Исследования возбужденных состояний протона на основе данных CLAS

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НИИЯФ МГУ

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

$$D_a^{\mu} = \partial^{\mu} + igA_a^{\mu}$$
$$F_a^{\mu\nu} = \partial^{\mu} A_a^{\nu} - \partial^{\nu} A_a^{\mu} - g f_{abc} A_b^{\mu} A_c^{\nu}$$

- Color matrices and structure constants

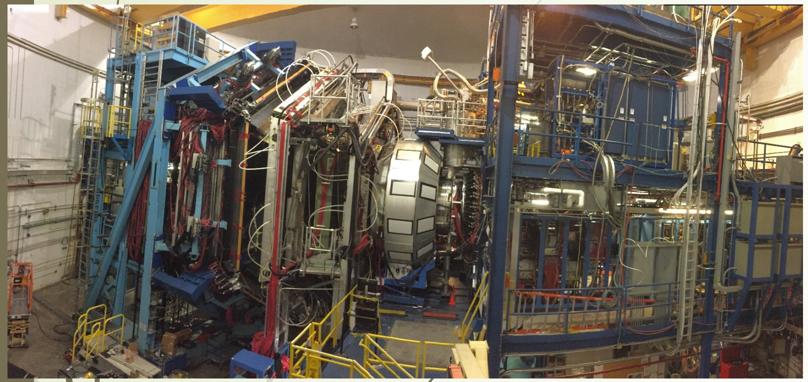
$$[T_a^{(F)}, T_b^{(F)}] = i f_{abc} T_c^{(F)}, \quad (T_a^{(A)})_{bc} = -i f_{abc}$$

- Lattice QCD
- Continuum QCD

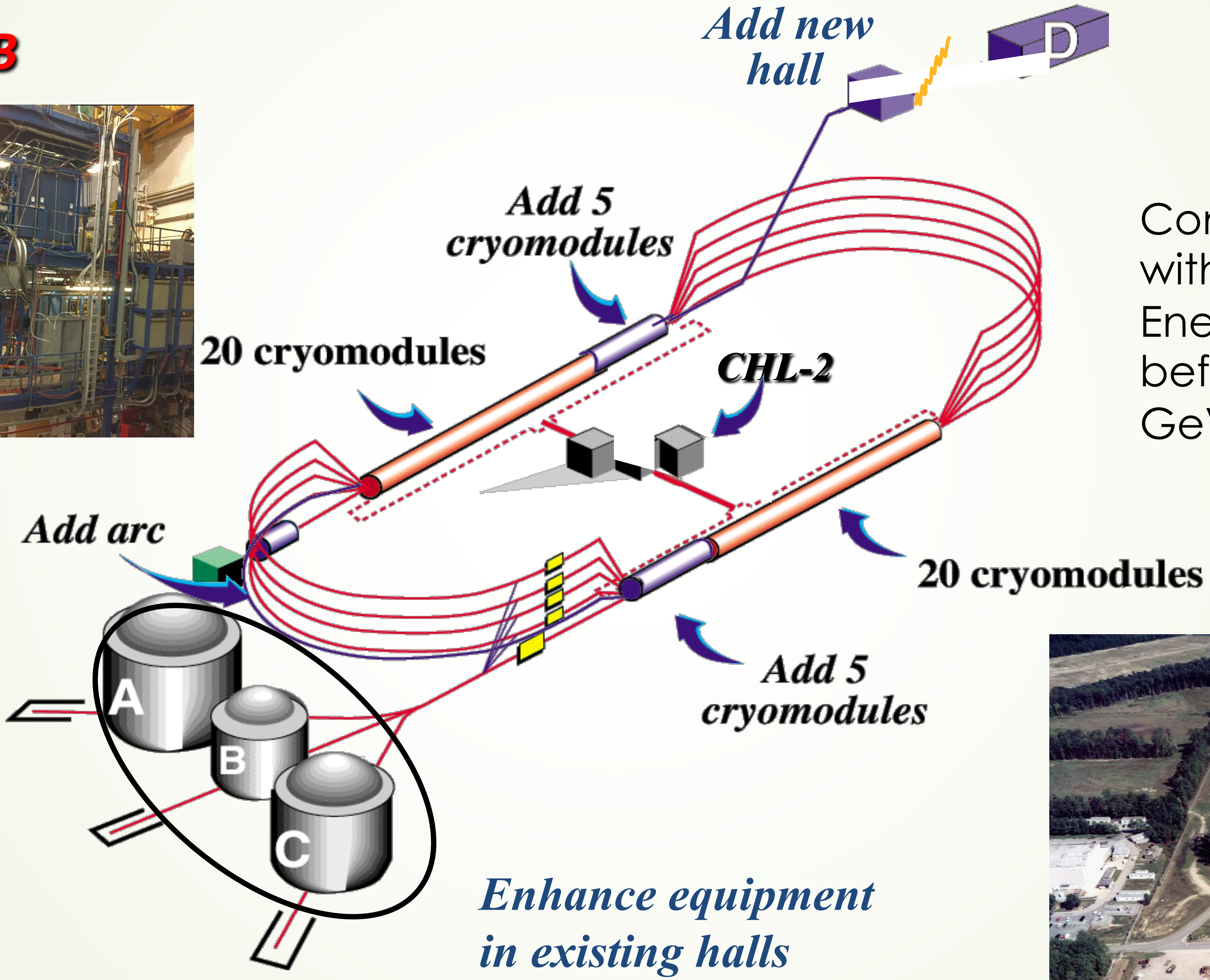
Light front quark models
AdS/CFT approaches
χ Quark-Soliton models
Hypercentral quark model
Covariant quark models
……………………………….

Jefferson Lab (Newport News, VA, USA)

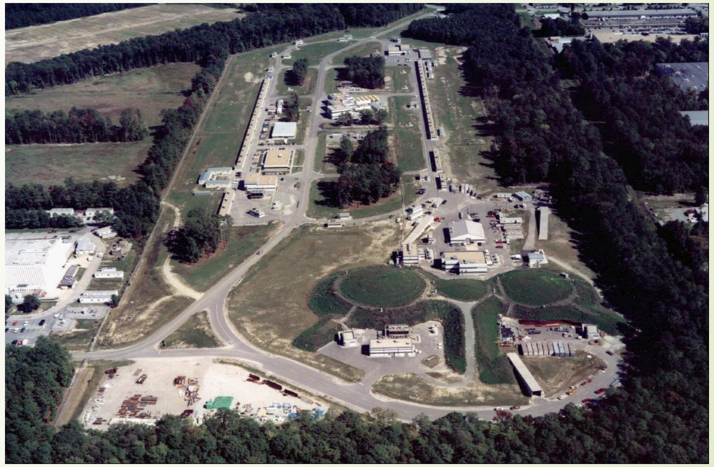
CLAS12 in Hall B



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
- $\gamma_v pN^*$ 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

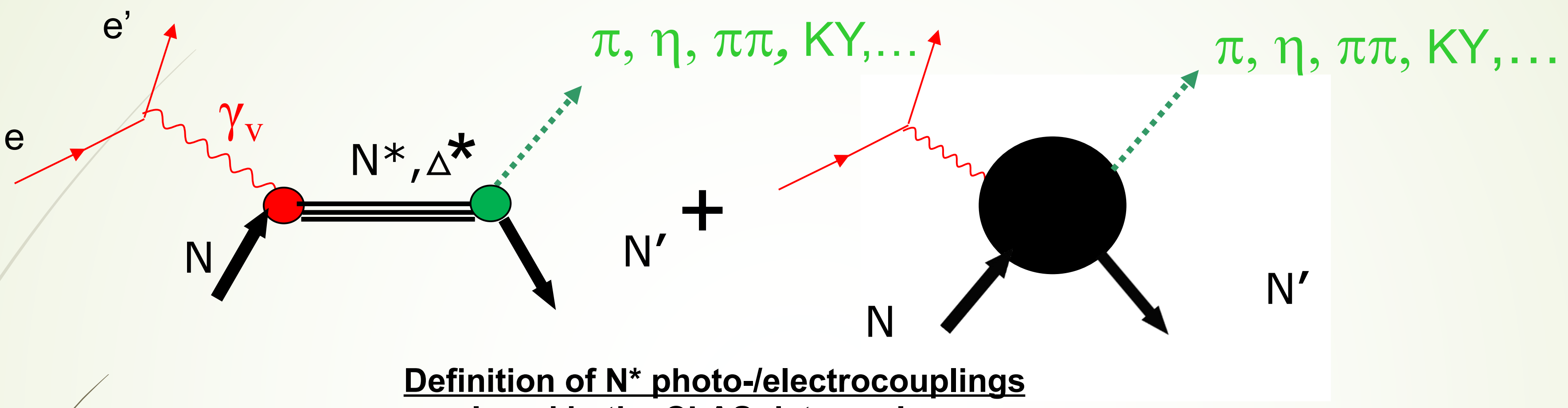
A unique source of information on many facets of strong QCD in generating excited nucleon states with different structural features

Review papers:

1. I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).
2. 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 $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes **Non-resonant amplitudes**



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

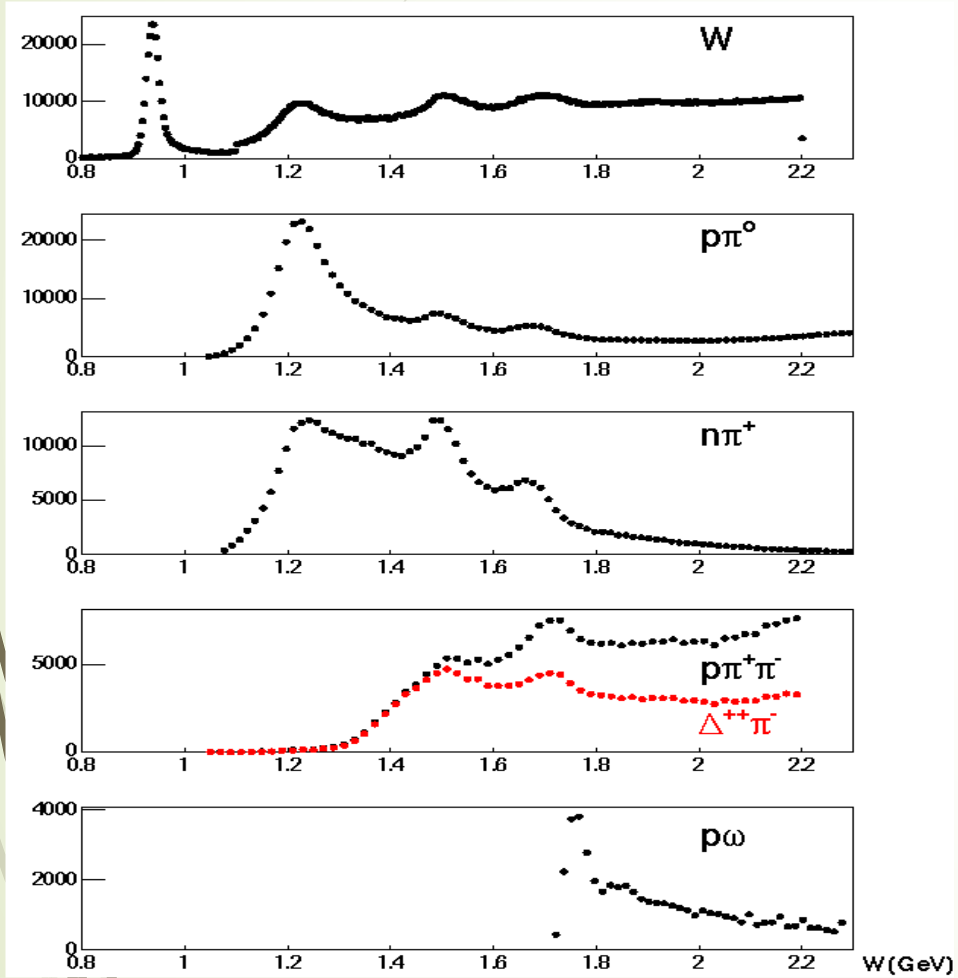
- **Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$**

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.**

Experimental yields of major electroproduction channels from CLAS for $Q^2<4$ 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
$\pi^+ n$	**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** **$d\sigma/d\Omega$**
$\pi^0 p$	**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!

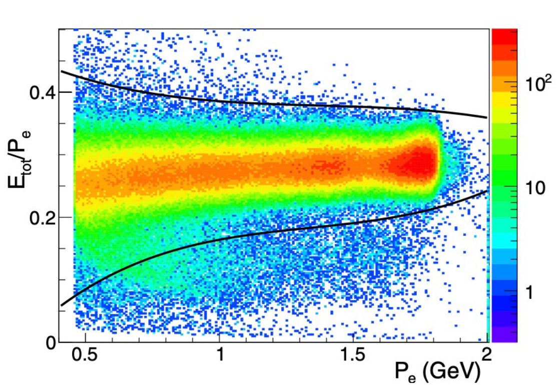
Almost full coverage of the final hadrons phase space

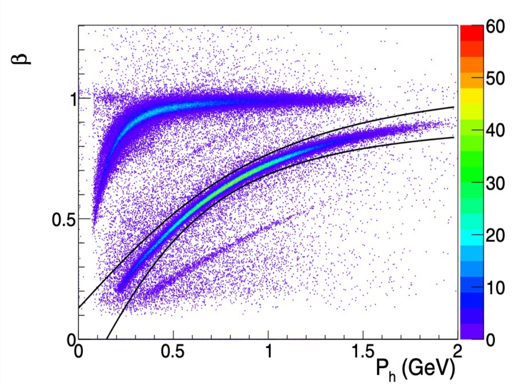
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

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

E. L. Isupov *et al.* (CLAS Collaboration)
Phys. Rev. C **105**, L022201 – Published 18 February 2022

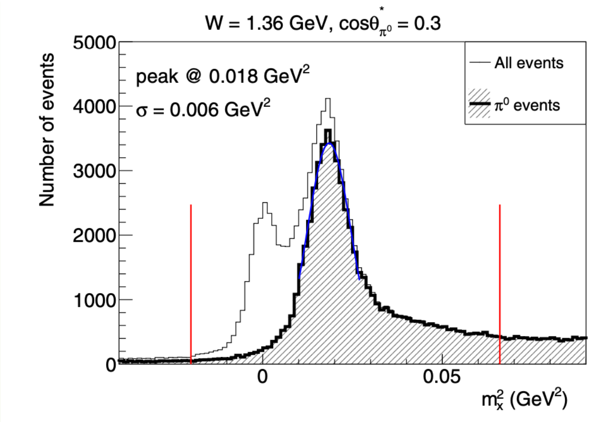
- CLAS detector data 12/2002 – 1/2003
- Beam energy: 2.036 GeV
- Beam polarization: ~ 80%
- Target: Liquid Hydrogen, thickness 2 cm
- Number of triggers: ~ 1.5 billion





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

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



Polarized Structure Function $\sigma_{LT'}$

$$\frac{d^2\sigma^h}{d\Omega^*_\pi} = \frac{p^*_\pi}{k^*_\gamma}[\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'} \sin\theta^*_\pi \sin\phi^*_\pi]$$

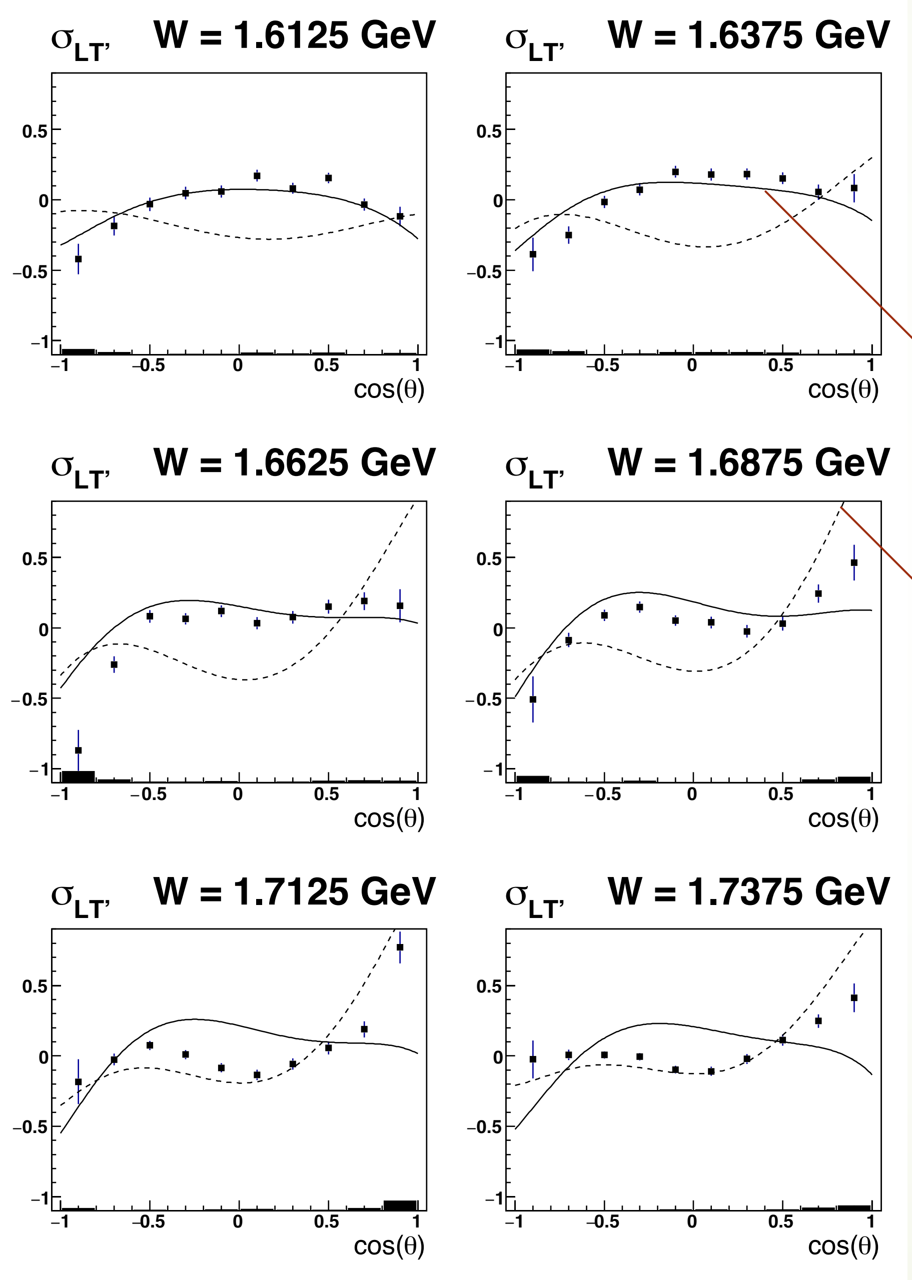
$$A_{LT'} = \frac{\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'} \sin\theta^*_\pi \sin\phi^*_\pi}{\sigma_0}$$

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

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

We have unpolarized cross sections from the same data.

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



MAID 2007 (solid line)

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

Legendre Polynomials of $\sigma_{LT'}$

l=0,1,2,3 $\sigma_{LT'}$=D0+D1*x+D2*0.5*(3*x^2 -1)+D3*0.5*(5*x^3 -3*x)

x = cos(θ)

sensitivity to P13(1720)
D1 ~ -Im(... 6*S1p*conj(E1p) - 6*S1p*conj(M1p) ...)

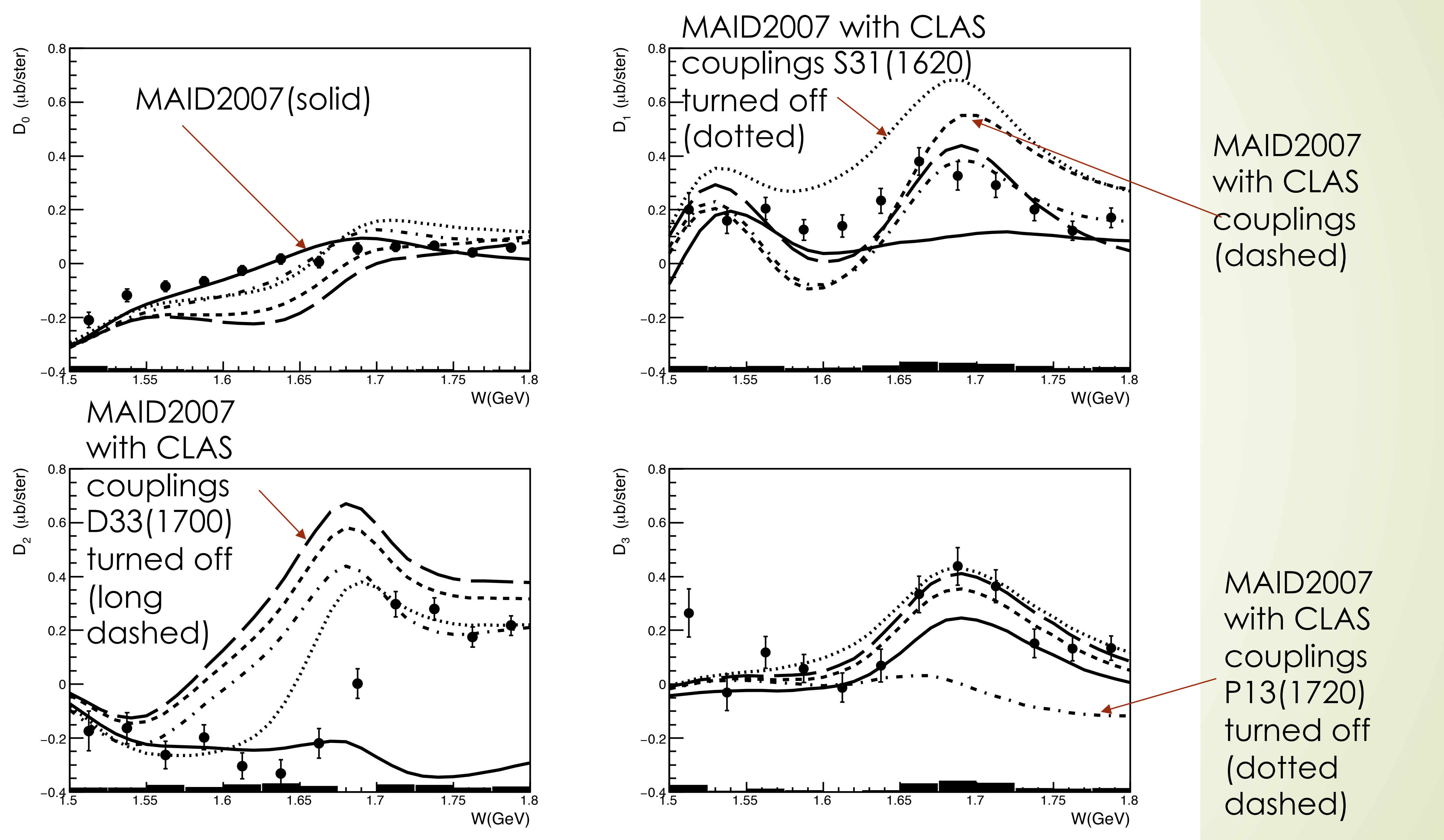
sensitivity to D33(1700)

D1 ~ -Im(... - 6*S2m*conj(E2m) - 6*S2m*conj(M2m)...)

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

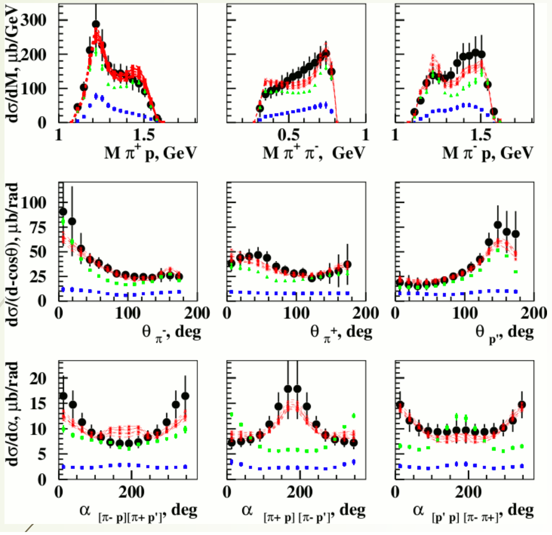
P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	L_{1-}
S_{11}	S_{31}	$\frac{1}{2}^+$	0^-	L_{0+}, E_{0+}
D_{13}	D_{33}	$\frac{1}{2}^+$	2^-	L_{2-}, E_{2-}
P_{11}	P_{31}	$\frac{1}{2}^+$	1^+	M_{1-}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	M_{1+}
P_{13}	P_{33}	$\frac{1}{2}^+$	1^+	L_{1+}, E_{1+}
F_{15}	F_{35}	$\frac{1}{2}^+$	3^+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

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

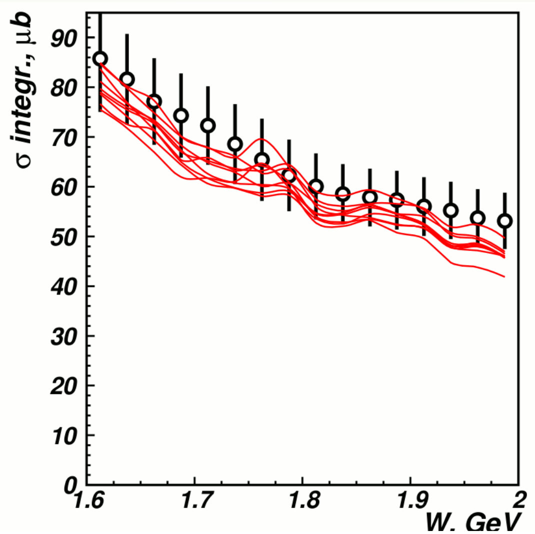


Resonance Photocouplings from the CLAS $\pi^+\pi^-p$ Photoproduction Cross Sections

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**

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

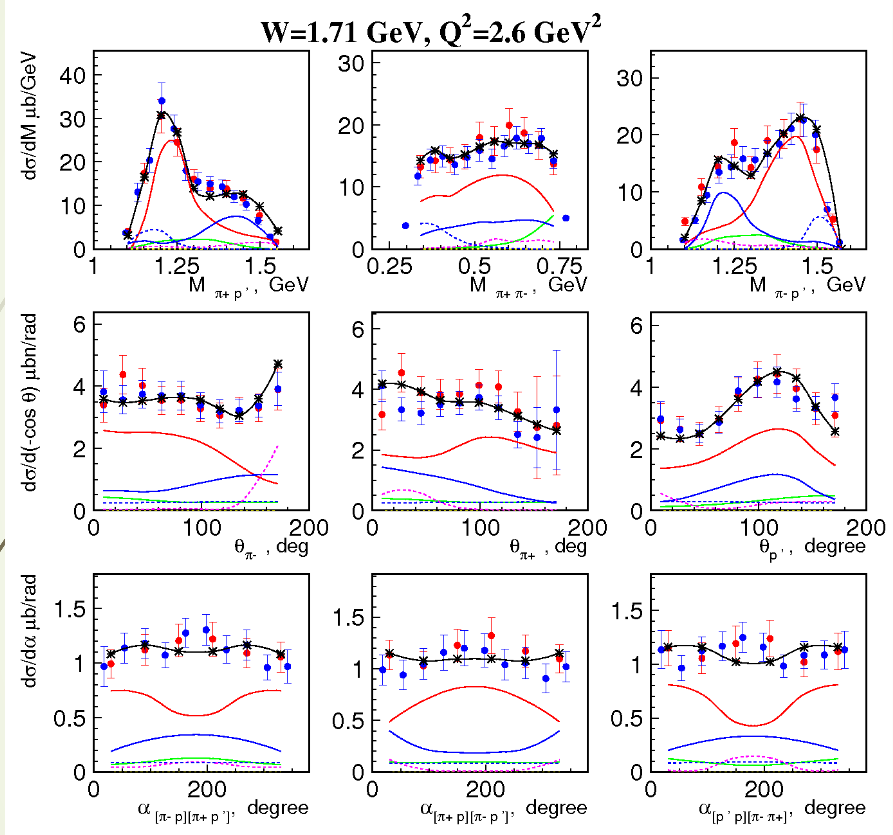
Resonances	$A_{1/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$	$A_{1/2}\times10^3$ PDG ranges $GeV^{-1/2}$	$A_{1/2}\times10^3$ multichannel analysis [7] $GeV^{-1/2}$	$A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $GeV^{-1/2}$	$A_{3/2}\times10^3$ PDG ranges $GeV^{-1/2}$	$A_{3/2}\times10^3$ multichannel analysis [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 $N\pi\pi$ 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

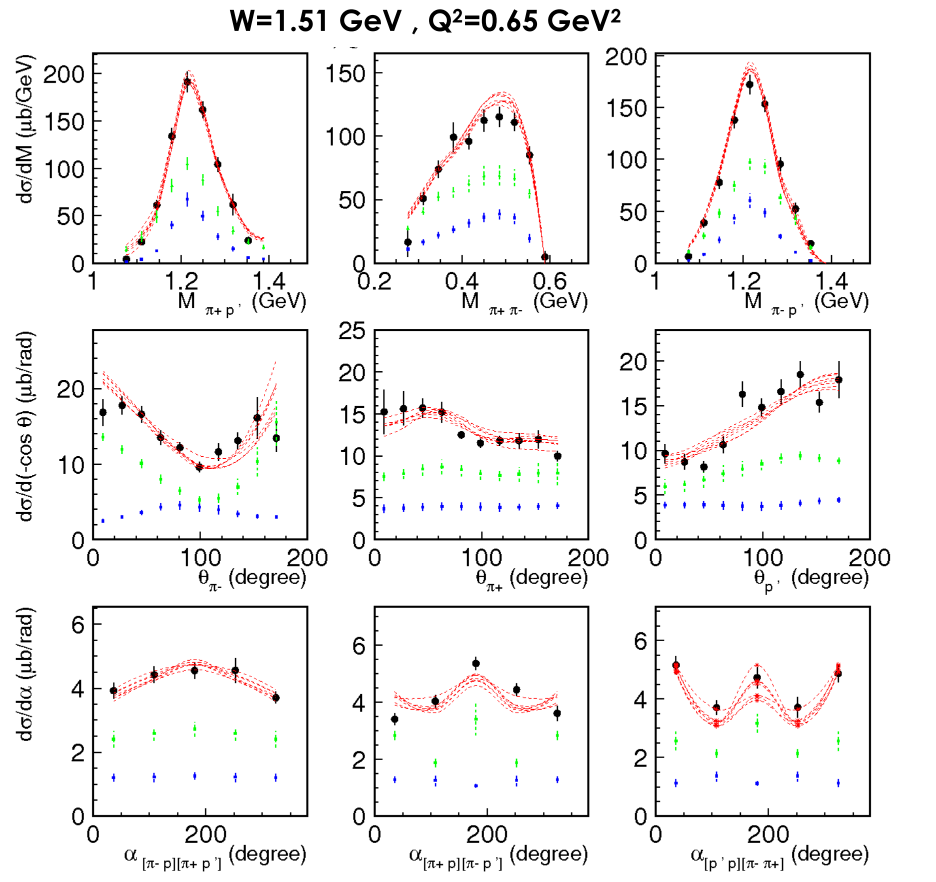
Contributing mechanisms seen in the data

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



Resonant and non-resonant contributions

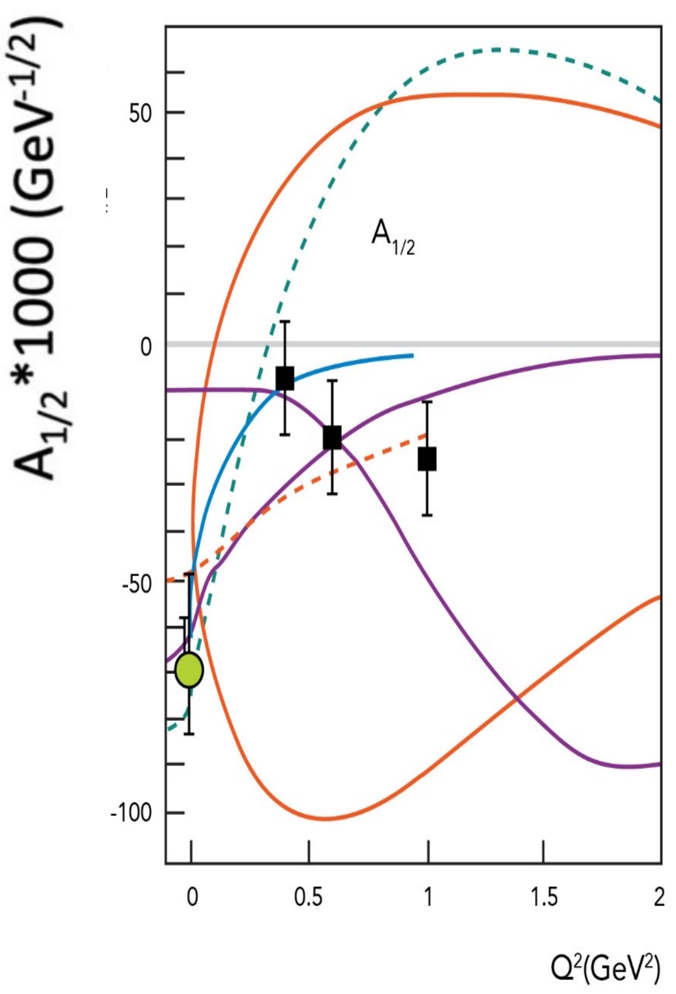
V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).

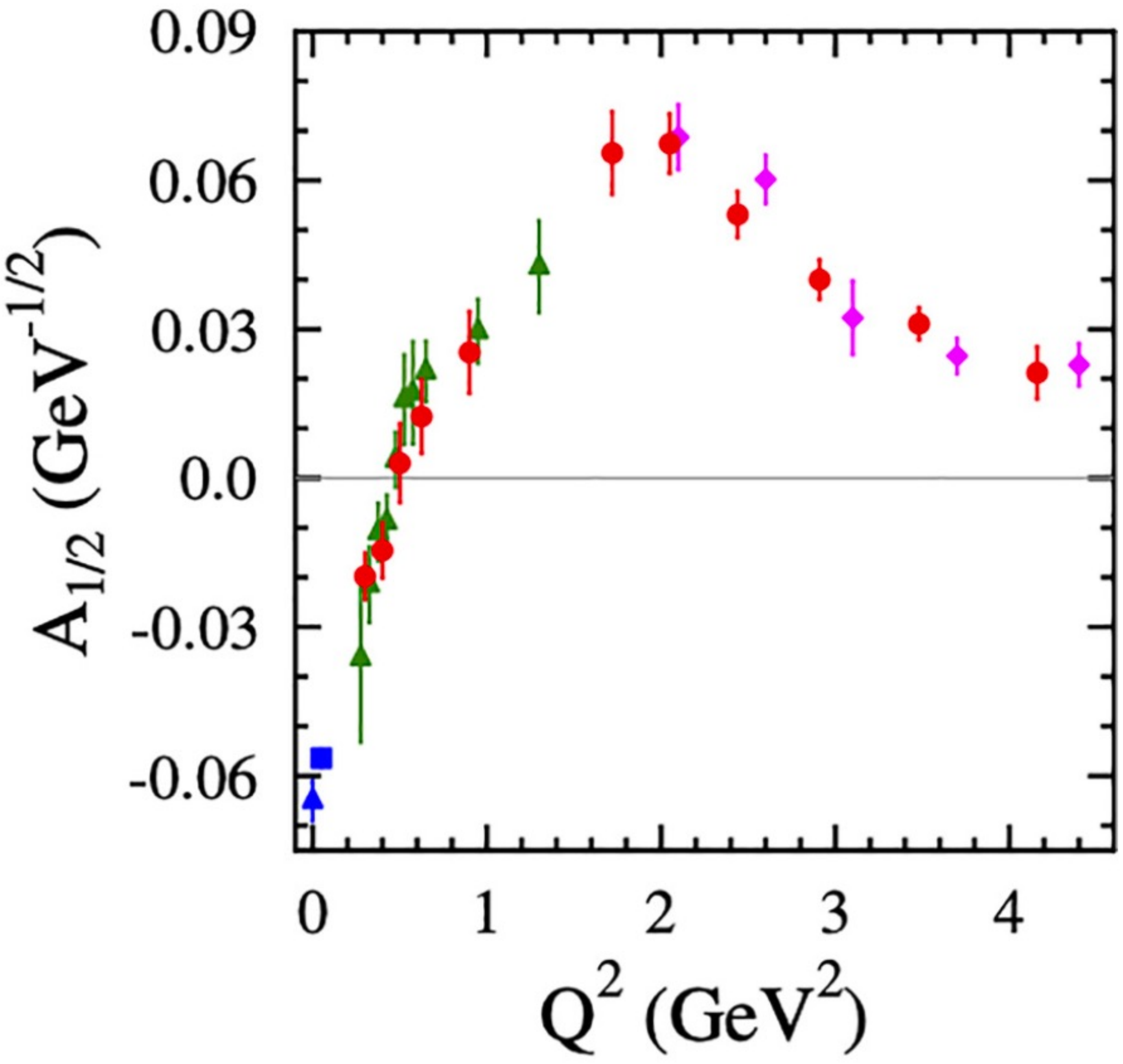


full JM
$\pi^-\Delta^{++}$
ρp
$\pi^+\Delta^0$
π^+ N(1520)3/2⁻
π^+ N(1680)5/2⁺

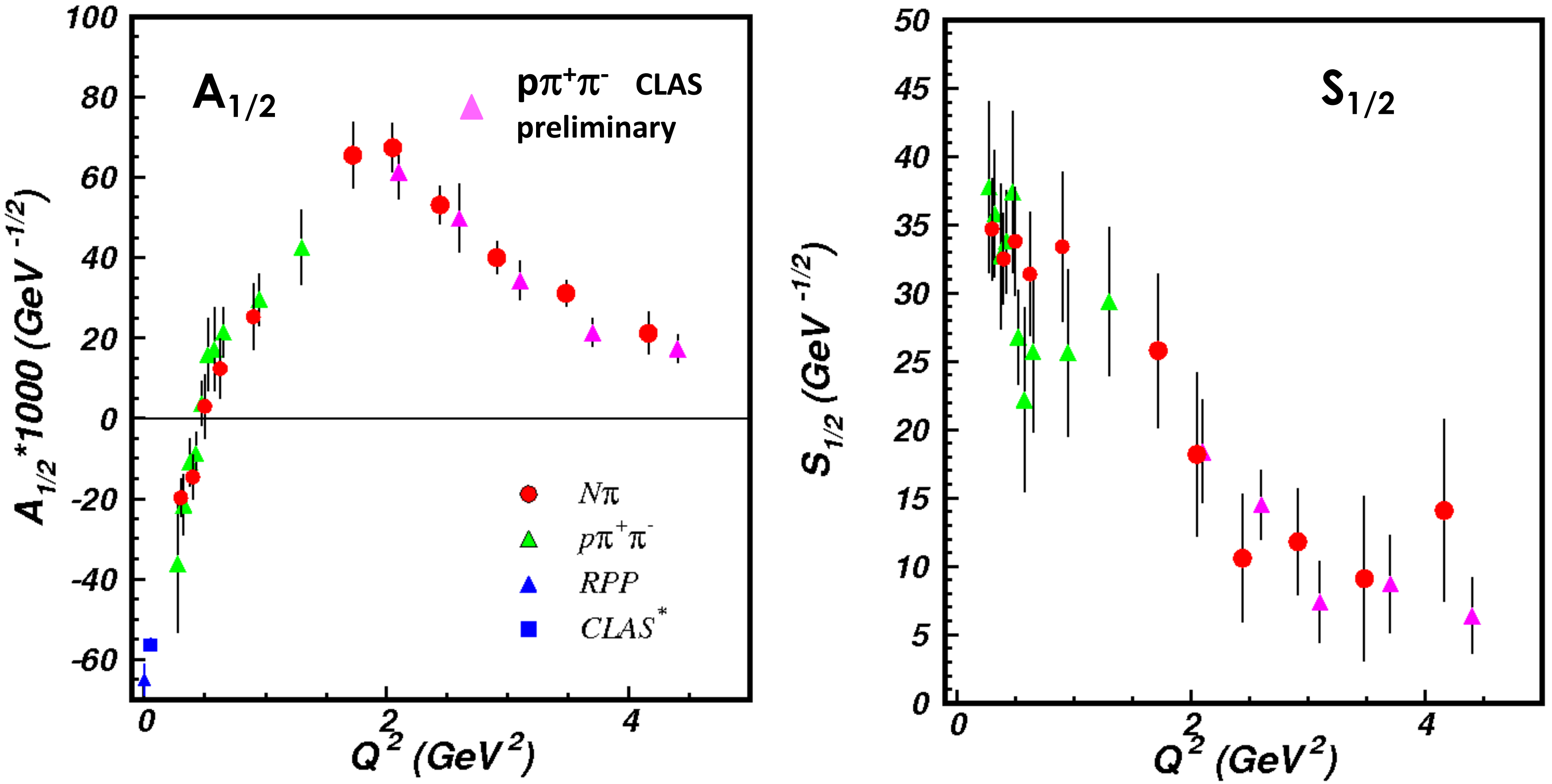
data fit within JM under variations of both resonant and background parameters
background cross sections
resonant cross sections

Roper resonance before and after CLAS



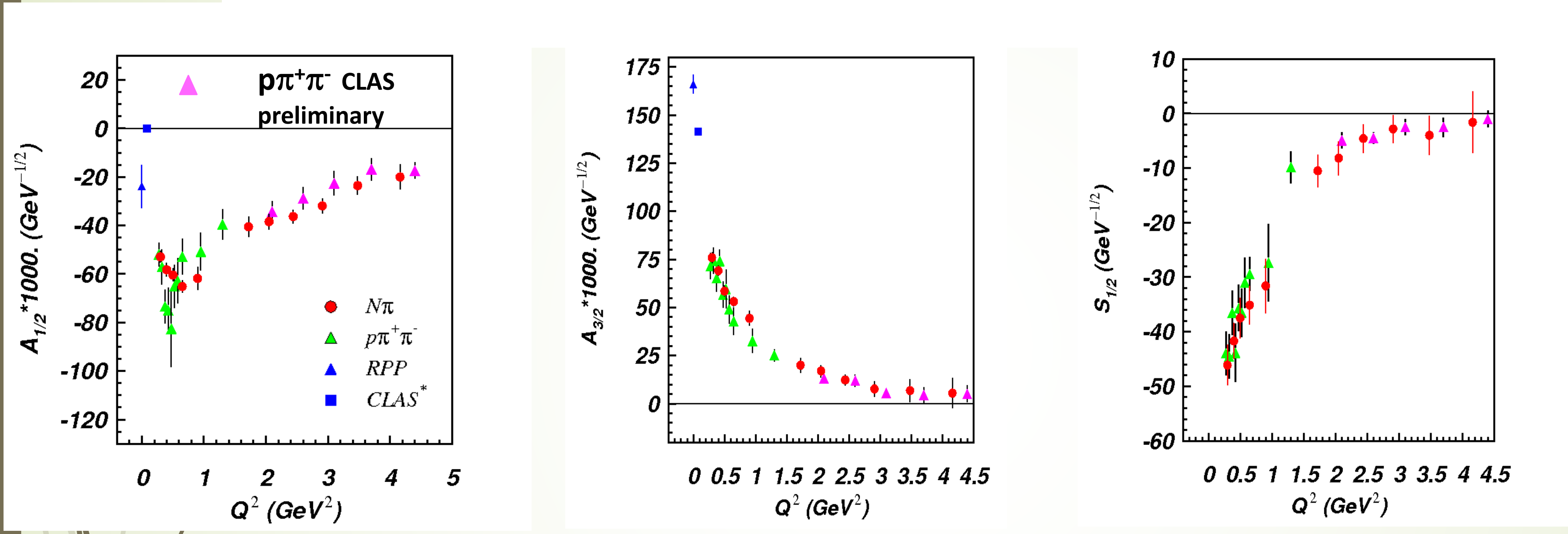


Electrocouplings of N(1440)1/2$^+$ from Nπ and $\pi^+\pi^-$p Electroproduction off Proton Data



Consistent results on N(1440)1/2$^+$ electrocouplings from the independent studies of two major Nπ 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

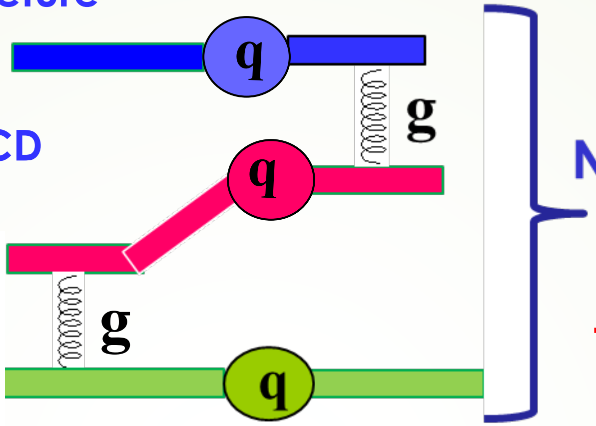


Consistent results from Nπ and $\pi^+\pi^-p$ electroproduction off proton data on electrocouplings of N(1440)1/2⁺ and N(1520)3/2⁻ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction models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

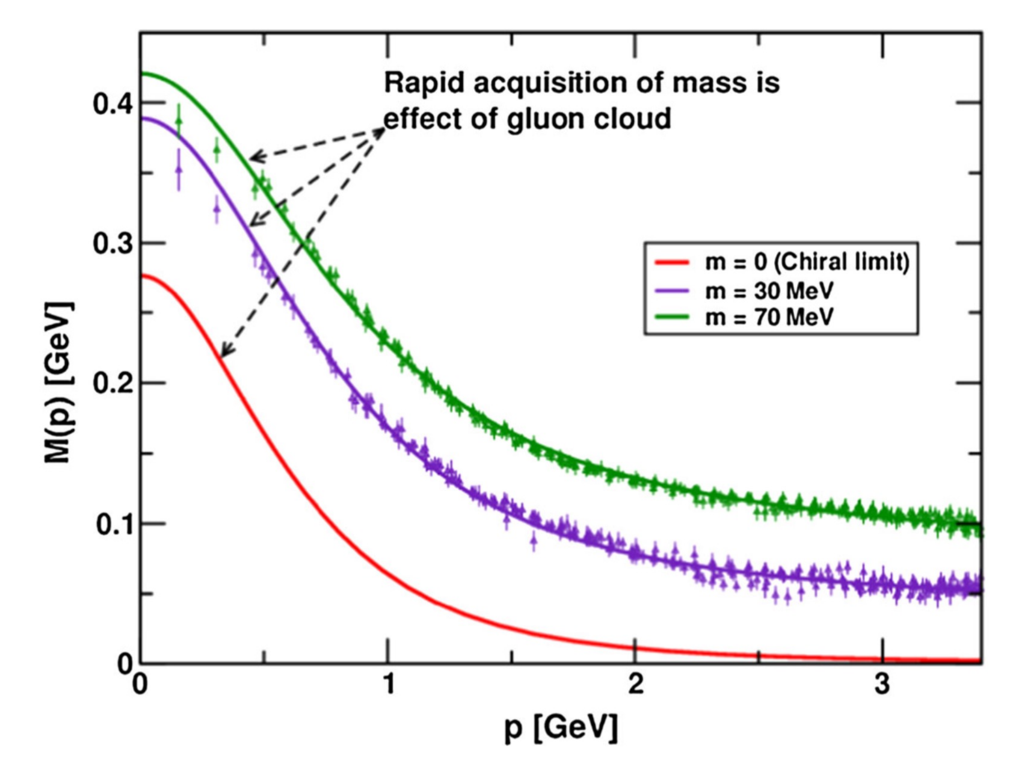
Excited Nucleon States and Insight into Strong QCD Dynamics

Two conceptually different approaches for description of nucleon/N* structure from first QCD principles:
- •Lattice QCD (LQCD)
- •Dyson-Schwinger Equation of QCD (DSEQCD)

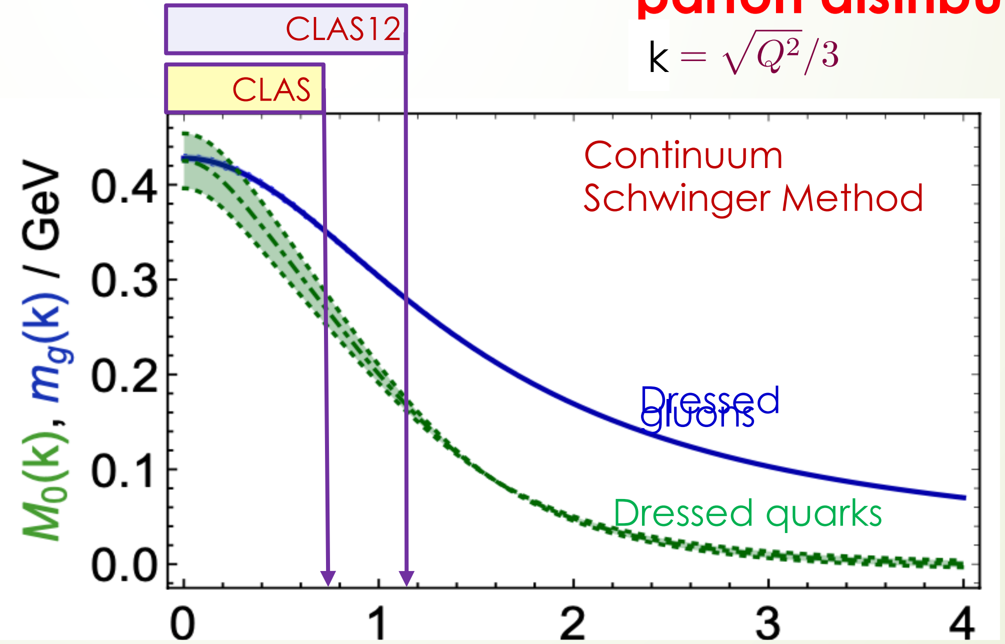
quark-quark correlations in baryons
Ch. Chen et al, Phys. Rev. D97, 034016 (2018)



N* structure studies address:
- Nature of > 98% of hadron mass
- Emergence of the ground nucleon
  parton distributions in 1D and 3D



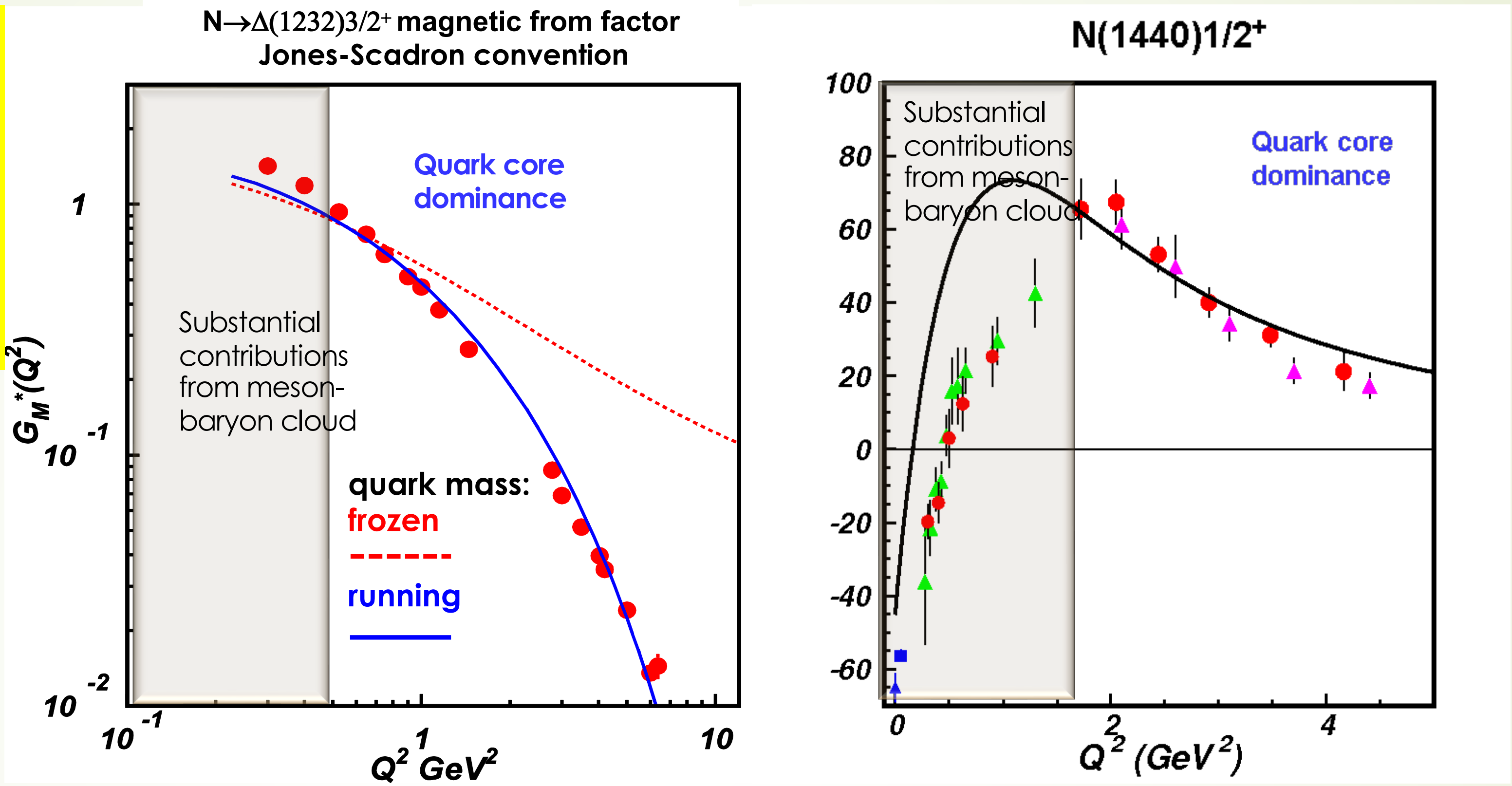
Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)



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 $Q^2>2.0$ GeV^2 achieved with <u>the same dressed quark mass function</u> 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.

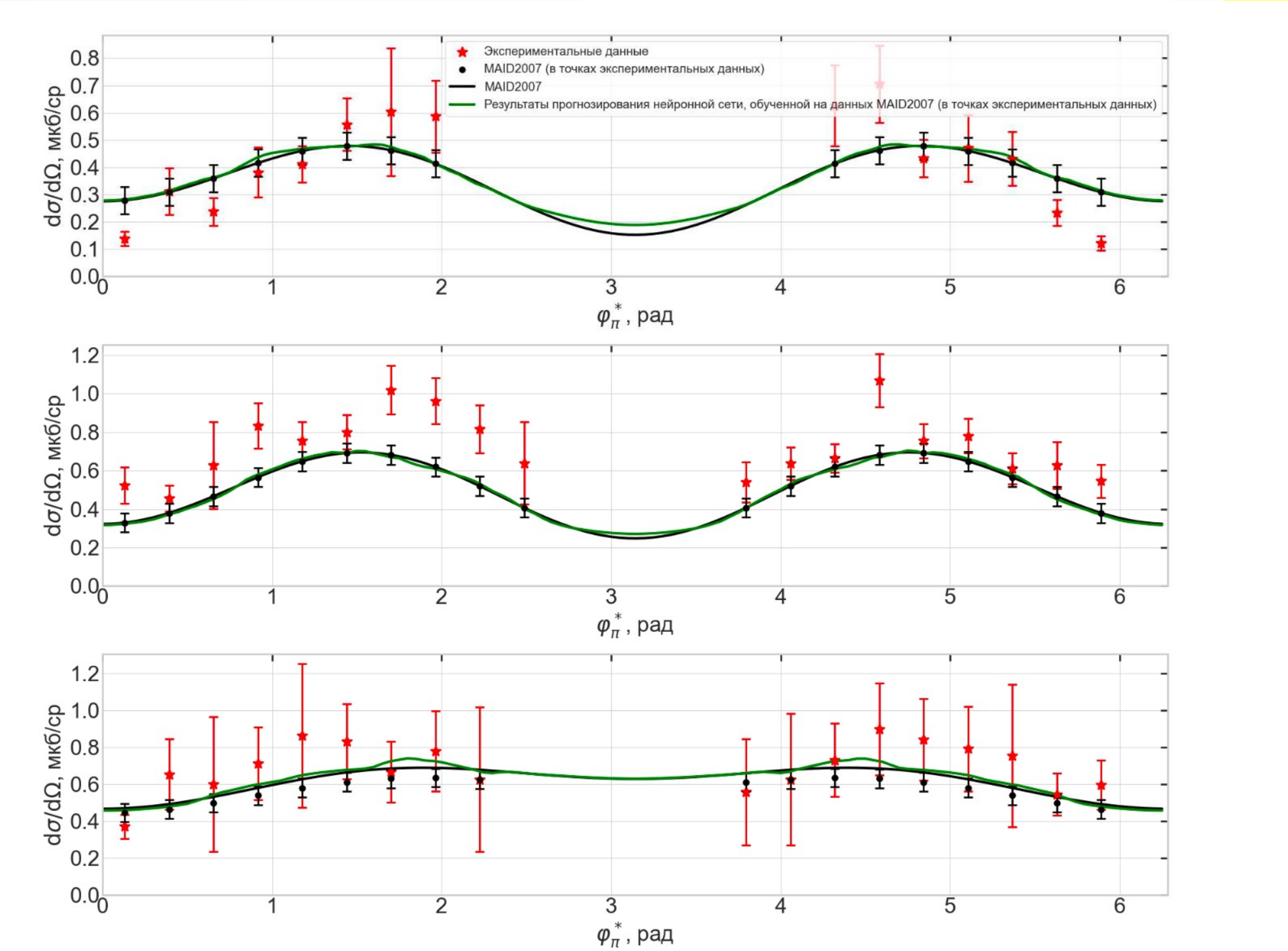
AI-Driven Reconstruction of π^+n Electroproduction Cross Sections within the CLAS Detector Areas of Zero Acceptance

A.V. Golda, E.L. Isupov, Moscow State U

W=1.23 GeV, Q^2=2.92 GeV^2, $\cos(\theta_\pi)$=-0.7

W=1.23 GeV, Q^2=2.92 GeV^2, $\cos(\theta_\pi)$=-0.1

W=1.75 GeV, Q^2=2.05 GeV^2, $\cos(\theta_\pi)$=0.3



The model π^+n cross sections were computed from MAID07 within the entire kinematic area (black lines)

AI was trained on the grid, where CLAS cross sections (red data points) are available, to reproduce the MAID07 quasi-data (black data points). The AI estimates (green lines) are compared with MAID07 results within the entire reaction phase space.

AI estimates well reproduce the MAID cross sections within areas of zero acceptance

Promising prospect to reconstruct π^+n electroproduction cross sections with the help of AI within the areas of zero acceptance. The information on π^+n cross sections within complete kinematics coverage offers new opportunities to explore $\gamma_v pN^*$ electrocouplings.

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!

Inclusive electron scattering @10.6 GeV from CLAS12

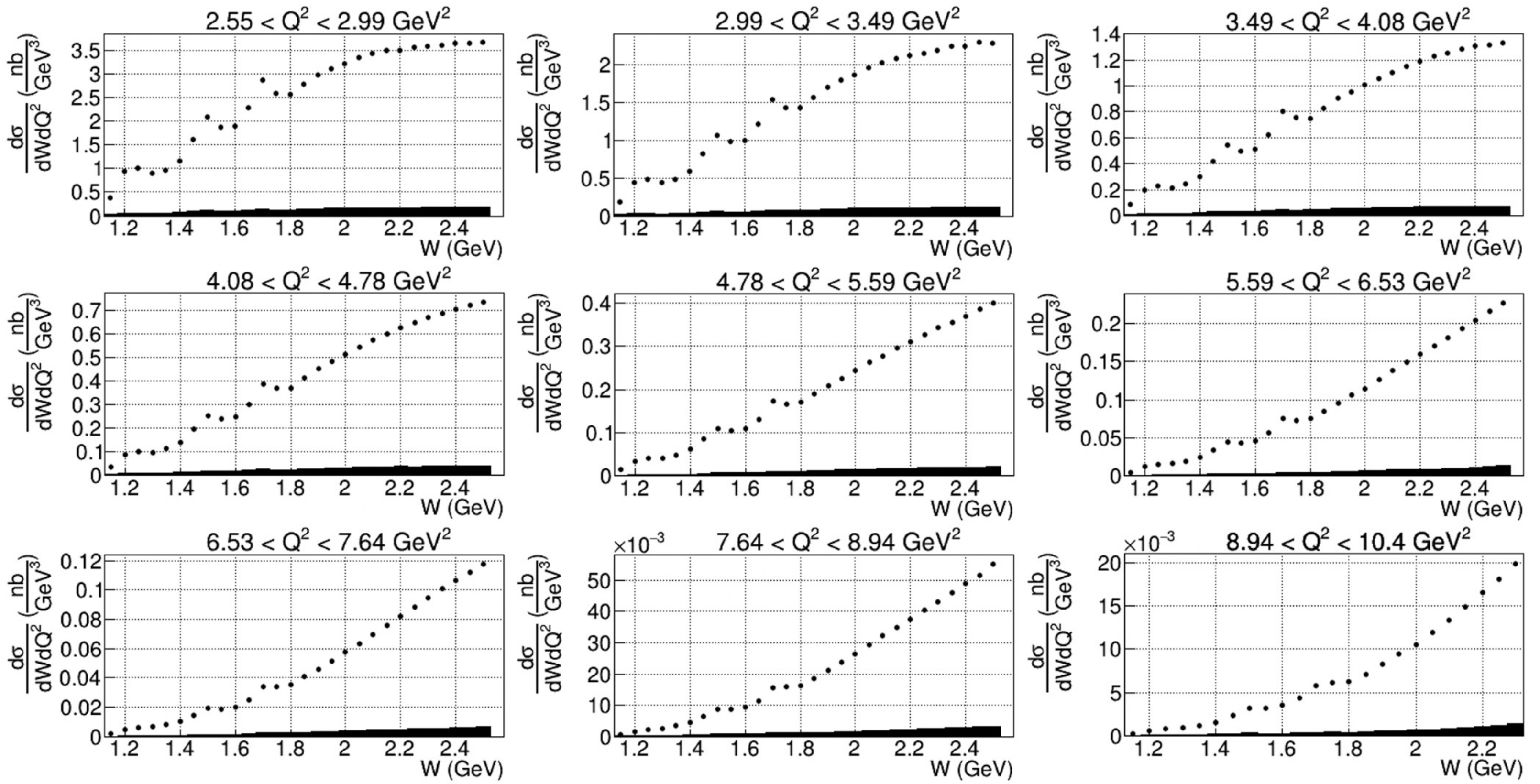


FIG. 30. Inclusive electron scattering cross sections determined from CLAS12 RG-A data. The statistical uncertainties on the CLAS12 data are shown but they are smaller than the data point size for the majority of the data points. The bin-by-bin systematic uncertainty is shown by the filled area at the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

Valerii Klimenko

Published by PRC
25 August 2025

Thank you for your attention!