Структура протона
Нуклонные резонансы

Е.Л. Исупов

Эксперименты Ферми по рассеянию пионов на протонах. Дельта-резонансы.

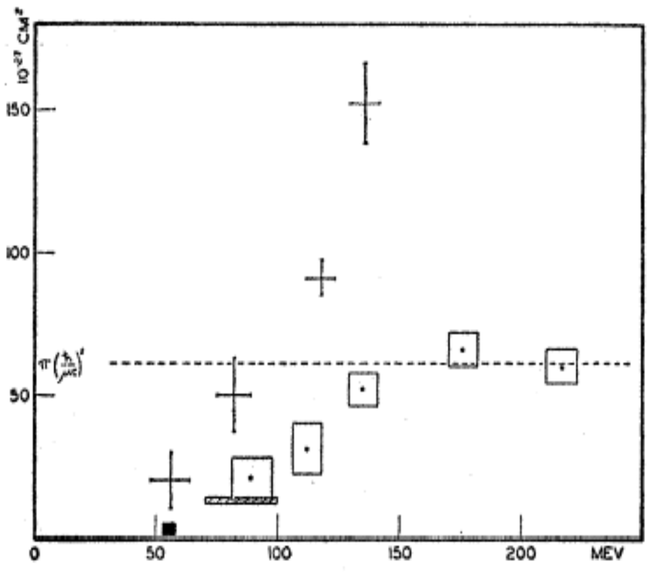
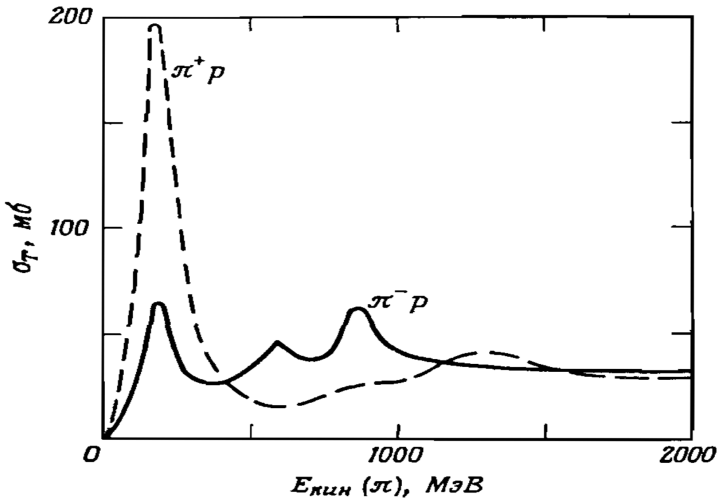


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the

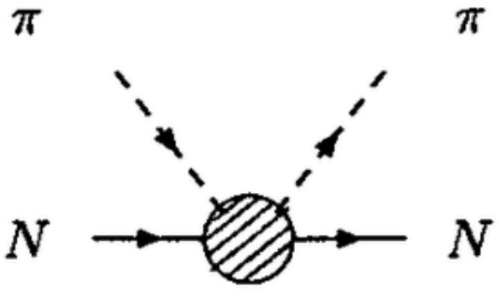


$$\pi^+ p \to \pi^+ p$$
$$\pi^- p \to \pi^- p$$

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

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

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



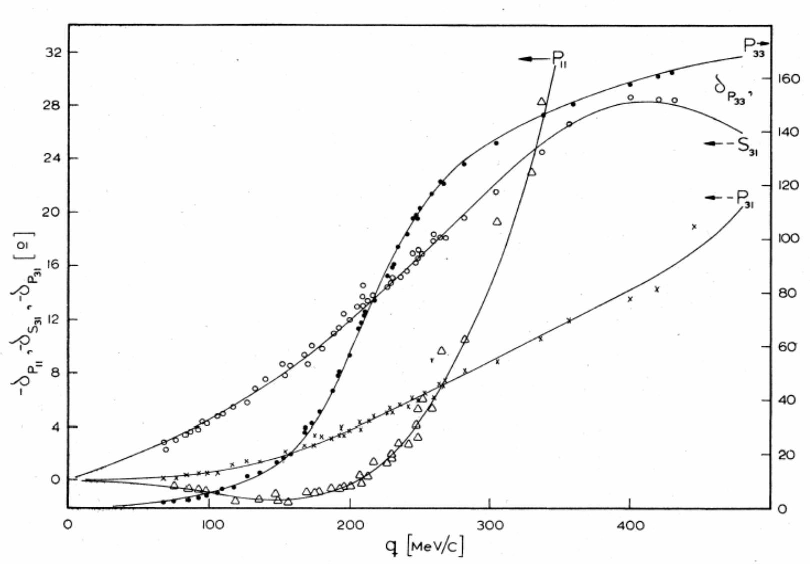


FIG. 1. Phase shifts in degrees for S_{31}, P_{11}, P_{31}, and P_{33} waves. The points have been taken from Refs. 11–17.

Фазовый анализ

New era in electromagnetic nuclear physics

- Electrons and photons are perfect tools to explore the properties of strongly interacting systems.
- In the past ~ 20 - 30 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

Baryon Resonances and SU(6) x O(3)

$|\text{Baryon}\rangle : \ \alpha\, |qqq\rangle + \beta\, |qqq(q\bar{q})| + \gamma\, |qqqG\rangle + ..$

3 Flavors: $\{u,d,s\} \longrightarrow SU(3)$

$\{qqq\}: \quad 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Quark spin $s_q = ½ \longrightarrow SU(2)$

$\{\vec{q}\vec{q}\vec{q}\}: \quad 6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20$

SU(6) multiplets decompose into flavor multiplets:

$56 = {}^4 10 \oplus {}^2 8$

$70 = {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$

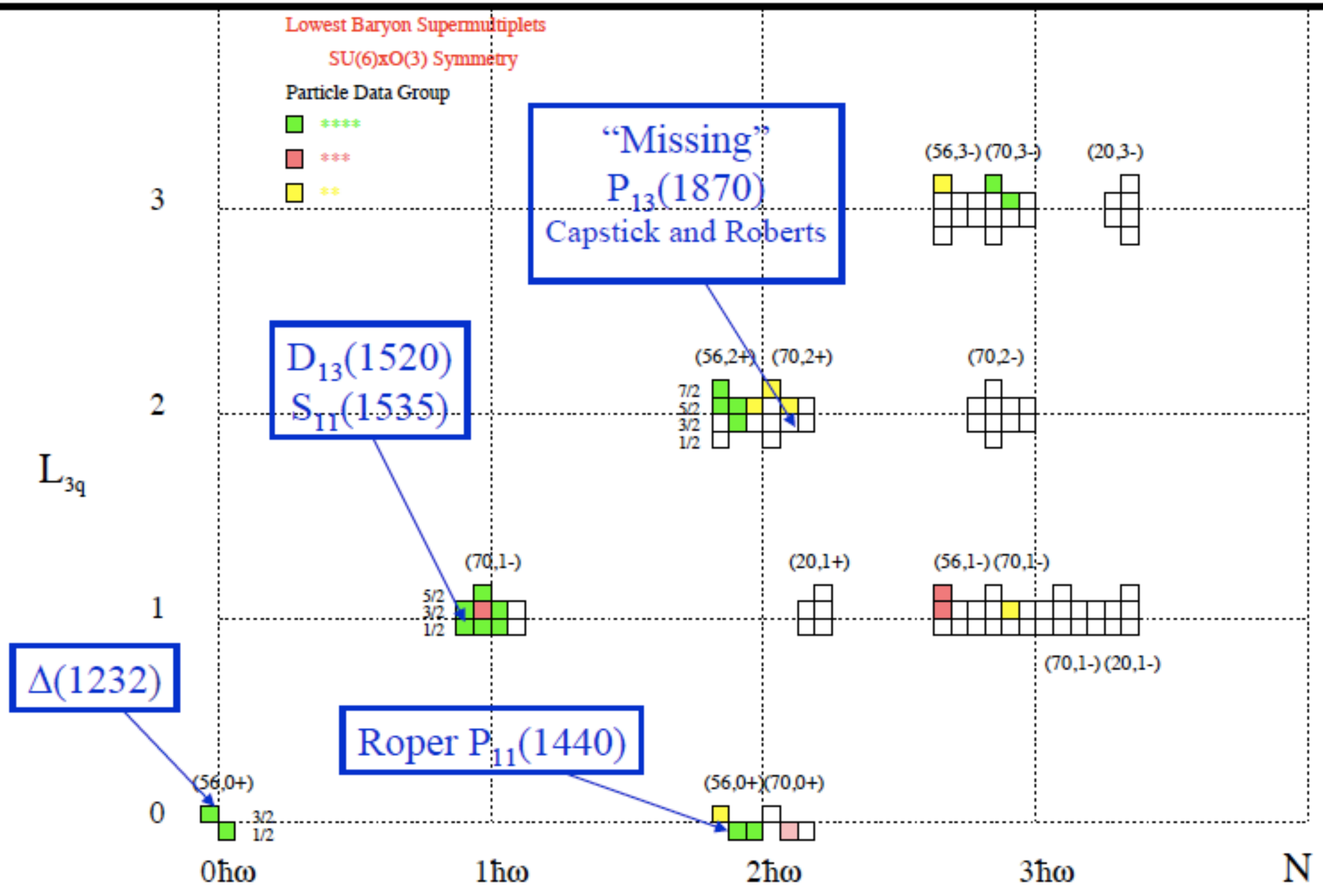
$20 = {}^2 8 \oplus {}^4 1$

O(3)

Baryon spin: $\vec{J} = \vec{L} + \Sigma \vec{s}_i$

parity: $P = (-1)^L$

SU(6) x O(3) Classification of Baryons

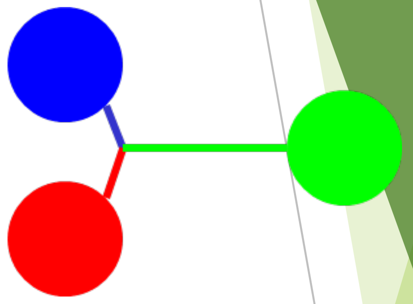


"Missing" Resonances?

Problem: symmetric CQM predicts many more states than observed (in πN scattering)

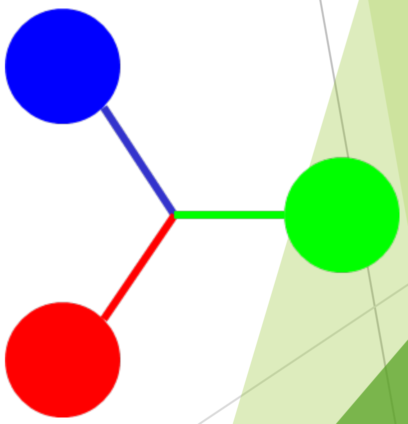
Possible solutions:

1. **diquark model**



- fewer degrees-of-freedom
- open question: mechanism for q^2 formation?

2. **not all states have been found**

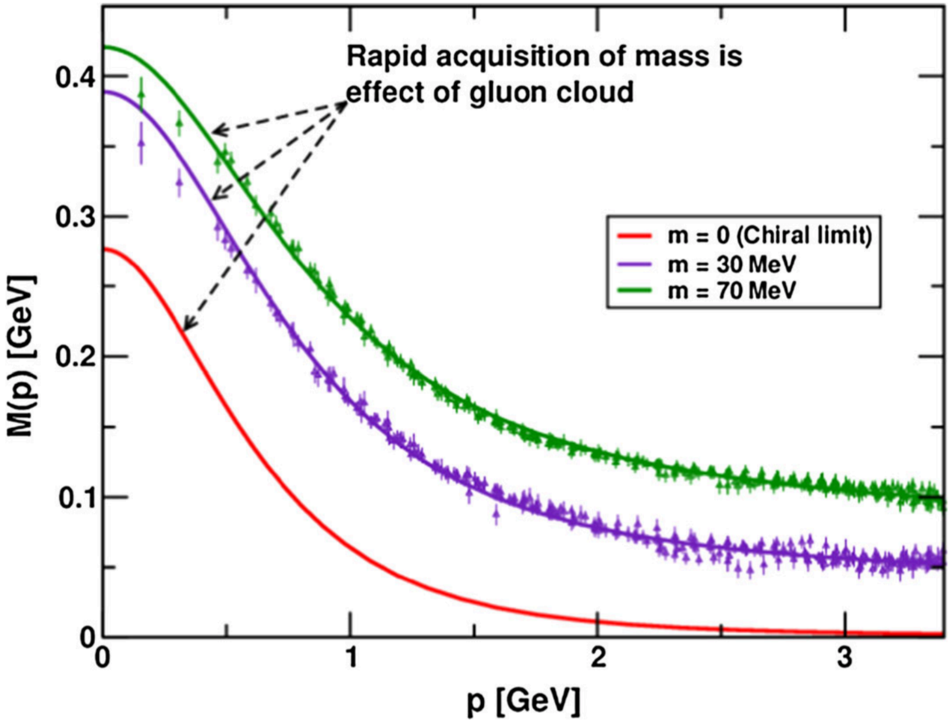


- possible reason: decouple from πN-channel
- model calculations: missing states couple to
  $\pi\pi N$ ($\pi\Delta$, ρN), ωN, KY

γ coupling not suppressed → electromagnetic excitation is ideal

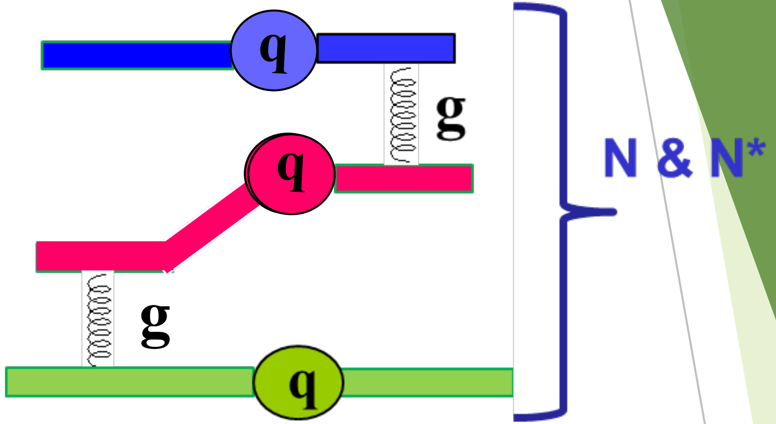
Excited Nucleon States and Insight into Strong QCD Dynamics

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)

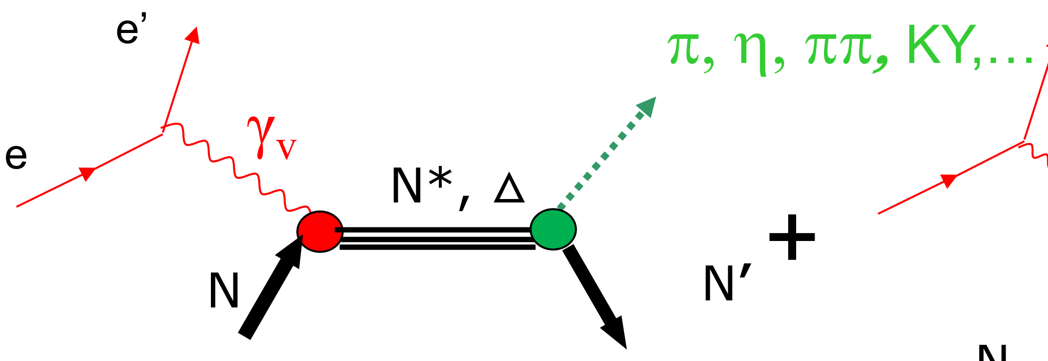


N* structure studies address:

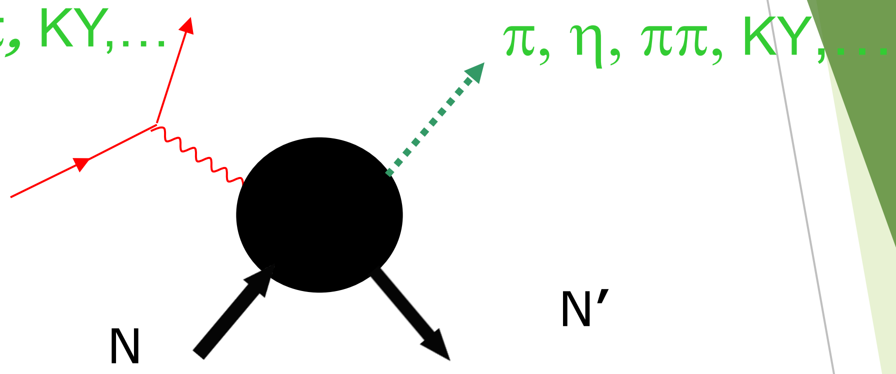
- Nature of > 98% of hadron mass
- Emergence of the ground nucleon parton distributions in 1D and 3D

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

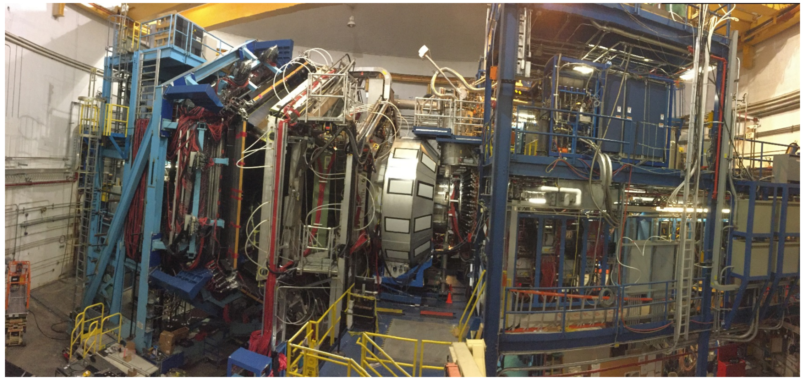
I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

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

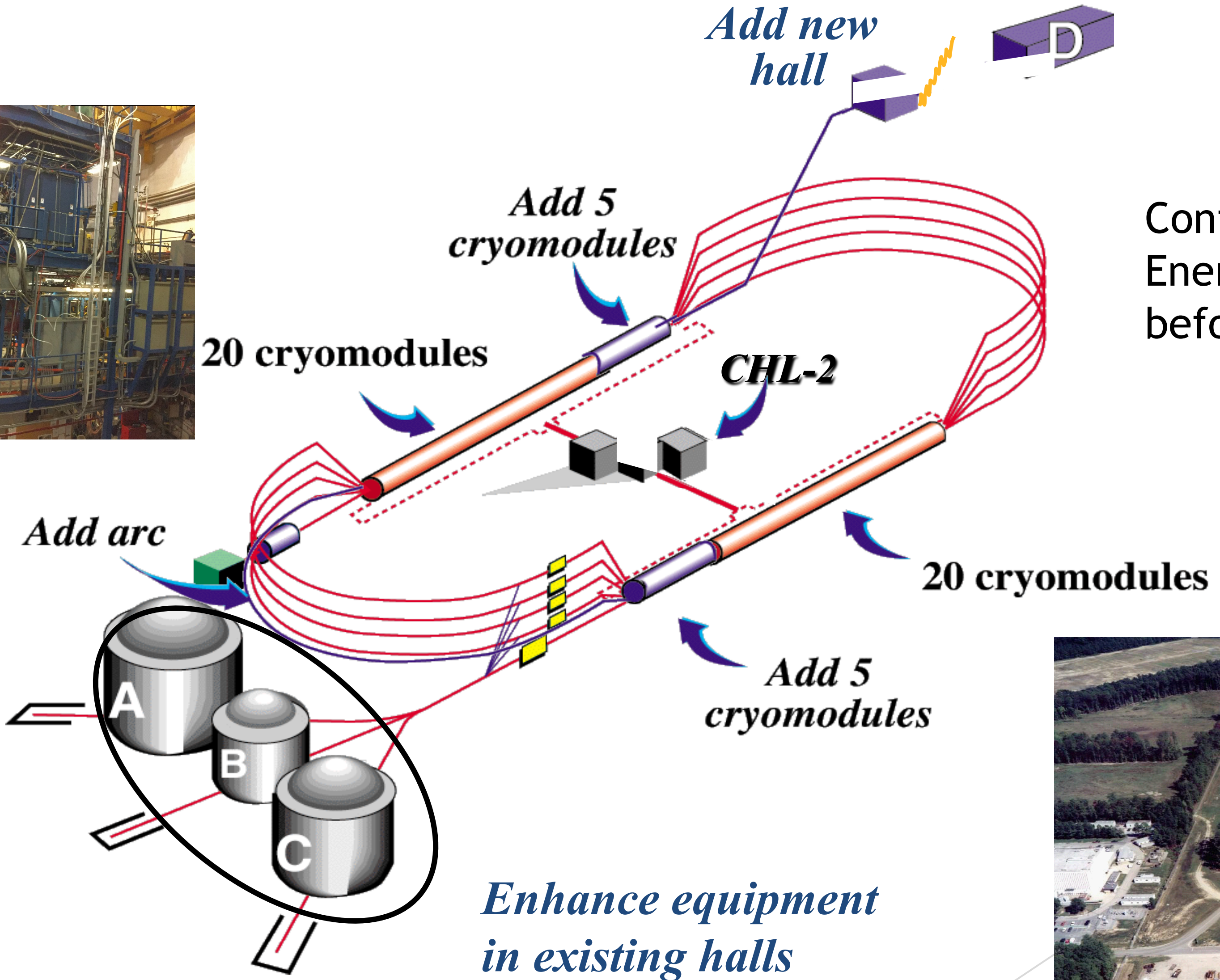
- **Consistent results on $\gamma_v pN^*$ electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.**

Jefferson Lab (Newport News, VA, USA)

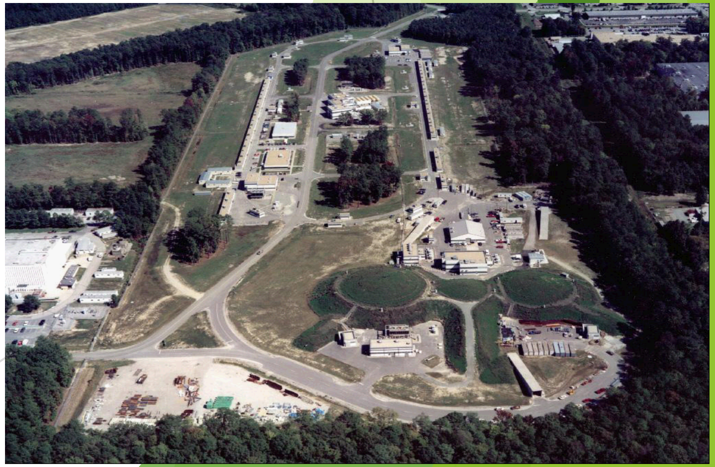
CLAS12 in Hall B



CLAS (1998-2012)



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. 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).

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	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

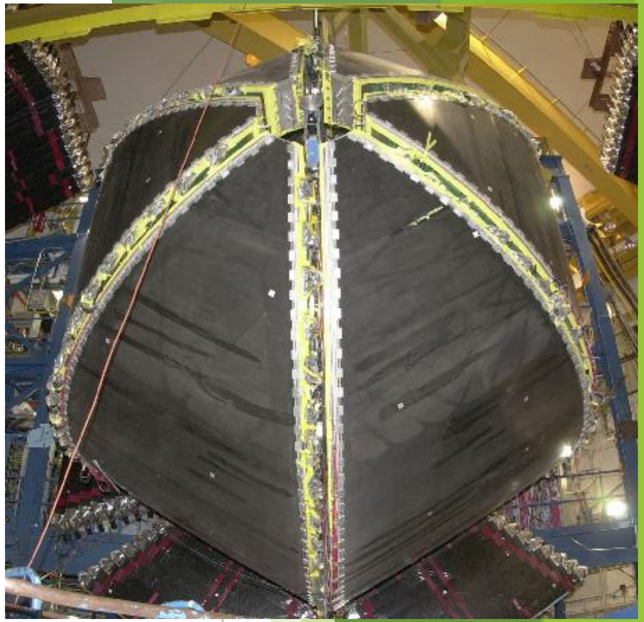
- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

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

Polarized Structure Function $\sigma_{LT'}$ from $ep \to ep\pi^0$ in the resonance region



- 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 billions

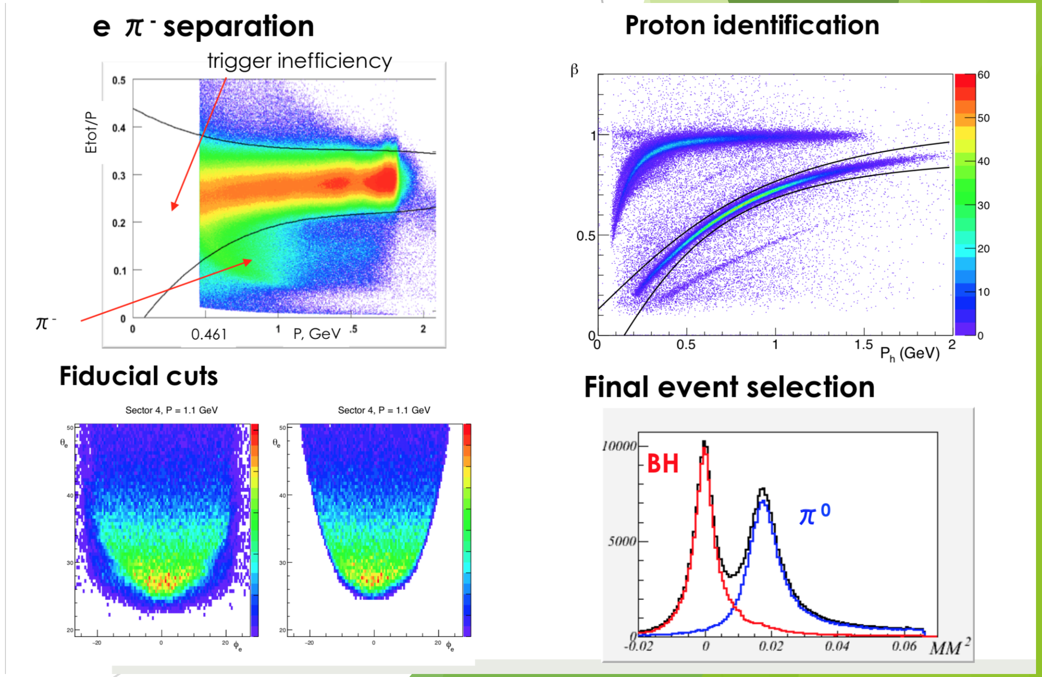
$0.4 < Q^2 < 1\ \mathrm{GeV}^2$

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

Exclusive $\pi^0 p$ electroproduction off protons in the resonance region at photon virtualities $0.4\ \mathrm{GeV}^2 \leq Q^2 \leq 1\ \mathrm{GeV}^2$

N. Markov,[8,36,*] K. Joo,[8] V.D. Burkert,[36] V.I. Mokeev,[36] L. C. Smith,[41] M. Ungaro,[36] S. Adhikari,[11]

Phys. Rev. C 101, 015208 – Published 21 January 2020



Polarized Structure Function $\sigma_{LT'}$

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

$$\sigma_0 = \sigma_T + \epsilon_L\sigma_L + \epsilon\sigma_{TT}\sin^2\theta_\pi^*\cos 2\phi_\pi^* + \sqrt{2\epsilon_L(1+\epsilon)}\ \sigma_{LT}\sin\theta_\pi^*\cos\phi_\pi^*\ ,$$

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

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

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

We have unpolarized cross sections from the same data.

Polarized Structure Function $\sigma_{LT'}$

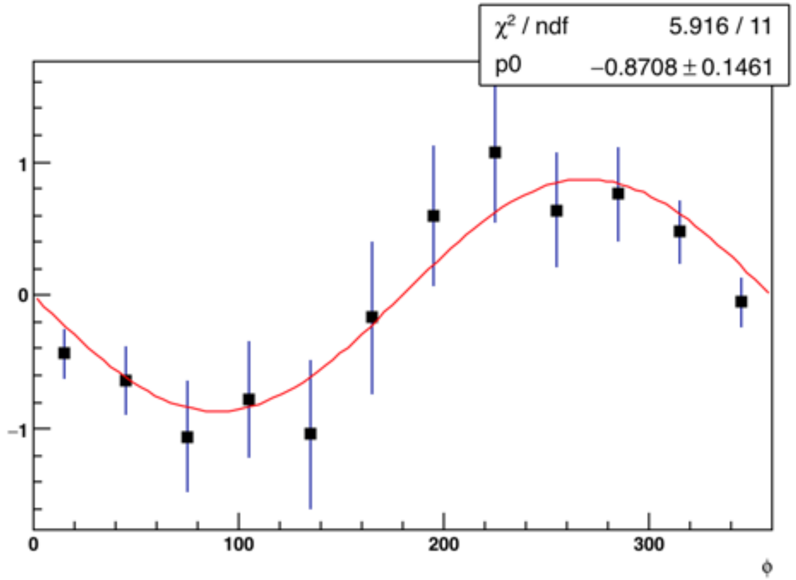
Binning:

28 W-bins from 1.1 to 1.8 GeV, width = 25 MeV
2 Q^2-bins [0.4-0.6] and [0.6-1.0] GeV^2
10 Cos(θ)-bins [-1,1] width = 0.2
12 Φ-bins [0,360] width = 30^o

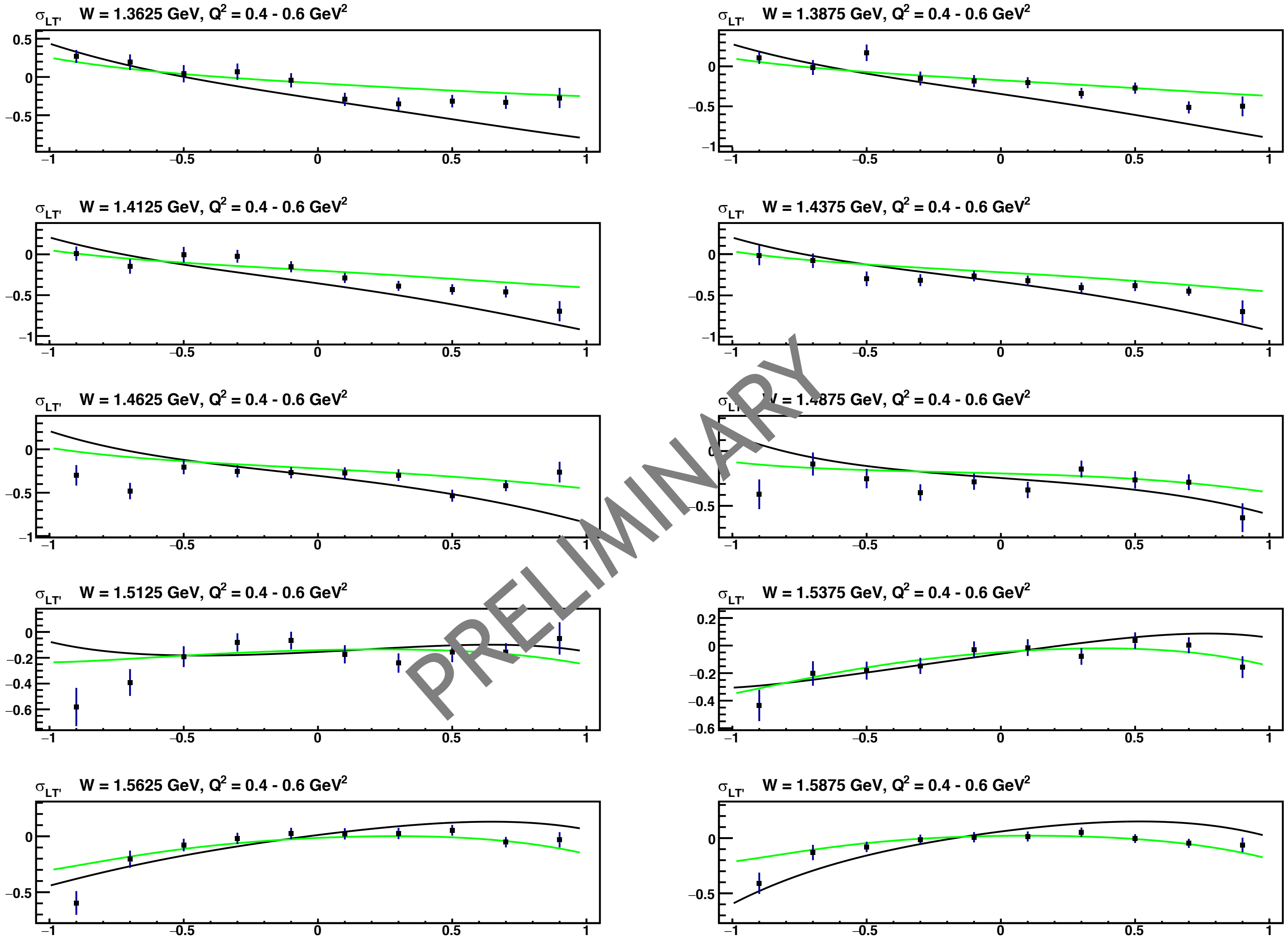
W = 1.66 GeV

Q^2 = 0.5 GeV^2

Cos(θ)=-0.9

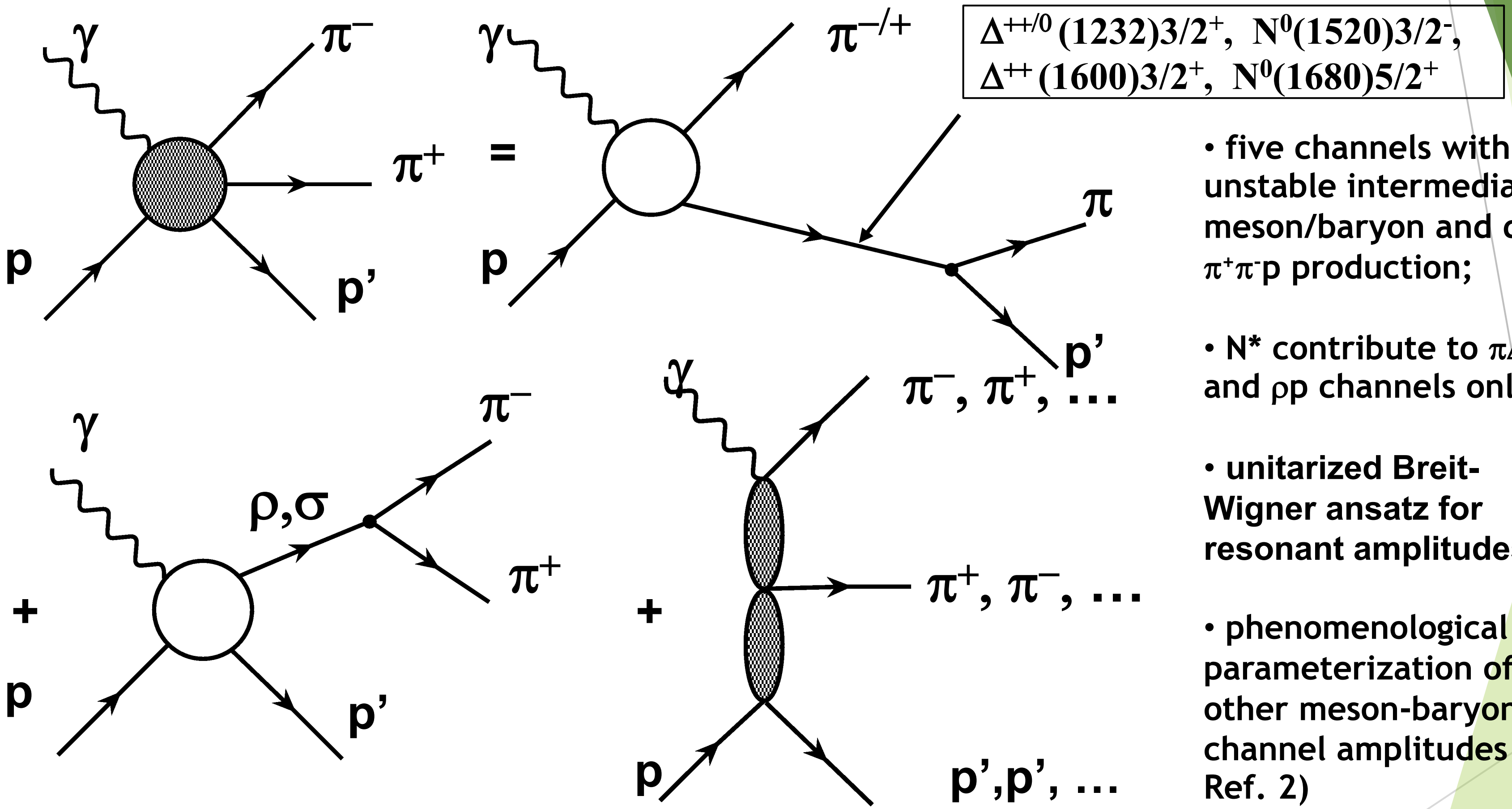


$\sigma_{LT'}$, $0.4<Q^2<0.6$ GeV^2 green-MAID2007, black-UIM



JM Model for Analysis of $\pi^+\pi^-p$ Photo-/Electroproduction

Major objectives: extraction of $\gamma_{r,v}pN^*$ photo-/electrocouplings and $\pi\Delta$, ρp decay widths

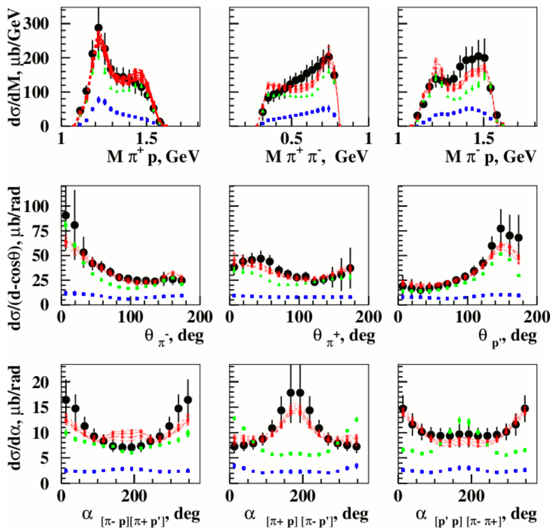


- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-p$ production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

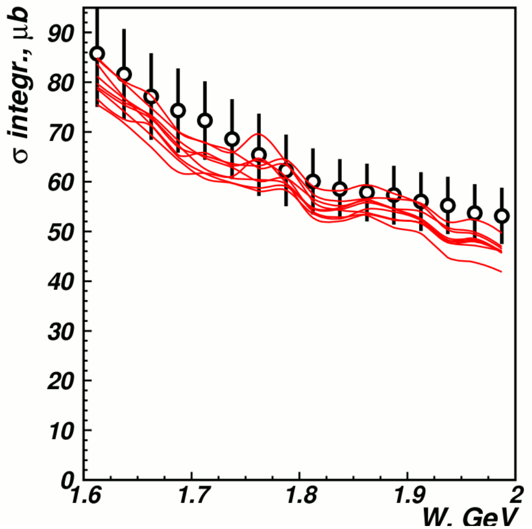
Good description of $\pi^+\pi^-p$ photo-/electroproduction off protons cross sections at 1.4 GeV<W<2.0 GeV and 0 GeV^2<Q^2<5.0 GeV^2

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

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

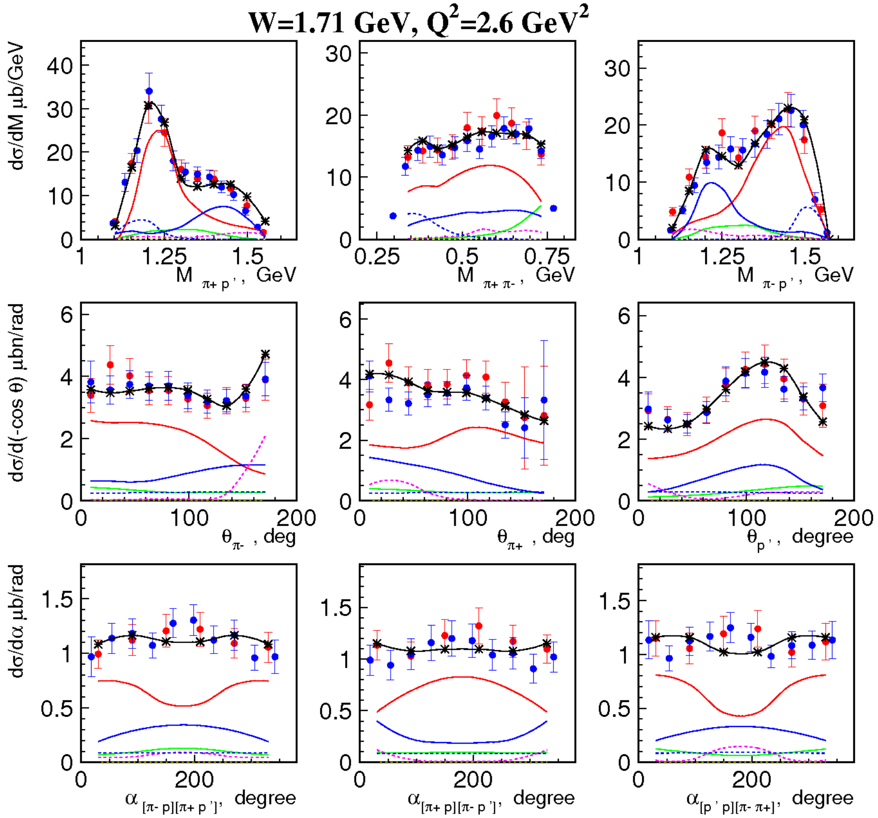
Resonances	$A_{1/2}\times10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{1/2}\times10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{1/2}\times10^3$ multichannel analysis [7] $\text{GeV}^{-1/2}$	$A_{3/2}\times10^3$ from $\pi^+\pi^-p$ $\text{GeV}^{-1/2}$	$A_{3/2}\times10^3$ PDG ranges $\text{GeV}^{-1/2}$	$A_{3/2}\times10^3$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

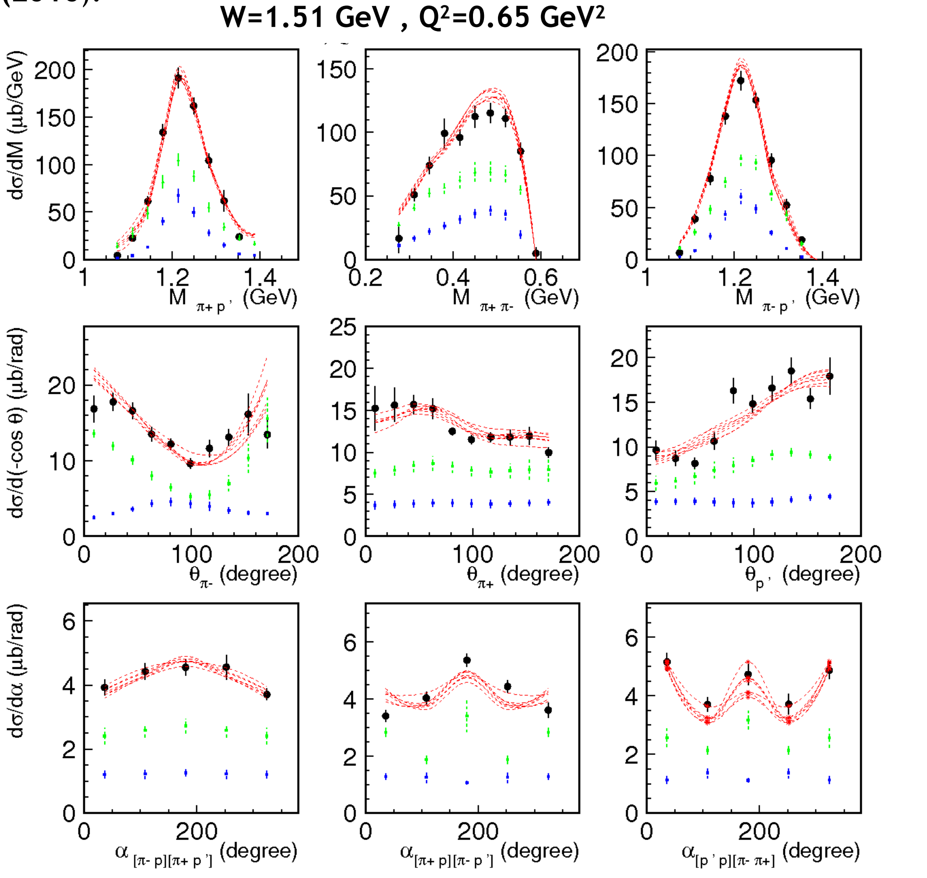
Contributing mechanisms seen in the data

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



full JM — ρp — π^+ N(1520)3/2$^-$

$\pi^-\Delta^{++}$ — $\pi^+\Delta^0$ — π^+ N(1680)5/2$^+$

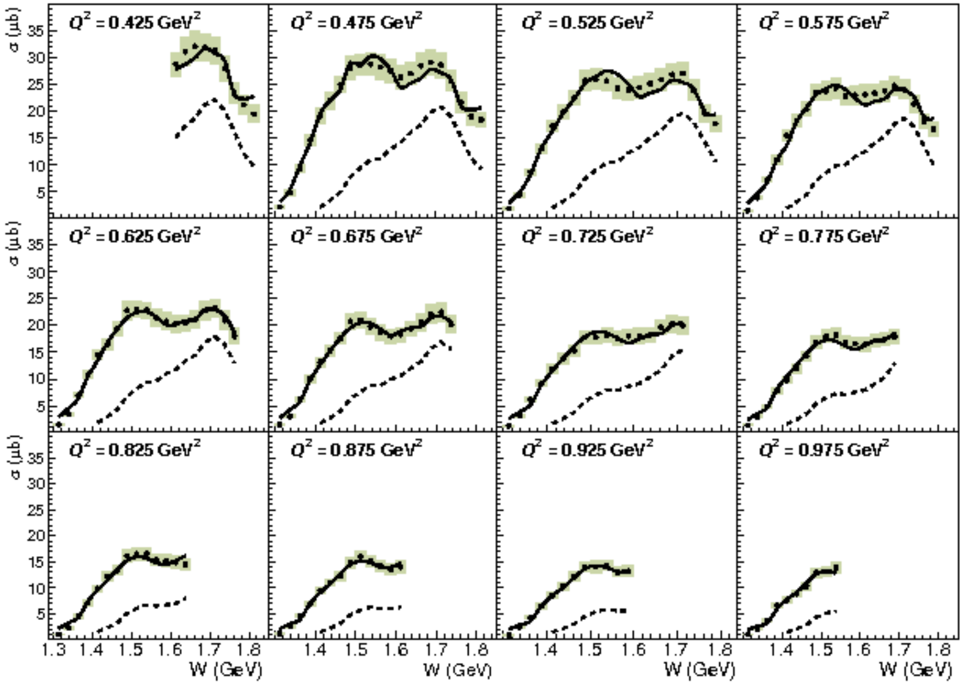
data fit within JM under variations of both resonant and background parameters

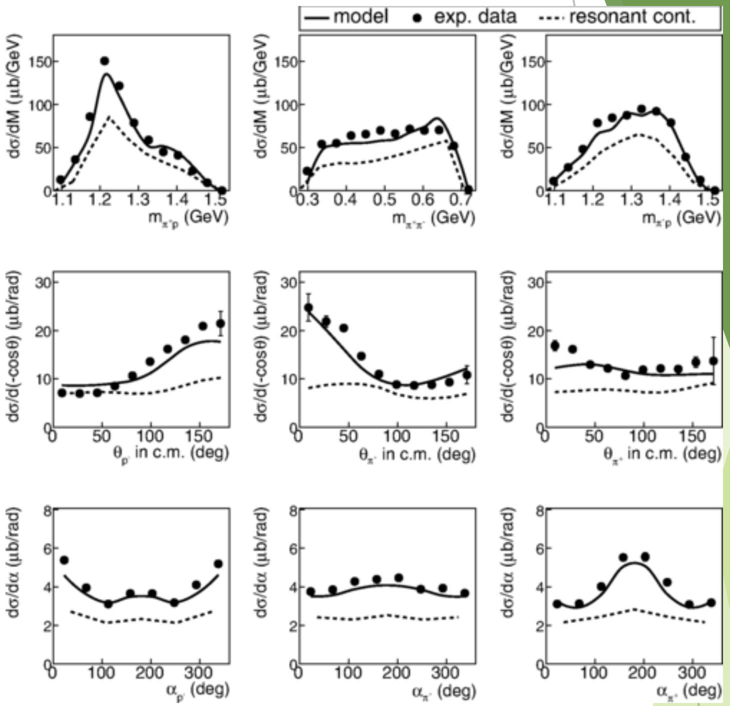
background cross sections

resonant cross sections

Recent CLAS Data on $\pi^+\pi^- p$ Electroproduction off Protons at $0.4<Q^2<1.0$ GeV^2

G. V. Fedotov, Iu. A. Skorodumina et al., CLAS Collaboration, Phys. Rev. C98, 025203 (2018)





9 one-fold differential cross sections at W<1.8 GeV and 0.4 GeV^2<Q^2<1.0 GeV^2 of the best statistical and systematical accuracy obtained with minimal bin size over Q^2 ever achieved (ΔQ^2= 0.05 GeV^2)

JM model/TWOPEG EG analysis:

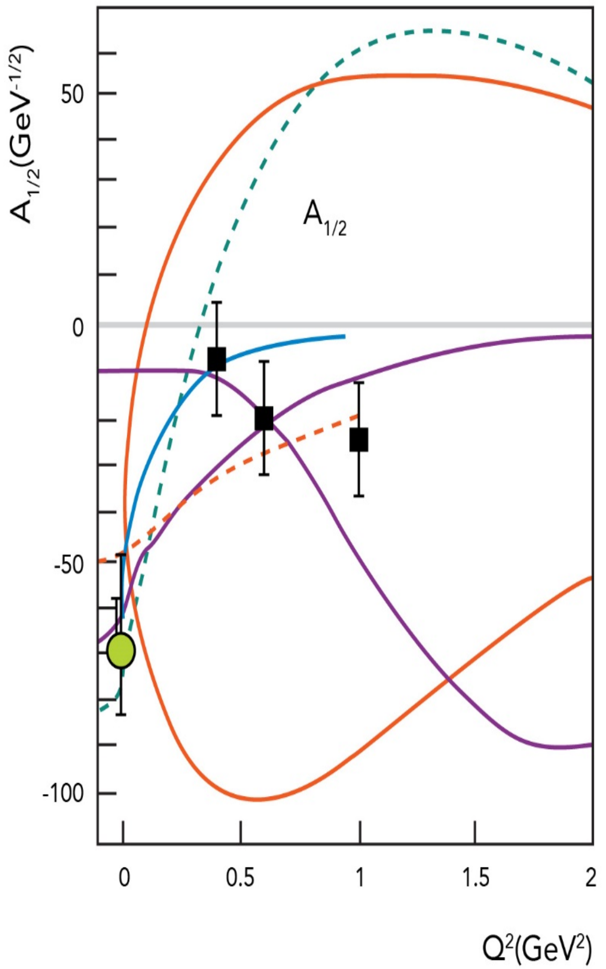
- - - - resonant contribution

——— full cross section

- Promising prospect to obtain 8 additional points on Q^2-evolution of N'(1720)3/2$^+$ electrocouplings in the range of 0.4 GeV^2<Q^2< 0.8 GeV^2

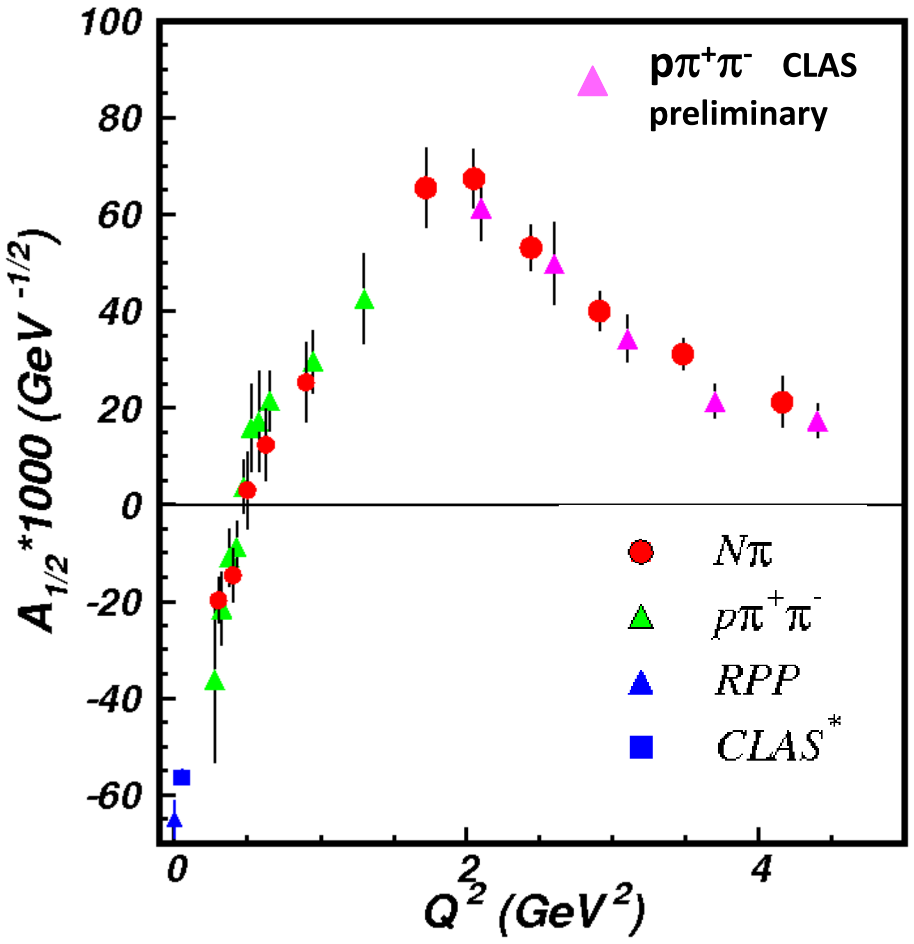
Roper Resonance in 2002 & 2019

2002



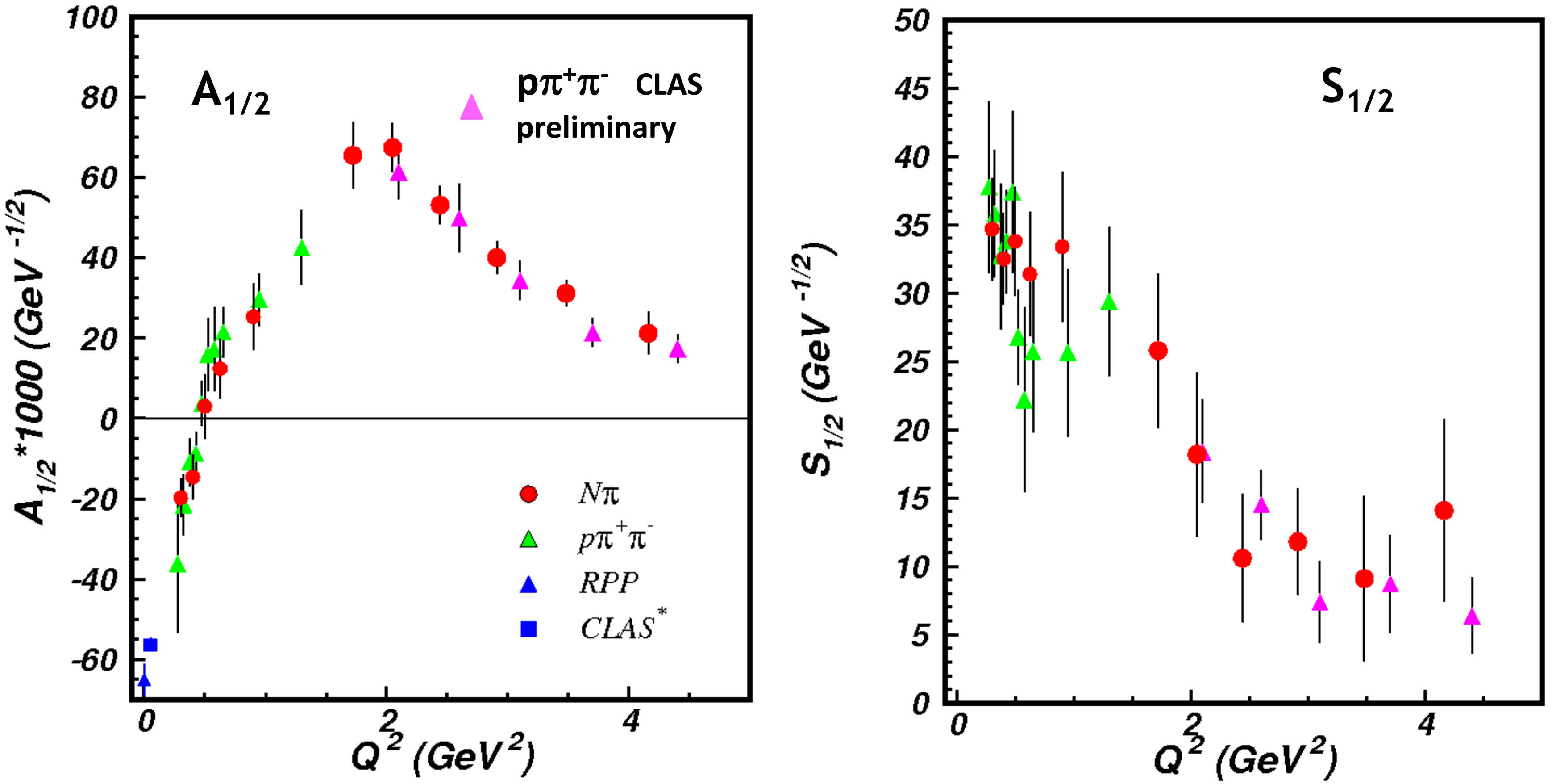
V. Burkert, Baryons 2002

2019



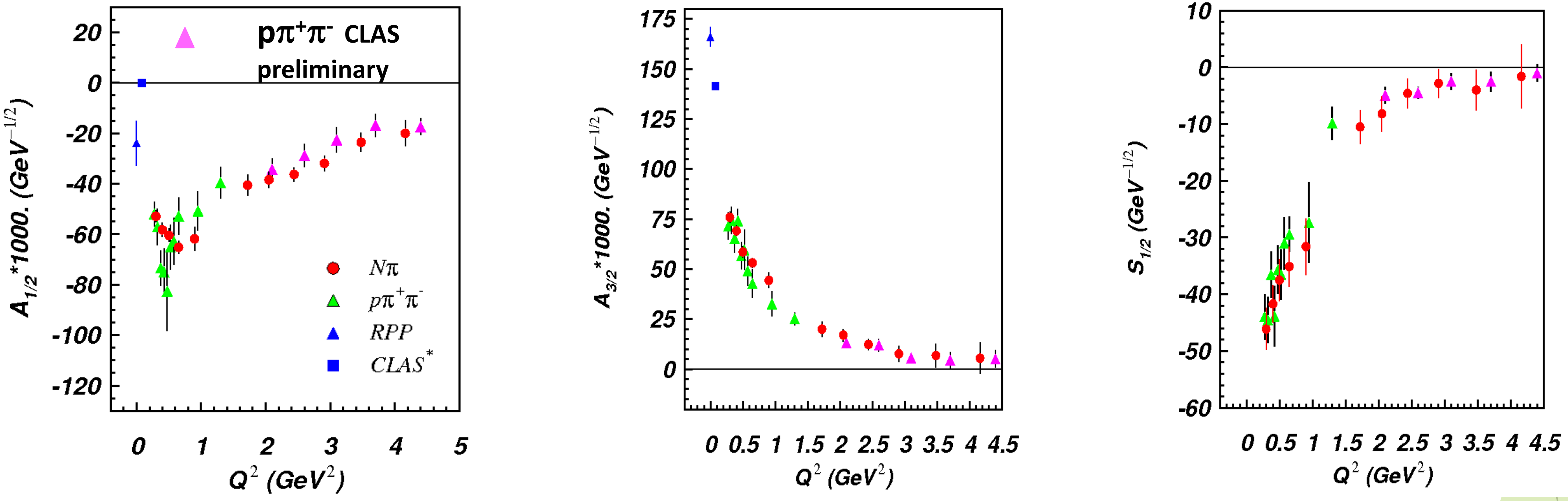
V. D. Burkert, Baryons 2016 and the recent update from the CLAS $\pi^+\pi^-p$ electroproduction off protons data

Electrocouplings of N(1440)1/2⁺ from Nπ and π⁺π⁻p Electroproduction off Proton Data



Consistent results on N(1440)1/2⁺ electrocouplings from the independent studies of two major Nπ and π⁺π⁻p electroproduction off proton channels with different non-resonant contributions strongly support credible extraction of these quantities in a nearly model-independent way.

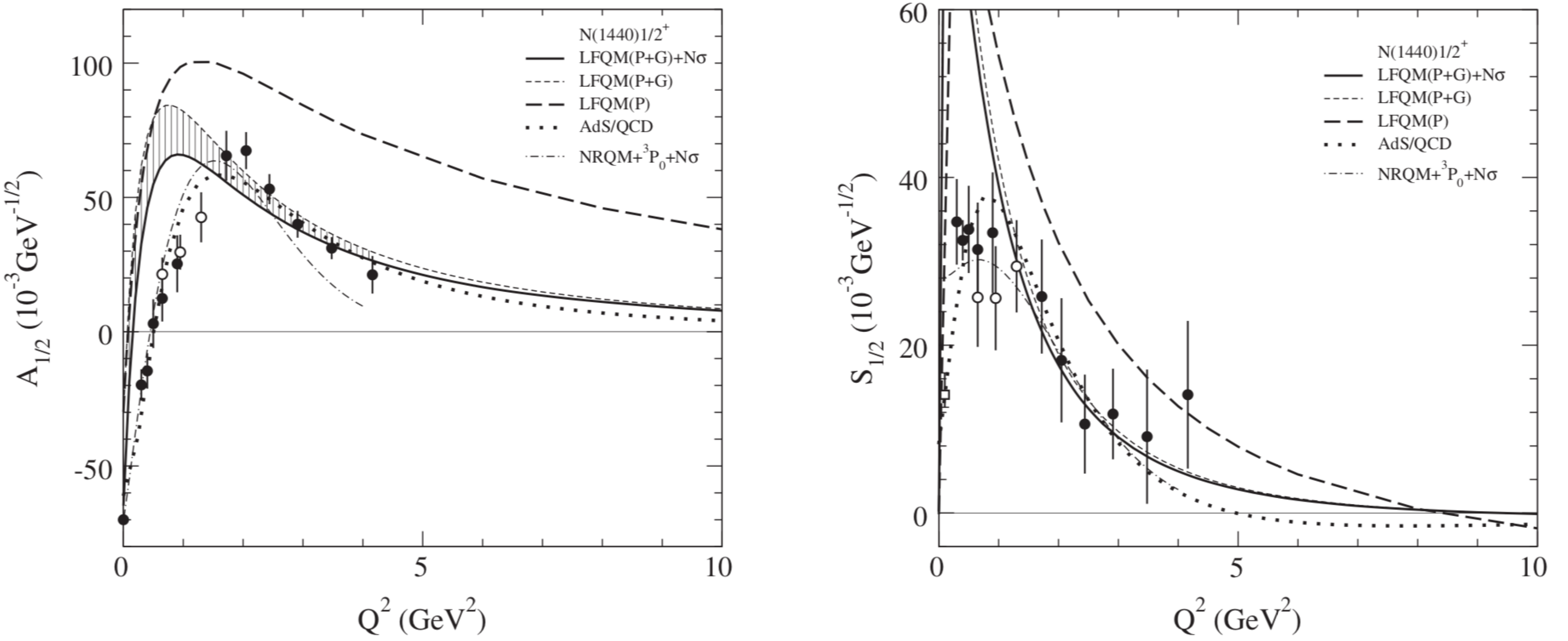
Electrocouplings of N(1520)3/2$^-$ from Nπ and $\pi^+\pi^-$p Electroproduction off Proton Data



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.

Расчеты в рамках кварковых моделей

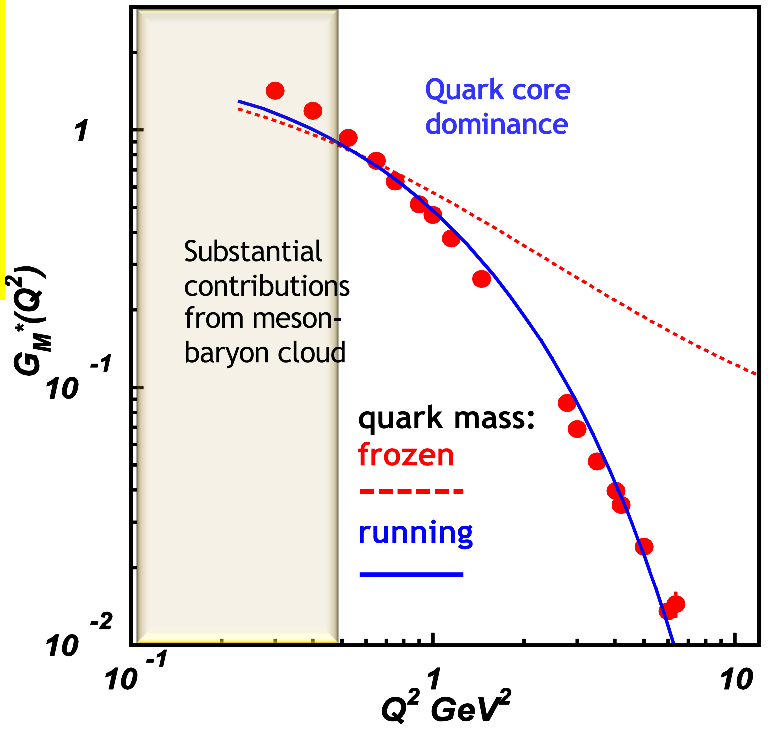
IGOR T. OBUKHOVSKY *et al.* PHYS. REV. D **100**, 094013 (2019)

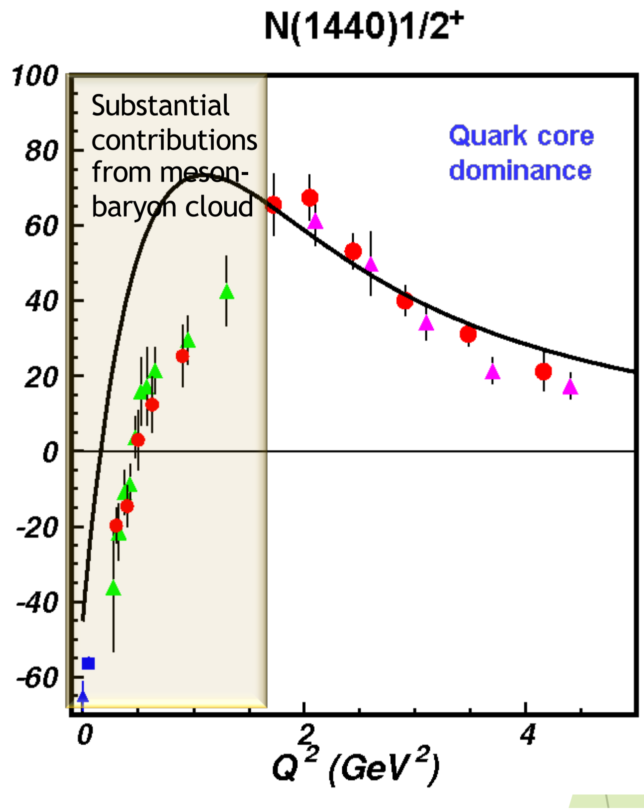


From Resonance Electrocouplings to Hadron Mass Generation

Dyson-Schwinger Equations (DSE):

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



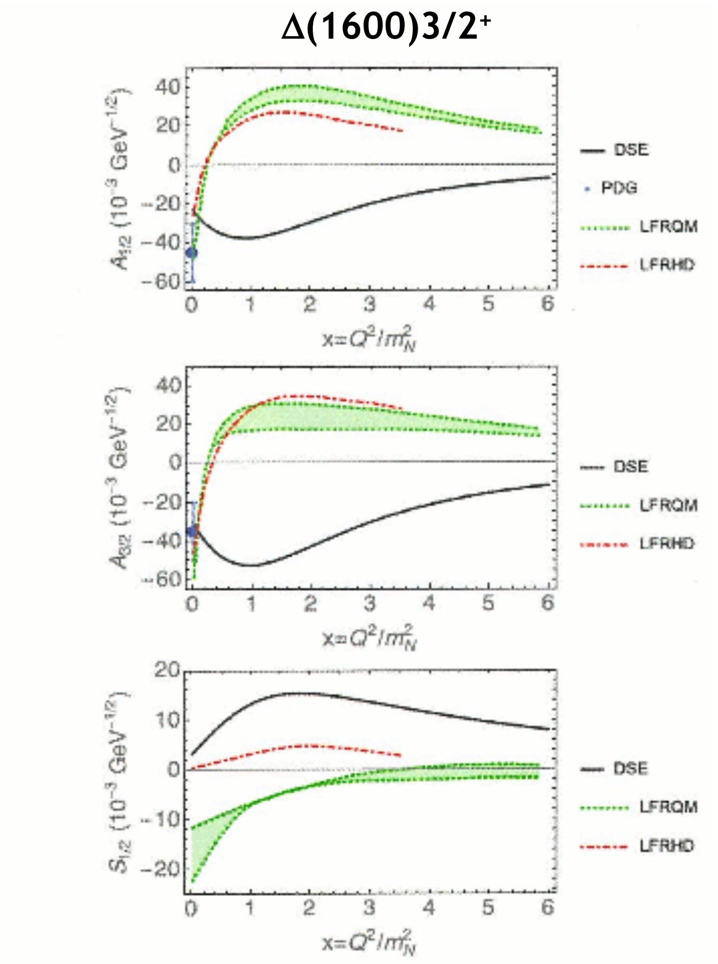


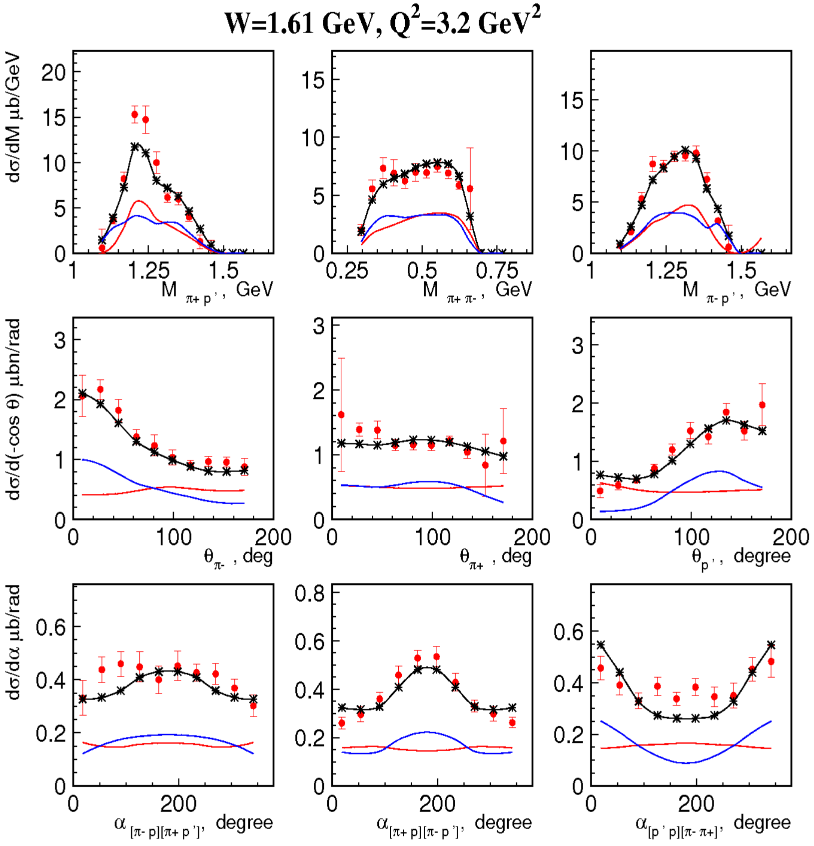
DSE analyses of the CLAS data on Δ(1232)3/2+ electroexcitation demonstrated that dressed quark mass is running with momentum.

Good data description at Q^2>2.0 GeV^2 achieved with 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.

Dressed Quark Mass Function from Electrocouplings of Radial Δ-Excitation





$\pi^+\pi^-p$ data from CLAS
A.Trivedi Few Body Syst. 60, 5 (2019)

N*
non-resonant contributions

Parameter free predictions for N→Δ(1600)3/2+ e.m. transition form factors from DSEQCD
Ya Lu et al, arXiv:1904.03205 [nucl-th]

Good description of the CLAS $\pi^+\pi^-p$ electroproduction off protons data was achieved at 1.4 GeV < W < 2.0 GeV and 2.0 GeV^2 < Q^2 < 5.0 GeV^2 within JM19 model.

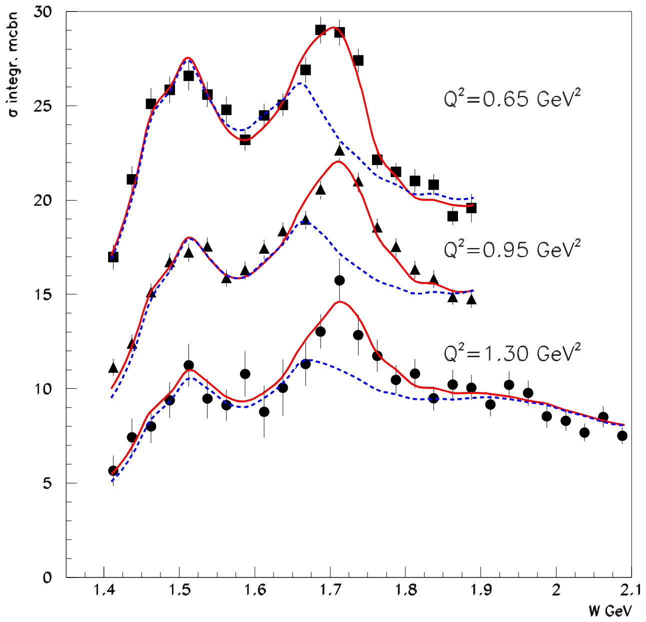
- Δ(1600)3/2$^+$ electrocouplings will be extracted soon.
- Confirmation of the DSE expectations will prove a relevance of dressed quark with running mass in the structure of Δ(1232)3/2$^+$ and radial nucleon and Δ excitations.
- Studies of [70,1$^-$] orbital excitations is the next step.

Evidence for the Existence of the New State N'(1720)3/2$^+$ from Combined $\pi^+\pi^-$p Analyses in both Photo- and Electroproduction

N(1720)3/2$^+$ hadronic decays from the CLAS data fit with conventional resonances only

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.



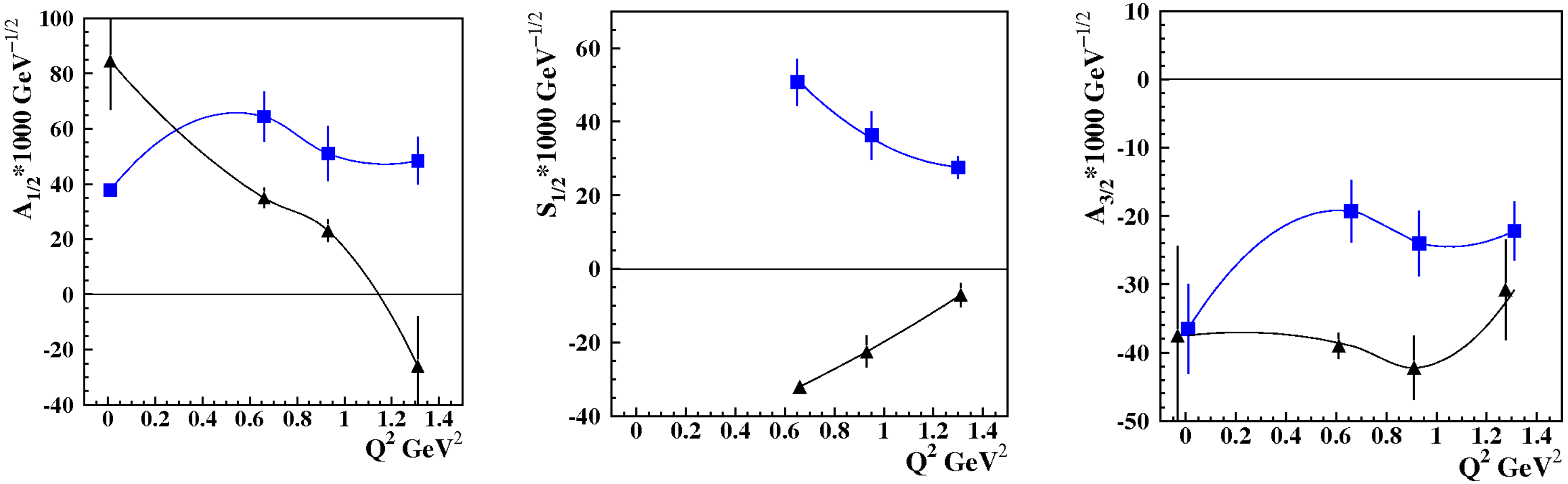
N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state

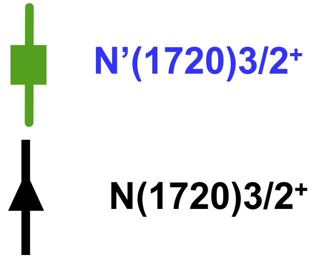
Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46
Δ(1700)3/2$^-$ electroproduction photoproduction	 77-95 78-93	 3-5 3-6

The successful description of the $\pi^+\pi^-$p photo- and electroproduction data achieved by implementing new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances contributing at W~1.7 GeV <u>provides strong evidence for the existence of the new N'(1720)3/2$^+$ state.</u>

The Parameters of the New N’(1720)3/2⁺ State from the CLAS Data Fit

The photo-/electrocouplings of the N’(1720)3/2⁺ and conventional N(1720)3/2⁺ states





Resonance	Mass, GeV	Total width, MeV
N’(1720)3/2⁺	1.715-1.735	120±6
N(1720)3/2⁺	1.743-1.753	112±8

- N’(1720)3/2⁺ is the only new resonance for which data on electroexcitation amplitudes have become available.
- Gaining insight into the “missing” resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.

Evidence for the New $N'(1720)3/2^+$ Nucleon Resonance from Combined Studies of CLAS $\pi^+\pi^-p$ Photo- and Electroproduction Data

V.I. Mokeev[a,*], V.D. Burkert[a], D.S. Carman[a], L. Elouadrhiri[a], E. Golovatch[b], R.W. Gothe[c], K. Hicks[d], B.S. Ishkhanov[b], E.L. Isupov[b], K. Joo[e], N. Markov[a,e], E. Pasyuk[a], A. Trivedi[c]

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[b] *Skobeltsyn Institute of Nuclear Physics and Physics Department, Lomonosov Moscow State University, 119234 Moscow, Russia*
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Submitted to Physics Letters B

CLAS12 N* Program at High Q^2

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 GeV, $Q^2 = 3 \rightarrow 12$ GeV^2, $W \rightarrow 3.0$ 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.*

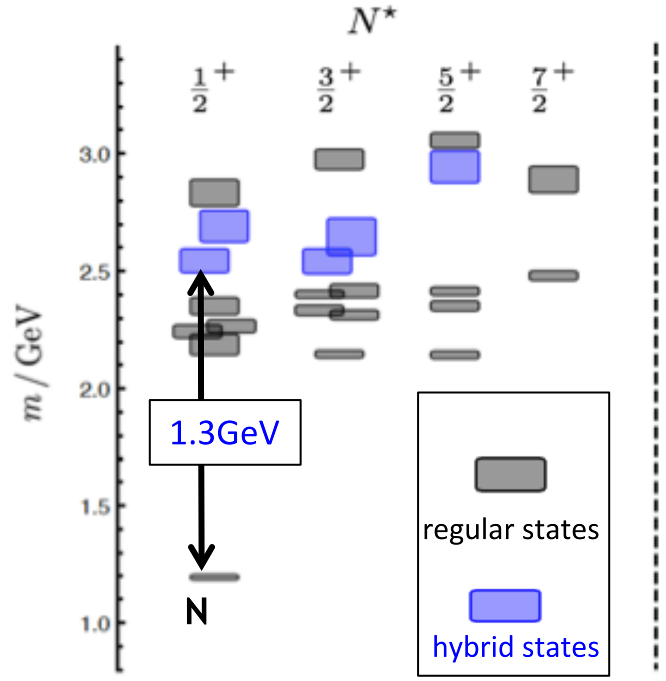
  CLAS12 is the only facility to map-out the N quark with minimal meson-baryon cloud contributions.*

The experiments already started in February 2018!

Hunting for Glue in Excited Baryons with CLAS12

Can glue be a structural component to generate hybrid q^3g baryon states?

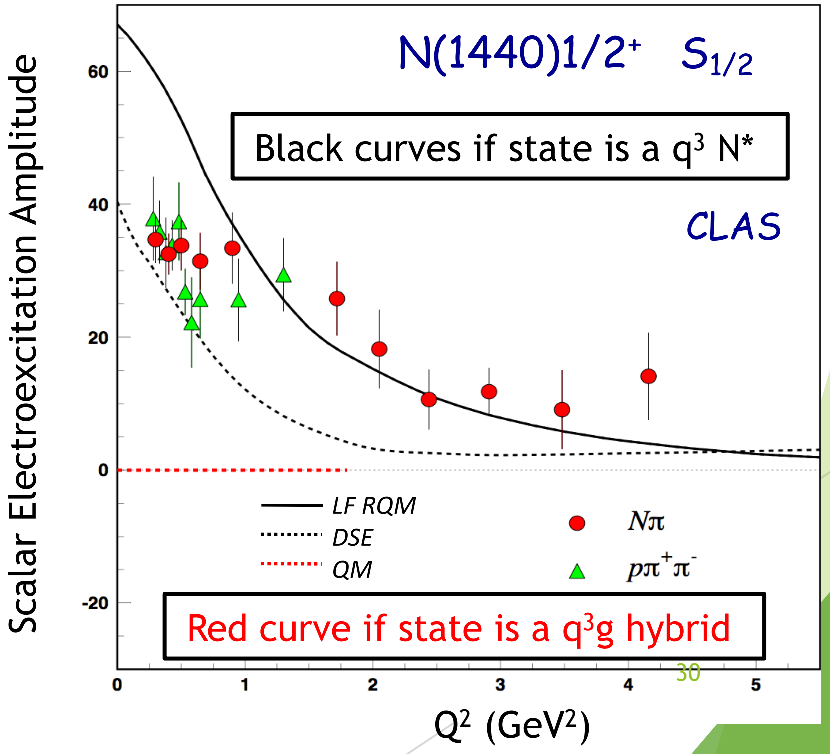
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



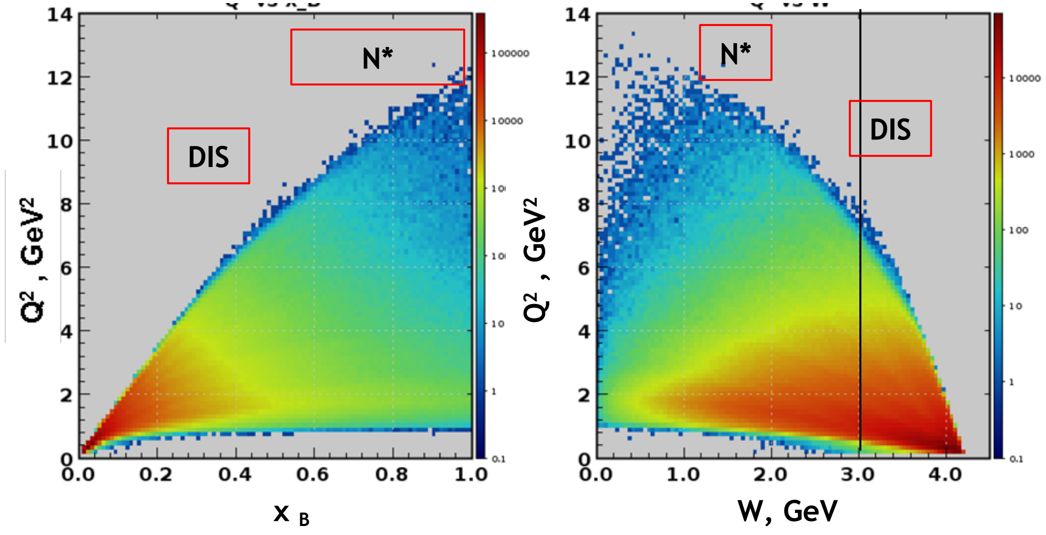
JLab LQCD group results

Search for hybrid baryons with CLAS12 in exclusive KY and $\pi^+\pi^-p$ electroproduction

LQCD and/or QM predictions on Q^2 evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state



12 GeV Era with the CLAS12 Detector



Physics run started successfully
in February 2018.

Спасибо за внимание!