

Electroproduction of nucleon excited states from CLAS/CLAS12 data

E. Isupov SINP MSU

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

Insight into the Strong QCD from the Synergy between Experiment, Phenomenology, and Theory

Experiment

Theory

Observables from the Experiments with the EM Probes:

- Differential cross sections
- Beam asymmetry
- Target asymmetries
- Recoil asymmetries
- Combinations of 2-fold and 3-fold asymmetries

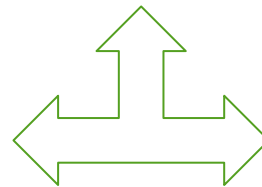
Phenomenology:

- Amplitude analyses
- Reaction models



Elastic/Transition form factors
 PDFs, PDA, TMD-functions
 Compton form factors
 Projection of GPD to observables

**Strong QCD
underlying
the hadron
generation**



QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(i \not{D}_a T_a - m)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu,a}$$

- Covariant derivative, gluon field tensor
- Color matrices and structure constants

$$D_a^\mu = \partial^\mu + igA_a^\mu$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - gf_{abc}A_b^\mu A_c^\nu$$

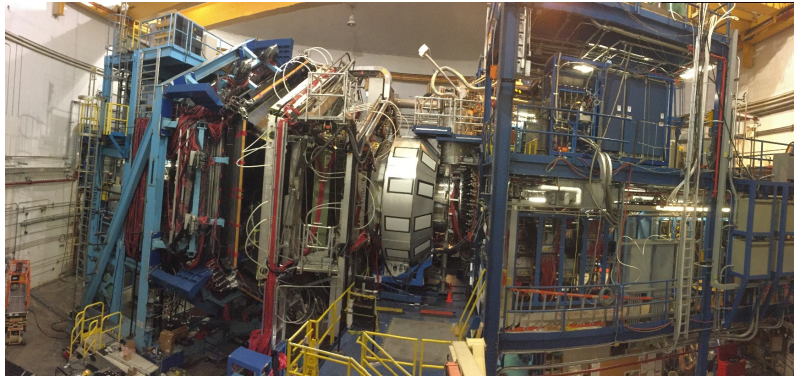


- Lattice QCD
- Continuum QCD

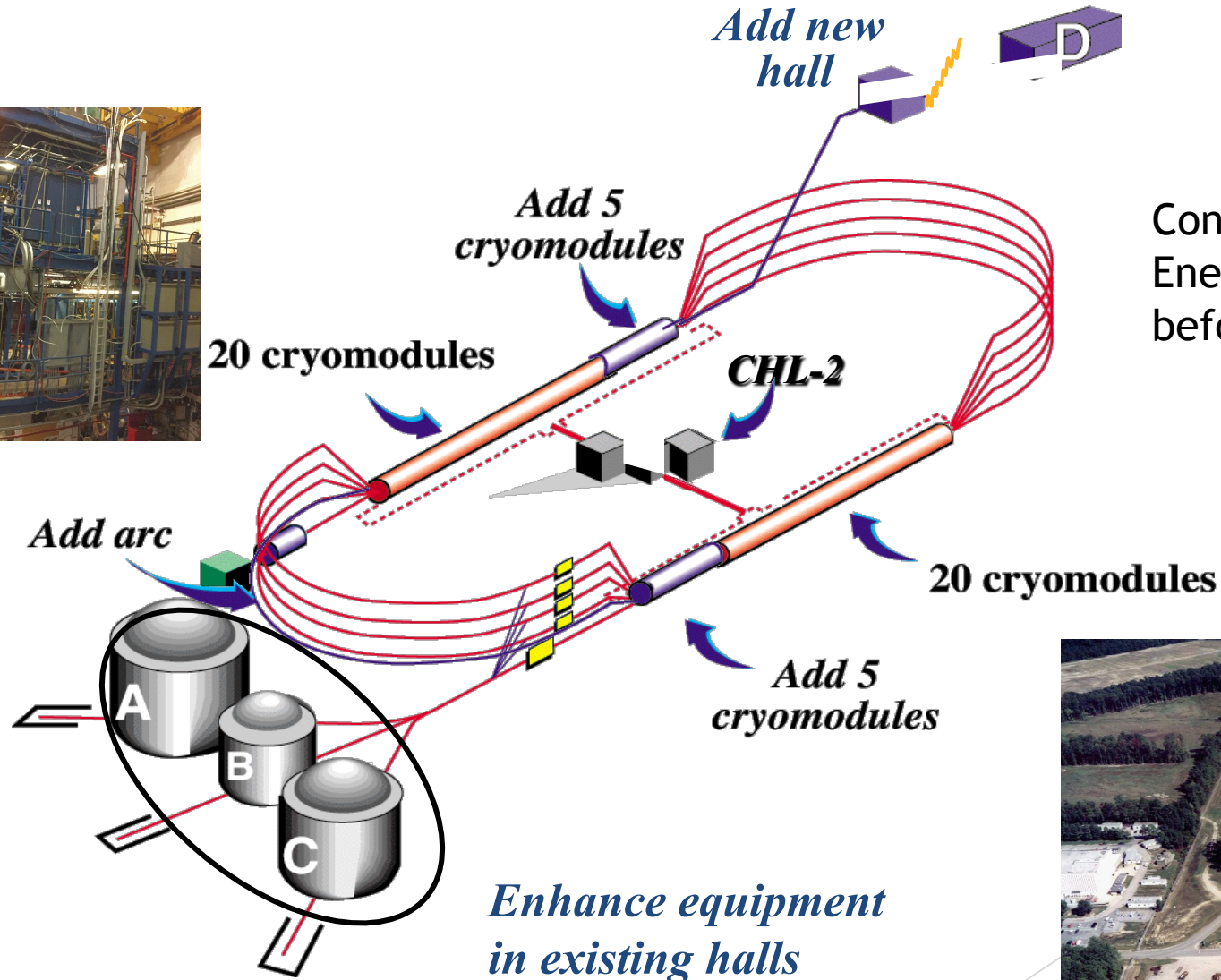
Light front quark models
 AdS/CFT approaches
 χ Quark-Soliton models
 Hypercentral quark model
 Covariant quark models

Jefferson Lab (Newport News, VA, USA)

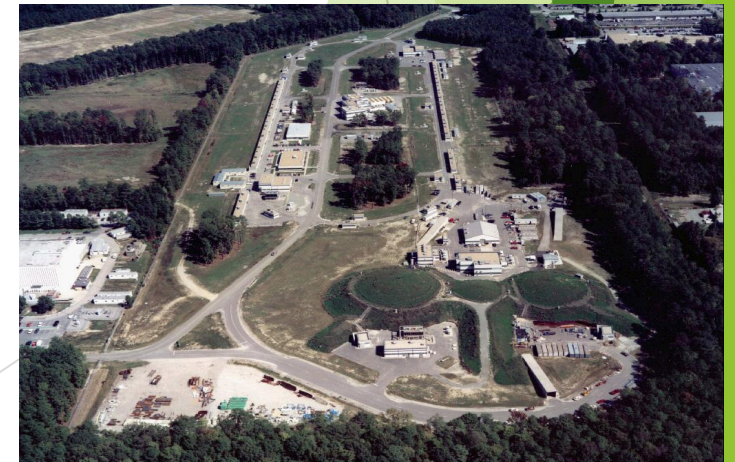
CLAS12 in Hall B



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:

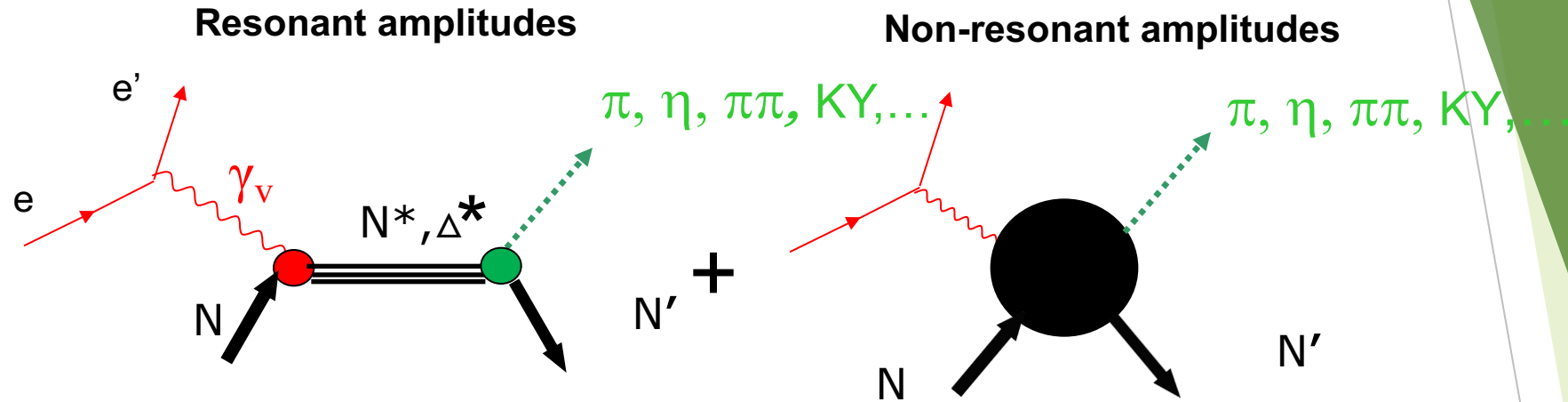
- N* spectrum with a focus on the new, so-called “missing” and hybrid resonance search
- $\gamma_v p N^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range 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. D.S. Carman, R.W. Gothe, V.I. Mokeev, and C.D. Roberts, *Particles* **6**, 416 (2023)
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



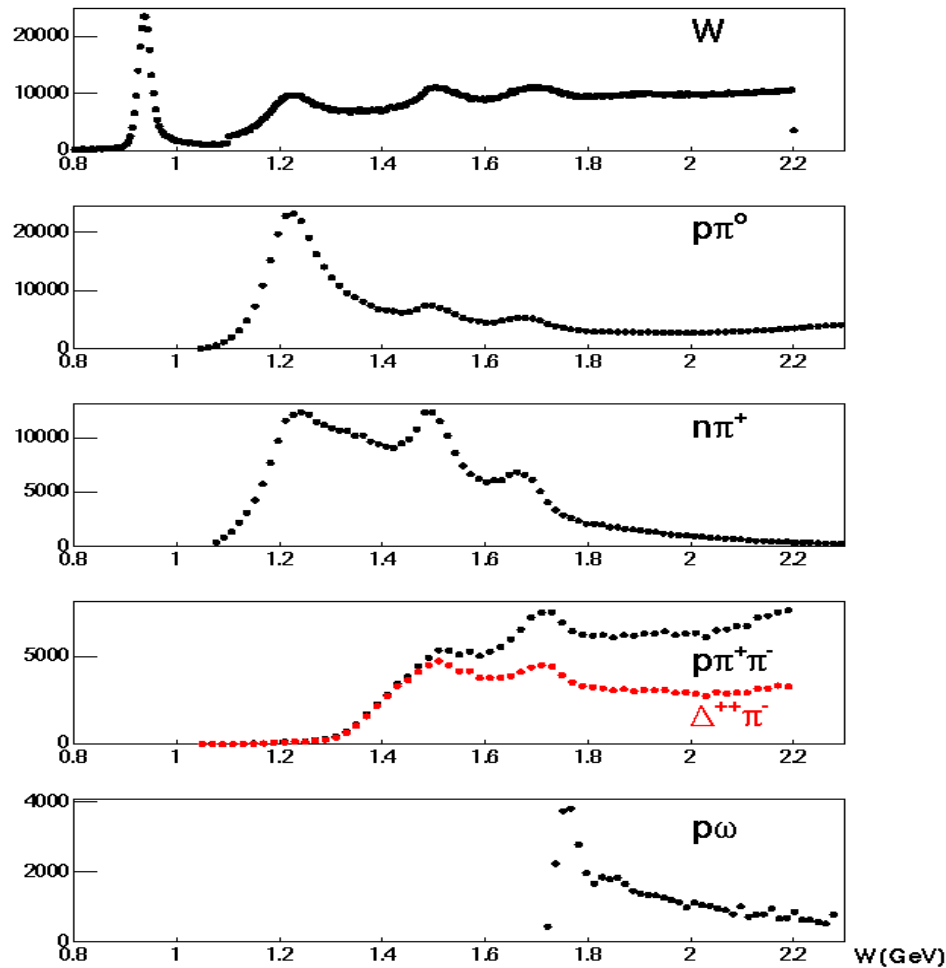
Definition of N^* photo-/electrocouplings employed in the CLAS data analyses:

- 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.

Experimental yields of major electroproduction channels from CLAS for $Q^2 < 4 \text{ GeV}^2$



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 140,000 data points!

Almost full coverage of the final hadrons 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 $\sigma_{LT'}$ from $\pi^0 p$ electroproduction data in the resonance region at $0.4 \text{ GeV}^2 < Q^2 < 1.0 \text{ GeV}^2$

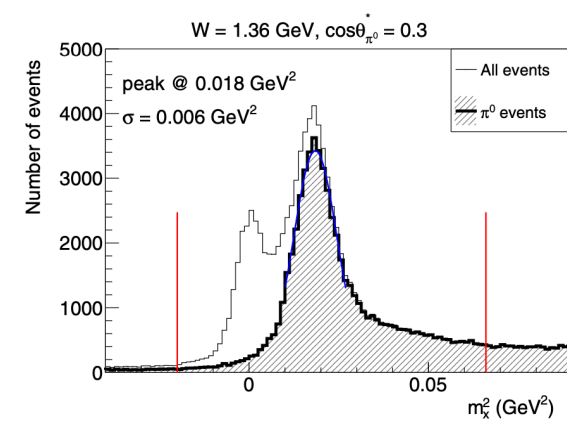
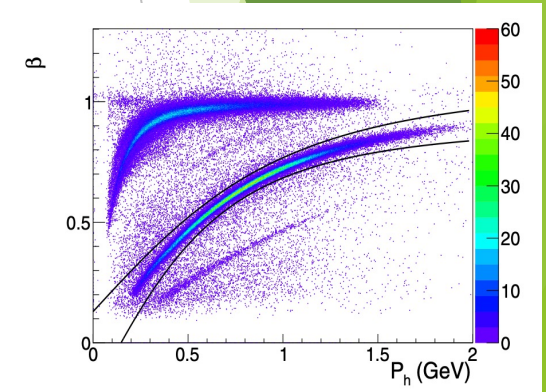
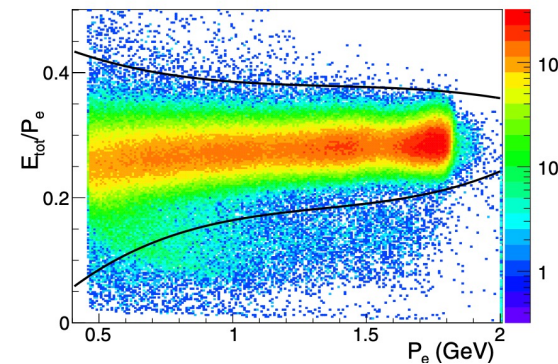
E. L. Isupov *et al.* (CLAS Collaboration)

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

- CLAS detector data 12/2002 – 1/2003
- Beam energy: 2.036 GeV
- Beam polarization: $\sim 80\%$
- Target: Liquid Hydrogen, thickness 2 cm
- Number of triggers: ~ 1.5 billion

$$0.4 < Q^2 < 1 \text{ GeV}^2$$

$$1.1 < W < 1.8 \text{ GeV}$$



Polarized Structure Function σ_{LT} ,

$$\frac{d^2\sigma^h}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*} [\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)} \sigma_{LT'} \sin\theta_\pi^* \sin\phi_\pi^*]$$

$$A_{LT'} = \frac{\sqrt{2\epsilon_L(1-\epsilon)} \sigma_{LT'} \sin\theta_\pi^* \sin\phi_\pi^*}{\sigma_0}$$

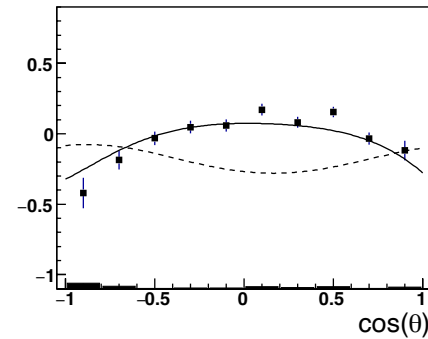
$$A_{LT'} = \frac{A_m}{P_e},$$

We have unpolarized cross sections from the same data.

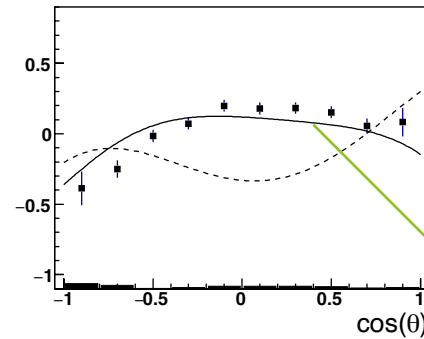
$$A_m = \frac{N_\pi^+ - N_\pi^-}{N_\pi^+ + N_\pi^-}$$

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

σ_{LT} , $W = 1.6125 \text{ GeV}$

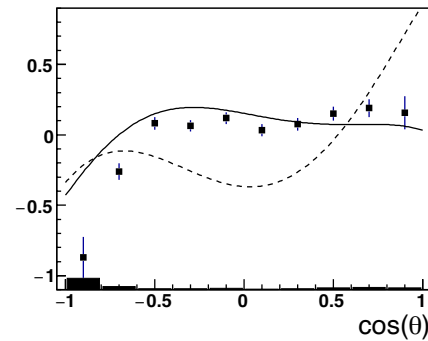


σ_{LT} , $W = 1.6375 \text{ GeV}$

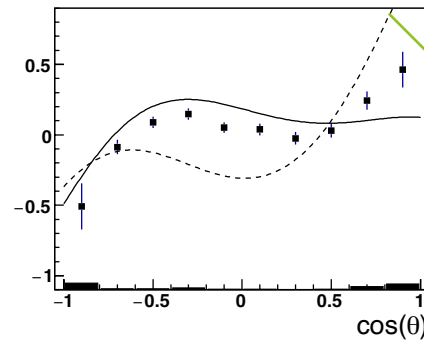


MAID 2007 (solid line)

σ_{LT} , $W = 1.6625 \text{ GeV}$

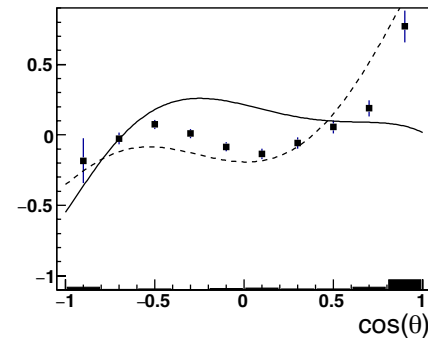


σ_{LT} , $W = 1.6875 \text{ GeV}$

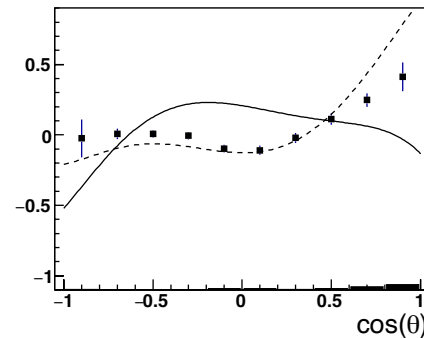


MAID 2007 with modified electrocouplings, taken from CLAS analyses (dashed line)

σ_{LT} , $W = 1.7125 \text{ GeV}$



σ_{LT} , $W = 1.7375 \text{ GeV}$



Legendre Polynomials of σ_{LT}

$$l=0,1,2,3 \quad \sigma_{LT} = D_0 + D_1 * x + D_2 * 0.5 * (3 * x^2 - 1) + D_3 * 0.5 * (5 * x^3 - 3 * x)$$

$$x = \cos(\theta)$$

sensitivity to P13(1720)

$$D_1 \sim -\text{Im}(\dots 6 * S_{1p} * \text{conj}(E_{1p}) - 6 * S_{1p} * \text{conj}(M_{1p}) \dots)$$

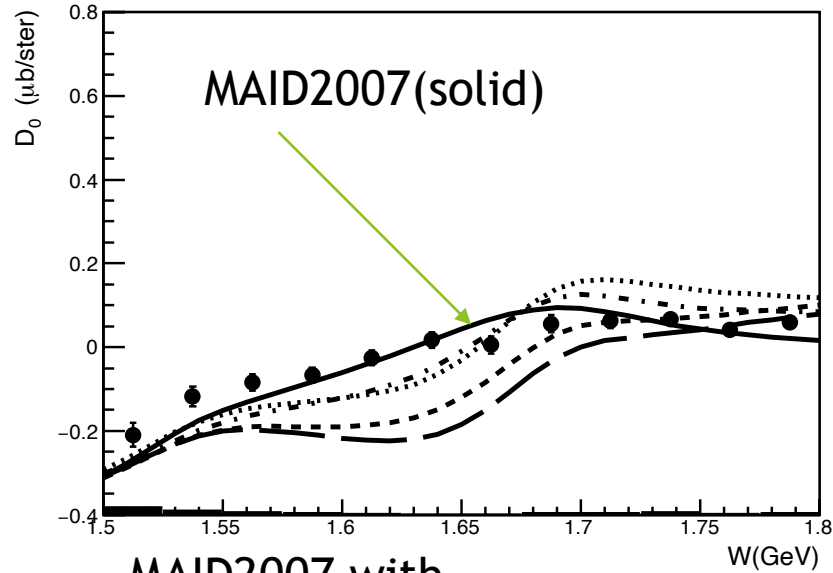
sensitivity to D33(1700)

$$D_1 \sim -\text{Im}(\dots - 6 * S_{2m} * \text{conj}(E_{2m}) - 6 * S_{2m} * \text{conj}(M_{2m}) \dots)$$

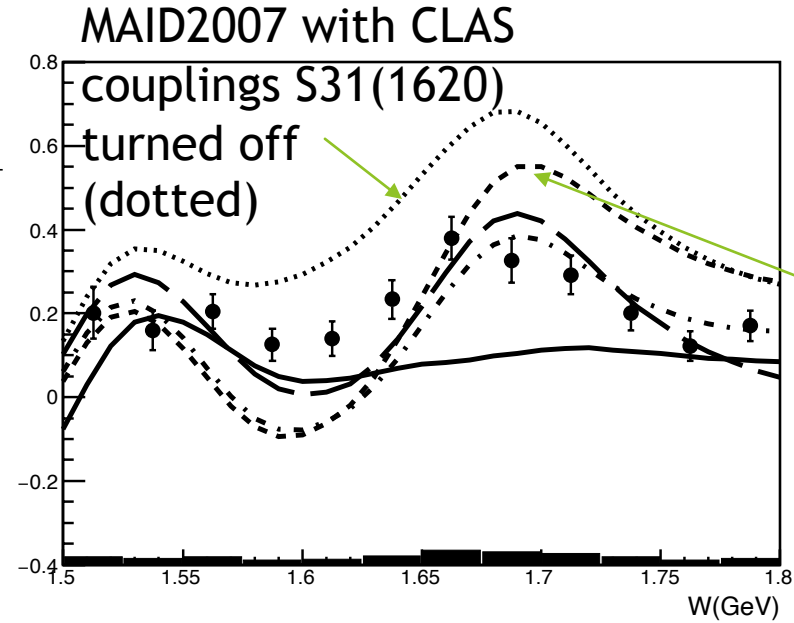
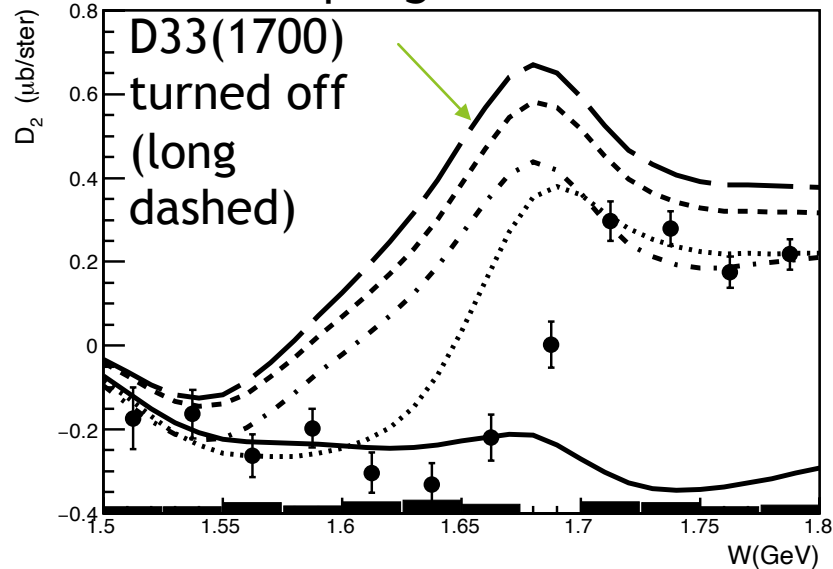
LP - effective way to present our data
and to demonstrate sensitivity to
different excited states of the nucleon

P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	L_{1-}
S_{11}	S_{31}	$\frac{1}{2}^+$	0^-	L_{0+}, E_{0+}
D_{13}	D_{33}	$\frac{1}{2}^+$	2^-	L_{2-}, E_{2-}
P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	M_{1-}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	M_{1+}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	L_{1+}, E_{1+}
F_{15}	F_{35}	$\frac{1}{2}^+$	3^+	L_{3-}, E_{3-}
D_{13}	D_{33}	$\frac{1}{2}^{+12}$	2^-	M_{2-}
D_{15}	D_{35}	$\frac{1}{2}^+$	2^-	M_{2+}

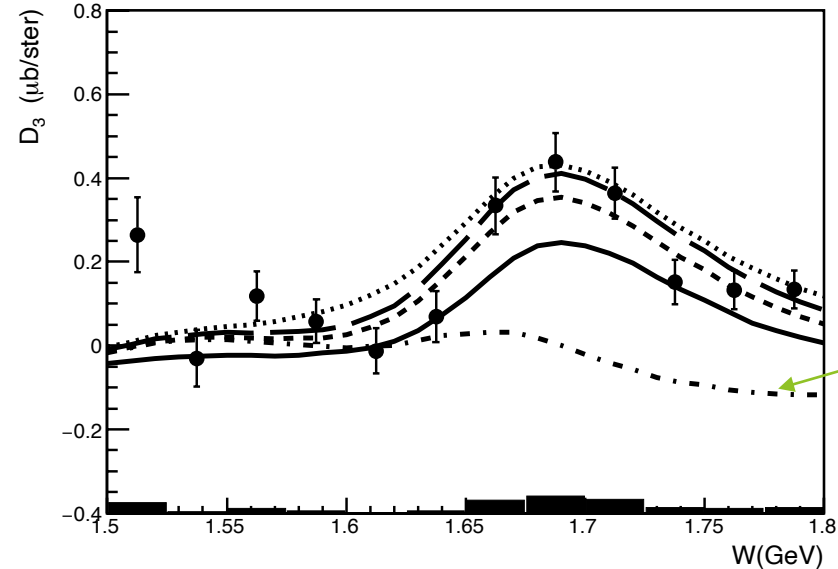
Legendre Moments of Polarized Structure Function σ_{LT} , $0.4 < Q^2 < 0.6 \text{ GeV}^2$



MAID2007 with
CLAS couplings



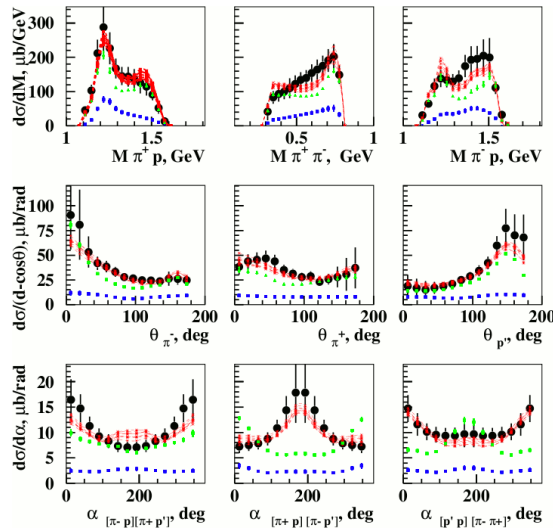
MAID2007 with
CLAS couplings
(dashed)



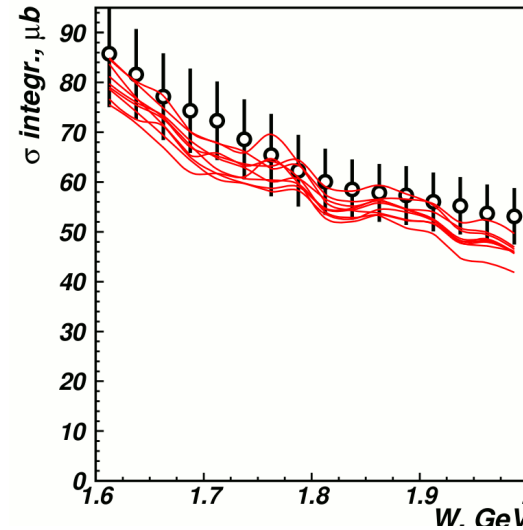
MAID2007 with
CLAS couplings
P13(1720)
turned off
(dotted
dashed)

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

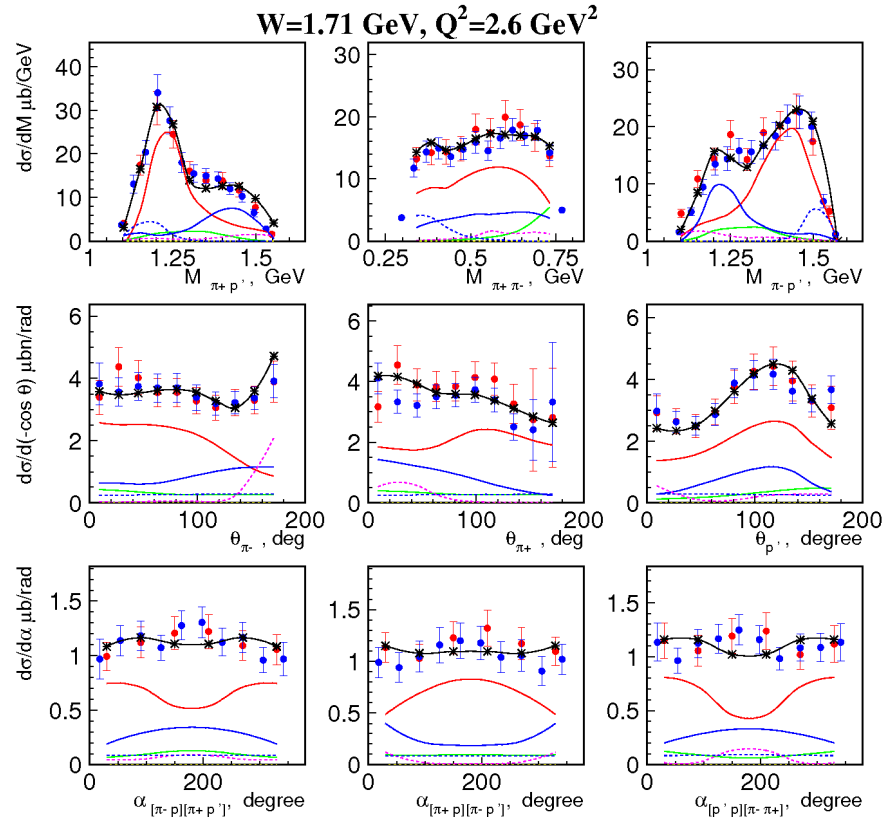
In 2019 partial update of the Review of Particle Physics the entries on photocouplings and $N\pi\pi$ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

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

Contributing mechanisms seen in the data

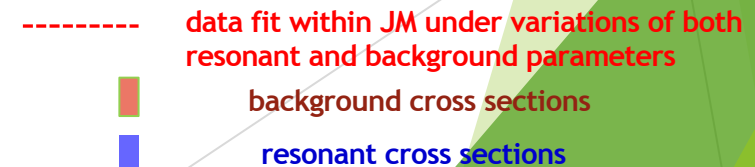
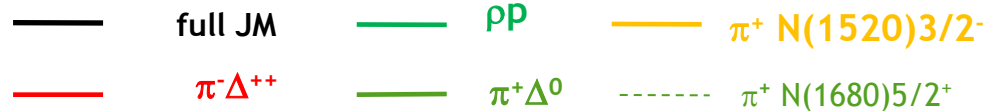
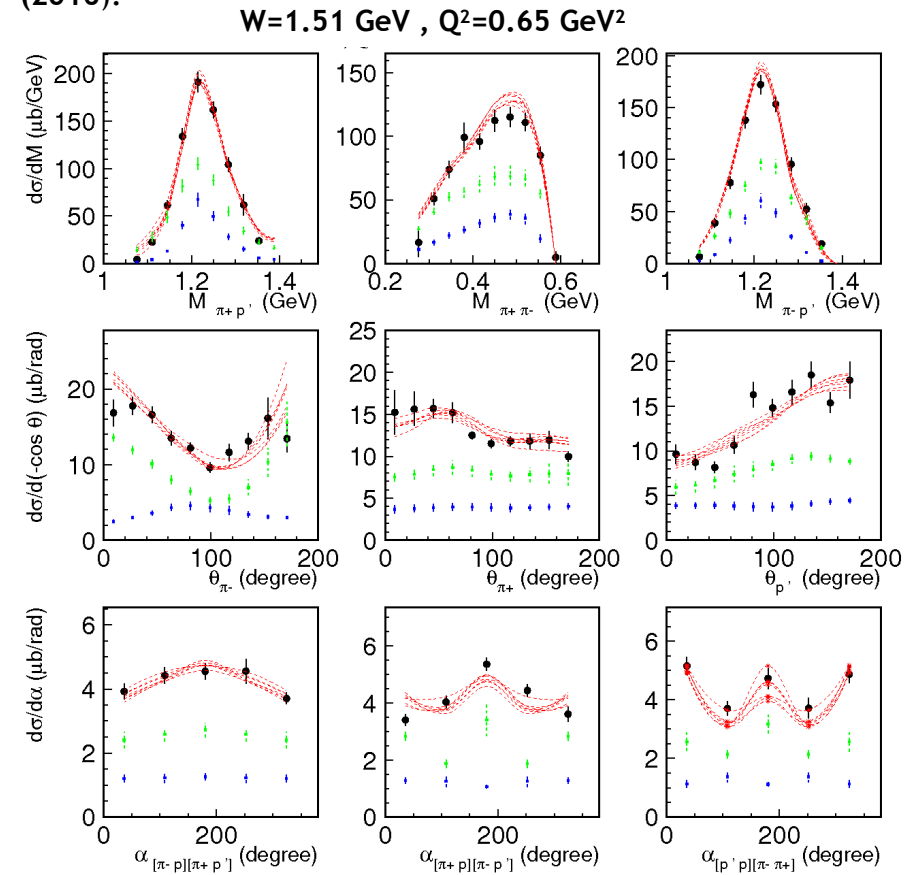
E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)

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

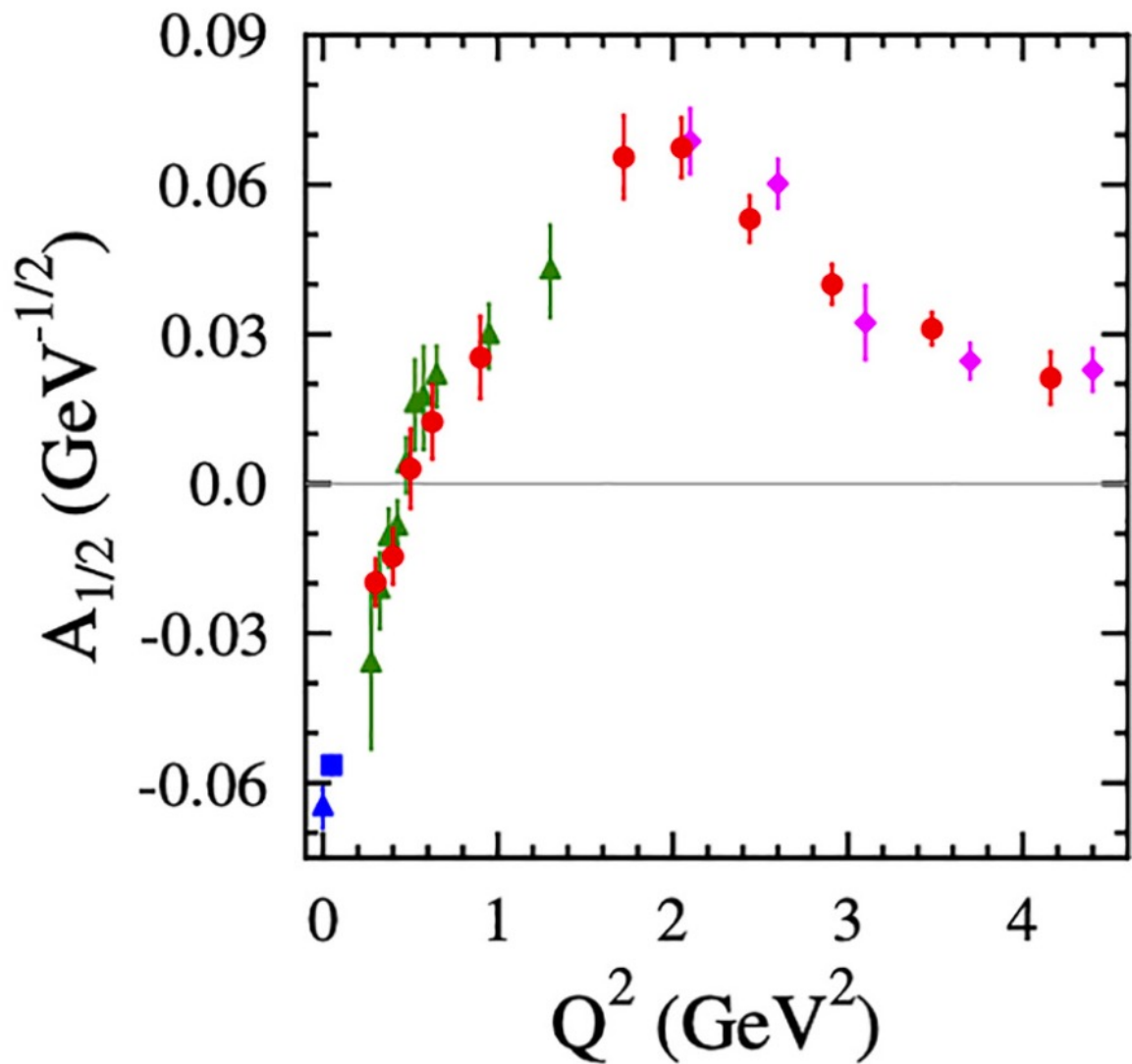
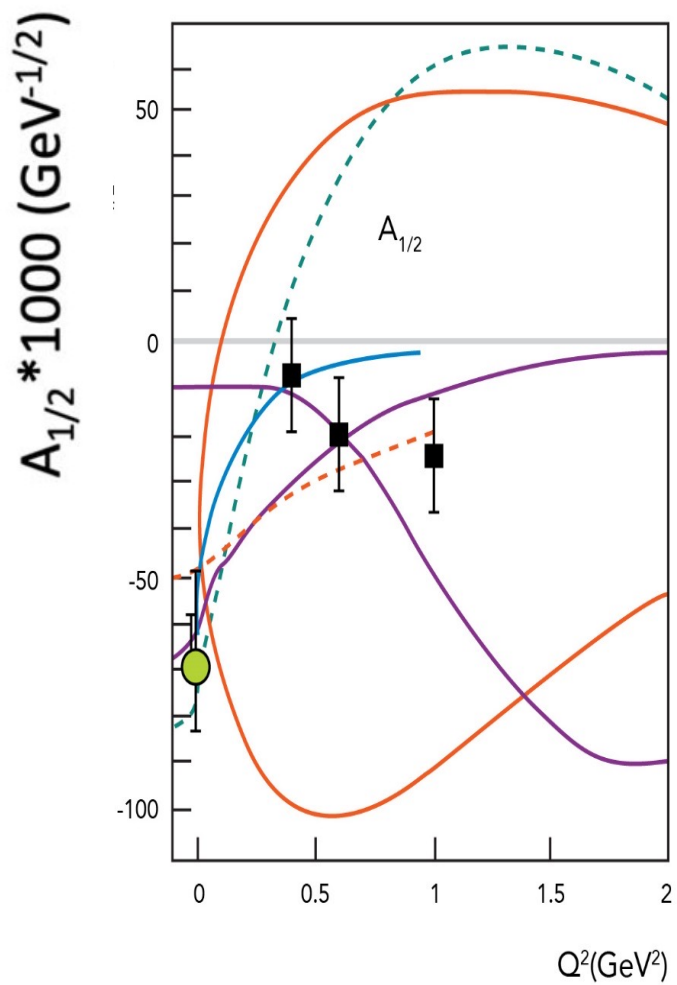


Resonant and non-resonant contributions

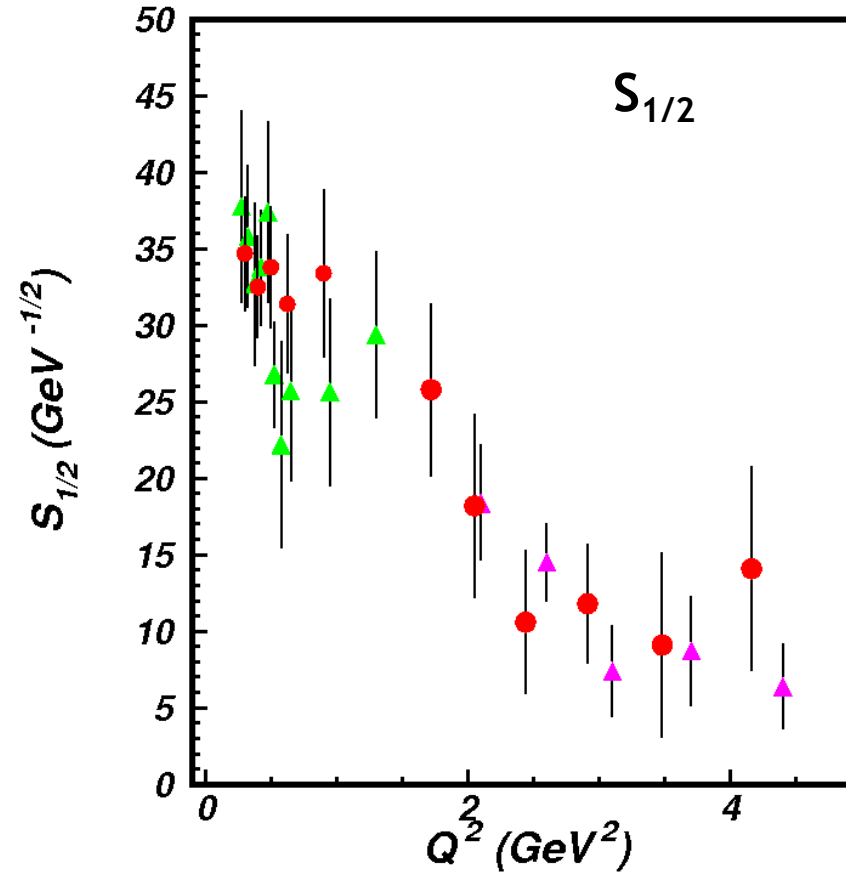
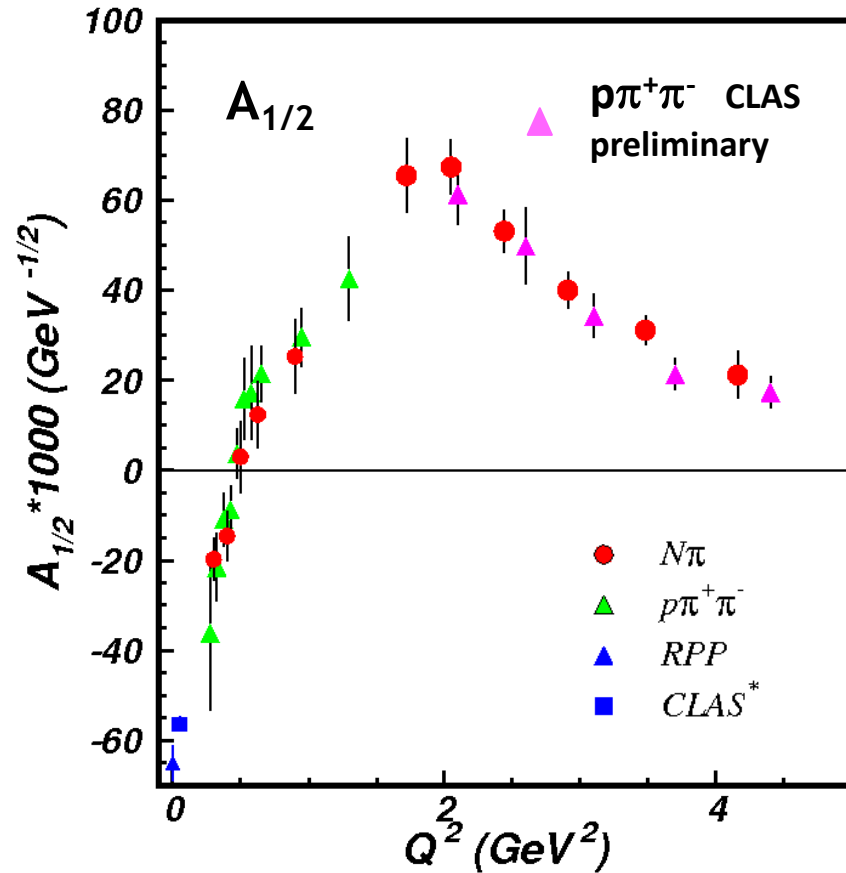
V.I. Moiseev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).



Roper resonance before and after CLAS

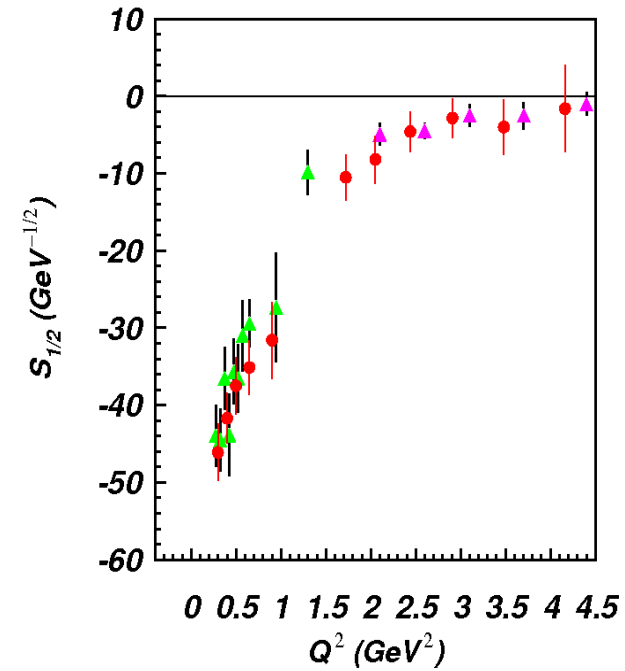
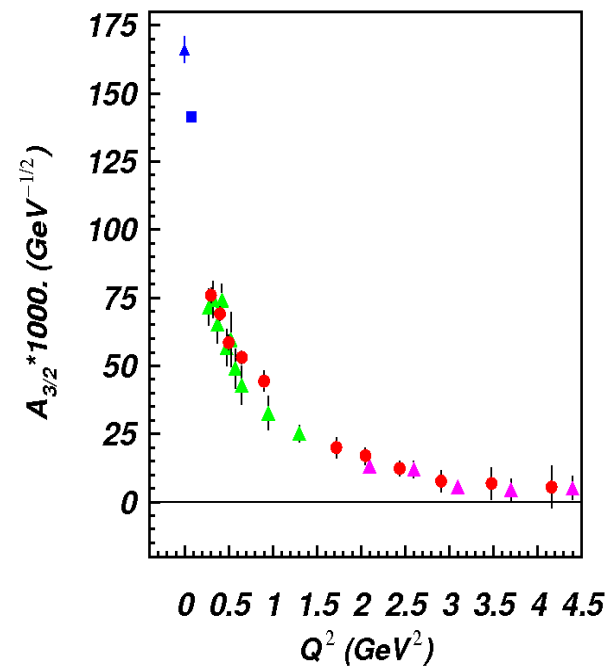
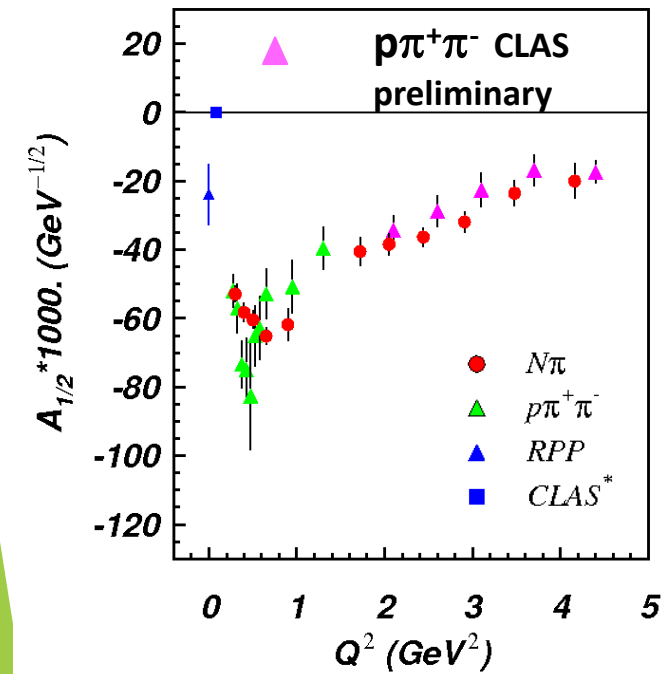


Electrocouplings of $N(1440)1/2^+$ from $N\pi$ and $\pi^+\pi^-p$ Electroproduction off Proton Data



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

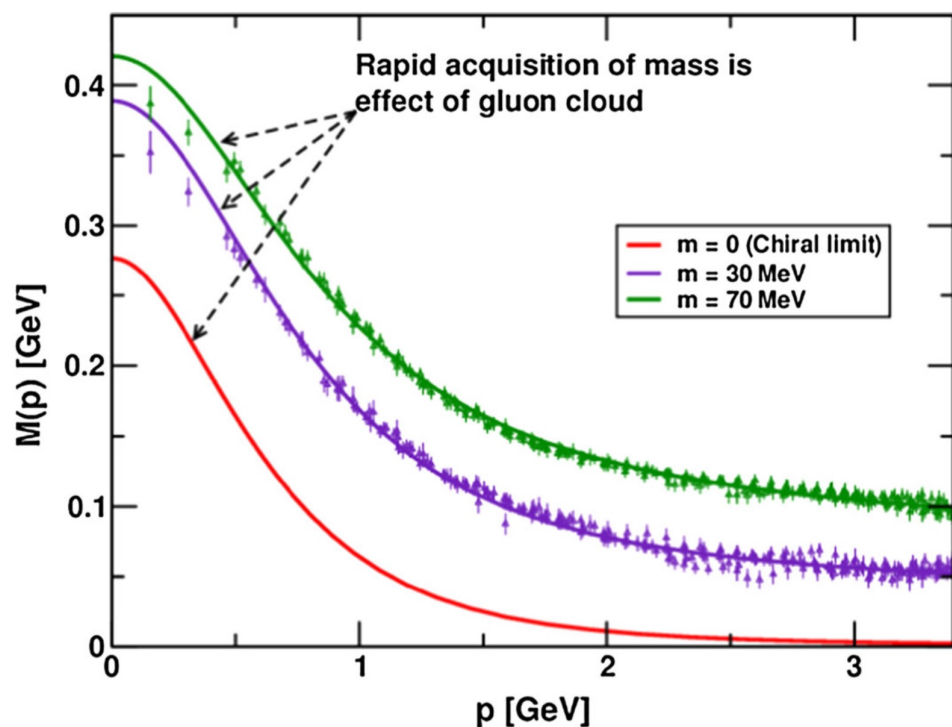


Consistent results from $N\pi$ and $\pi^+\pi^-p$ electroproduction off proton data on electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ resonances with the biggest combined contribution into the resonant parts of both channels at $W < 1.55$ GeV strongly support the capabilities of the developed reaction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

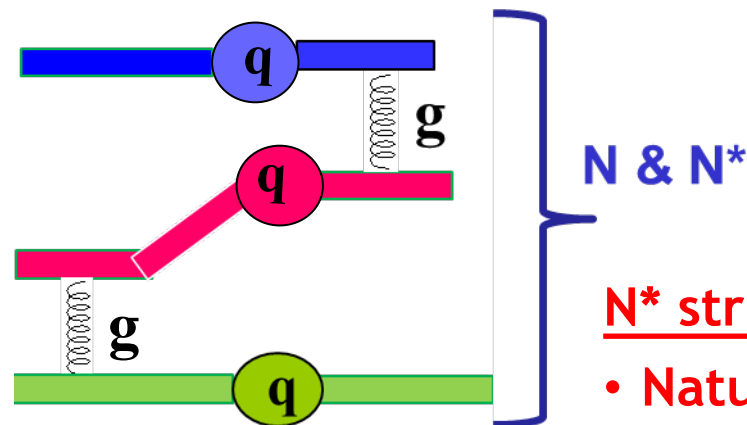
Two conceptually different approaches for description of nucleon/ N^* structure from first QCD principles:

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



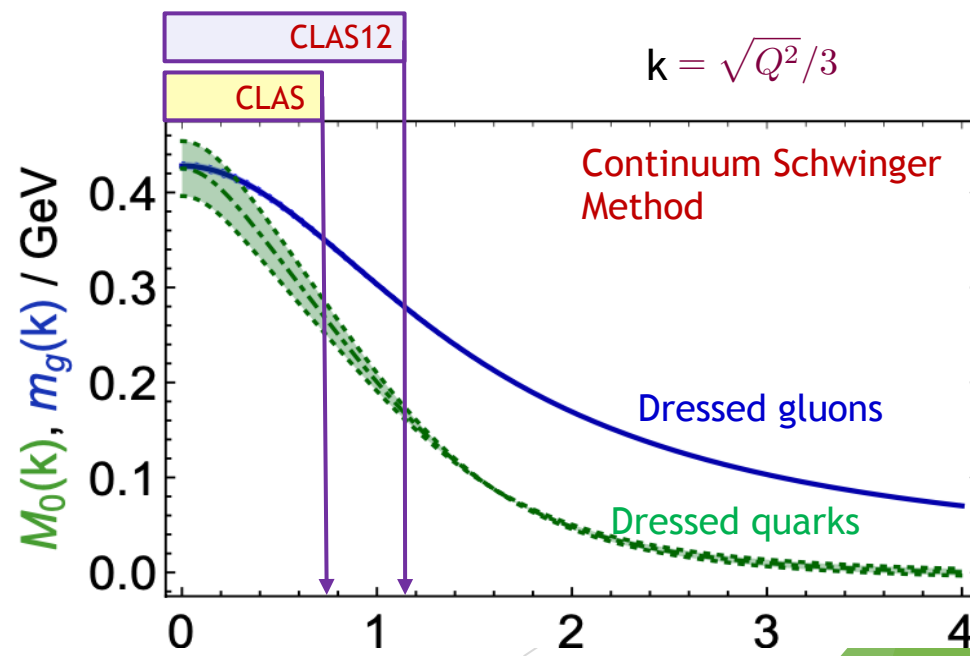
Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)

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



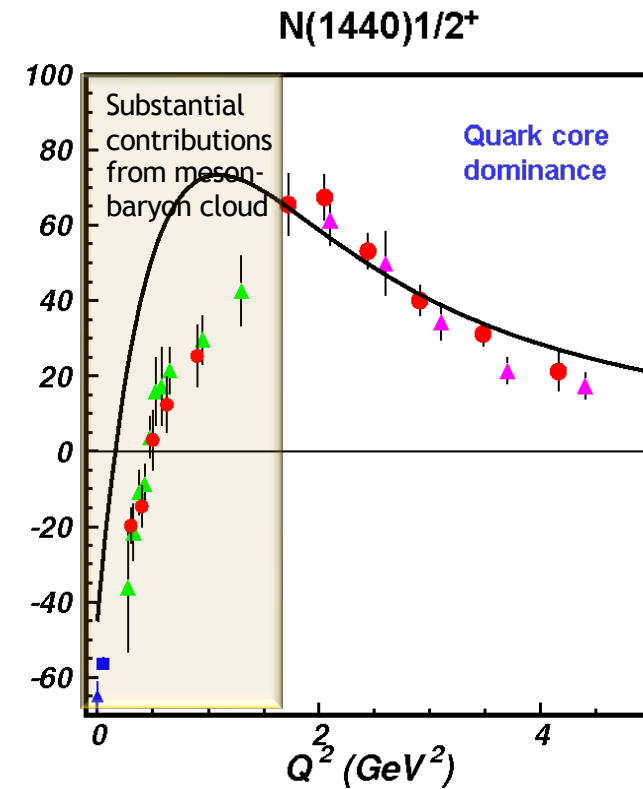
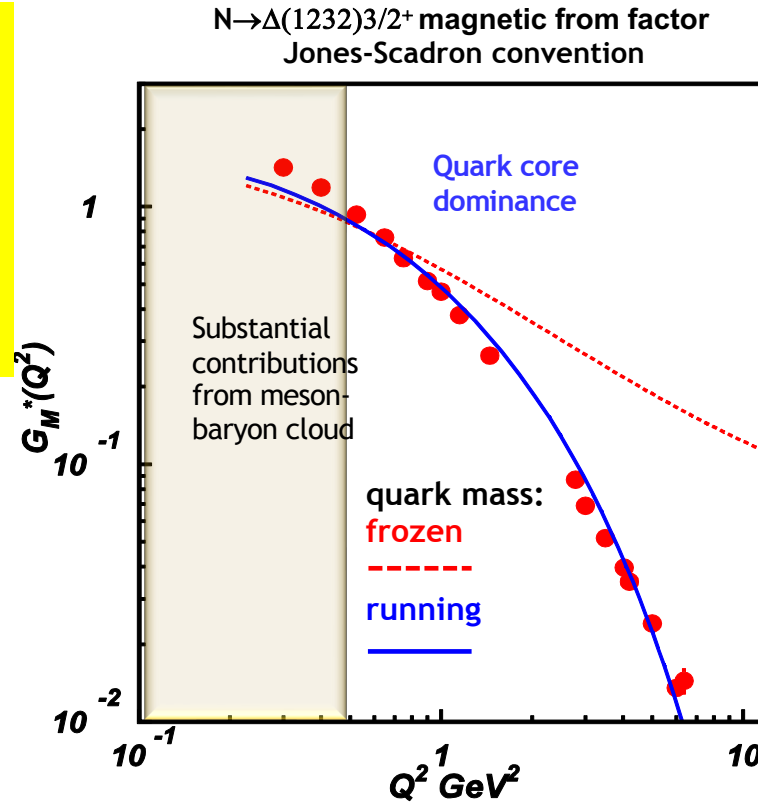
N^* structure studies address:

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



Dyson-Schwinger Equations (DSE):

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

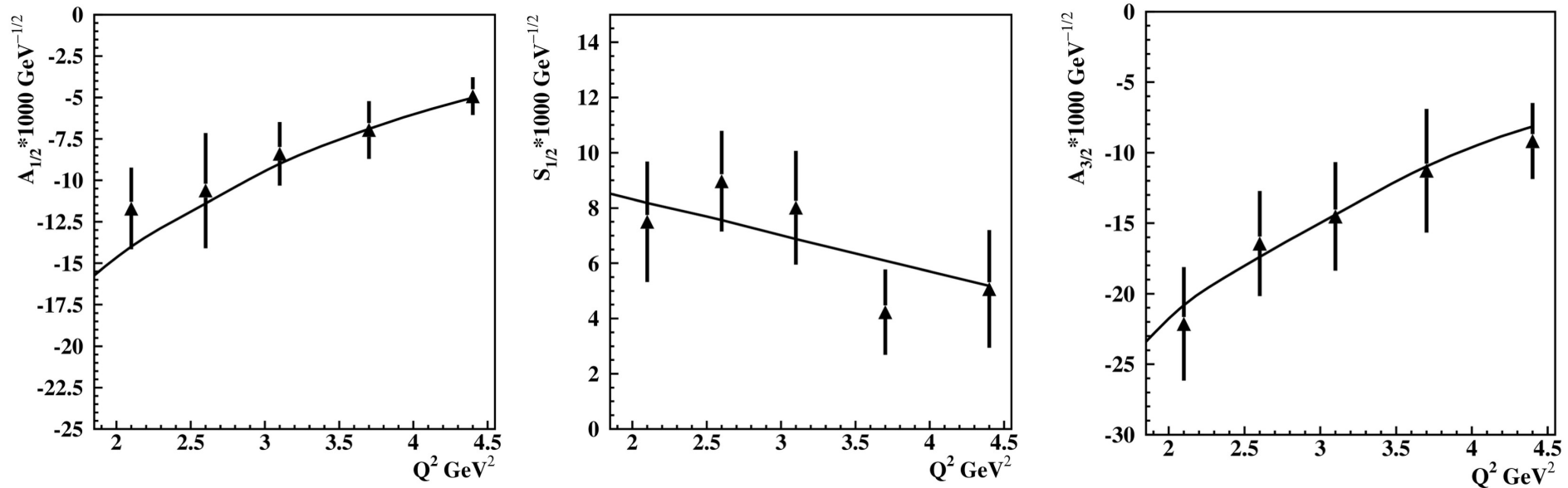


DSE analyses of the CLAS data on $\Delta(1232)3/2^+$ electroexcitation demonstrated that dressed quark mass is running with momentum.

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.

$\Delta(1600)3/2^+$ Electrocouplings : CSM Prediction vs. Data Determination



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

Electrocouplings from analyses of $\pi^+\pi^-p$ differential cross sections at $W=1.46 - 1.66 \text{ GeV}$, for $2.0 < Q^2 < 5.0 \text{ GeV}^2$ [V.I. Mokeev et al., PRC 108, 025204 (2023)].

CLAS results on $\Delta(1600)3/2^+$ electrocouplings confirmed the CSM predictions, solidifying evidence for gaining insight into the dressed quark mass function and, consequently, into EHM from studies of $\gamma_\nu p N^*$ electrocouplings.

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!

Inclusive electron scattering @10.6 GeV from CLAS12

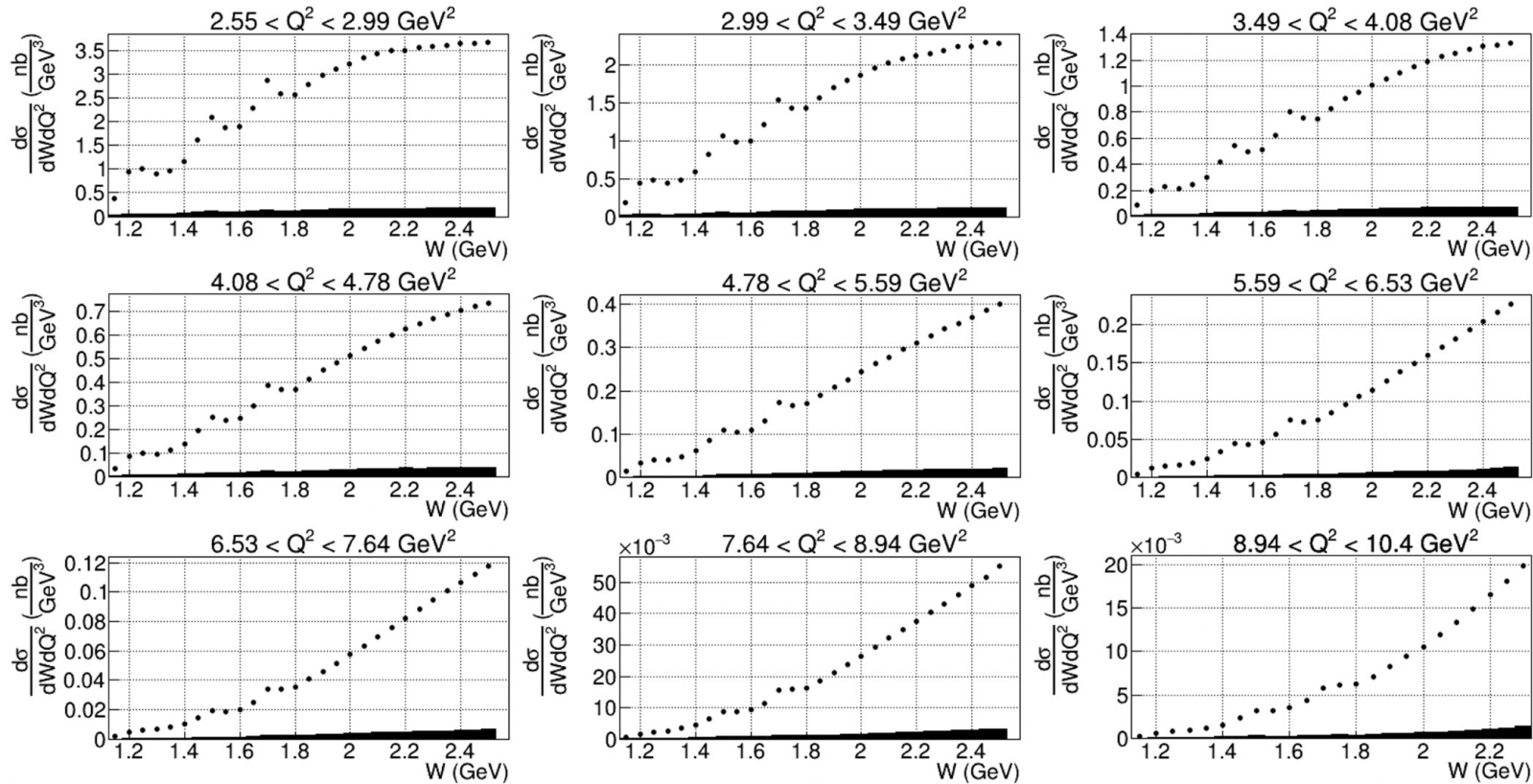


FIG. 30. Inclusive electron scattering cross sections determined from CLAS12 RG-A data. The statistical uncertainties on the CLAS12 data are shown but they are smaller than the data point size for the majority of the data points. The bin-by-bin systematic uncertainty is shown by the filled area at the bottom of each plot.

Valerii Klimenko

Accepted by PRC
26 June 2025

Thank you for your attention!

The slide features a white background with a decorative graphic on the right side. This graphic consists of several overlapping, semi-transparent green triangles and polygons in various shades of green, ranging from light lime to dark forest green. The shapes are arranged in a way that they appear to be layered, creating a sense of depth and movement. The overall aesthetic is clean and modern.