

Electromagnetic form factors of nucleon resonances from CLAS

QFTHEP-2019

Evgeny Isupov SINP MSU

50 years of scaling and parton model!

► Observed Behavior of Highly Inelastic Electron-Proton Scattering

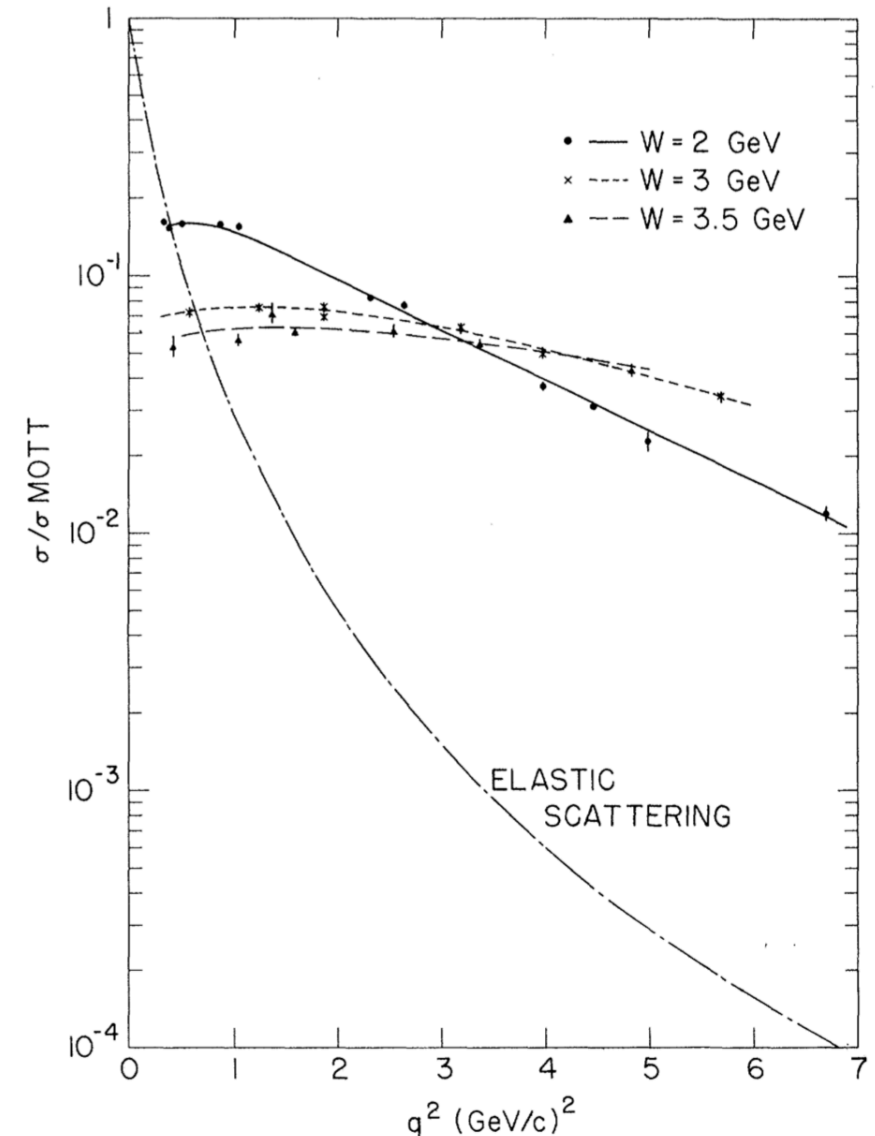
M. Breidenbach, J. I. Friedman, H. W. Kendall, E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor

Phys. Rev. Lett. **23**, 935 - Published 20 October 1969

► Inelastic Electron-Proton and γ -Proton Scattering and the Structure of the Nucleon

J. D. Bjorken and E. A. Paschos

Phys. Rev. **185**, 1975 - Published 25 September 1969



New era in electromagnetic nuclear physics

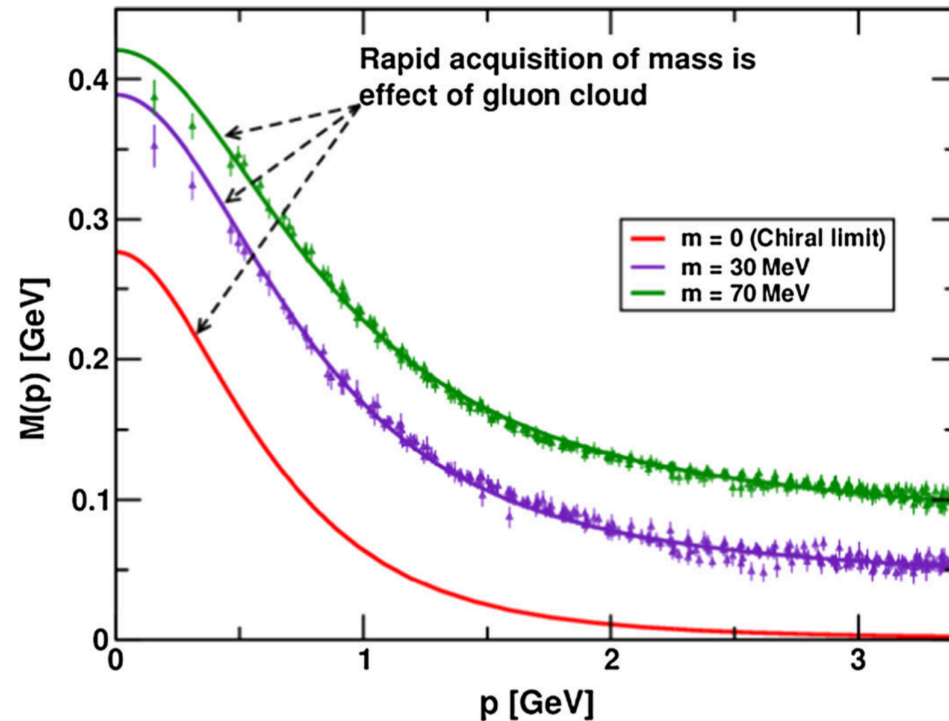
- ▶ Electrons and photons are perfect tools to explore the properties of strongly interacting systems.
- ▶ In the past ~ 25 years many facilities with high-quality continuous beam and large acceptance detectors were launched.

MAMI Mainz
ELSA Bonn
GRAAL Grenoble
LEPS Osaka
JLAB Newport News

Excited Nucleon States and Insight into Strong QCD Dynamics

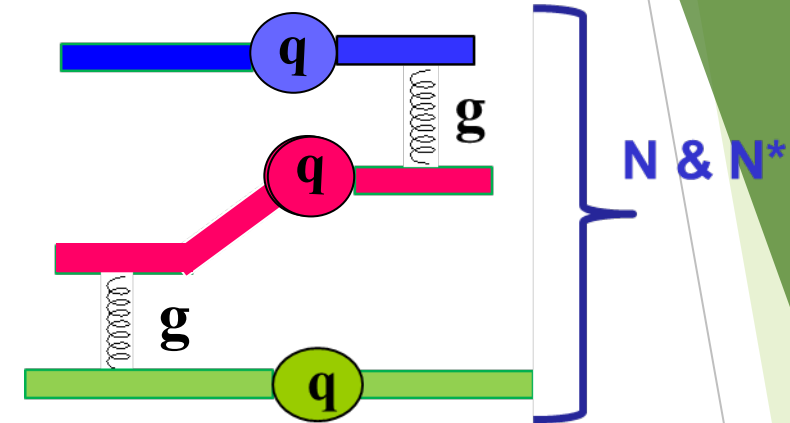
Two conceptually different approaches for description of nucleon/ N^* structure from first QCD principles:

- Lattice QCD (LQCD)
- Dyson-Schwinger Equation of QCD (DSEQCD)



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

quark-quark correlations in baryons
Ch. Chen et al, Phys. Rev. D97, 034016 (2018)

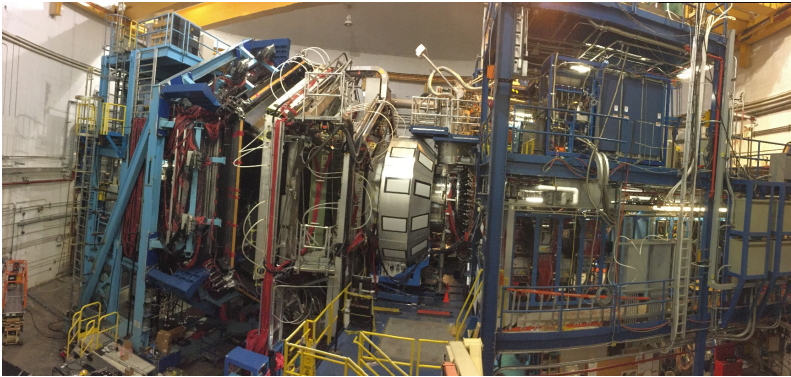


N^* structure studies address:

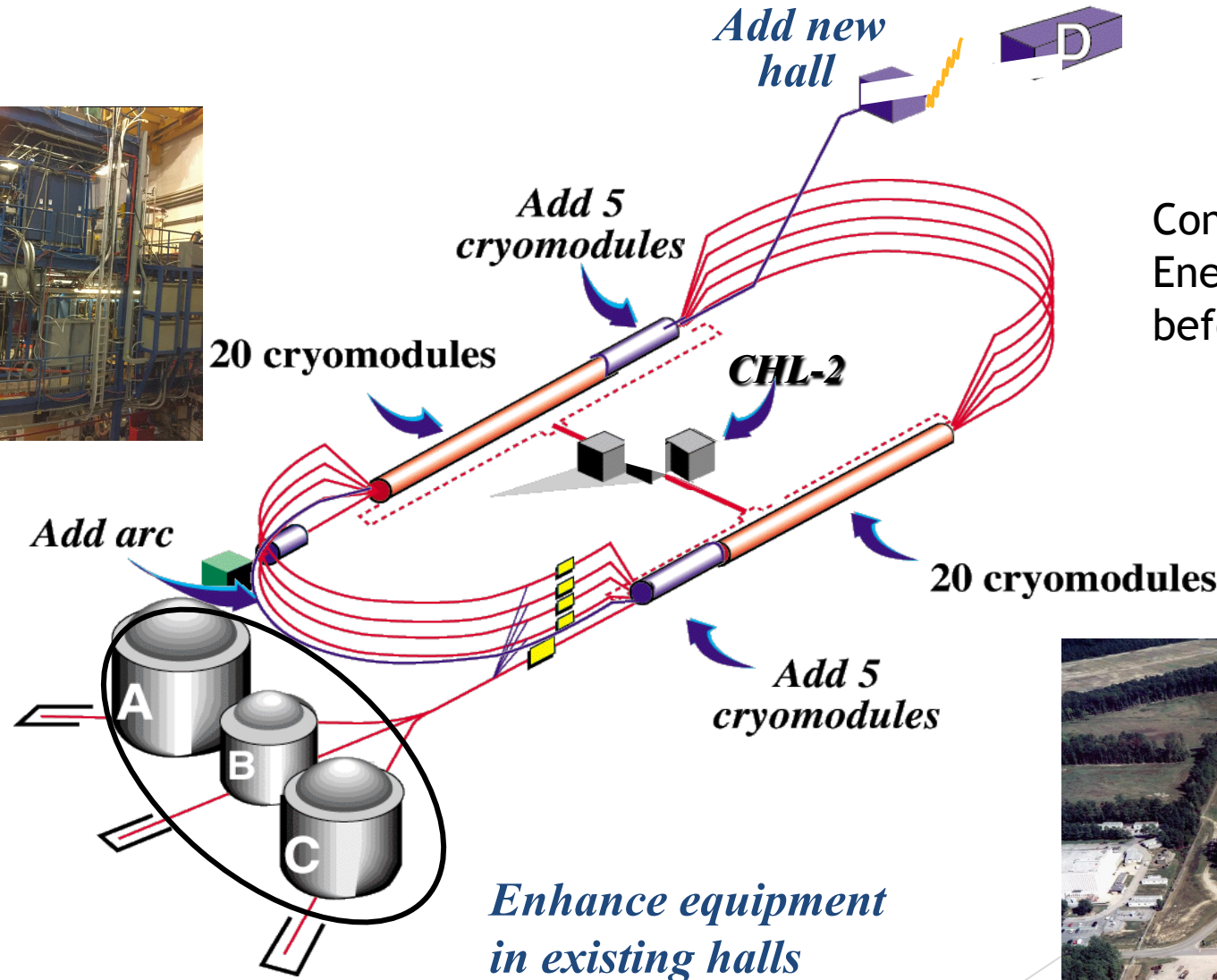
- Nature of $> 98\%$ of hadron mass
- Emergence of the ground nucleon parton distributions in 1D and 3D

Jefferson Lab (Newport News, VA, USA)

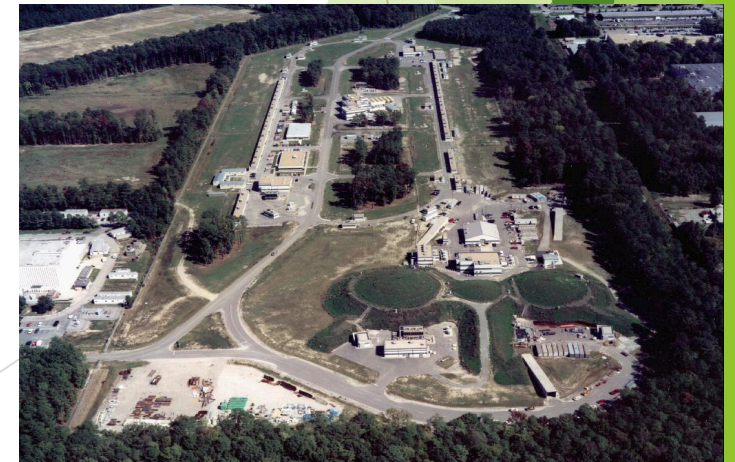
CLAS12 in Hall B



CLAS (1998-2012)



Continuous electron beam with
Energy = 11 GeV
before upgrade: Energy = 6 GeV



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

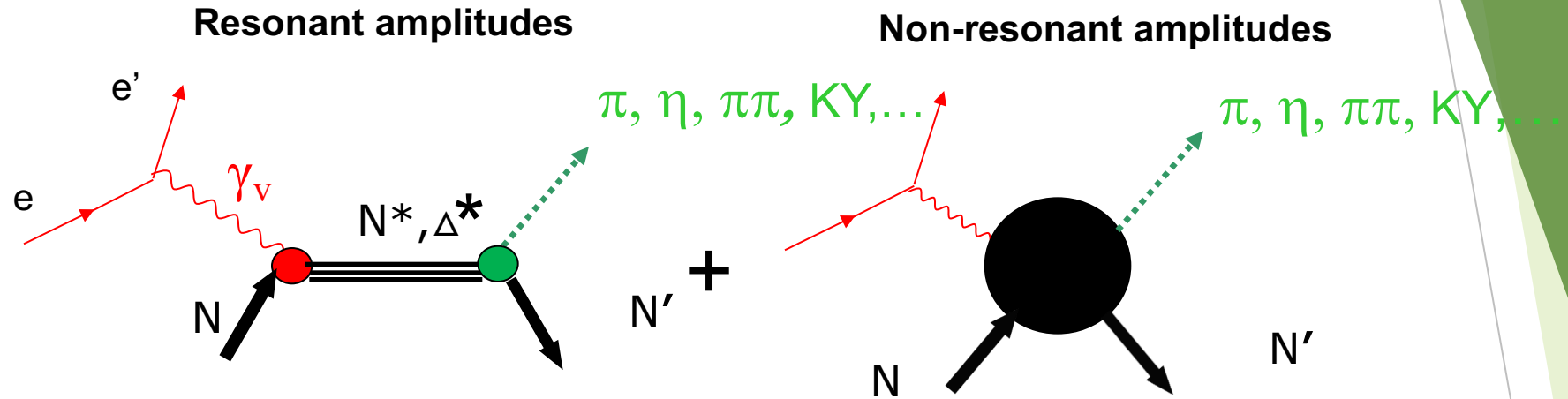
- N* spectrum with a focus on the new, so-called “missing” and hybrid resonance search
- $\gamma_v p N^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range 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]*.
3. C.D. Roberts, *Few Body Syst.* 59, 72 (2018).
4. V.I. Mokeev, *Few Body Syst.* 59, 46 (2018).

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



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'
$\pi^+\pi^-p$	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

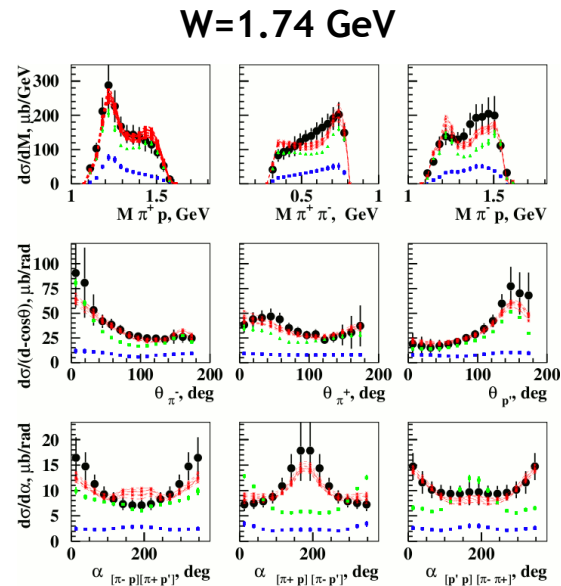
- $d\sigma/d\Omega$ —CM angular distributions
- A_b, A_t, A_{bt} —longitudinal beam, target, and beam-target asymmetries
- P^0, P' —recoil and transferred polarization of strange baryon

Over 120,000 data points!

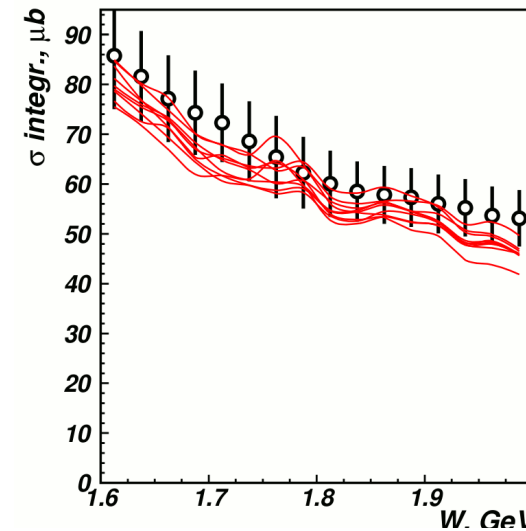
Almost full coverage of the final hadron phase space

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

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



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

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

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

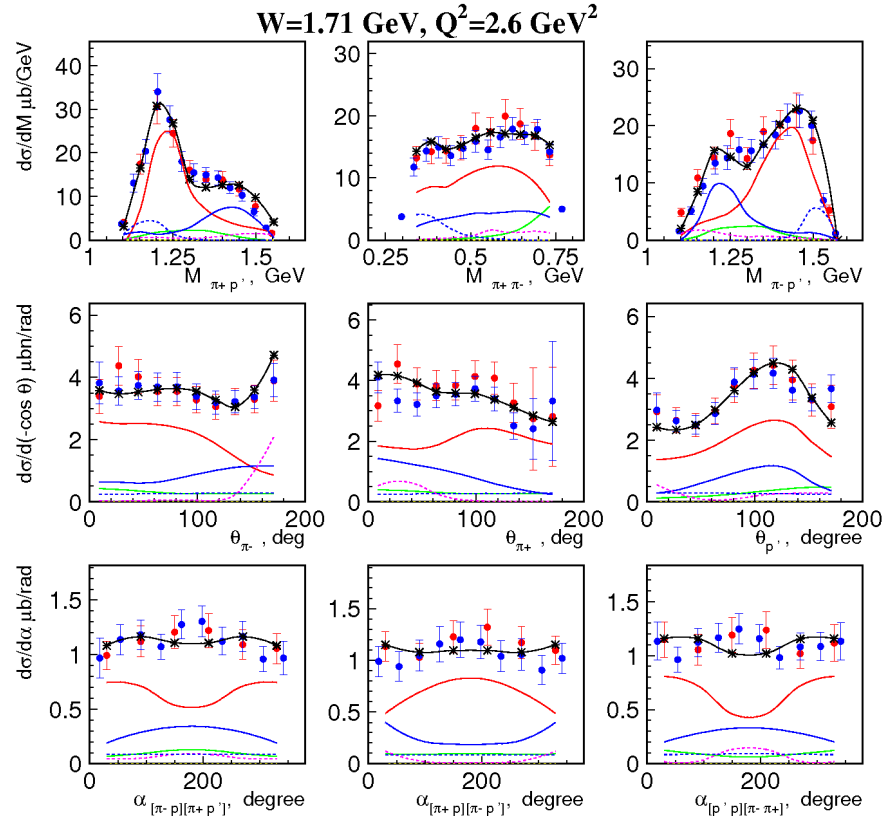
In 2019 partial update of the Review of Particle Physics the entries on photocouplings and $N\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

Accessing resonance electrocouplings from the $\pi^+\pi^-p$ differential electroproduction off protons cross sections

Contributing mechanisms seen in the data

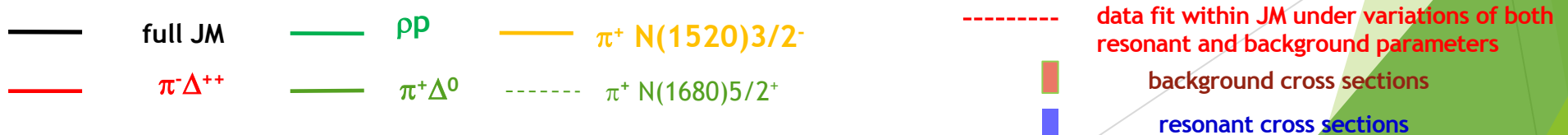
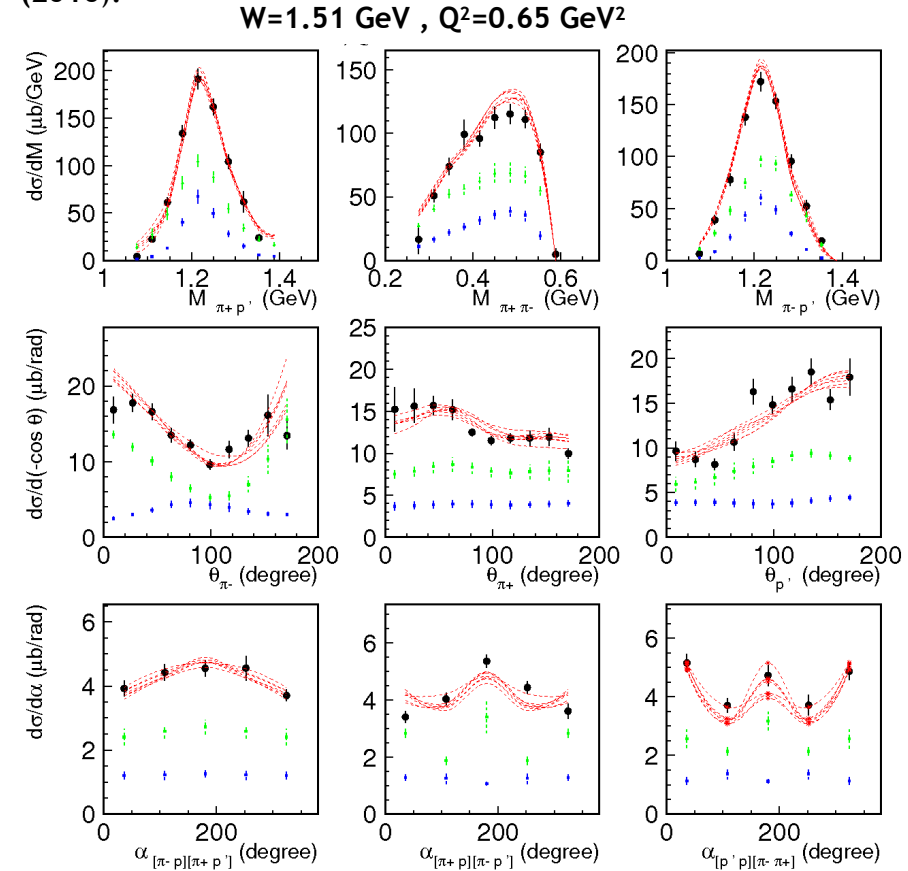
E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)

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



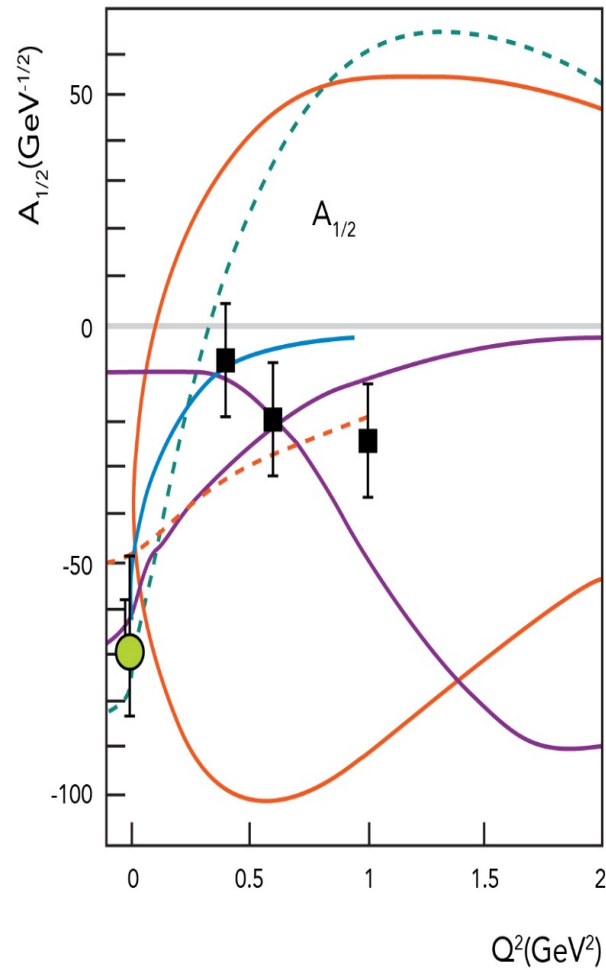
Resonant and non-resonant contributions

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



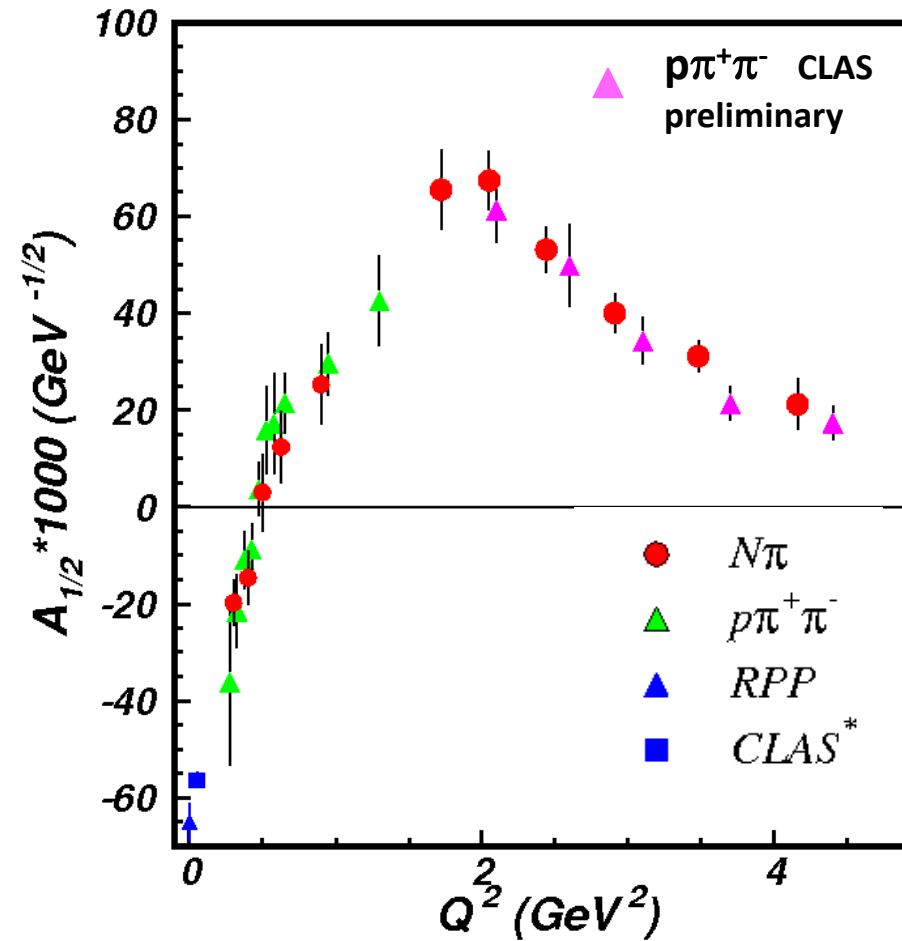
Roper Resonance in 2002 & 2019

2002



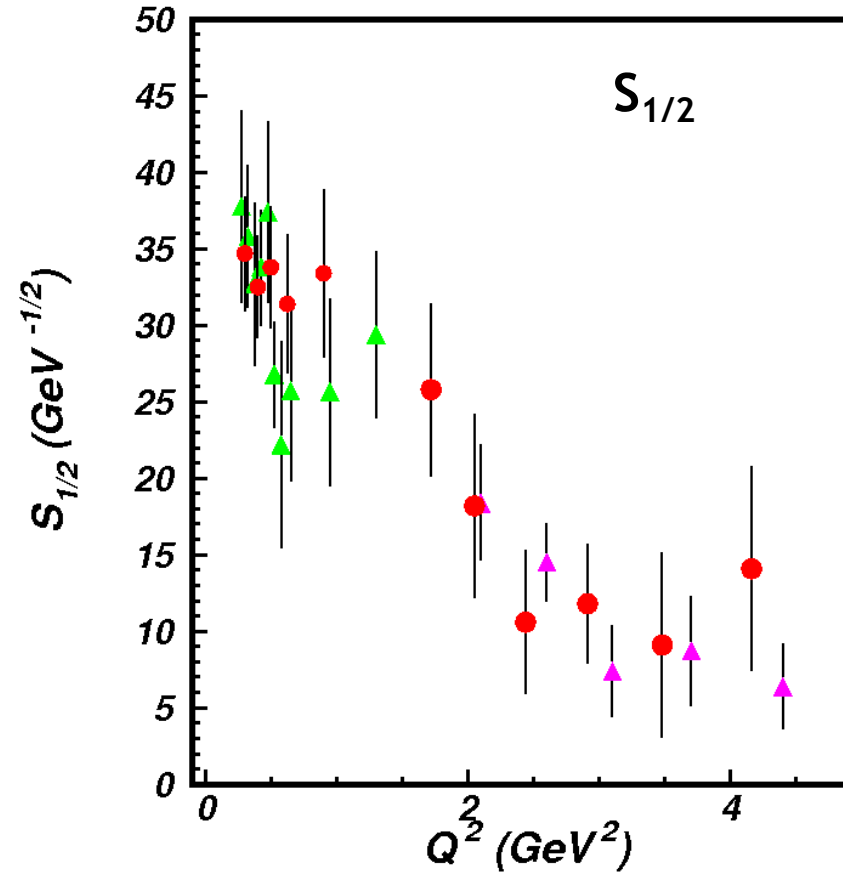
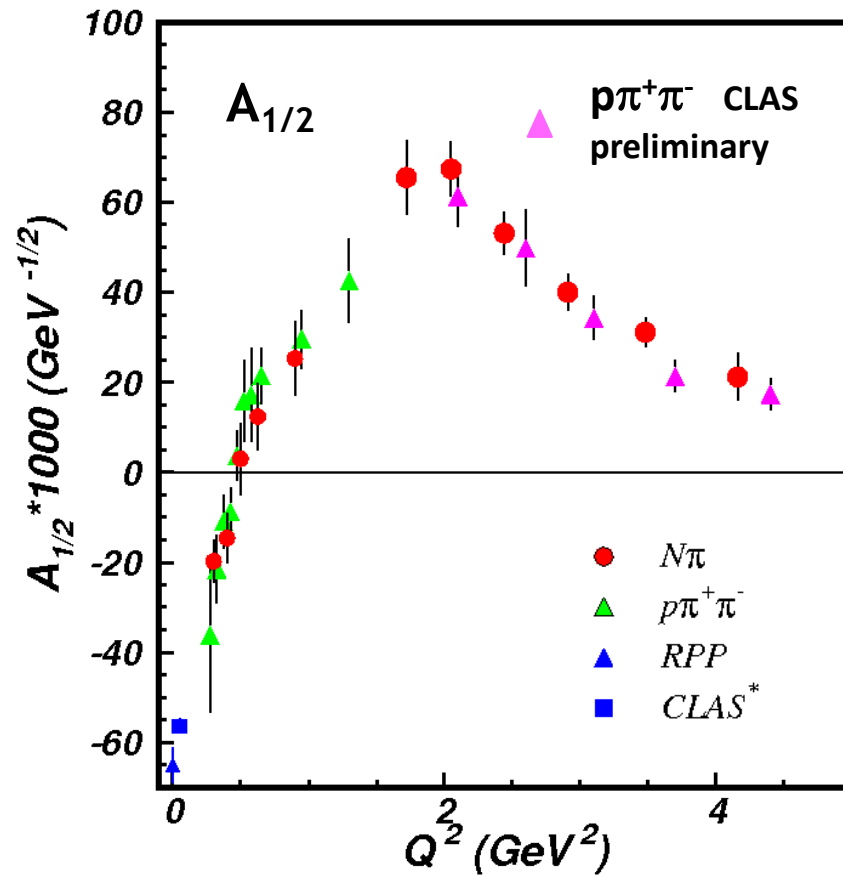
V. Burkert, Baryons 2002

2019



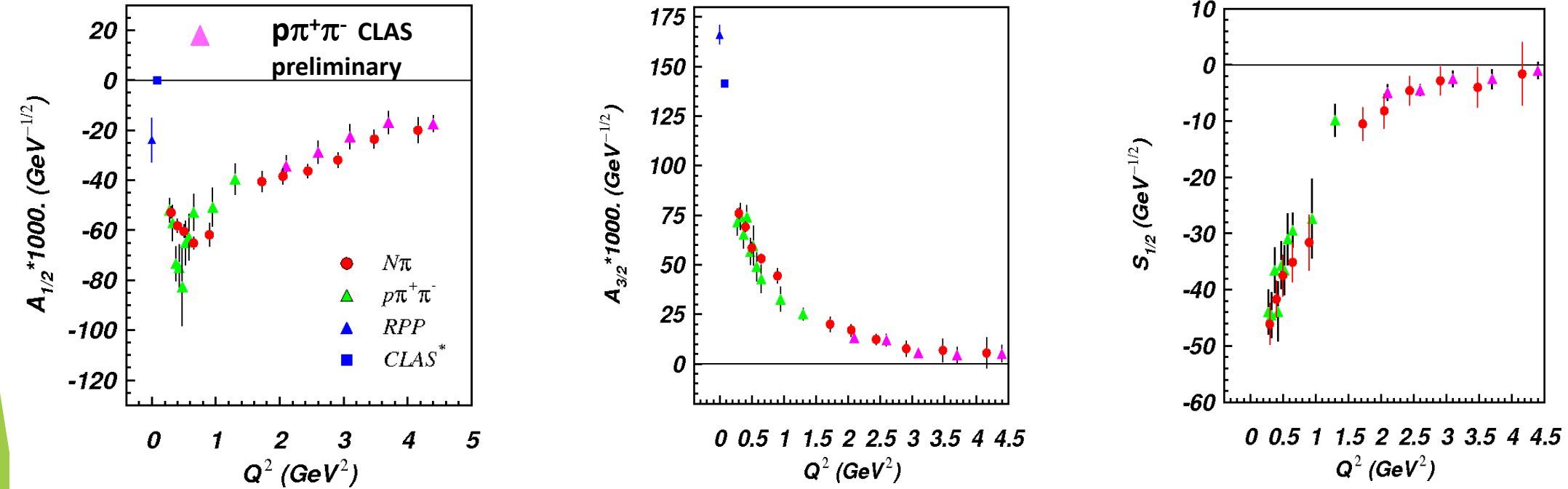
V. D. Burkert, Baryons 2016 and the recent update from the CLAS $\pi^+\pi^-p$ electroproduction off protons data

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.

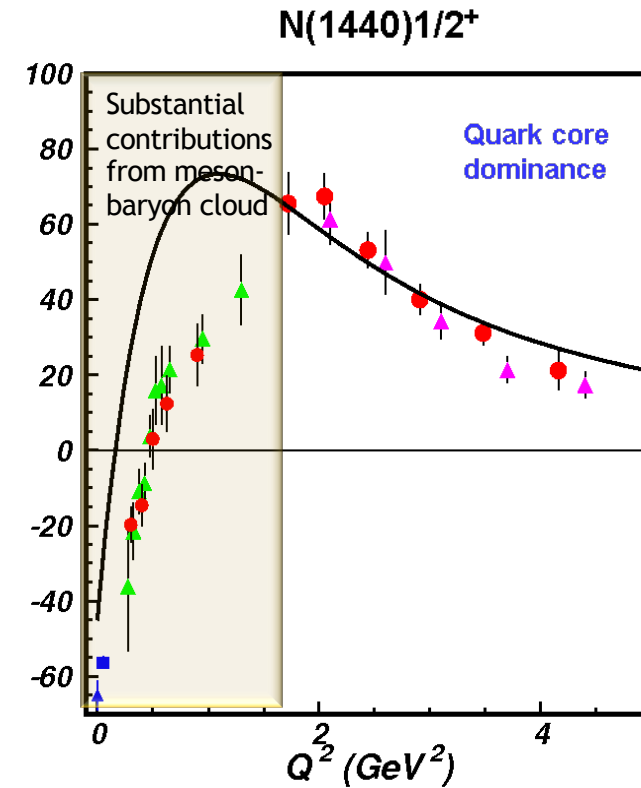
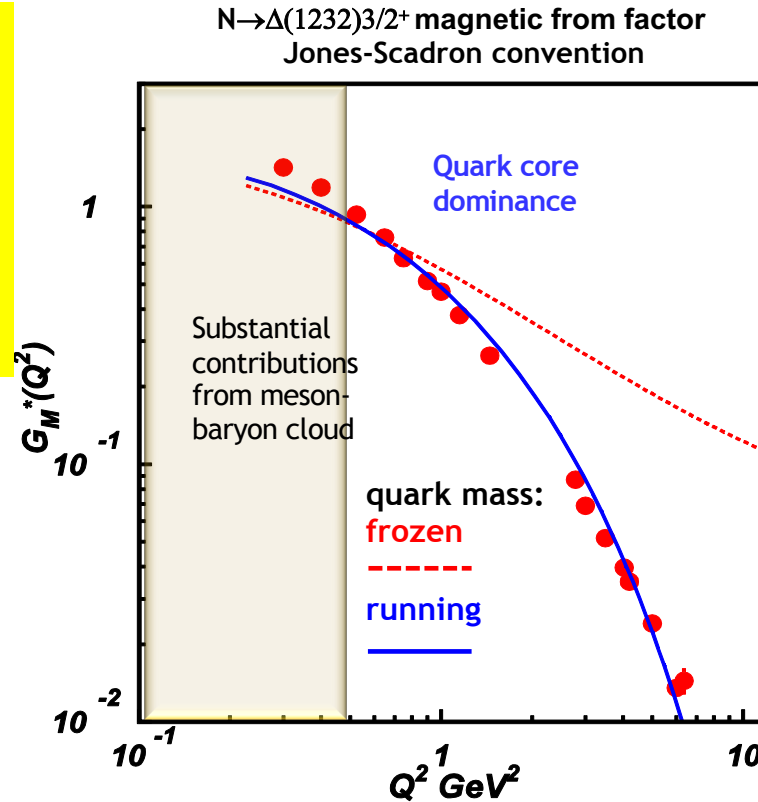
Electrocouplings of $N(1520)3/2^-$ from $N\pi$ and $\pi^+\pi^-p$ Electroproduction off Proton Data



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.

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 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!

Summary

- ▶ 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

Thank you for your attention!