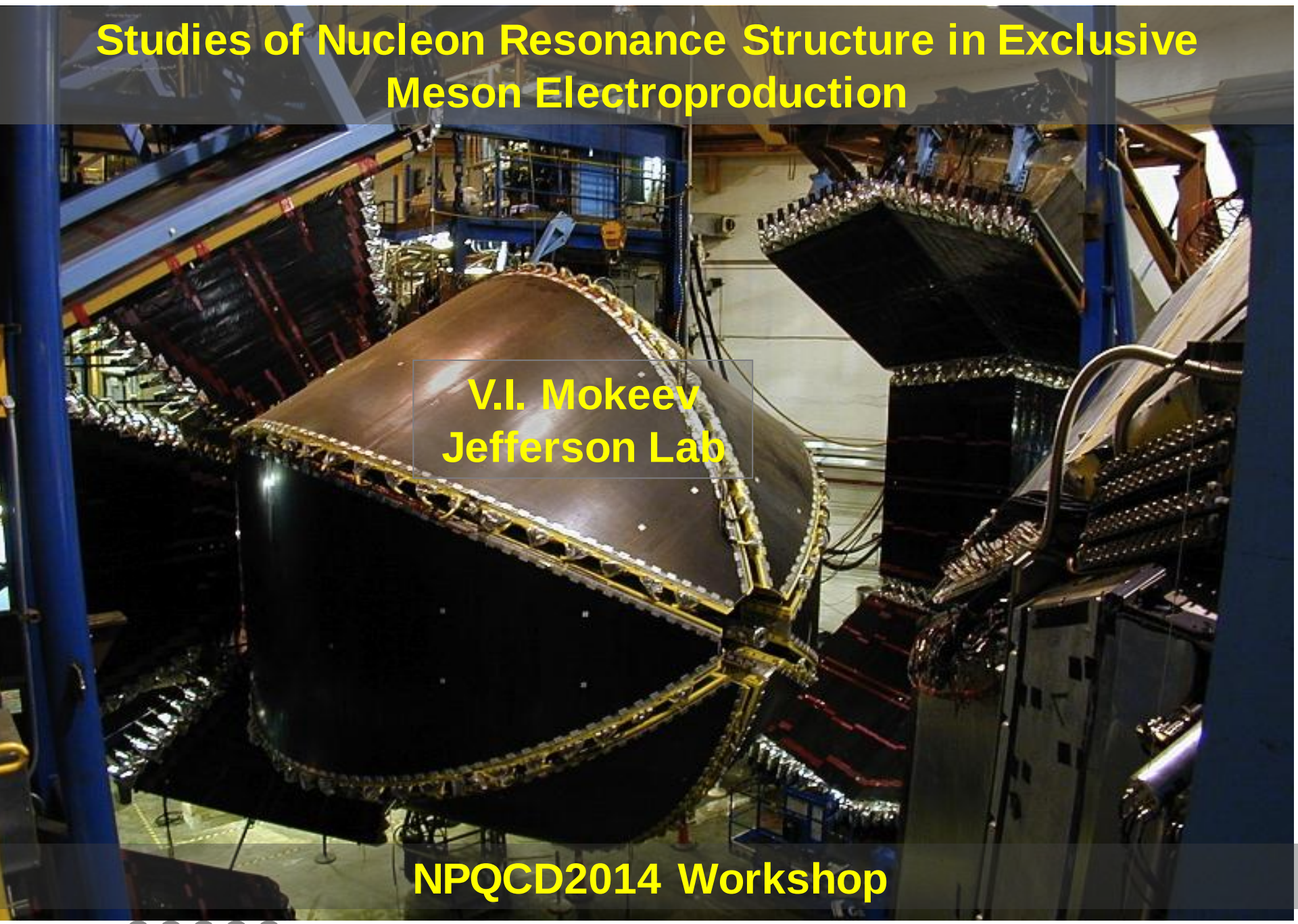
Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction



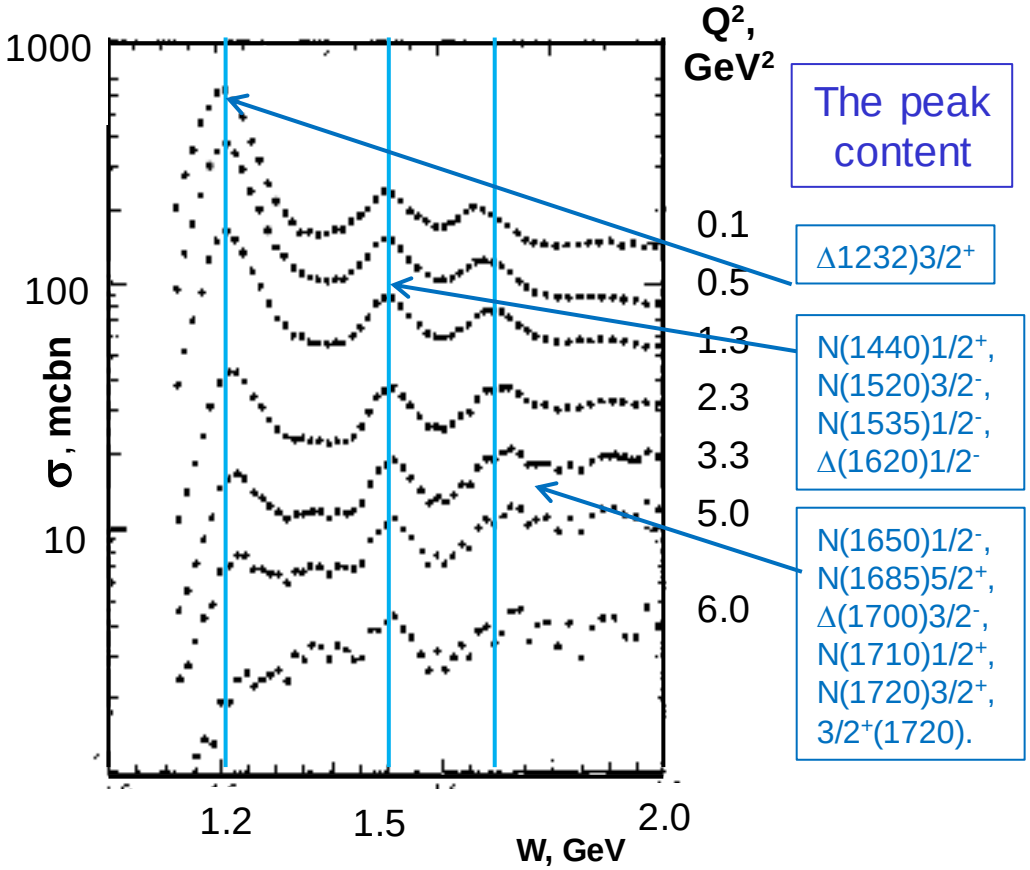
V.I. Mokeev
Jefferson Lab

NPQCD2014 Workshop

Nucleon Resonances in Inclusive Electron Scattering

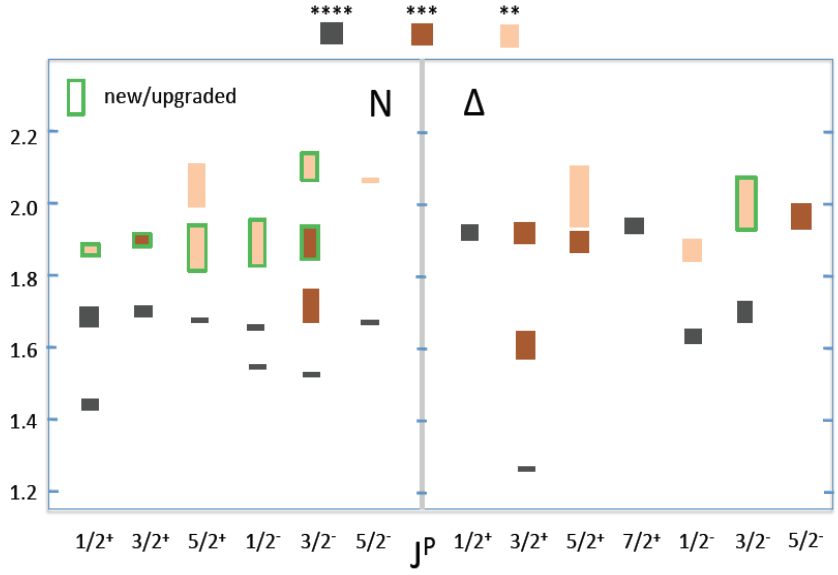
Total virtual photon cross sections

F. Foster and G.Hughes, Rep. Progr. Phys. 46, 1445 (1983).



Excited nucleon state spectrum

Status of 2014 after updates provided by analyses of the recent exclusive meson photoproduction data from JLAB, ELSA, MAMI, GRAAL, LEPS (V. D. Burkert, Int. J. Mod. Phys. Conf. Ser.,26, 1460050 (2014)).



Quantum excitations of nucleon constituents (infinite amount of current quarks and gauge gluons) should generate the spectrum of excited N*-states.

Data on all essential <u>exclusive</u> meson electroproduction channels are needed in order to determine parameters of prominent nucleon resonances.

N* Studies in Exclusive Meson Electroproduction with CLAS

Our experimental program seeks to determine

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

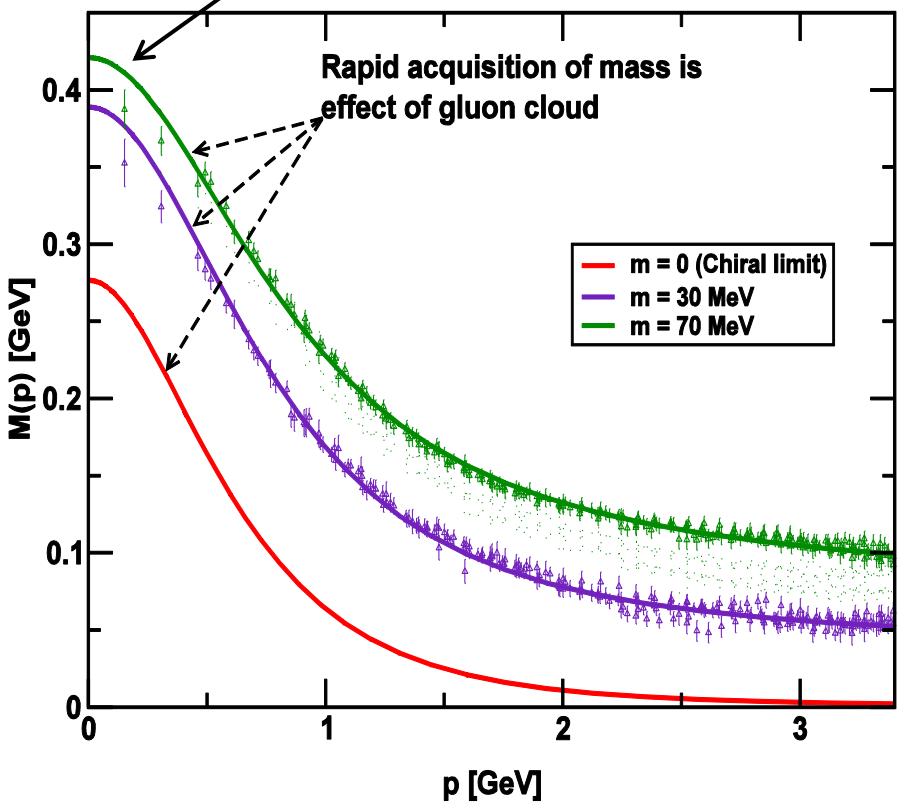
Unique source of information on different manifestations of the non-perturbative strong interaction in the generation of different excited nucleons and their emergence from QCD.

See details in the review papers:

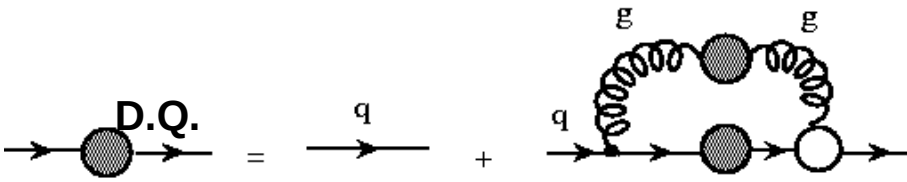
1. **I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).**
2. **I.G. Aznauryan et al., Int. J. Mod. Phys. E22, 133015 (2013).**
3. **I. C. Cloët and C. D. Roberts, Prog. Part. Nucl. Phys, 77, 1 (2014).**
4. **A. Bashir et al., Comm. Theor. Phys. 58, 79 (2012).**

Dynamical Constituents of the Ground and Excited Nucleons

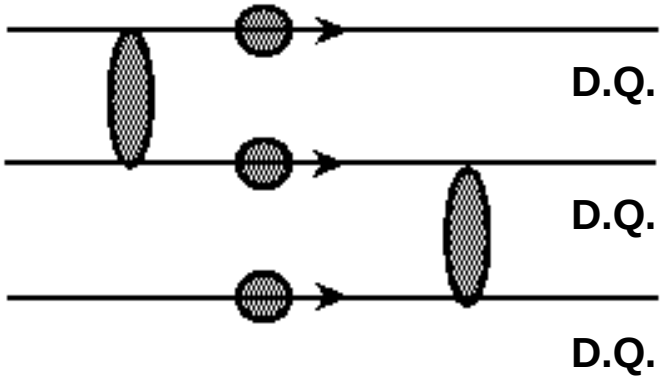
quark/gluon confinement



Emergence of dressed dynamical quarks:



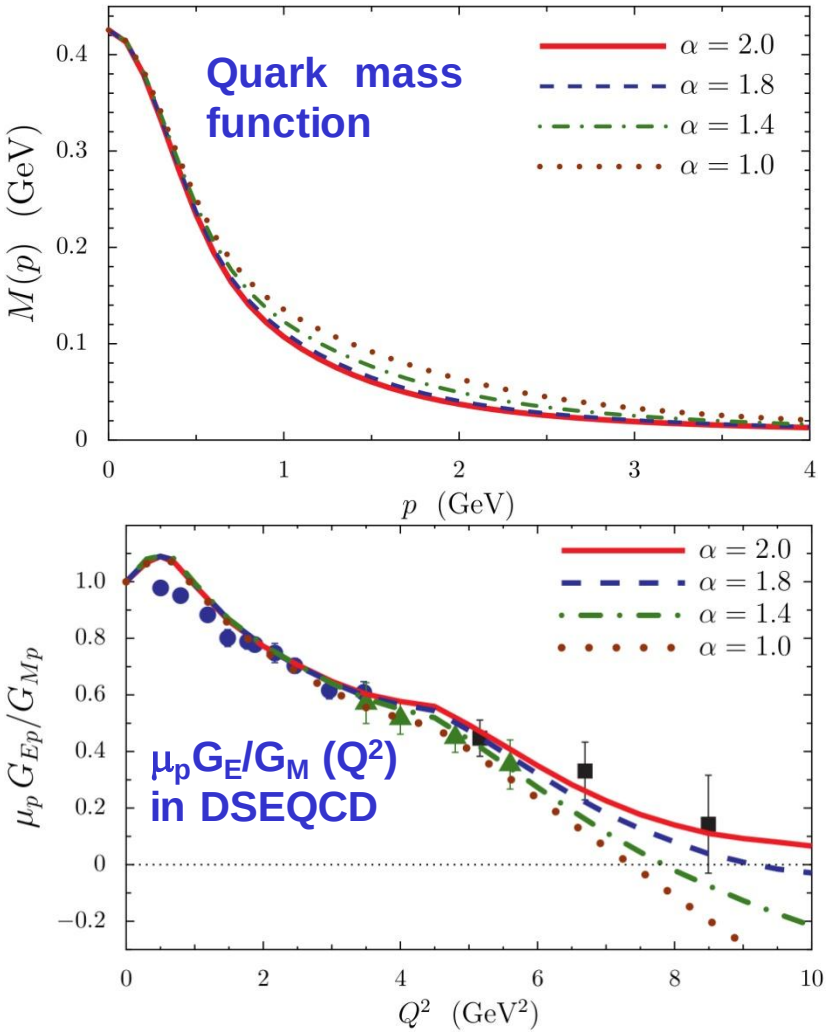
N/N* states as the bound systems of dressed dynamical quarks:



- **more than 98% of dressed quark (N/N*) masses as well as their dynamical structure are generated non-perturbatively through dynamical chiral symmetry breaking (DCSB). The Higgs mechanism accounts for less than 2% of the nucleon and N* mass.**

- **the momentum dependence of the dressed quark mass reflects the transition from quark/gluon confinement to asymptotic freedom.**

Mapping Dressed Quark Mass Function from the Results on Elastic and Transition $\gamma_v NN^*$ Electrocouplings



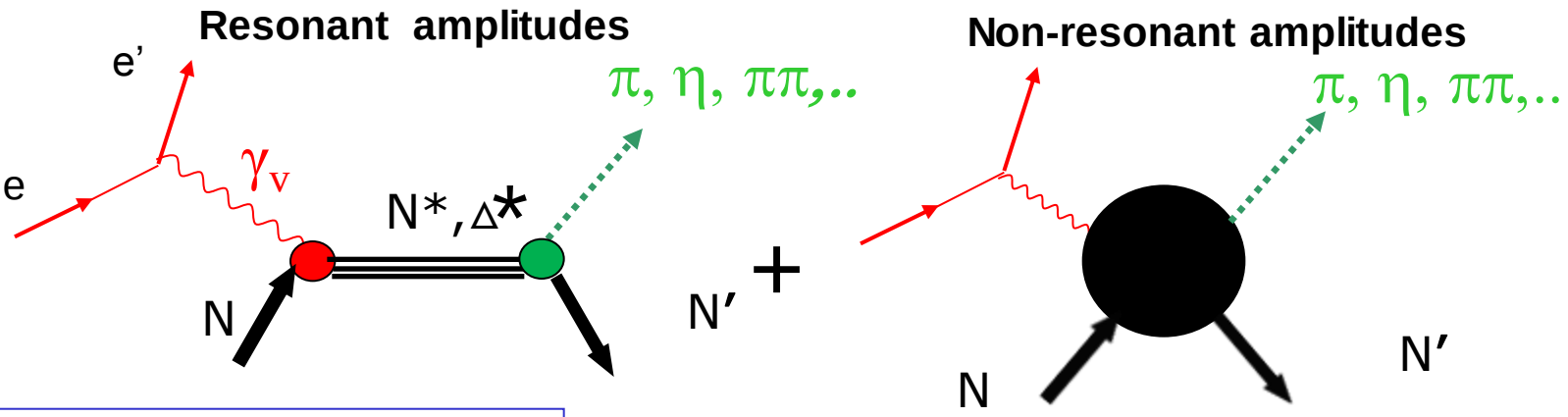
I.C.Cloët, C.D.Roberts, A.W.Thomas, Phys. Rev. Lett. 111, 101803 (2013).

- **data on elastic form factors at Q^2>5.0 GeV^2 are sensitive to momentum dependence of quark mass function.**
- **mass function should be the same for dressed quarks in the ground and excited nucleon states.**
- **consistent results on dressed quark mass function determined from the data on elastic form factors and transition $\gamma_v NN^*$ electrocouplings are critical for reliable extraction of this quantity.**

Mapping dressed quark mass function addresses the most challenging problems of hadron physics:

- **how >98% of hadron masses are generated non-perturbatively?**
- **how quark-gluon confinement in baryons emerges from QCD?**

Definition of γ_vNN* electrocouplings and basics for their extraction from the data on exclusive meson electroproduction off nucleons



- $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
  or
- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$
  or
- $G_M(Q^2)$, $G_E(Q^2)$, $C_C(Q^2)$

N*'s photo-/electrocouplings γ_vNN* are defined at W=M_{N^*} through the N* electromagnetic decay width $\Gamma\gamma$:

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

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 electroexcitation and hadronic parameters to the data.**

- **Consistent results on γ_vNN* electrocouplings from different meson electroproduction channels and different analysis approaches demonstrated reliable extraction of N* parameters.**

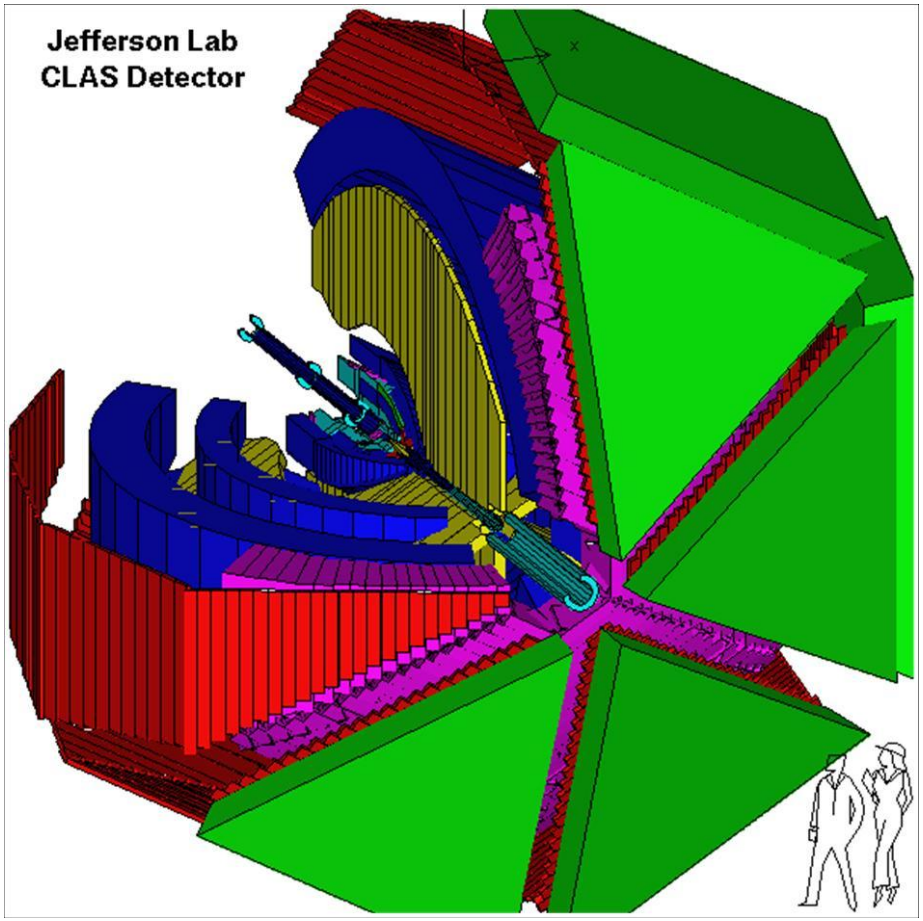
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter & 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 and the CLAS detector makes Hall-B@JLAB the only facility operational worldwide, that is capable of measuring unpolarized cross sections and polarization asymmetries of most exclusive meson electroproduction channels with substantial contributions at W<3.0 GeV and Q^2<5.0 GeV^2.

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
π^+n	1.1-1.38 1.1-1.55 1.1-1.7	0.16-0.36 0.3-0.6 1.7-4.5	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b
π^0p	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 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	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^0 P' –recoil and transfered 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:

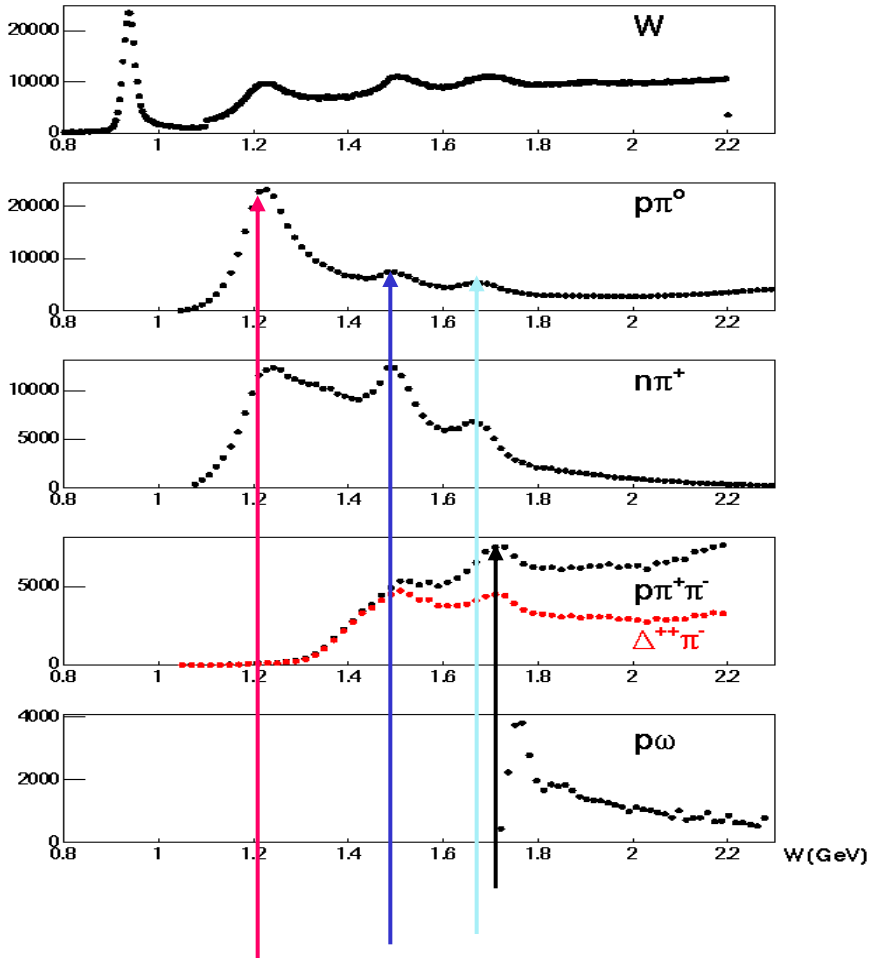
http://depni.sinp.msu.ru/cgi-bin/jlab/db.cgi

N* Electroexcitation in Exclusive Meson Electroproduction off Protons

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

State	Bran. Fract. to Nπ.	Bran. Fract. to Nη	Bran.Fract. Nππ
$\Delta(1232)P_{33}$	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



Nπ/Nππ channels are major and complementary sources of information on γ_vNN* electrocouplings of most resonances with masses up to 1.8 GeV

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

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

➢ $\pi^+ n$ and $\pi^0 p$ 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 πN, $\gamma_{r,v} N \rightarrow \pi N$, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

T.-S. H. Lee , AIP Conf. Proc. 1560, 413 (2013).

H. Kamano et al., Phys. Rev. C88, 035209 (2013).

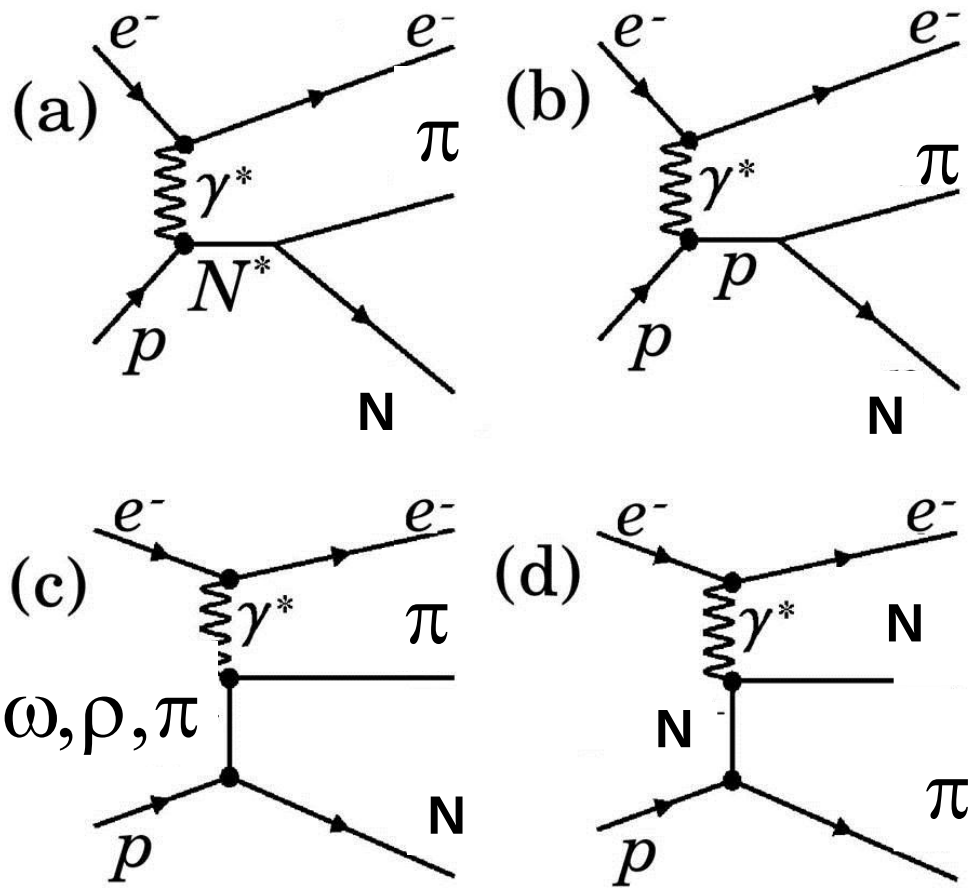
The Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from $N\pi$ Exclusive Electroproduction off Protons

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

Unitary Isobar Model (UIM)

•the real parts of invariant $N\pi$ electroproduction amplitudes are computed from their imaginary parts employing 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.



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

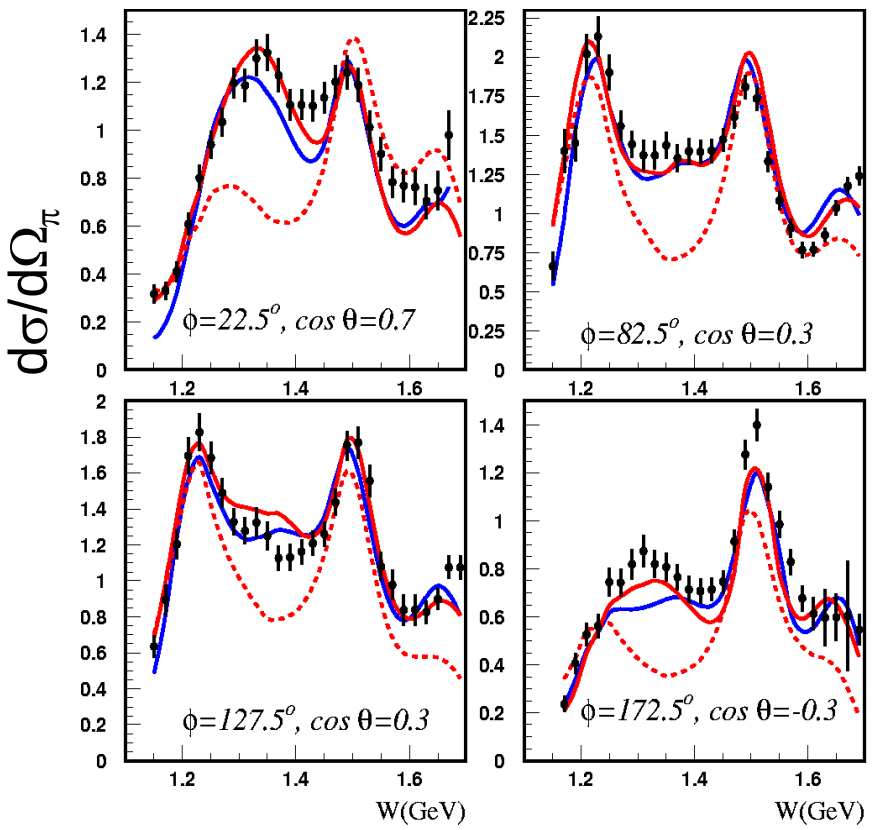
Fits to $\gamma p \to \pi^+ n$ Differential Cross Sections and Structure Functions

Q^2=2.05 GeV^2

DR

DR w/o P11

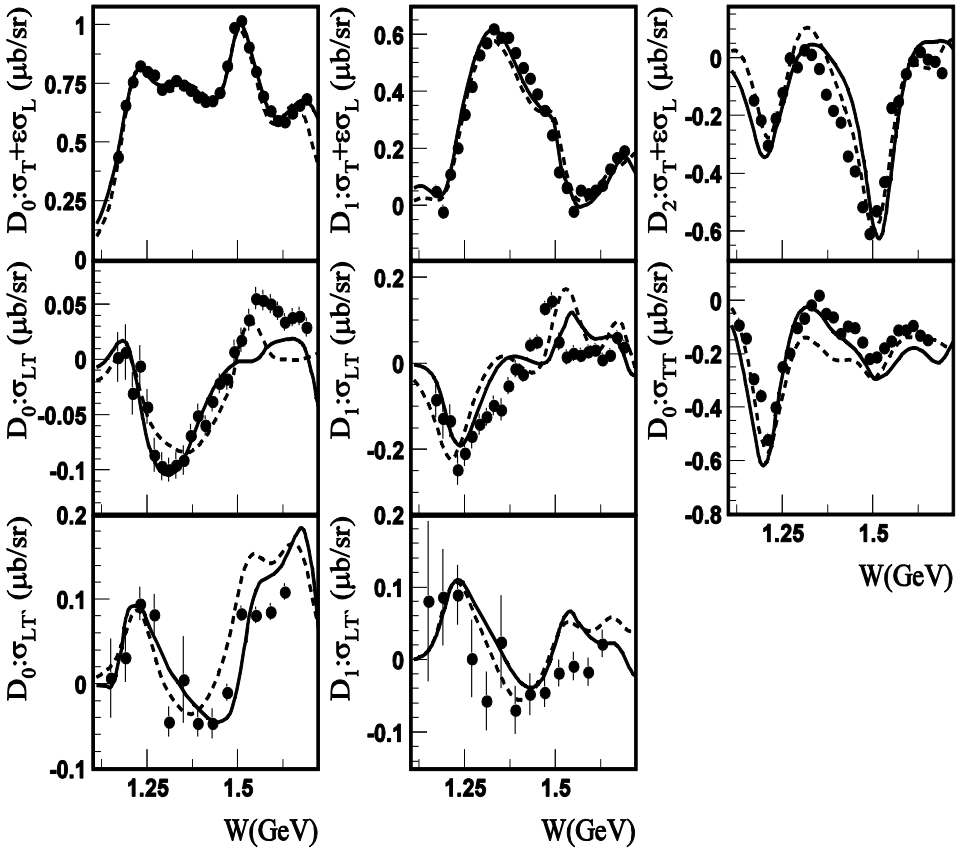
UIM



Q^2=2.44 GeV^2

DR

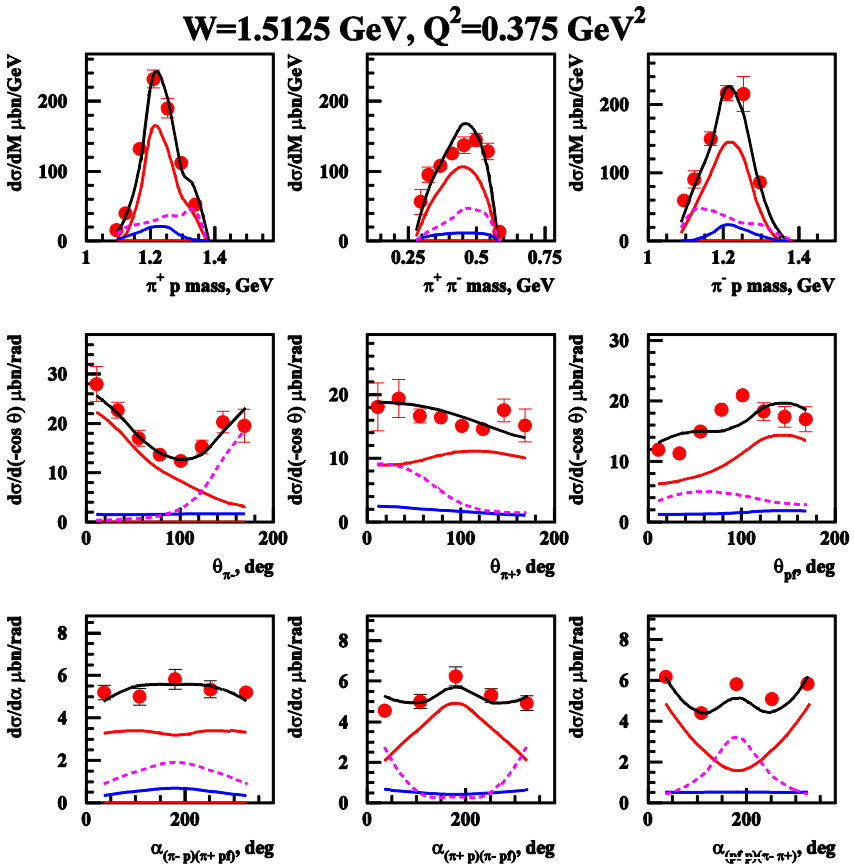
UIM



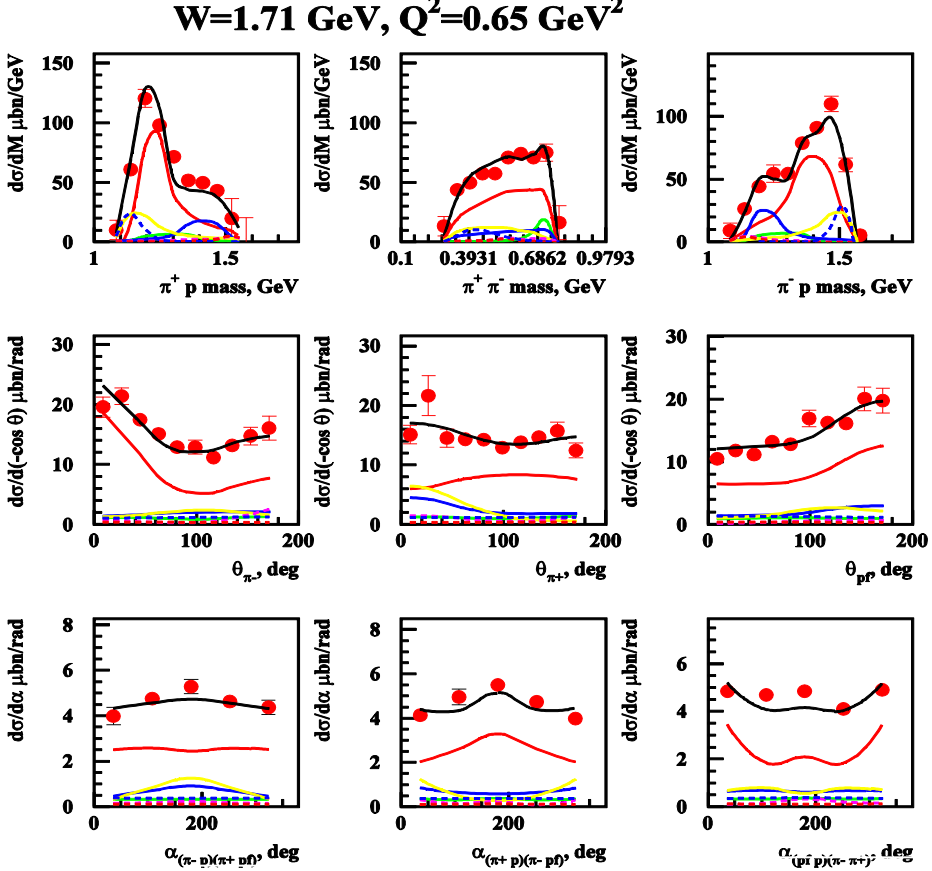
Legendre moments D_l (l=0,1,2) from various structure functions

The CLAS Data on $\pi^+\pi^-p$ Differential Cross Sections and their Fit 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 et al, PRL 91 (2003), 022002
1.40<W<2.30 GeV; 0.5<Q^2<1.5 GeV^2

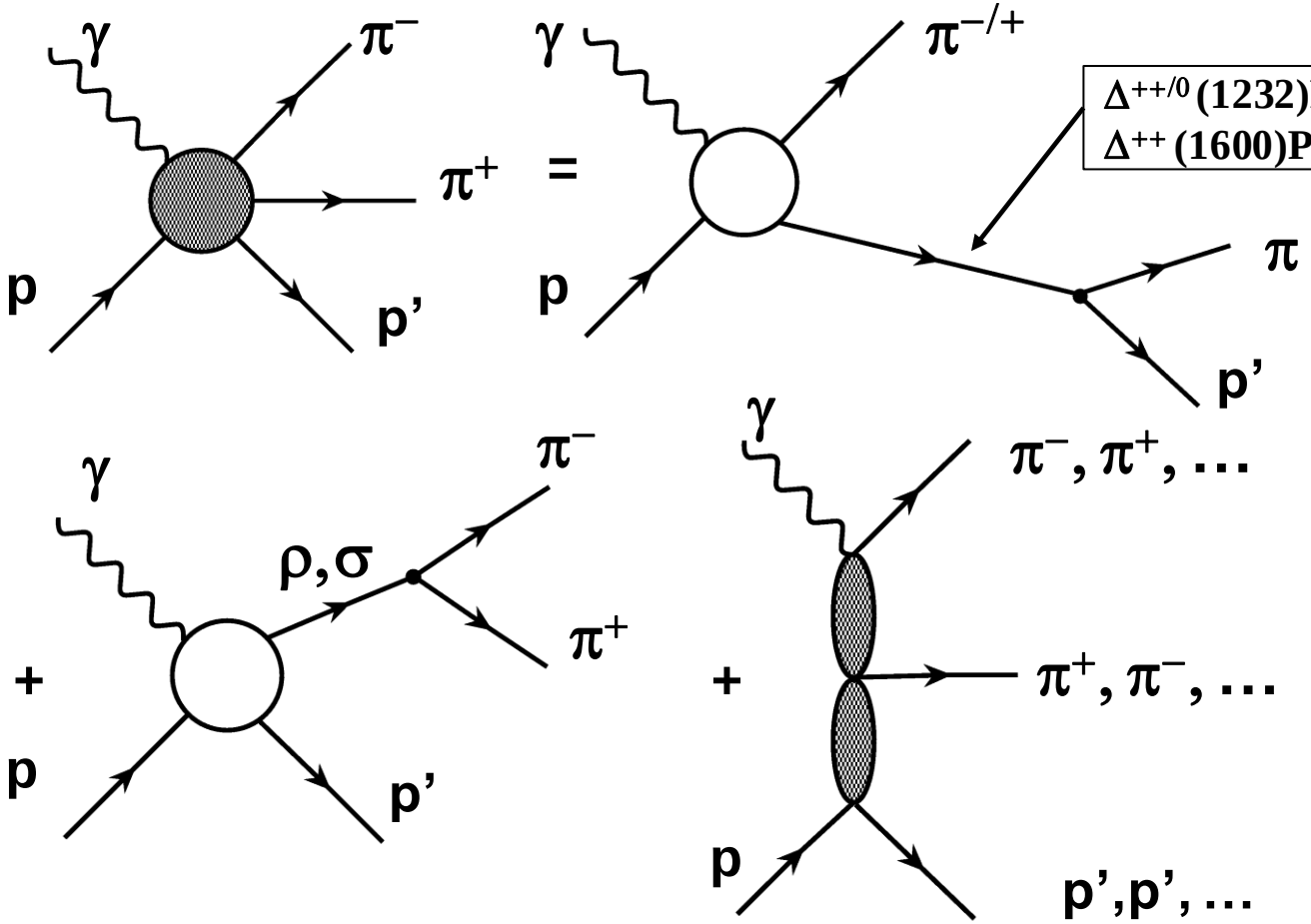


full JM calc. — $\pi^+\Delta^0$ — ρp ------- $\pi^+F^0_{15}(1680)$

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

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

Major objectives: extraction of γ_vNN* electrocouplings and $\pi\Delta$, ρp decay widths.

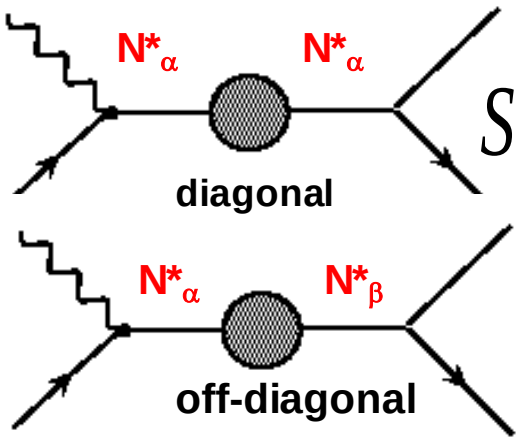


- seven meson-baryon channels and direct $\pi^+\pi^-p$ production.
- N* contribute to $\pi\Delta$ and ρp channels only.
- unitarized Breit-Wigner ansatz for resonant amplitudes.

- V.I.Mokeev, V.D. Burkert, et al., (CLAS Collaboration) Phys. Rev. C86, 035203 (2012).
- V.I.Mokeev, V.D. Burkert , et al., Phys. Rev. C80, 045212 (2009).

Unitarized Breit-Wigner Ansatz for Resonant Amplitudes

Resonant amplitude : $T^{res}_{\gamma p \to MB} = f_{\beta MB} S_{\alpha\beta} f_{\alpha\gamma p}$



Inverse of the JM unitarized N* propagator:

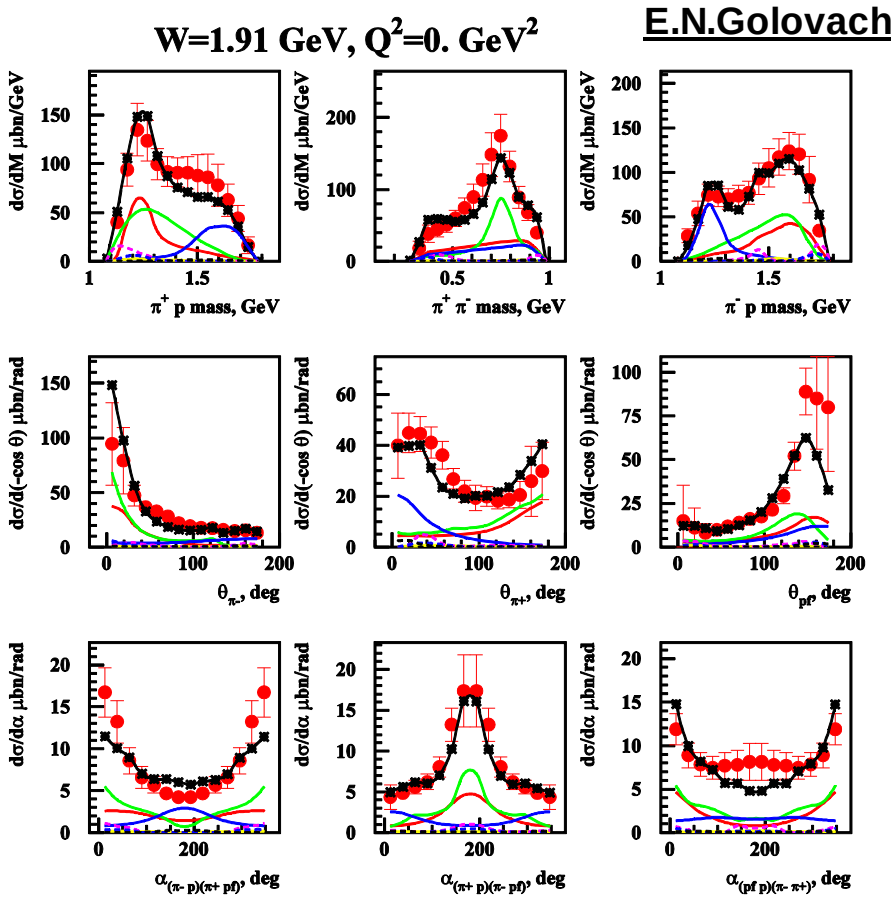
$$S^{-1}_{\alpha\beta} = M^{2}_{N^*}\delta_{\alpha\beta} - i\left(\sum_i \sqrt{\Gamma_{\alpha}}_i \sqrt{\Gamma_{\beta}}_i\right)\sqrt{M_{N^*_\alpha}}\sqrt{M_{N^*_\beta}} - W^{2}\delta_{\alpha\beta}$$

Off-diagonal transitions incorporated into the full resonant amplitudes of the JM model:

$S_{11}(1535) \leftrightarrow S_{11}(1650)$
$D_{13}(1520) \leftrightarrow D_{13}(1700)$
$3/2^{+}(1720) \leftrightarrow P_{13}(1700)$

Full resonant amplitude of unitarized Breit-Wigner ansatz is consistent with restrictions imposed by a general unitarity condition.

Impact of the preliminary results on $\pi^+\pi^-$p photoproduction



Data error bars: quadratic sum of statistical and systematical
------- σp
legend for other lines is shown in the slide #13

Only available data on:
- **9 one-fold differential cross sections;**
- **28 correlated two-fold differential cross sections**

at W from 1.61 GeV to 2.84 GeV

Pronounced differences for three distributions over α-angles in $\pi^+\pi^-$p photo- and electroproduction

Photoproduction data description requires 3-body final state interaction parameterized as :

$$M_i = M_{i_0}\gamma_i\left(1+\beta_i e^{i\alpha_{\pi^-}}\right)$$

$$\gamma_i = \gamma_i\left(s_{\pi^+\pi^-}, s_{\pi^+p}, t_{\gamma\pi^+}, t_{\gamma\pi^-}, t_{pp_f}\right)$$

$$\beta_i = \beta_i(\alpha_{\pi^-})$$

i= $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, ρp, π^+N(1520)3/2$^-$, $\pi^-\Delta^{++}$(1600)3/2$^+$, π^+N(1680)5/2$^+$, σp, 2π direct

Dependencies of the factors γ_i and β_i from aforementioned variables were inferred from the data.

- **Manifestations of three-body final state interaction were observed for the first time.**
- **Exploration of their Q^2 evolution at small photon virtualities from 0.05 to 0.25 GeV^2 in the future experiments with the CLAS12 detector is of particular interest.**

Fitting Procedures and Uncertainty Estimates

Simultaneous non-restricted variation of the following resonant/non-resonant JM model parameters according to the normal distribution:

-γ_vNN* electrocouplings with $\sigma-$parameter equal to 30% from their initial values;

- $\pi\Delta$ and ρp hadronic decays for the N*-states under studies with $\sigma-$parameters, that cause total N* width to float slightly above RPP ranges;

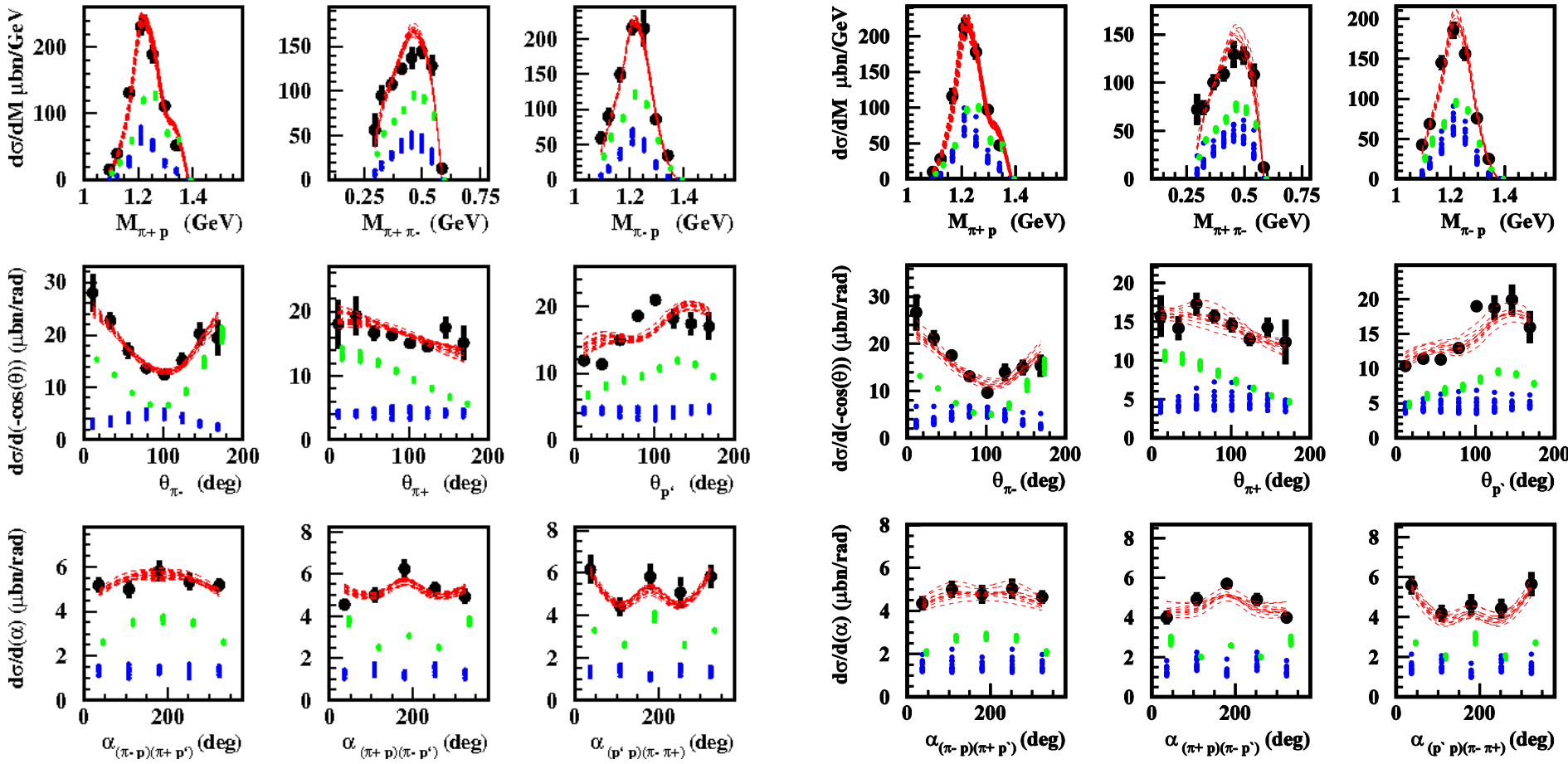
-magnitudes of extra-contact terms in $\pi\Delta$ channels; magnitudes of the amplitudes of $\pi^+ N^0(1520) D_{13}$, $\pi^+ N^0(1680) F_{15}$, $\pi^- \Delta^{++}(1620) P_{33}$ channels and of the direct 2π production amplitudes with σ-parameters 10 -30 % from their starting values.

- **χ^2/d.p. fit of nine 1-fold diff. cross sections in each bin of W and Q^2 . The computed cross sections closest to the data were selected with $\chi^2/d.p.<\chi^2/d.p._{thr}$., which was defined so that the cross sections selected in the fit should be inside the uncertainties for most of the data points.**
- **Mean values of N* parameters resulting to the computed cross sections selected in the fit and their r.m.s were assigned to resonance parameters inferred from the data and their uncertainties, respectively.**

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

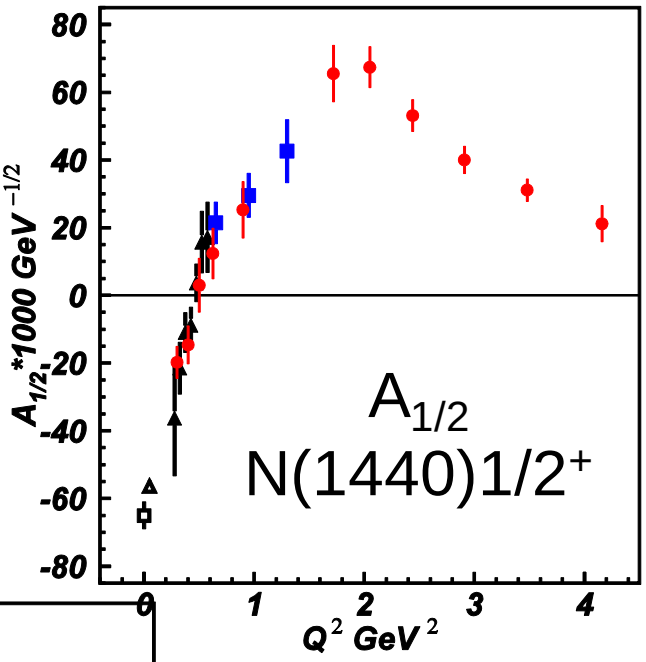
resonant part

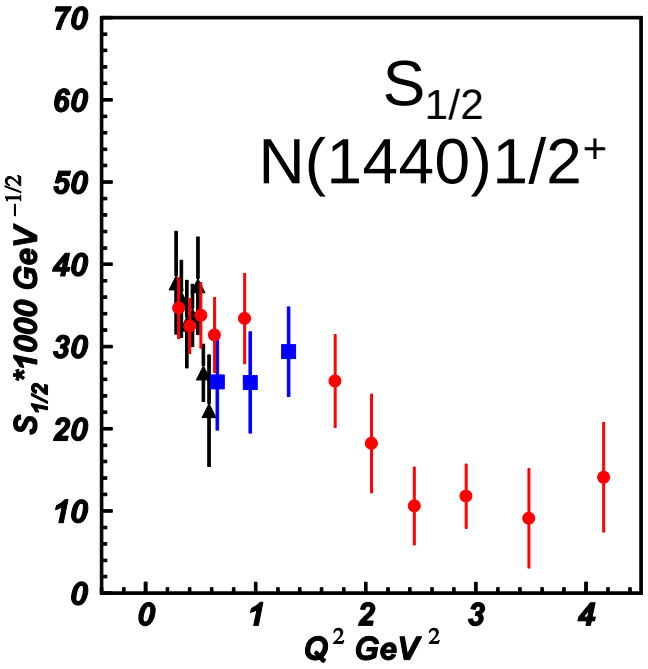
non-resonant part

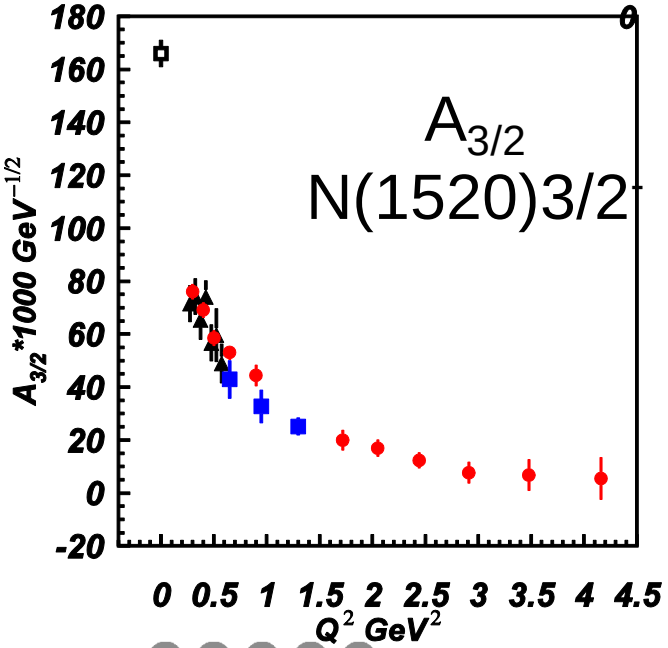
γ_vNN* Electrocouplings of Low-Lying Resonances

CLAS data:

- $N\pi$ 2009
- $\pi^+\pi^-p$ 2012
- $\pi^+\pi^-p$ prelim.



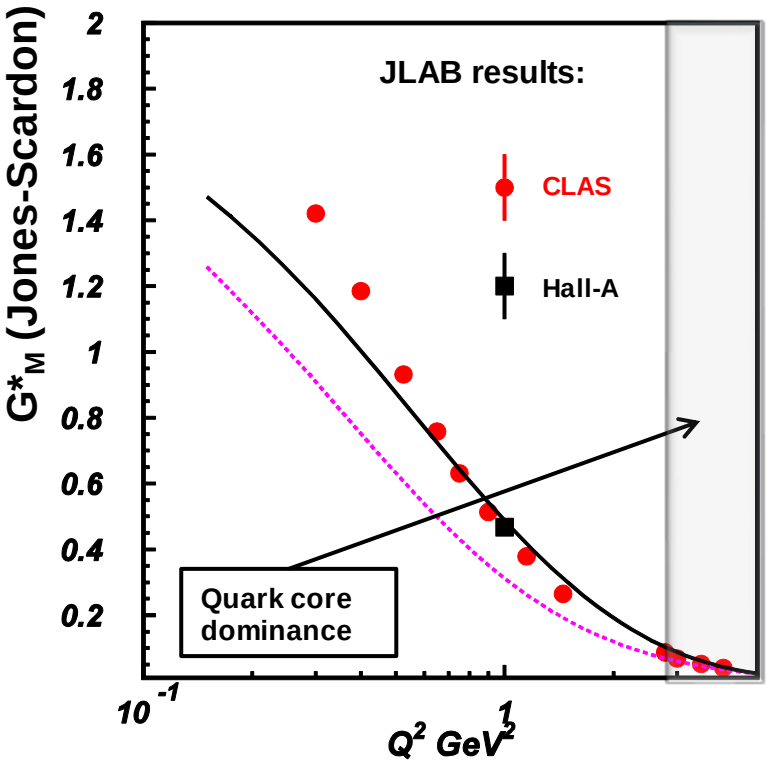




Consistent values of low-lying resonance electrocouplings determined in independent analyses of $N\pi$ and $\pi^+\pi^-p$ exclusive channels strongly support:

- **reliable electrocoupling extraction;**
- **capabilities of the reaction models to obtain resonance electrocouplings in independent analyses of $N\pi$ and $\pi^+\pi^-p$ electroproduction channels.**

Studies of N→Δ Magnetic Form Factor

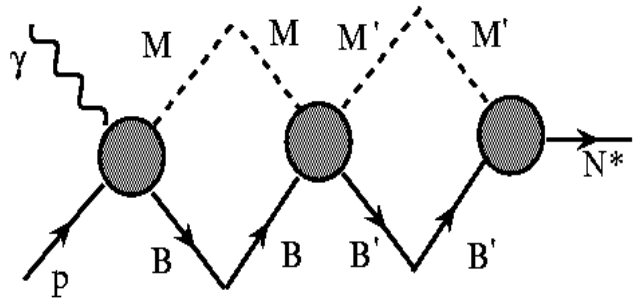


Quark core contribution from DSEQCD:
J.Segovia, et al.,arXiv:1408.2919

———	first evaluation with realistic qq-interaction and running dressed quark mass
.....	bare G^*_M inferred from exp. data within Argonne-Osaka reaction model.

First DSEQCD description of elastic and N→Δ magnetic form factors achieved with the same dressed quark mass function!

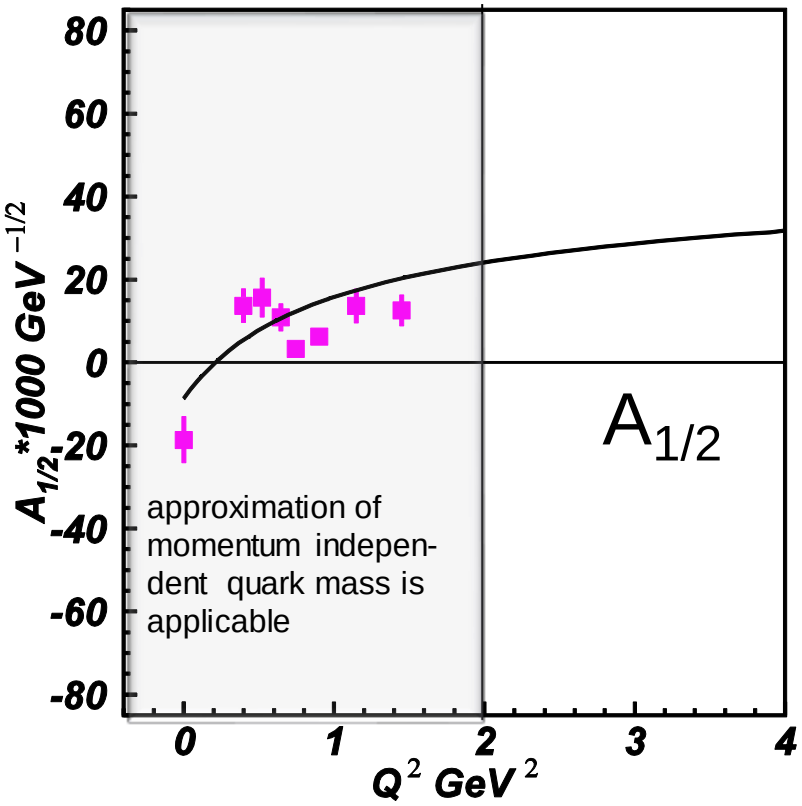
The mechanisms of the meson-baryon dressing



- beyond the scope of DSEQCD.
- evaluated in the global analysis of Nπ hadro-, photo-, and electroproduction data within the framework of Argonne-Osaka coupled channel approach (N.Suzuki, et al., Phys.Rev. C82, 045206 (2010)).

Interplay between inner core of three dressed quarks and external meson-baryon cloud determines the structure of Δ(1232)3/2⁺ resonance

Quark Core in the Structure of N(1440)1/2$^+$



Quark core contribution:

from DSEQCD.

from Nπ hadro-, photo- and electroproduction experimental data (Argonne-Osaka model)..

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

- **Simplified contact interaction generates momentum independent quark mass.**

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

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

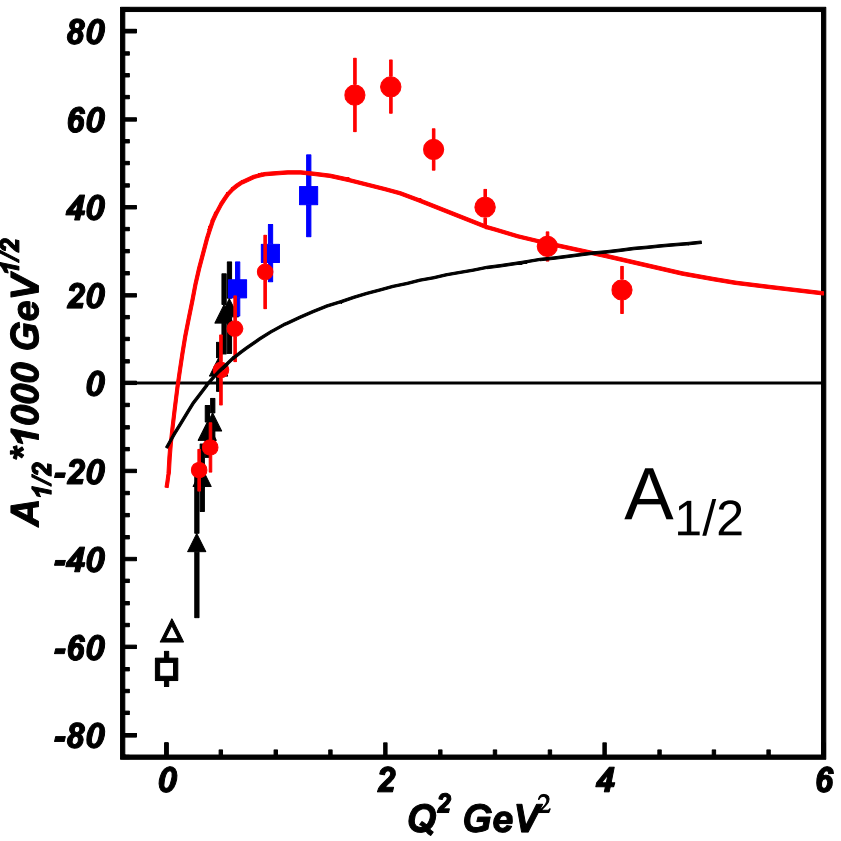
$$m_q^{bare} = 0.007 GeV \Rightarrow m_q^{dressed} = 0.368 GeV$$

- **Account for non-perturbative generation of dressed quark mass.**

DSEQCD expectations are consistent with quark core contributions inferred from the experimental data at Q^2<2.0 GeV^2

Future DSEQCD evaluations with realistic qq-interaction and running quark mass are of particular importance to extend based on QCD predictions for quark core contributions at higher Q^2.

Quark Core & Meson-Baryon Cloud in the Structure of N(1440)1/2$^+$



Quark core from DSEQCD with momentum independent quark mass.

Quark core and MB cloud from advanced LF quark model with running quark mass.

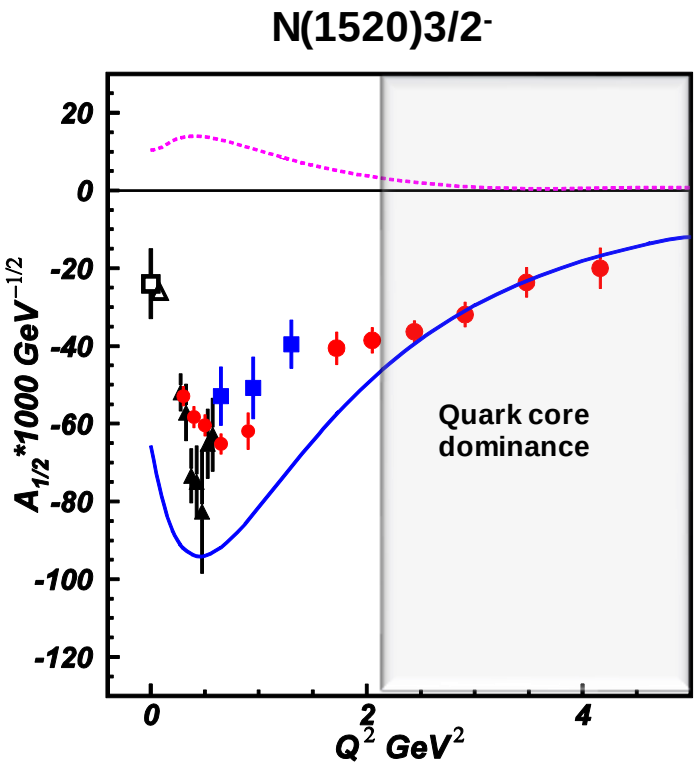
Advanced Light Front model (I.G. Aznauryan and V.D, Burkert Phys. Rev. C85, 055202 (2012)):

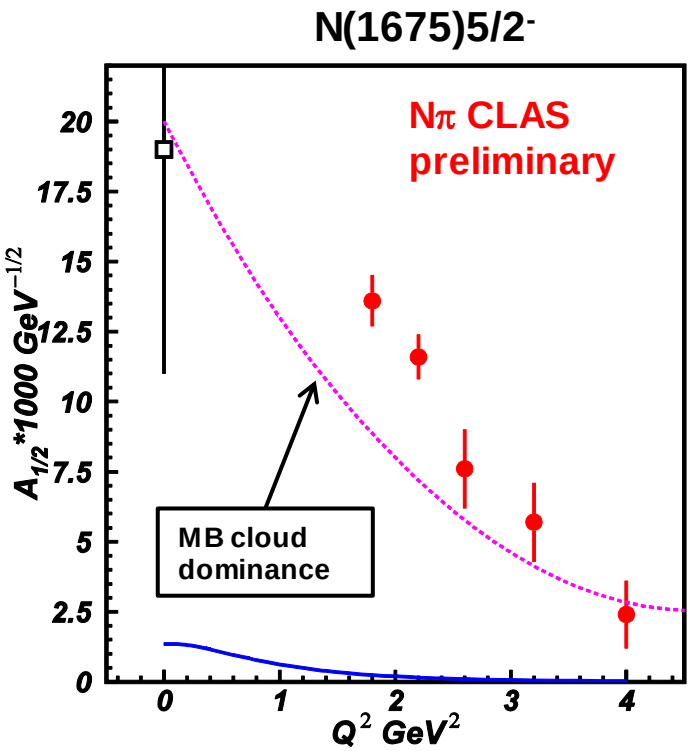
- the contributions from three dressed quarks in the first radial excitation and meson-baryon cloud are taken into account;
- the model employs momentum dependent dressed quark mass function from DSEQCD .

Combined contribution from inner quark core and external meson-baryon cloud to the N(1440)1/2$^+$ structure in entire area of photon virtualities covered by measurements Q^2<5.0 GeV^2 .

Better data description at high Q^2 achieved in the LF quark model offer an evidence for running quark mass.

Interplay between Quark Core and Meson-Baryon Cloud in the N* Structure





MB dressing abs. values (Argonne-Osaka).

E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012).

Almost direct access to:

- **quark core from the data on N(1520)3/2⁻ state electrocouplings at Q^2>2.0 GeV^2: prospect to map-out dressed quark mass function and explore dressed qqG vertex beyond rainbow-ladder truncation;**
- **meson-baryon cloud from the data on N(1675)5/2⁻ state electrocouplings: important to check capabilities of coupled channel models to isolate meson-baryon cloud;**

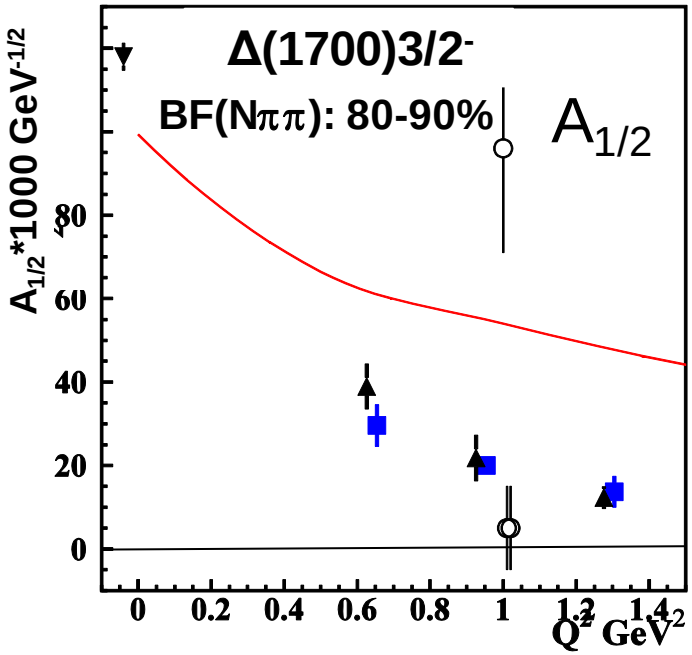
Quark core contribution increases with Q^2 in a gradual transition towards quark core dominance at Q^2>5 GeV^2

Preliminary $\Delta(1700)3/2^-$ electrocouplings from the $\pi^+\pi^-p$ CLAS data

Nπ world
V.D.Burkert, et al., PRC 67, 035204 (2003).

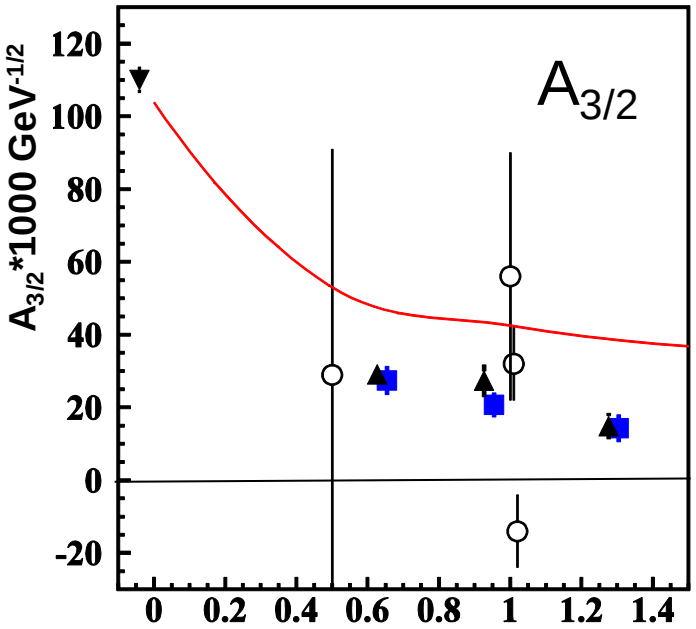
Nππ CLAS preliminary
N* hadr. coupl. are varied
fixed D(1700)3/2⁻ hadr. couplings

Nπ Q^2=0, CLAS
M.Dugger, et al., PRC 79,065206 (2009).



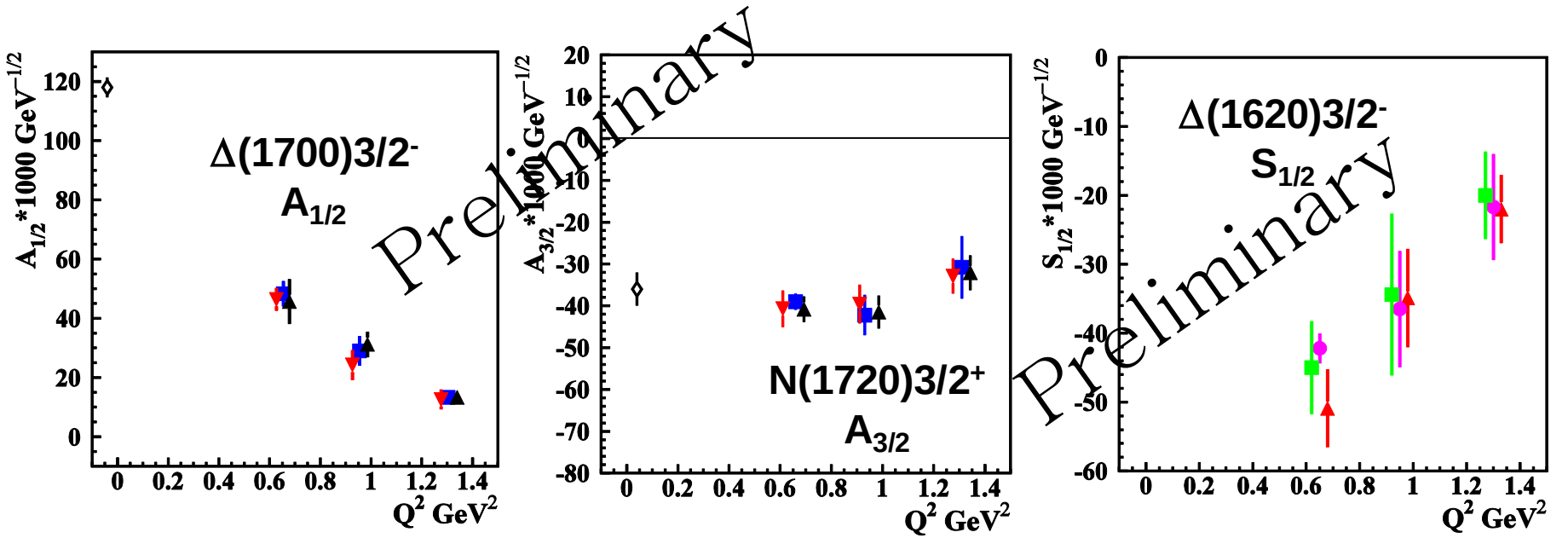
- Studies of $\pi^+\pi^-p$ electroproduction for the first time provided accurate information on $\Delta(1700)3/2^-$ electrocouplings.

- They were determined varying both electrocouplings and $\pi\Delta$, ρp hadronic decay widths of all excited states contributing to the third resonance peak.



Computed from N(1520)3/2⁻ and N(1535)1/2⁻ electrocouplings within the SQTM approach:
I.G. Aznauryan and V.D. Burkert, Progr. Nucl. Part. Phys. 67, 1 (2012).

The status and prospects on extraction of high lying N* electrocouplings from the CLAS data



Independent fits in different W-intervals:

green: 1.46<W<1.56 GeV
magenta: 1.56<W<1.66 GeV
red: 1.61<W<1.71 GeV
blue: 1.66<W<1.76 GeV
black: 1.71<W<1.81 GeV

consistent electrocoupling values offer sound evidence for their reliable extraction.

$\pi^+\pi^-$p electroproduction channel provided first preliminary results on $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ electrocouplings with good accuracy.

Prospect: evaluation of high-mass N* electrocouplings from independent analyses of KY channels. Reaction models capable of extracting resonance electrocouplings from the fit of unpolarized cross sections and polarization asymmetries measured in KY electroproduction are needed!

The review of the results in N* physics with CLAS:

•I.Aznauryan, V.Burkert, T-S.H.Lee, and V.Mokeev, J.Phys. Conf.Ser. **299,** 012008 (2011).

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

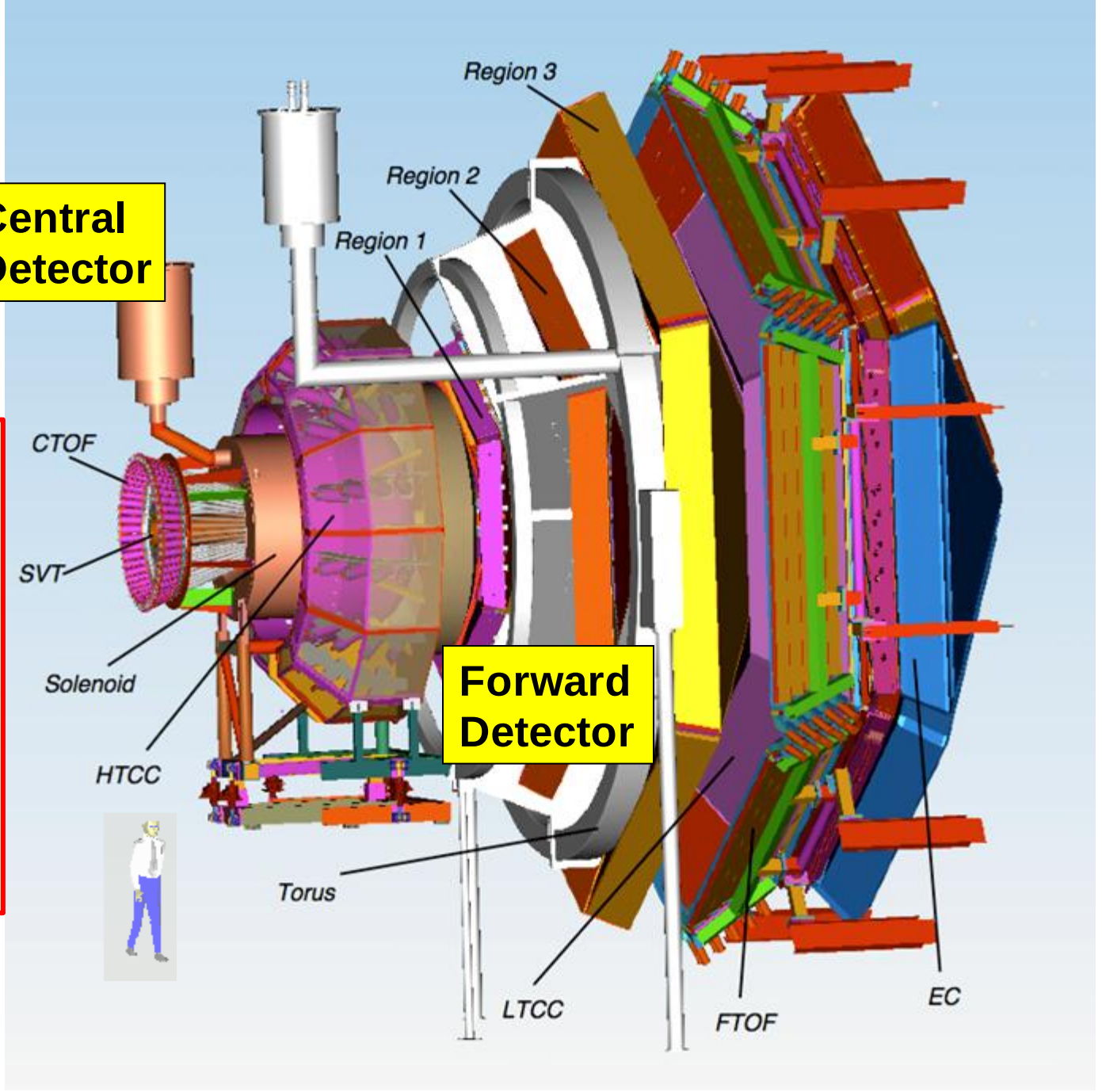
The 6 GeV era came to a successful close in May 2012 after fifteen years of running many productive world-class experiments. We are poised to continue our very successful experimental program with CLAS12.

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.**

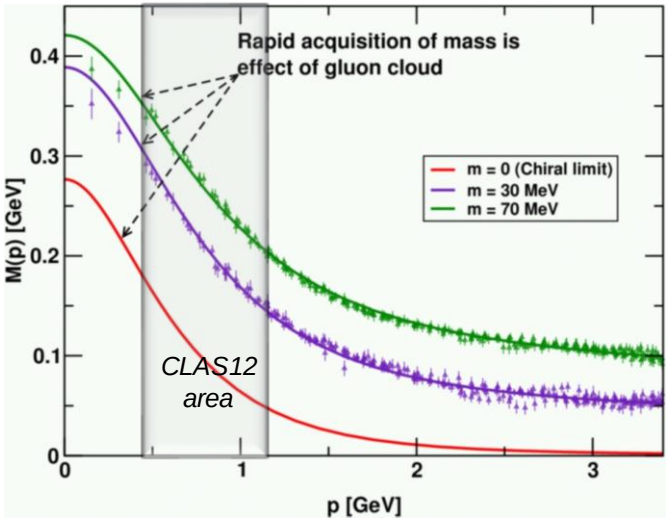


N* Structure at High Photon Virtualities in Exploration of Strong Interaction

CLAS12 is the only facility foreseen in the world capable of determining electrocouplings of all prominent N* at $5<Q^2<12$ GeV^2. For the first time, almost direct access to the quark core at the distances where the transition from quark-gluon confinement to perturbative QCD regime is expected.

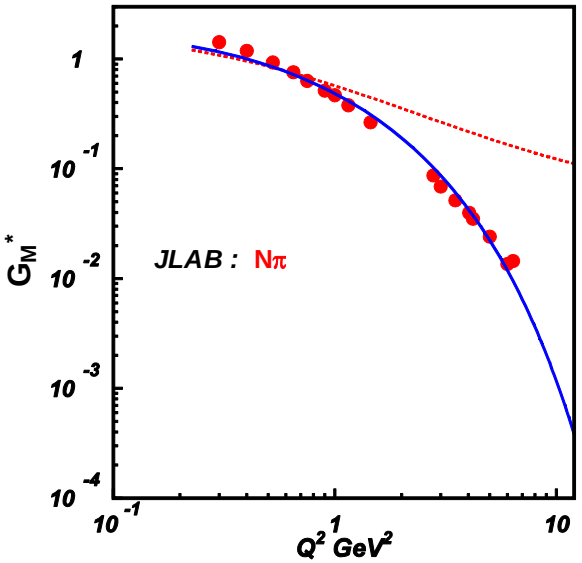
Dressed quark mass function

C.D. Roberts, Prog. Part. Nucl. Phys. (2008) 50.



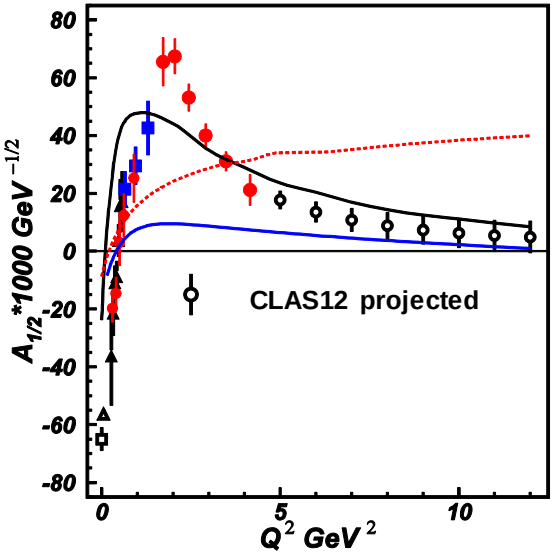
$\Delta(1232)3/2^+$
Jones-Scadron convention

J. Segovia et al., arXiv:1408,2919 [nucl-th].



N(1440)1/2 $^+$

D.J. Wilson et al., Phys. Rev C85 (2012) 045205 DSEQCD.
I.G. Aznauryan & V.D. Burkert, Phys. Rev. C85 (2012) 055202 LF QM.



Consistent results on quark mass function from electrocouplings of different resonances at $Q^2 > 5$ GeV^2:

- **will prove relevance and reliable access to this fundamental ingredient;**
- ***address two of the most challenging problems in the Standard Model: <u>the emergence of the dominant part of hadron masses and quark-gluon confinement</u> .***

DSEQCD : ***(quark core only)*** ····· *constant quark mass.* —— *running quark mass.*

Light Front Quark Model (quark core & MB cloud) —— *running quark mass from DSEQCD.*

Conclusions and Outlook

- High quality meson electroproduction data from CLAS allowed us to determine the electrocouplings of most well established resonances in mass range up to 1.8 GeV from independent analyses of π^+n, π^0p, ηp and $\pi^+\pi^-p$ electroproduction channels.

- Consistent electrocoupling values for the transitions to $N(1440)1/2^+$ and $N(1520)3/2^-$ states obtained in independent analyses of $N\pi/N\pi\pi$ exclusive channels demonstrated capabilities of the developed reaction models for reliable extraction of N*-parameters in independent analyses of $N\pi$ and $\pi^+\pi^-p$ electroproduction data.

- Preliminary results on electrocouplings of $N(1650)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$ resonances were obtained from analysis of the CLAS π^+n data at $1.5<Q^2<5.0$ GeV^2 and for $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances from $\pi^+\pi^-p$ electroproduction data at $0.5<Q^2<1.5$ GeV^2 for the first time.

- Physics analyses of the CLAS results on resonance electrocouplings revealed the structure of N*-states at $Q^2<5.0$ GeV^2 as complex interplay between meson-baryon and quark degrees of freedom. The studies of different N*-states are essential in order to disentangle different components in the N* structure.

- CLAS data on resonance electrocouplings of different N* states in mass range <1.8 GeV offer a unique opportunity for the hadron structure theory to explore many facets of non-perturbative strong interaction in the generation of excited nucleons of different quantum numbers. Exciting time for the further development of DSEQCD, LQCD and advanced quark models with inputs from QCD field theory approaches for description of these resonance electrocouplings.

Conclusions and Outlook

- **Future analyses of the CLAS $N\pi$, $\pi^+\pi^-p$ and KY photo/electroproduction data will allow electrocouplings to be obtained for all prominent N* states at photon virtualities $Q^2<5.0$ GeV^2. Reaction models for extraction of N* parameters from KY electroproduction data are urgently needed.**

- **N*- studies with the CLAS12 detector is the only foreseen worldwide program allowing us to obtain N*-electrocouplings at the highest photon virtualities ever achieved in exclusive processes: 5 GeV^2 $<Q^2<$12 GeV^2 from analyses of $N\pi$, $\pi^+\pi^-p$ and KY exclusive channels.**

- **Almost direct access to quark degrees of freedom in the N* structure at the distances where transition from quark gluon confinement to pQCD regime is expected will address the most challenging open questions in the Standard Model: on the nature of quark-gluon confinement and dominant part of hadron masses.**

Back -up

Summary of the CLAS data on KY electroproduction off protons

Observables	Channel	Coverage over Q^2, GeV^2	Coverage over W, GeV	References
$P_{x,y,z}$	$K\Lambda, K\Sigma^0$	0.7-5.4	1.60-2.60	[1]
A_e	$K\Lambda$	0.65-1.0	1.60-2.05	[2]
$d\sigma/d\Omega$	$K\Lambda, K\Sigma^0$	0.5-2.8	1.60-2.40	[3]
$P_{x,y,z}$	$K\Lambda$	0.3-1.5	1.60-2.15	[4]

1. D.S. Carman et al.,(CLAS Collaboration), Phys. Rev. C79, 065205 (2009).
2. R. Nasseripour et al., (CLAS Collaboration), Phys. Rev. C77, 065208 (2008).
3. P. Ambrozewicz et al., (CLAS Collaboration), Phys. Rev. C75, 045203 (2007).
4. D.S. Carman et al., (CLAS Collaboration), Phys. Rev. Lett. 90, 131804 (2003).

More than 85% of meson electroproduction data worldwide were obtained in experiments with the CLAS detector and available in the CLAS Physics Data Base: http://clasweb.jlab.org/physicsdb/

Signals from N* states in the CLAS KY electroproduction data

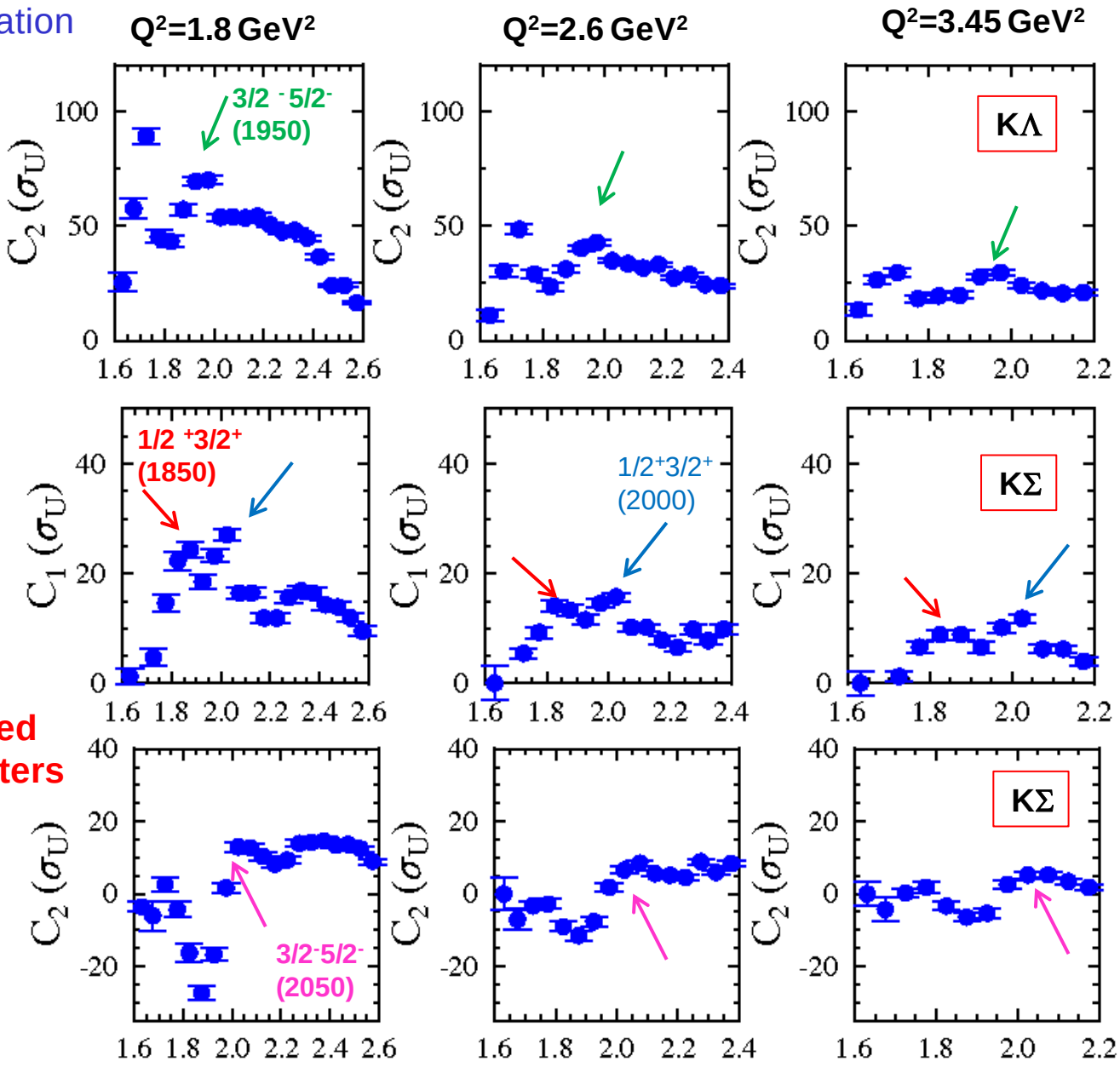
D.Carman, private communication

$$C_l = \int \{ \frac{d\sigma}{d\theta_{K_T}} + \varepsilon \frac{d\sigma}{d\theta_{K_L}} \} P_l(z) d(-z)$$

$$z = \cos(\theta_K)$$

the structures in W-dependencies of C_l – moments at the same W-values in all Q^2-bins are consistent with the contributions from resonances of spin-parities listed in the plots

reaction model(s) are needed for extraction of N* parameters from KY electroproduction



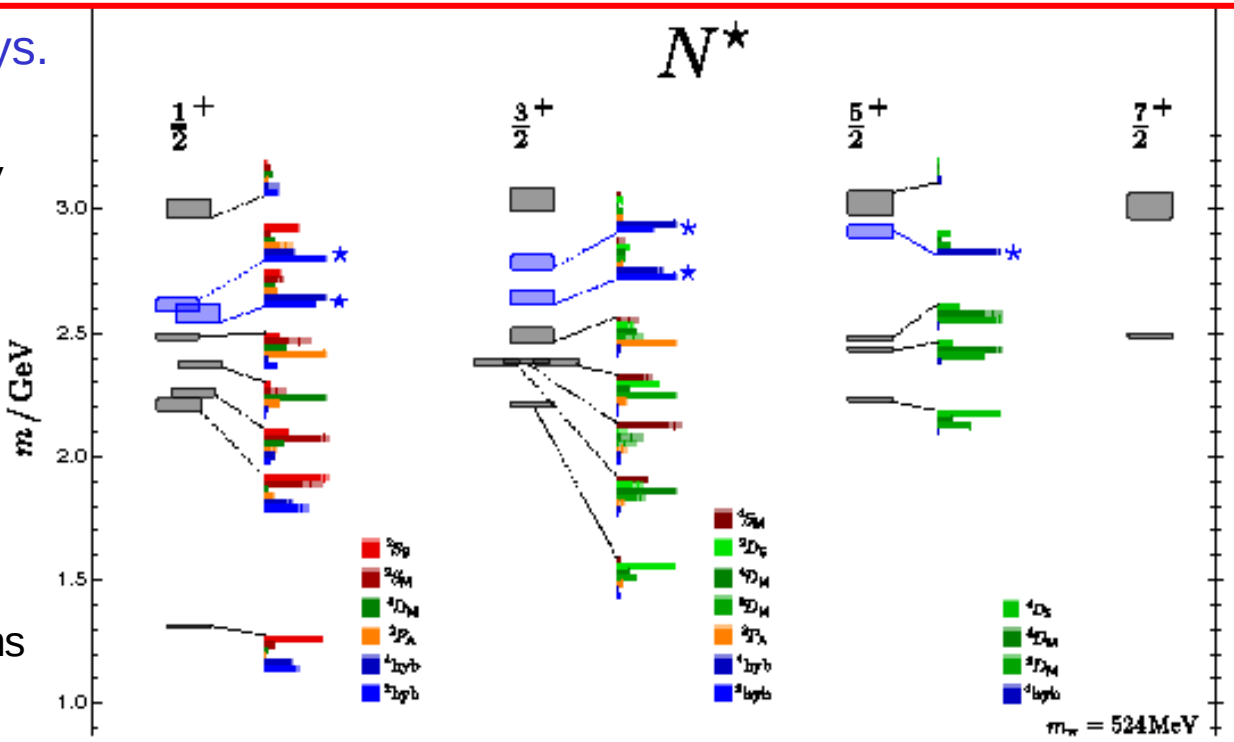
Impact of the Recent LQCD studies of N* Spectrum and Structure on the N* Program with CLAS/CLAS12

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.**

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

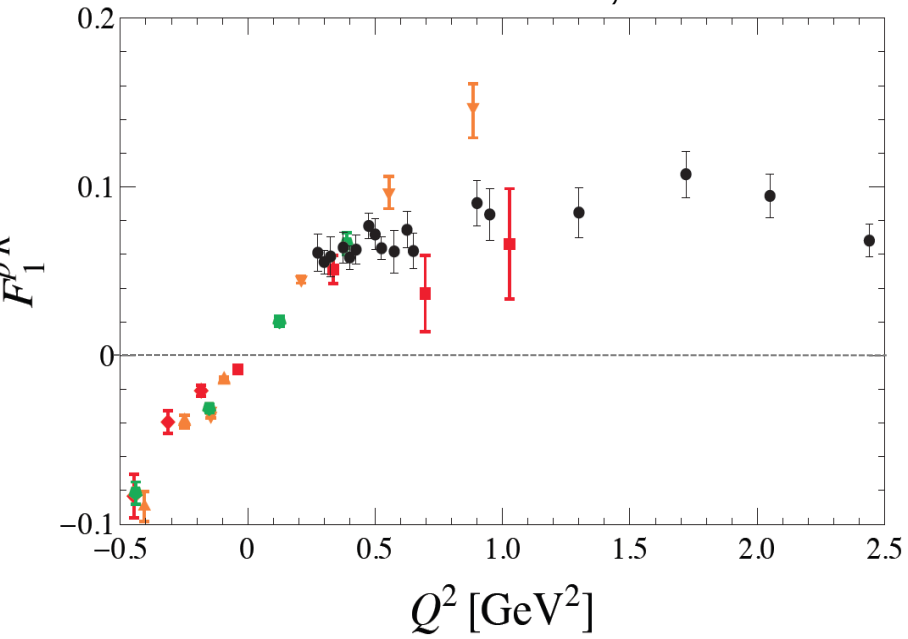
Includes the quark loops in the sea , which are critical in order to reproduce the CLAS data at Q^2<1.0 GeV^2

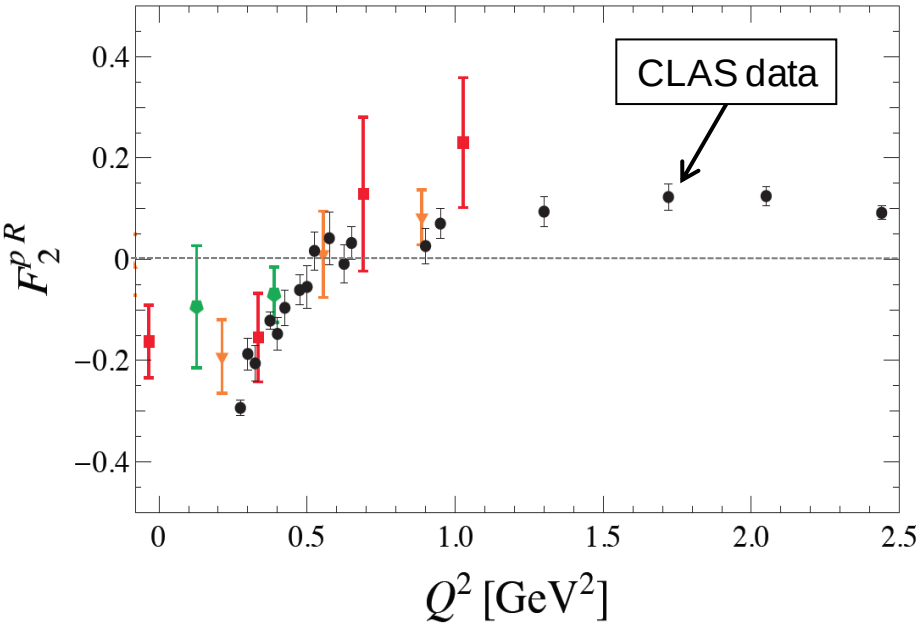
$A_{1/2}$, $S_{1/2}$ => F_1^*, F_2^*

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

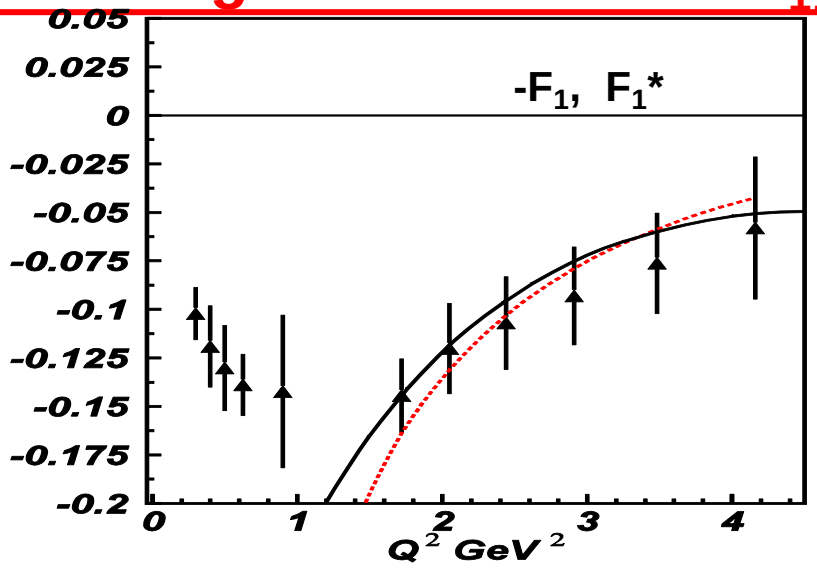


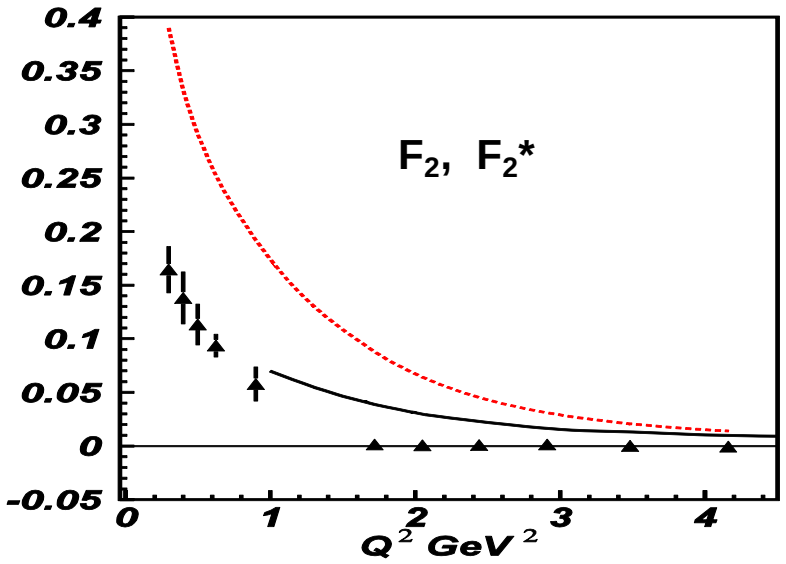


- **Exploratory LQCD results provide reasonable description of the CLAS data from the QCD Lagrangian.**

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

Evidence for chiral symmetry breaking from Q^2-evolution of the ground state and $S_{11}(1535)$ parity partner form factors





In chiral symmetry limit:

$$-F_1(Q^2) = (-Q^2)G_1(Q^2) = F_1^*(Q^2);$$

$$F_2(Q^2) = -\frac{(M+m)m}{\kappa}G_2(Q^2) = F_2^*(Q^2);$$

$1/2+ \to 1/2-$ transition current:

$$J_\mu = (-Q^2\gamma_\mu - q_\nu\gamma^\nu q_\mu)G_1(Q^2) - \frac{1}{2}(M+m)\, i\,\sigma^{\mu\nu}q_\nu G_2(Q^2)$$

M,m are $S_{11}(1535)$ and proton masses, k= 1.79

F_1^*, F_2^* $p \to S_{11}(1535)$ form factors from the CLAS data

parameterization of elastic Dirac F_1 and Pauli F_2 form factors

Evaluation of F_1^* and F_2^* starting from QCD within the framework of Light Cone Sum Rule & LQCD.
V.Braun et al., Phys. Rev. Lett., 103, 072001 (2009) .
Update: LCSR at NLO is in progress
J.Rohrwild, priv. com.