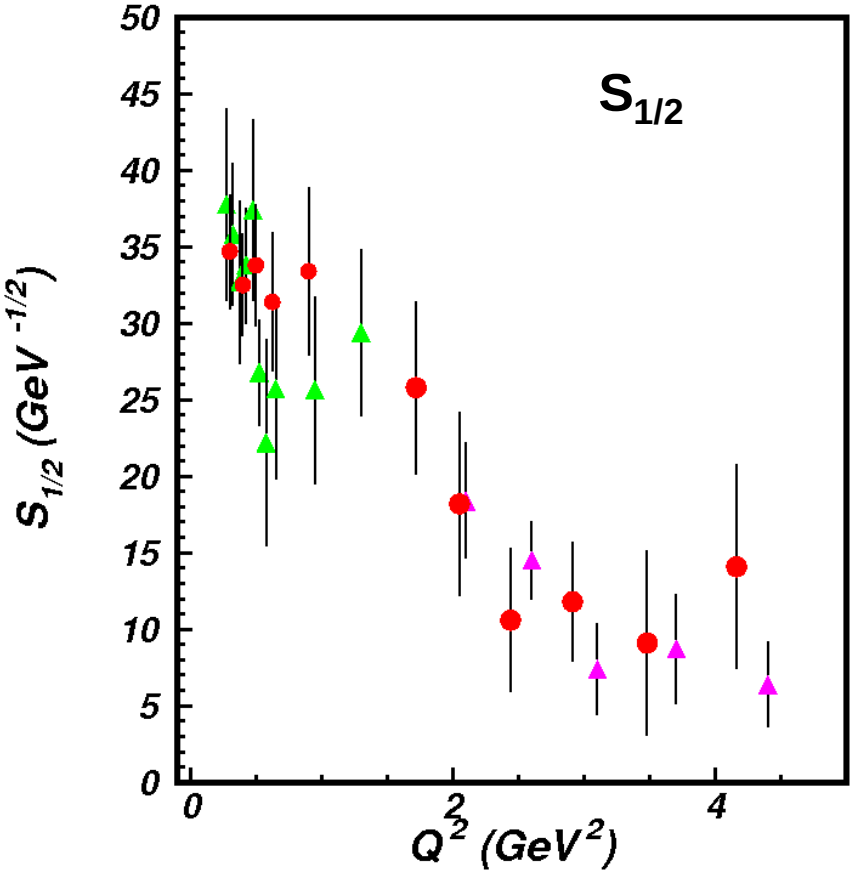
## 2019




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

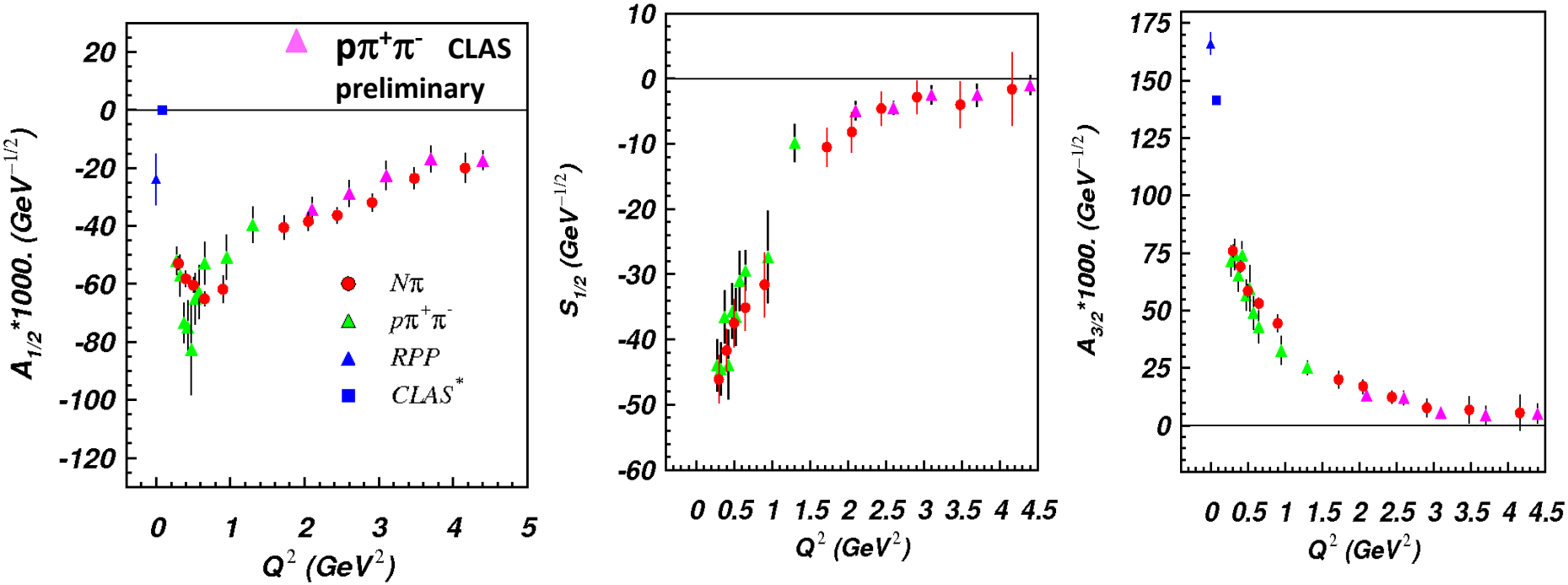
# Electrocouplings of N(1440)1/2$^+$ from N$\pi$ and $\pi^+\pi^-$p Electroproduction off Proton Data




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 Nπ and $\pi^+\pi^-$p Electroproduction off Proton Data

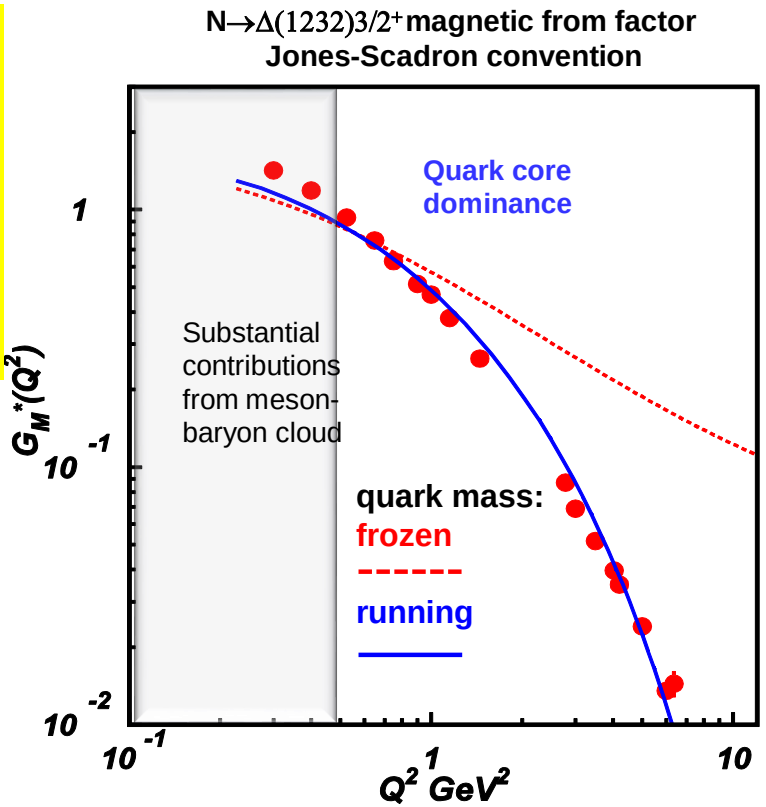


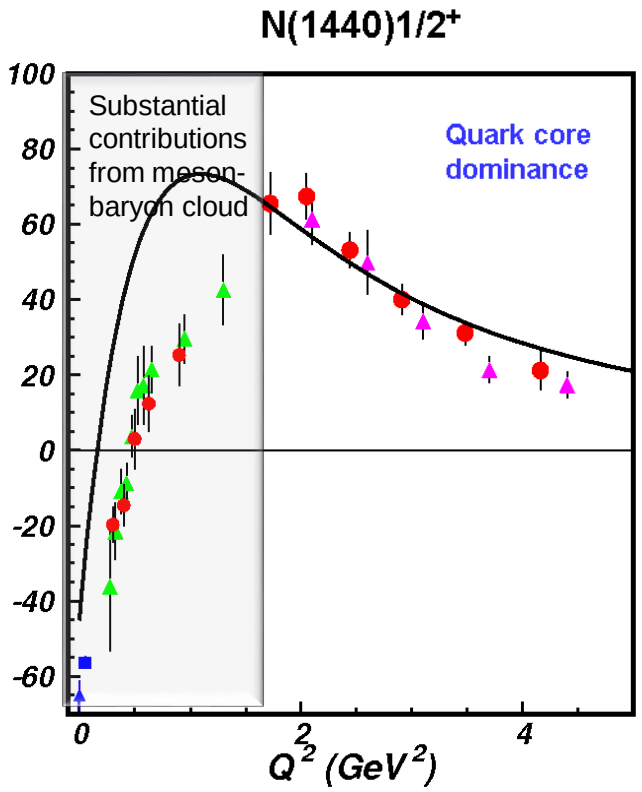

Consistent results from Nπ and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction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

# 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).**



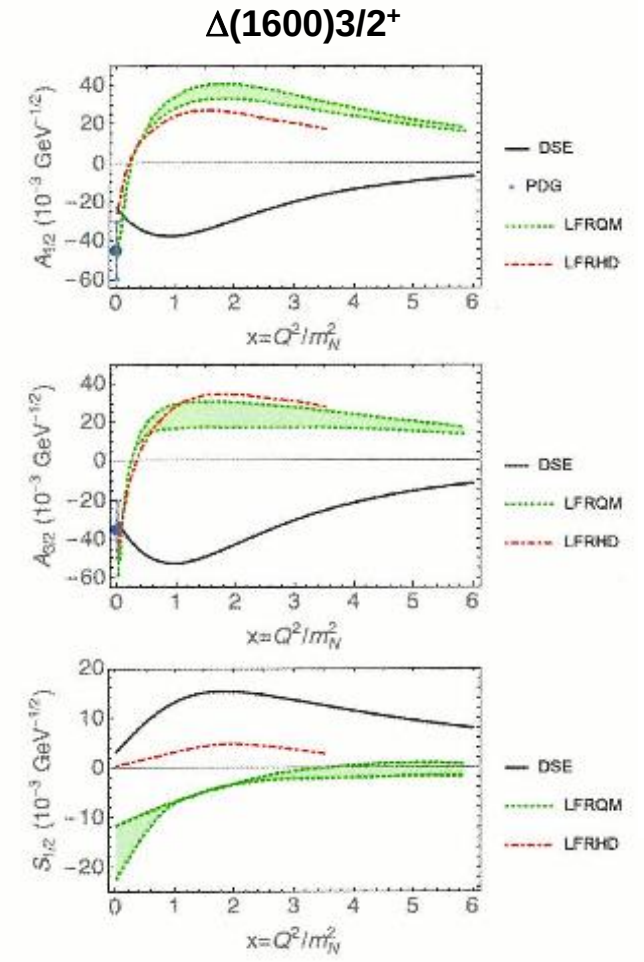



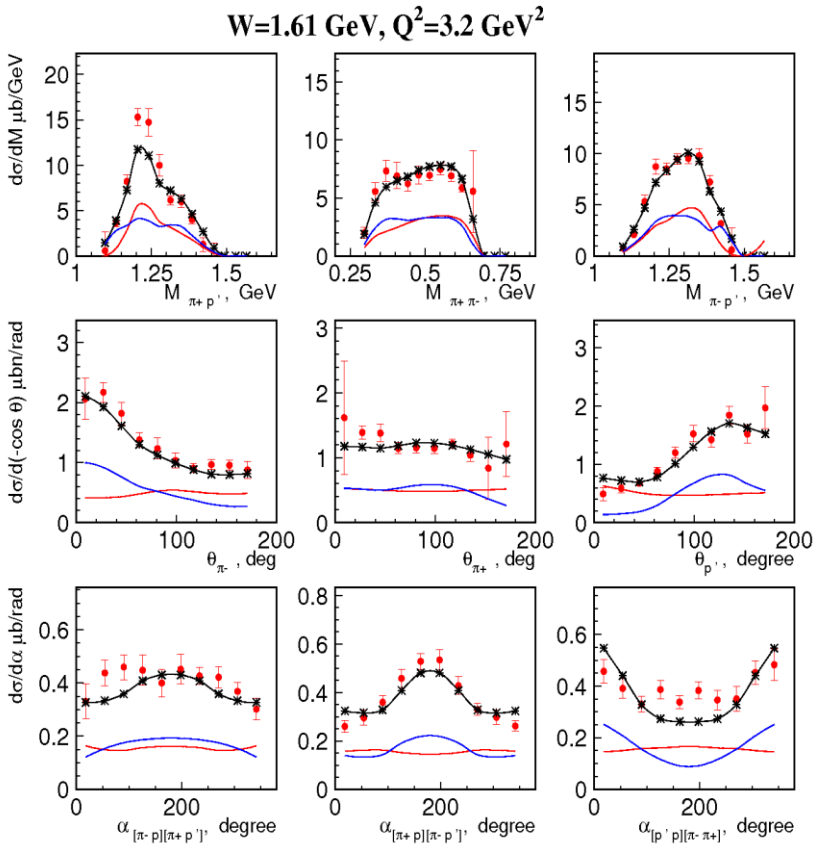

***DSE analyses of the CLAS data on Δ(1232)3/2⁺ electroexcitation demonstrated that dressed quark mass is running with momentum.***

**Good data description at $Q^2$>2.0 GeV² 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. $\gamma_v pN^*$ 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, phenomenologists and theorists.**

# Dressed Quark Mass Function from Electrocouplings of Radial Δ-Excitation




**π⁺π⁻p data from CLAS**
**A.Trivedi Few Body Syst. 60, 5 (2019)**

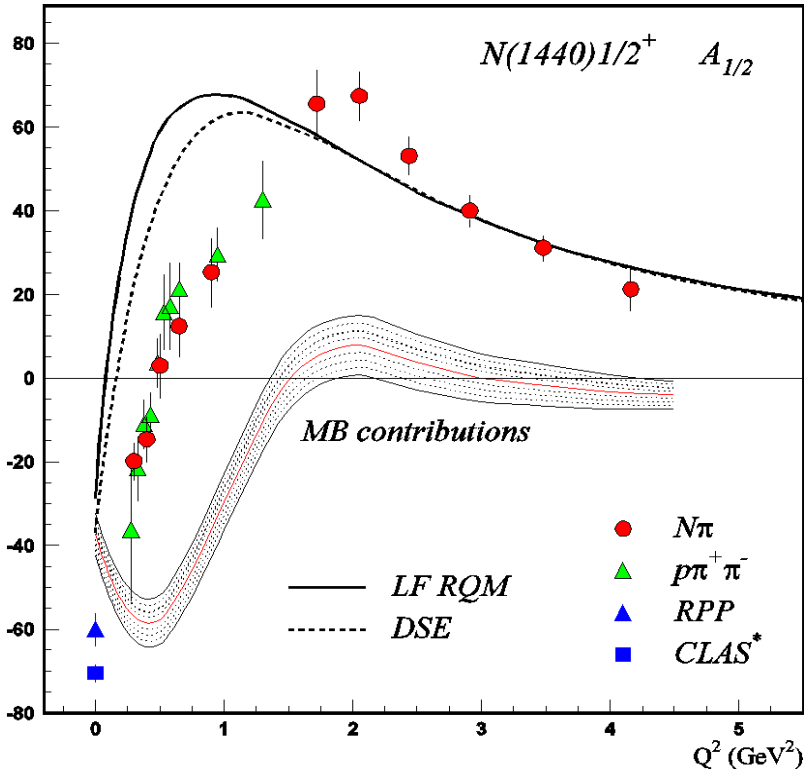
**N***
**non-resonant contributions**

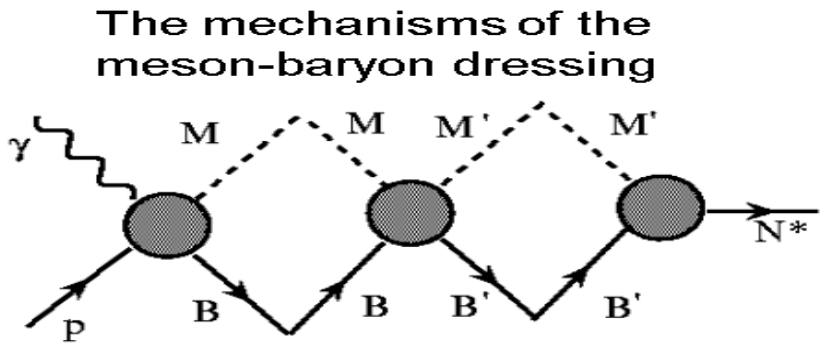
**Parameter free predictions for N→Δ(1600)3/2+ e.m. transition form factors from DSEQCD**
**Ya Lu et al, arXiv:1904.03205 [nucl-th]**

**Good description of the CLAS π⁺π⁻p electroproduction off protons data was achieved at 1.4 GeV < W < 2.0 GeV and 2.0 GeV² < Q² < 5.0 GeV² within JM19 model.**

- **Δ(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 $GeV^2$ 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**

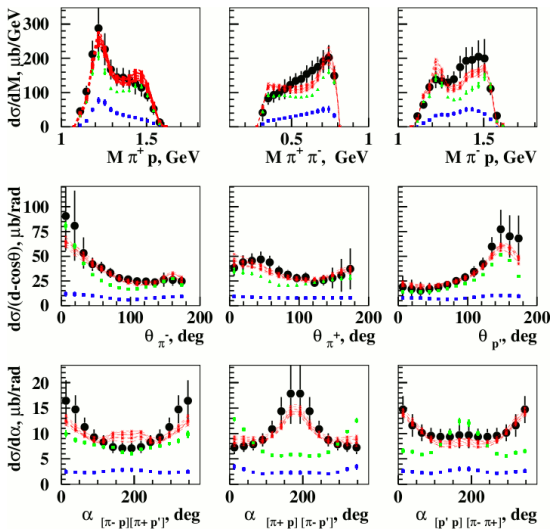
**LF RQM-Light Front relativistic quark model: V.D. Burkert, I.G. Aznauryan, Phys . Rev. C85, 055202 (2012); Phys. Rev. C95, 065207 (2017).**

**Quark core description within LF RQM and DSE is consistent**

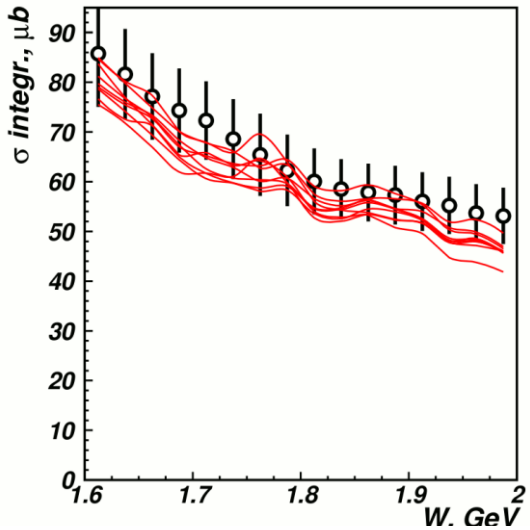
**For more details on resolving Roper puzzle see:**
**V. D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019).**

# Resonance Photocouplings from the CLAS $\pi^+\pi^-p$ Photoproduction Cross Sections

**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 | $A_{1/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$ | $A_{1/2}\times10^3$ PDG ranges $GeV^{-1/2}$ | $A_{1/2}\times10^3$ multichannel analysis [7] $GeV^{-1/2}$ | $A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$ | $A_{3/2}\times10^3$ PDG ranges $GeV^{-1/2}$ | $A_{3/2}\times10^3$ multichannel analysis [7] $GeV^{-1/2}$ |
|---|---|---|---|---|---|---|
| $\Delta(1620)1/2^-$ | 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 Nππ 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~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⁺ Nππ decays than in PDG 02*

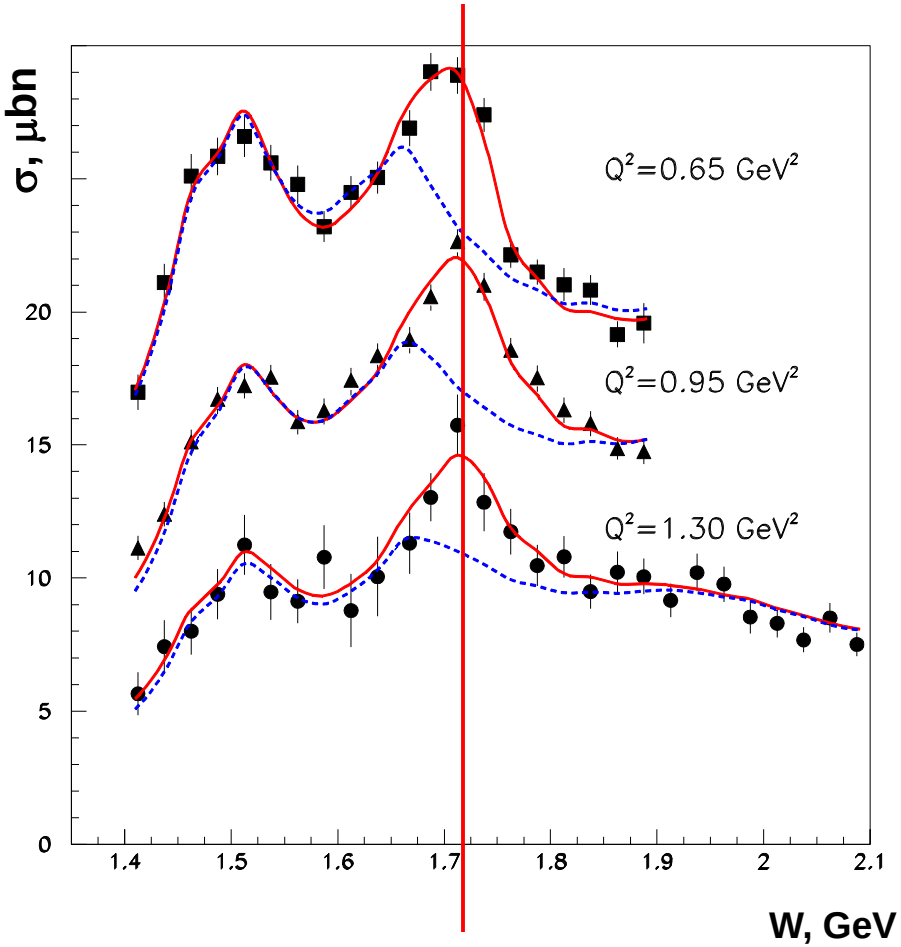
Two equally successful ways for the data description:

No new states, different than in PDG 02'
N(1720)3/2⁺ Nππ hadronic decay widths:

| | $\Gamma_{tot,}$ MeV | BF(πΔ) % | BF(ρp) % |
|---|---|---|---|
| **N(1720)3/2⁺ decays fit to the CLAS Nππ 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⁺:

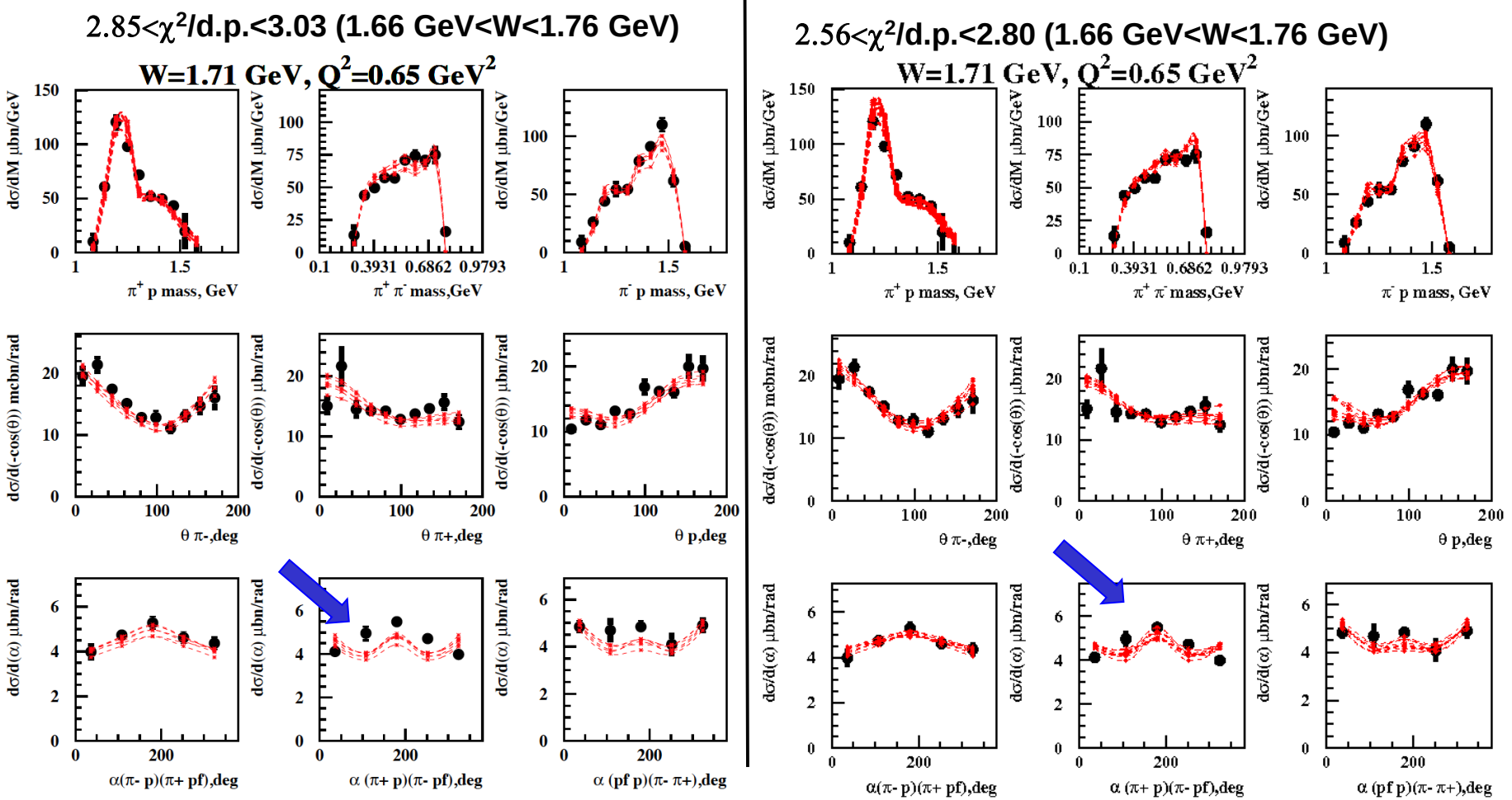
| | $\Gamma_{tot,}$ MeV | BF(πΔ) % | BF(ρp) % |
|---|---|---|---|
| **N'(1720)3/2⁺ New** | **119±6** | **47-64** | **3-10.** |
| **N(1720)3/2⁺ Conventional** | **112±8** | **39-55** | **23-49** |



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

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

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



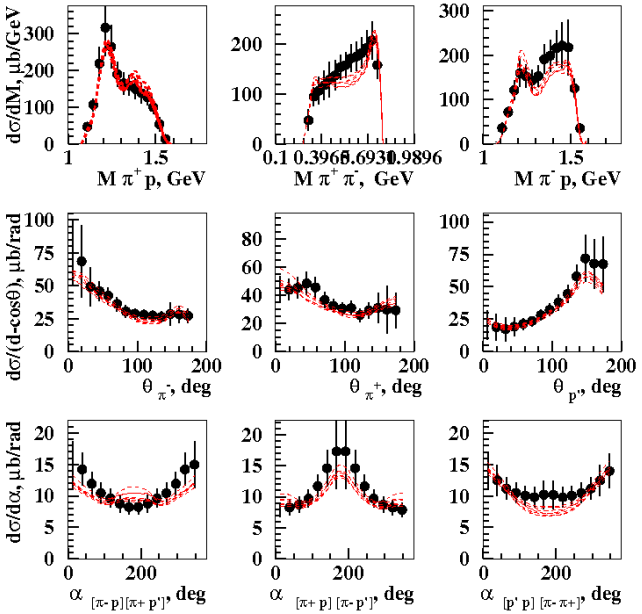

- Fit of $\theta_{\pi-}$, $\theta_{\pi+}$, $\theta_p$ angular distributions requires essential contribution(s) from the resonance(s) of $J^\pi=3/2^+$.
- Single state of $J^\pi=3/2^+$ should have major $\pi\Delta$ (>60%) and minor $\rho$p (<5%) decays in order to reproduce pronounced $\Delta$–peaks in $\pi^+$p and to avoid $\rho$-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$^+$

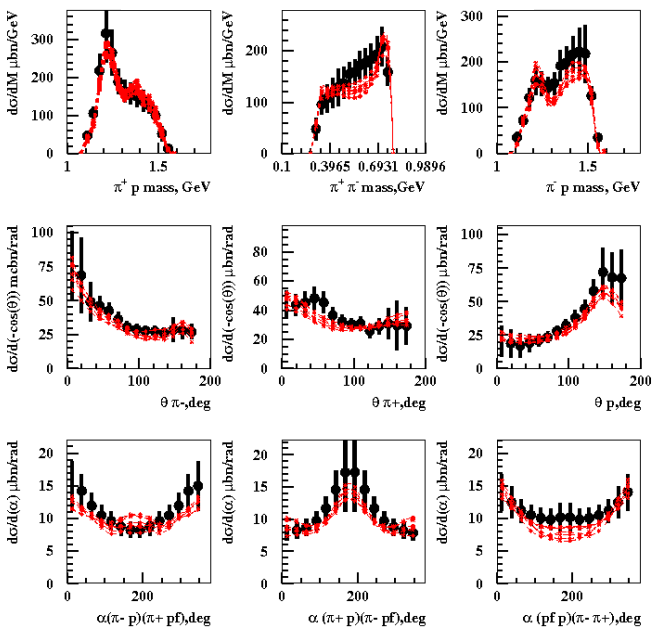
**E.N. Golovach et al., CLAS Collaboration, Phys. Lett. B 788, 371 (2019).**

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

**N'(1720)3/2$^+$ on**




**N'(1720)3/2$^+$ off**




**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$^+$ $\longrightarrow$ $1.19 < \chi^2/\text{d.p.} < 1.28$**

**N(1720)3/2$^+$ only $\longrightarrow$ $1.08 < \chi^2/\text{d.p.} < 1.26$**

**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**

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

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

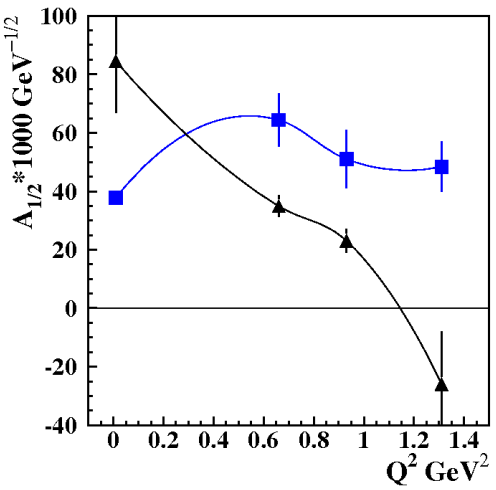
**N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state**

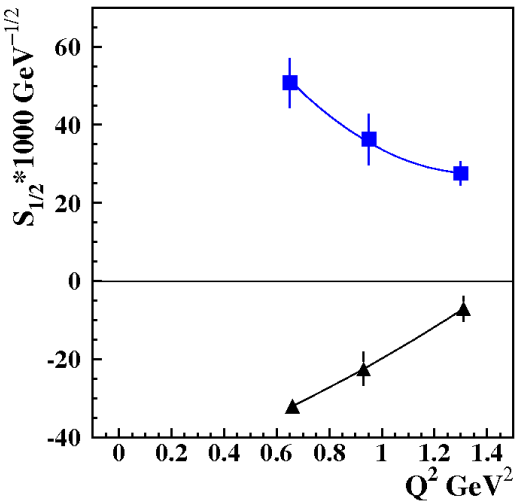
| Resonance | BF($\pi\Delta$), % | BF($\rho$p), % |
|---|---|---|
| N'(1720)3/2$^+$<br>electroproduction<br>photoproduction | <br>47-64<br>46-62 | <br>3-10<br>4-13 |
| N(1720)3/2$^+$<br>electroproduction<br>photoproduction | <br>39-55<br>38-53 | <br>23-49<br>31-46 |
| $\Delta$(1700)3/2$^-$<br>electroproduction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

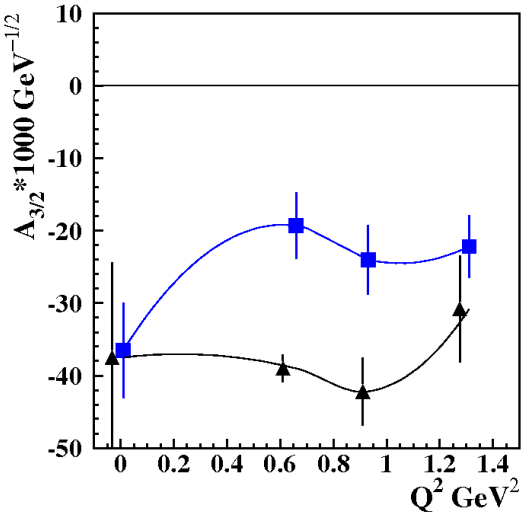
**The successful description of the $\pi^+\pi^-$p photo- and electroproduction data achieved by implementing new N'(1720)3/2$^+$ state with $Q^2$-independent hadronic decay widths of all resonances contributing at W~1.7 GeV provides strong evidence for the existence of the new N'(1720)3/2$^+$ state.**

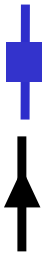
# The Parameters of the New N'(1720)3/2$^+$ State from the CLAS Data Fit

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



N'(1720)3/2$^+$

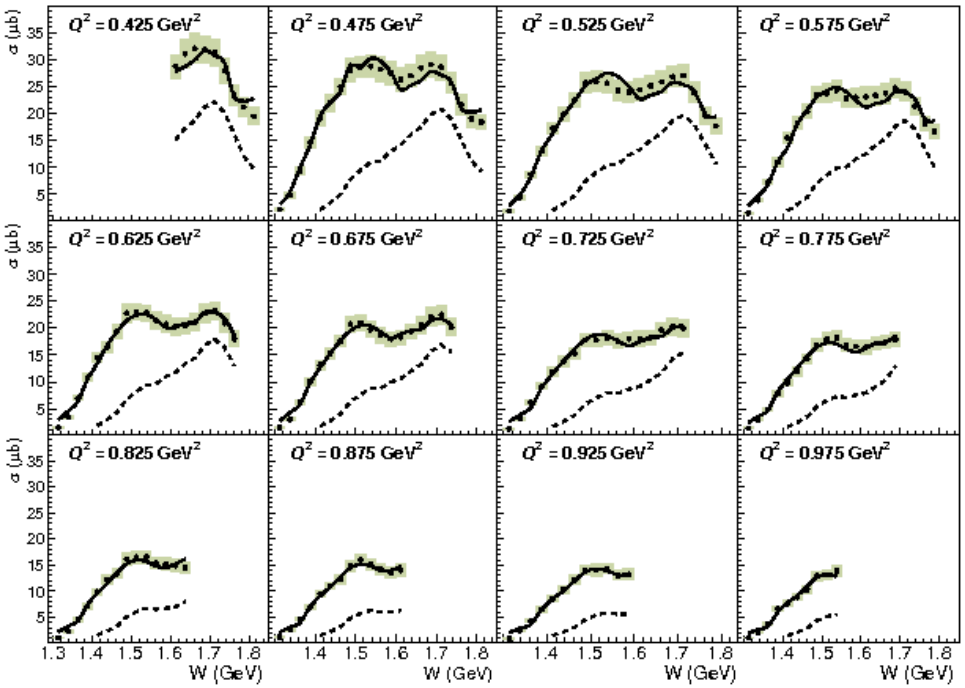
N(1720)3/2$^+$

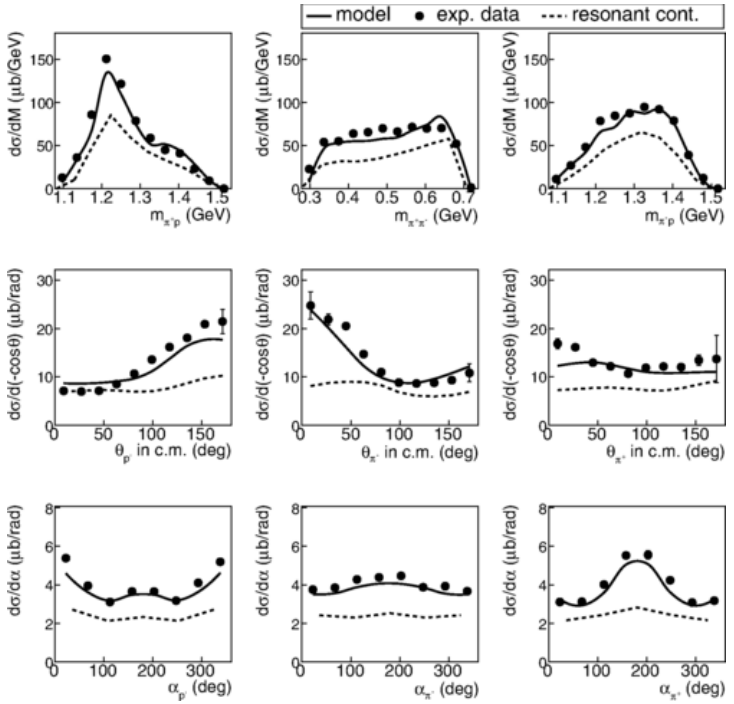
| Resonance | Mass, GeV | Total width, MeV |
|---|---|---|
| N'(1720)3/2$^+$ | 1.715-1.735 | 120±6 |
| N(1720)3/2$^+$ | 1.743-1.753 | 112±8 |

- 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 $0.4<Q^2<1.0$ 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 GeV and 0.4 GeV$^2$<$Q^2$<1.0 GeV$^2$ of the best statistical and systematical accuracy obtained with minimal bin size over $Q^2$ ever achieved ($\Delta Q^2$= 0.05 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 GeV$^2$<$Q^2$< 0.8 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 $0<Q^2<5.0$ GeV$^2$.**

- **Photocouplings and $\pi\Delta$, $\rho p$ 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 $\pi^+n$, $\pi^0p$, $\eta p$, and $\pi^+\pi^-p$ electroproduction channels.**

- **<u>Profound impact on the exploration of strong QCD dynamics:</u>**

  **a) possessing a traceable connection to the QCD Lagrangian, first DSE evaluation of $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes have become available;**

  **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.**

# 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.**

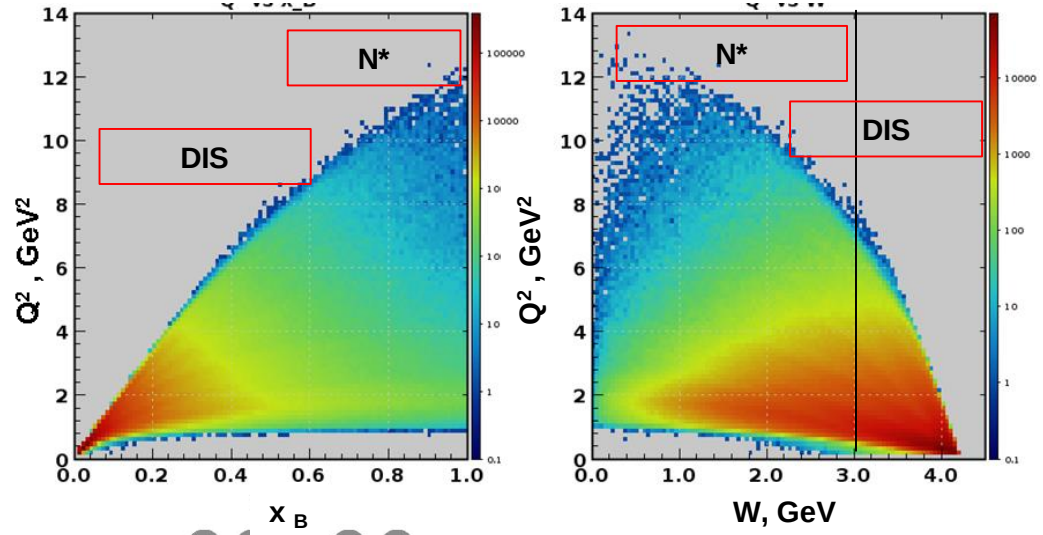
- **Electrocouplings of most resonances in the mass range up to 2.0 GeV will be obtained at 2.0 GeV$^2$<$Q^2$<5.0 GeV$^2$ from the new CLAS data on $\pi^+\pi^-p$ electroproduction in the near term future.**

- **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.; EU efforts on the QCD-related theoretical interpretation in the talk by Ch. Fischer, Thursday, June 13, 9.00 a.m.**

# Back Up

# 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

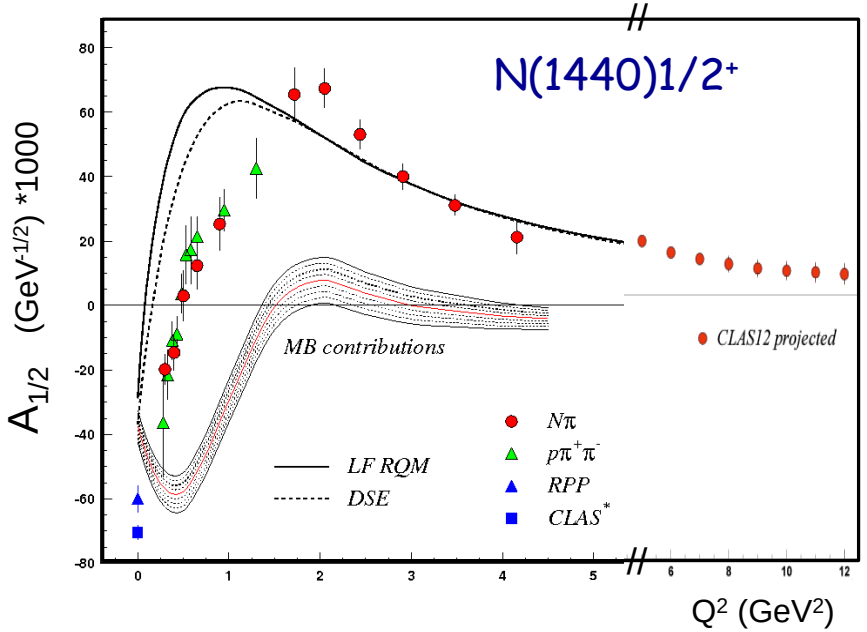
**N* electroexcitation studies at JLab will address the critical open questions:**

*How is >98% of visible mass generated?*

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

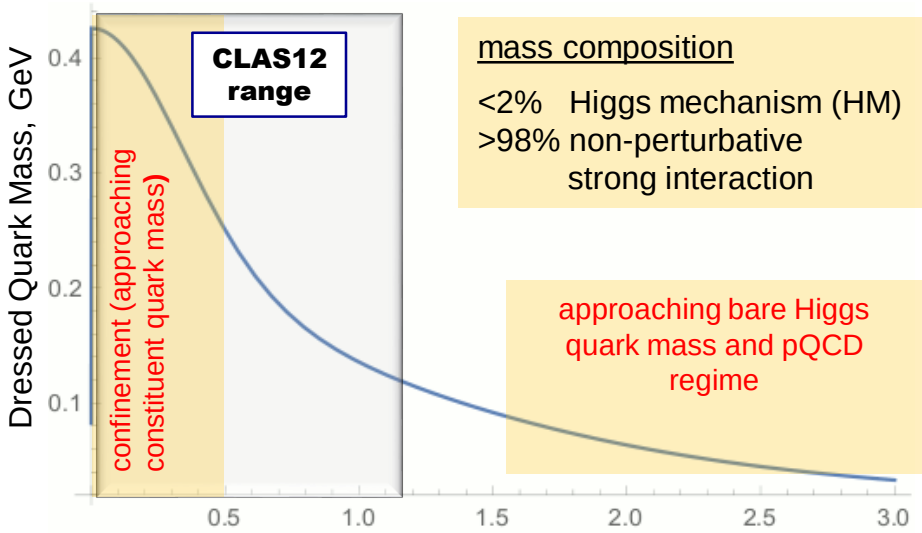
*What is the behavior of QCD's running coupling at infrared momenta?*

**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



# 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**

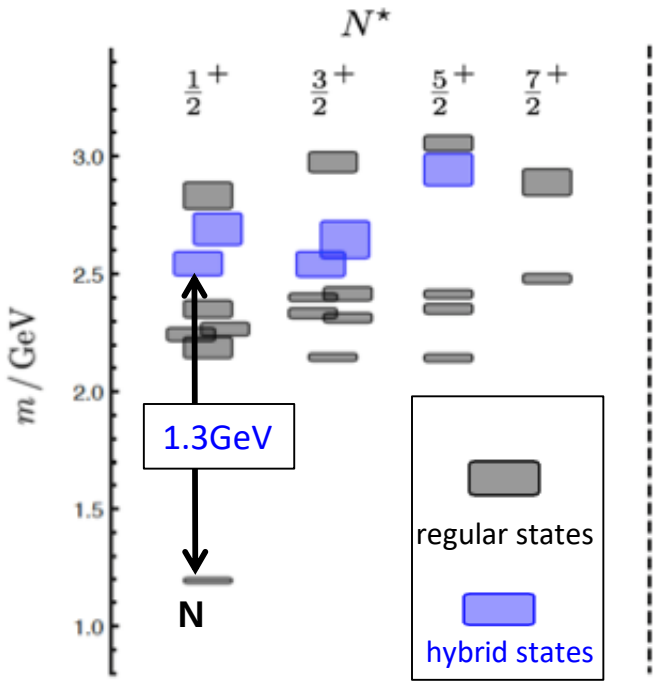
| Run Group conditions: |
|---|
| $E_b$ = 6.6 GeV, 50 days |
| $E_b$ = 8.8 GeV, 50 days |

- 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?**

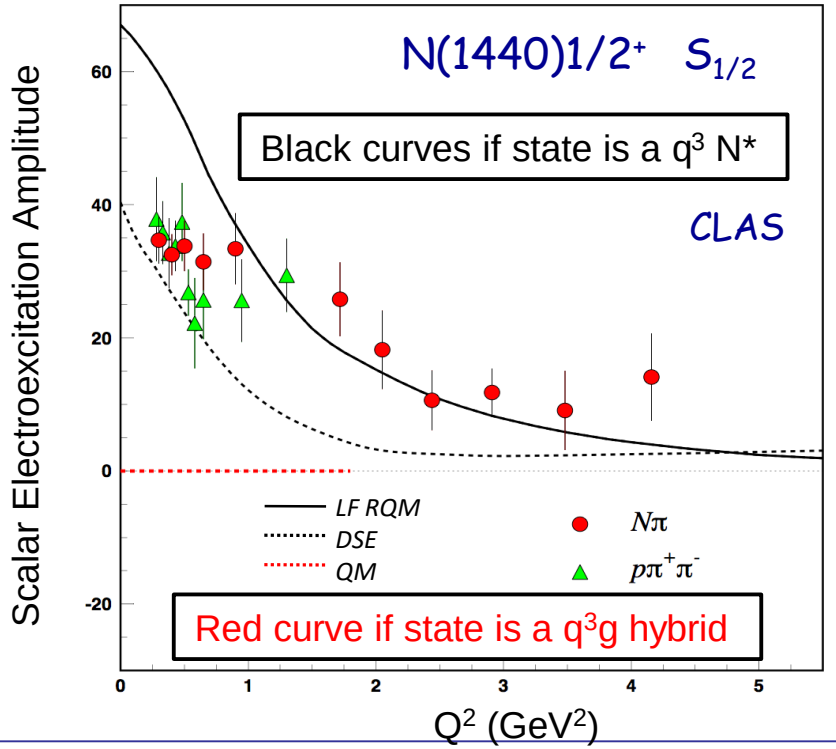
Predictions of the N* spectrum from QCD show both regular $q^3$ *and* hybrid $q^3g$ states




*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



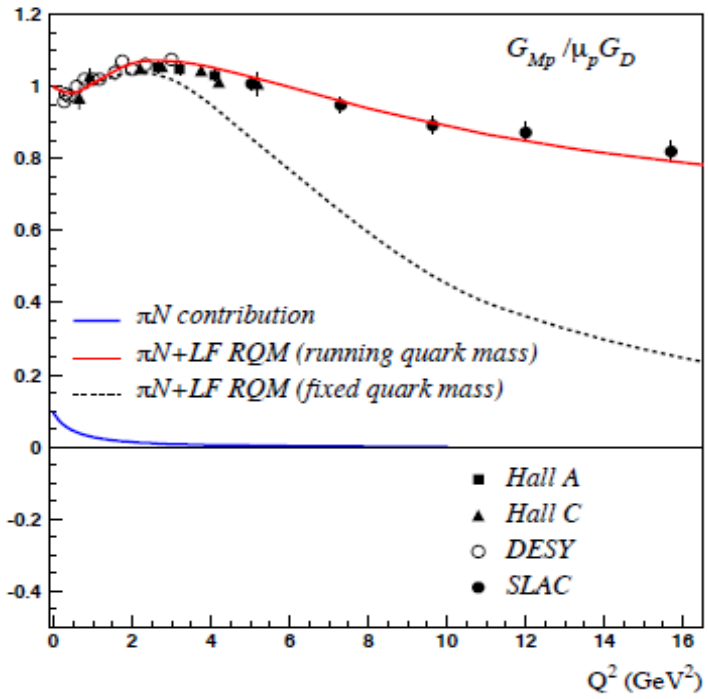
# Quark Model with Input from QCD-based Approaches

**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$^2$**