Nucleon Resonance Structure from the CLAS@JLAB Meson Electroproduction Data

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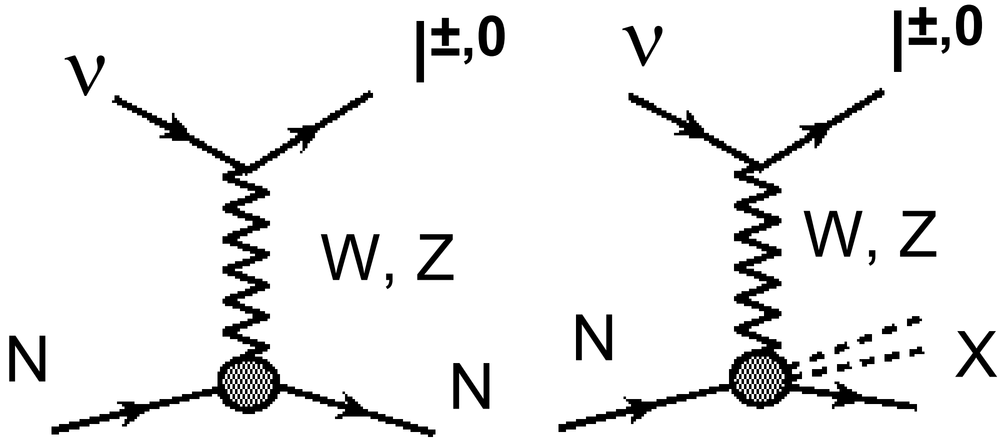
16^{th} Lomonosov Conference on Elementary Particle Physics

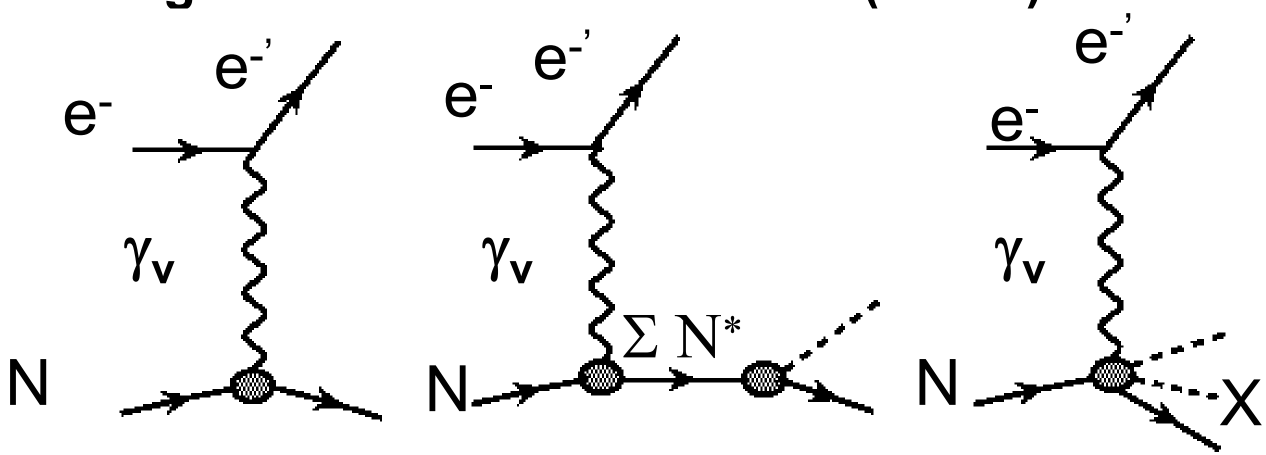
Weak and Electromagnetic Interactions as the Tools for Exploration of the Ground and Excited Nucleon State Structure

Weak interaction: neutrino-nucleon scattering:



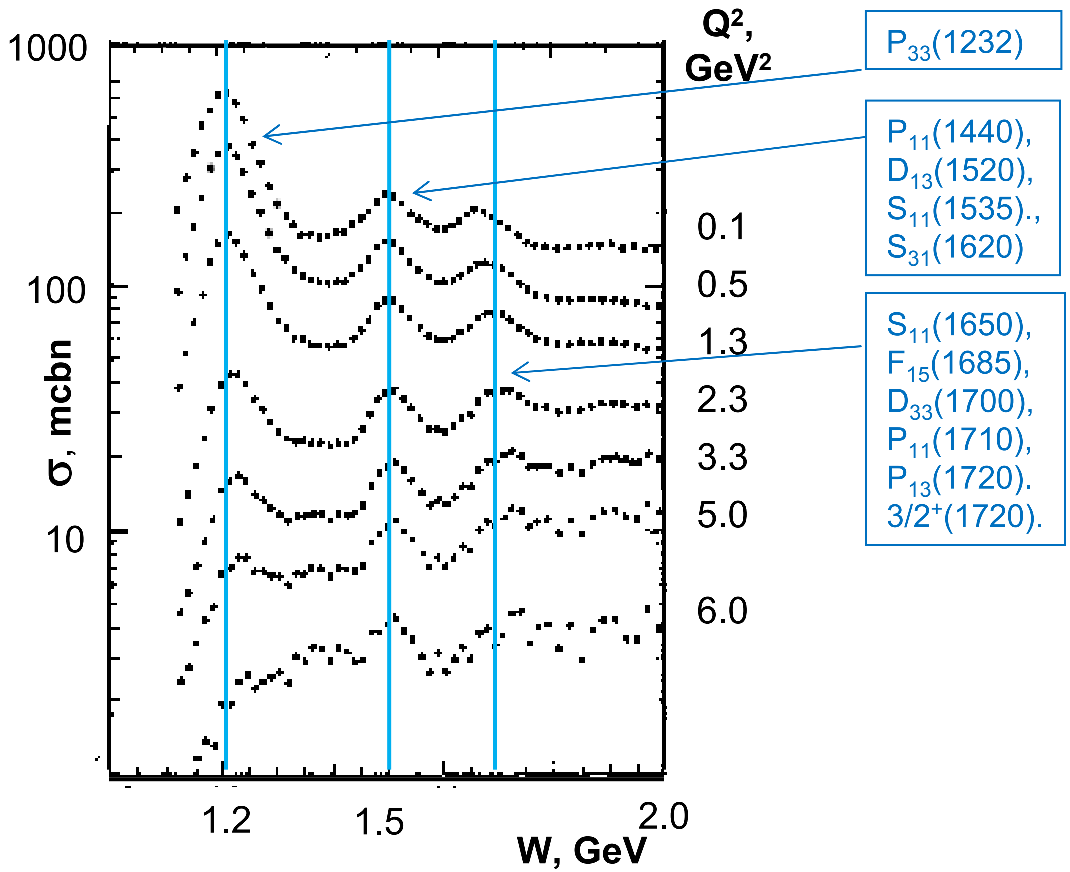
Бруно Понтекорво

Electromagnetic interaction: electron (muon)-nucleon scattering:



N*-States in Inclusive Electron Scattering

Total virtual photon cross sections
F. Foster and G.Hughes, Rep. Progr. Phys. 46, 1445 (1983).



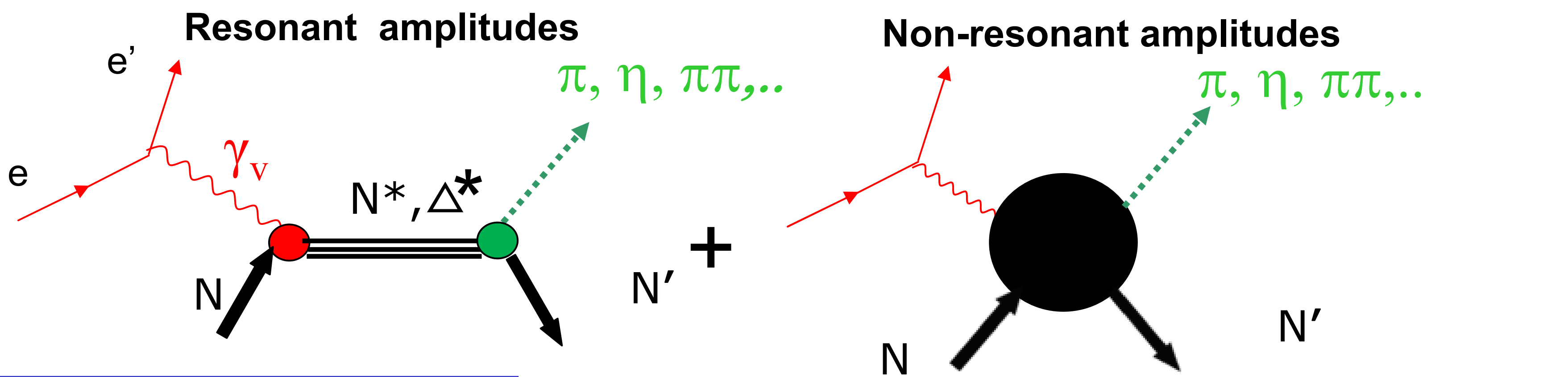
What we knew 30 years ago:

- three resonant peaks.
- different Q^2-evolution of these peaks

⬇

- different structure of different N*-states.

Extraction of $\gamma_v NN^*$ Electrocouplings from the Data on Exclusive Meson Electroproduction off Protons



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

or

- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$

or

- $G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$

See details in:
I.G.Aznauryan and V.D.Burkert,
Progr. Part. Nucl. Phys. 67, 1 (2012).

- **Separation of resonant/non-resonant contributions within the framework of reaction models; Breit-Wigner ansatz for parameterization of resonant amplitudes; fit of resonance electrocouplings and hadronic parameters to the data.**

Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of N* parameters.

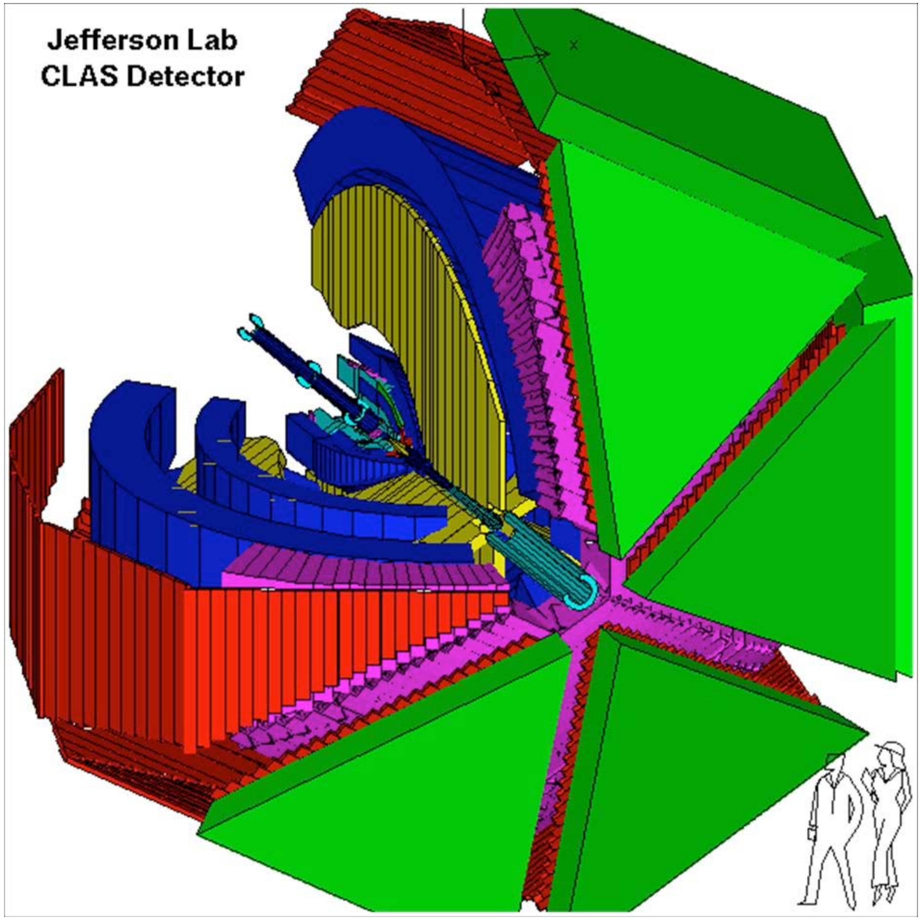
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

Time-of-flight counters
plastic scintillators,
684 PMTs



Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs

Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

The unique combination of the CEBAF continuous electron beam with the best worldwide parameters and the CLAS detector of nearly 4π acceptance makes Hall-B@JLAB the most versatile facility operational worldwide for exploration of the nucleon structure.

Motivation and Objectives for the Studies of the $\gamma_v pN^*$-Electrocouplings in Exclusive Meson Electroproduction

The CLAS experimental program seeks to determine

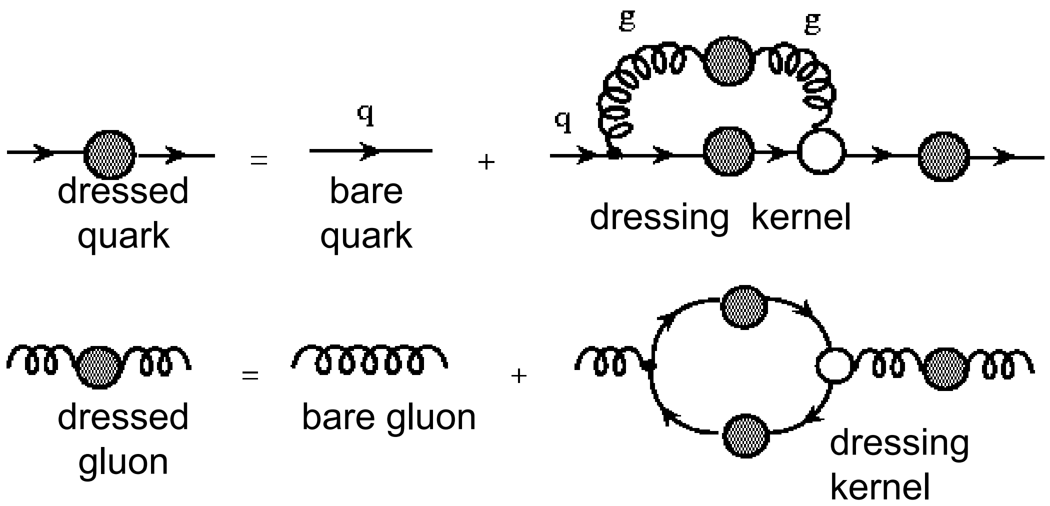
$\gamma_v pN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electro-production channels independently and in global multi- channel analyses.

This information is needed to study the evolution of relevant degrees of freedom in N* structure with distance and to access the non-perturbative strong interaction which generates N* states as bound systems of quarks and gluons: I. G. Aznauryuan et al., Int. J. Mod. Phys. E22, 133015 (2013).

The non-perturbative strong interaction represents the most important part of the Standard Model that we have yet to explore.

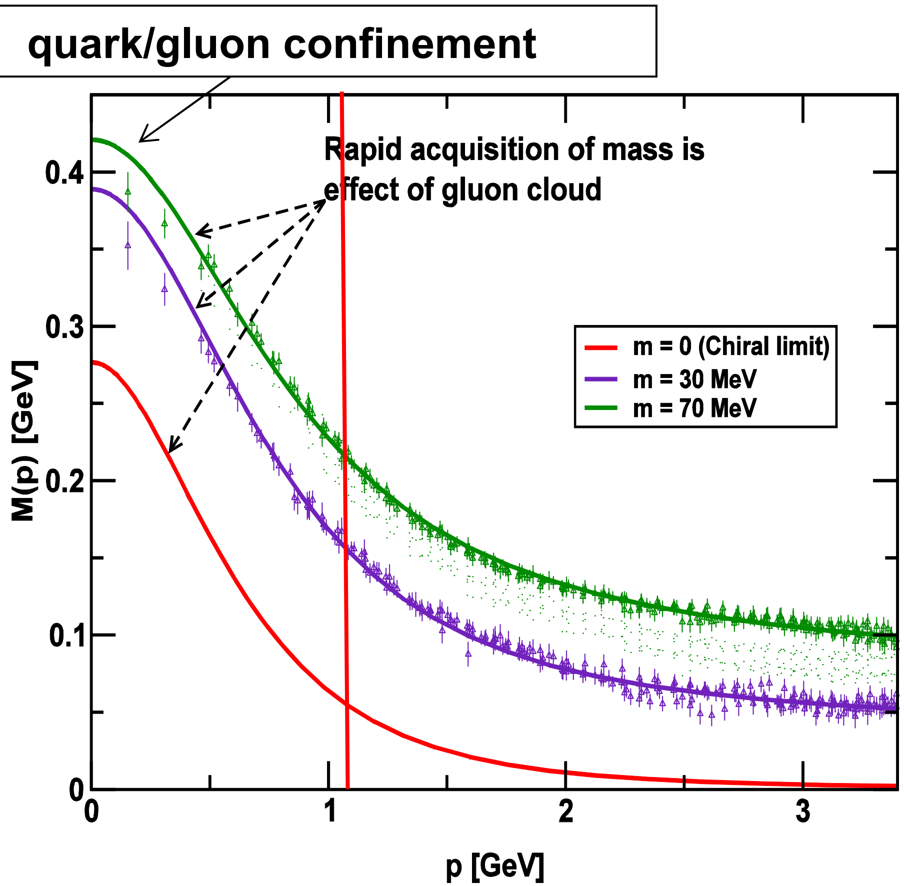
Non-Perturbatively Generated Effective Degrees of Freedom in the Ground and Excited Nucleon State Structure

Emergence of dressed constituent quarks (C.Q.) and gluons:



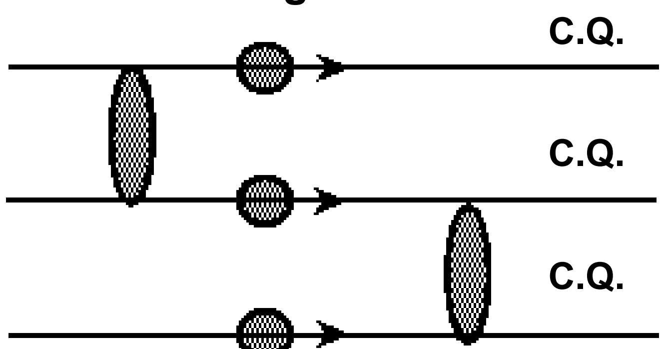
•Dressed quarks and gluons acquire dynamical, momentum dependent structure and masses in the regime of large α_s which is relevant for the N* formation.

•Their non-perturbative interactions are very complex and far beyond the scope of pQCD.



Available/future data on elastic form factors and $\gamma_v pN^*$-electrocouplings from CLAS/CLAS12 detectors offer the access to the dressed quark mass function in the range of momenta p up to 1.15 GeV.

The N/N* generation:



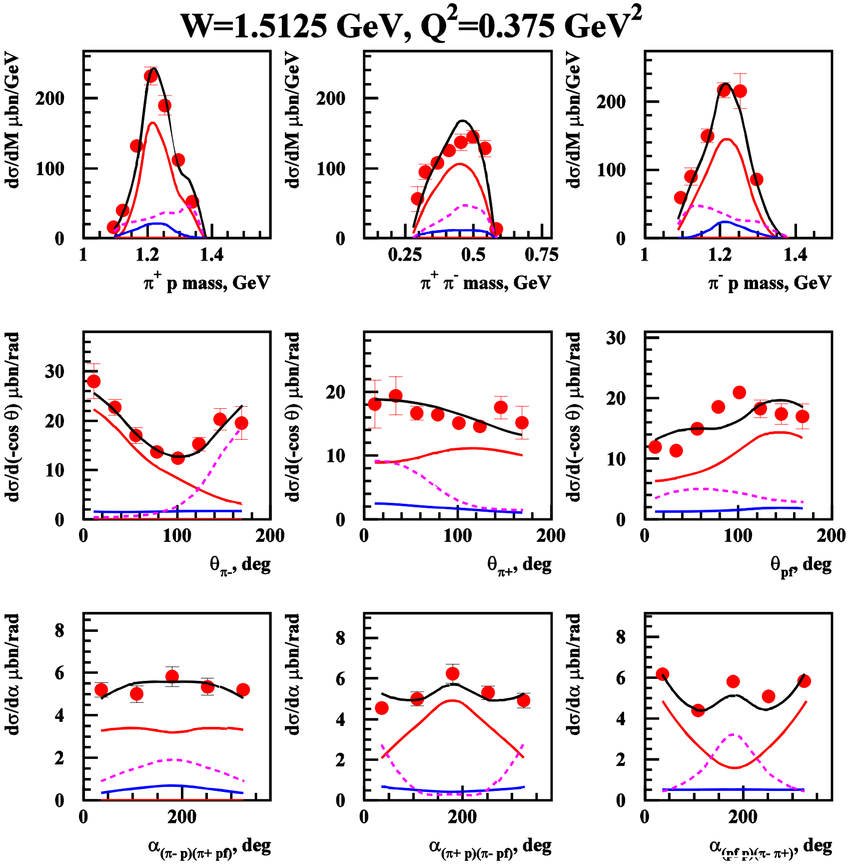
Exploration of the N/N* state structure addresses the most fundamental questions:

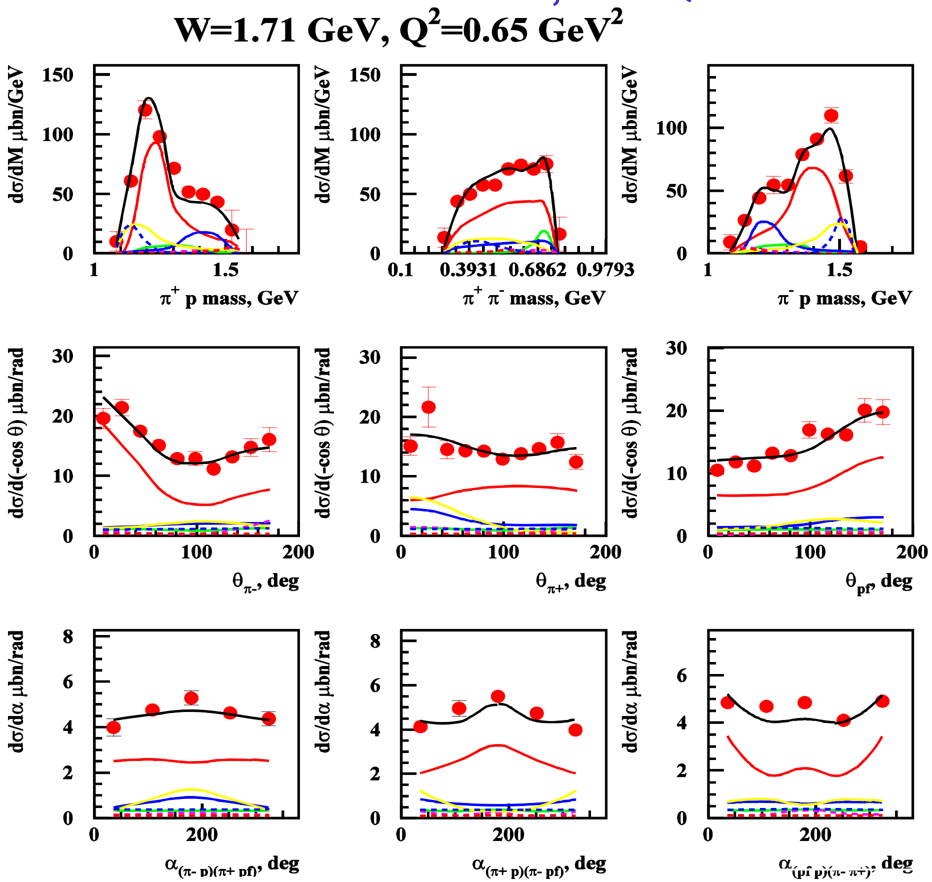
- **Nature of >98 % of the hadron mass in Universe, which is generated non-perturbatively . The Higgs mechanism is almost irrelevant for the light hadron mass generation.**
- **How quark-gluon confinement in baryons emerges from the QCD.**

The CLAS Data on $\pi^+\pi^-p$ Differential Cross Sections and their Description within the Framework of Meson-Baryon Reaction Model JM

G.V.Fedotov et al, PRC 79 (2009), 015204
1.30<W<1.56 GeV; 0.2<Q^2<0.6 GeV^2

M.Ripani, V.I,Mokeev et al, PRL 91 (2003), 0220021.40<W<2.30 GeV; 0.5<Q^2<1.5 GeV^2



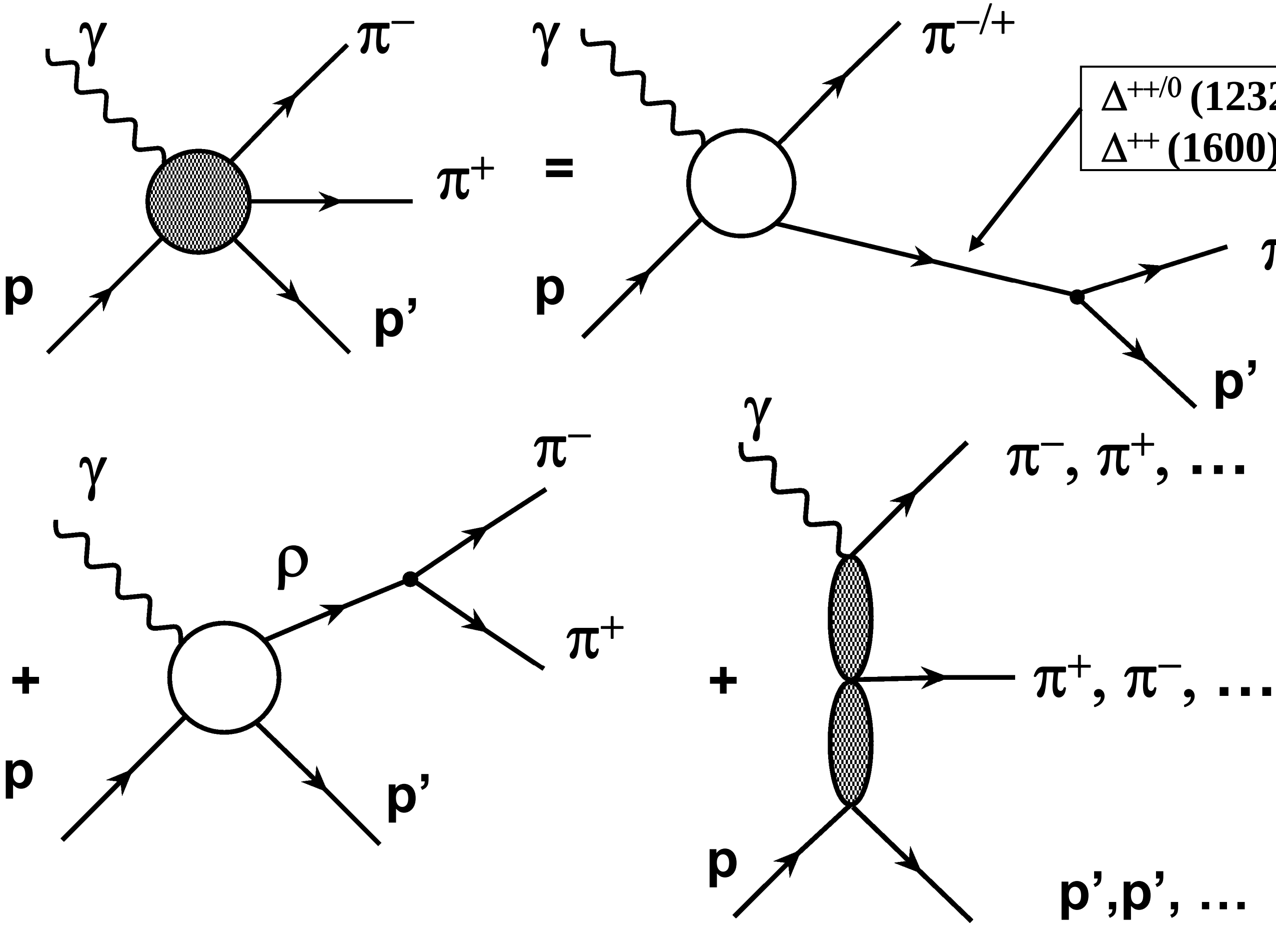


full JM calc. — $\pi^+\Delta^0$ — ρp — $\pi^+F^0_{15}(1680)$

$\pi^-\Delta^{++}$ — 2π direct — $\pi^+D^0_{13}(1520)$

The JM Model for Analysis of the $\pi^+\pi^-p$ Electroproduction

Major objectives: extraction of $\gamma_v NN^*$ electrocouplings and the $\pi\Delta$, ρp decay widths.

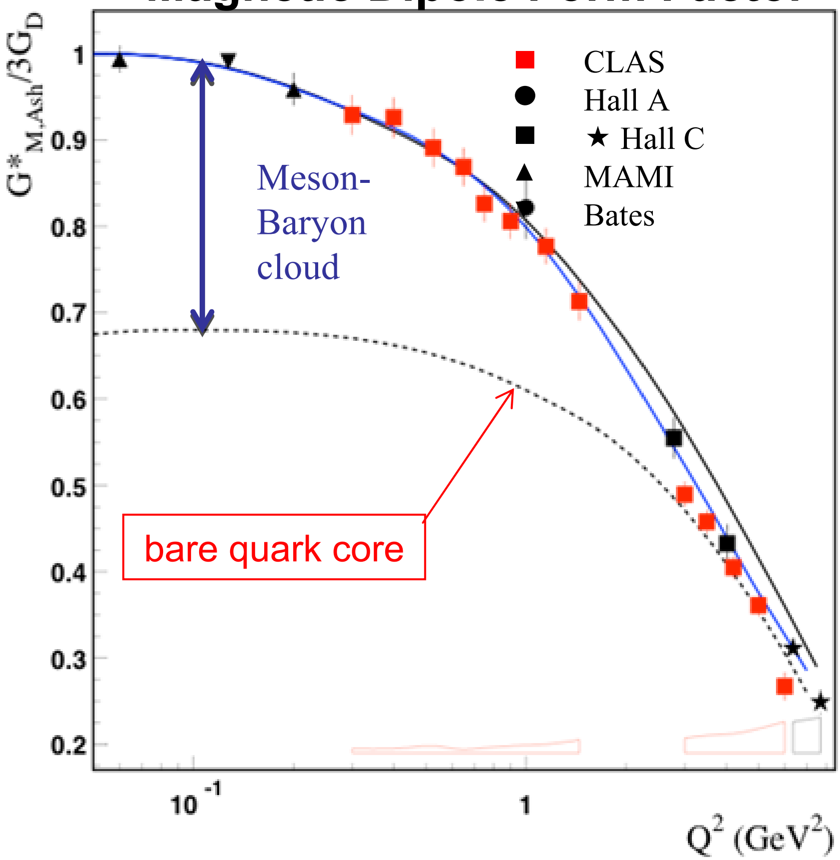


- six meson-baryon channels and direct $\pi^+\pi^-p$ production.
- N* contribute to $\pi\Delta$ and ρp channels only.
- unitarized Breit-Wigner ansatz for resonant amplitudes.

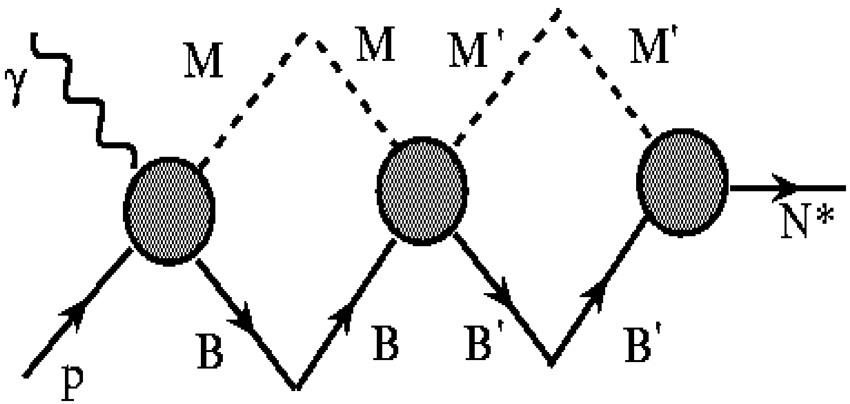
- Developed in Collaboration between JLAB and SINP at MSU.
- Only available worldwide approach for extraction of resonance parameters from the $\pi^+\pi^-p$ electroproduction data.

N Δ Magnetic Transition Form Factor and the Components of the N* Structure

Magnetic Dipole Form Factor



The mechanisms of the meson-baryon dressing

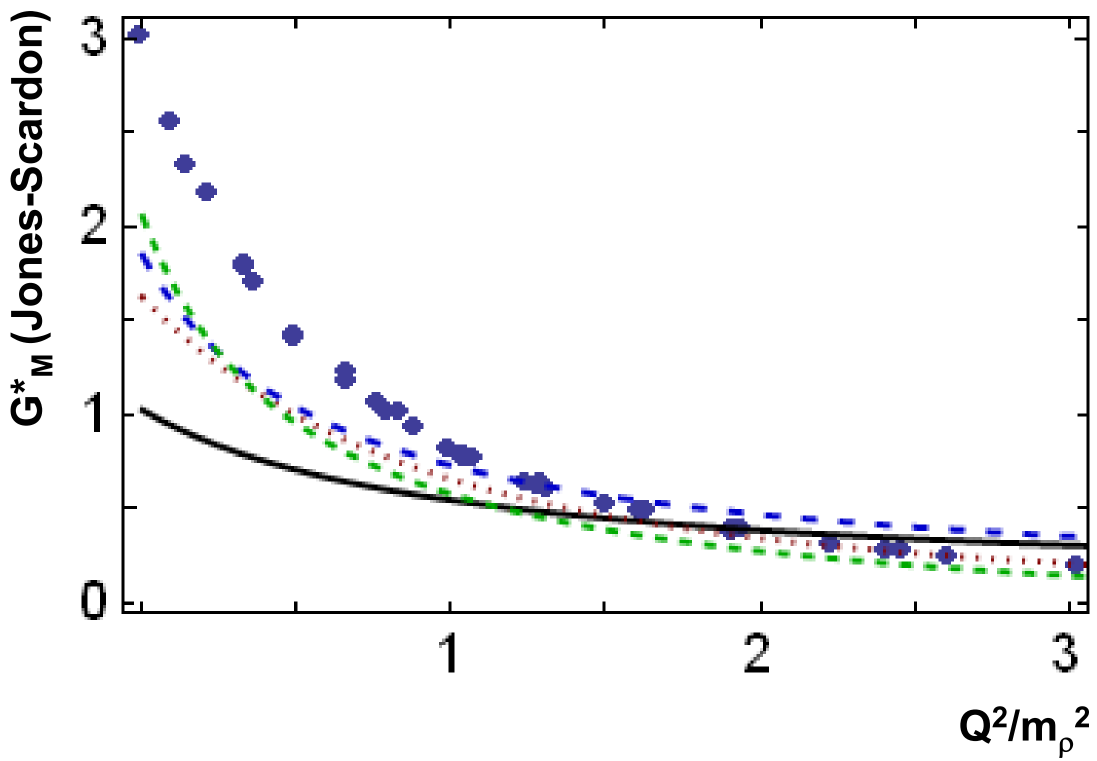


T. Sato and T-S. H. Lee, PRC 63, 055201 (2001).

- **Successful description of NΔ transition form factors was achieved taking into account the contributions from the external meson-baryon cloud and the internal core of three dressed constituent quarks.**

Quark Core Contribution to N→Δ Magnetic Form Factors from the QCD Lagrangian

Quark core contribution from DSEQCD:J.Segovia, et al., arXiv:1305.0292[nucl-th].



contact interaction.

contact interaction & quark anomalous magn. moment.

projection for quark running mass.

bare G^*_M inferred from exp. data within Argonne-Osaka c.c. approach.

Promising potential of DSEQCD approaches in describing the quark core contribution from the first principles of QCD.

The P_{11}(1440) and D_{13}(1520) Structure from the CLAS Electrocoupling Data

CLAS data:

Nπ 2009 — **$\pi^+\pi^-p$ 2012**

$\pi^+\pi^-p$ prelim.

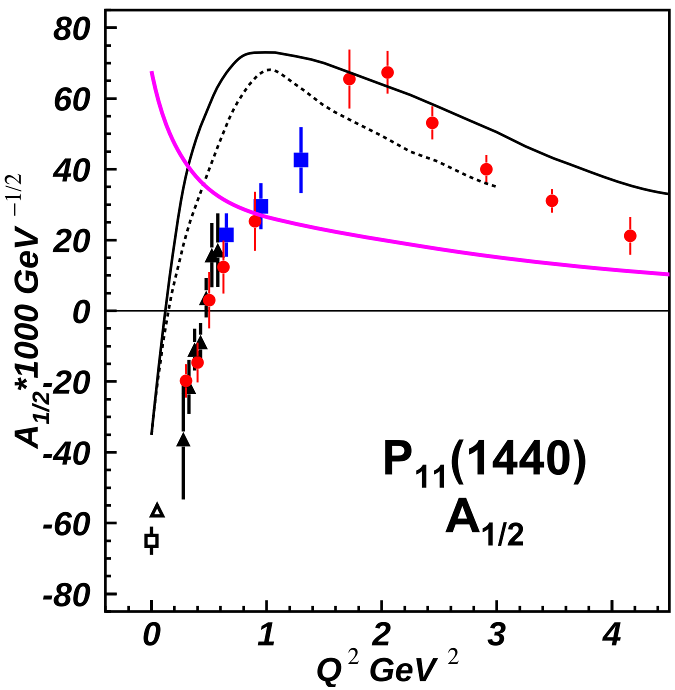
P_{11} (1440) Quark core from the quark models:

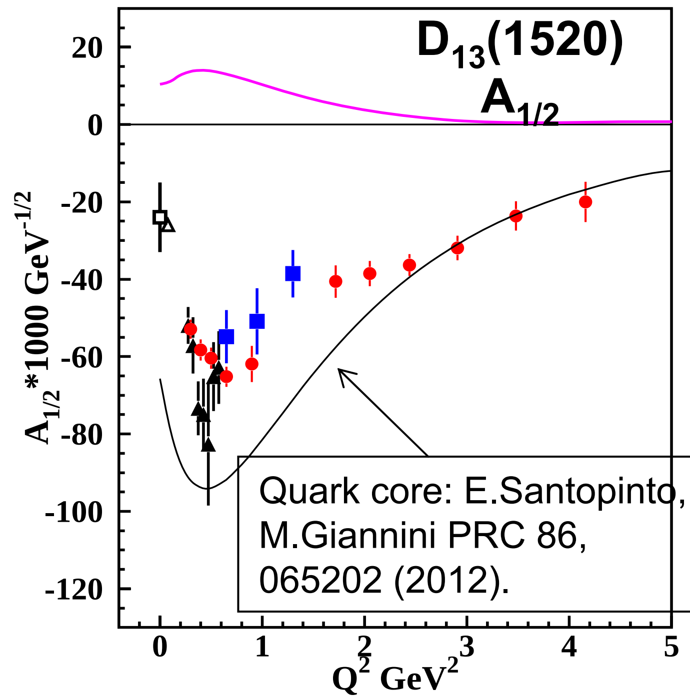
——— I.G.Aznauryan, PRC 76, 025212 (2007).

------ S.Capstick and B.D.Keister, PRD 51, 3598 (1995).

Meson-Baryon dressing: (absolute values)

——— B,Julia-Diaz et al., PRC 77, 045205 (2008).





- **Consistent values of P_{11}(1440) electrocouplings determined in independent analyses of Nπ and $\pi^+\pi^-p$ exclusive channels strongly support <u>reliable electrocoupling extraction.</u>**

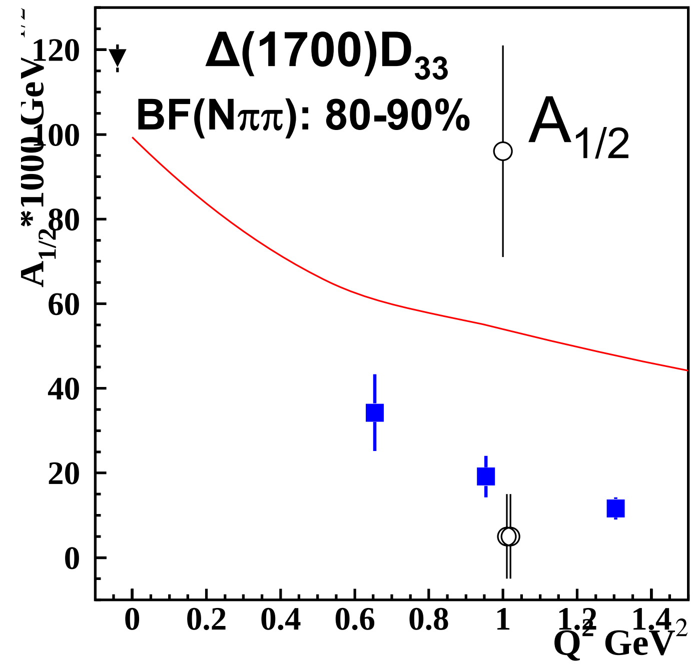
- The physics analyses of these results revealed the *P_{11}(1440)* and D_{13}(1520) structure as a combined contribution of: a) quark core as a first *radial and orbital L=1 excitations of the 3-quarks, respectively and b) meson-baryon dressing*.

High-Lying Resonance Electrocouplings from the $\pi^+\pi^-p$ CLAS Data Analysis

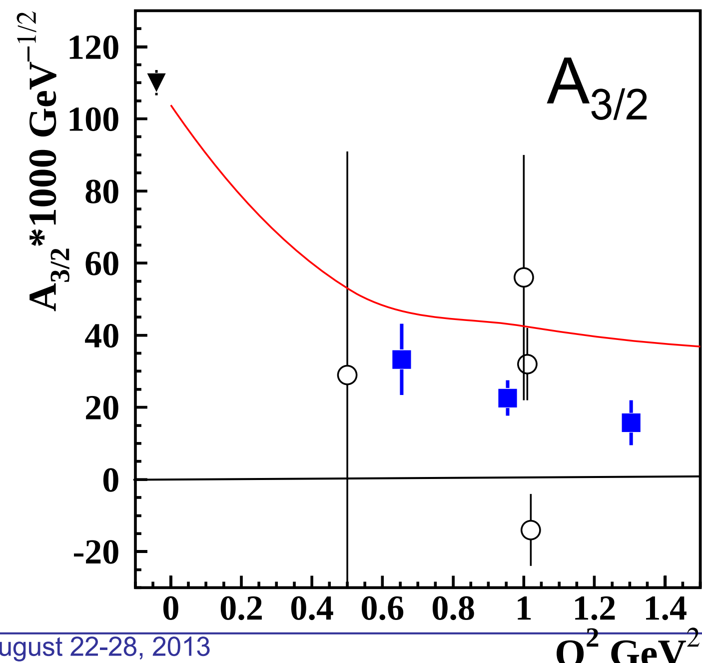
$N\pi$ world
V.D.Burkert, et al., PRC 67, 035204 (2003).

$N\pi\pi$ CLAS preliminary

$N\pi$ Q^2=0, CLAS
M.Dugger, et al., PRC 79,065206 (2009).



$\pi^+\pi^-p$ electroproduction channel provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy.



SQTM approach:
I.G. Aznauryan and V.D. Burkert, Progr. Nucl. Part. Phys. 67, 1 (2012).

Conclusions and Outlook

- **High quality meson electroproduction data from the CLAS detector allowed us to determine electrocouplings of the most excited states in the mass range of W<1.8 GeV from analyses of Nπ and Nη and N$\pi\pi$ exclusive electroproduction off protons for the first time. Consistent values of γ_vNN* electrocouplings from independent analyses of Nπ/N$\pi\pi$ and Nπ/Nη channels confirmed reliable extraction of these fundamental quantities.**

- **Analyses of γ_vNN* electrocouplings revealed the N*-structure as internal core of three constituent quarks surrounded by external meson-baryon cloud. Resonances of different quantum numbers provided complementary information on the N* structure. The data on electrocouplings of all prominent N*-states are needed.**

- **Electrocouplings of most N*-states in mass range up to 2.0 GeV will be determined in few years from analyses of N$\pi\pi$ electroproduction at photon virtualities up to 5.0 GeV^2 and will be compared with the available/future results of Nπ and KY exclusive electroproduction.**

Conclusions and Outlook

- The dedicated experiment on N* studies with the CLAS12 detector at the largest photon virtualities ever achieved in exclusive meson electroproduction $5.0<Q^2<12$ GeV^2 is tentatively scheduled for the first year of running after completion of the Jefferson Lab 12 GeV Upgrade Project.

- The N* program with the CLAS12 detector opens up the prospects to explore the nature of confinement and dynamical chiral symmetry breaking in baryons and to elucidate the emergence of >98 % of nucleon and N* masses from QCD.

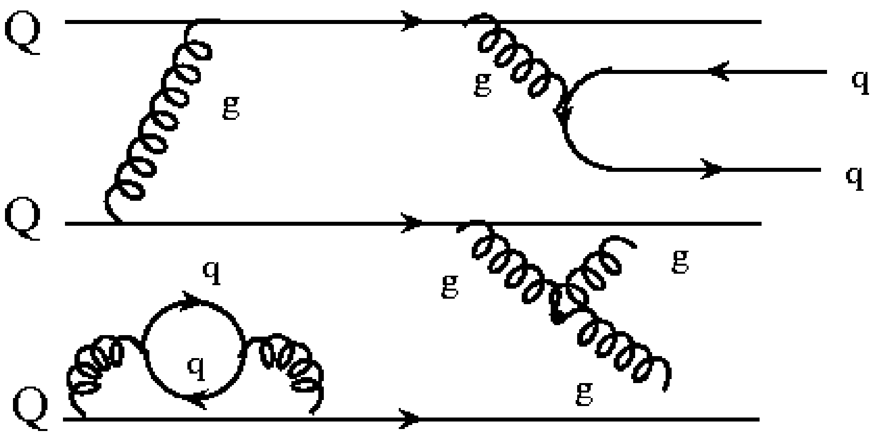
→ see the White Paper by I.G. Aznauryan et al., ``Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction“ published in Int. Journ. of Modern Physics E22 (2013) 133015 by the international group of theorists and experimentalists from USA, EU, Russia, Armenia, and Latin America.

Back up

The Ground and Excited Nucleon State Structure as a Key part in Exploration of Hadron Matter

•Nucleons and pions are the first stable composite systems of quarks and gluons generated after the Big Bang by strong interaction in non-perturbative regime. They are the building blocks of atomic nuclei

The structure of the nucleon ground state from the studies of elastic form factors and different parton structure functions:



Three valence current quarks (Q) embedded in the sea of gluons (g) and $q\bar{q}$-pairs

<u>Particular features of nucleon structure:</u>

•infinite amount of contributing current quarks and gauge gluons;
• leading role of quark/gluon creation and annihilation;
•all constituents are substantially off-shell;
•important role of relativistic effects;
•frame-dependence of nucleon structure.

Summary of the 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
$\pi^+ n$	1.1-1.40 1.1-1.55 1.1-1.7	0.15-0.40 0.3-0.6 1.7-4.2	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b
$\pi^0 p$	1.1-1.40 1.1-1.7 1.1-1.7	0.15-0.40 0.4-0.7 0.75-6.0	$d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b,A_t,A_{bt} $d\sigma/d\Omega$
ηp	1.5-2.0	0.2-4.0	$d\sigma/d\Omega$
$K^+\Lambda$	1.65-2.35 1.65-2.35	0.65-2.55 1.4-2.6	$d\sigma/d\Omega$ P’
$K^+\Sigma^0$	1.7-2.1 1.8-2.5 1.7-2.6	0.5-2.55 1.5-3.50 1.8-3.50	$d\sigma/d\Omega$ P’ $d\sigma/d\Omega$
$\pi^+\pi^- p$	1.3-1.6 1.4-2.1	0.2-0.6 0.5-1.5	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’ –recoil polarization of strange baryon

Almost full coverage of the final hadron phase space in πN, $\pi^+\pi^-$p, ηp, and KY electroproduction

The data are available in the CLAS Physics Data Base establiished at SINP@MSU:

http://depni.sinp.msu.ru/cgi-bin/jlab/db.cgi

Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

- **Analyses of different meson electroproduction channels independently:**

➢ π^+n and π^0p channels:

Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)

I.G.Aznauryan, Phys. Rev. C67, 015209 (2003).

I.G.Aznauryan et al., CLAS Coll., Phys Rev. C80, 055203 (2009).

➢ ηp channel:

Extension of UIM and DR

I.G.Aznauryan, Phys. Rev. C68, 065204 (2003).

Data fit at W<1.6 GeV, assuming $S_{11}(1535)$ dominance

H.Denizli et al., CLAS Coll., Phys.Rev. C76, 015204 (2007).

➢ $\pi^+\pi^-p$ channel:

Data driven JLAB-MSU meson-baryon model (JM)

V.I.Mokeev, V.D.Burkert et al., Phys. Rev. C80, 045212 (2009).

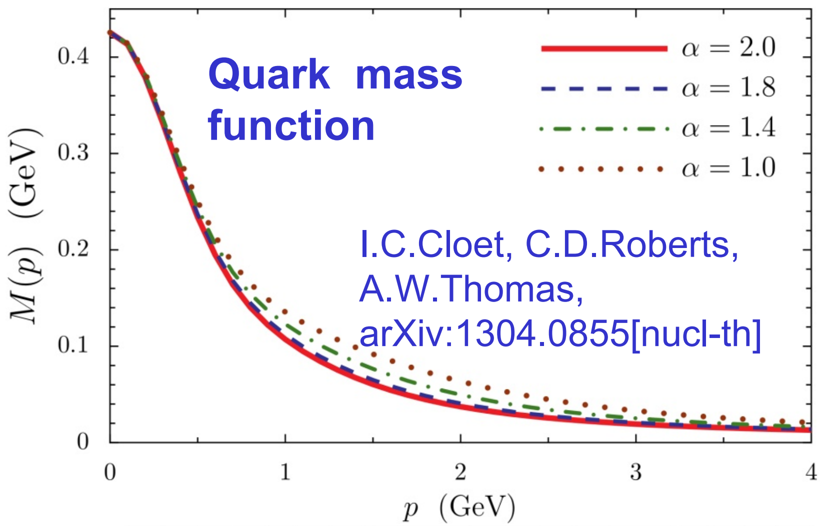
V.I.Mokeev et al., CLAS Coll., Phys. Rev. C86, 035203 (2012).

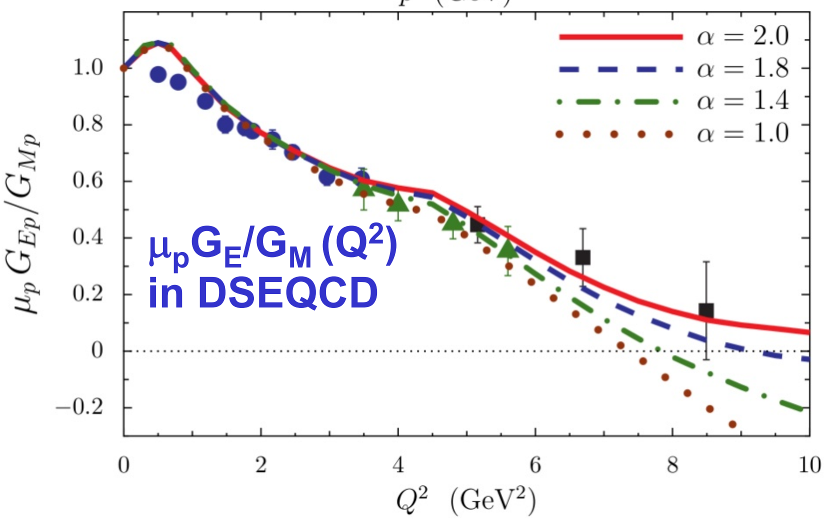
- **Global coupled-channel analyses of the CLAS/world data of $\pi N, \gamma_v N \rightarrow \pi N, \eta N, \pi\pi N, K\Lambda, K\Sigma$ exclusive channels:**

H. Kamano, S. Nakamura, T.-S. H. Lee and T. Sato, AIP Conf.Proc. 1432 (2012) 74-79.

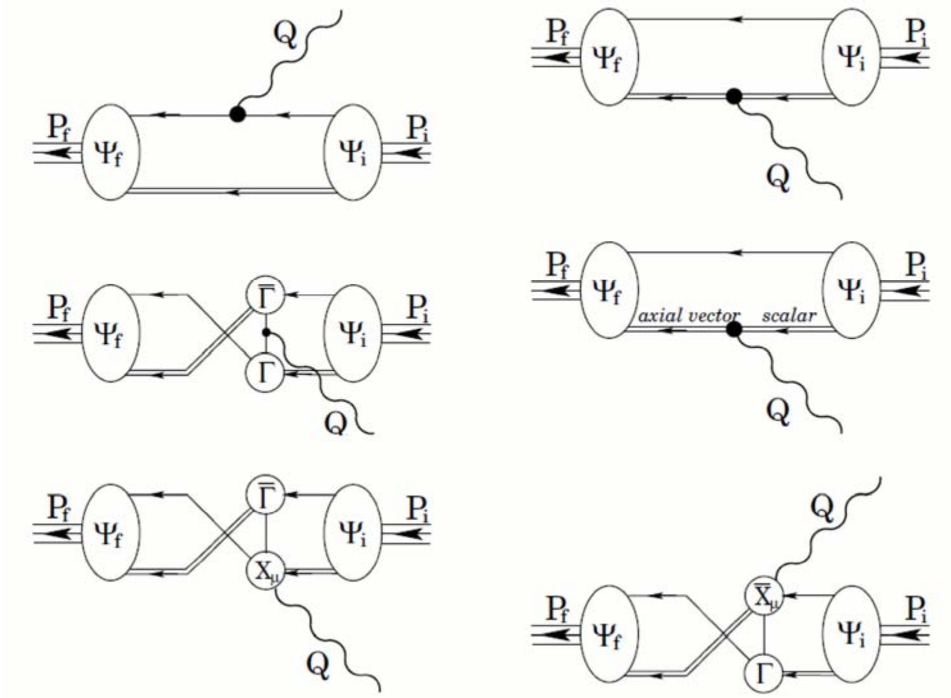
H. Kamano, S. Nakamura, T.-S. H. Lee and T. Sato, arXiv:1305.4351[nucl-th].

Mapping Dressed Quark Mass Function





Description of N* electroexcitation in DSEQCD



Similar studies for the $P_{33}(1232)$, $P_{11}(1440)$, and $S_{11}(1535)$ electrocouplings are in progress.

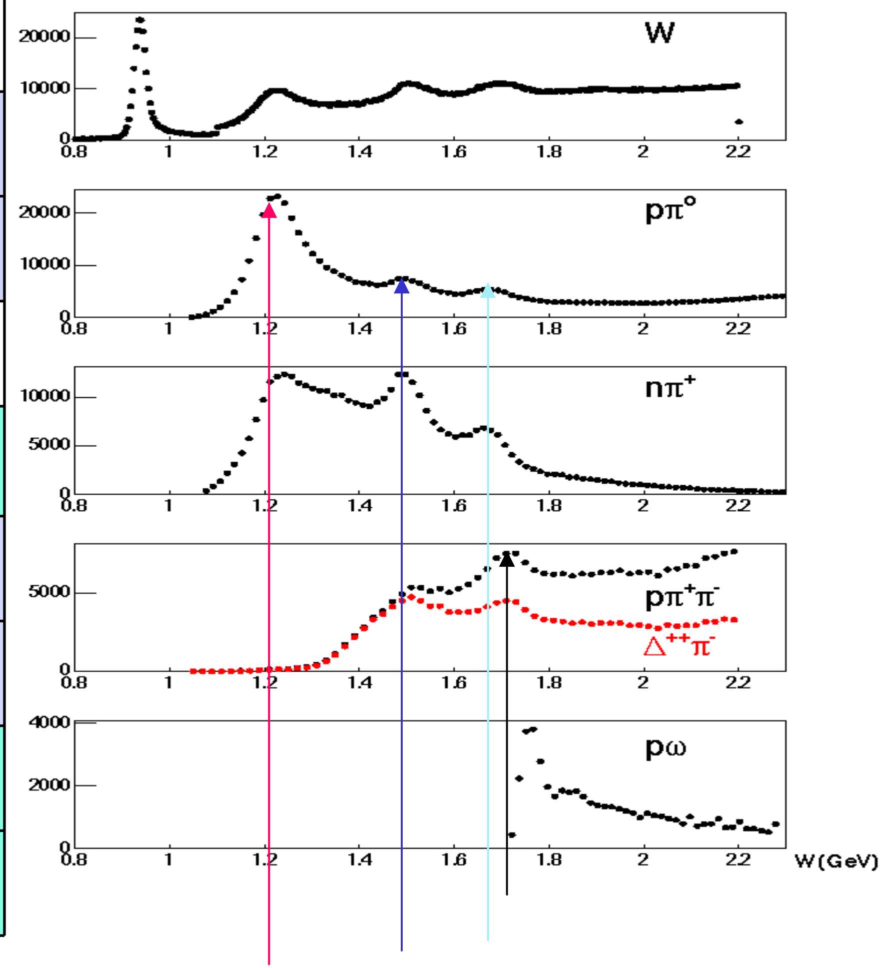
- **Elastic form factors are sensitive to momentum dependence of quark mass function.**
- **Quark mass function extracted from elastic f.f. and $\gamma_v NN^*$ electrocouploings should be the same.**
- **Data on $\gamma_v NN^*$ electrocouplings are of particular importance in order to access dressed quark mass function and dynamical structure.**

N* Electroexcitation in Exclusive Meson Electroproduction off Protons

Hadronic decays of prominent N*s at W<1.8 GeV.

State	Bran. Fract. to $N\pi$.	Bran. Fract. to $N\eta$	Bran.Fract. $N\pi\pi$
$\Delta(1232)P_{33}$	0.995		
$N(1440)P_{11}$	0.55-0.75		0.3-0.4
$N(1520)D_{13}$	0.55-0.65		0.4-0.5
$N(1535)S_{11}$	0.48±0.03	0.46±0.02	
$\Delta(1620)S_{31}$	0.20-0.30		0.70-0.80
$N(1650)S_{11}$	0.60-0.95	0.03-0.11	0.1-0.2
$N(1685)F_{15}$	0.65-0.70		0.30-0.40
$\Delta(1700)D_{33}$	0.1-0.2		0.8-0.9
$N(1720)P_{13}$	0.1-0.2		> 0.7

CLAS data on yields of meson electroproduction at $Q^2<4$ GeV^2



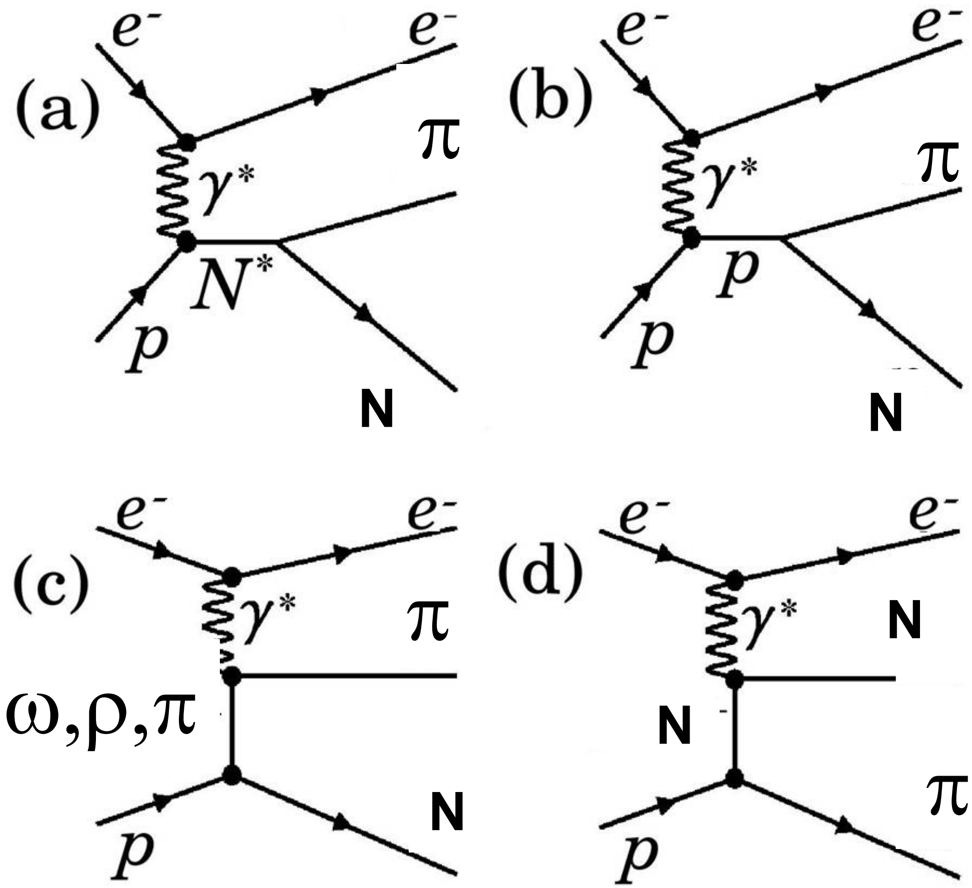
The Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from $N\pi$ Exclusive Electroproduction off Protons

The Model based on fixed-t Dispersion Relations (DR)

•the real parts of 18 invariant $N\pi$ electroproduction amplitudes are computed from their imaginary parts employing model independent fixed-t dispersion relations.

•the imaginary parts of the $N\pi$ electroproduction amplitudes at W>1.3 GeV are dominated by resonant parts and were computed from N* parameters fit to the data.

Unitary Isobar Model (UIM)



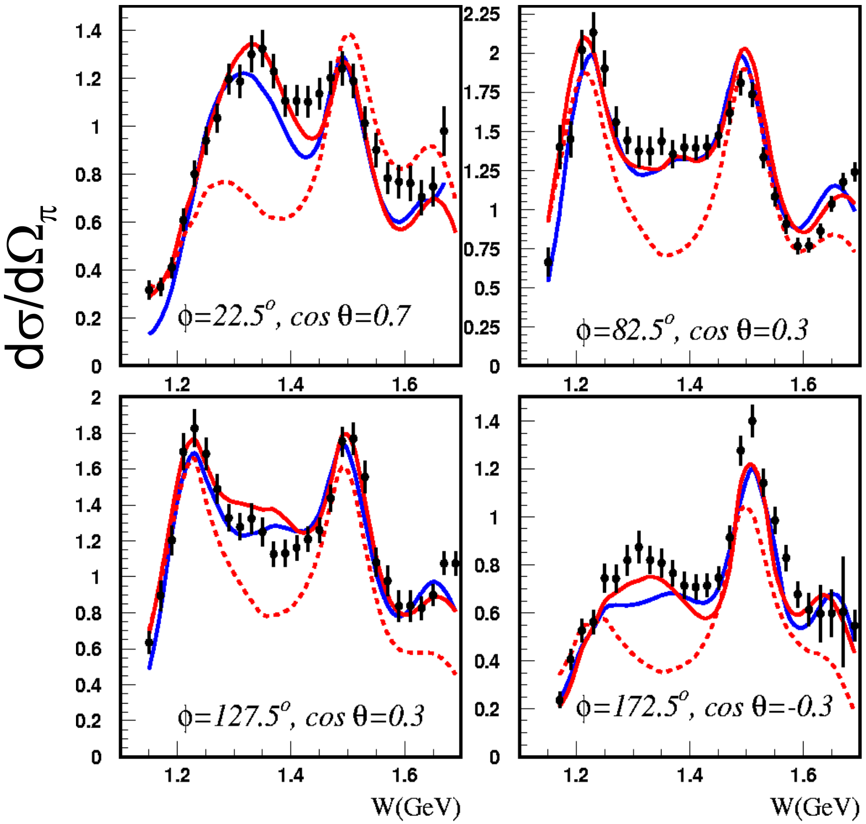
I. G.Aznauryan, Phys. Rev. C67, 015209 (2003), I.G.Aznauryan, V. D.Burkert, et al. (CLAS Collaboration), PRC 80. 055203 (2009).

➡ K.Park talk, Session B4, Wednesday , May 29th , 16.15-16.40

Fits to γp→π⁺n Differential Cross Sections and Structure Functions

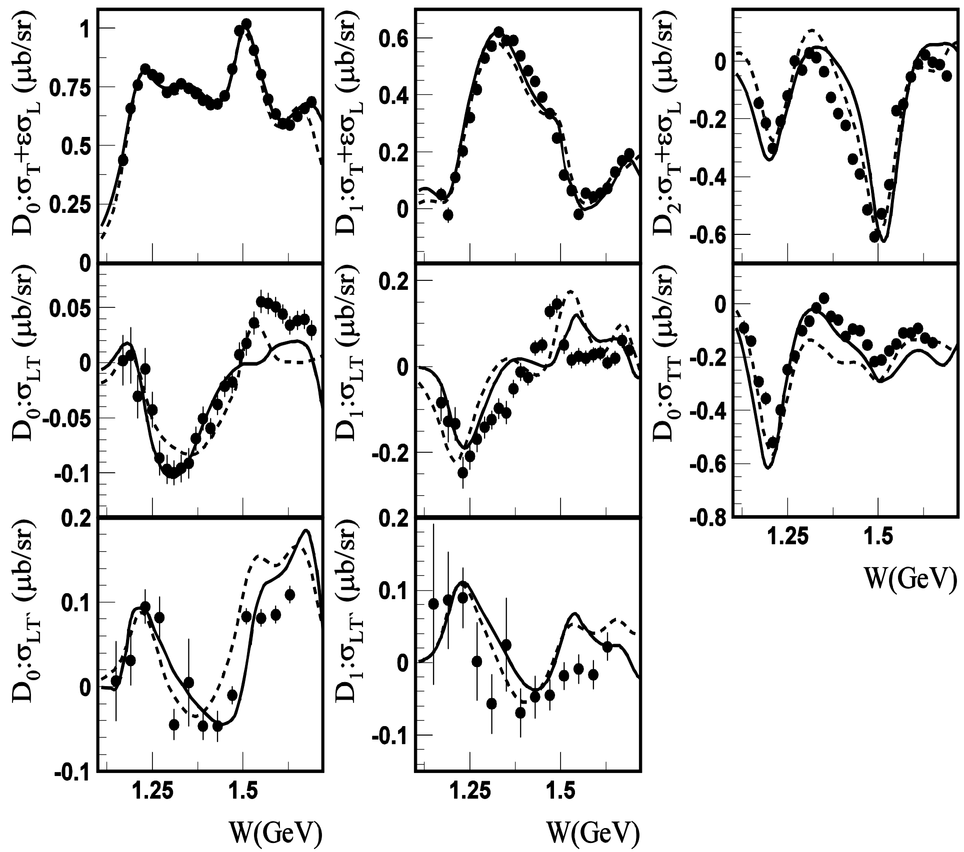
Q^2=2.05 GeV^2

DR
DR w/o P11
UIM



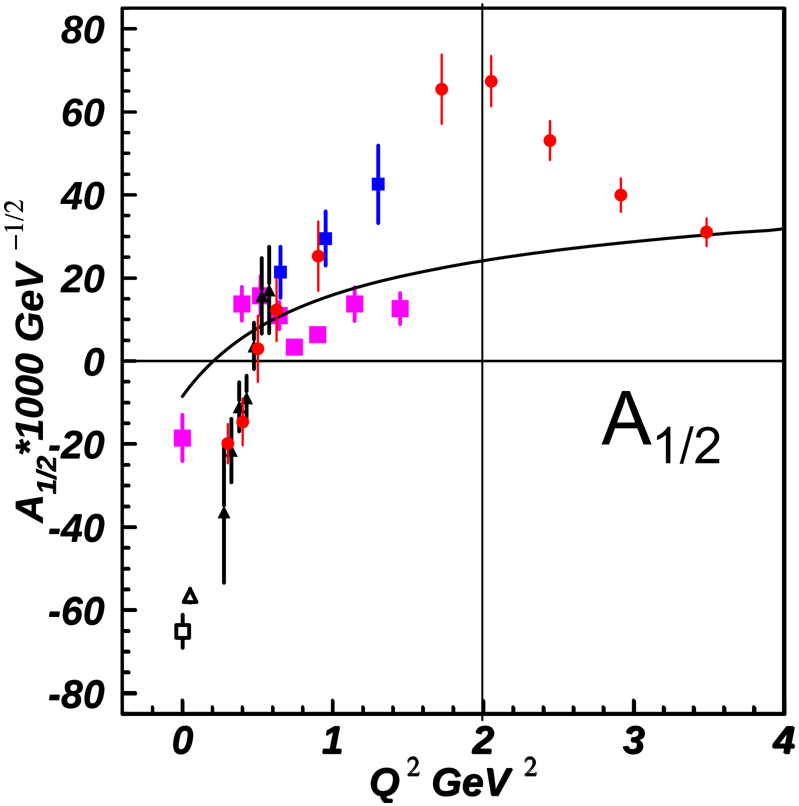
Q^2=2.44 GeV^2

DR
UIM



Legendre moments D_l (l=0,1,2) from various structure functions

Quark Core vs Meson-Baryon Cloud in the Structure of $P_{11}(1440)$



First evaluation of the quark core contribution to the $P_{11}(1440)$ electrocouplings starting from QCD Lagrangian within Dyson-Schwinger Equations of QCD:

D.J.Wilson, et al, Phys. Rev. C85, 025205 (2012).

- **Poincare-covariant, symmetry preserving DSEQCD evaluation.**
- **Account for quark mass/structure formation in dressing of bare quark by gluon cloud.**
- **Simplified contact interaction generates momentum independent quark mass.**

$$g^2 D_{\mu\nu}(p-q) \Rightarrow \delta_{\mu\nu} \frac{4\pi\alpha_{IR}}{m_G^2}$$

$$\frac{\alpha_{IR}}{4\pi} = 0.93 \qquad m_G = 0.8GeV$$

$$m_q^{bare} = 0.007\,GeV \Rightarrow m_q^{dressed} = 0.368\,GeV$$

Consistent results on the quark core contribution from:

DSEQCD.

global meson photo-, electro-, and hadroproduction data analysis within EBAC/ Argonne-Osaka approach.

Measured dressed electrocouplings are substantially different from the estimated quark core contribution. Different data analyses suggest sizable meson-baryon cloud at Q^2<5.0 GeV^2 which gradually decreases with Q^2.

High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

MAID analysis of $N\pi$ electroproduction L.Tiator et al., Eur. Phys. J. Spec. Top. 198, 141 (2011).

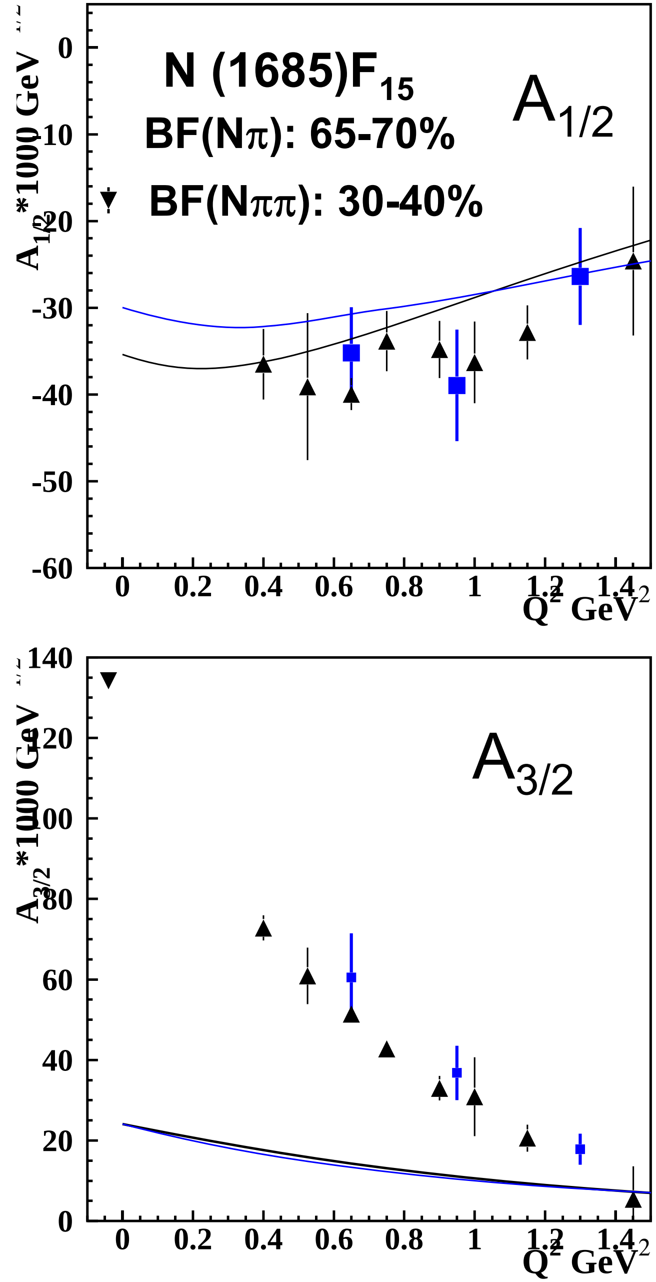
The results from $\pi^+\pi^-p$ channel confirmed the previously available from MAID analysis of $N\pi$ electroproduction

Hypercentral constituent quark model by M.M.Giannini, E.Santopinto, PRC 86, 065202 (2012).

Bethe-Salpeter Bonn model by M.Ronninger, B.Ch.Metsch, EPJ A49, 8 (2013).

Difference between the experimental results and QM expectations is likely related to meson-baryon cloud contributions.

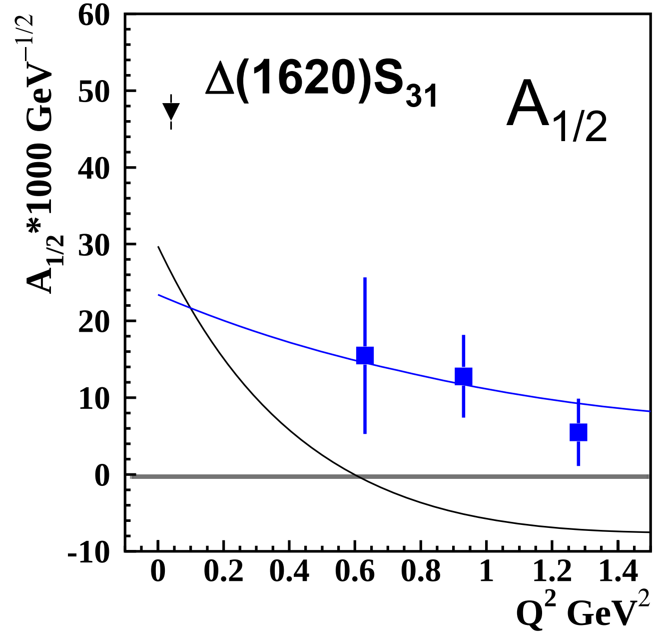
Evaluations of meson-baryon cloud contributiions to electrocouplings of high mass resonances are needed.



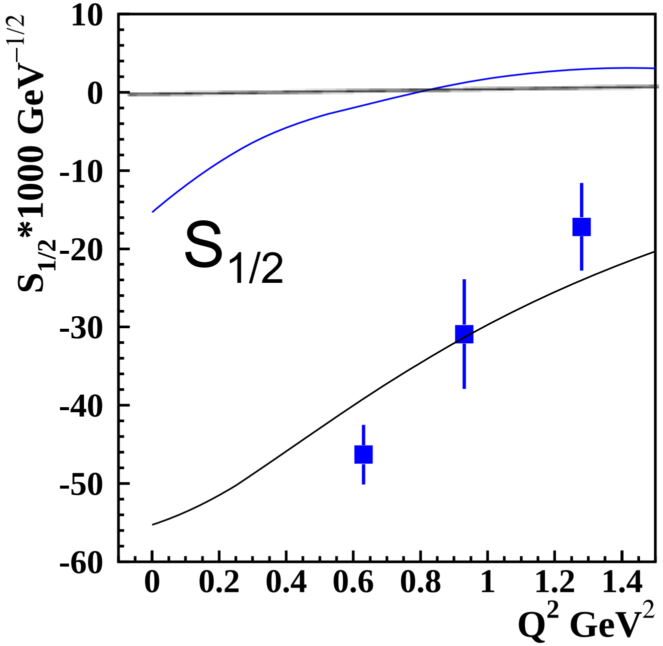
High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

Hypercentral constituent quark model by M.Giannini,E.Santopinto, PRC 86, 065202 (2012).

Bethe-Salpeter Bonn model by M.Ronninger, B.Ch.Metsch, EPJ A49, 8 (2013).

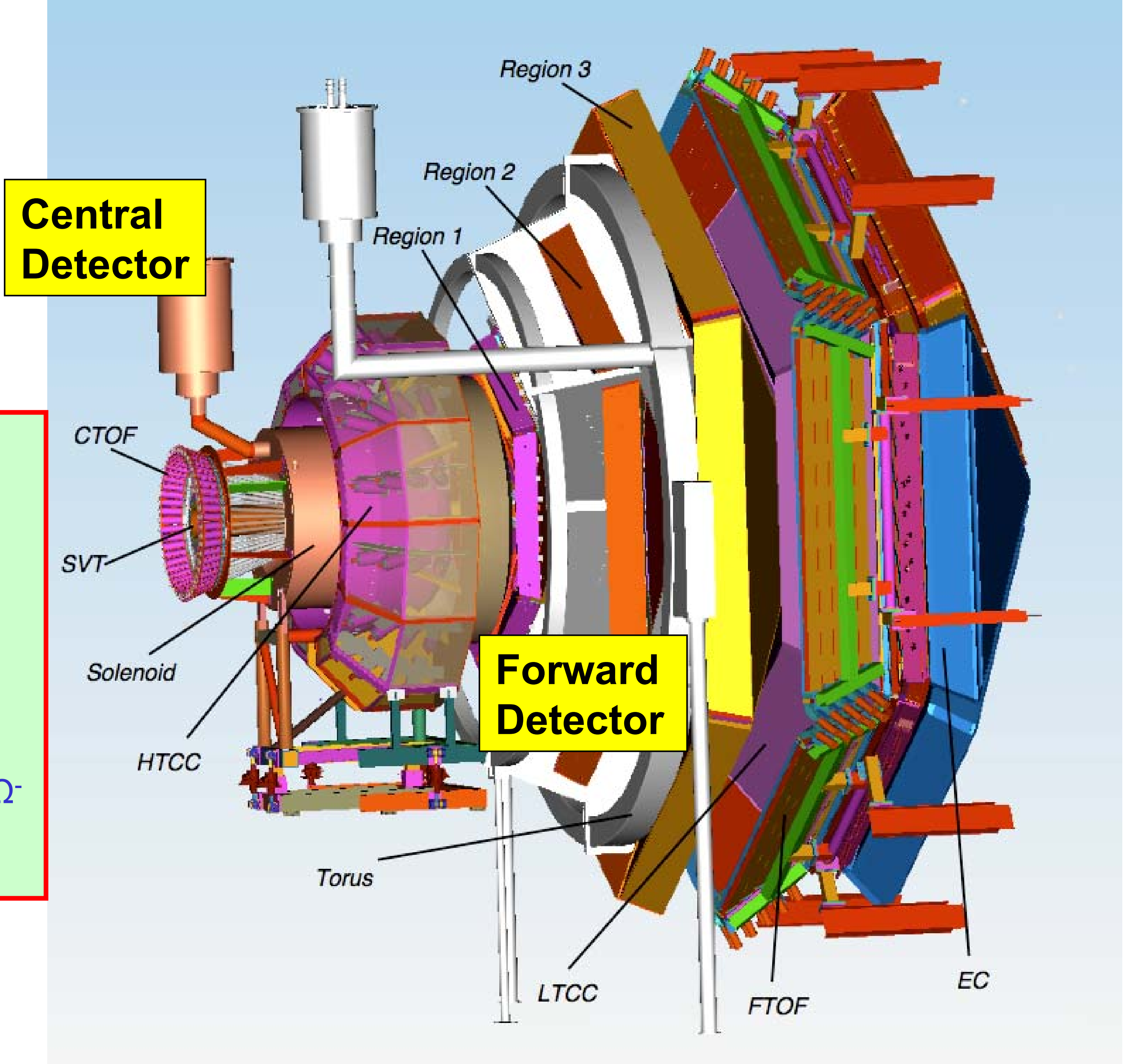


- Only known N*-state with dominant longitudinal electroexcitation at Q^2>0.5 GeV^2 .
- This feature is well reproduced within the framework of hypercentral quark model.



- Data on electrocouplings of most excited proton states in mass range up to 1.8 GeV demonstrated distinctive differences in the structure of resonances of different quantum numbers.
- The studies of the ground and all prominent excited state structure combined are needed in order to explore the mechanisms of the ground and N*-state formation from quarks and gluons.

CLAS12



CLAS12 **supports a broad program in hadronic physics.**

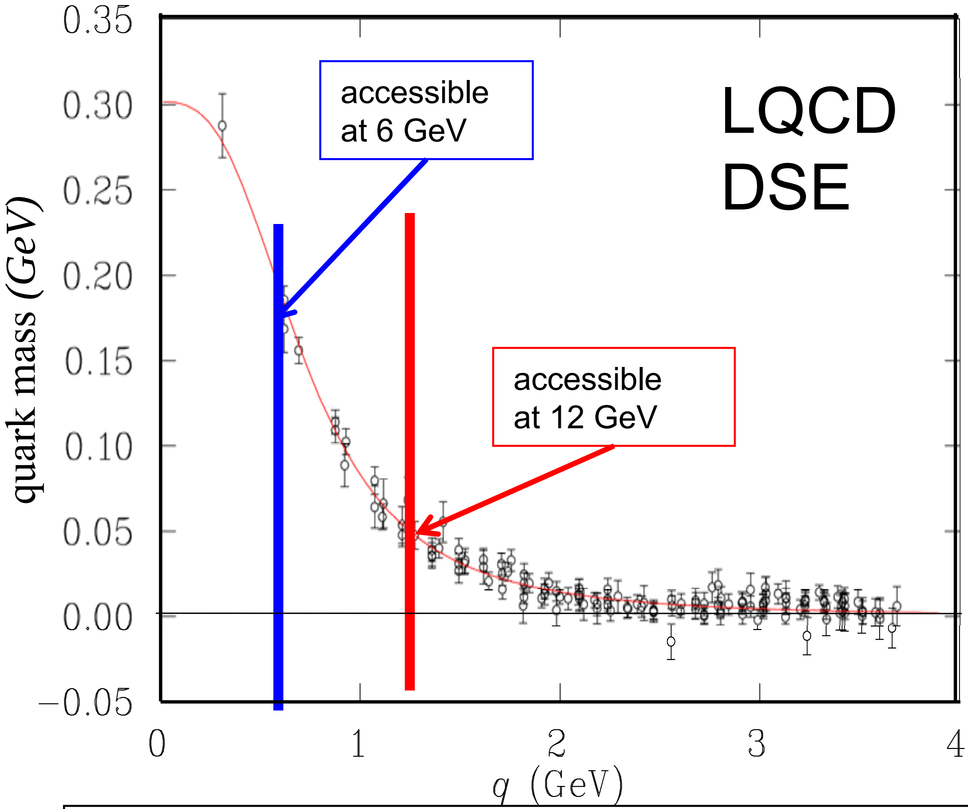
Plans to study excited baryons and mesons:

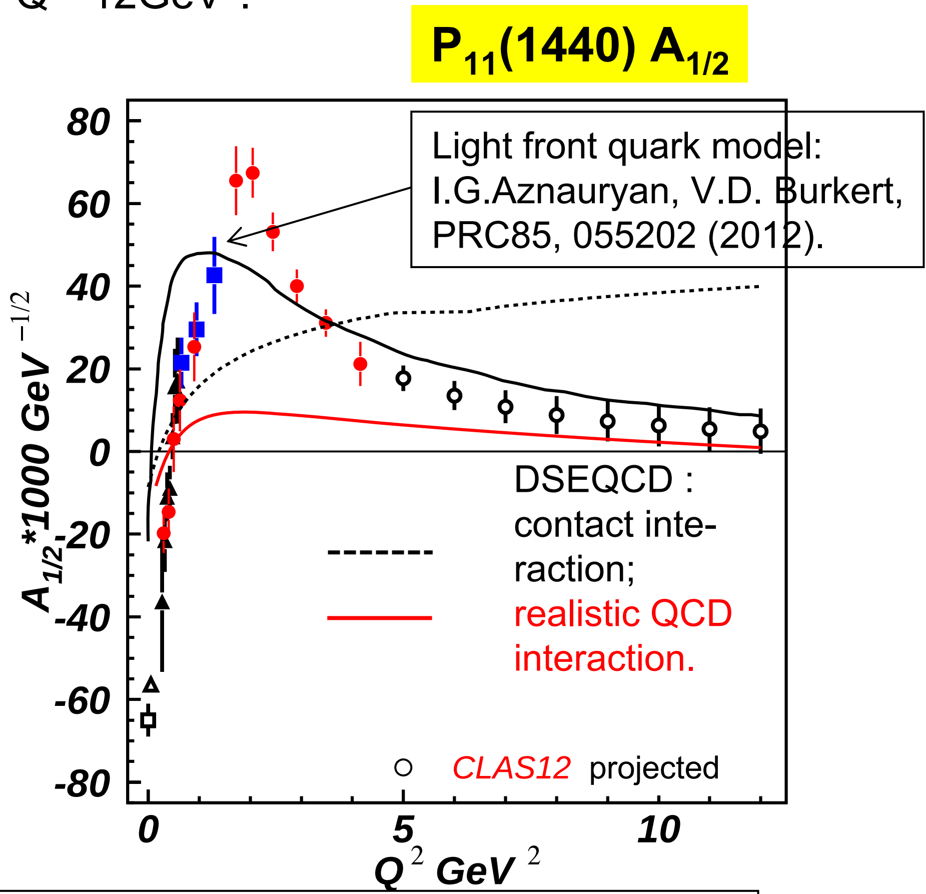
- Search for hybrid mesons and baryons
- Spectroscopy of Ξ* , Ω^-
- **N* Transition form factors at high Q^2.**

Resonance Transitions with the CLAS12

Resonance electrocouplings in regime of quark core dominance can be related to the running quark masses and their dynamical structure.

12 GeV experiment E12-09-003 will extend access to electrocouplings for all prominent N* states in the range up to Q^2=12GeV^2.





Probe the transition from confinement to pQCD regimes, allowing us to explore how confinement in baryons emerge from QCD and how >98 % of baryon masses are generated non-perturbatively via dynamical chiral symmetry breaking.

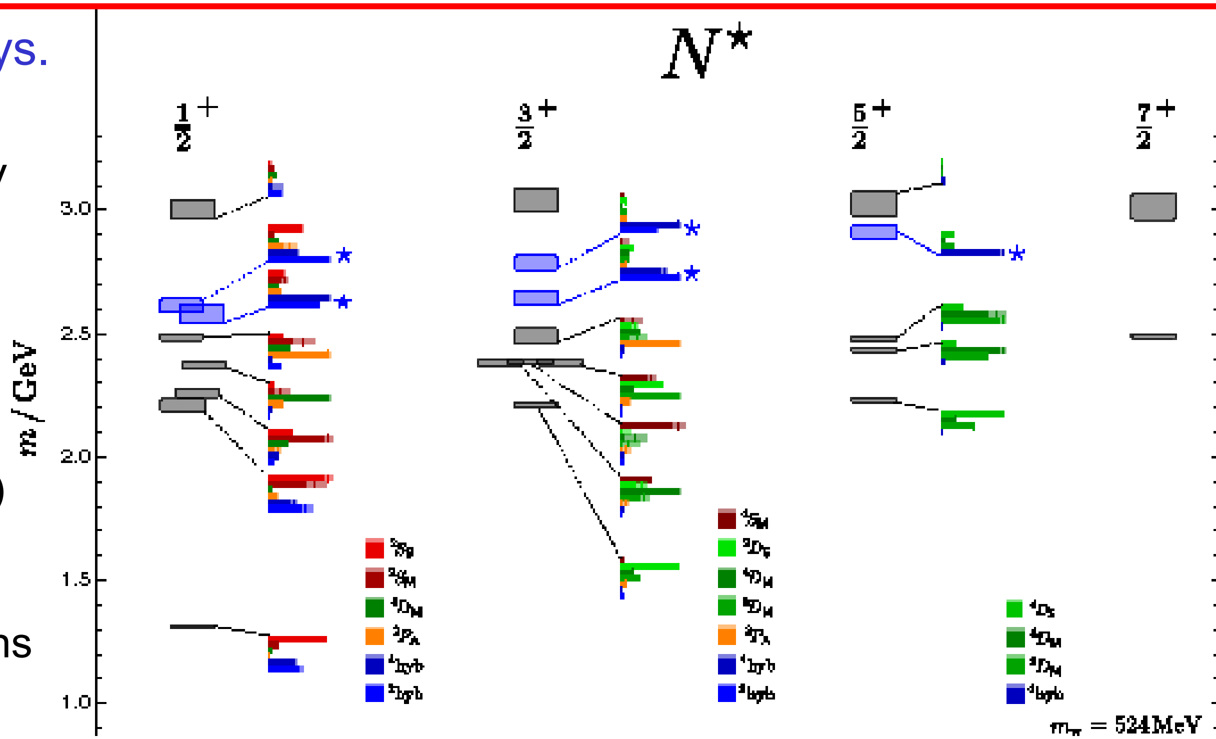
Impact of the Recent LQCD studies of N* Spectrum and Structure on the N* Program with CLAS/CLAS12

J.J.Dudek, R.G.Edwards, Phys. Rev. D85, 054016 (2012).

•each N* state with M_{N^*} <1.8 GeV has partner in computed LQCD spectrum, but level ordering is not always consistent to the data

•wave functions of the low-lying N* states dominate by 1-2 SU(6) configurations, while the wave function of high lying N*'s may contain many SU(6) configurations

•presence of hybrid-N*s with dominant contribution of hybrid components at M_{N^*}>1.9 GeV marked by ★



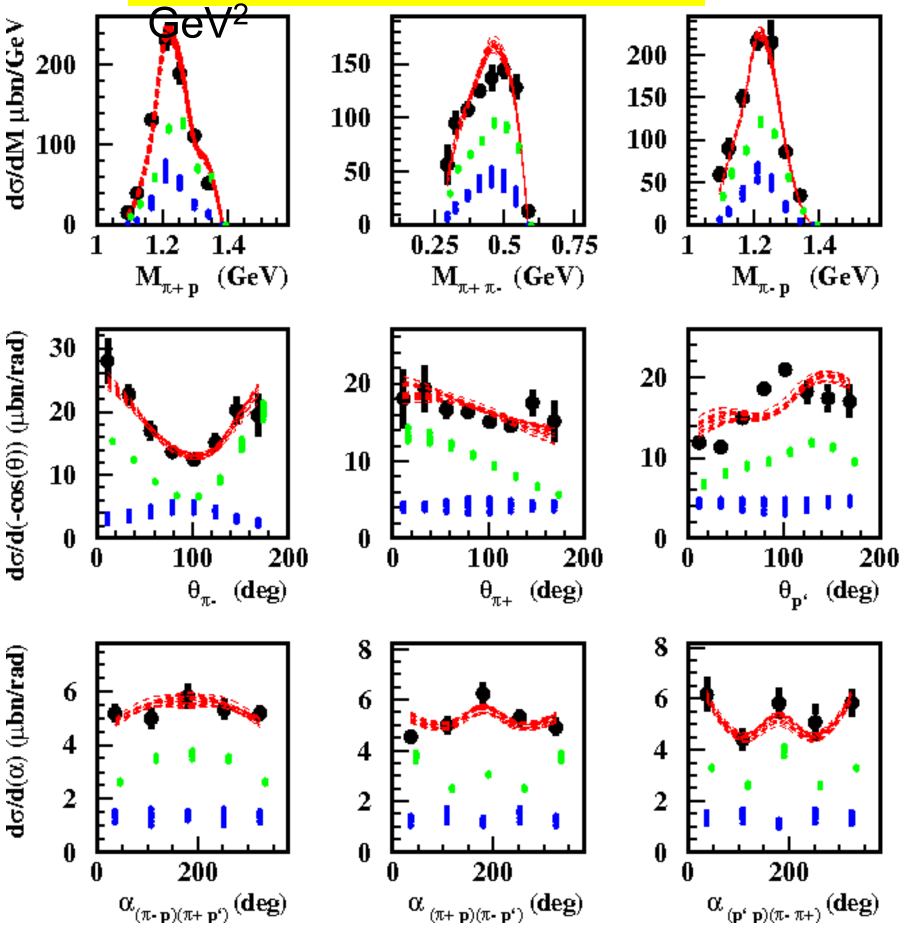
Should be verified by experiment !

New direction in N* studies proposed in V.D.Burkert, arXiv:1203.2373 [nucl-ex]:
Search for hybrid N*-states looking for:

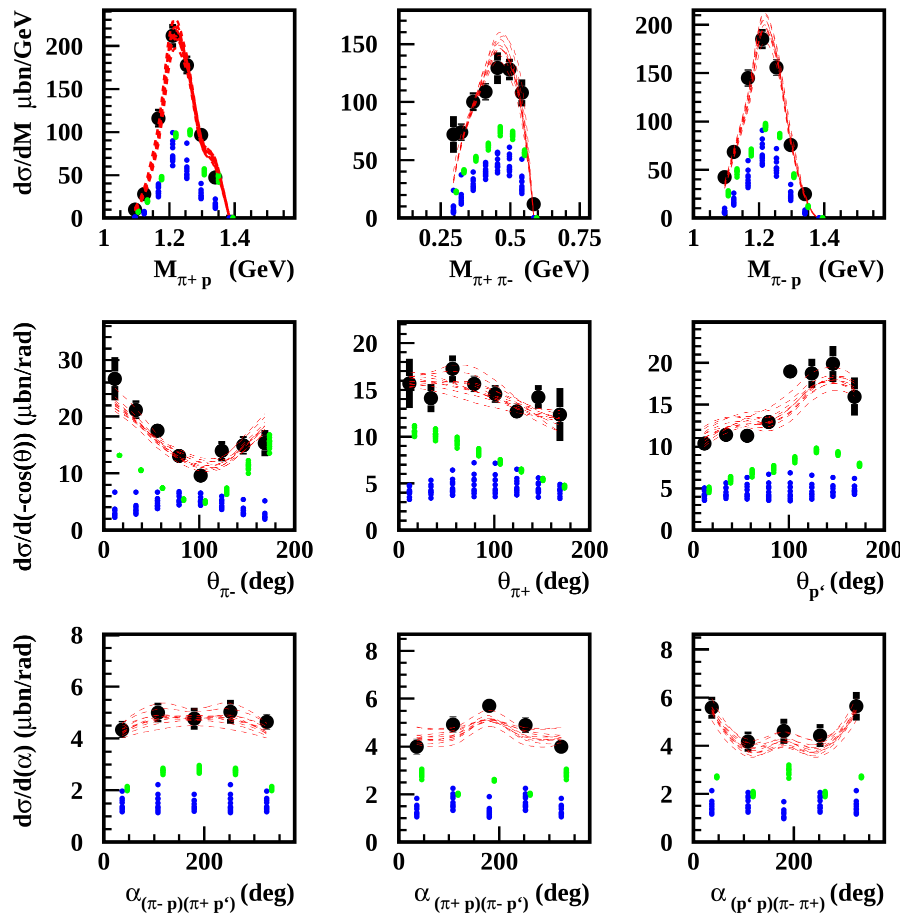
- **overpopulation of SU(6)-multiplet;**
- **particular behavior of γ_vNN* electrocouplings, which reflects presence of the hybrid component.**

Resonant /non-resonant contributions from the fit of $\pi^+\pi^-p$ electroproduction cross sections within the JM model

W=1.51 GeV, Q^2=0.38 GeV^2



W=1.51 GeV, Q^2=0.43 GeV^2



Reliable isolation of the resonant cross sections is achieved

full cross sections within the JM model

resonant part

non-resonant part

Transition N-P_{11}(1440) form factors in LQCD

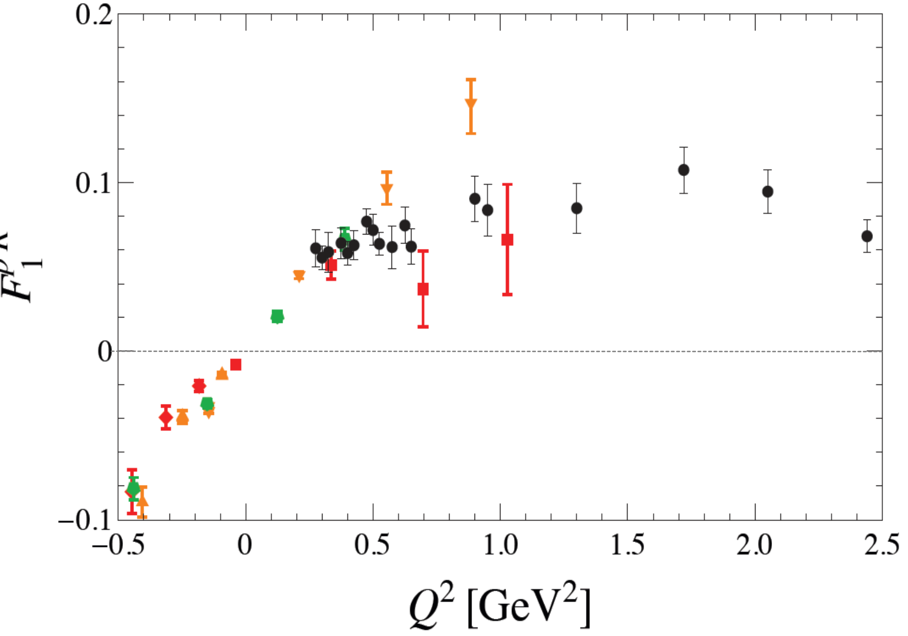
Includes the quark loops in the sea , which are critical in order to reproduce the CLAS data at Q^2<1.0 GeV^2

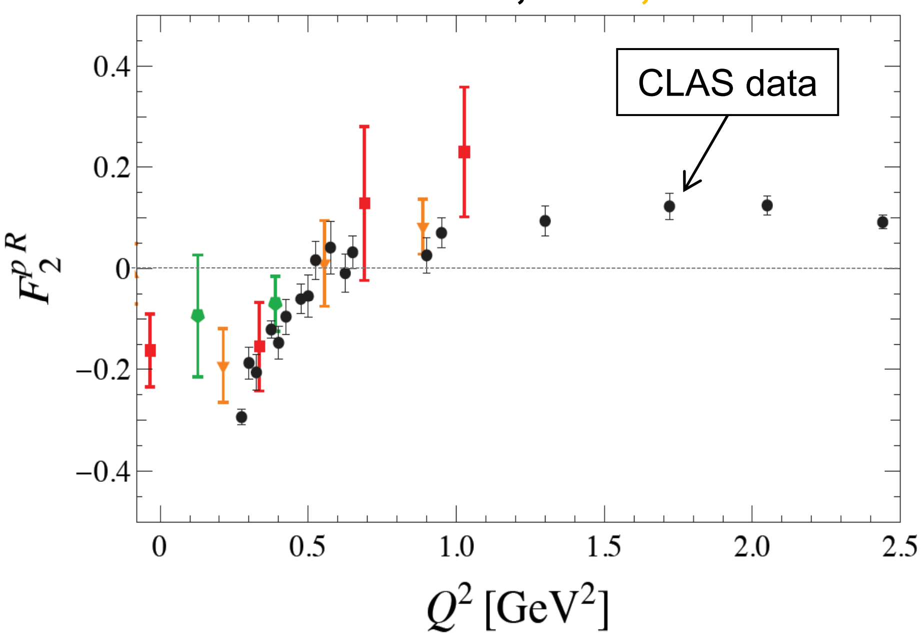
$A_{1/2}$, $S_{1/2}$ => F_1^*, F_2^*

H.W. Lin and S.D. Cohen, arXiv:1108.2528

M_π = 390, 450, 875 MeV

L box =3.0, 2.5, 2.5 f





•Exploratory LQCD results provide reasonable description of the CLAS data from the QCD Lagrangian.

•Prospects for LQCD evaluation with improved projection operators, approaching physical mp in the box of appropriate size.