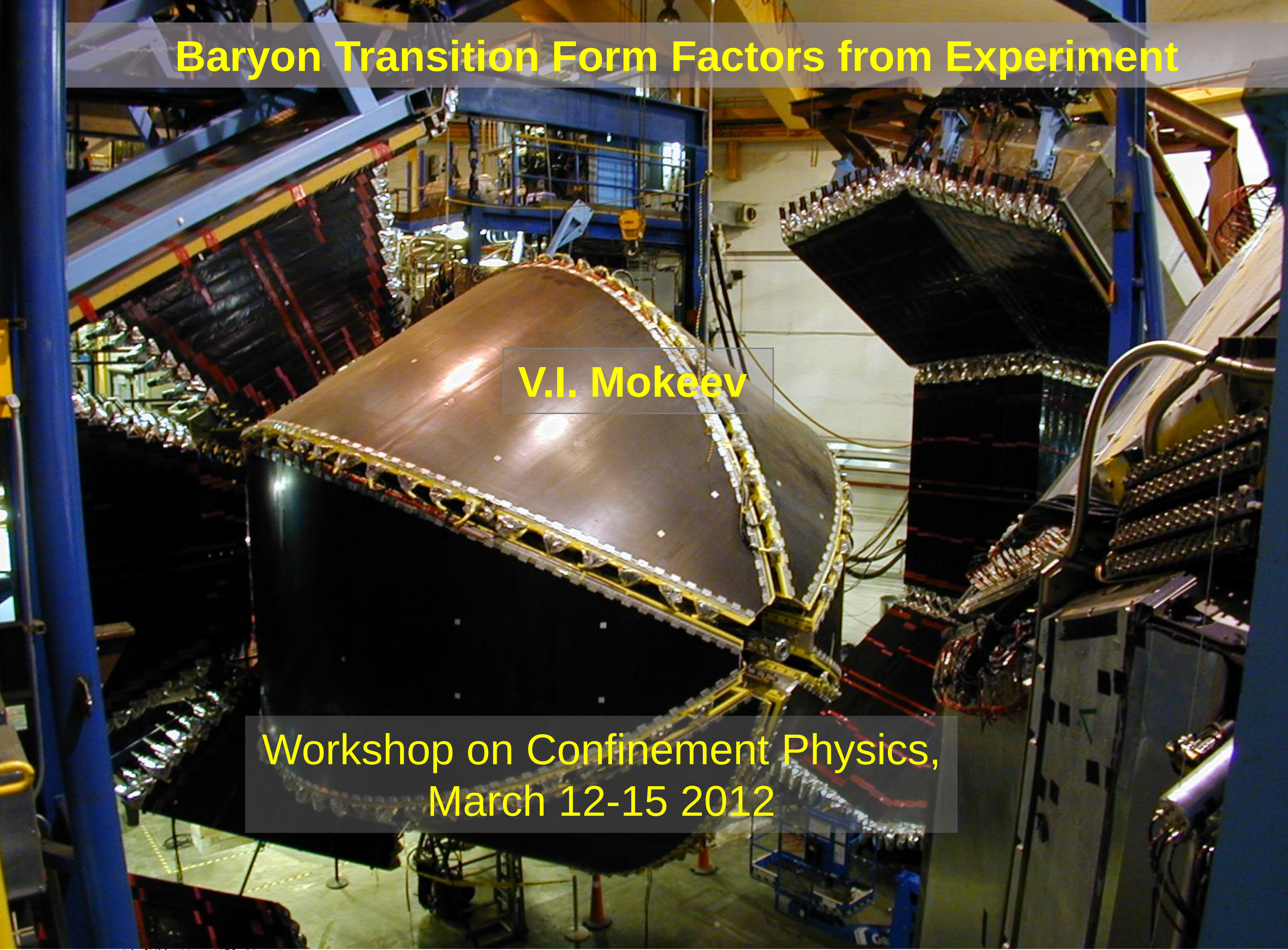
Baryon Transition Form Factors from Experiment



V.I. Mokeev

Workshop on Confinement Physics,
March 12-15 2012

Outline

- **The studies of γ_vNN* electrocouplings as an important direction in exploration of confinement in baryons.**
- **Basic principles for extraction of γ_vNN* electrocouplings from exclusive meson electroproduction data.**
- **Reaction models for extraction of γ_vNN* electrocouplings from the data on pion electroproduction off protons.**
- **First results on resonance electrocouplings and their impact on exploration of N* structure.**
- **Conclusions and Outlook.**

The studies of nucleon resonance (N*) structure: motivation and objectives

Our experimental program seeks to determine

$\gamma_v NN^*$ transition helicity amplitudes (electrocouplings) at photon virtualities $0.2 < Q^2 < 5.0$ GeV^2 for most of the excited proton states analyzing major meson electroproduction channels independently and combined.

This information allows us to:

- **establish relevant degrees of freedom in N* structure at different distances;**
- **study the non-perturbative strong interactions which are responsible for N* formation as the bound systems of quarks and gluons and how they emerge from QCD.**

What can be studied from the data on $\gamma_v NN^*$ electrocoupling

Several Workshops were organized by the CLAS Collaboration and the EBAC to foster the theory efforts to relate the data on $\gamma_v NN^*$ electrocouplings to the mechanisms of the N* formation:

- Electromagnetic N-N* Transition Form Factors Workshop, Jefferson Lab, 13-15 Oct. 2008 www.jlab.org/conferences/EmNN/index.html , the White Paper is published in: arXiv:0907.1901 [nucl-th]
- Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities with the CLAS 12 Detector, Jefferson Lab, May 16th 2011 www.jlab.org/conferences/electroproduction/

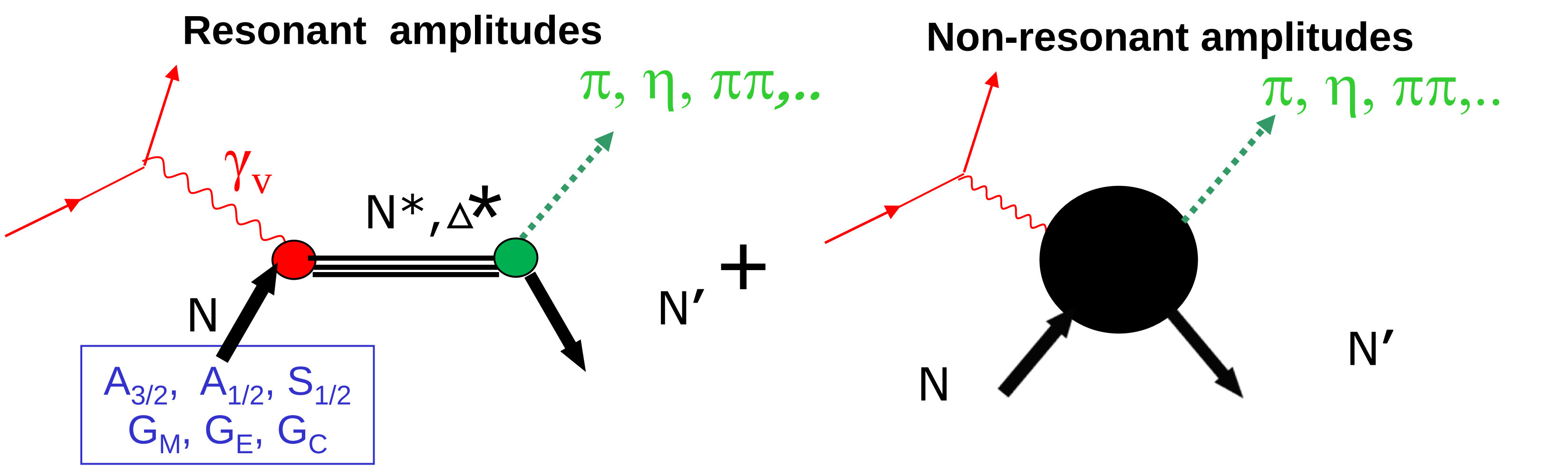
Lattice QCD and Dyson-Schwinger Equations of QCD are making a remarkable progress toward to the description of $\gamma_v NN^*$ electrocouplings from the first QCD principles (arXiv:1108.2528 [hep-lat] , arXiv:1201.2349 [hep-ph] , arXiv:1112.0473 [hep-lat] , arXiv:1112.2212 [nucl-th], arXiv:1101.4244 [nucl-th]).

First results on low lying resonance electrocouplings from the QCD-motivated AdS/CFT approach (arXiv:1108.0965 [hep-ph]).

Progress in phenomenological constituent quark models, including the first attempts to implement QCD-motivated expectations on momentum-dependent quark running mass (arXiv:1201.5759 [hep-ph]).

Hadron structure theory will be capable to relate the data on $\gamma_v NN^*$ electrocouplings to the non-pertubative strong interaction mechanisms which are responsible for N* formation in confinement regime allowing us to explore confinement in baryons based on the experimental data on the structure of ground and excited nucleon states at different transverse distances.

Extraction of N* electrocouplings from analyses of exclusive electroproduction channels



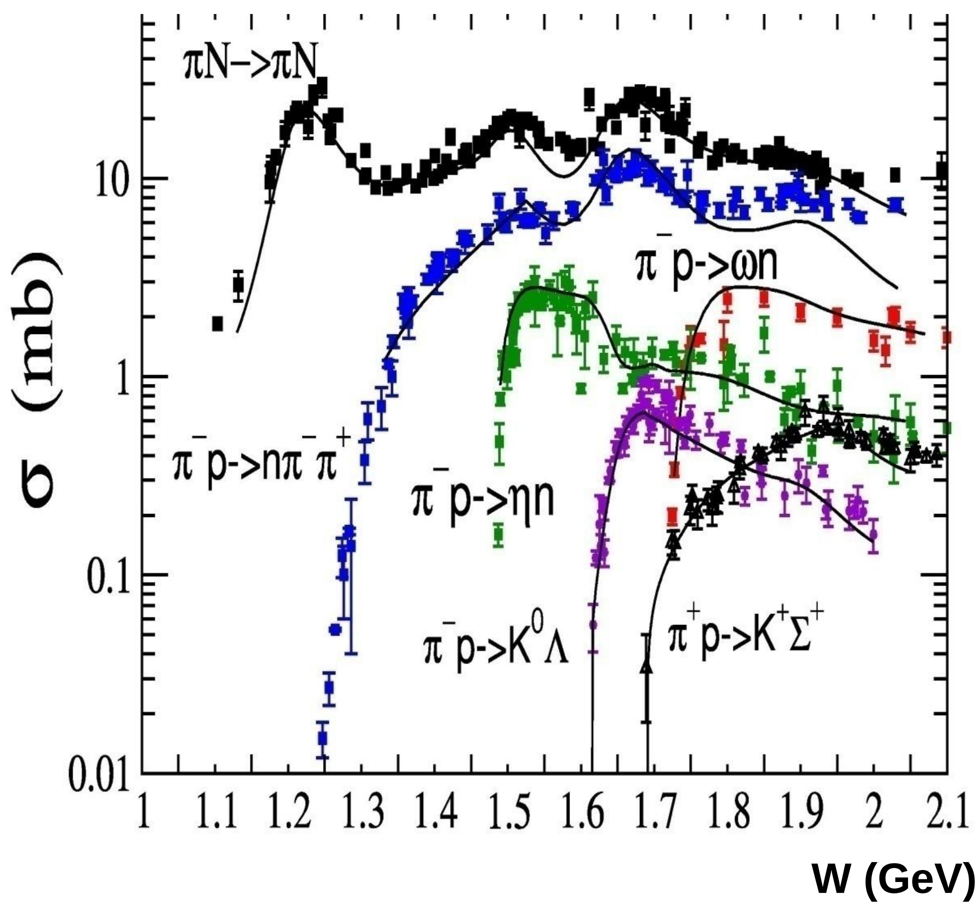
- **Separation of resonant/non-resonant contributions represents most challenging part and currently can be achieved only within the framework of reaction models.**

- **N* 's can couple to different exclusive channels with entirely different non-resonant amplitudes, while their electrocouplings should remain the same in all exclusive electroproduction channels.**

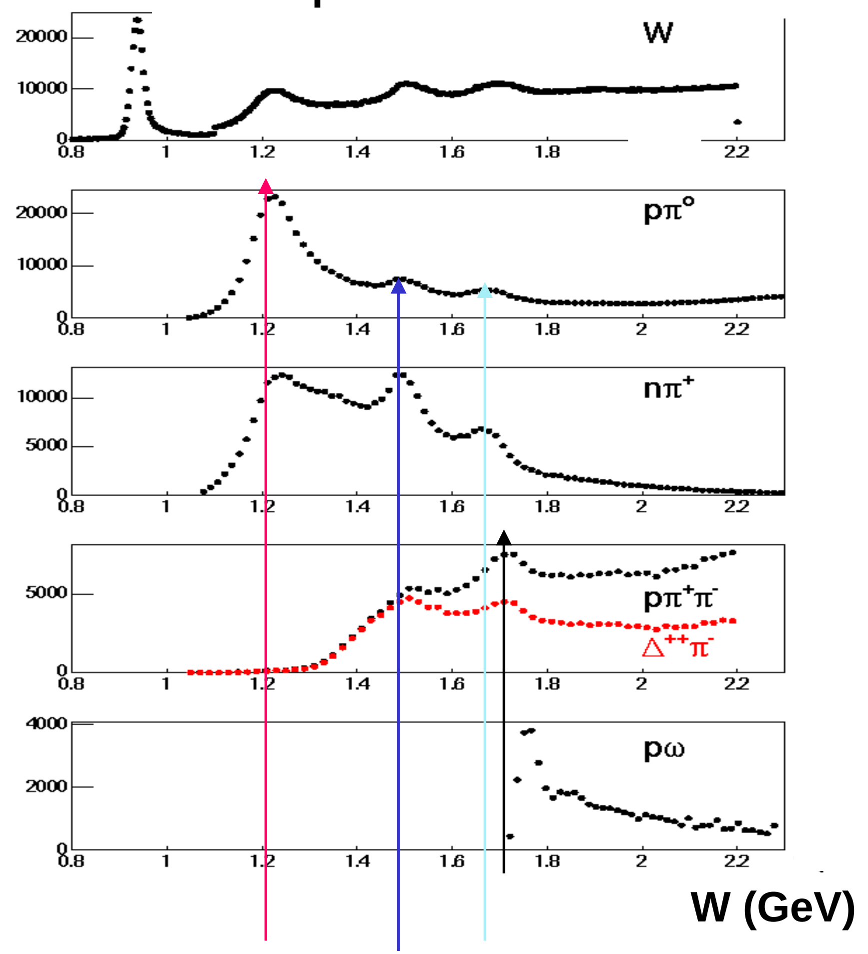
- **Consistent results from the analyses of major meson electroproduction channels show reliable N* electrocoupling extraction.**

The particular role of the Nπ and Nππ electroproduction channels in the studies of N* electrocouplings

Exclusive Nπ→final hadrons cross sections.



CLAS data on yields of meson electroproduction channels.



Nπ and Nππ channels are the major and sensitive to N*'s contributors to meson exclusive electro-production in the N* excitation region. They are strongly coupled by Nπ↔Nππ FSI. Explicit accounting for the Nπ↔Nππ FSI is of particular importance for the N* Program with the CLAS detector. The general framework has been developed in the EBAC-DCC approach (arXiv:1108.0324[nucl-th], nucl-th/0608051).

Summary of the CLAS data on single-pion electroproduction off protons

Number of data points >116000, W<1.7 GeV, $0.15<Q^2<6.0$ GeV^2 , almost complete coverage of the final state phase space.

Observables	Q^2 area, GeV^2	Number of data points
$d\sigma/d\Omega(\pi^0)$	0.16-1.45 3.0-6.0	39830 9000
$d\sigma/d\Omega(\pi^+)$	0.25-0.60 1.7-4.3	25588 30 849
$A_e(\pi^0)$, $A_t(\pi^0)$	0.25-0.65	3981
$A_e(\pi^+)$, $A_t(\pi^+)$	0.40-065 1.7 - 3.5	1730 3 535
$A_{et}(\pi^0)$	0.25-0.61	1521

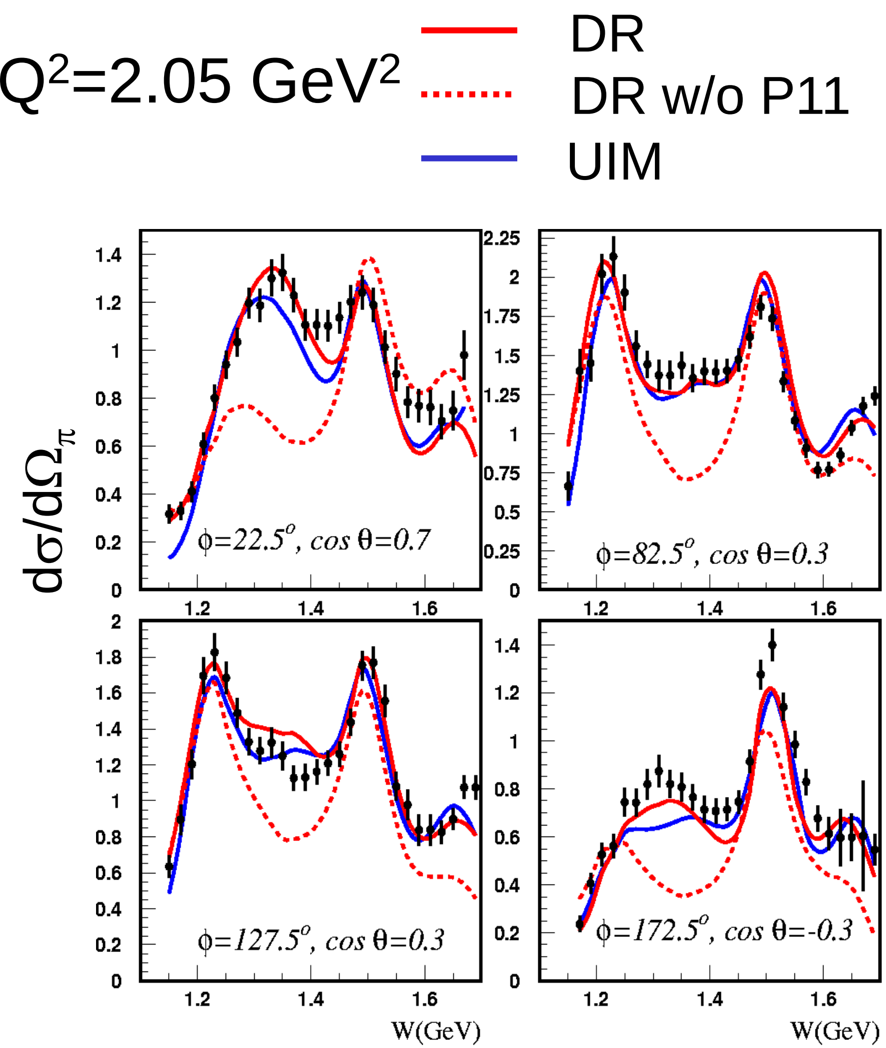
Low Q^2 results:
I. Aznauryan *et al*., PRC 71, 015201 (2005); PRC 72, 045201 (2005).

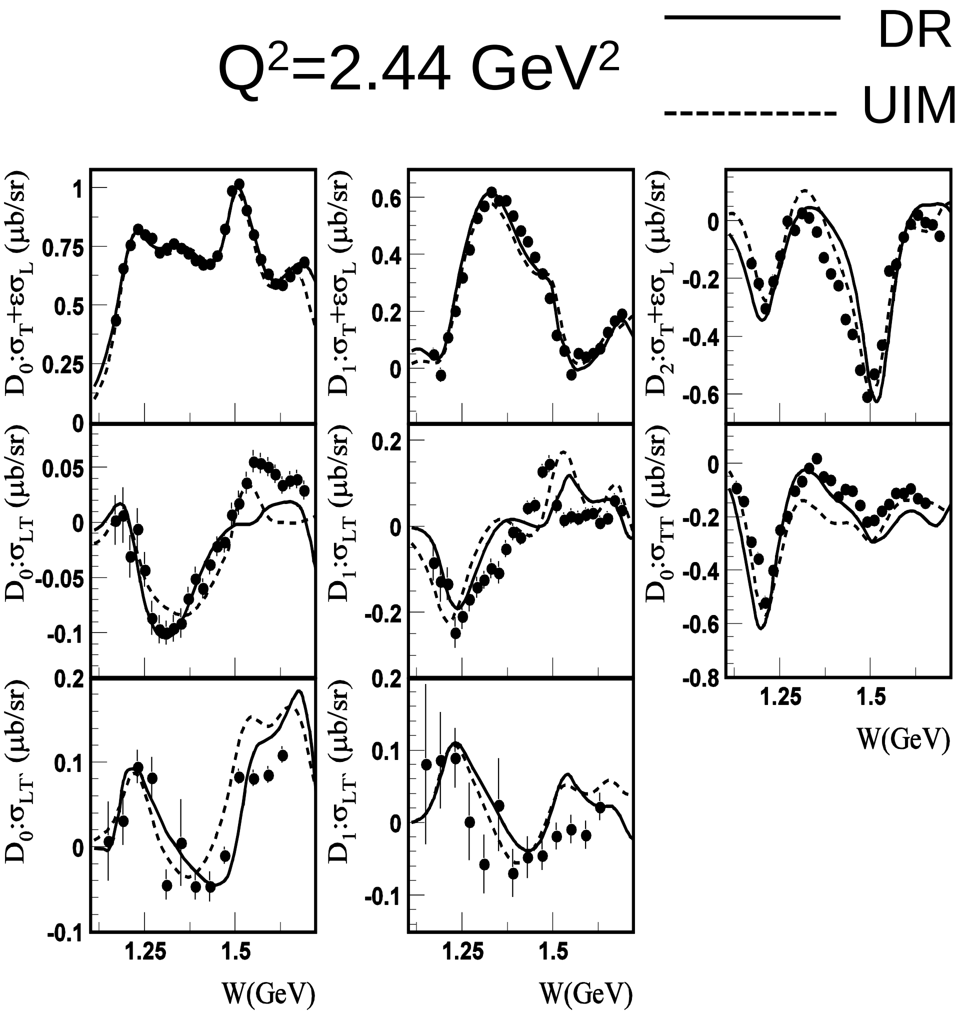
High Q^2 results on Roper:
I. Aznauryan *et al*., PRC 78, 045209 (2008).

Final analysis:
I.G.Aznauryan, V.D.Burkert, et al. (CLAS Collaboration), PRC 80. 055203 (2009).

All data sets can be found in:
http://clasweb.jlab.org/physicsdb/

Fits to $\gamma p \rightarrow \pi^+ n$ differential cross sections and structure functions

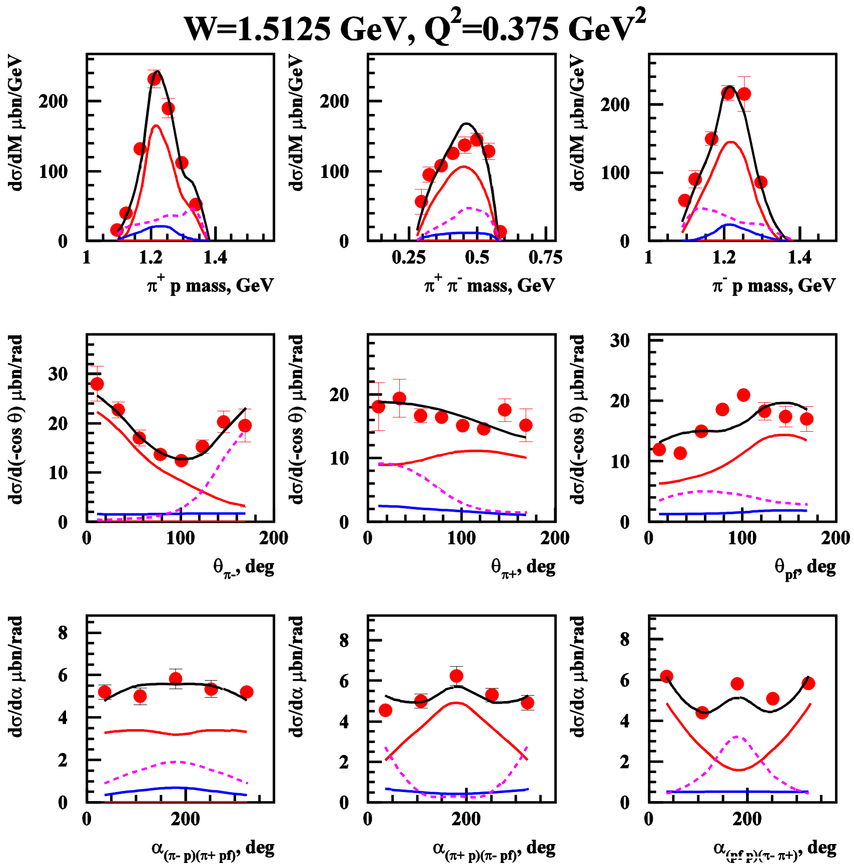


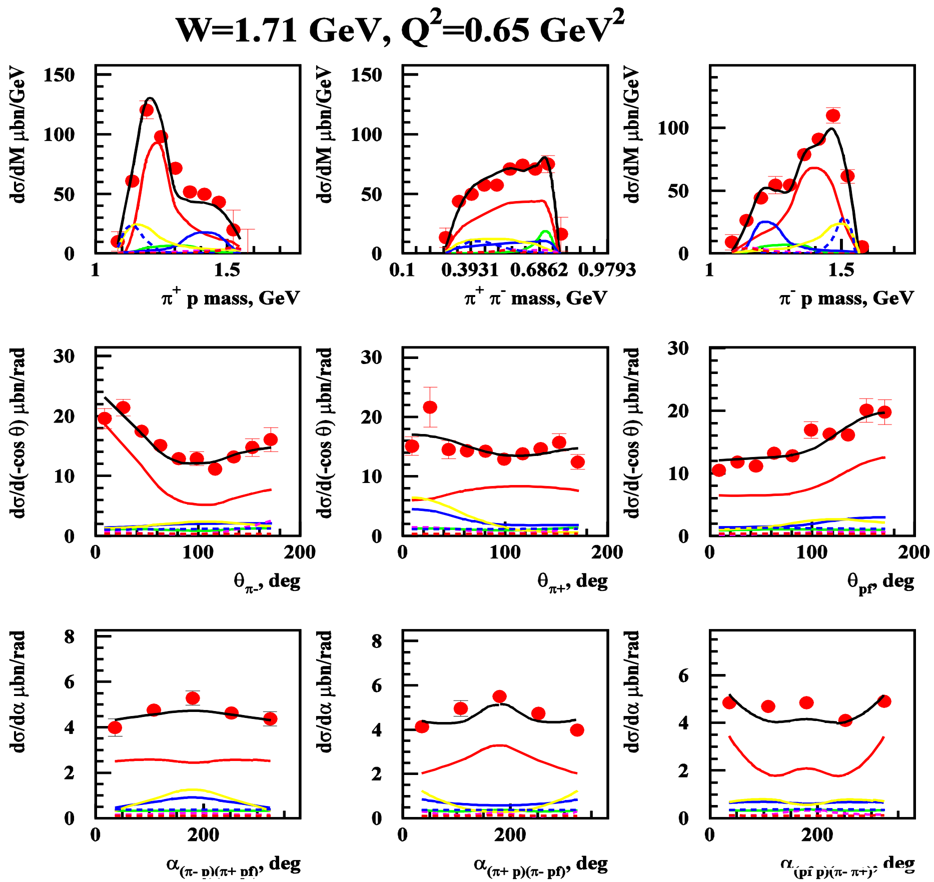


L=0 Legendre moments from various structure functions

The CLAS data on $\pi^+\pi^-p$ differential cross sections and the data description within the JM model

G.V.Fedotov et al, PRC 79 (2009), 015204 | **M.Ripani et al, PRL 91 (2003), 022002**





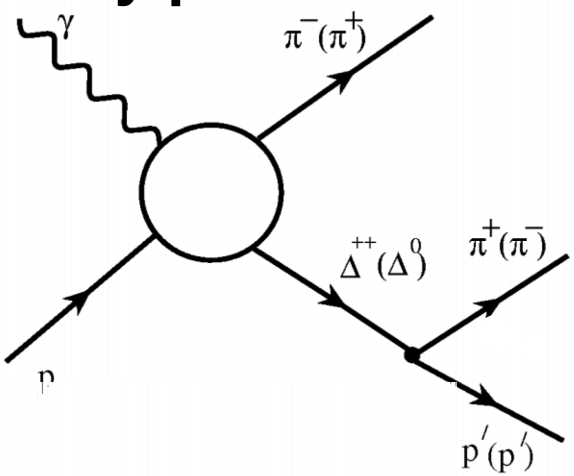
full JM calc. — $\pi^+\Delta^0$ — ρp — $\pi^+F^0_{15}(1685)$

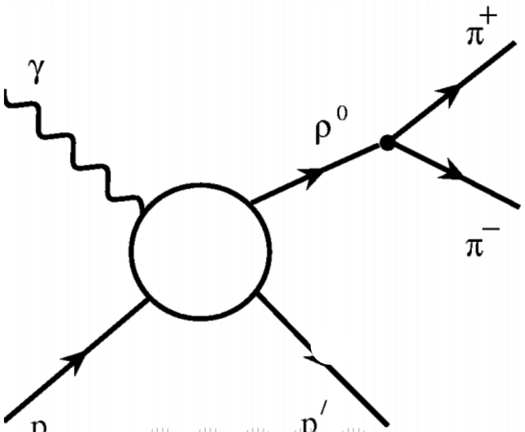
$\pi^-\Delta^{++}$ — 2π direct — $\pi^+D^0_{13}(1520)$

JLAB-MSU meson-baryon model (JM) for N* electrocoupling extraction from the $\pi^+\pi^-p$ electroproduction data

V. I. Mokeev , V.D. Burkert, T.-S.H. Lee *et al*., Phys. Rev. C80, 045212 (2009)

3-body processes:





Isobar channels included:

$\pi^-\Delta^{++}$

- **All well established N*s with $\pi\Delta$ decays and $3/2^+(1720)$ candidate.**
- **Reggeized Born terms with effective FSI and ISI treatment (absorptive approximation).**
- **Extra $\pi\Delta$ contact term.**

$\rho^0 p$

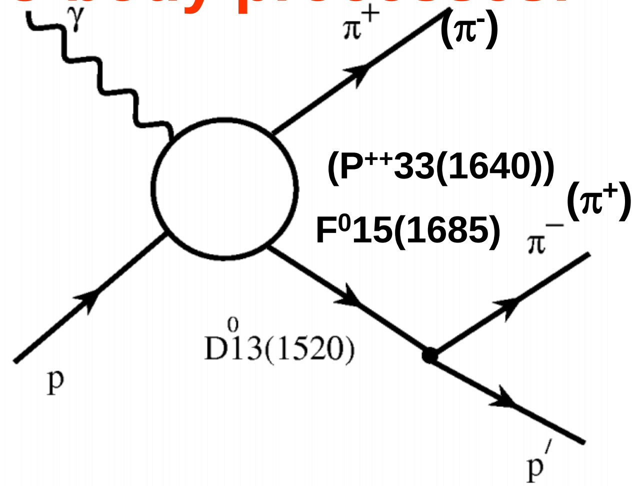
•All well established N*s with ρp decays and $3/2^+(1720)$ candidate.

•Diffractive ansatz for non-resonant part and ρ-line shrinkage in N* region.

Unitarized Breit-Wigner anstaz for resonant amplitudes.

JLAB-MSU meson-baryon model (JM) for N* electrocoupling extraction from the $\pi^+\pi^-p$ electroproduction data

3-body processes:



Isobar channels included:

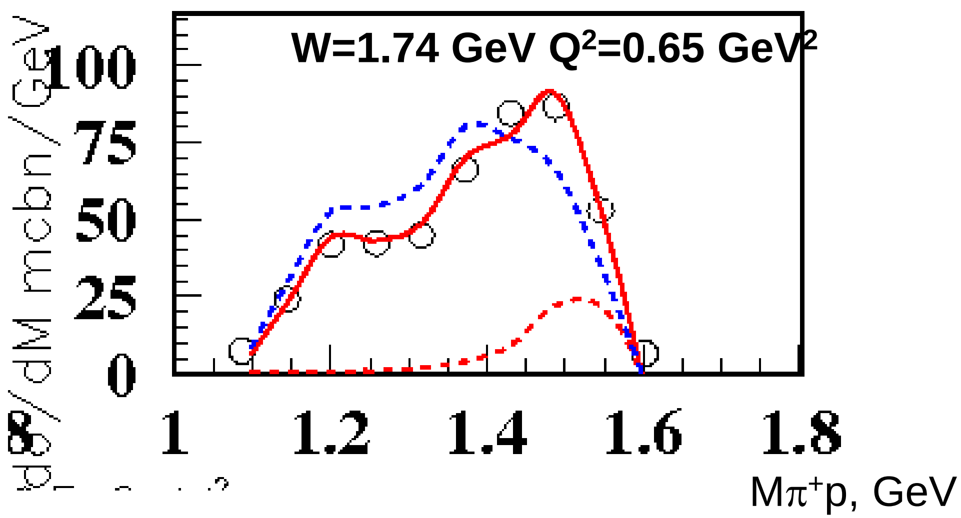
- $\pi^+D^0_{13}(1520)$, $\pi^+F^0_{15}(1685)$, $\pi^-P^{++}_{33}(1640)$ isobar channels observed for the first time in the CLAS data at W > 1.5 GeV.

Evidence for $\pi^+D^0_{13}(1520)$ isobar channel in the CLAS $\pi^+\pi^-p$ data

full JM results with $\pi^+D^0_{13}(1520)$ implemented

full JM results without $\pi^+D^0_{13}(1520)$ and adjusted direct 2π production

$\pi^+D^0_{13}(1520)$ contribution



N* parameters of the JM model and their relationships to the observables

Regular Breit-Wigner (BW) ansatz as the start point :

$$T_{res} = \sum_{N^*} \frac{\langle \lambda_f | T_{dec} | \lambda_{N^*} \rangle \langle \lambda_{N^*} | T_{em} | \lambda_\gamma \lambda_p \rangle}{M_{N^*}^2 - W^2 - i\Gamma_{N^*}(W) M_{N^*}}$$

$\langle \lambda_f | T_{dec} | \lambda_{N^*} \rangle$ **amplitudes are related to the partial N* decay widths to the $\pi\Delta$ or ρp final states of definite helicity λ_f**

$$\langle \lambda_f | T_{dec} | \lambda_{N^*} \rangle = \langle \lambda_f | T^0_{dec} | \lambda_{N^*} \rangle d^{J_{N^*}}_{\lambda_{N^*}\lambda_f}(\cos(\theta_f)) e^{i\lambda_{N^*}\varphi_f}$$

$$\langle \lambda_f | T^0_{dec} | \lambda_{N^*} \rangle = f_{dec}(J_{N^*}, M_{N^*}, p, p^{N^*}) \sqrt{\Gamma_{\lambda_f}}$$

f_{dec} is the kinematical factor, which depends on resonance spin, mass and abs. CM 3-momenta values of the stable final hadron averaged over the line of unstable final hadron at the running W (p) and at $W=M_{N^*}$ (p^{N^*}). θ_f and φ_f are the CM final stable hadron ermission angles.

Definition of $\gamma_v NN^*$ electrocouplings :

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

$\Gamma\gamma$ is N* electromagnetic decay width, $q_{\gamma N^*}$ is abs. photon CM 3-momentum value at $W=M_{N^*}$.

The $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ $\gamma_v NN^*$ electrocouplings and $\Gamma_{\lambda f}$ N* partial decay widths are determined at resonant point $W=M_{N^*}$.

The relationships between N* electroproduction amplitudes T_{em} and $\gamma_v NN^*$ electrocouplings $A_{1/2}$, $A_{3/2}$, $S_{1/2}$

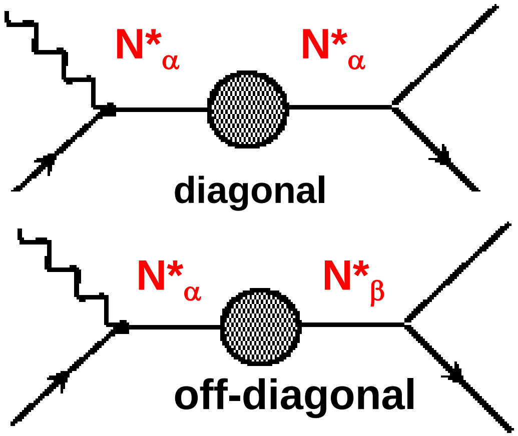
$$\langle \lambda_{N^*} | T_{em} | \lambda_\gamma \lambda_p \rangle = f_{em}(M_{N^*}, q_\gamma, q_{\gamma N^*}) * \left\{ \begin{matrix} A_{1/2}(Q^2), A_{3/2}(Q^2) \\ \sqrt{2} S_{1/2}(Q^2) \end{matrix} \right.$$

are obtained imposing the requirement: fully integrated resonant cross section should be described by the relativistic Breit-Wigner formula in a case of single contributing resonance.

Exact expressions for the factors f_{em} and f_{dec} can be found in: M.Ripani et al., Nucl. Phys. A673, 220 (2000).

Unitarized Breit-Wigner anstaz for resonant amplitudes

I.J.R.Aitchison, Nuclear Physics , A189 (1972), 417.



Inverse of the JM unitarized N* propagator:

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

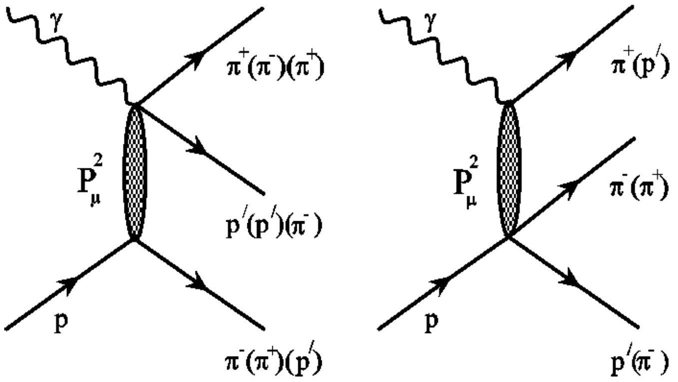
Off-diagonal transitions incorporated into the full resonant amplitudes of the JM model:

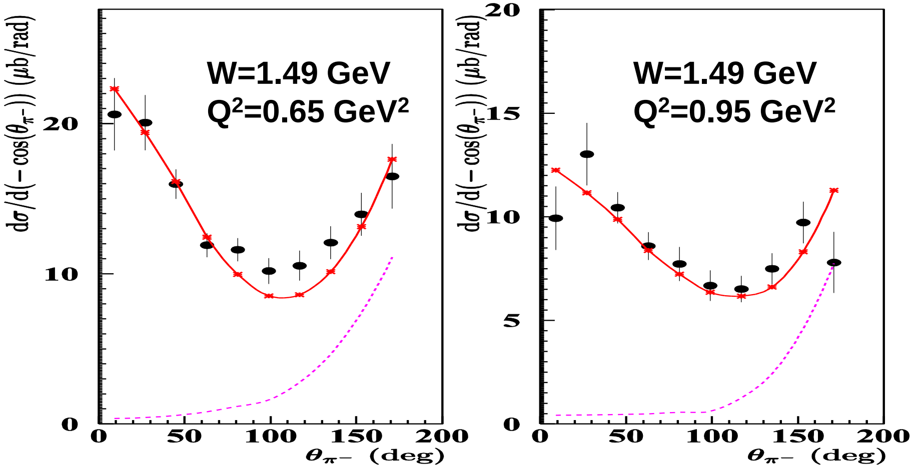
$S_{11}(1535) \leftrightarrow S_{11}(1650)$
$D_{13}(1520) \leftrightarrow D_{13}(1700)$
$3/2^+(1720) \leftrightarrow P_{13}(1700)$

Full resonant amplitude of unitarized Breit-Wigner ansatz is consistent with restrictions imposed by a general unitarity condition, as well as with the resonant EBAC-DCC ansatz in on-shell approximation.

Access to 2π-direct production mechanisms

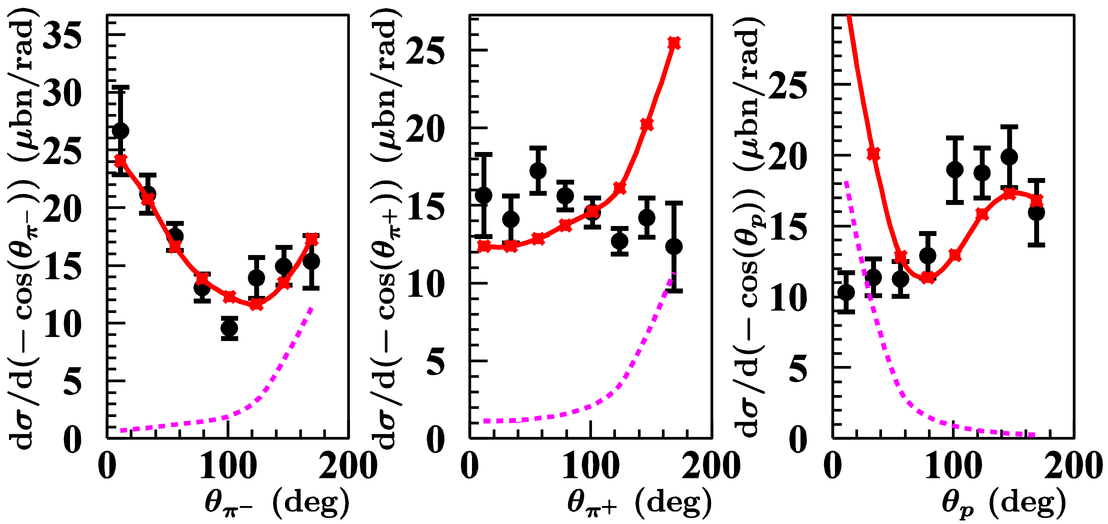
2π–direct production processes required by unitarity condition were established for the first time in analysis of the CLAS data.





Exchange processes needed to describe π^- CM angular distributions at backward angles

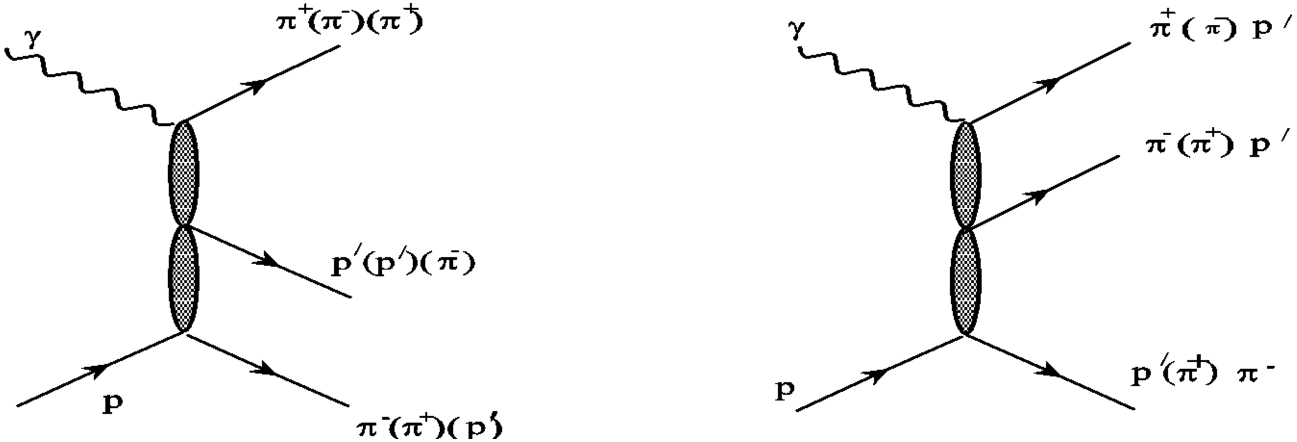
W=1.51 GeV
Q²=0.43 GeV²



- - - Contributions from 2π–direct production parameterized by the diagrams above

Parameterization of 2π-direct production should be further improved in order to reproduce π^+ and proton CM angular distributions.

2π–direct production amplitudes of JM12 version

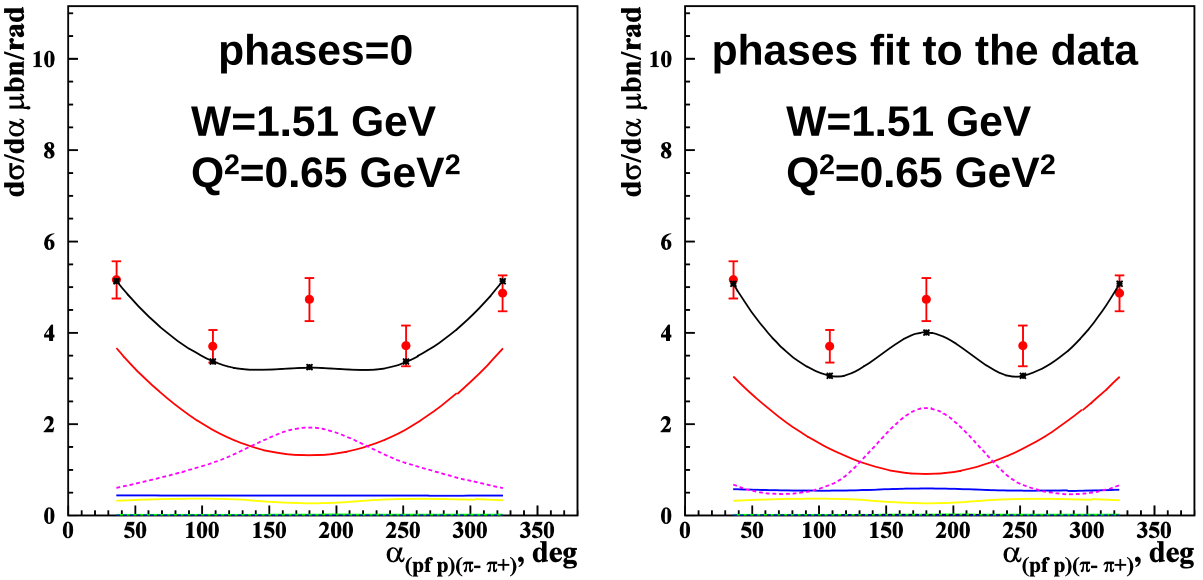


consistent with the data on all 1d-cross sections.
(see slide #9)

Substantial contributions at W<1.5 GeV

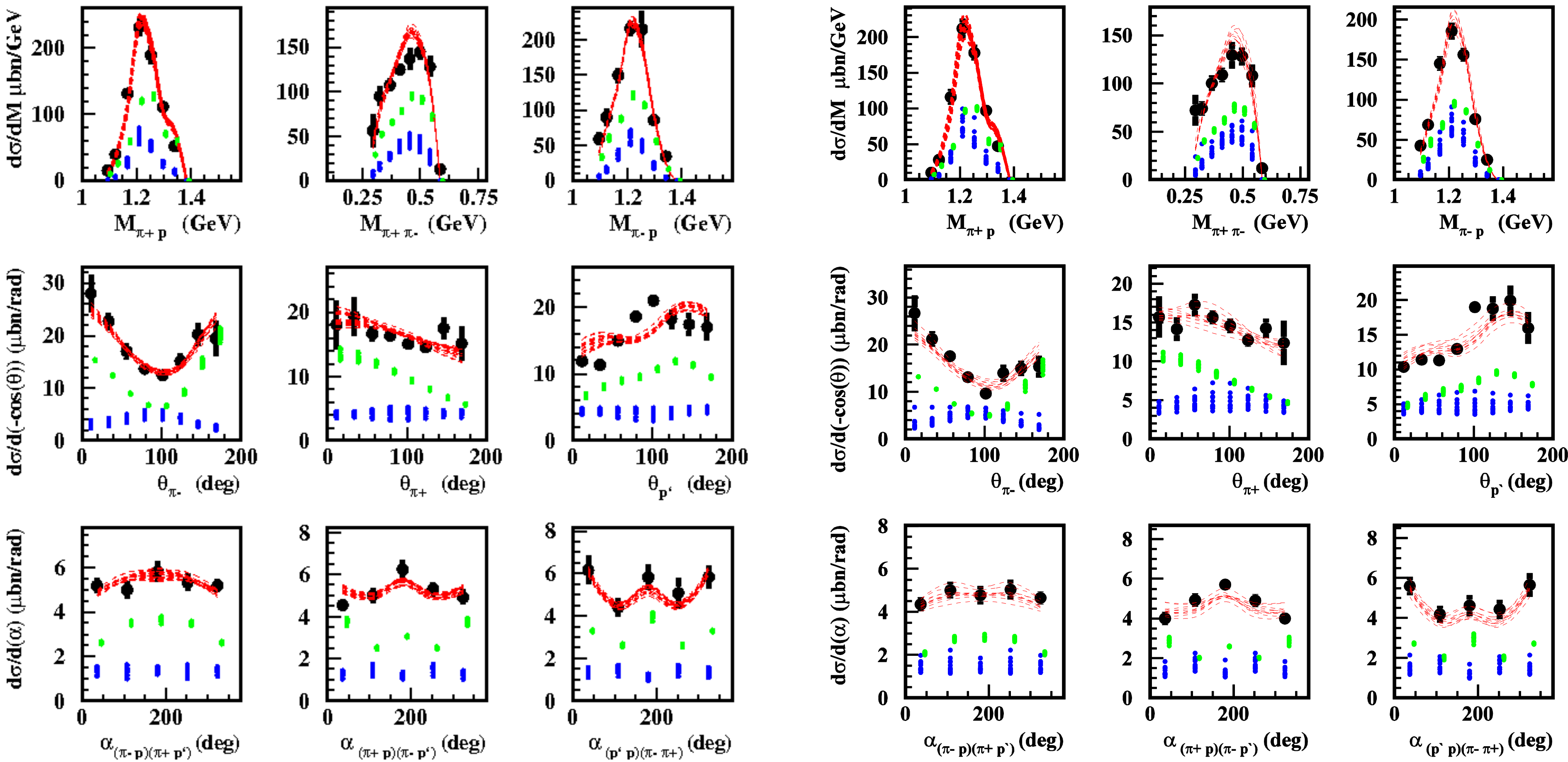
Negligible at W>1.70 GeV.

Angular distributions over α-angles are sensitive to the phases of 2π-direct production amplitudes, allowing us to determine their values in the data fit.



Fit quality and separation between the resonant and non-resonant contributions

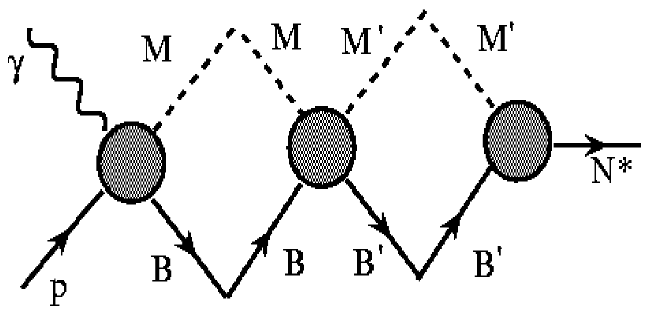
W=1.51 GeV, Q^2=0.38 GeV^2 | W=1.51 GeV, Q^2=0.43 GeV^2



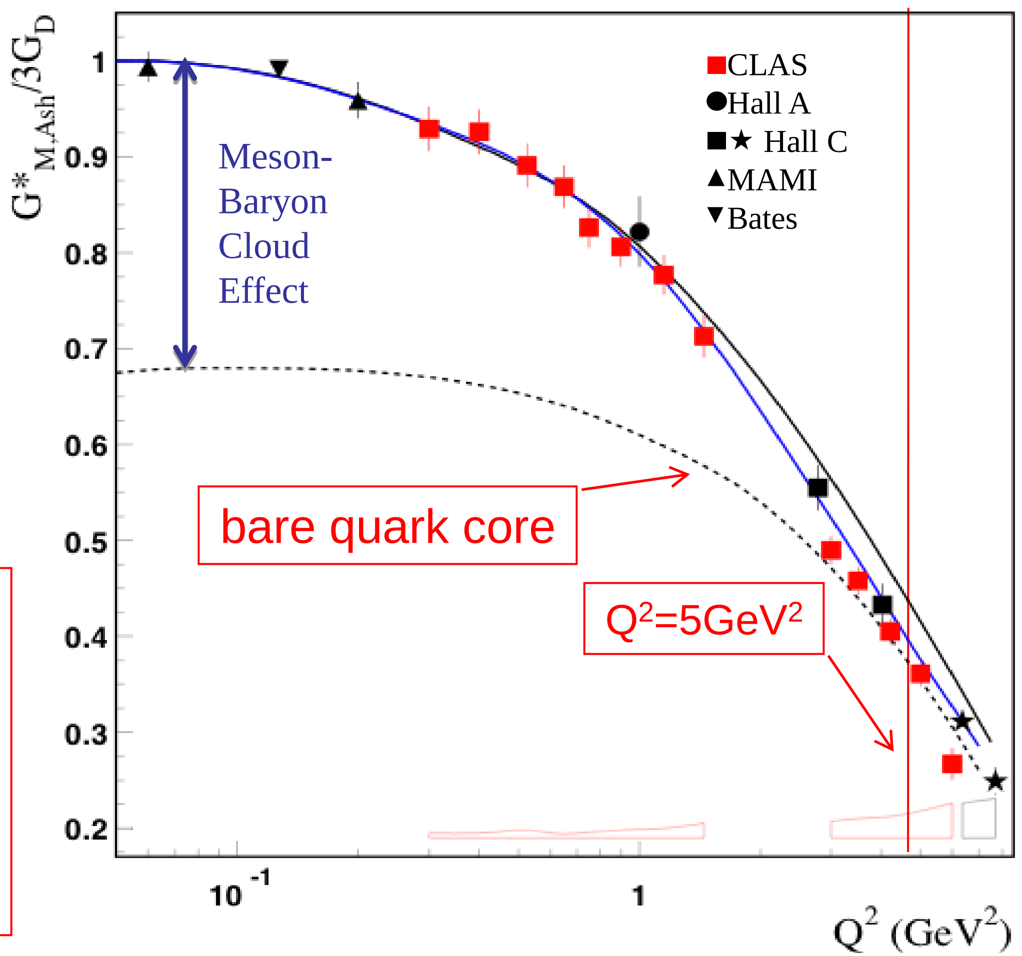
full cross sections | resonant part | non-resonant part

NΔ Transition Form Factor – $G_{M.}$ Meson-baryon dressing vs Quark core contribution in EBAC analysis.

- One third of G^*_M at low Q^2 is due to contributions from meson–baryon (MB) dressing:



Within the framework of relativistic QM [B.Julia-Diaz *et al.*, PRC 69, 035212 (2004)], the bare-core contribution is very well described by the three-quark component of wave function



The $P_{11}(1440)$ electrocouplings from the CLAS data

LF quark models:

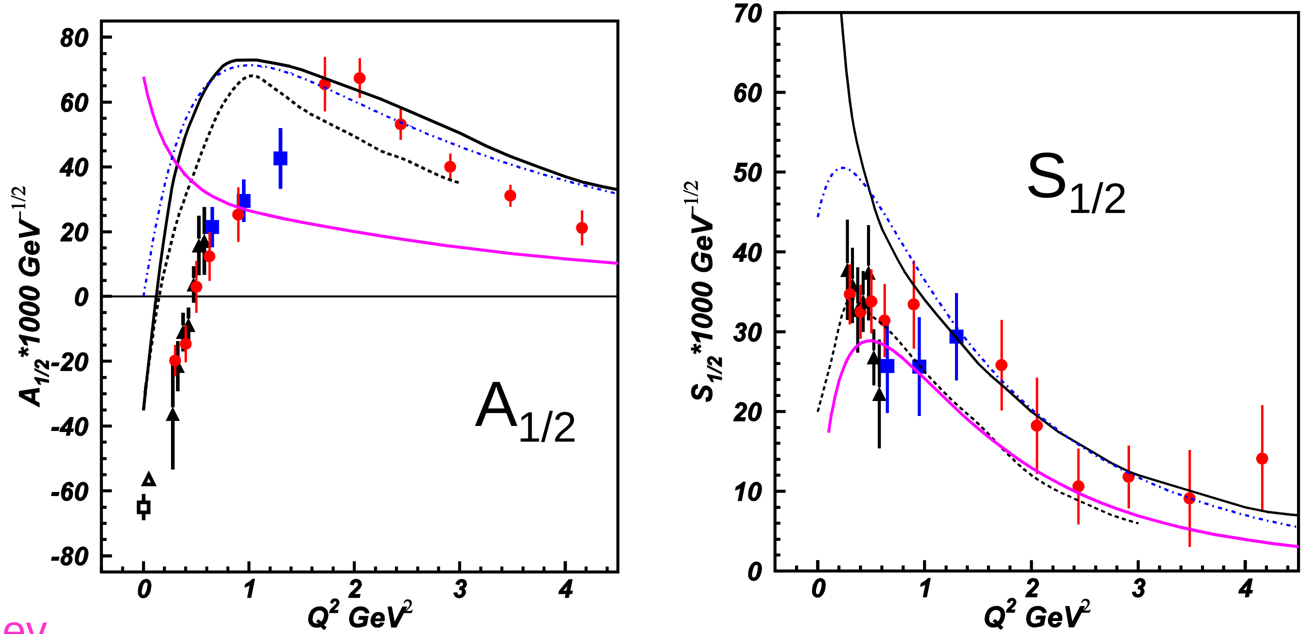
I. Aznauryan.

S. Capstick.

Relativistic covariant approach by G.Ramalho /F.Gross .

EBAC-DCC MB dressing (absolute values).

B,Julia-Diaz et al., Phys. Rev. C77, 045205 (2008)



$\pi^+\pi^-p$ 2012

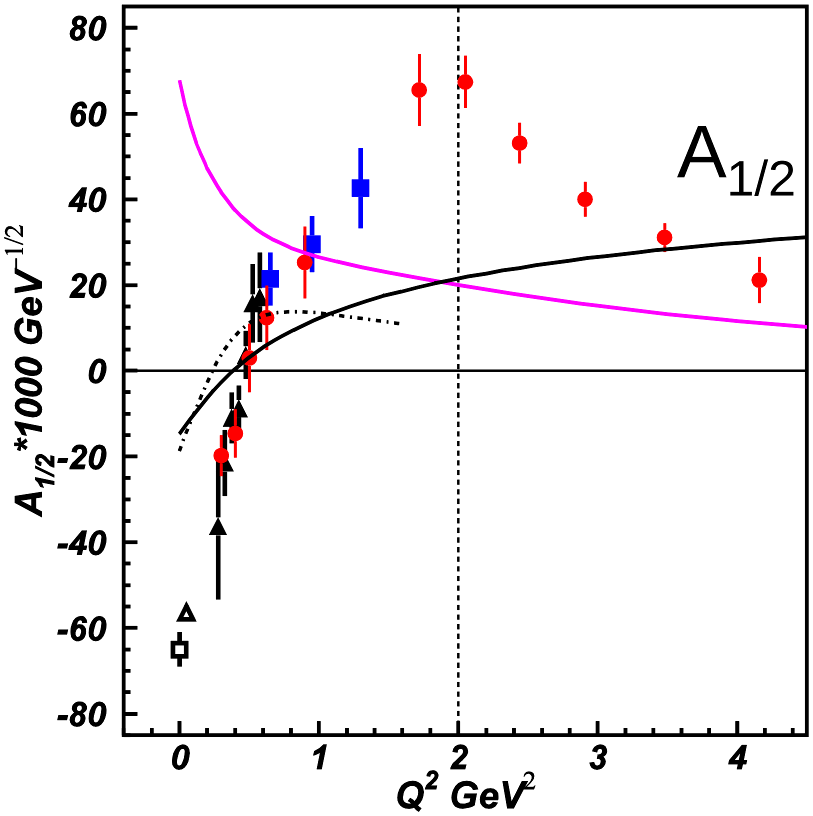
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

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

- The physics analyses of these results revealed the ***$P_{11}(1440)$*** structure as a combined contribution of: a) quark core as a first ***radial excitation of the nucleon as a 3-quark ground state and b) meson-baryon dressing***.

Roper resonance electrocouplings from DSEQCD



First estimates of bare quark core contribution from QCD:

DSEQCD.

parameterization of the EBAC-DCC bare electrocouplings.

meson-baryon dressing EBAC-DCC (abs. values).

- **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.**

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

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

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

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

Support for substantial contributions from meson-baryon cloud to the P_{11}(1440) structure . Next DSEQCD evaluations with realistic quark-quark interaction will demonstrate the data sensitivity to momentum dependence of dressed quark mass.

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

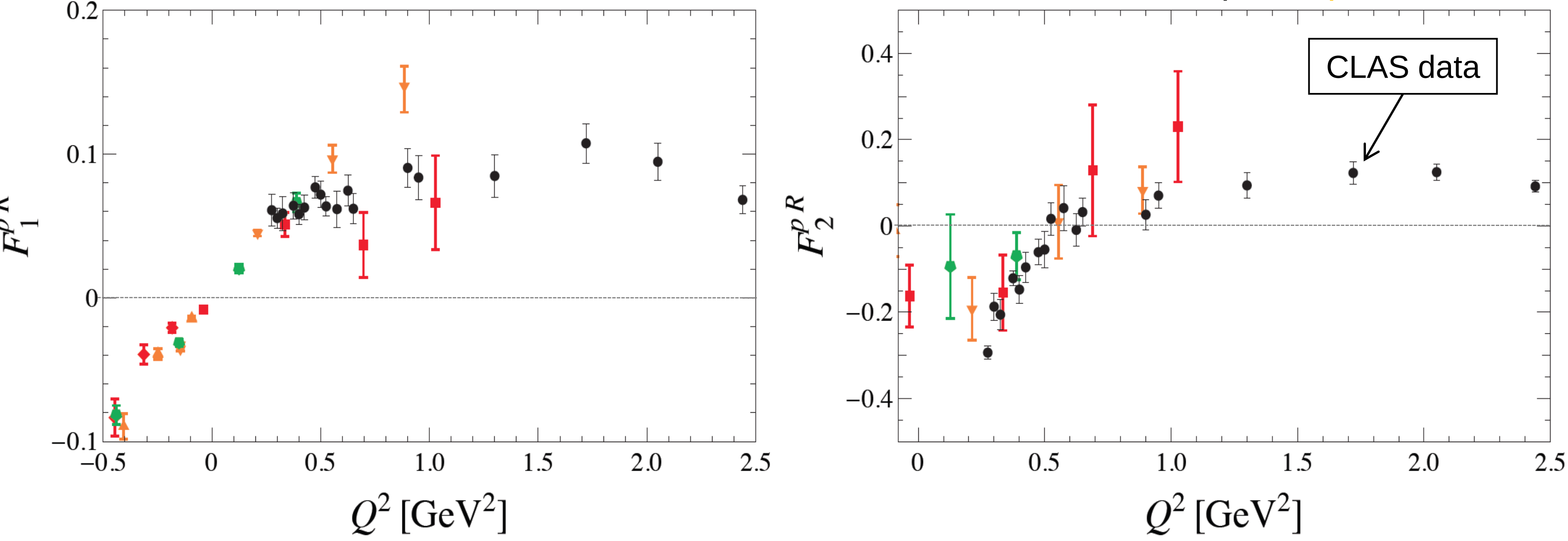
Includes the quark loops in the sea , which are critical in order to reproduce the CLAS data at Q^2<1.0 GeV^2

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

M_π = 390, 450, 875 MeV

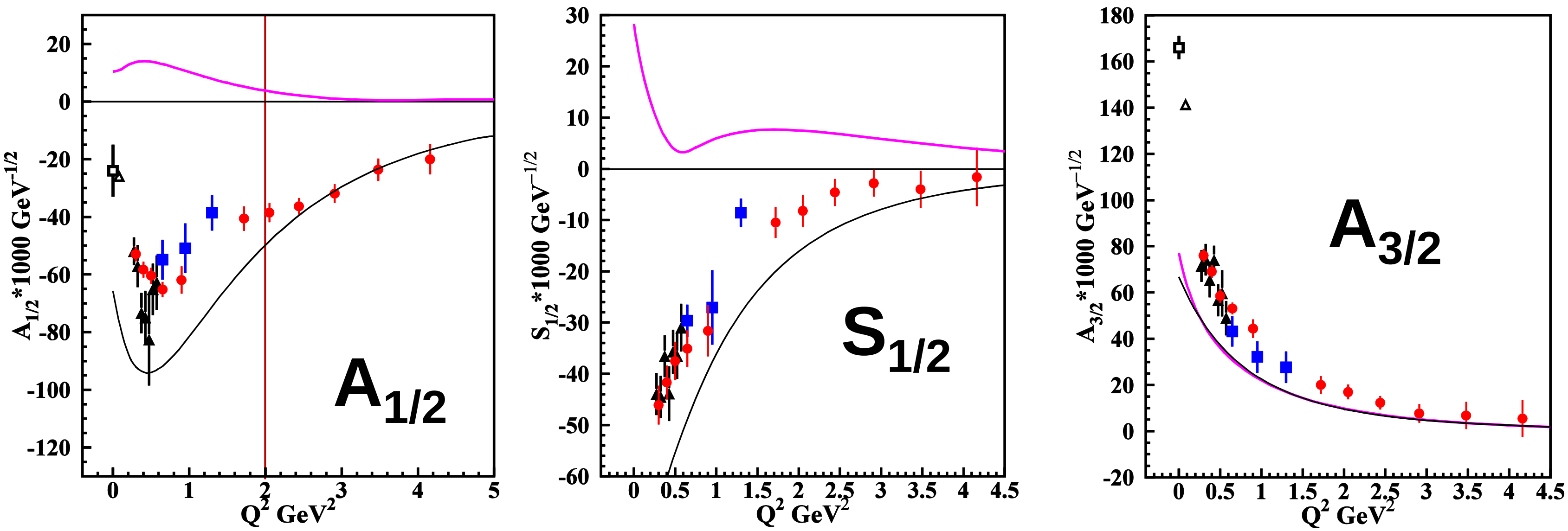
L box =3.0, 2.5, 2.5 f

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



Exploratory LQCD results are consistent with the CLAS data. Approaching physical M_π and extending projection operators by creation of multi particle states, LQCD is making progress toward evaluation of γ_vNN* electrocouplings from the first QCD principles.

The $D_{13}(1520)$ electrocouplings from the CLAS data



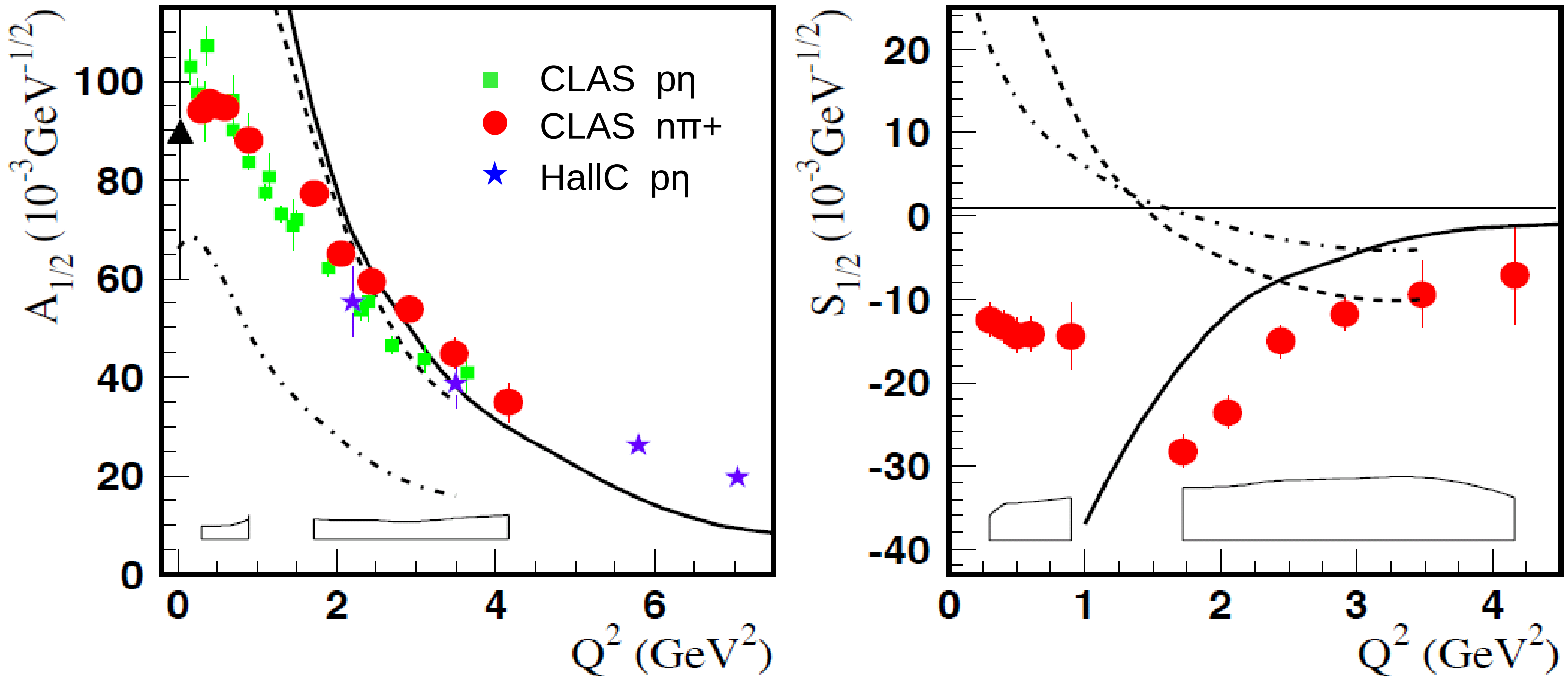
MB dressing abs val. (EBAC)

M.Giannini/E.Santopinto hCQM

- a reasonable agreement between the results from $N\pi$ and $\pi^+\pi^-p$ exclusive channels.
- electrocoupling behavior at $Q^2>2.0$ GeV^2 suggests substantial contribution from 3 dressed quarks in the first orbital excitation.
- evidence for a sizable meson-baryon cloud at $Q^2<1.0$ GeV^2.

CLAS data on $A_{1/2}$ electrocoupling for the first time offer almost direct access to quark core at $Q^2>2.0$ GeV^2 and they are of particular interest for the QCD-based models of N* structure.

S_{11} (1535) electrocouplings and their interpretation



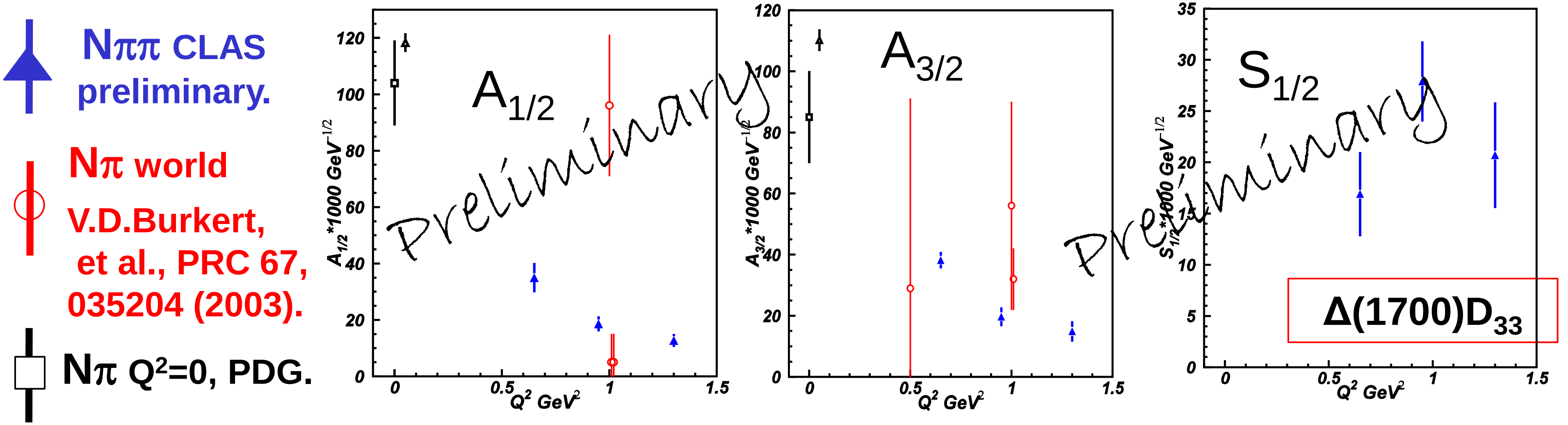
Analysis of pη channel assumes $S_{1/2}$=0
Branching ratios: $\beta_{N\pi} = \beta_{N\eta} = 0.45$

- **$A_{1/2}$ (Q^2) from Nπ and pη are consistent**
- **First extraction of $S_{1/2}$(Q^2) amplitude**

➢***QCD-based LQCD & LCSR calculations (black solid lines) by Regensburg*** **Univ. Group reproduces data trend at Q^2>2.0 GeV^2**

➢**Successful description of S_{11}(1535) electrocouplings at Q^2>2.0 GeV^2 basesd on OCD! (V.Braun et al., Phys. Rev. Lett., 103, 072001 (2009))**

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



Analysis of the $\pi^+\pi^-p$ electroproduction data provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{35}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy.

The results on electrocoupling of the resonances in the mass range from 1.6 to 1.8 GeV will be finalized in near term future after evaluation of the phases of the 2π-direct production mechanisms from the $\pi^+\pi^-p$ CLAS data fit.

Conclusions and Outlook

- **The CLAS detector at Hall-B extended considerably available data on $N\pi$, $N\eta$ electroproduction and provided only available worldwide data on nine differential and fully integrated $\pi^+\pi^-p$ electroproduction cross sections in N* excitation region and at photon virtualities $Q^2<5.0$ GeV^2. Data analysis within the framework of phenomenological reaction models allowed us to account for all essential contributing mechanisms and to separate resonant and non-resonant contributions for extraction of $\gamma_v NN^*$ electroplings.**

- **The data on G^*_M form factor and R_{EM}, R_{SM} ratio for $p\rightarrow\Delta$ transition were extended up to photon virtualitites 6.5 GeV^2. No evidence for the onset of pQCD was found.**

- **For the first time electrocouplings of the $P_{11}(1440)$ and $D_{13}(1520)$ states have become available from $N\pi$ ($Q^2<5.0$ GeV^2) and $\pi^+\pi^-p$ ($Q^2<1.5$ GeV^2) channels. The results from major electproduction channels with different non-resonant processes are consistent, offering an evidence for reliable electrocoupling extraction and for credibility of the reaction models employed in the data analyses.**

Conclusions and Outlook

- **Physics analyses of the CLAS data on electrocoupling of resonances in the mass range < 1.6 GeV revealed that the structure these states at Q^2<5.0 GeV^2 is determined by combined contributions from external meson-baryon cloud and internal core of three dressed quarks. Relative contribution from quark degrees of freedom increases with Q^2**

- **Preliminary results on S_{31}(1620), S_{11}(1650), F_{15}(1685), D_{33}(1700), and P_{13}(1720) electrocouplings at 0.5<Q^2<1.5 GeV^2 have become available from the $\pi^+\pi^-p$ electroproduction channel.**

- **The first results on electrocouplings of most resonances in the mass range up to 1.80 GeV open up new prospects for the based on QCD studies of hadron structure paving a way for exploration of confinement in baryons.**

- **Analysis of the preliminary CLAS $\pi^+\pi^-p$ electroproduction data at 2.0<Q^2<5.0 GeV^2 is in progress with a goal of determining all prominent N* state electrocouplings in the mass range up to 2.0 GeV and at Q^2 up to 5.0 GeV^2 .**

BACK-UP

The special procedure for the CLAS data fit

•Resonant and non-resonant parameters of the JM model listed in the Table below are varied simultaneously employing unrestricted normal distributions around their start values.

•For each trial set of non-resonant and resonant parameters nine differential cross sections are computed and χ^2/d.p. are obtained in point by point comparison between the measured and computed cross sections.

•Bunches of computed cross section are selected with $\chi^2/d.p. < \chi^2/d.p._{max}$, determined by the requirement that selected in the fit computed cross sections should be inside the data uncertainties for most data points.

•$\gamma_v NN^*$ electrocouplings obtained in these equally good fits were averaged. Their mean values are treated as extracted from the data, while dispersions are taken as uncertainties

Resonance var. parameters	σ, % from res. parameter start value	Non-resonance var. parameters	σ, as % from non-res. parameter start value
$P_{11}(1440)$,$D_{13}(1520)$,$S_{31}(1620)$, $S_{11}(1650)$,$F_{15}(1685)$ electrocouplings	30	Magnitude of the additional contact term amplitudes in $\pi^-\Delta^{++}$ sub-channel	15
$P_{11}(1440)$,$D_{13}(1520)$,$S_{11}(1535)$ $\pi\Delta$,ρp decay widths	30	Magnitude of the additional contact term amplitudes in $\pi^+\Delta^0$ sub-channel	20
		Magnitude of six 2π-direct production amplitudes	15

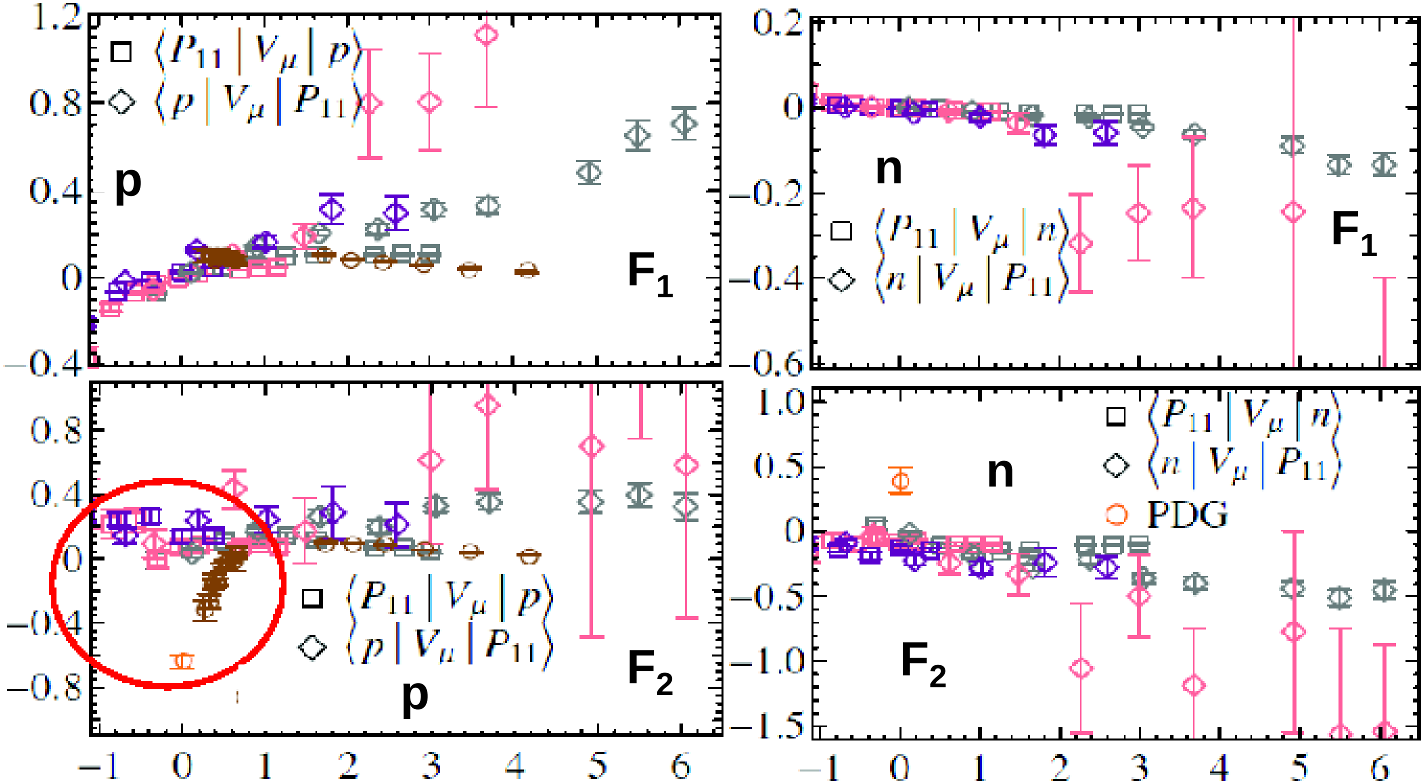
Nucleon-Roper Form Factors

§ Still quenched

Lattice QCD

- Of anisotropic clover ($a \approx 0.1$ fm, $\xi \approx 3$)
- $M_\pi \approx$ 480, 720, 1100 MeV

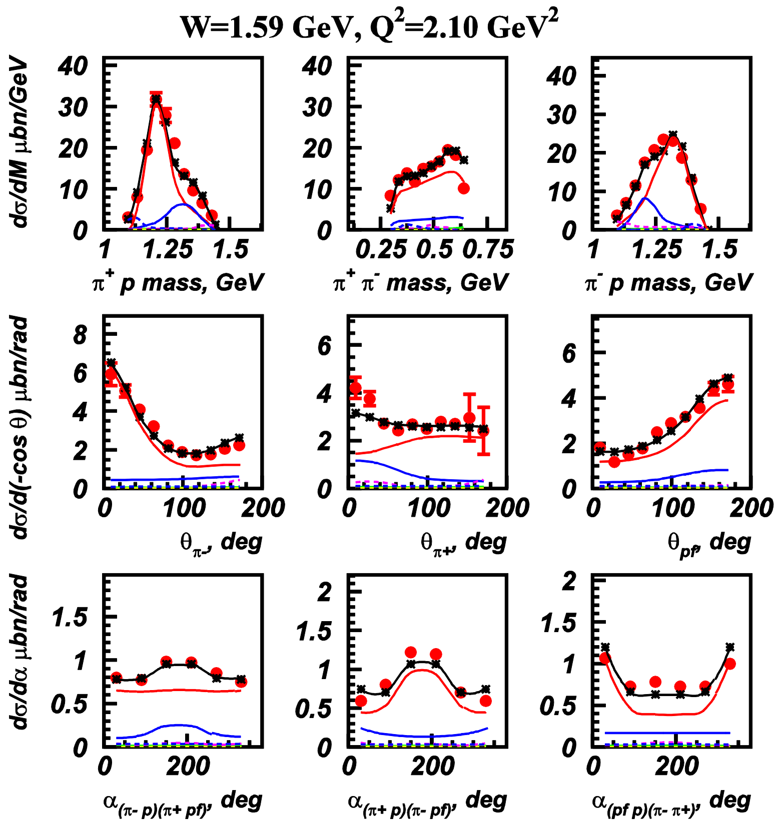
Computed from CLAS results on P_{11}(1440) electro couplings



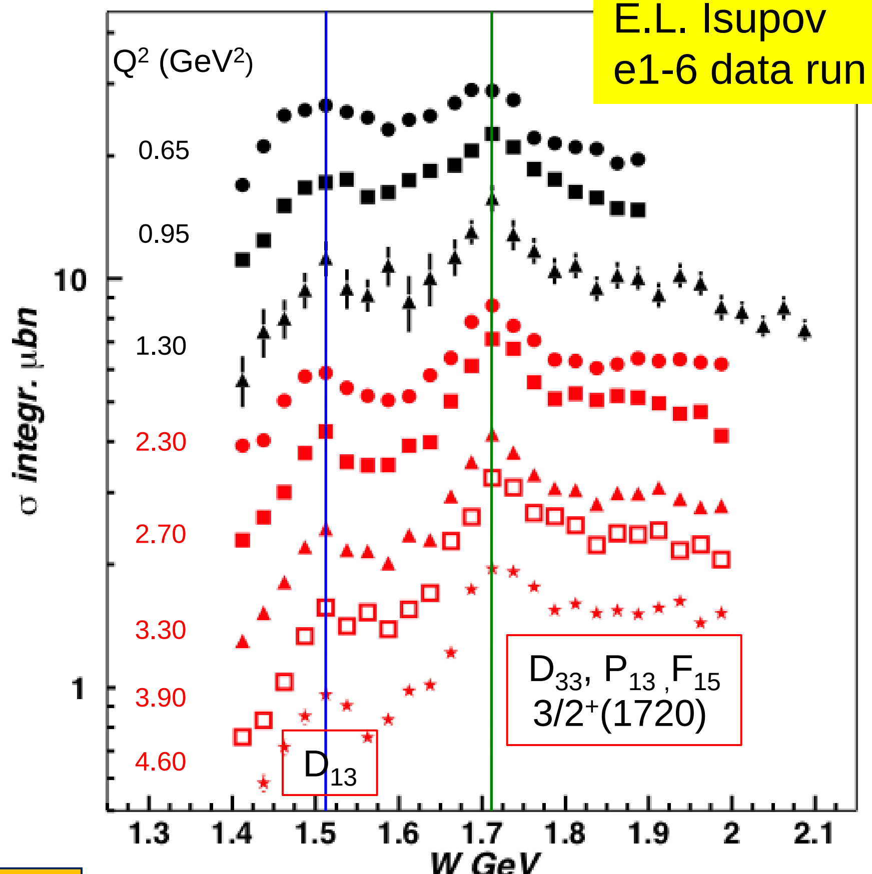
HWL et. al, PoS LATTICE2008:140 (2008)

Extension of the $\pi^+\pi^-p$ electroproduction analyses toward photon virtualities up to 5.0 GeV^2

γ_vNN*electrocouplings will become available for most excited proton states with masses less then 2.0 GeV and at photon virtualities up to 5.0 GeV^2



Extension of JM model toward high Q^2



Resonance structures become more prominent with increasing Q^2.