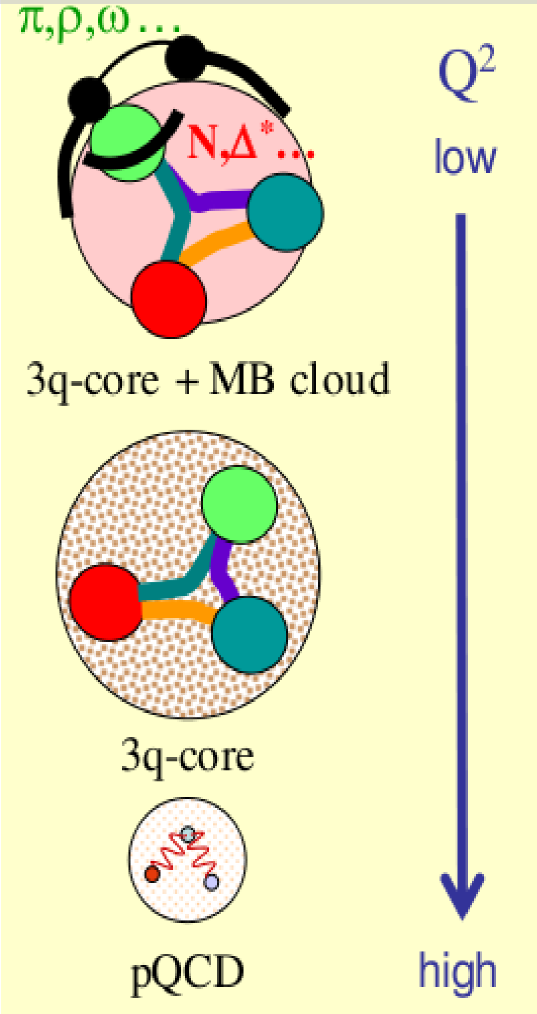
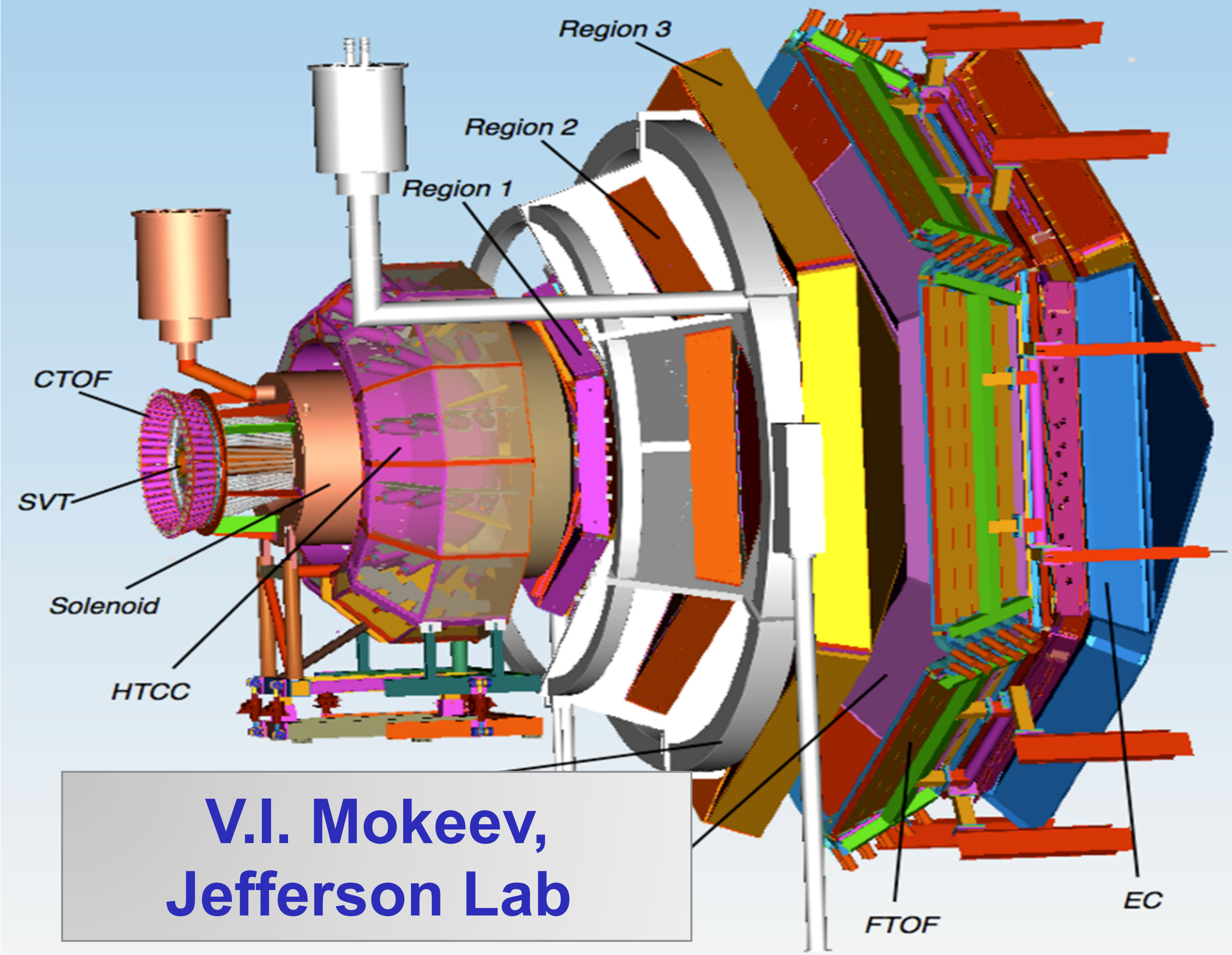
Updates on the Studies of N* Structure with CLAS and the Prospects with CLAS12





V.I. Mokeev, Jefferson Lab

ECT* 2015 Workshop on Nucleon Resonances, Trento, October 12-16, 2015, Italy

Major Directions in the Studies of N*-Spectrum and Structure with CLAS

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

- $\gamma_v NN^*$ electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels
- extend knowledge on N*-spectrum and on resonance hadronic decays from the data for photo- and electroproduction reactions with multiple mesons in the final state

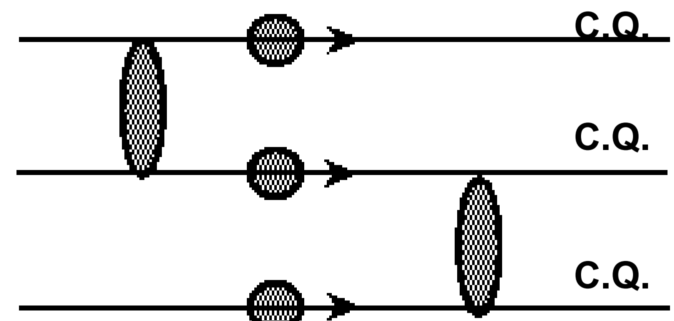
A unique source of information on different manifestations of the non-perturbative strong interaction in generating different excited nucleon states as relativistic bound systems of quarks and gluons.

Review papers:

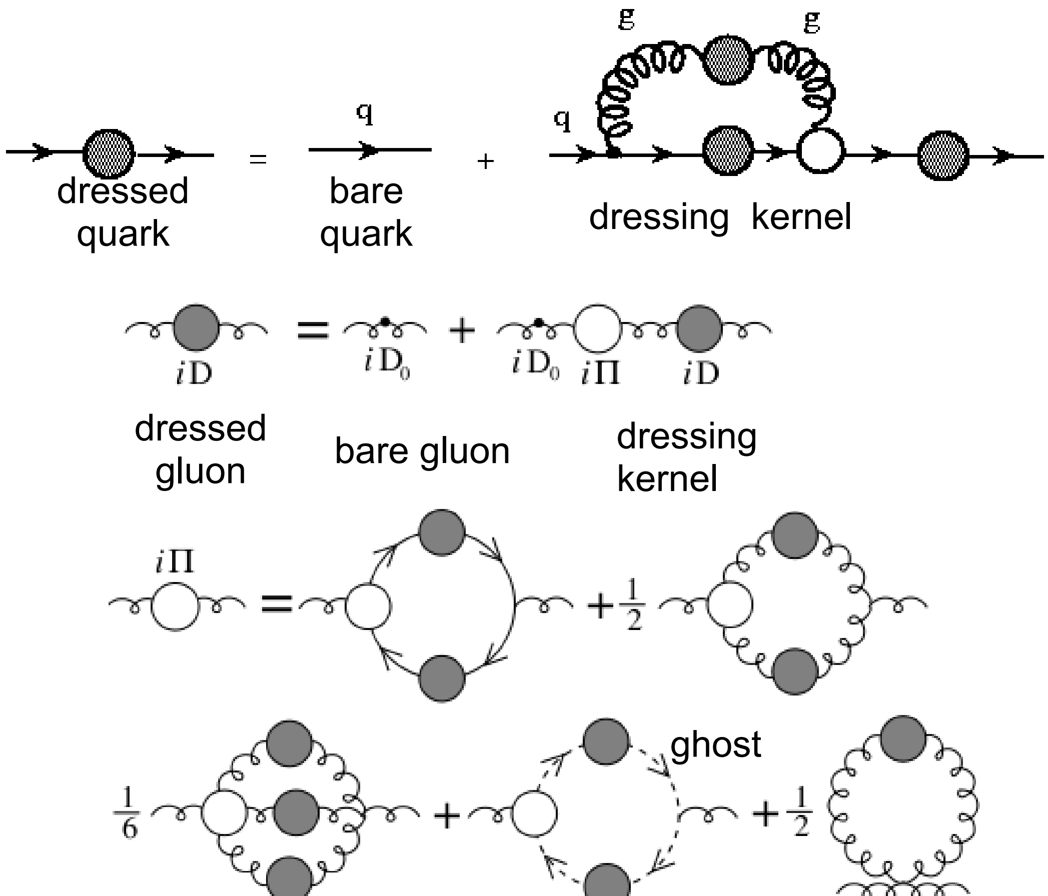
1. **I.G. Aznauryan and V.D. Burkert, Progr. Part. Nucl. Phys. 67, 1 (2012).**
2. **I.G. Aznauryan et al., Int. J. Mod. Phys. E22, 133015 (2013).**
3. **I.C. Cloët and C.D. Roberts, Prog. Part. Nucl. Phys. 77, 1 (2014).**

Excited Nucleon States and Insight to Non-Perturbative Strong Interaction

Studies of N* spectrum/structure suggest that ground and excited nucleon states consist of three dressed (constituent) quarks (C.Q.) coupled by non-perturbative strong interaction (ovals in the plot).

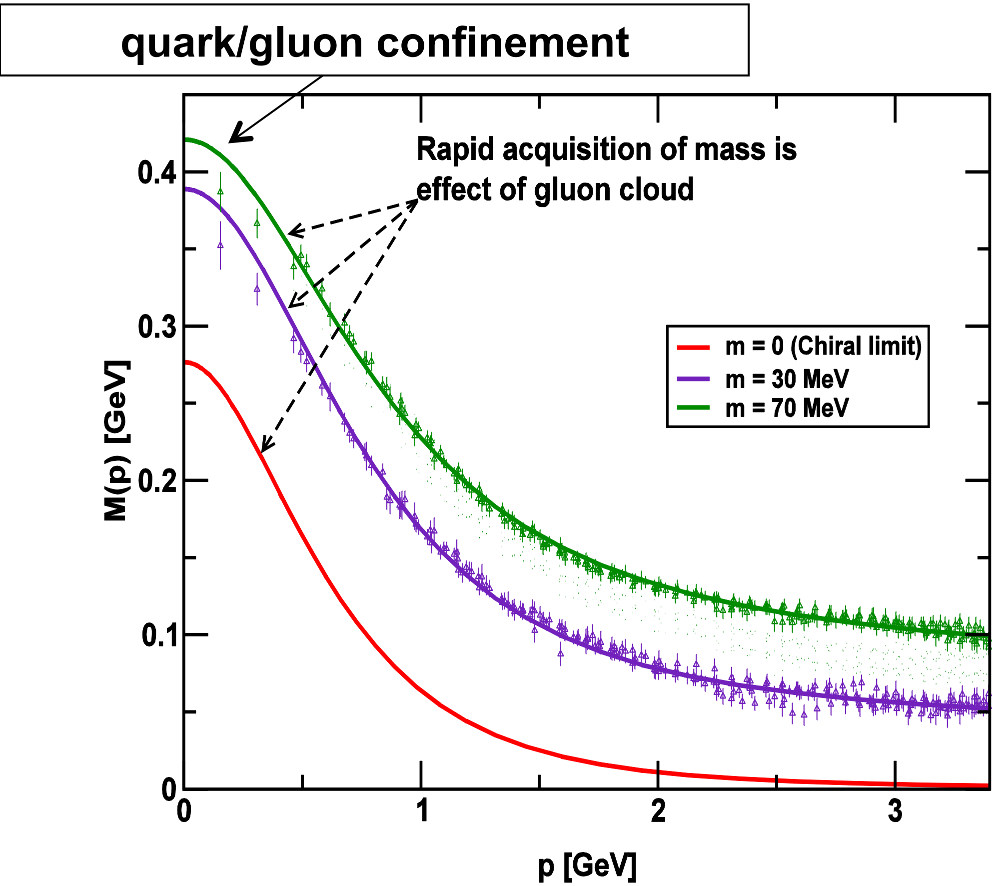


Emergence of dressed quarks and gluons



In the regime of large α_s that is relevant for N* formation, dressed quarks and gluons are substantially different with respect to the bare quarks and gauge gluons. They acquire dynamical structure and momentum-dependent mass.

Dressed Quark Evolution from pQCD to Confinement Regimes



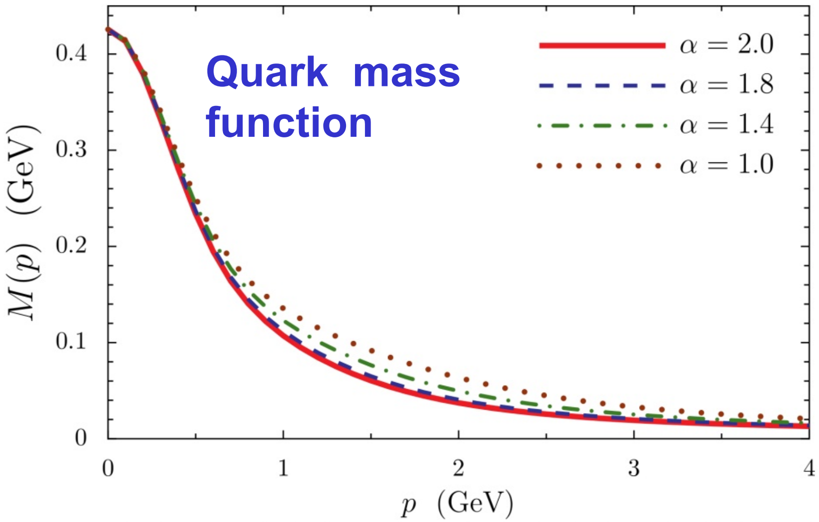
Consistent results from two different QCD-based approaches:

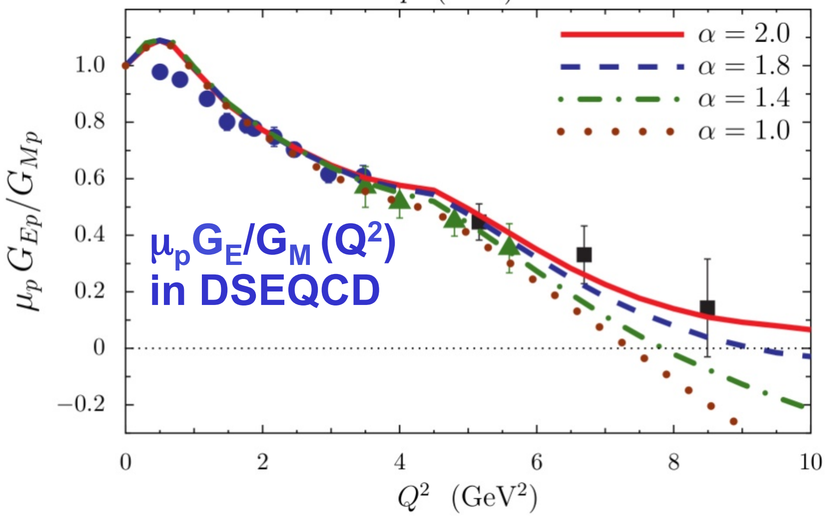
•LQCD - P.O. Bowman, et al., PRD **71**, 054505 (2005) (points with error bars).
•DSEQCD – C.D. Roberts, Prog. Part. Nucl. Phys. **61,** 50 (2008) (lines).

• **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 & N* mass.**

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

Quark Mass Function from the Studies of N/N* Structure





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

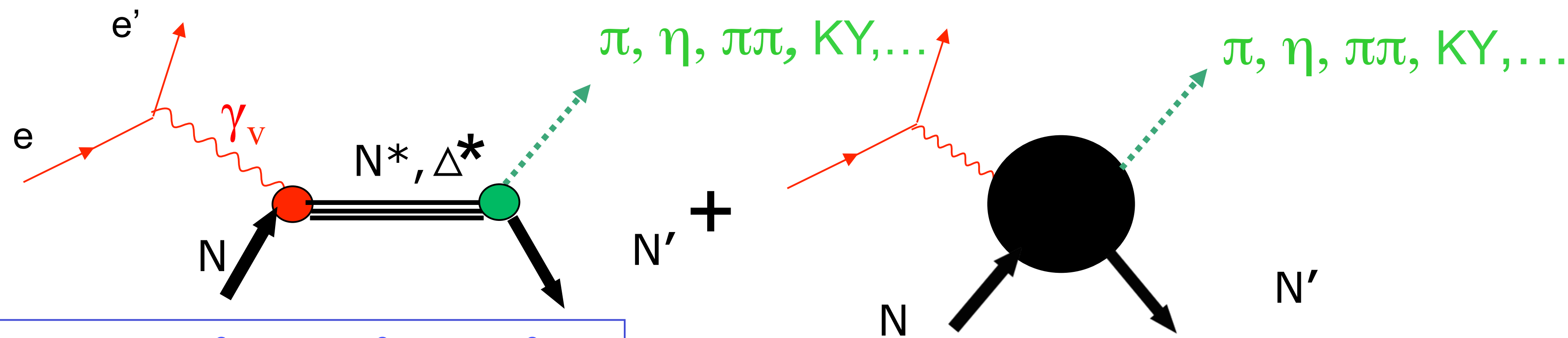
- **elastic form factors are sensitive to momentum dependence of quark mass function.**
- **mass function should be the same for dressed quarks in the ground and excited nucleon states.**
- **consistent results on dressed quark mass function determined from the data on elastic form factors and transition γ_vNN* electrocouplings are critical for reliable extraction of this quantity.**
- **results on transition γ_vNN* electrocouplings offer access to dynamics of quark-gluon vertex dressing beyond simplified rainbow-ladder truncation.**

See Colloquium talk by C.D. Roberts Wednesday, October 14, 2.00 pm.

Studies of γ_vNN* electrocouplings (transition N→N* form factors) represent the central direction in the exploration of the strong interaction in the non-perturbative regime.

Extraction of $\gamma_v NN^*$ Electrocouplings from the Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes **Non-resonant amplitudes**



•Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
or
•$G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$
or
•$G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$
I.G. Aznauryan and V.D. Burkert, Progr. Part. Nucl. Phys. 67, 1 (2012).

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

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

Γ_γ stands for N* electro-magnetic decay widths at the photon point (Q^2=0) and $W=M_{N^*}$ on the real energy axis.

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

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
$\pi^+ n$	1.1-1.38 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 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 transferred polarization of strange baryon

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

The data on exclusive electroproduction for all listed final states are available from CLAS and stored in the CLAS Physics Data Base http://clas.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 pion 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).

I.G. Aznauryan et al., CLAS Coll., Phys. Rev. C91, 045203 (2015).

Reggeized background employing DR & Finite Energy Sum Rules: under development by JPAC

➢ **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).

V.I. Mokeev, V.D. Burkert et al., arXiv:1509.05460[nucl-ex].

B_5 Veneziano model for 3-body background: under development by JPAC

Global coupled-channel analyses of the CLAS/world data of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

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

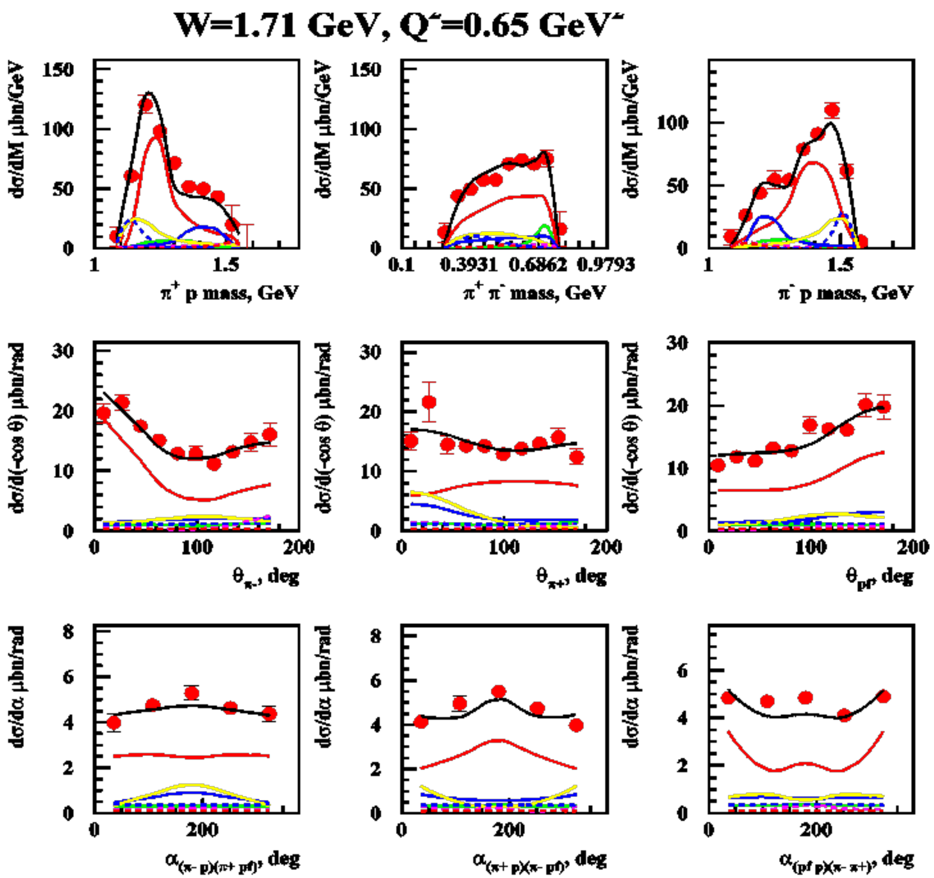
H. Kamano et al., Phys. Rev. C88, 035209 (2013).

→ **See the talks by T-S.H. Lee Tuesday, October 13, 2.40 pm, H. Kamano and T. Sato Tuesday, October 13 3.40 pm.**

Fits to Differential Cross Sections

$\gamma_v p \rightarrow \pi^+ \pi^- p$

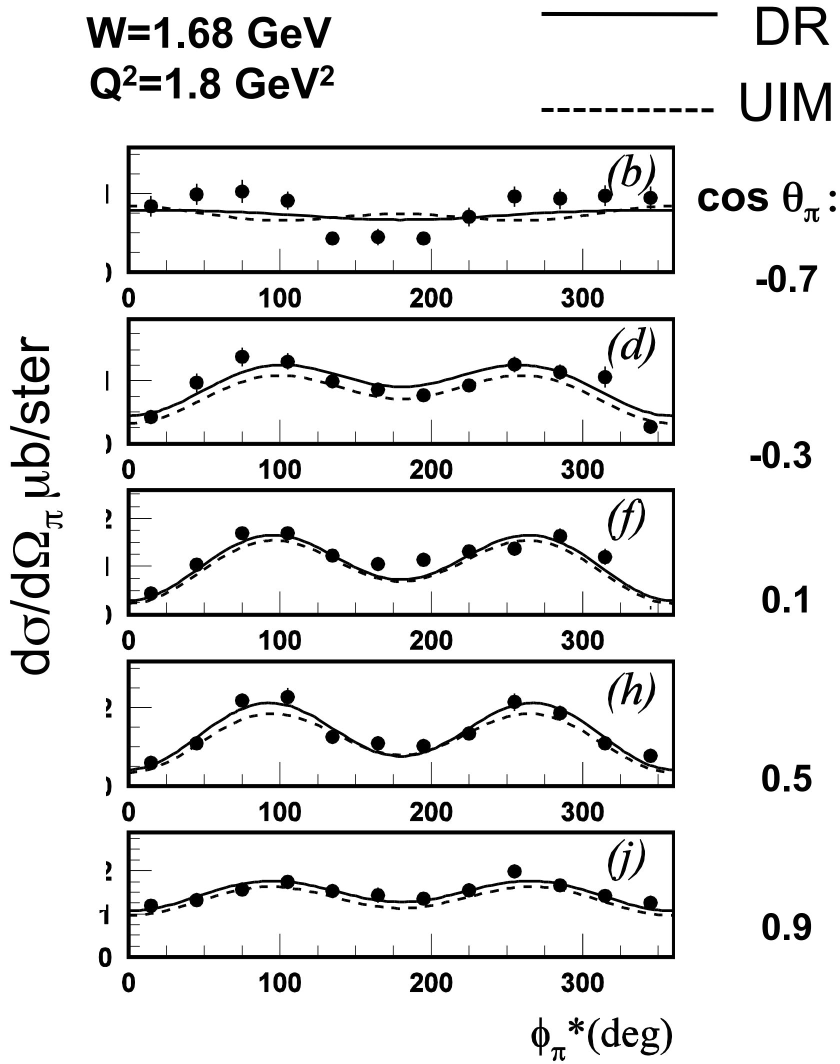
M. Ripani et al., PRL 91, 022002 (2003),
1.40<W<2.30 GeV; 0.5<Q^2<1.5 GeV^2



$\gamma_v p \rightarrow \pi^+ n$

K. Park et al., Phys. Rev. C91, 052014 (2015)

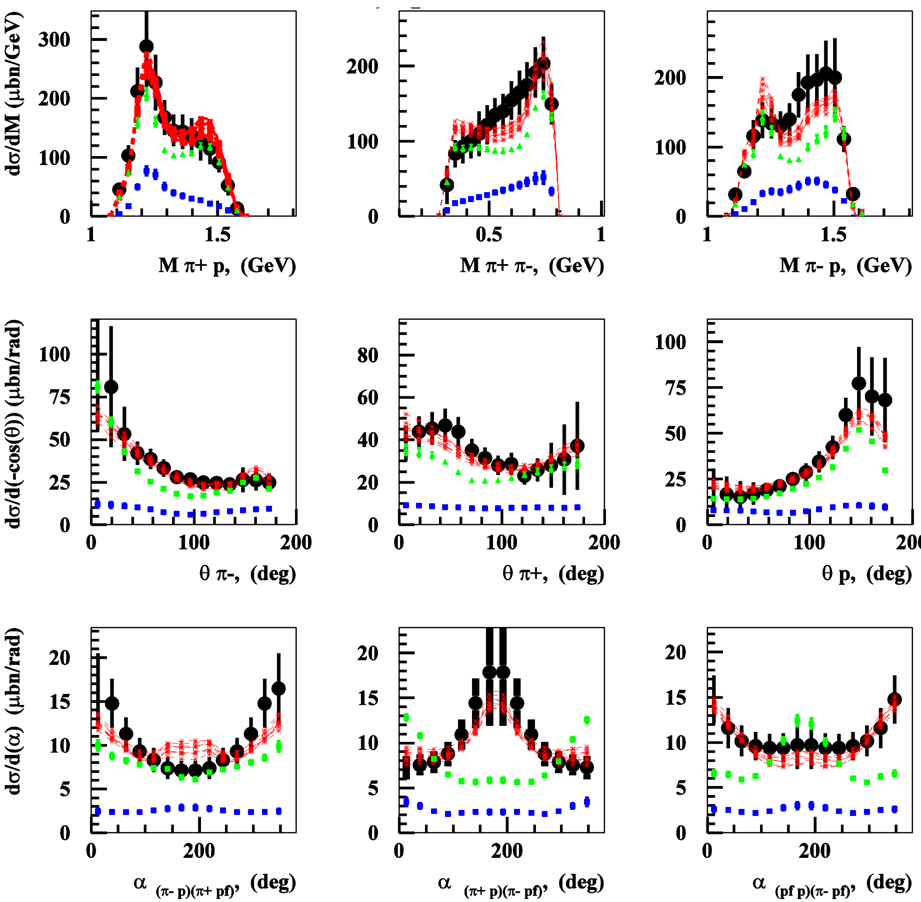
W=1.68 GeV
Q^2=1.8 GeV^2



Resonant /Non-Resonant Contributions from the Fit of $\pi^+\pi^-p$ Photo-/Electroproduction Cross Sections within the JM Model

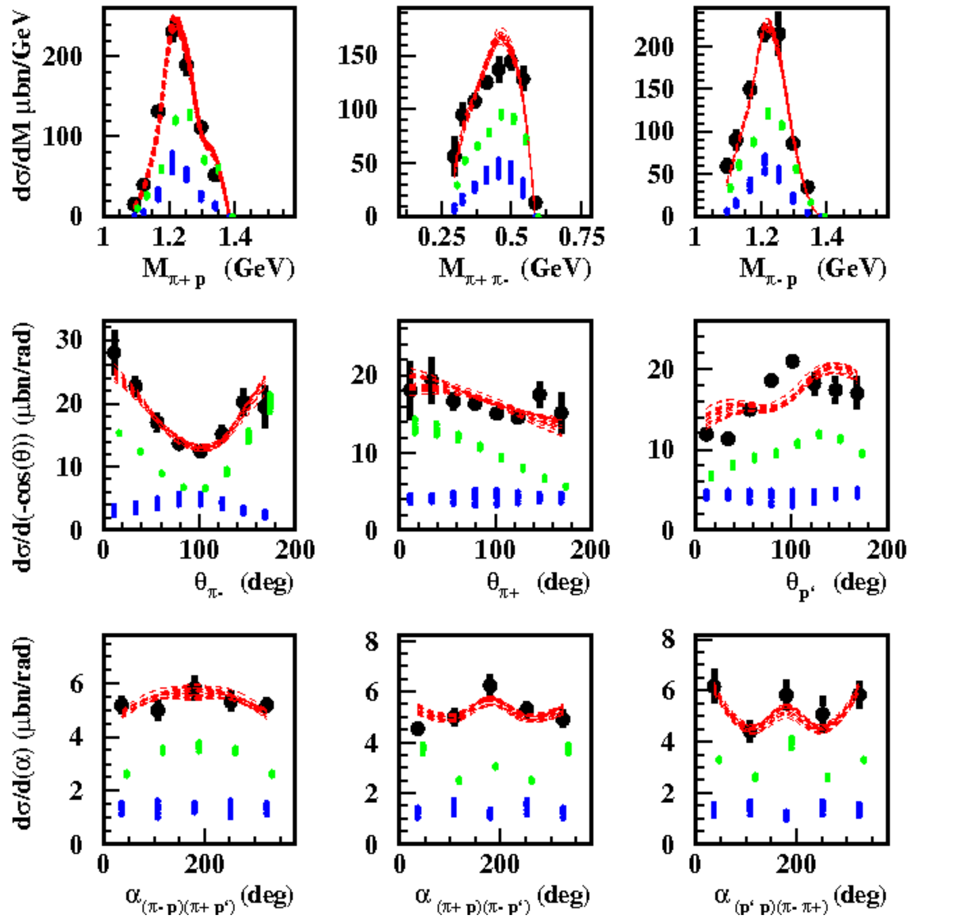
W=1.74 GeV, Q^2=0. GeV^2

E. N. Golovach. preliminary



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

G. V. Fedotov et al, CLAS Coll. PRC 79, 015204 (2009)



Data uncertainties at Q^2=0 are dominated by systematics

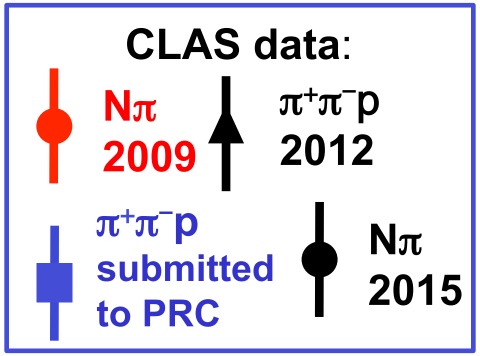
Reliable isolation of the resonant cross sections is achieved

full cross sections within the JM model

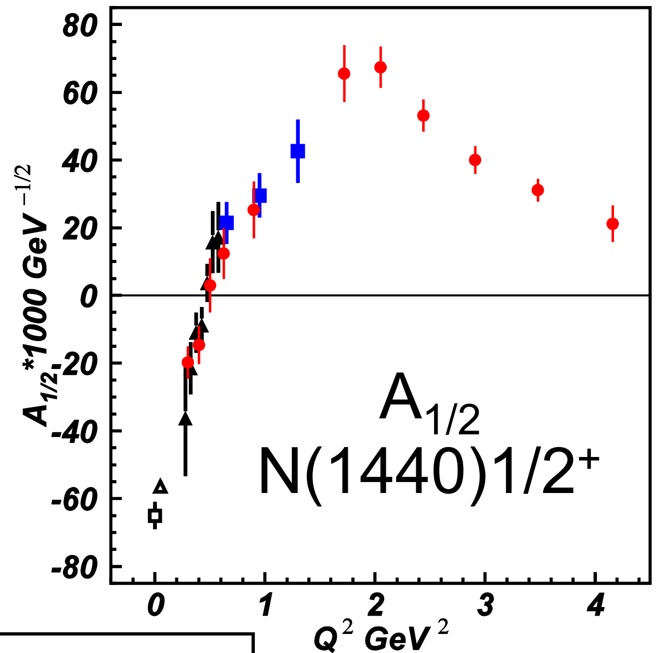
resonant part

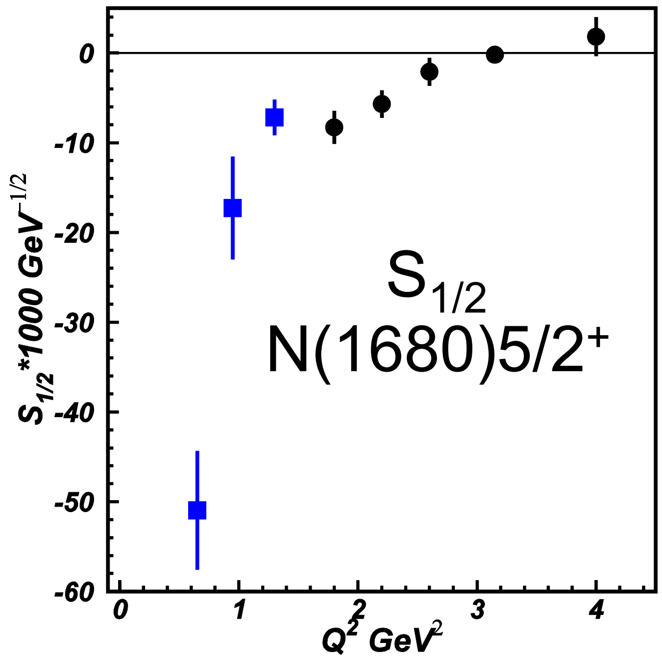
non-resonant part

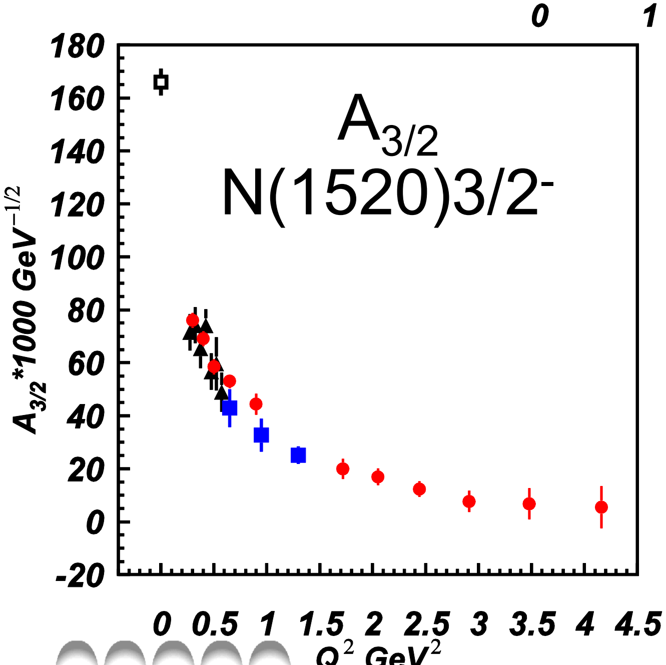
$\gamma_v NN^*$ Electrocouplings from $N\pi$ and $\pi^+\pi^-p$ Electroproduction



I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
K. Park et al., Phys. Rev. C91, 052014 (2015).



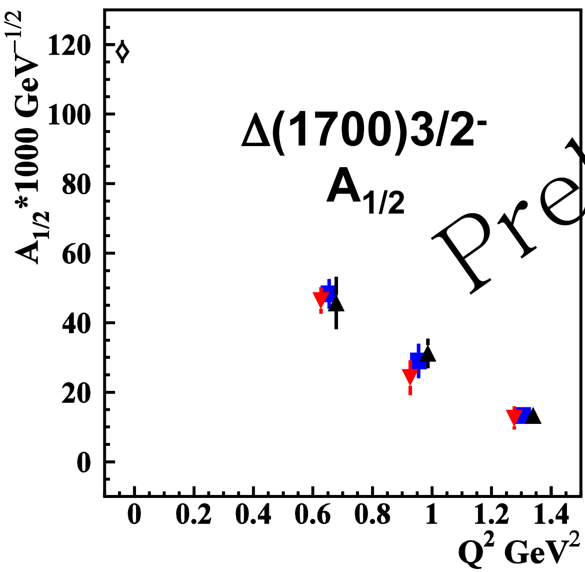


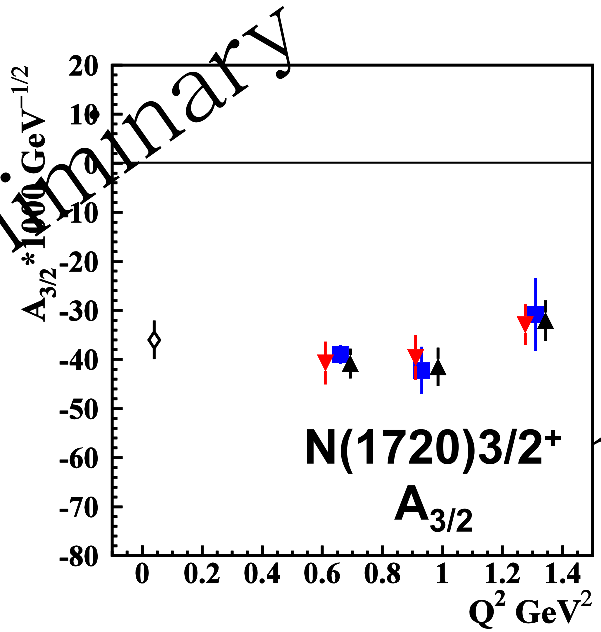


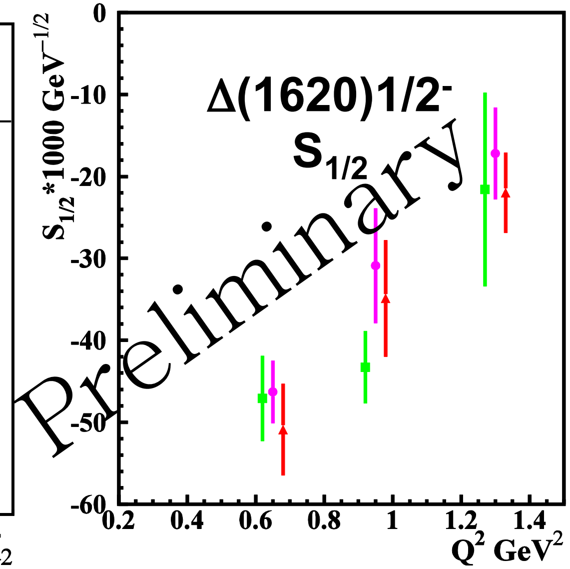
Consistent values of resonance electrocouplings from analyses of $N\pi$ and $\pi^+\pi^-p$ exclusive channels strongly support:

- **reliable electrocoupling extraction;**
- **capabilities of the reaction models to obtain resonance electrocouplings in independent analyses of these channels.**

Status and Prospects on Extraction of High-Lying N* Electrocouplings from CLAS Data







<u>**Independent fits in different W-intervals:**</u>

green: 1.51<W<1.61 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 Δ(1620)1/2$^-$, N(1650)1/2$^-$, N(1680)5/2$^+$, Δ(1700)3/2$^-$, and N(1720)3/2$^+$ electrocouplings with good accuracy.

<u>Prospect:</u> evaluation of high-mass N* electrocouplings from independent analyses of KY channels.

→ **<u>See the talk by D. Carman, Tuesday, October 13, 9.20 am.</u>**

Summary of the Published/Ready for Publication Results on $\gamma_v pN^*$ Electrocouplings from CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v NN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$	0.16-6.0
	$N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$	0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$	0.25-1.50
	$\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.5-1.5

The values of resonance electrocouplings can be fond in:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

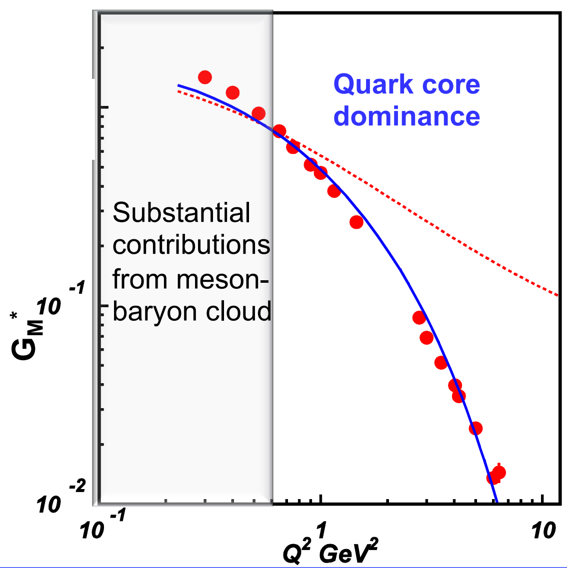
The prospects:

- $\gamma_v pN^*$ electrocoupling of all prominent nucleon resonances in mass range $M_{N^*}<2.0$ GeV will be determined from independent analyses of $N\pi$, $N\pi\pi$, and KY channels;
- the web-site will be developed for evaluation of $\gamma_v pN^*$ electrocouplings for the aforementioned resonances at 0.2 $GeV^2 < Q^2 <$ 5.0 GeV^2.

Access to the Dressed Quark Mass Function from the Data on the Transition $N \to N^*$ Form Factors

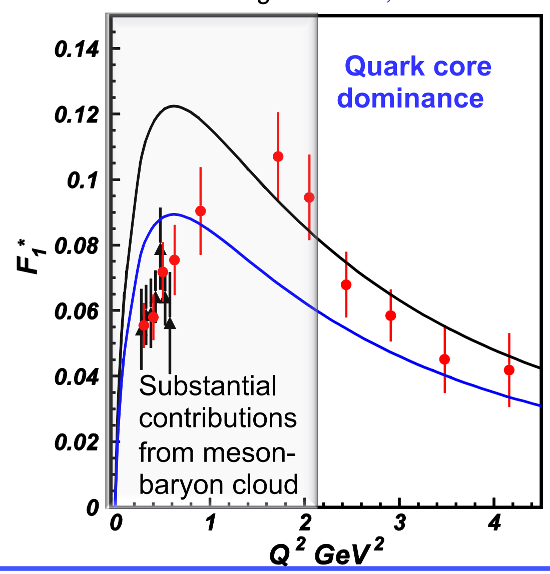
$\Delta(1232)3/2^+$
Jones-Scadron convention

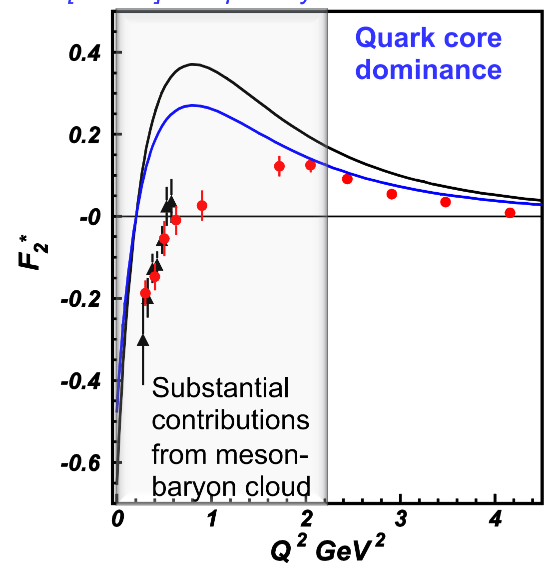
J. Segovia et al., Few Body Syst. 55,1185 (2014).



N(1440)1/2$^+$
Dirac F_1^* and Pauli F_2^*
$N \to N(1440)1/2^+$ transition form factors

J. Segovia et al., arXiv: 1504.04386[nucl-th] accepted by PRL





The quark core contributions to transition form factors computed in a common DSEQCD framework starting from the QCD Lagrangian:

- - - - - - - **Contact qq interaction, frozen constituent quark mass.**

——— **Realistic qq interaction, running quark mass.** (blue)

——— **Realistic qq interaction, running quark mass,** (black)

——— **the same but multiplied by the common factor fit to the data on the leading $A_{1/2}$ coupling at Q^2>3.0 GeV^2 (slide#18), which accounts for the product of the quark core fractions in ground and N(1440)1/2$^+$ states** (blue)

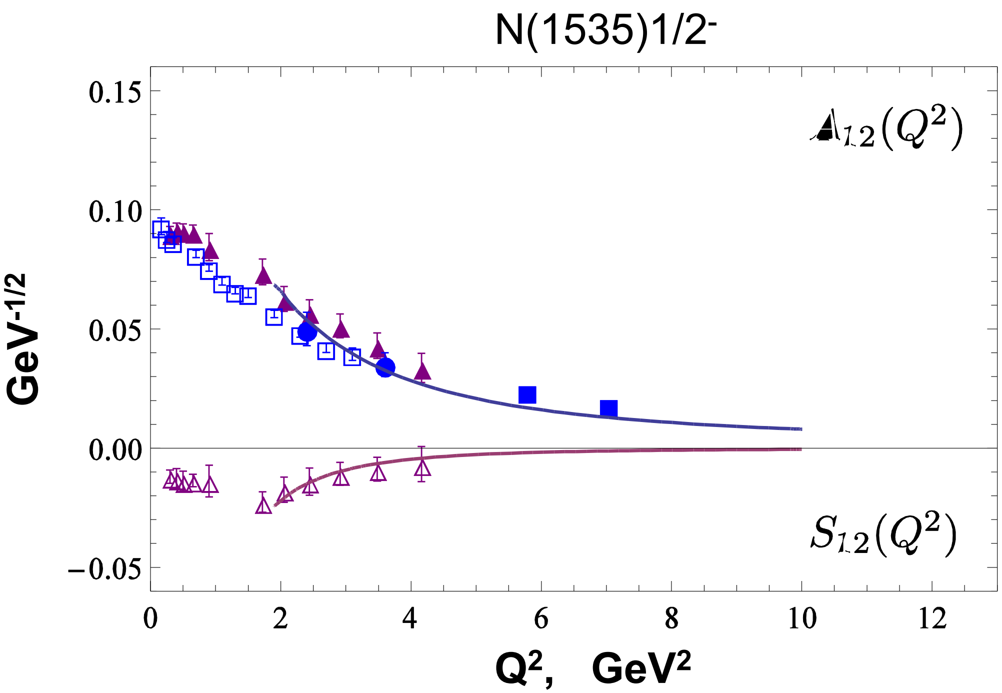
Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground and excited nucleon states of distinctively different structure provides strong evidence for:

- **the relevance of dressed quark predicted by DSEQCD;**
- **promising prospect to probe dressed quark mass function from the results on nucleon elastic and transition form factors.**

Discussion on the Future Efforts on Interpretation of the Experimental Results on N* Spectrum/Structure within DSEQCD

- Extension of DSEQCD evaluation of the N→N* transition form factor for the resonance of different quantum numbers:
  a) first orbital excitation of quark core in $N(1535)1/2^-$, $N(1520)3/2^-$, $N(1650)1/2^-$
  b) first orbital excitation of quark core in $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$
- What we will learn from the studies of the N* states with quark core of L=1 on non-perturbative strong interaction dynamics in addition to the information available from ground states, spin-flavor flip, and radial excitations?
- Prospects to compute quark distribution amplitudes in N* states and the transition N→N* GPD's
- How can we probe di-quark correlations in different N* states from the data on resonance electrocouplings?
- Synergy between DSEQCD and Quark Models for the N* structure.

Relating $\gamma_v NN^*$ Electrocouplings to the first Principles of QCD within the Framework of Light Cone Sum Rule (LCSR) & Lattice QCD (LQCD) Approaches



I.V. Anikin, V.M. Braun, N. Offen, Phys. Rev. D92, 014018 (2015)

The shape parameters of N(1535)1/2- leading twist quark distribution amplitude (DA) φ_{ij}, η_{ij} were fit to the CLAS electrocoupling data within LCSR, while normalization parameters λ_{1N^*}, f_{N^*} were taken from the LQCD evaluations at the central values (V.M. Braun et al., Phys. Rev D89, 094511 (2014)).

Successful description of the CLAS data at Q^2>2.0 GeV^2, where LCSR is applicable, with normalization parameters from LQCD demonstrates the approach potential of relating $\gamma_v NN^*$ electrocouplings to the first principles of QCD

Method	$\lambda_1^N/\lambda_1^{N^*}$	$f_{N^*}/\lambda_1^{N^*}$	φ_{10}	φ_{11}	η_{10}	η_{11}
LCSR	0.633	0.027	0.36(>1)	-0.95(>1)	0.00(29)	0.94(71)
LQCD	0.633(43)	0.027(2)	0.28(12)	-0.86(10)	N./A.	N./A.

See the talks by: V.M. Braun, Monday, October 12, 2.40 pm.
D.G. Richards, Thursday, October 15, 9.20 am.

Discussion on the Future Efforts on Interpretation of the Experimental Results on N* Spectrum/Structure within LQCD

- Prospect for extension of LCSR for accessing quark DA of different excited proton states.

- Prospect for LQCD evaluation of DA moments of different excited proton states.

- Possibility to compare N(1535)$1/2^-$ quark DA: a) fit to the electrocoupling data within LCSR, b) derived employing LQCD b) derived employing DSEQCD. Can consistency of these results prove understanding of non-perturbative strong interaction from the first principles of QCD?

- Prospect for LQCD evaluation of resonance electrocouplings accounting for decays of excited nucleon states and approaching physical pion mass.

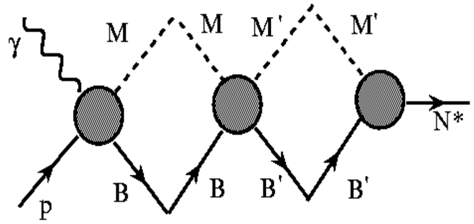
- Possibilities for mutual comparison between LQCD and DSEQCD.

- Predictive power of the approaches based on the first principles of QCD:
  - a) hybrid baryon spectrum
  - b) hybrid baryon electrocouplings
  - c) electrocouplings and hadronic decays of ``missing" N*

Quark Core and Meson-Baryon Cloud in the Structure of N(1440)1/2+ Resonance

Quark core from DSEQCD

The mechanisms of meson-baryon dressing :

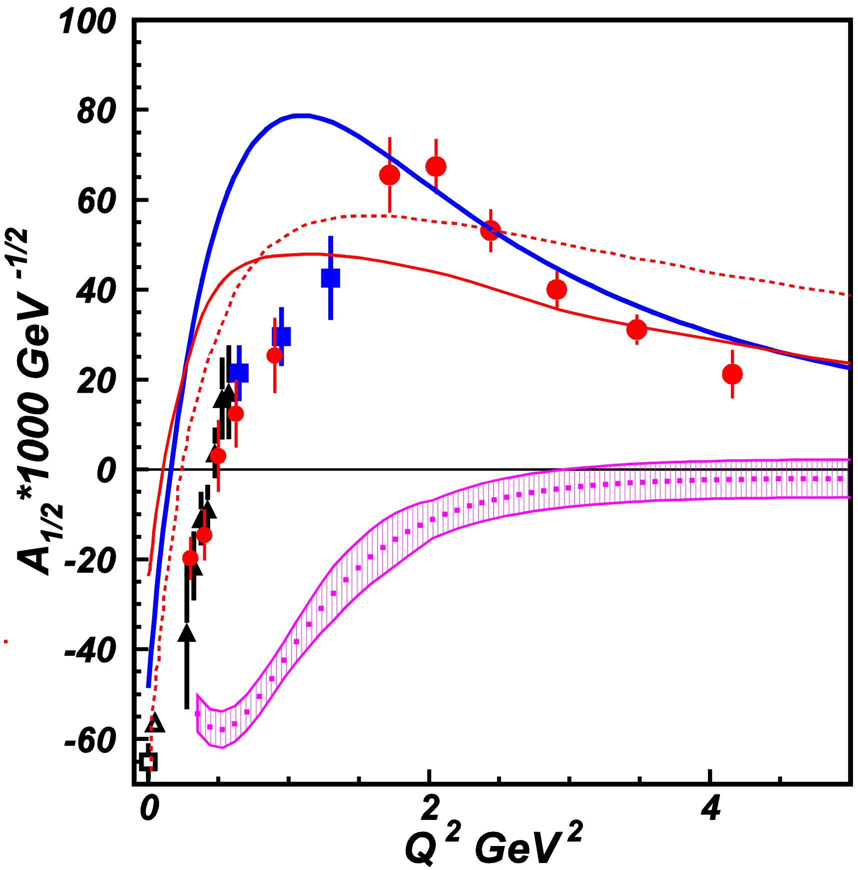


Description of the N(1440)1/2+ $A_{1/2}$ electrocoupling by the light front quark models that incorporate the inner core and outer meson-baryon (MB) cloud:

Nπ loops MB cloud; running quark mass.
I.G .Aznauryan, V.D. Burkert, Phys. Rev. C85, 055202 (2012).

Nσ loops for MB cloud; frozen constituent quark mass.
I.T. Obukhovsky, et al., Phys. Rev. D89, 014032 (2014).

MB cloud inferred from the CLAS data as the difference between the data fit and evaluated within DSEQCD quark core

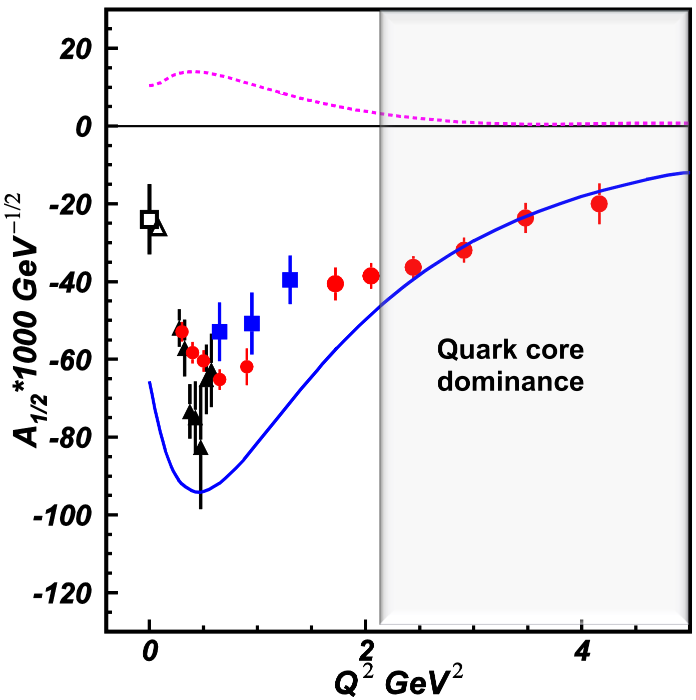


Successful description of the N(1440)1/2+ quark core from the QCD Lagrangian has been achieved for the first time with the framework of DSEQCD!

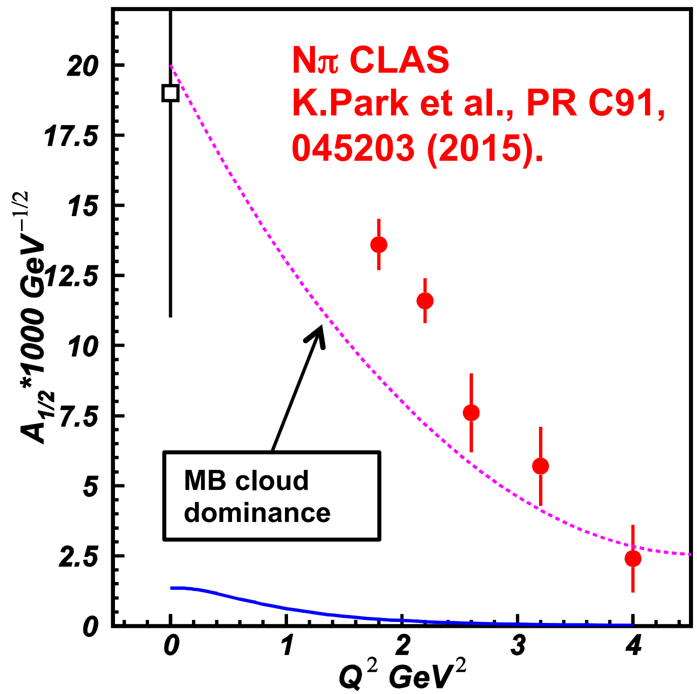
The structure of N(1440)1/2+ resonance is determined by complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baryon cloud.

Interplay Between Quark Core and Meson-Baryon Cloud in the Structure of Different Excited Nucleon States

N(1520)3/2$^-$



N(1675)5/2$^-$



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$^-$: prospect to explore dressed quark mass function, qqG vertex, and di-quark correlations;**
- **meson-baryon cloud from the data on N(1675)5/2$^-$: shed light on the transition from confined quarks in inner core to colorless mesons and baryons in N* exterior**

CLAS12 N* Program

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Burkert, Mokeev, Stoler, Joo, Gothe, Cole	*Carman, Mokeev, Gothe*

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

E_b = 11 GeV, Q^2 = 3 → 12 GeV^2, W → 3.0 GeV with the almost complete coverage of the final state phase space

- **See the talk by R.W. Gothe, Tuesday,October 13, 2.00 pm.**

CLAS12 is the only facility foreseen in the world capable to map-out N quark core under almost negligible contributions from meson-baryon cloud*

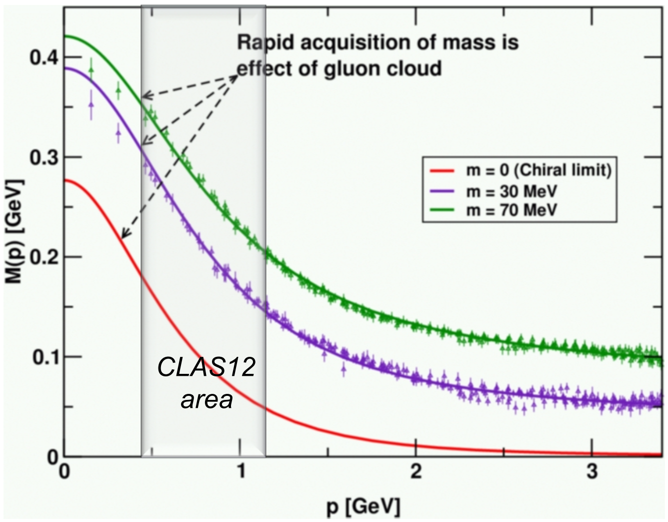
A unique opportunity to probe dressed quark mass function in the transition from confinement to pQCD regime and to explore the nature of confinement and its emergence from QCD from the results on transition N→N form factors/electrocouplings*

The experiments will start in the first year of running with the CLAS12 detector.

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

Dressed quark mass function

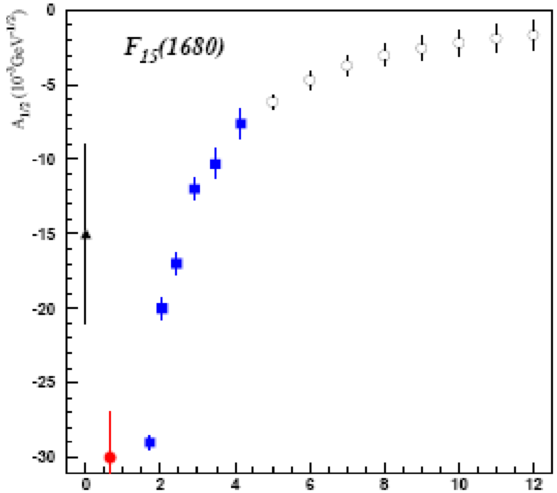
C.D. Roberts, Prog. Part. Nucl. Phys. (2008) 50.



Resonance electrocouplings

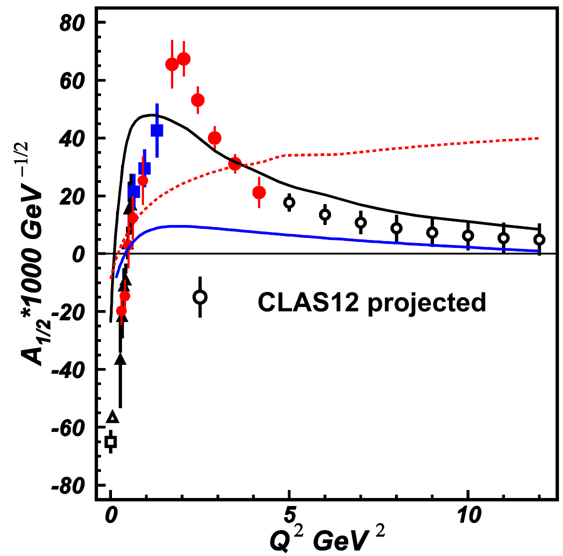
(available from CLAS and expected from CLAS12)

N(1680)5/2 +



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.



DSEQCD : *(quark core only)* .... *constant quark mass.*

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

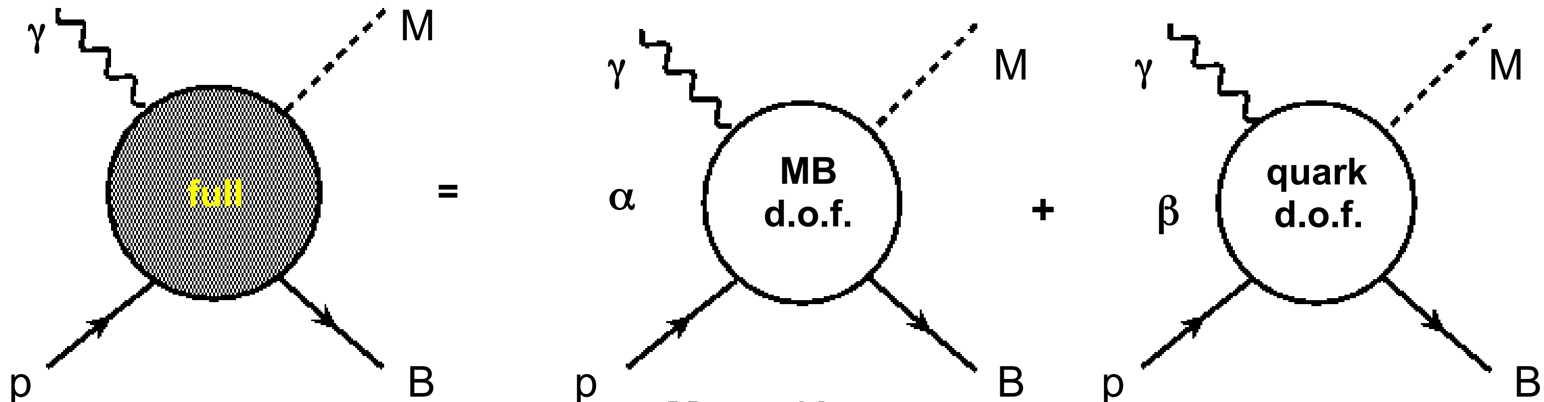
Opportunity to probe dressed quark mass function in the transition from quark-gluon confinement to pQCD regimes for the first time.

Consistent results on quark mass function from electrocouplings of different resonances at Q^2 > 5 GeV^2 will prove reliable access to this fundamental quantity.

Important direction in the recommendations of the 2014 Town Meeting on QCD and Hadron physics for the next US Long Range Plan, S.J. Brodsky et al., arXiv:1520.05728 [hep-ph].

Development of the Reaction models with Explicit Implementation of Quark Degrees of Freedom for Extraction of $\gamma_v NN^*$ Electrocouplings at $Q^2>5.0$ GeV^2

- Modeling of the amplitudes other than photon-proton s-channel resonances for the exclusive $N\pi$, KY, $\pi\Delta$, and ρp electroproduction at Q^2 up to 12 GeV^2 from minimal accessible W<2.0 GeV to 3.0 GeV. The models should account for:
  a) hard processes in terms of diagrams with factorized explicit quark degrees of freedom;
  b) relevant soft contributions in terms of meson-baryon degrees of freedom.



$\mathbf{M} = \pi, K, \rho$
$\mathbf{B} = N/\Delta, Y, p$
$\alpha + \beta = 1$

- Adjustment of the reaction model parameters to all measured with the CLAS observables at $Q^2>3.0$ GeV^2

See the talk by: P. Kroll, Thursday, October 15, 11.10 am.

The most urgent task for theory support of the upcoming experiments on the N* structure studies with CLAS12!

Contact person: Volker D. Burkert

A Letter of Intent to the Jefferson Lab PAC43

Signature of the hybrid-baryons:

(qqq)g

Search for Hybrid Baryons with CLAS12 in Hall B

Annalisa D'Angelo,[1,2] Ilaria Balossino,[11] Luca Barion,[11] Marco Battaglieri,[3] Vincento Bellini,[12] Volker Burkert,[4] Simon Capstick,[5] Daniel Carman,[4] Andrea Celentano,[3] G. Ciullo,[11] Marco Contalbrigo,[11] Volker Credé,[5] Raffaella De Vita,[3] E. Fanchini,[3] Gleb Fedotov,[6] A. Filippi,[10] Evgeny Golovach,[6] Ralf Gothe,[7] Boris S. Ishkhanov,[6,13] Evgeny L. Isupov,[6] Valeri P. Koubarovski,[4] Lucilla Lanza,[2] P. Lenisa,[11] Francesco Mammoliti,[12] Victor Mokeev,[4,6] A. Movsisyan,[11] Mikhail Osipenko,[3] Luciano Pappalardo,[11] Marco Ripani,[3] Allesando Rizzo,[2] Jan Ryckebusch,[8] Iuliia Skorodumina,[7,13] Concetta Sutera,[12] Adam Szczepaniak,[9,4] Mauro Taiuti,[3] M. Turisini,[11] Maurizio Ungaro,[4] and Veronique Ziegler[4]

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[10] *INFN, Sezione di Torino, Torino, Italy*
[11] *INFN Ferrara e Universitá di Ferrara, Italy*
[12] *INFN, Sezione di Catania, Catania, Italy*
[13] *Physics Department at Lomonosov Moscow State University, Leninskie Gory, Moscow 119991, Russia.*

(Dated: May 17, 2015)

New baryon state in the mass range from 2.1 GeV to 2.4 GeV of spin-parity $1/2^+$ or $3/2^+$

qqq-configuration should be in {8}-color state

⇩

Peculiar Q^2-dependence of hybrid-baryon electro-couplings

Recommendation:
The PAC encourages the preparation of a full proposal. However, we emphasize that the 11 GeV running should be put forward as a **Run Group Proposal**, if it is indeed to run in parallel with other approved experiments. Further, the additional beam time at 6.6 and 8.8 GeV must be considered as a **separate proposal** that may include other measurements that could be carried out with the additional beam time.

Models for electrocoupling extraction:
Ghent, JPAC, BnGa, JM

Flagship experiment for the studies of the N* structure at $0.05\ GeV^2 < Q^2 < 1.0\ GeV^2$

→ **See the talks by: L. Lanza, Tuesday, October 13, 11.10 am.**

The N* Structure at Low Photon Virtualities with CLAS12

Use of the CLAS12 forward tagger will make it possible to obtain the data on $N\pi$, KY, $N\pi\pi$ electroproduction at 0.05 GeV^2 < Q^2 < 1.0 GeV^2 of the best statistical and systematical accuracy ever achieved.

An excellent opportunity to extend the approaches for amplitude extraction from the photoproduction data to electroproduction at small Q^2 and to determine N* parameters under minimal model assumptions:

See the talk by: A. Sarantsev, Tuesday, October 13, 11.50 am.
A. D'Angelo, Friday, October 16, 9.20 am.

New opportunities from the N* structure studies at low Q^2:

- **Check evidence for new N* states from exclusive photoproduction data in analyses of exclusive photo-/electroproduction data combined examining possibility to fit the data with Q^2-independent N* hadronic parameters.**
- **Explore how $S_{1/2}$ electrocouplings are approaching the photon point at Q^2 as low as 0.05 GeV^2.**
- **The studies of N* meson-baryon dressing in details.**
- **Opportunities to probe di-quark correlations in N* states of different quantum numbers.**

Conclusions

- **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 analyses of π^+n, π^0p, ηp and $\pi^+\pi^-p$ electroproduction channels. Consistent electrocoupling values obtained independently from $N\pi/N\pi\pi$ exclusive channels demonstrated reliable electrocoupling extraction and capabilities of the developed reaction models to determine N*-parameters from independent analyses of $N\pi/N\pi\pi$ exclusive electroproduction.**

- **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.**

- **Successful description of elastic and transition form factors to different low-lying resonances achieved at Q^2>2.5 GeV^2 within the framework of DSEQCD demonstrated promising opportunity to probe dressed quark mass function getting an access to the essence of non-perturbative strong interaction and its emergence from QCD.**

- **First results on N(1535)1/2$^-$ quark distribution amplitudes (DA) have recently become available from analyses of the CLAS electrocoupling data within the framework of the Light Cone Sum Rules and Lattice QCD offering another promising avenue of relating resonance electrocouplings to the first principles of QCD.**

Outlook

- **After 12 GeV Upgrade CLAS12 will be only available facility worldwide capable of obtaining electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV^2 and highest photon virtialities ever achieved for exclusive reactions from 5.0 GeV^2 to 12 GeV^2 from the measurements of exclusive Nπ, $\pi^+\pi^-$p, and KY electroproduction.**

- **The expected results will allow us:**
  a) search for hybrid baryons;
  b) establish the existence of new baryon states based on the fits of photo-/ electroproduction data with Q^2-independent N* hadronic parameters;
  c) explore the emergence of meson-baryon cloud from quark-gluon confinement and di-quark correlations;
  d) access quark distribution amplitudes in N* states;
  e) to probe the dressed quark mass function at the distance scales where the transition from quark-gluon confinement to pQCD regime is expected, <u>addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and quark-gluon confinement.</u>

- **Development of the reaction models for extraction of γ_vpN* electrocouplings at Q^2>5.0 GeV^2 accounting for the quark d.o.f in non-resonant amplitudes is <u>urgently</u> needed for support of N* Program with CLAS12!**

- **Success of N* Program with the CLAS12 <u>strongly depends from productive synergy between experiment/phenomenology/theory.</u> It will be very beneficial for Jefferson Lab and hadron physics community worldwide.**

Back up

First Interpretation of the Structure at W~1.7 GeV in $\pi^+\pi^-p$ Electroproduction

The JM03 analysis of <u>three of nine</u> one-fold differential cross sections (*M.Ripani et al., Phys. Rev. Lett. 91, 022002 (2003)).*

conventional states only, consistent with PDG 02.

implementing 3/2⁺(1720) candidate or conventional states only with different than in PDG 02 N(1720)3/2⁺ Nππ decays.

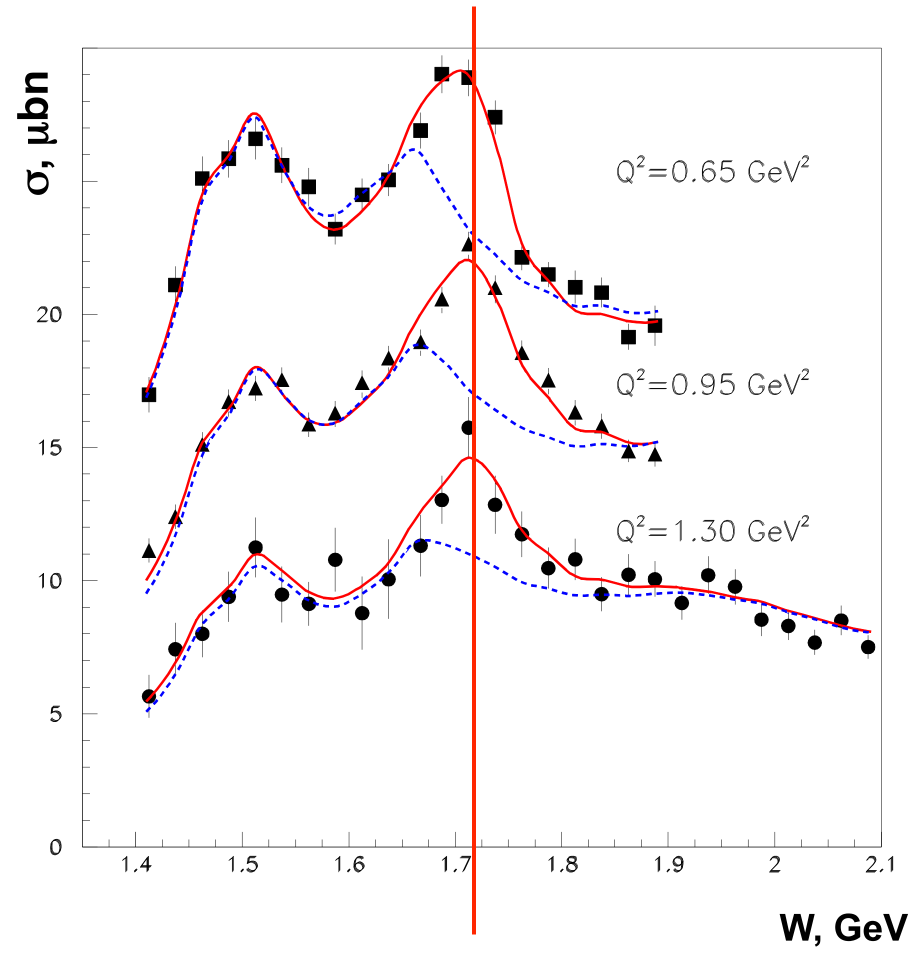
<u>Two equally successful ways for the data description:</u>

different than in PDG 02' N(1720)3/2⁺ Nππ hadronic decay widths:

	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
N(1720)3/2⁺ decays fit to the CLAS Nππ data	**114±19**	**63±12** **75±12 (BnGa12)**	**19±9**
N(1720)3/2⁺ PDG 02'	**150-300**	**<20**	**70-85**

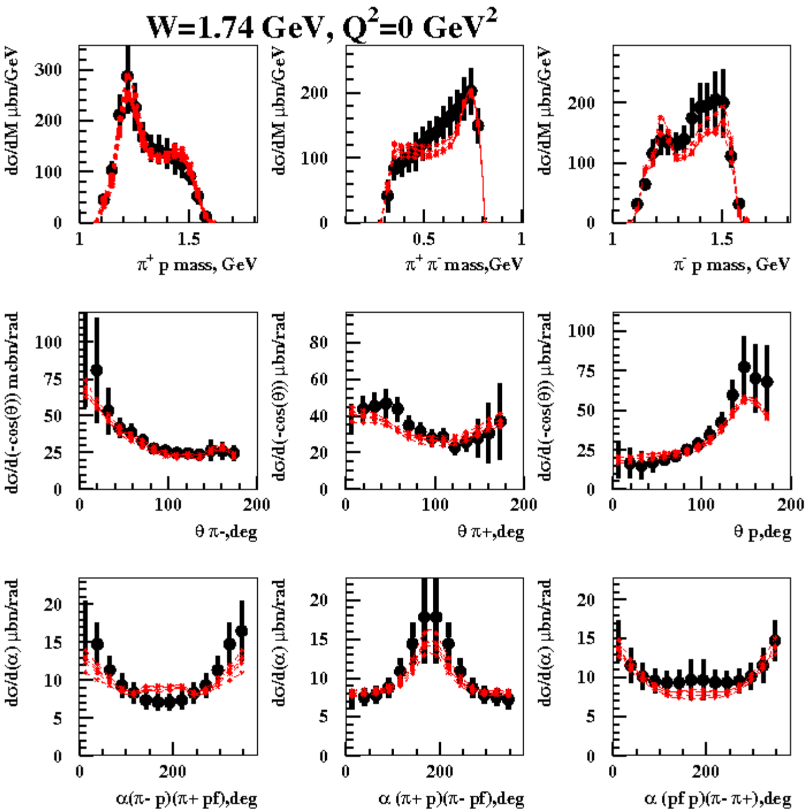
new 3/2⁺(1720) state and consistent with PDG 02' Nππ hadronic decays of N(1720)3/2⁺:

	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
3/2⁺(1720) candidate	**88±17**	**41±13**	**17±10.**
N1720)3/2⁺ conventional	**161±31**	**<20**	**60-100**



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

Fit of the CLAS data within the framework of the JM15:

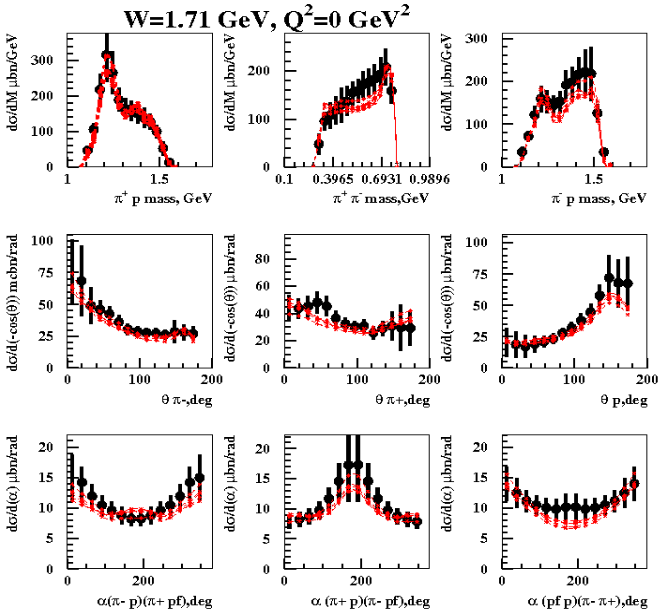


Resonance	$A_{1/2}$, GeV$^{-1/2}$ *1000, JM15/RPP12	$A_{3/2}$, GeV$^{-1/2}$ *1000 JM15/RPP12
$N(1650)1/2^-$	63±6 53±16	
$N(1680)5/2^+$	-29±3 -15±6	133±14 133±12
$N(1700)3/2^-$	-5±4 -18±13	30±22 -2±24
$N'(1720)3/2^+$	40±3 N/A	-43±8 N/A
$N(1720)3/2^+$	89±16 97±3 (*)	-35±13 -39±3(*)
$\Delta(1600)3/2^+$	-26±10 -23±20	-19±9 -9±21
$\Delta(1620)1/2^-$	33±4 27±11	
$\Delta(1700)3/2^-$	97±19 104±15	84±11 85±22
$\Delta(1905)5/2^+$	25±4 26±11	-57±10 -45±20
$\Delta(1950)7/2^+$	-68±16 -76±12	-123±20 -97±10

(*)M. Dugger et al., Phys. Rev. C76, 025211 (2007).

Consistent results on photocouplings of resonances with masses above 1.6 GeV from analyses of $N\pi$ and $\pi^+\pi^-p$ channels demonstrate reliable extraction of these fundamental quantities.

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



Almost the same quality of the photoproduction data fit at 1.66 GeV <W<1.76 GeV and Q^2=0, 0,65, 0.95, 1.30 GeV^2 was achieved with and without N'(1720)3/2$^+$ new states

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

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

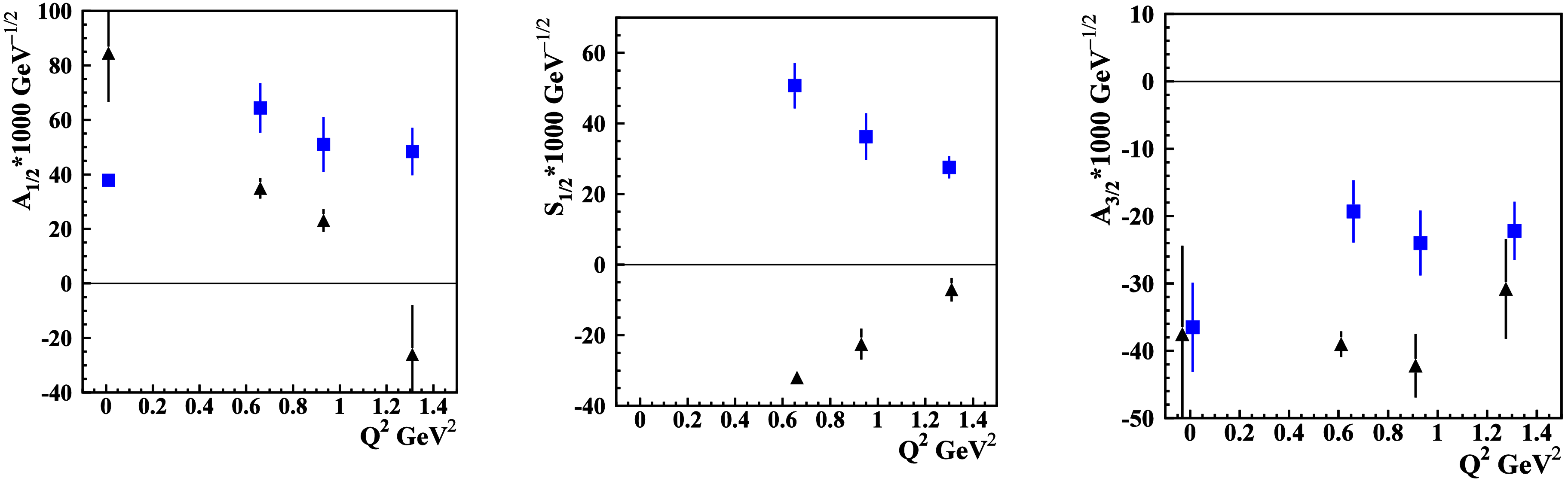
Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46
Δ(1700)3/2$^-$ electroproduction photoproduction	 77-95 78-93	 3-5 3-6

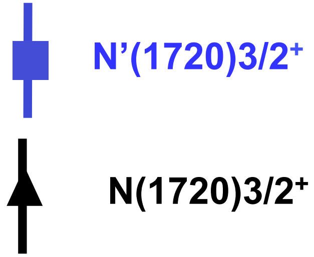
The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

Successful description of $\pi^+\pi^-p$ 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 provides strong evidence for the existence of new N'(1720)3/2$^+$ state.

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

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

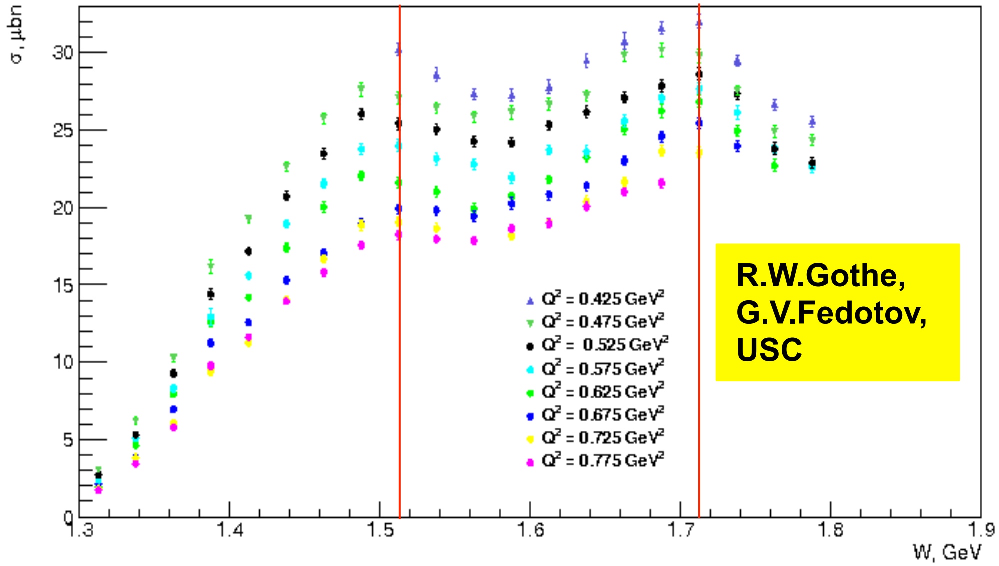




Resonance	Mass, GeV	Total width, MeV
N'(1720)3/2⁺	1.715-1.735	120±6
N (1720)3/2⁺	1.743-1.753	112±8

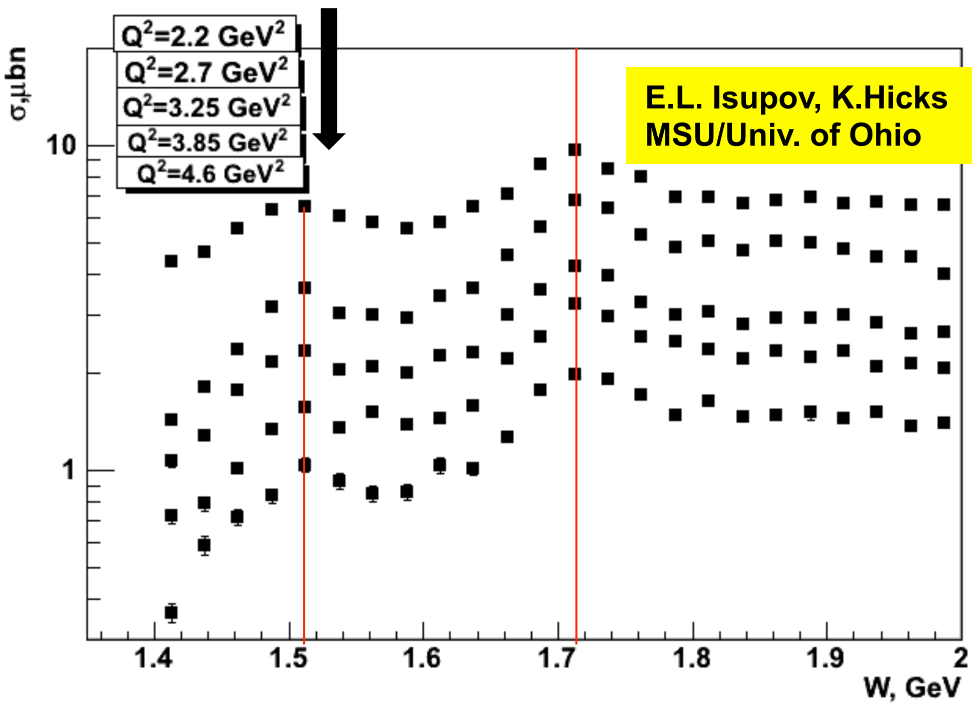
N'(1720)3/2⁺ is the only candidate state for which the results on Q^2-evolution of transition electrocouplings have become available offering the insight to the structure of the new baryon state.

Extension of the CLAS $\pi^+\pi^-p$ Electroproduction Data



<u>Fully integrated $\pi^+\pi^-p$ electroproduction cross sections off protons</u>

- **Nine 1-fold differential cross sections are available In each bin of W and Q^2 shown in the plots.**
- **Resonance structures are clearly seen at W ~1.5 GeV and ~1.7 GeV at $0.4 < Q^2 < 5.0$ GeV^2 (red lines) .**



<u>Analysis objectives:</u>

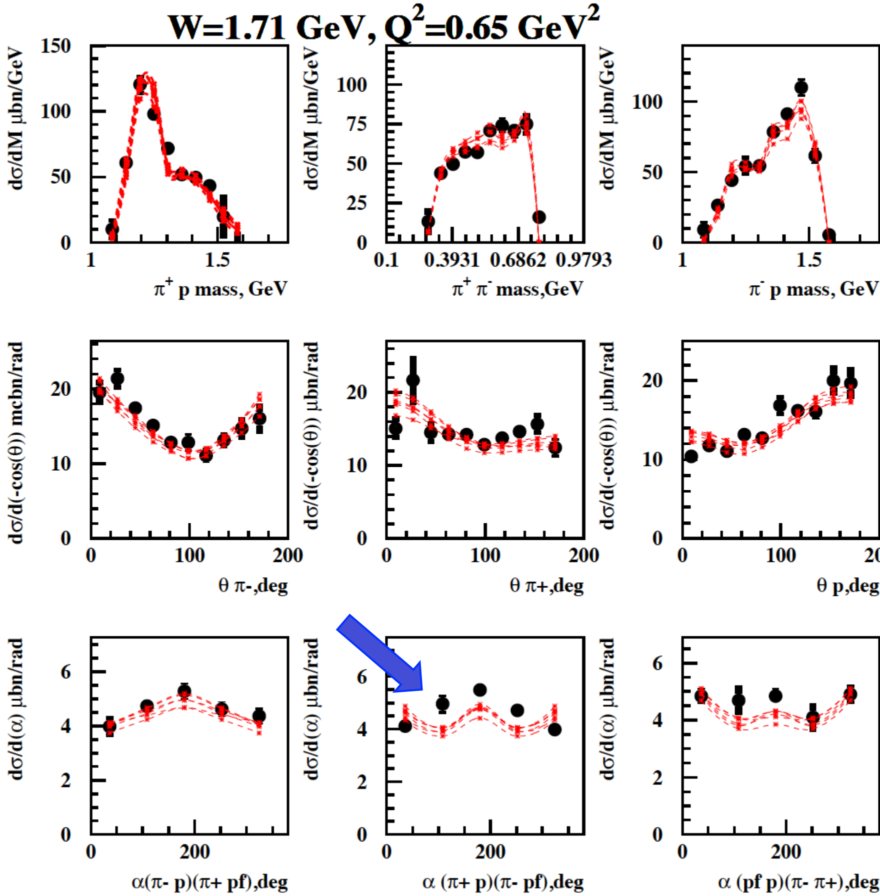
- **Extraction of $\gamma_v NN^*$ electrocouplings and $\pi\Delta$, ρp decay widths for most N*s in mass range up to 2.0 GeV and $0.4 < Q^2 < 5.0$ GeV^2 within the framework of JM-model.**
- **Exploration of the signals from $3/2^+(1720)$ candidate-state (M.Ripani et al., Phys. Rev. Lett 91, 022002 (2003)) with a goal to achieve decisive conclusion on the state existence and structure.**
- **First results on electrocouplings of high-lying (M_{N^*}>1.6 GeV) orbital nucleon excitations and high-lying parity partners.**

Analysis of the $ep \to \pi^+\pi^- p$ CLAS data at W~1.7 GeV in the JM15 model

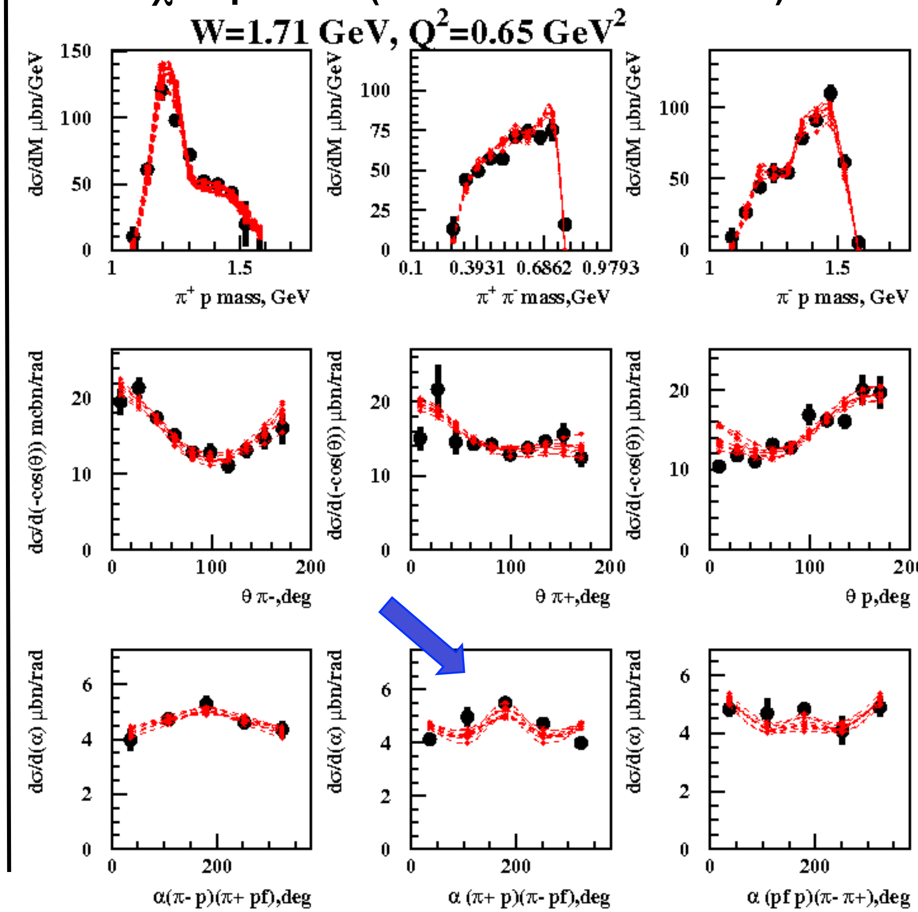
conventional N*-states with $\pi\Delta$, ρp couplings fit to the data

3/2⁺(1720) candidate state is included to the fit

$2.85 < \chi^2$/d.p.< 3.03 (1.66 GeV<W<1.76 GeV)

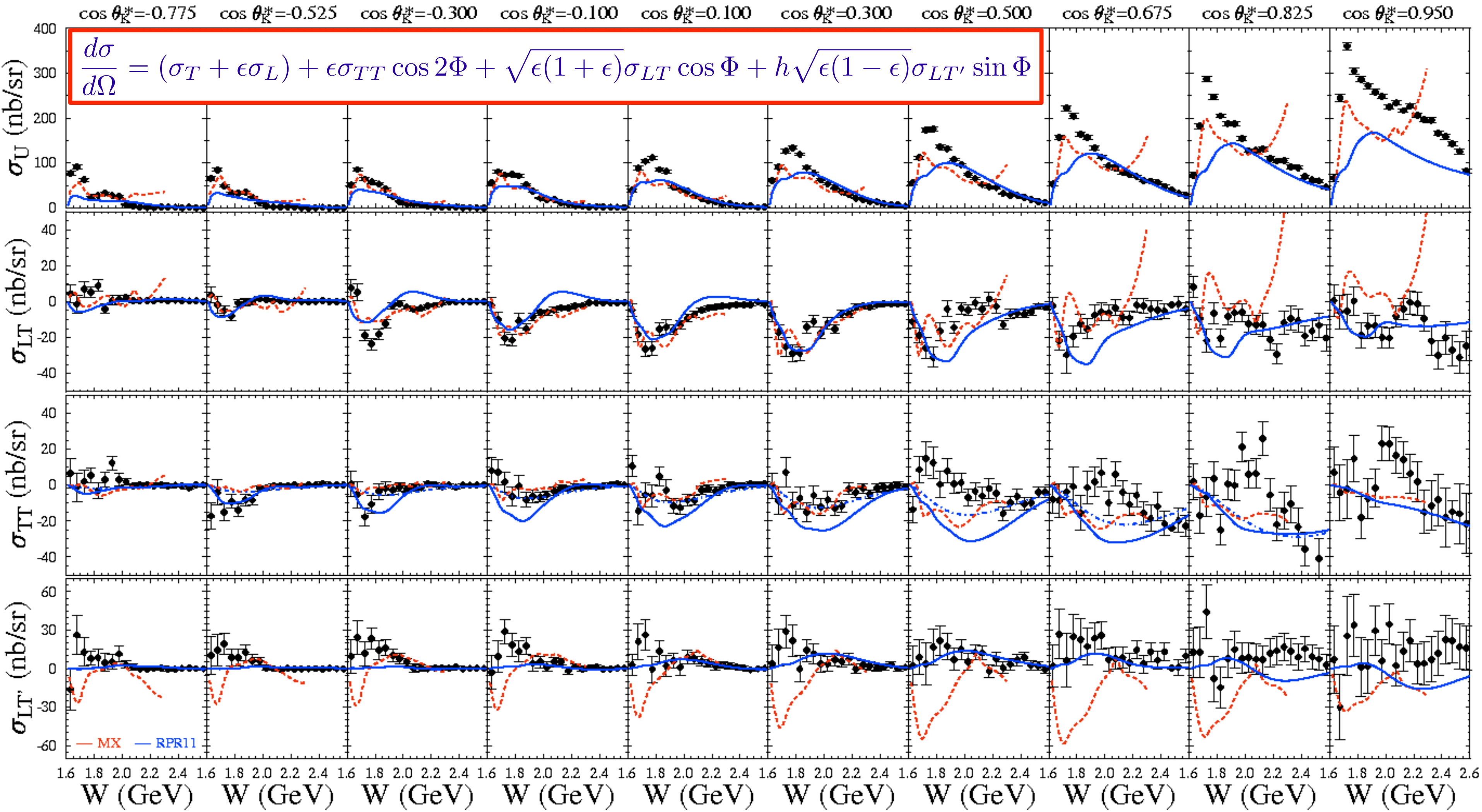


$2.56 < \chi^2$/d.p.< 2.80 (1.66 GeV<W<1.76 GeV)



- Fit of $\theta_{\pi-}$, $\theta_{\pi+}$, θ_p angular distributions requires essential contribution(s) from the resonance(s) of $J^\pi=3/2^+$.
- Single state of $J^\pi=3/2^+$ should have major $\pi\Delta$ (>60%) and minor ρp (<5%) decays in order to reproduce pronounced Δ−peaks in $\pi^+ p$ and to avoid the ρ-peak formation in $\pi^+\pi^-$ mass distributions.

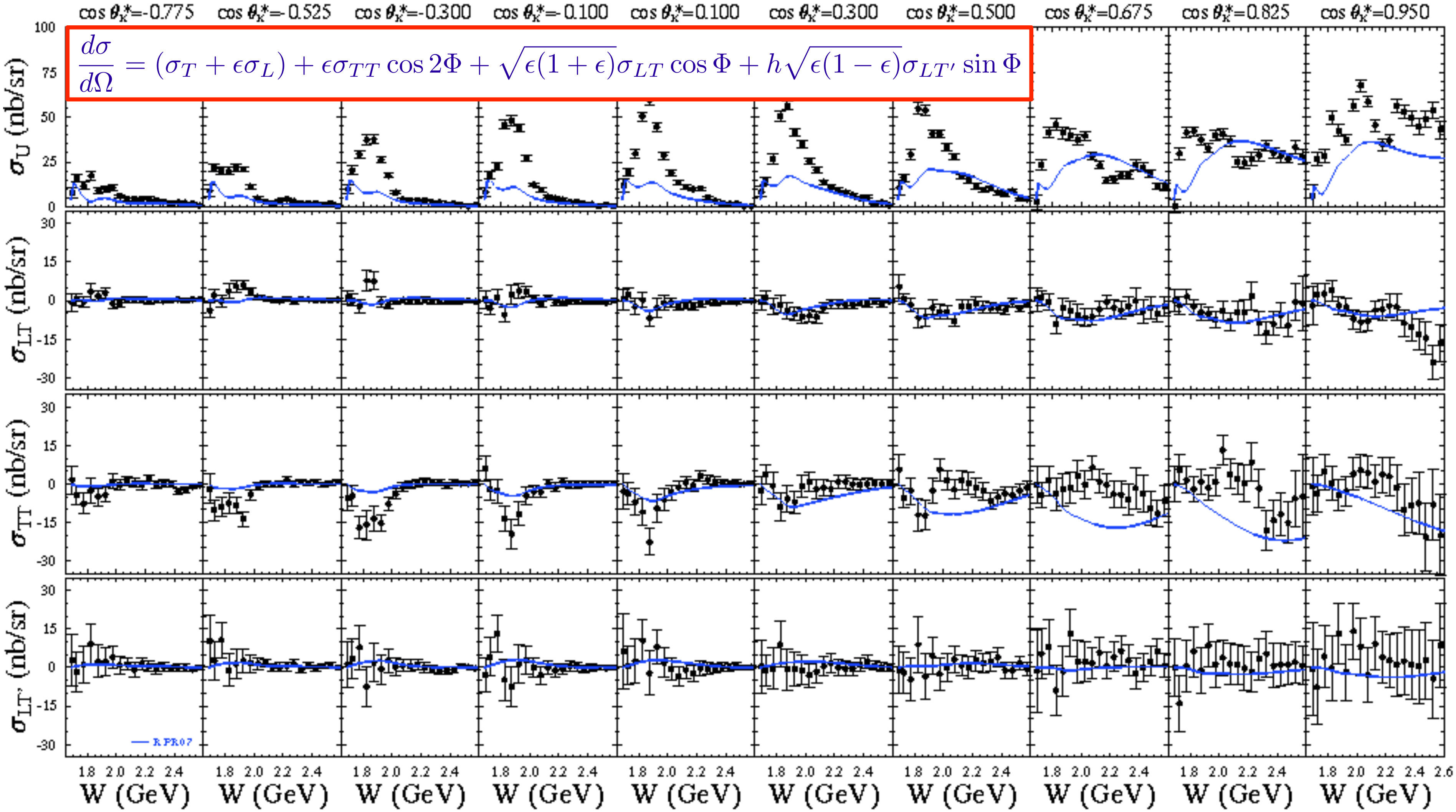
K⁺Λ Structure Functions



E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = $\boxed{1.80,}$ 2.60, 3.45 GeV^2 *[Carman et al., PRC 87, 025204 (2013)]*

$K^+\Sigma^0$ Structure Functions

$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \epsilon\sigma_{TT}\cos 2\Phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + h\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\Phi$$



E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *[Carman et al., PRC 87, 025204 (2013)]*

Signals from N* states in the CLAS KY electroproduction data

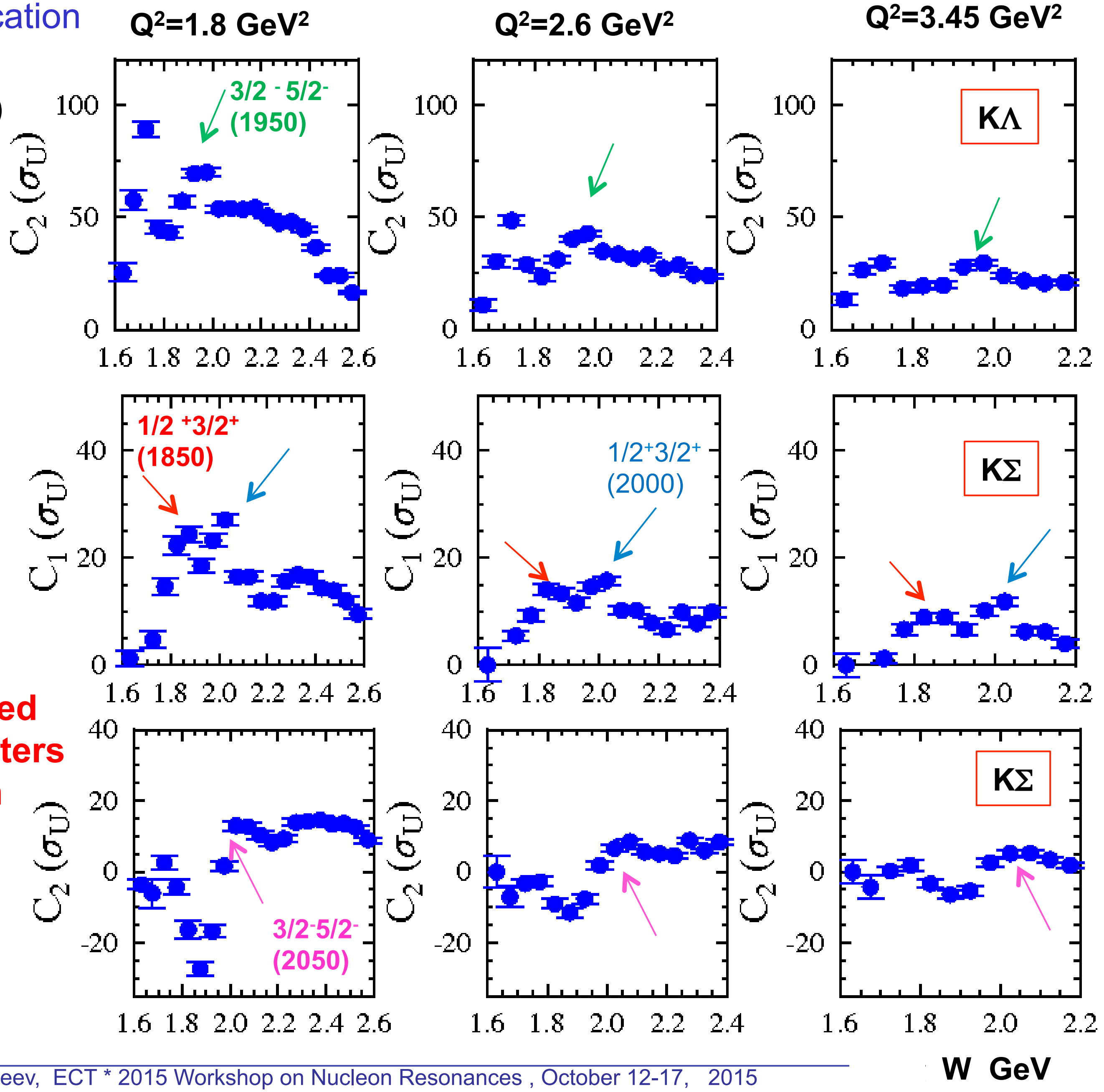
D.Carman, private communication

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

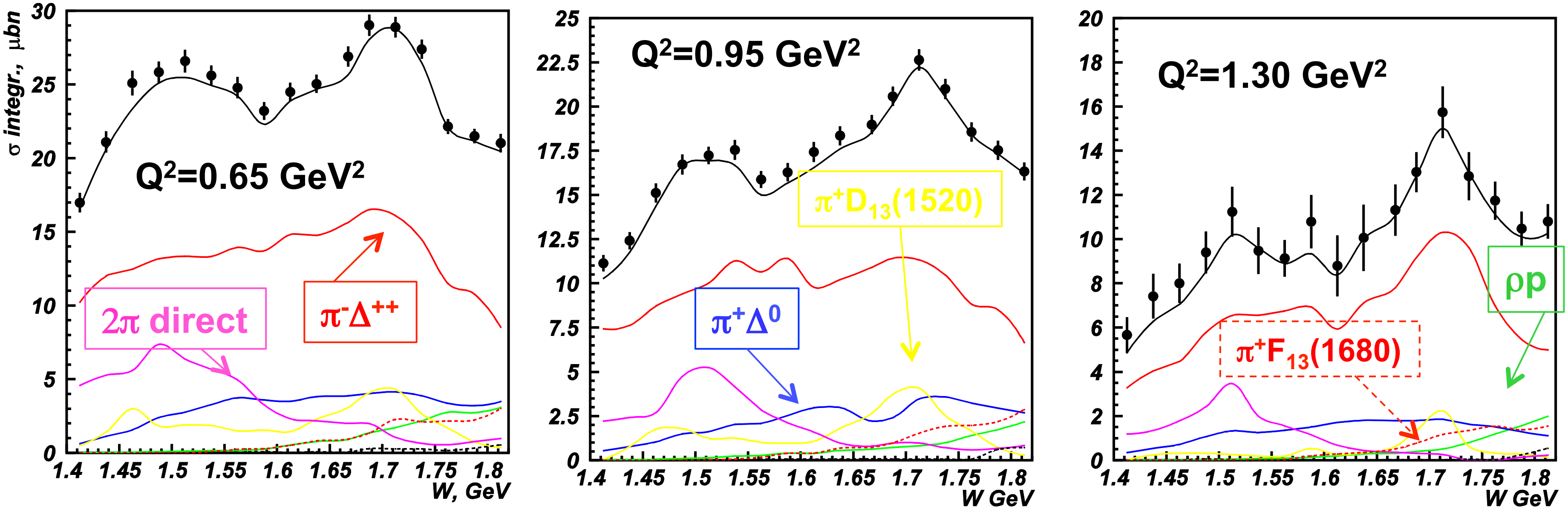
$$z = \cos(\theta_K)$$

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



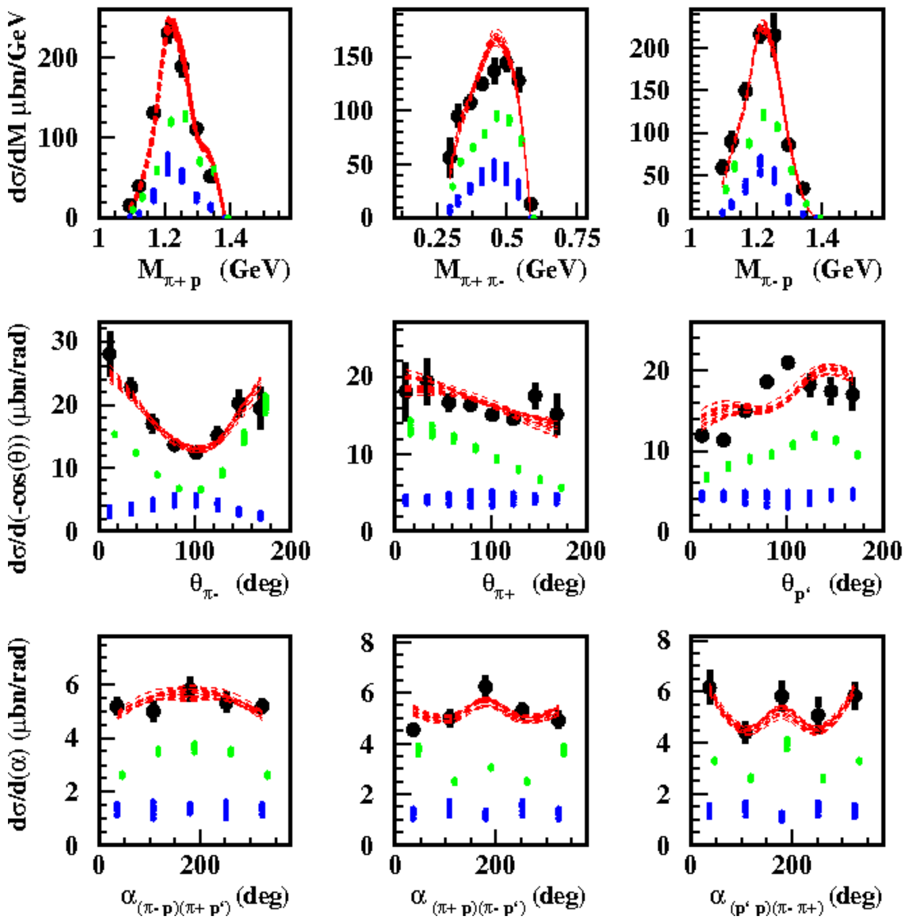
Charting Meson-Baryon Mechanisms of the JM Model



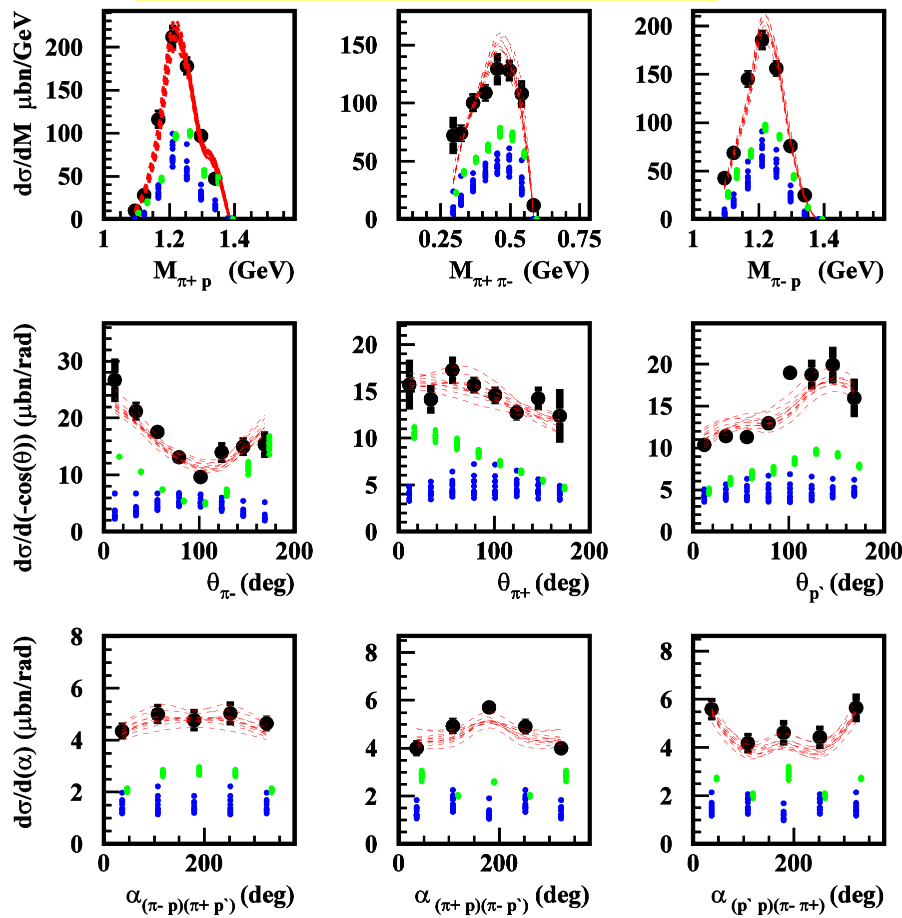
- $\pi^-\Delta^{++}$ meson-baryon channel accounts for the major part of $\pi^+\pi^-p$ electroproduction cross section. Relative resonant contribution to $\pi^-\Delta^{++}$ channel increases with Q^2.
- 2π direct production decreases substantially at W from 1.5 to 1.7 GeV offering an indication for sizable final hadronic interactions between the $\pi^+\pi^-p$ final state and others open meson-baryon channels.
- $\pi\Delta$, ρp-amplitudes decomposed over PW's of angular momenta J can be provided from the data fit.
- The request for reaction theory: guidance for the development of analytical continuation of $\pi\Delta$, ρp-amplitudes allowing us to extract resonance electrocouplings from residues at the resonance pole positions.

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

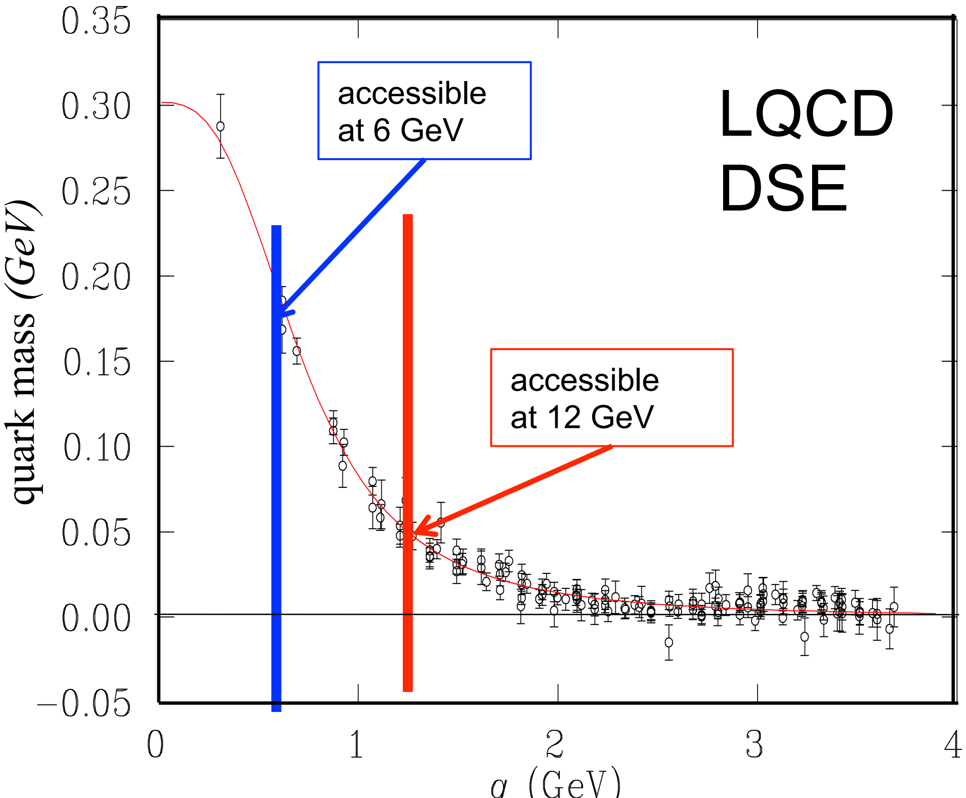
resonant part

non-resonant part

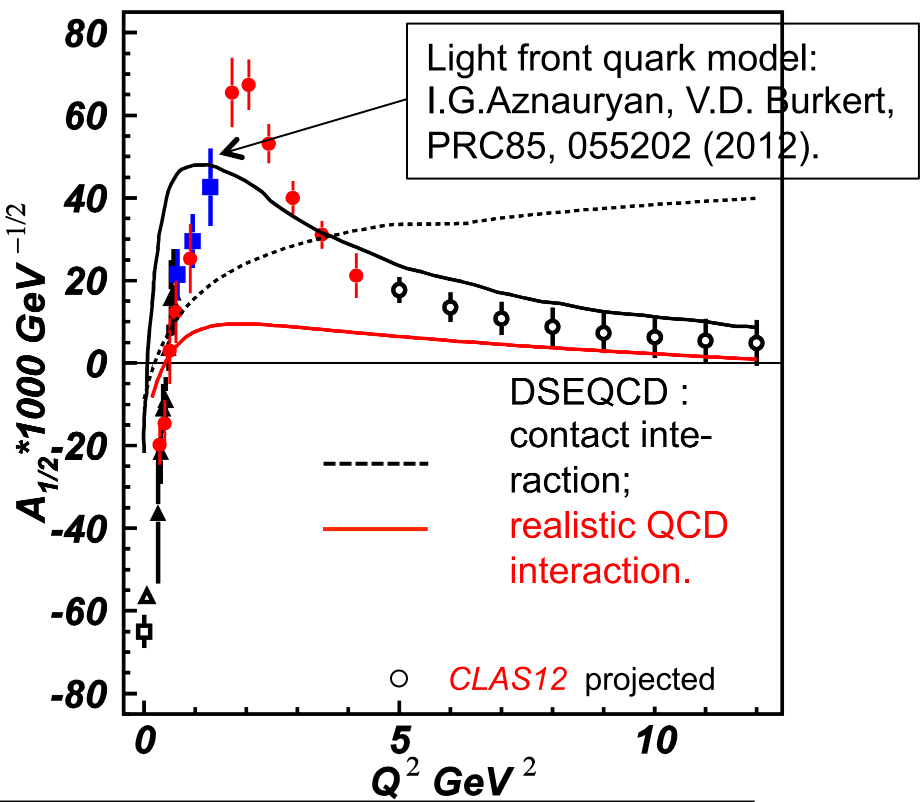
Resonance Transitions with the CLAS12

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 $Q^2=12 GeV^2$.



$P_{11}(1440)\ A_{1/2}$

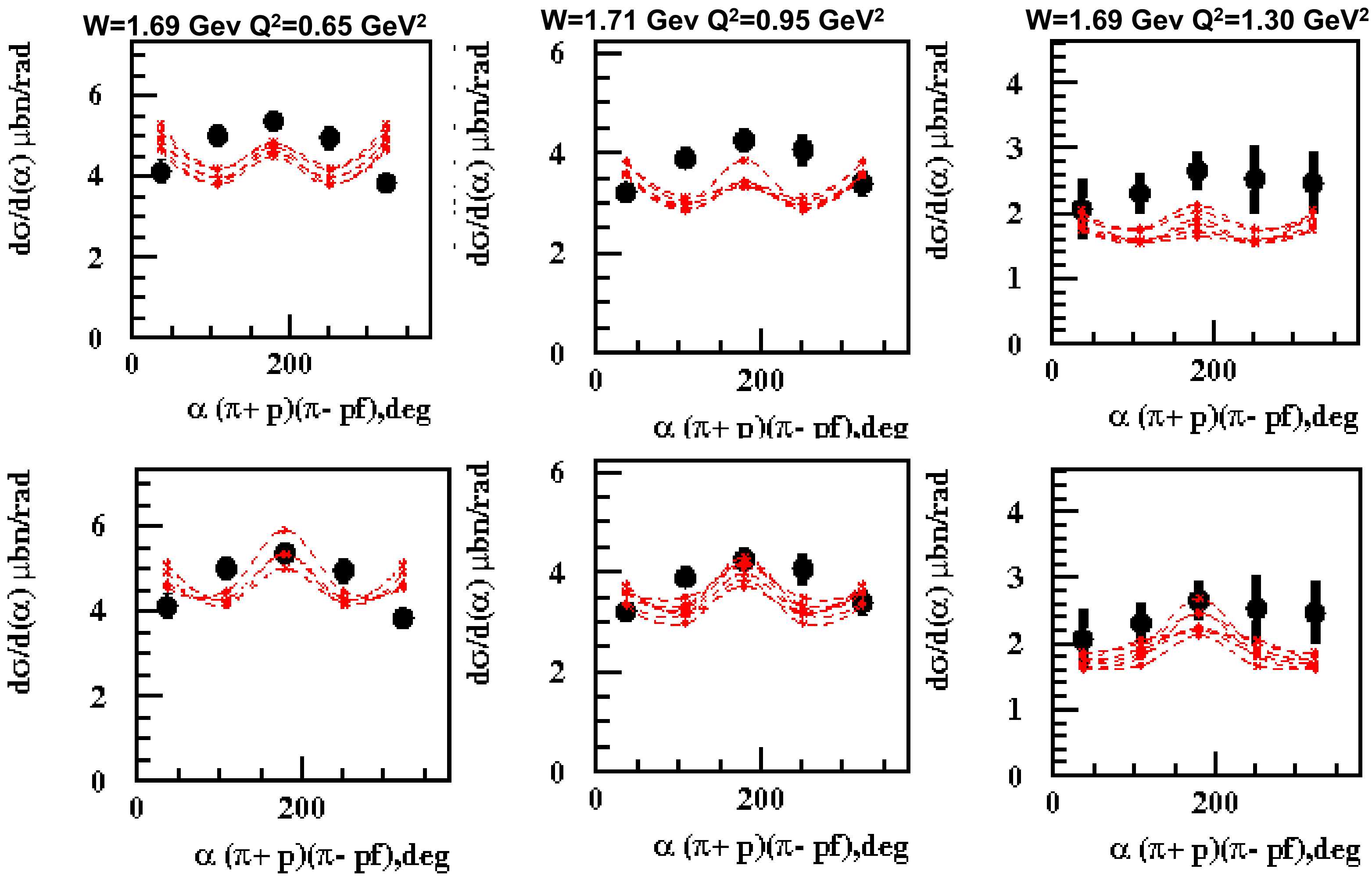


Probe the transition from confinement to pQCD regimes, allowing us to explore how confinement in baryons emerge from QCD and how >98 % of baryon masses are generated non-perturbatively via dynamical chiral symmetry breaking.

Evidence for 3/2⁺(1720) Candidate-State in $\pi^+\pi^-p$ Electroproduction

Conventional states only:

Conventional & 3/2⁺(1720) candidate-state:



Successful data description requires two nearly degenerated N*-states of $J^\pi=3/2^+$. One of them (new) decays mostly (47-64%) to the $\pi\Delta$ with minor decays (<10%) to the ρp final states, the other (conventional N(1720)3/2⁺) has comparable decay probabilities to the $\pi\Delta$ (39−55%) and to the ρp (23-49%) final states.