ADVANCES IN N* PHYSICS WITH CLAS/CLAS12

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NUCLEUS-2020

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

Experiment

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
$\alpha_s \sim 1$

Theory

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
……

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

- $\gamma_v pN^*$ electrocouplings at photon virtualities Q^2 up to 5.0 GeV^2 for most of excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range up to 12 GeV^2 and down to 0.05 GeV^2 from CLAS12 data and explore N* structure evolution in the transition from the strong to the pQCD regimes
- explore hadron mass emergence by mapping out running quark mass in the transition from almost massless pQCD quarks to fully dressed constituent quarks

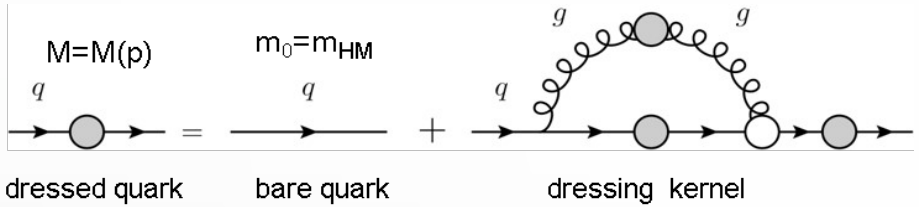
- **A unique source of information on many facets of strong QCD in generating N* states with different structural features**
- **Consistent results on dressed quark mass function from independent studies of different N* electroexcitations validate insight to EHM**

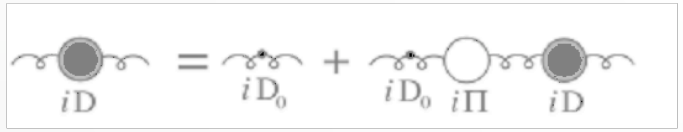
Review papers:

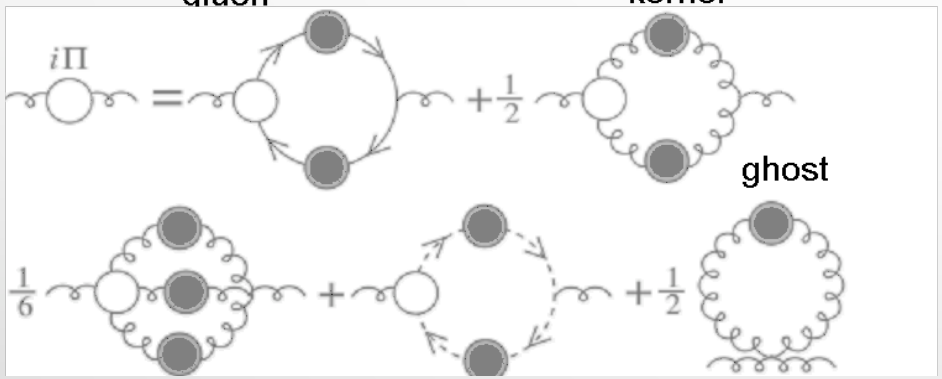
1. I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)
2. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)
3. C.D. Roberts, Few Body Syst. 59, 72 (2018)
4. D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)

Basics for Insight into EHM from Data on N* Electrocouplings

Emergence of Dressed Quarks and Gluons
D. Binosi et al, Phys. Rev. D 95, 031501 (2017)



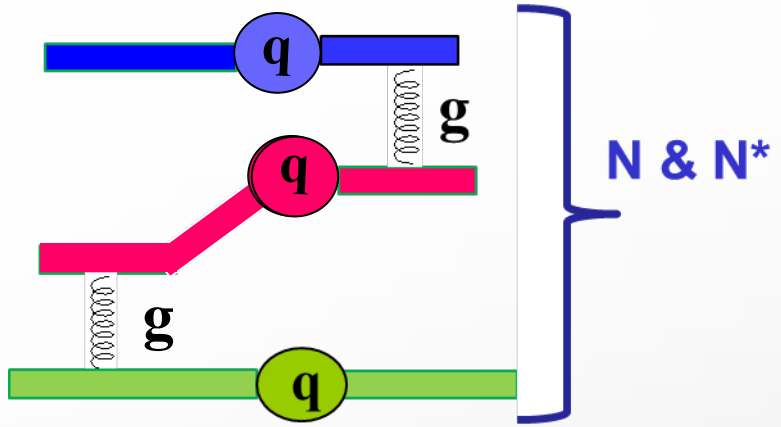




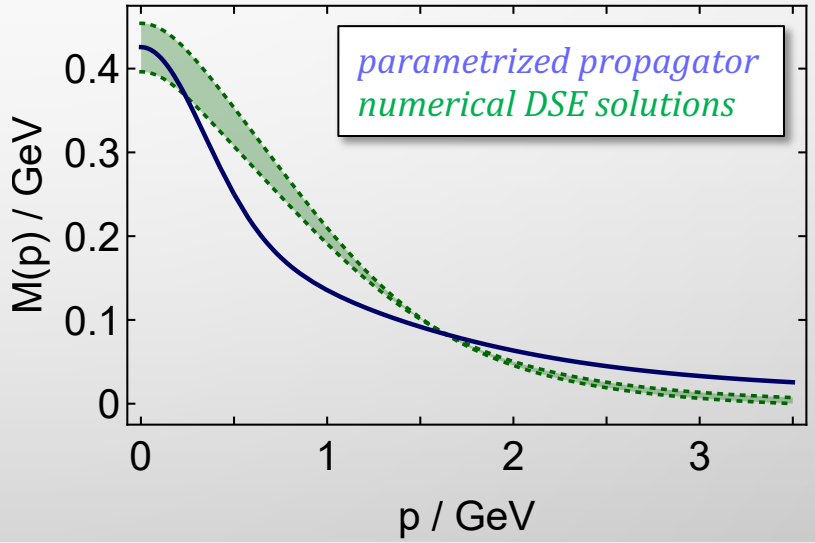
Data on N* electrocoupling are sensitive to the quark propagators and allow us to:

- **Map out quark mass function**
- **Constrain the ground nucleon and meson form factors, PDA, & PDF**

Dressed Quark Borromeo Binding in N/N*
J. Segovia et al., arXiv:1908:0572 [nucl-th]

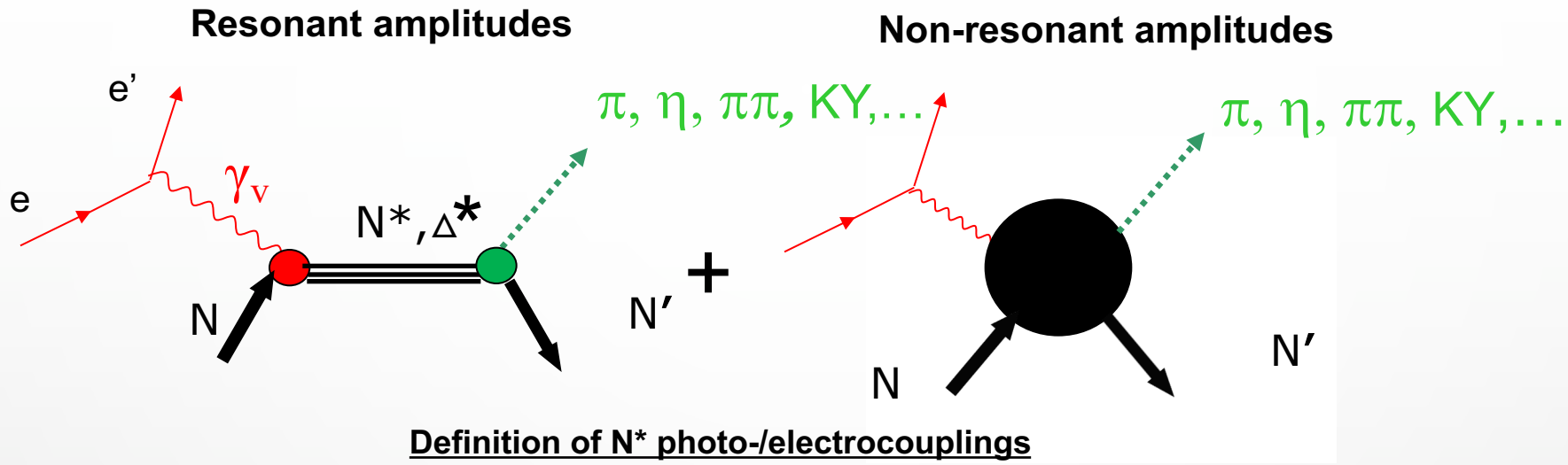


Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)



Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

Extraction of γ_vNN* Electrocouplings from Exclusive Meson Electroproduction off Nucleons



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

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

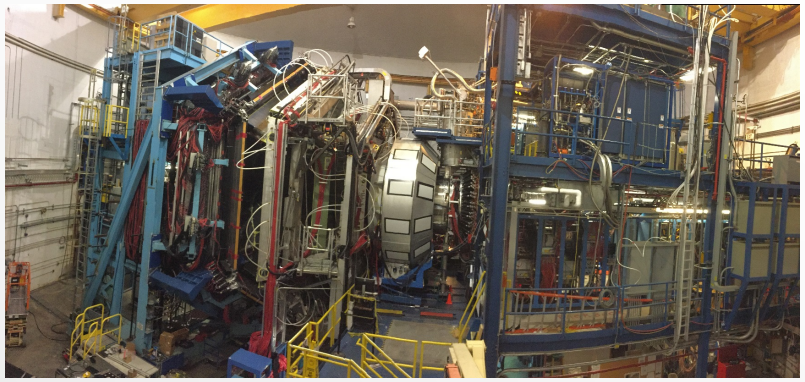
I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

$$\Gamma_\gamma = \frac{k^2_{\gamma_{N^*}}}{\pi}\frac{2M_N}{(2J_r+1)M_{N^*}}\left[|A_{1/2}|^2+|A_{3/2}|^2\right]$$

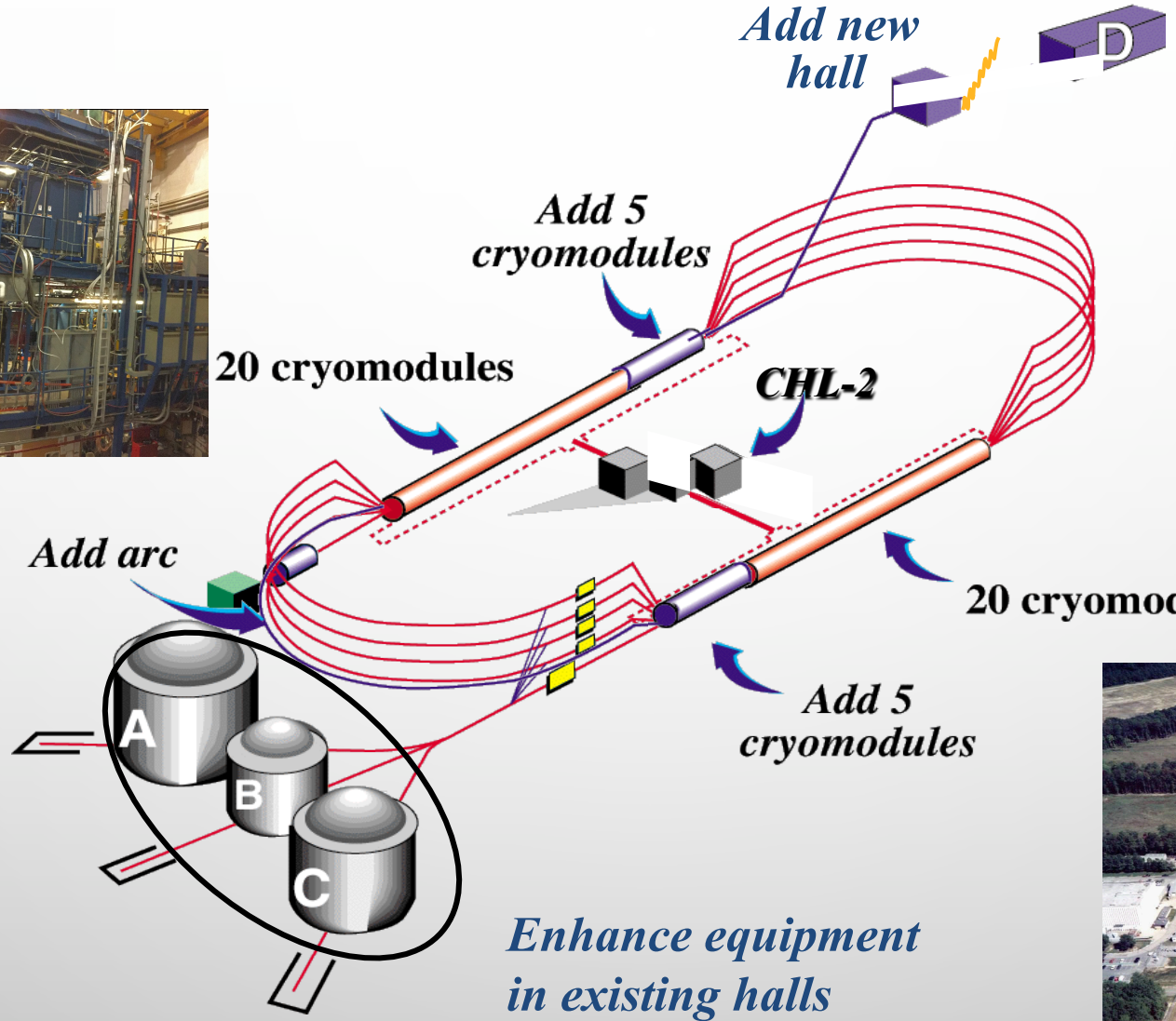
- **Consistent results on γ_vpN* electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.**

Jefferson Lab (Newport News, VA, USA)

CLAS12 in Hall B

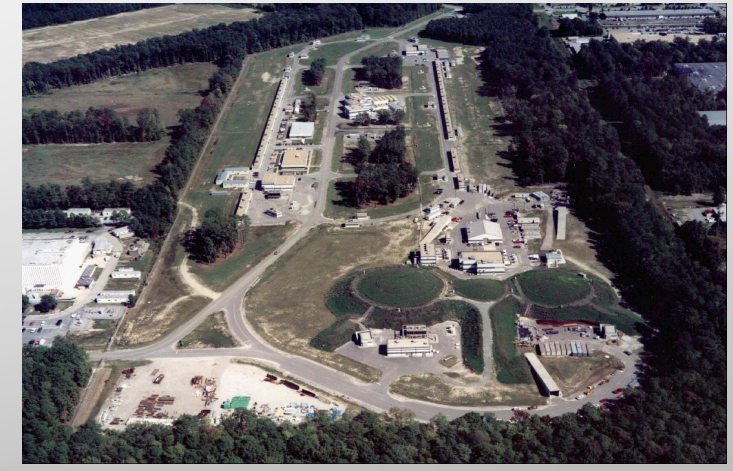


CLAS (1998-2012)



Enhance equipment in existing halls

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



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}** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$**
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

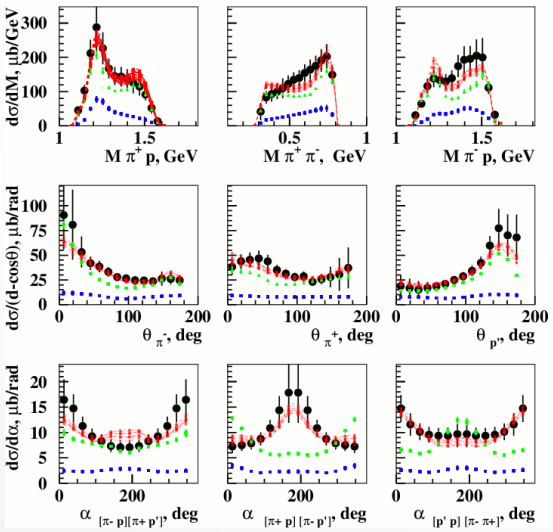
Over 130,000 data points!

Almost full coverage of the final hadron phase space

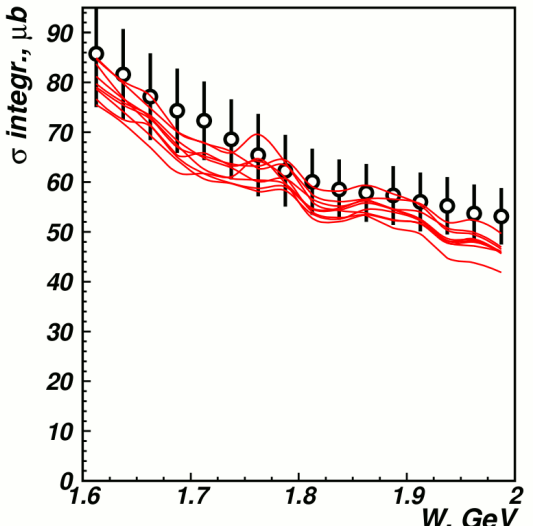
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

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

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 χ^2/d.p.<1.30

Resonances	$A_{1/2}\times10^3$ from $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{1/2}\times10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{1/2}\times10^3$ multichannel analysis [7] $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ PDG ranges $\mathrm{GeV}^{-1/2}$	$A_{3/2}\times10^3$ multichannel analysis [7] $\mathrm{GeV}^{-1/2}$
$\Delta(1620)1/2^-$	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

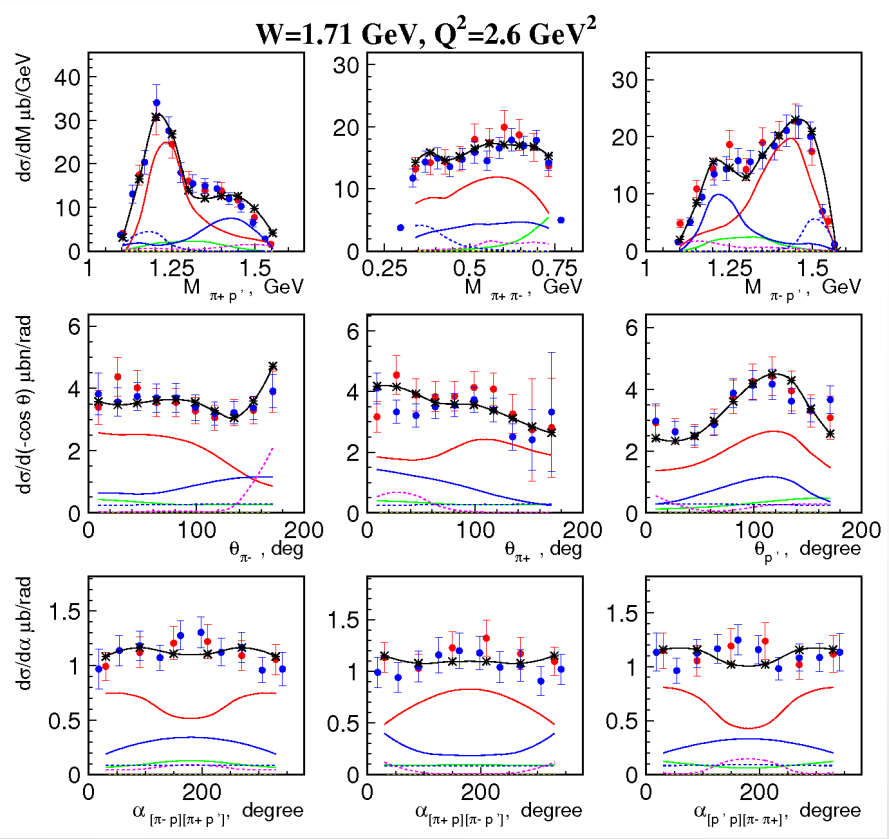
In 2019 partial update of the Review of Particle Physics the entries on photocouplings and Nππ decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-p$ photoproduction with CLAS.

ACCESSING RESONANCE ELECTROCOUPLINGS FROM THE $\Pi^+\Pi^-$P DIFFERENTIAL ELECTROPRODUCTION OFF PROTONS CROSS SECTIONS

Contributing mechanisms seen in the data

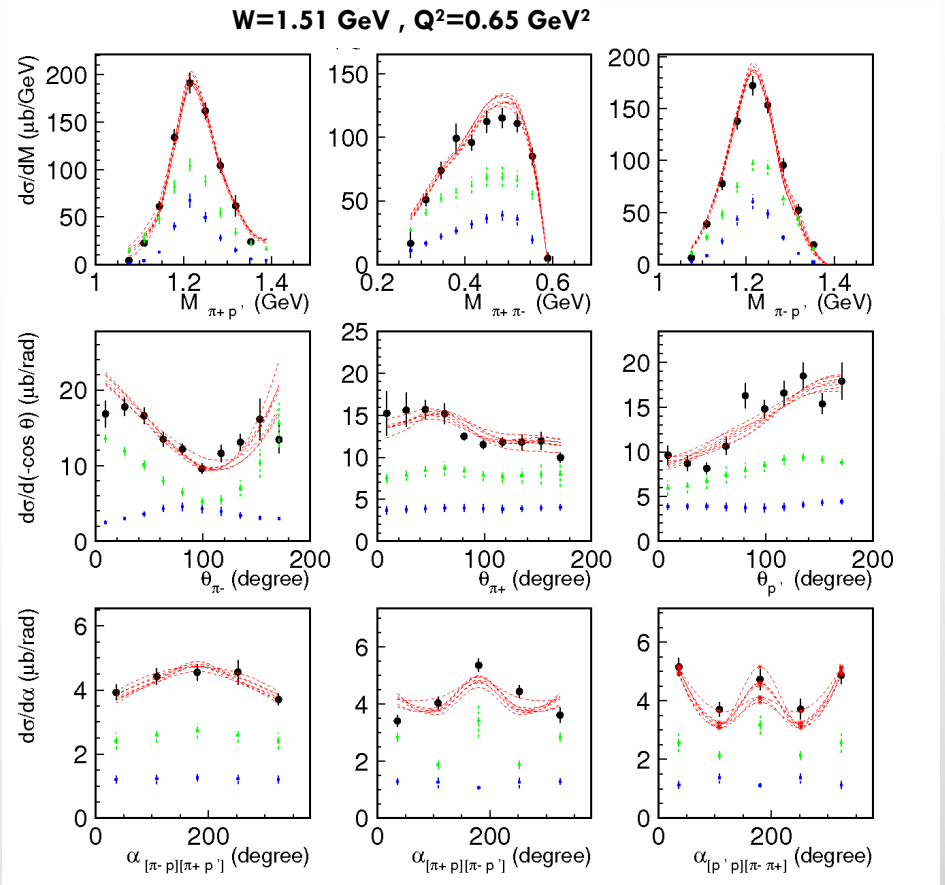
E. Isupov et al., CLAS Coll., Phys. Rev. C96, 025209 (2017)

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

$\pi^+\Delta^0$

$\pi^+ N(1520)3/2^-$

$\pi^+ N(1680)5/2^+$

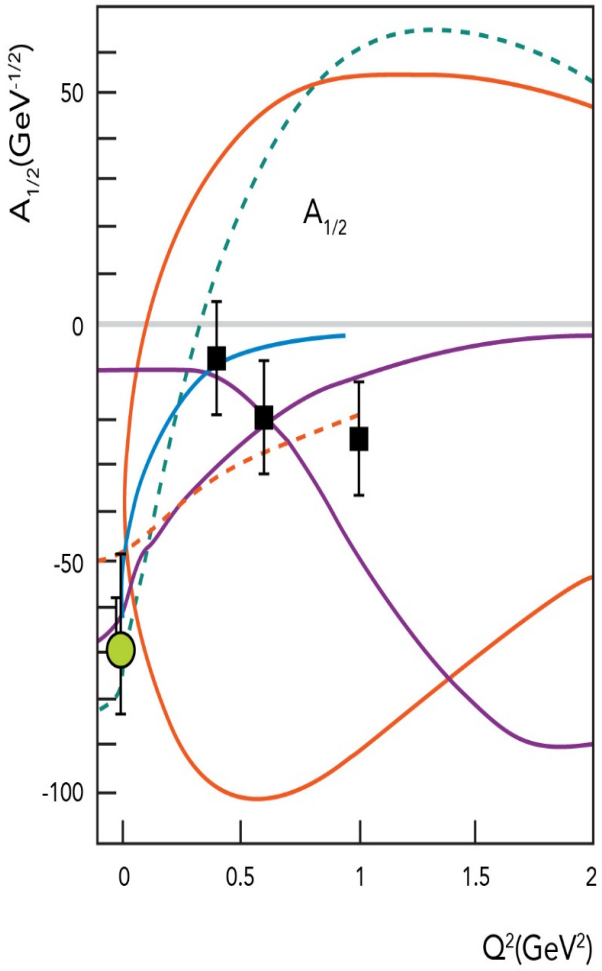
data fit within JM under variations of both resonant and background parameters

background cross sections

resonant cross sections

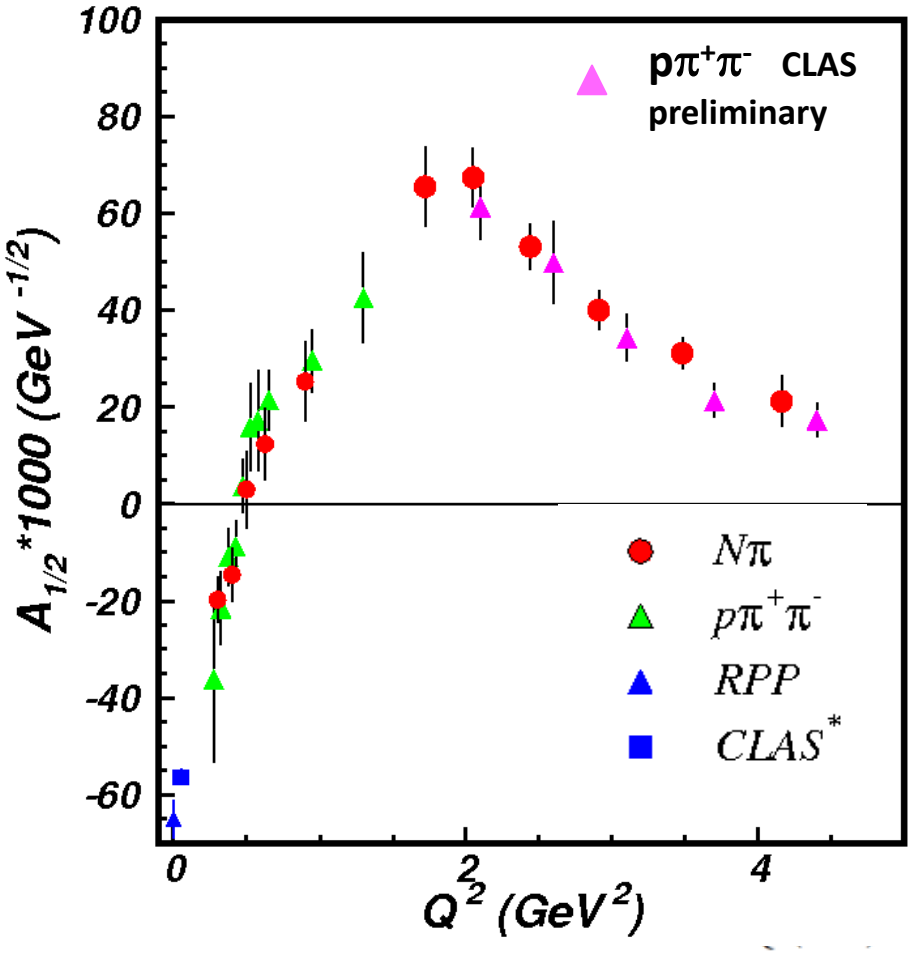
Roper Resonance in 2002 & 2019

2002



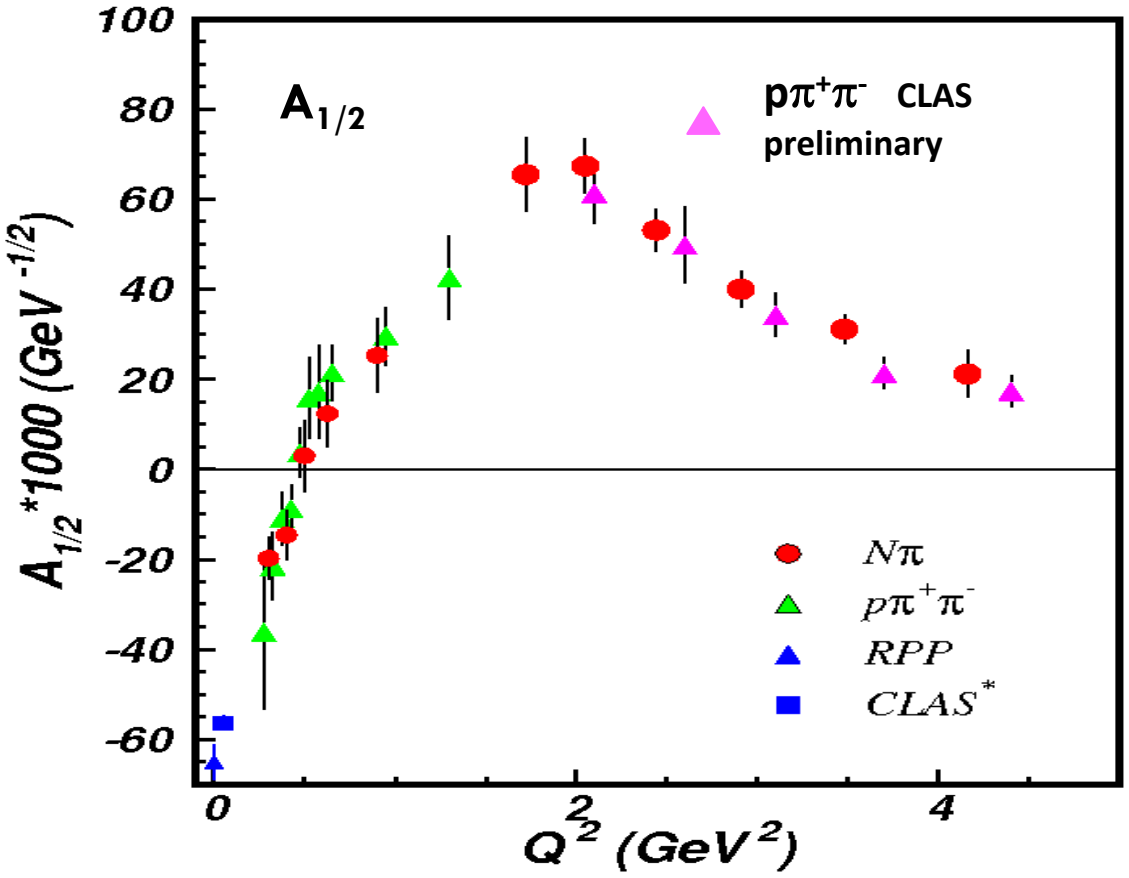
V. Burkert, Baryons 2002

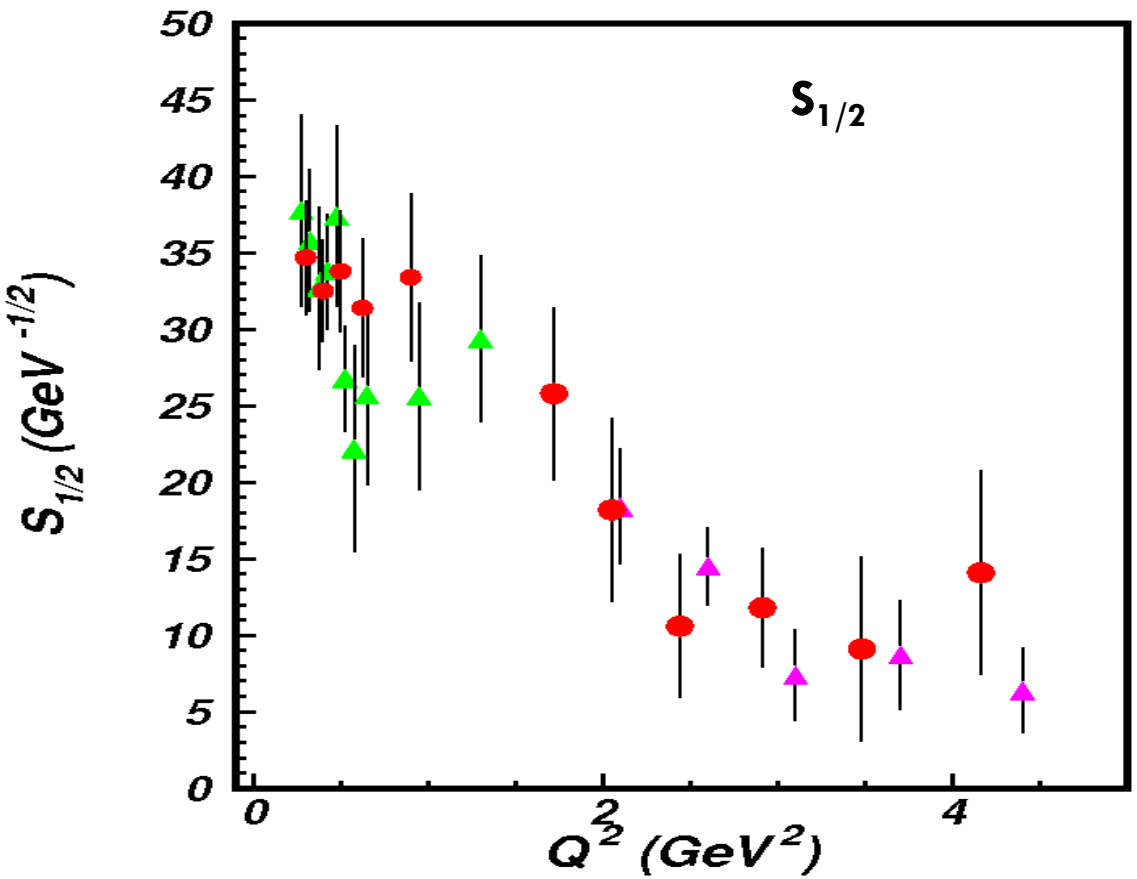
2019



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

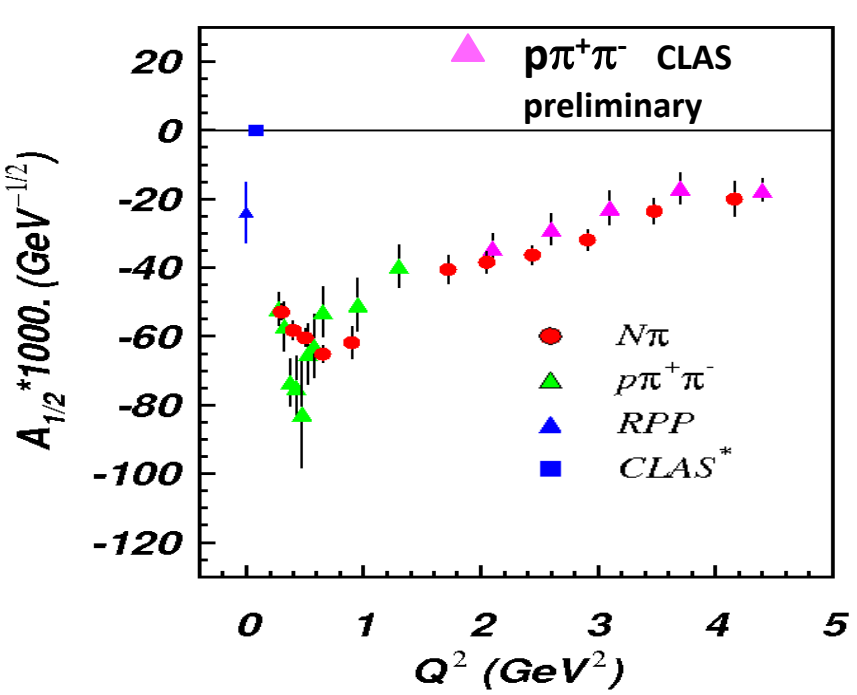
Electrocouplings of N(1440)1/2$^+$ from Nπ and $\pi^+\pi^-$p Electroproduction off Proton Data

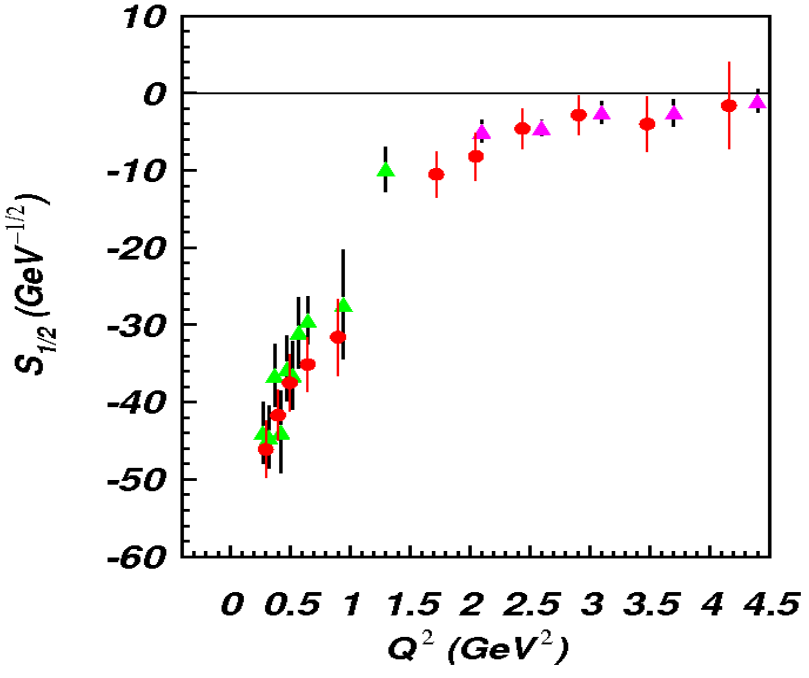


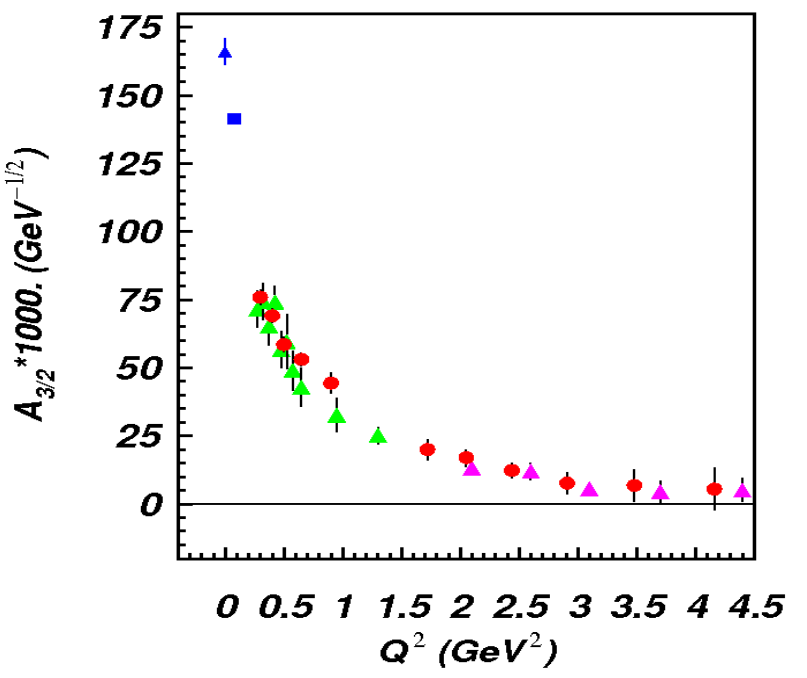


Consistent results on N(1440)1/2$^+$ electrocouplings from the independent studies of two major Nπ and $\pi^+\pi^-$p electroproduction off proton channels with different non-resonant contributions allows us to determine the systematic uncertainties of the results in a nearly model-independent way.

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

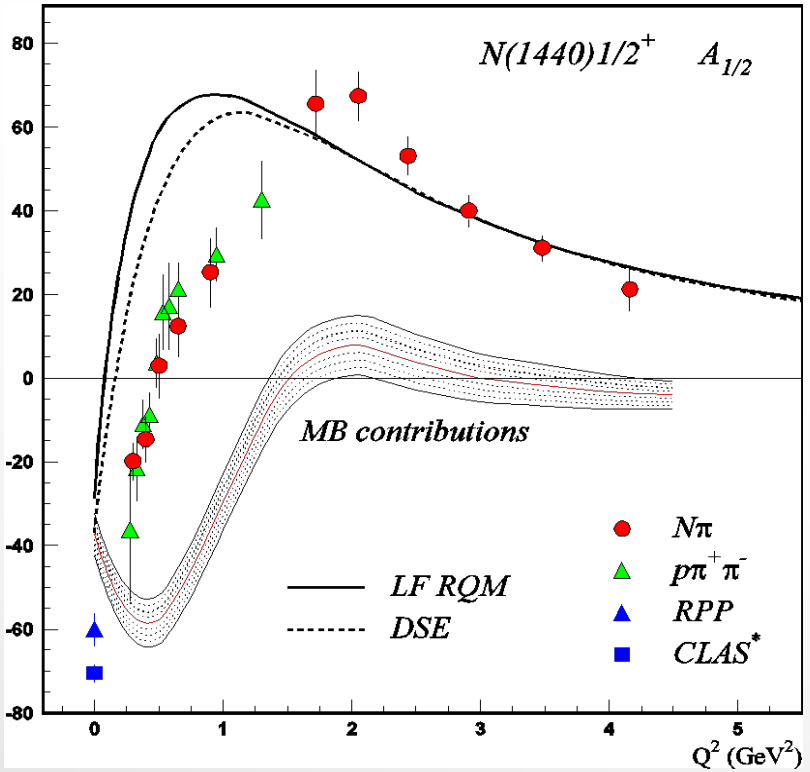




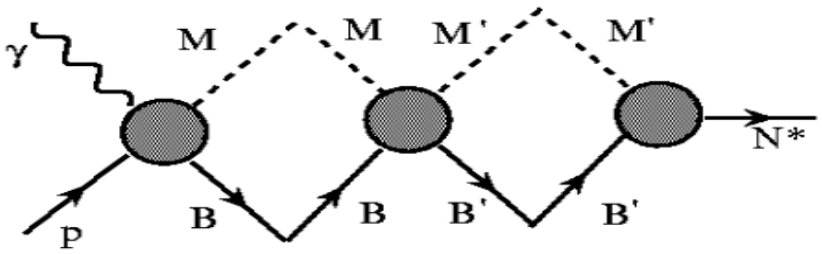


Consistent results from Nπ and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances support the capabilities of the developed reaction models for credible extraction of resonance electrocouplings from independent analyses of both Nπ and $\pi^+\pi^-$p electroproduction.

Resolving Puzzle of the Roper Structure



The mechanisms of the meson-baryon dressing



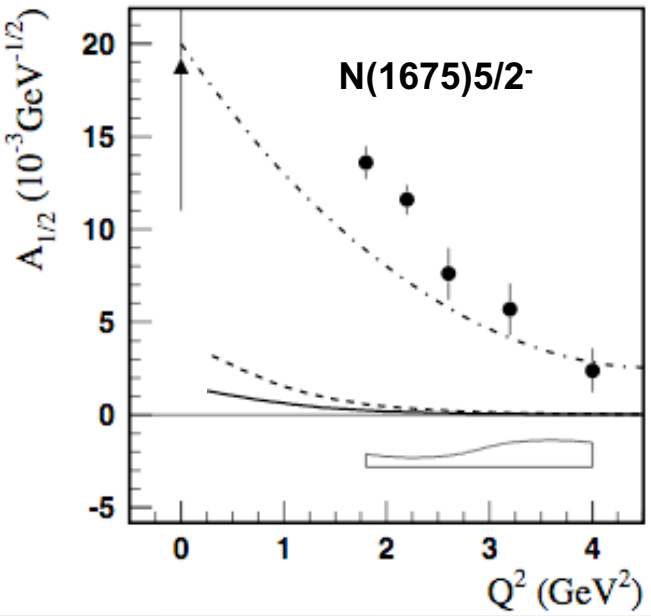
CLAS data in the range of $Q^2<5.0$ GeV^2 reveal the structure of $N(1440)1/2^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

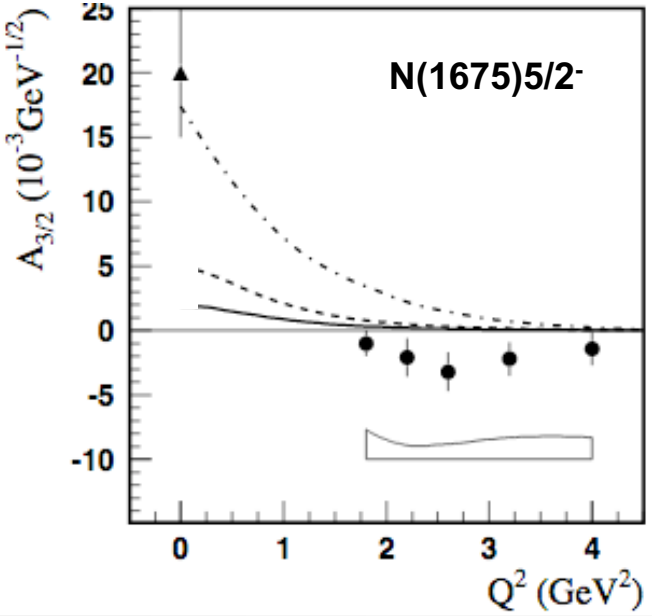
LF RQM-Light Front Relativistic Quark Model: V.D. Burkert, I.G. Aznauryan, Phys . Rev. C85, 055202 (2012); Phys. Rev. C95, 065207 (2017)

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)

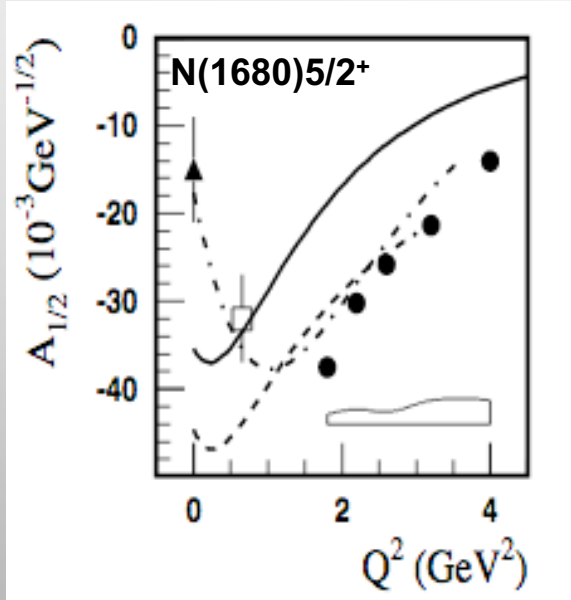
Electrocouplings of High-Lying Resonances from π^+n Electroproduction off Proton Data

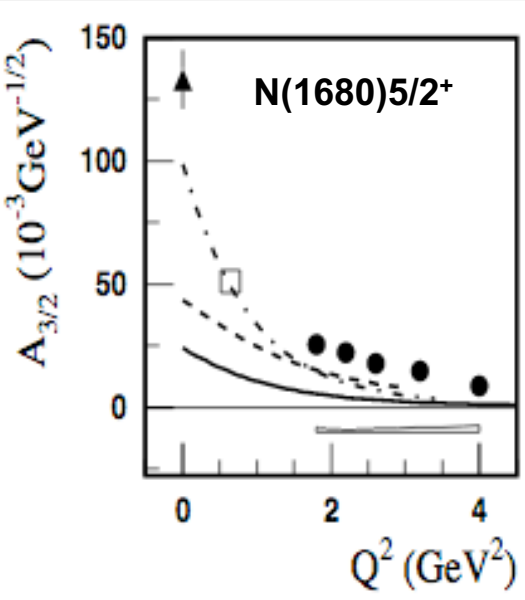


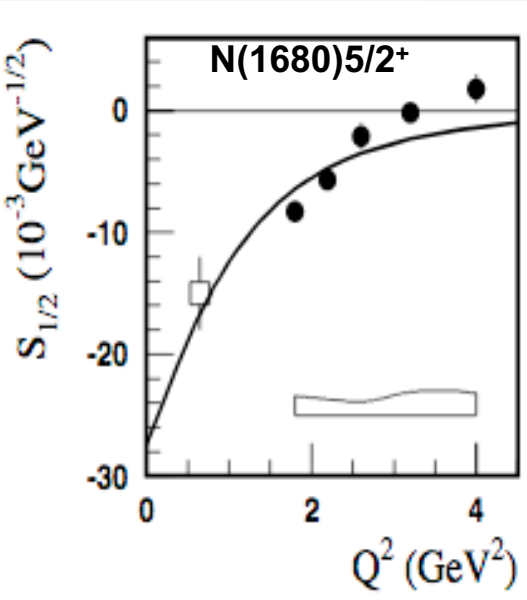


K.Park et al., CLAS Collab.,
Phys. Rev. C91, 045203 (2015).

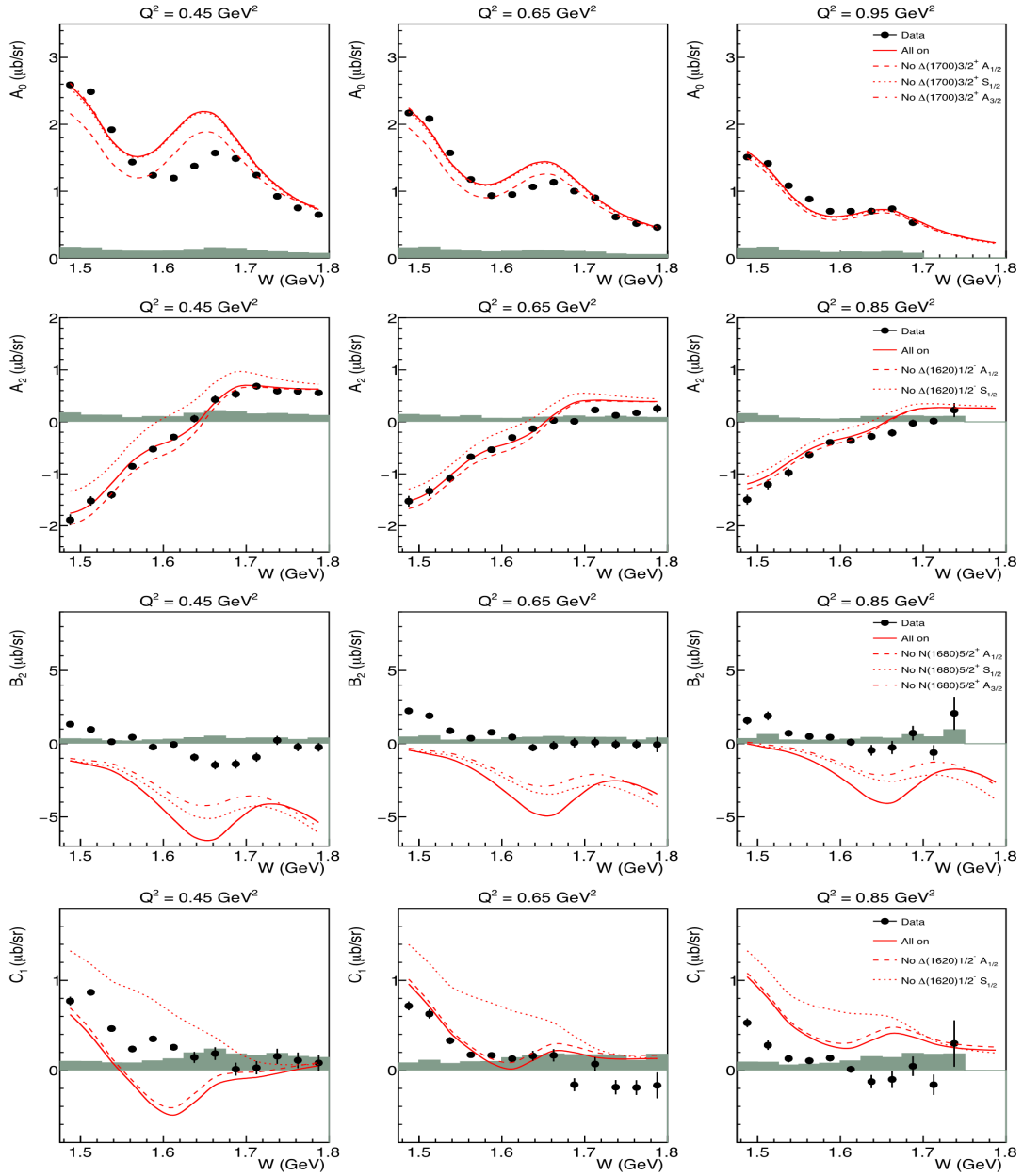
The first results on electrocouplings of N(1675)5/2$^-$, N(1680)5/2$^+$, and N(1710)1/2$^+$ resonances have Become available at 2.0<Q2<5.0 GeV^2 from the CLAS $n\pi^+$ electroproduction data







First Results on $\pi^0 p$ Electroproduction in the Third Resonance Region



Legendre moments

$\Delta(1700)3/2^-$ electrocouplings are turned on/off

$\Delta(1620)1/2^-$ electrocouplings are turned on/off

$N(1680)5/2^+$ electrocouplings are turned on/off

$\Delta(1620)1/2^-$ electrocouplings are turned on/off

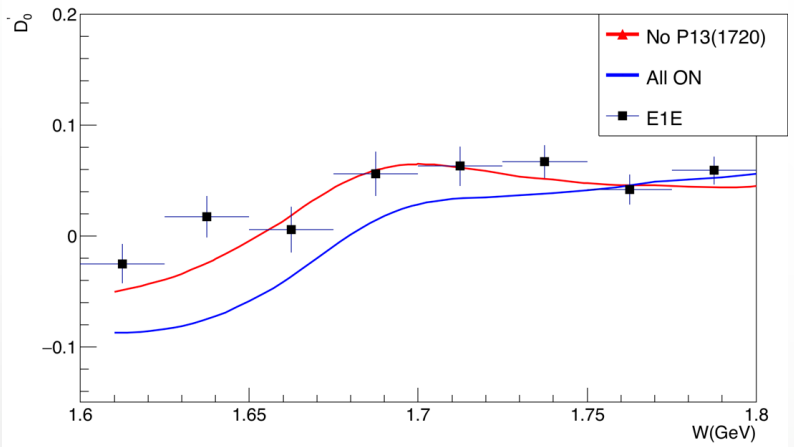
N.Markov et al., CLAS Collab., Phys. Rev. C101, 015208 (2020).

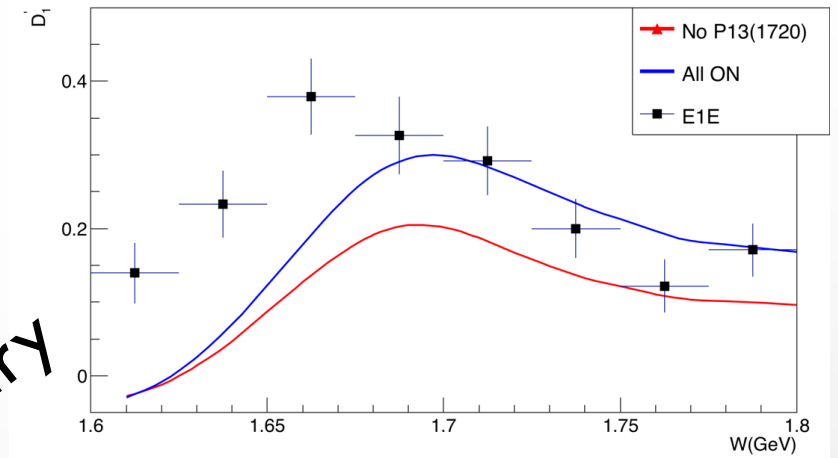
Legendre moments demonstrate the sensitivity to electrocouplings of excited nucleon states in the third resonance region.

Combined studies of $p\pi^0$ and $n\pi^+$ electroproduction channels are needed to determine electrocouplings of the resonances in the third resonant region.

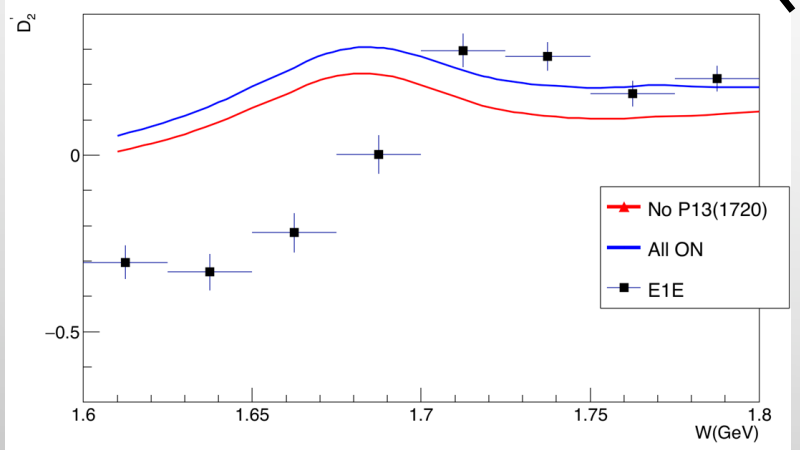
LEGENDRE MOMENTS OF $\sigma_{LT'}$ FOR Π^0P ELECTROPRODUCTION IN THE 3 RESONANCE REGION

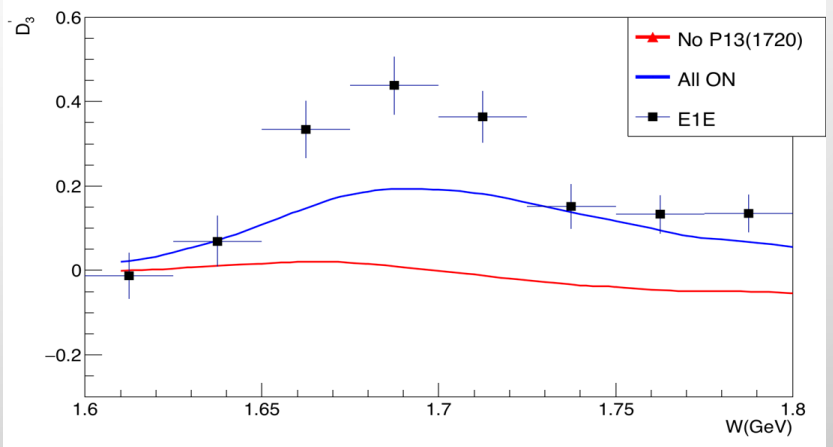
$0.4<Q^2<0.6$ GeV^2





Preliminary

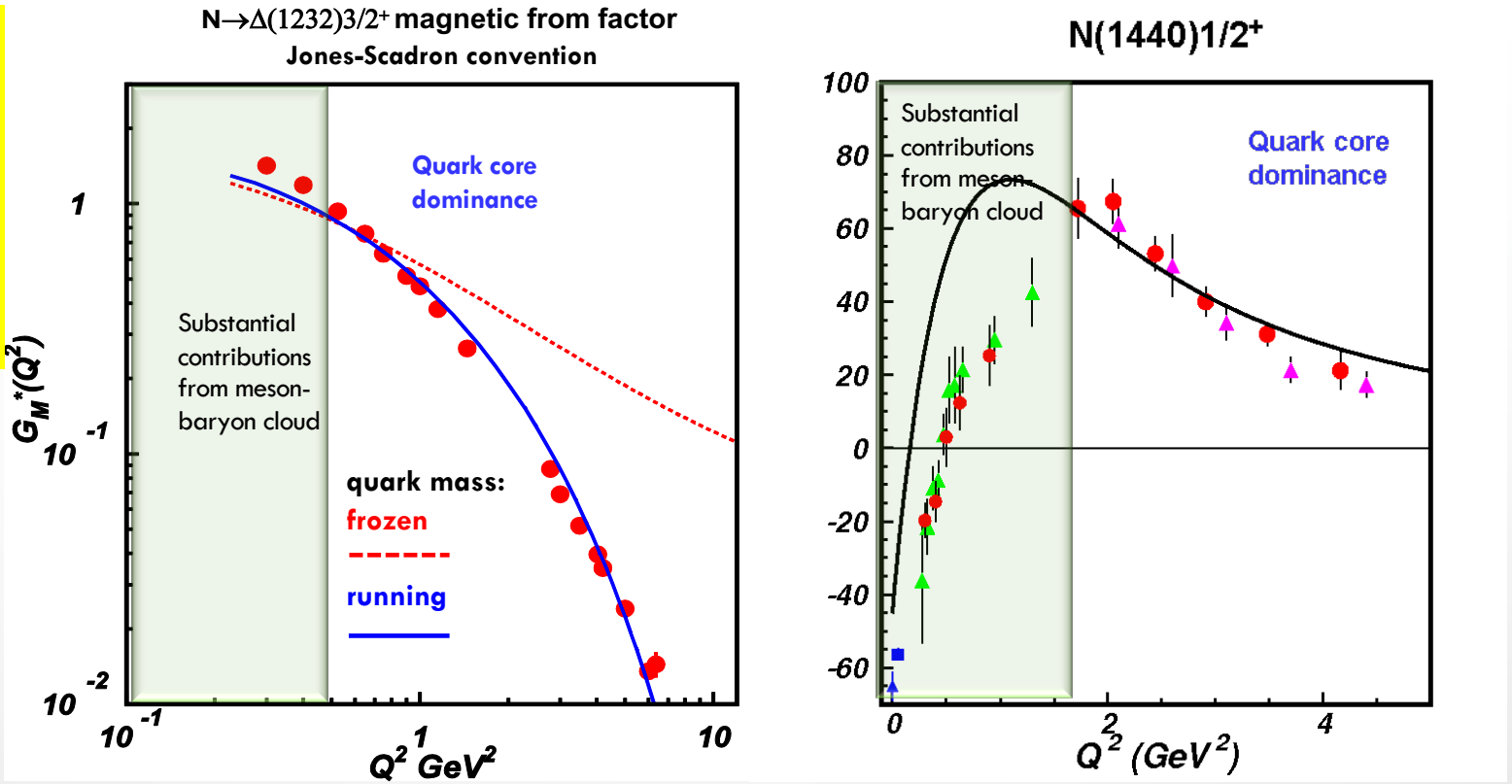




Combined studies of $p\pi^0$ and $n\pi^+$ electroproduction channels are needed to determine electrocouplings of the resonances in the third resonant region.

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 $Q^2>2.0$ 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. $\gamma_v pN^*$ 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.

Hadron Structure Experiments (E12-09-003, E12-06-108A)

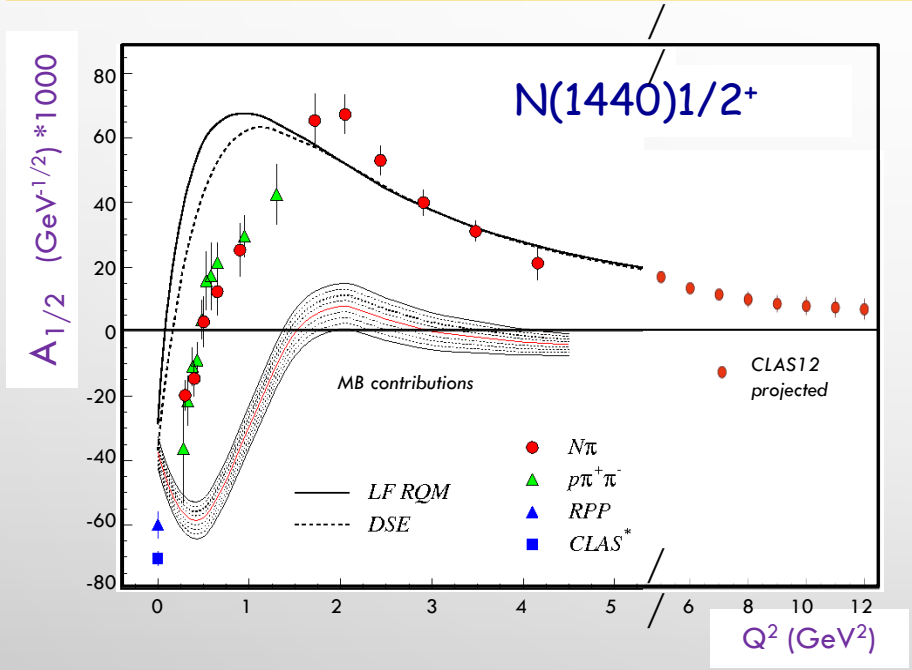
N* electroexcitation studies with CLAS12 will address the critical open questions:

How is >98% of hadron mass generated and how is it related to Dynamical Chiral Symmetry Breaking?

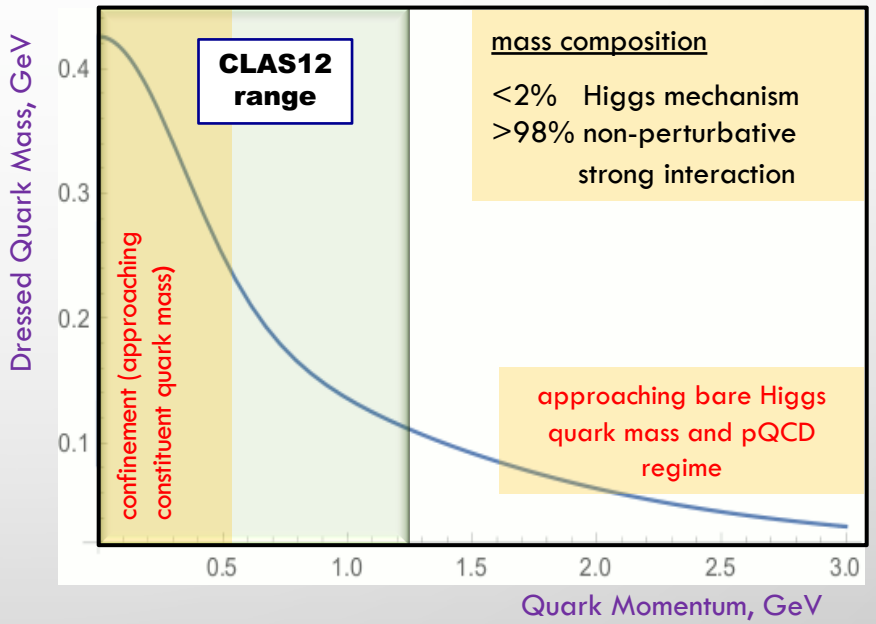
What is the behavior of QCD's running coupling at infrared momenta?

Mapping out the quark mass function from CLAS12 data on the $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances for Q^2:[5:12] GeV^2 will allow us to explore how the dominant part of hadron mass is generated in the transition from the strong QCD to pQCD regimes

Chart the QCD running coupling from the results on the electrocouplings of orbital excited resonances



CLAS results vs. theory expectations with running quark mass

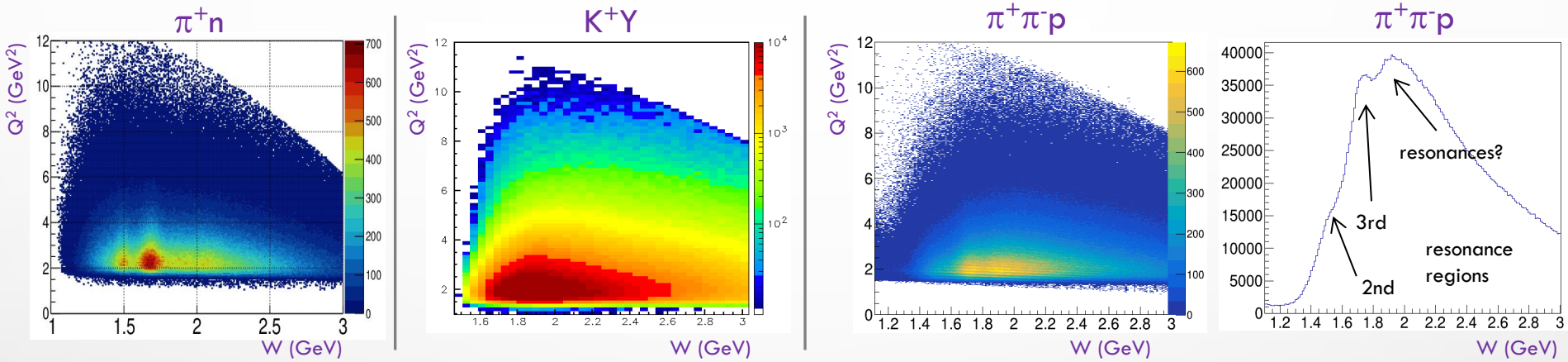


V.D. Burkert, C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)
D.S. Carman, K. Joo, V.I. Mokeev, FBS 61, 29 (2020)

N* Electroexcitation to high Q^2 with CLAS12

Expected outcome: The first results on the $\gamma_v pN^*$ electrocouplings of most N* states from data in the range $W < 3.0$ GeV and $Q^2 > 5.0$ GeV^2 for exclusive reaction channels: πN, $\pi\pi N$, KY, K^*Y, KY^*

kinematic coverage for RG-A data @ 10.6 GeV



Expected events per Q^2/W bin for full RG-A dataset

π^+n			$K^+\Lambda$ & $K^+\Sigma^0$					$\pi^+\pi^-p$		
Q^2 [GeV^2]	W [GeV] 1.5-1.55	W [GeV] 1.7-1.75	Q^2 [GeV^2]	W_Λ [GeV] 1.7-1.75	W_Σ [GeV] 1.7-1.75	W_Λ [GeV] 1.9-1.95	W_Σ [GeV] 1.9-1.95	Q^2 [GeV^2]	W [GeV] 1.7-1.75	W [GeV] 1.9-1.95
			1.4-2.2	63417	6012	66564	33170			
			2.2-3.0	72144	5364	77443	28720			
5.2-5.8	15272	4175	3.0-4.0	52358	3945	51991	18936	5.2-5.8	2813	2808
5.8-6.5	10737	2637	4.0-5.0	24833	3103	26690	5925	5.8-6.5	1822	1969
6.5-7.2	7367	1684	5.0-6.0	11203	1598	11160	2642	6.5-7.2	1159	1294
7.2-8.1	4567	1290	6.0-7.0	5566	648	6300	943	7.2-8.1	661	924
8.1-9.1	2742	540	7.0-8.0	2606	338	3276	633	8.1-9.1	364	414
9.1-10.5	1453	194	8.0-9.0	1440	244	936	86	9.1-10.5	118	179

This will extend the Q^2 range of the $\gamma_v pN^*$ electrocouplings to 8-10 GeV^2 for each of these channels – *the data collected so far will limit us to 6-8 GeV^2*

CONCLUSIONS

- **High-quality meson electroproduction 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 π^+n, π^0p, ηp, and $\pi^+\pi^-p$ electroproduction channels. Resonance electrocouplngs will become available for N* in the mass range <2.0 GeV and at $Q^2<5.0$ GeV^2 (CLAS) and at $Q^2<12$ GeV^2 (CLAS12).**

- **Physics analyses of the $\gamma_v pN^*$ electrocouplings have revealed the structure of excited nucleons as a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud, offering the new avenue on exploration of the emergence of deconfined mesons and baryons in outer cloud from dressed quarks and gluons confined within quark core.**

- **CLAS12 is the only facility in the world capable of obtaining the 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.**

- **The expected results will allow us to map out the dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected,**
  addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.

THANK YOU FOR YOUR ATTENTION!