

Nucleon resonance structure and emergence of hadron mass from CLAS/CLAS12 data

Nucleus-2022

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Fermi experiments on pion-nucleon scattering

Delta(1232)

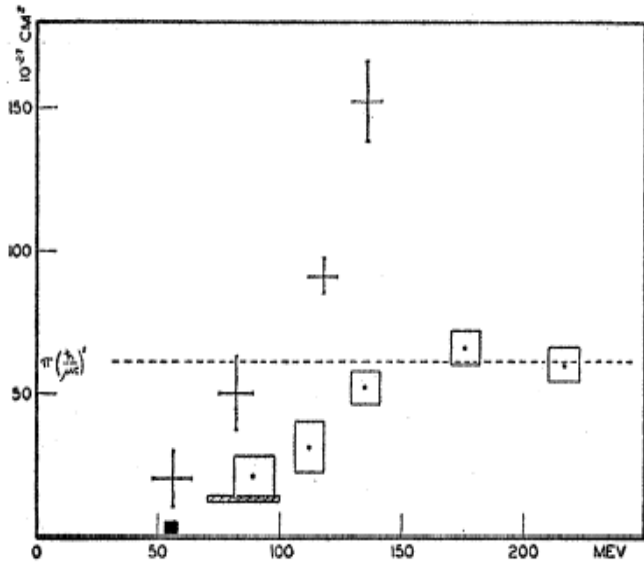
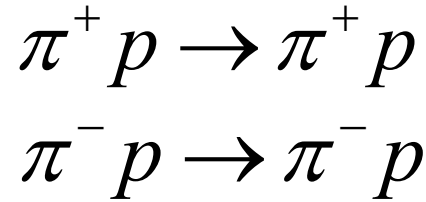


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia he



$$L_{2I,2J}$$

$$P_{33}(1232) \quad F_{15}(1680)$$

$$\Delta(1232)3/2^+ \quad N(1680)5/2^+$$

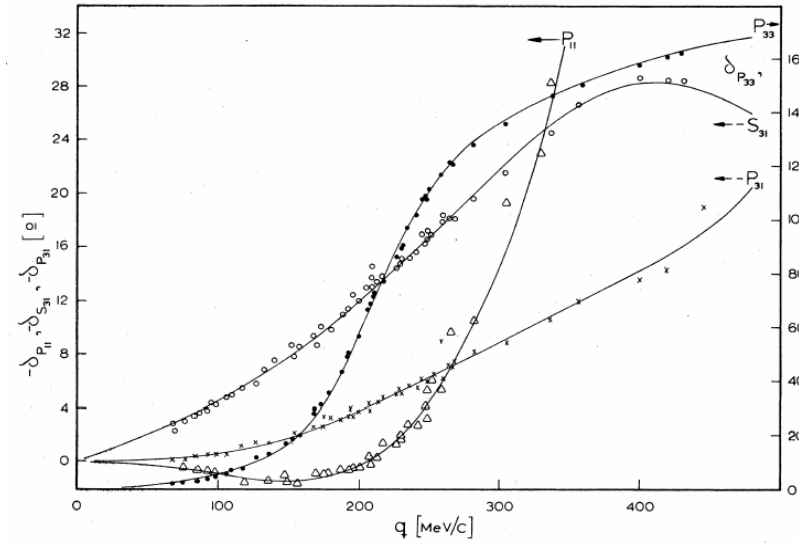
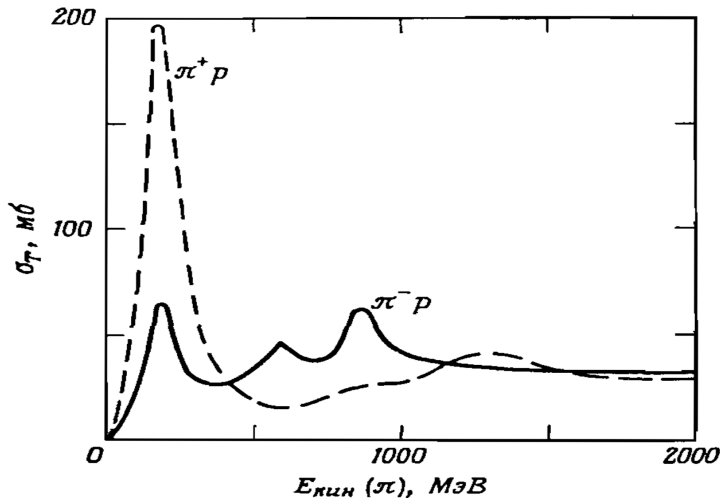
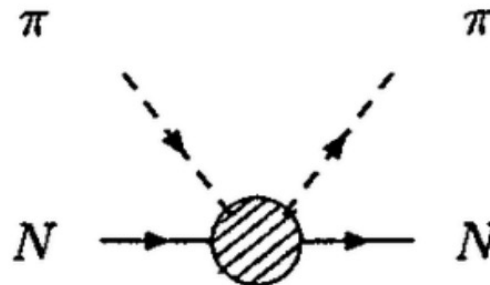


FIG. 1. Phase shifts in degrees for S_{31} , P_{11} , P_{31} , and P_{33} waves. The points have been taken from Refs. 11-17.

Partial Waves



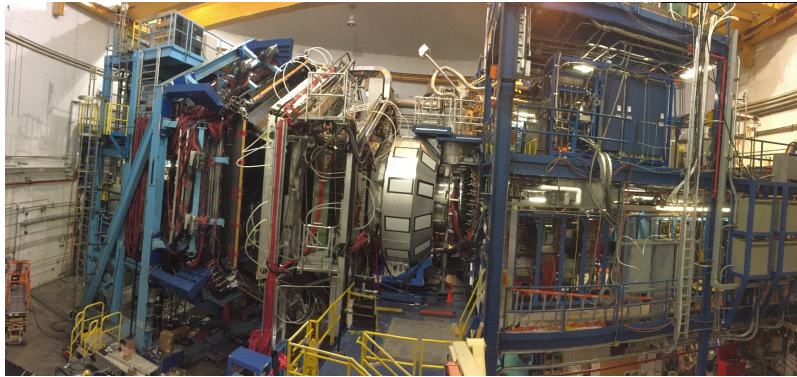
New era in electromagnetic nuclear physics

- ▶ 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.

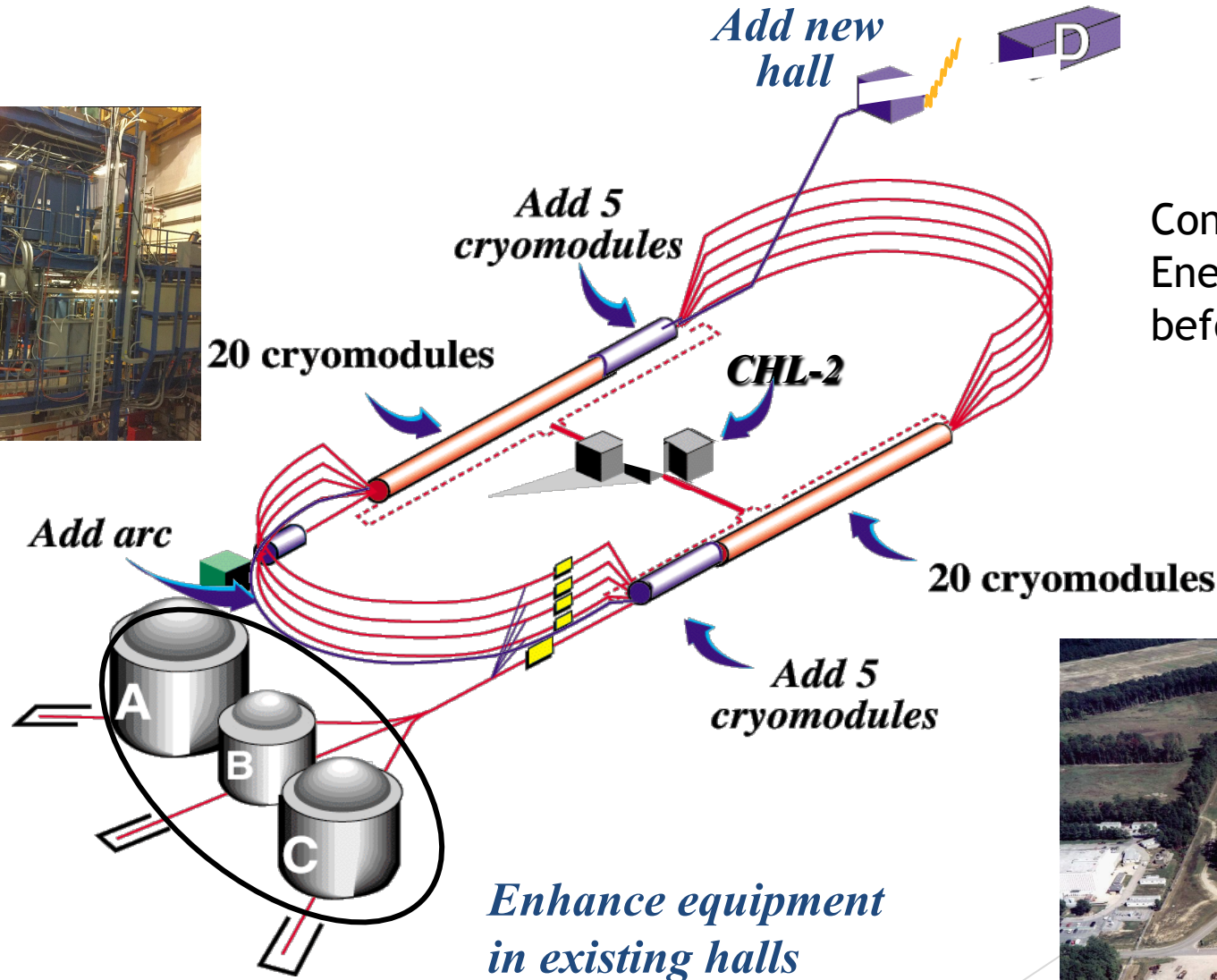
MAMI Mainz
ELSA Bonn
GRAAL Grenoble
LEPS Osaka
JLAB Newport News

Jefferson Lab (Newport News, VA, USA)

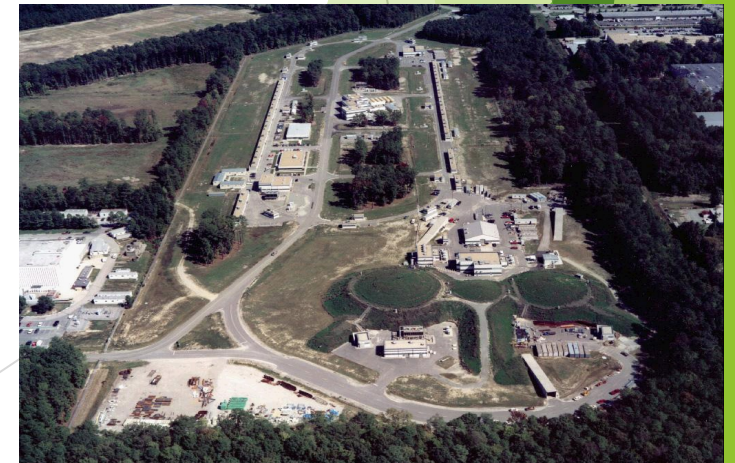
CLAS12 in Hall B



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:

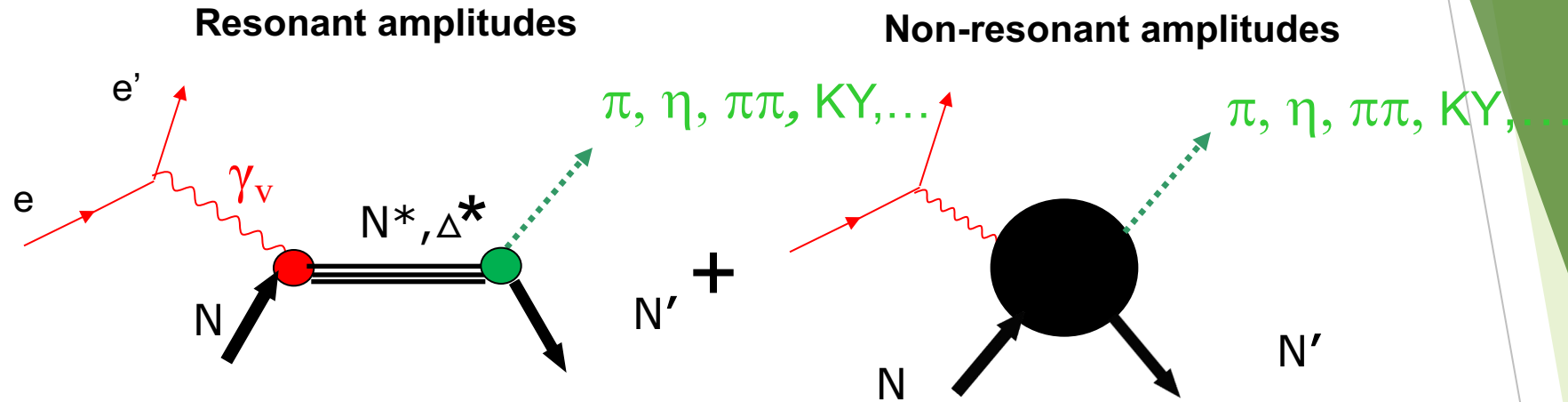
- N* spectrum with a focus on the new, so-called “missing” and hybrid resonance search
- $\gamma_v p N^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range 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 \[nucl-ex\]](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).

Extraction of $\gamma_{\nu}NN^*$ 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 $\gamma_{\nu}pN^*$ 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
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 1.1-1.8	0.16-0.36 0.4-1.8 3.0-6.0 0.4-1.0	$d\sigma/d\Omega$ $d\sigma/d\Omega, A_b, A_t, A_{bt}$ $d\sigma/d\Omega$ $d\sigma/d\Omega, A_b$
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

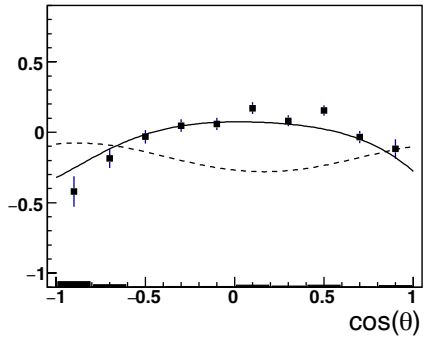
Over 120,000 data points!

Almost full coverage of the final hadron phase space

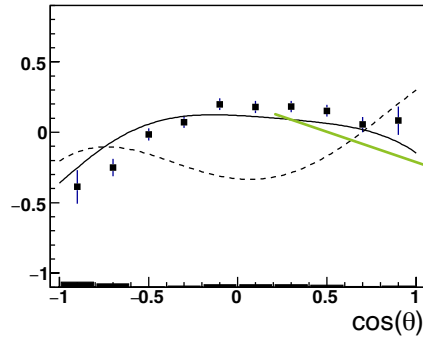
The measured observables from CLAS are stored in the CLAS Physics Data Base <http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi>

Polarized Structure Function $\sigma_{LT'}$, $0.4 < Q^2 < 0.6 \text{ GeV}^2$

$\sigma_{LT'}$ $W = 1.6125 \text{ GeV}$

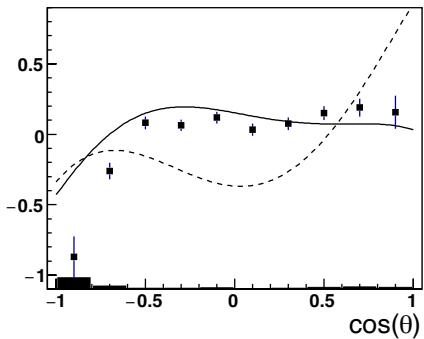


$\sigma_{LT'}$ $W = 1.6375 \text{ GeV}$

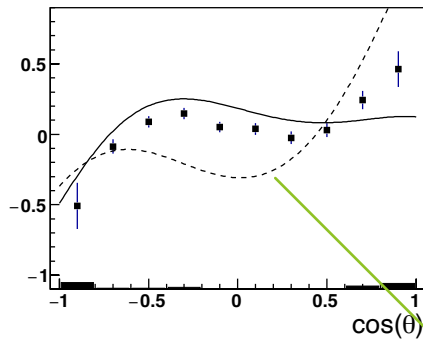


MAID 2007 (solid line)

$\sigma_{LT'}$ $W = 1.6625 \text{ GeV}$



$\sigma_{LT'}$ $W = 1.6875 \text{ GeV}$

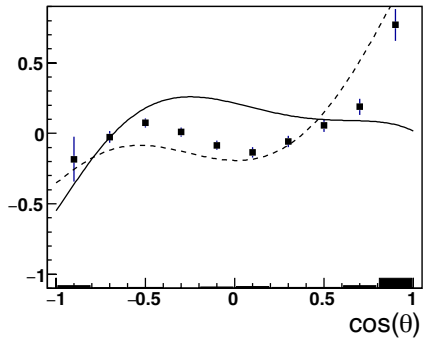


Polarized structure function $\sigma_{LT'}$ from $\pi^0 p$ electroproduction data in the resonance region at $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$

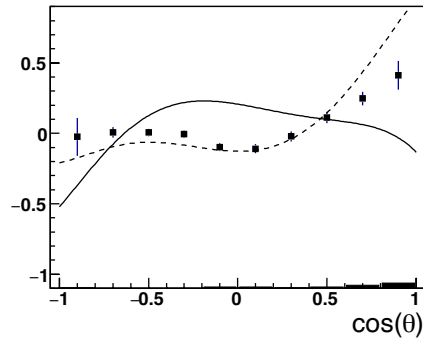
E. L. Isupov *et al.* (CLAS Collaboration)

Phys. Rev. C **105**, L022201 – Published 18 February 2022

$\sigma_{LT'}$ $W = 1.7125 \text{ GeV}$



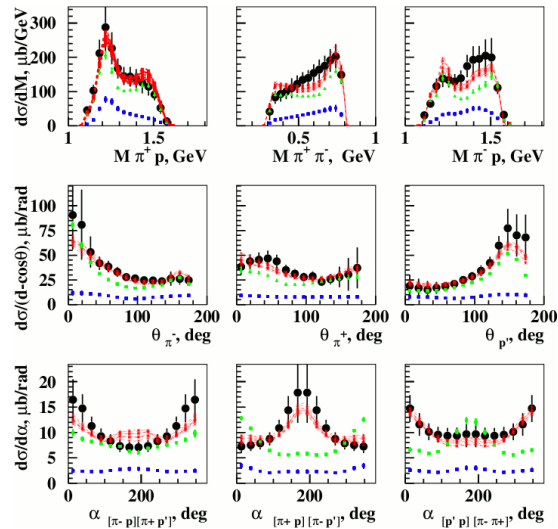
$\sigma_{LT'}$ $W = 1.7375 \text{ GeV}$



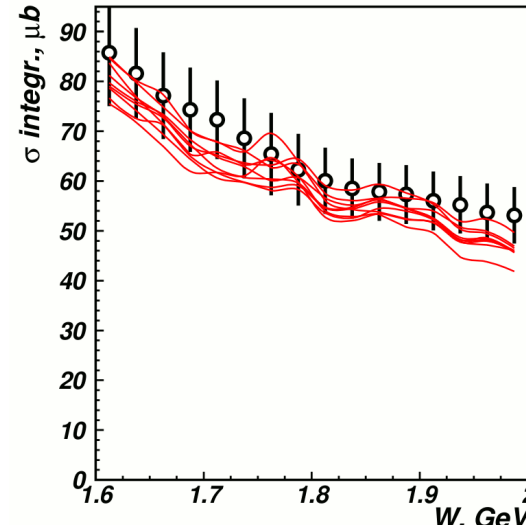
MAID 2007 with modified electrocouplings, taken from CLAS analyses (dashed line)

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	$A_{1/2} \times 10^3$ 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

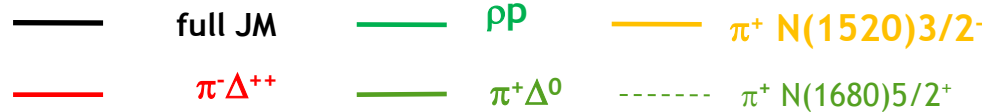
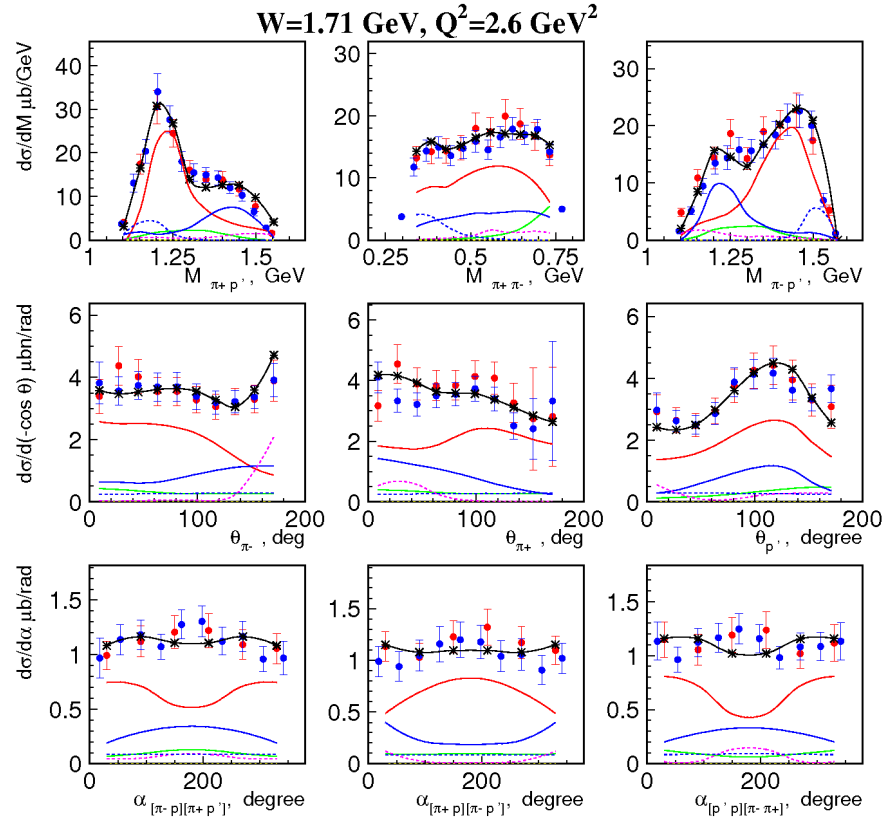
In 2019 partial update of the Review of Particle Physics the entries on photocouplings and $N\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

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

Contributing mechanisms seen in the data

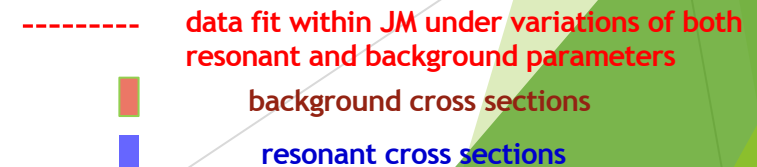
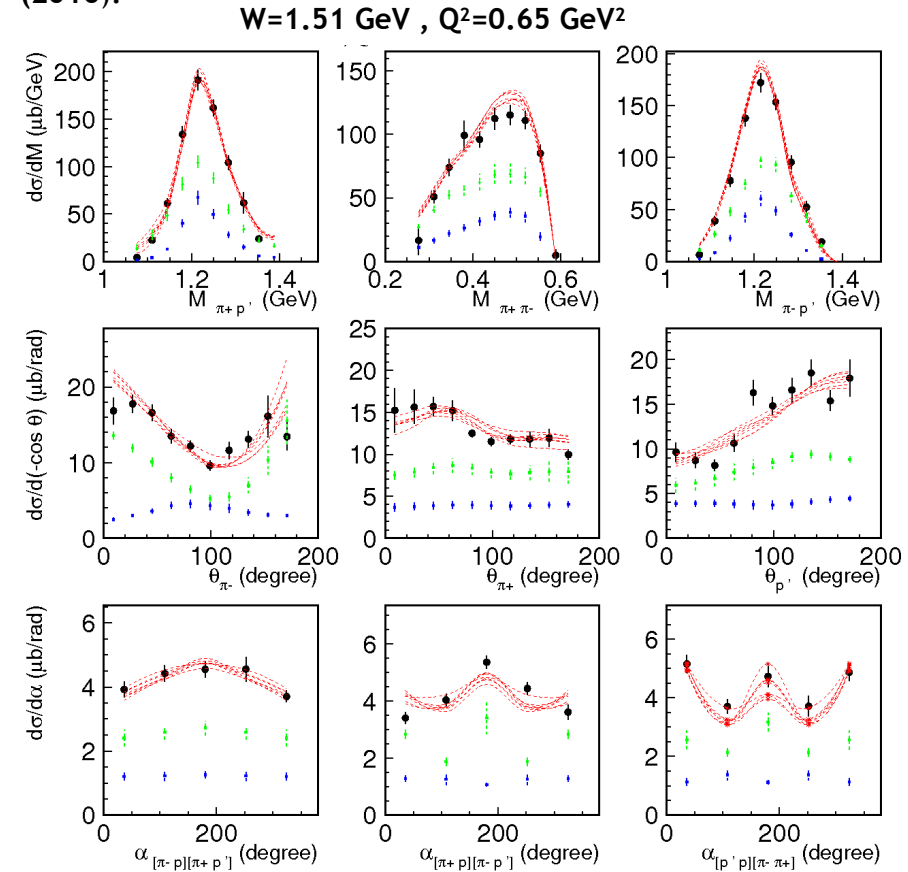
E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)

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



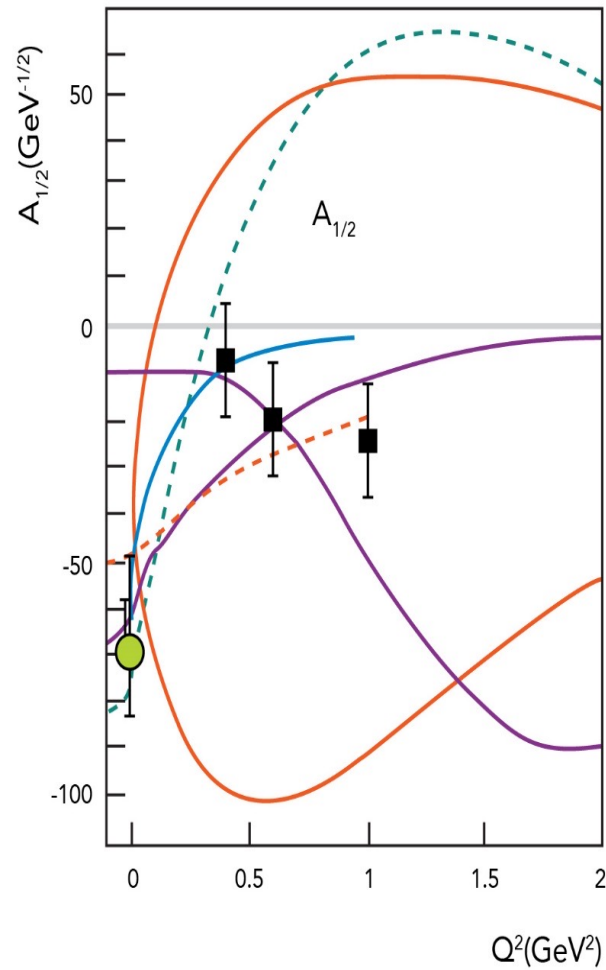
Resonant and non-resonant contributions

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



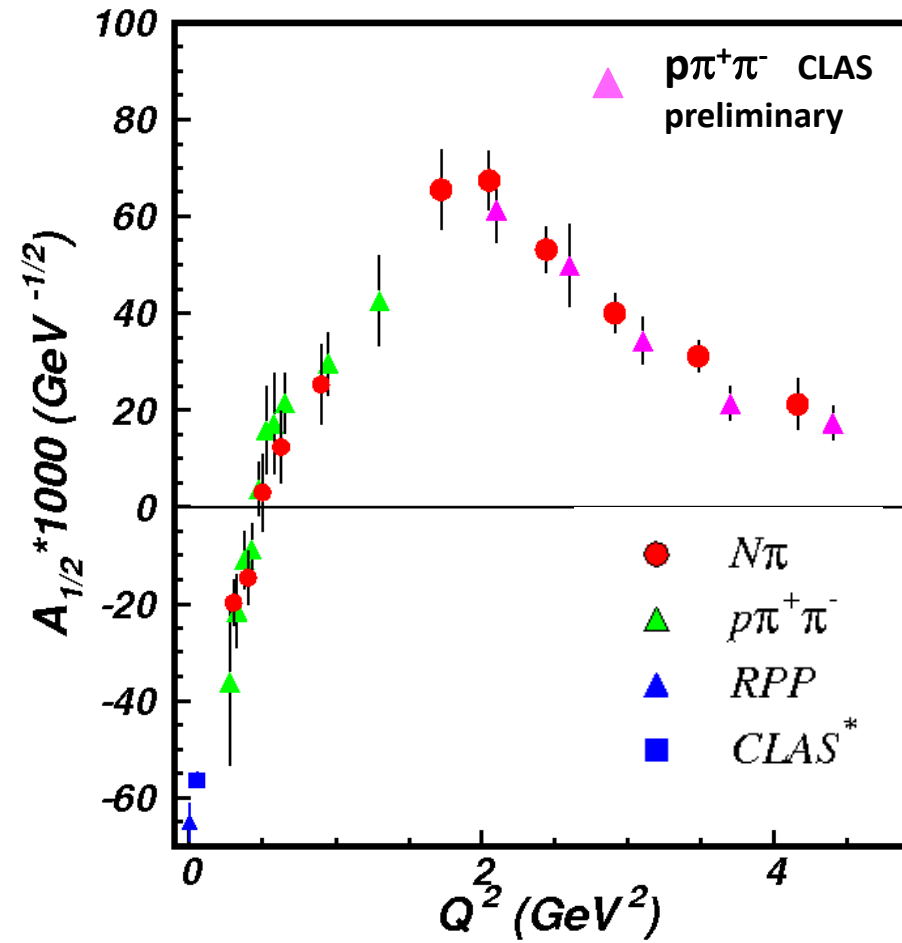
Roper Resonance in 2002 & 2019

2002



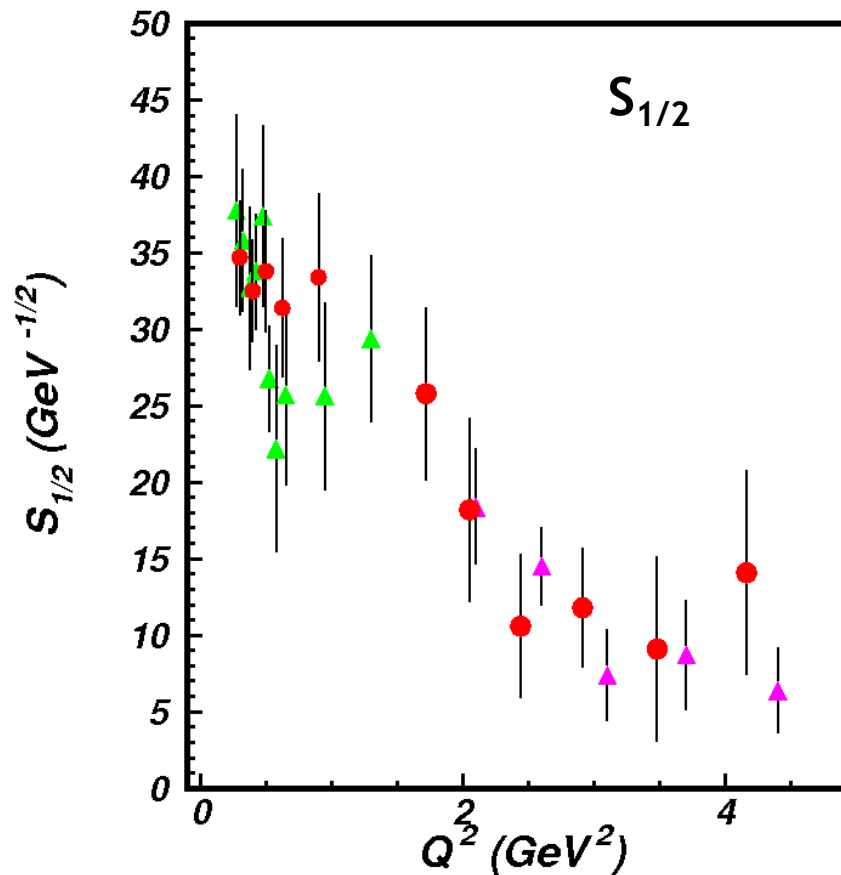
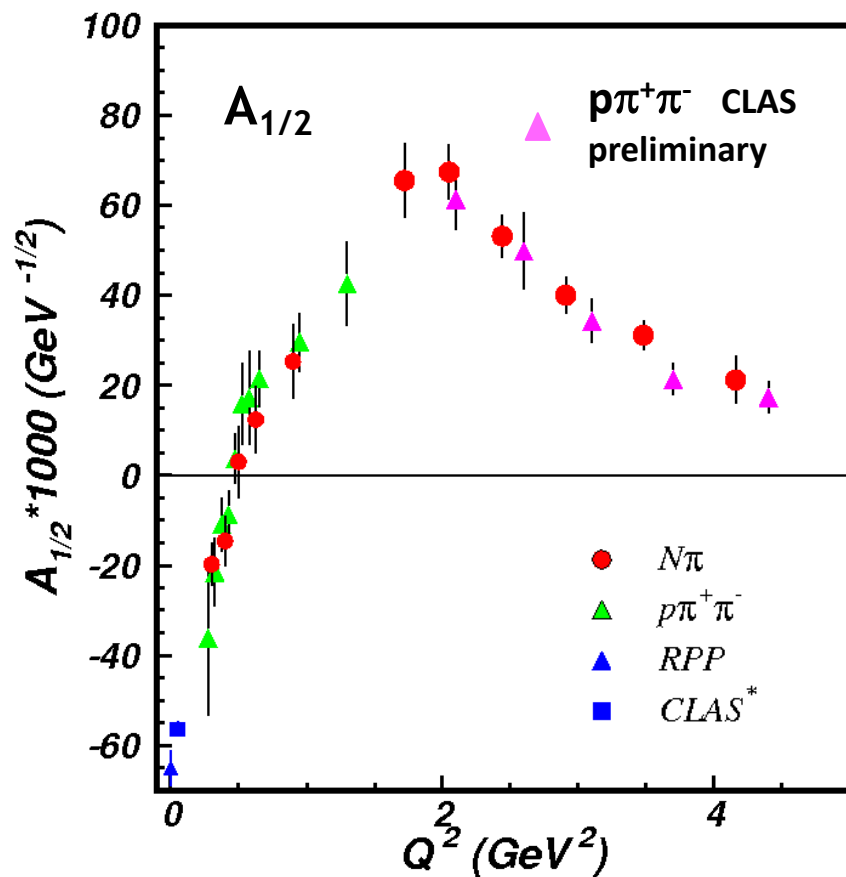
V. Burkert, *Baryons 2002*

2019



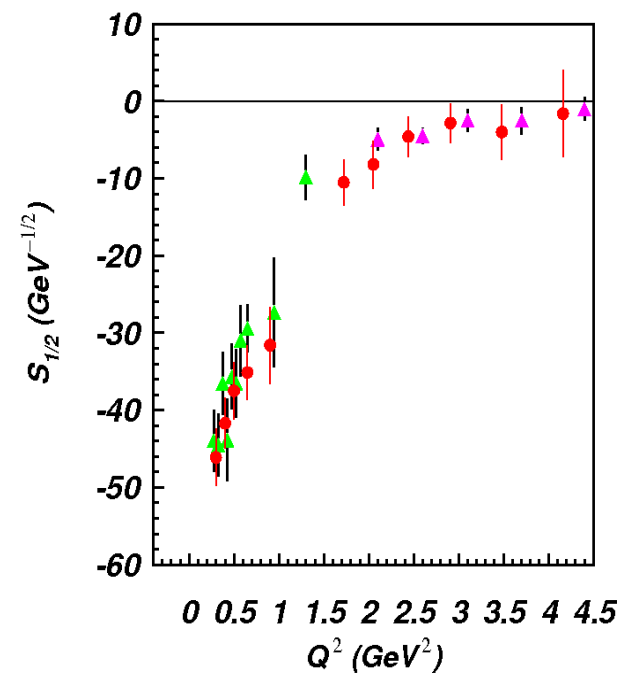
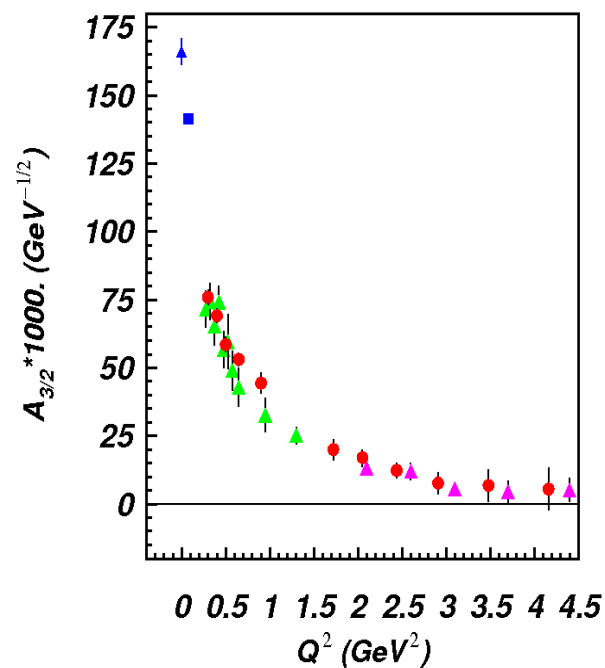
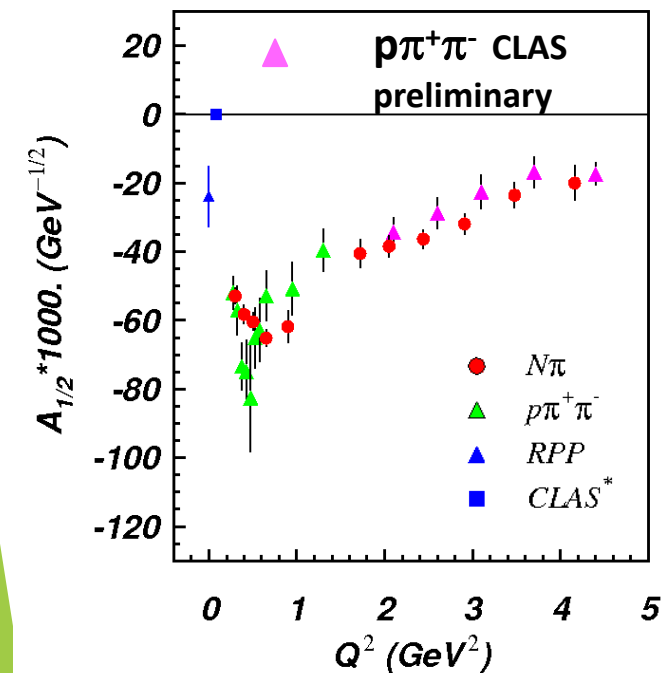
V. D. Burkert, *Baryons 2016* and the recent update from the CLAS $\pi^+\pi^-p$ electroproduction off protons data

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

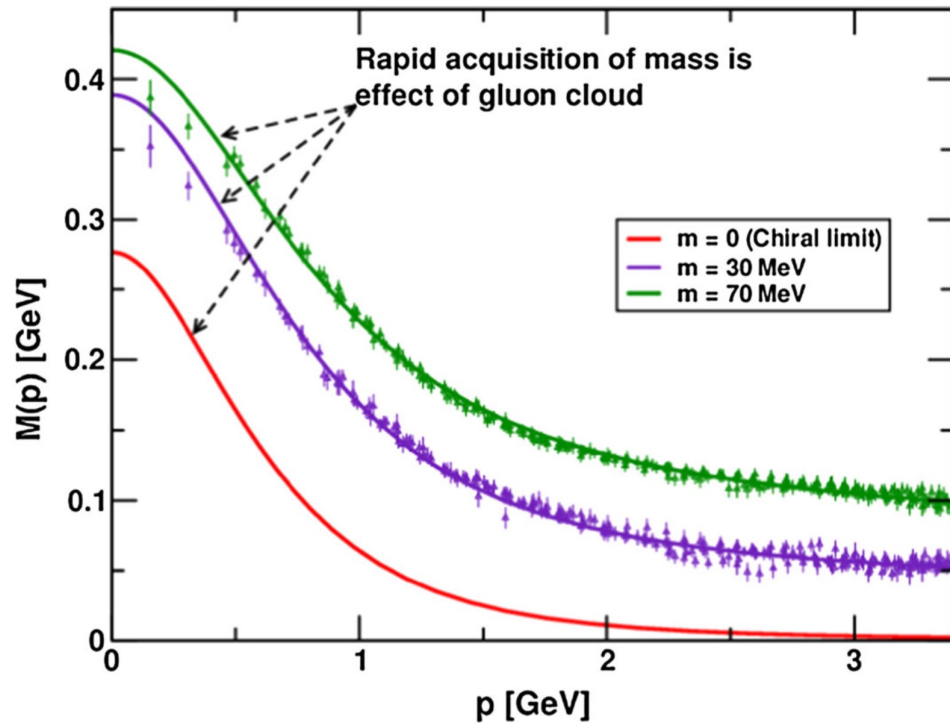


Consistent results from $N\pi$ and $\pi^+\pi^-p$ electroproduction off proton data on electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ resonances with the biggest combined contribution into the resonant parts of both channels at $W < 1.55$ GeV strongly support the capabilities of the developed reaction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

Excited Nucleon States and Insight into Strong QCD Dynamics

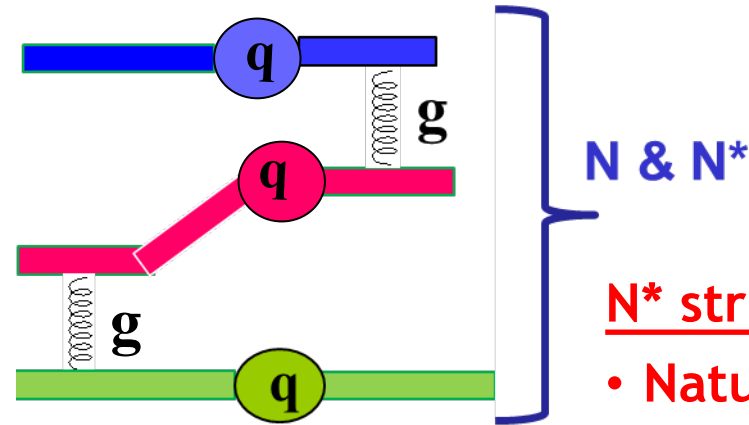
Two conceptually different approaches for description of nucleon/ N^* structure from first QCD principles:

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



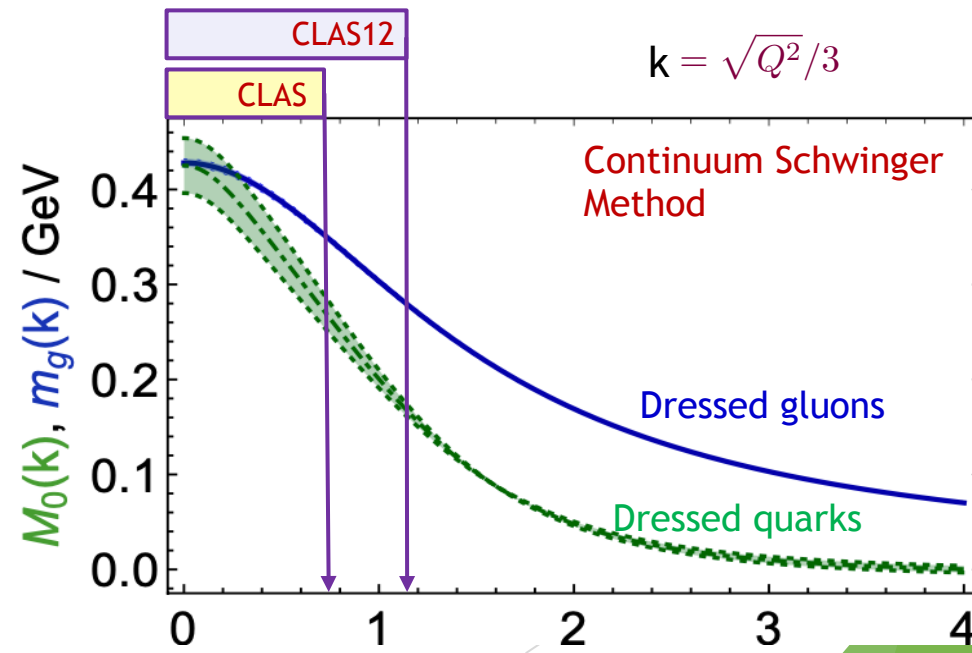
Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)

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



N^* structure studies address:

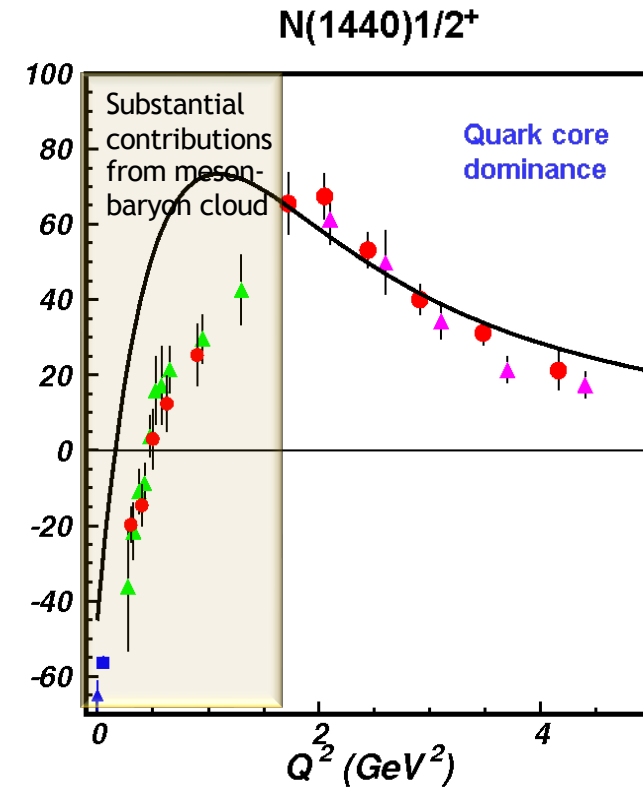
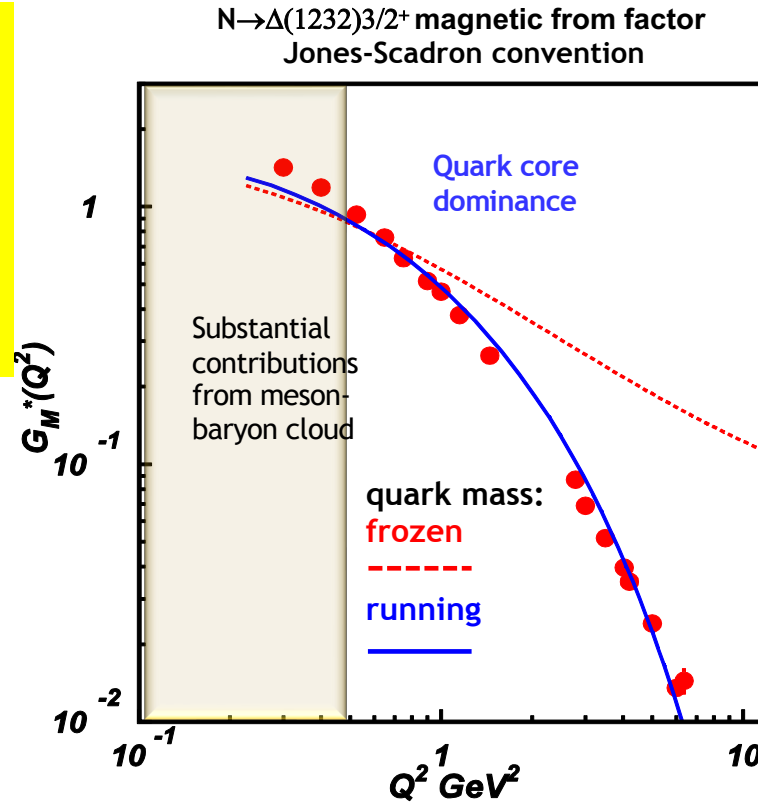
- Nature of > 98% of hadron mass
- Emergence of the ground nucleon parton distributions in 1D and 3D



Craig Roberts

Dyson-Schwinger Equations (DSE):

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

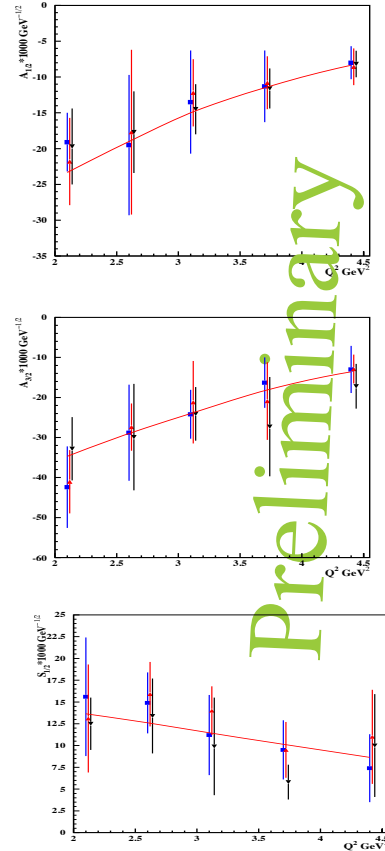
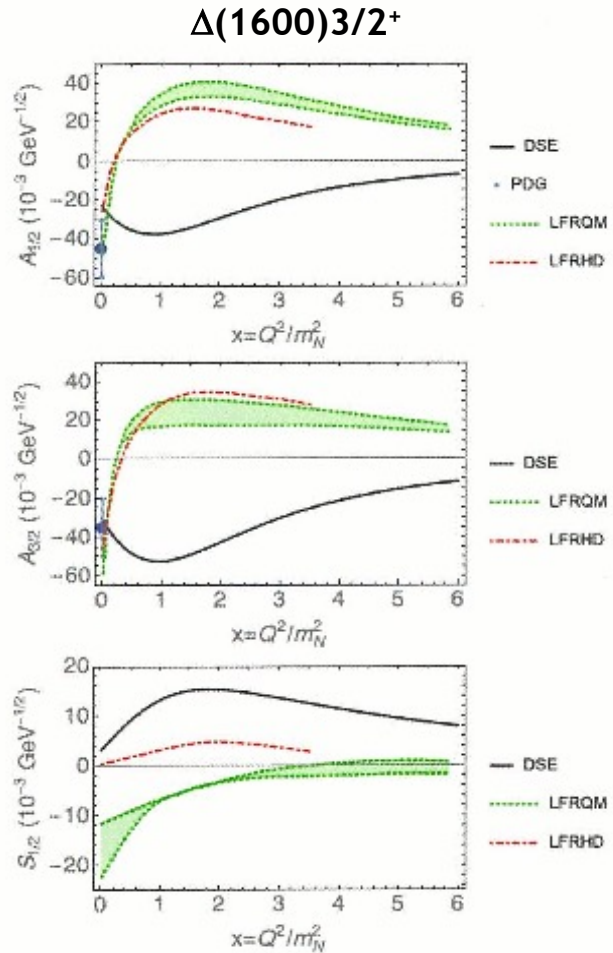


DSE analyses of the CLAS data on $\Delta(1232)3/2^+$ electroexcitation demonstrated that dressed quark mass is running with momentum.

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



Viktor Mokeev
Spring 2022

Ya Lu et al., PRD 100, 034001 (2019)

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 are preliminary extracted.
- Confirmation of the DSE expectations may prove a relevance of dressed quark with running mass in the structure of $\Delta(1232)3/2^+$ and radial nucleon and Δ excitations.
- Studies of $[70, 1^-]$ orbital excitations is the next step.

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!

► More results on CLAS/CLAS12 later today:

15.00 Nucleon resonance contributions to inclusive electron scattering

Vitaly Chesnokov

15.20 $N\pi$ electroproduction in the resonance region in 12 GeV era

Anna Golubenko

15.40 First results from CLAS12 on $\pi^+\pi^-p$ electroproduction in fully exclusive kinematic

Anna Frolova

15.50 Studies of double pion electroproduction with CLAS12 in kinematics with missing hadron

Aleksandr Bulgakov

16.00 Evaluation of $K\Lambda$ and $K\Sigma^0$ electroproduction cross sections from the CLAS data

Maksim Davydov

16.20 The computational tool for evaluation of $N\pi$ electroproduction cross sections

Almaz Nasrtdinov

Thank you!

The background features abstract, overlapping geometric shapes in various shades of green, ranging from light lime to dark forest green. These shapes are primarily located on the right side of the frame, creating a modern, layered effect against the white background.