

Resonance Electrocouplings in Two Pion Channel

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N, N^* quark core

PWA 2013 Workshop



Motivation for the Studies of the N*-Structure

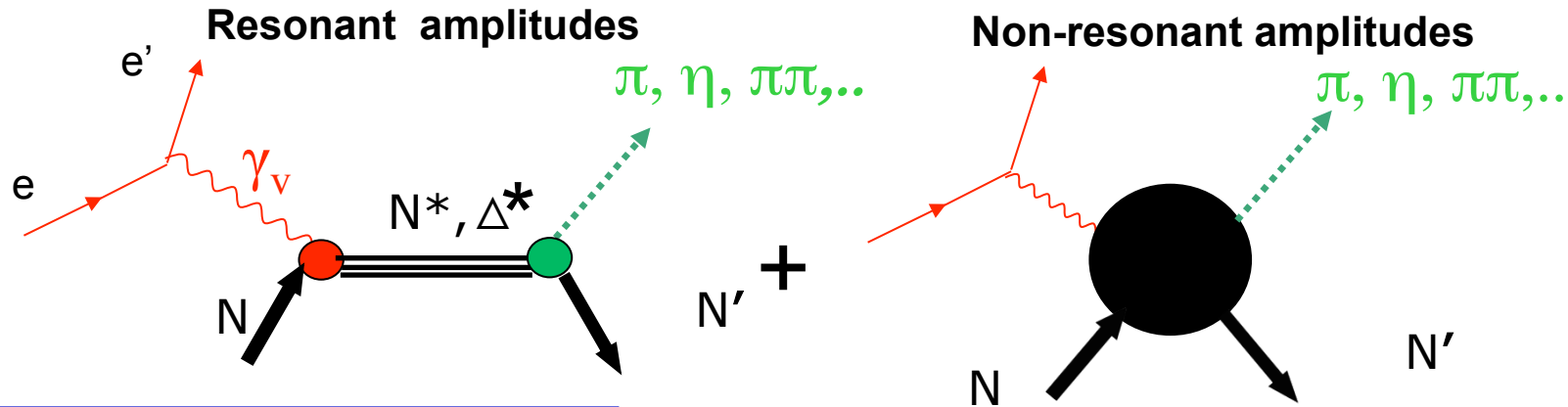
The experimental program on the studies of N* structure in exclusive meson electroproduction with CLAS seeks to determine:

- $\gamma_v NN^*$ electrocouplings at photon virtualities up to 5.0 GeV² for most of the excited proton states through analyzing major meson electroproduction channels independently and in global multi-channel analyses;
- extend available knowledge on resonance hadronic decays in particular for the multi-meson final states.

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



Access to $\gamma_v NN^*$ Electrocouplings from the Data on Exclusive Meson Electroproduction



- 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).

N^* 's photo-/electrocouplings $\gamma_{r,v} NN^*$ can be defined at $W=M_{N^*}$ through the N^* electromagnetic decay width Γ_γ as:

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

$$F_{virt} = 4K M_N \quad \text{invariant flux of virtual photons}$$

$$K = \frac{W^2 - M_N^2}{2M_N} \quad q_c = \frac{W^2 - M_N^2}{2W}$$

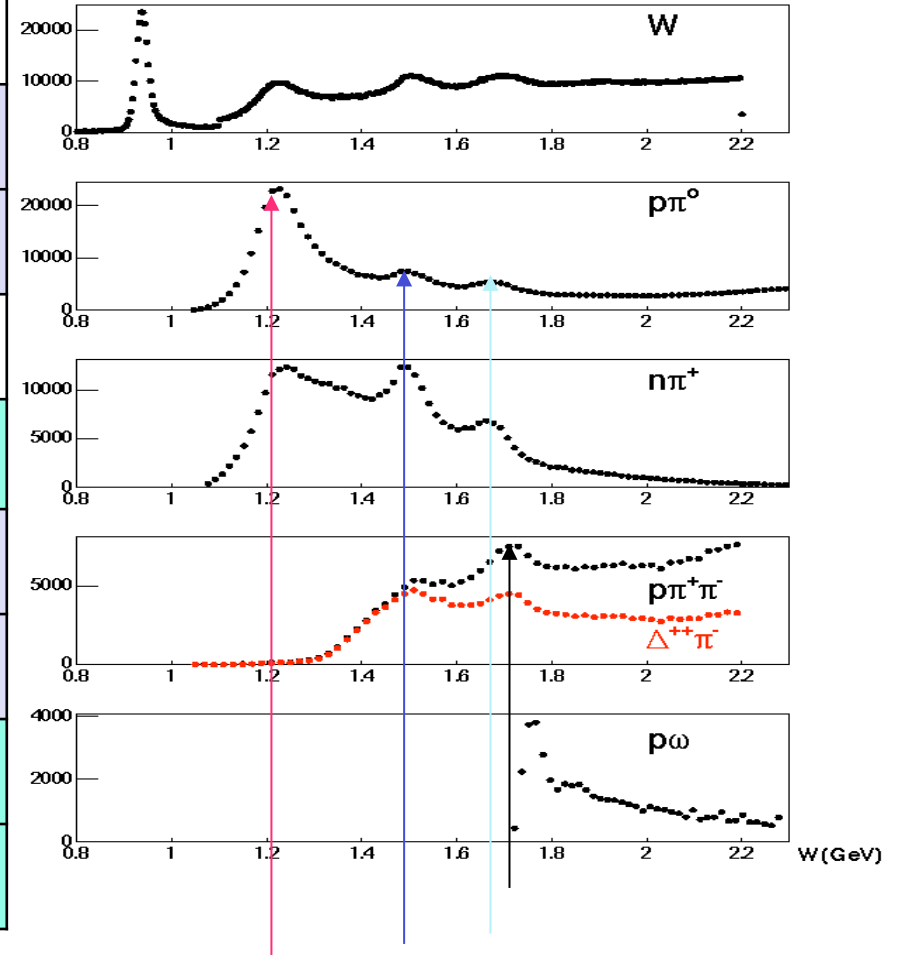
- **Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of these quantities.**

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 $Q^2 < 4 \text{ GeV}^2$



$N\pi/N\pi\pi$ channels are major sources of information on $\gamma_V NN^*$ electrocouplings.



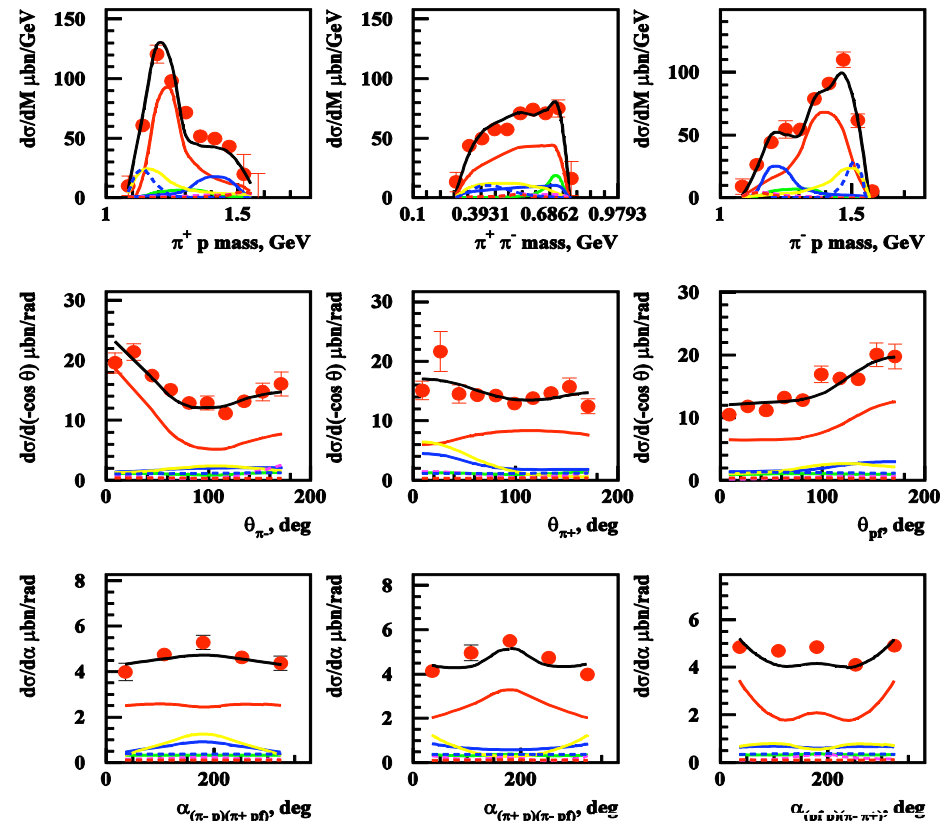
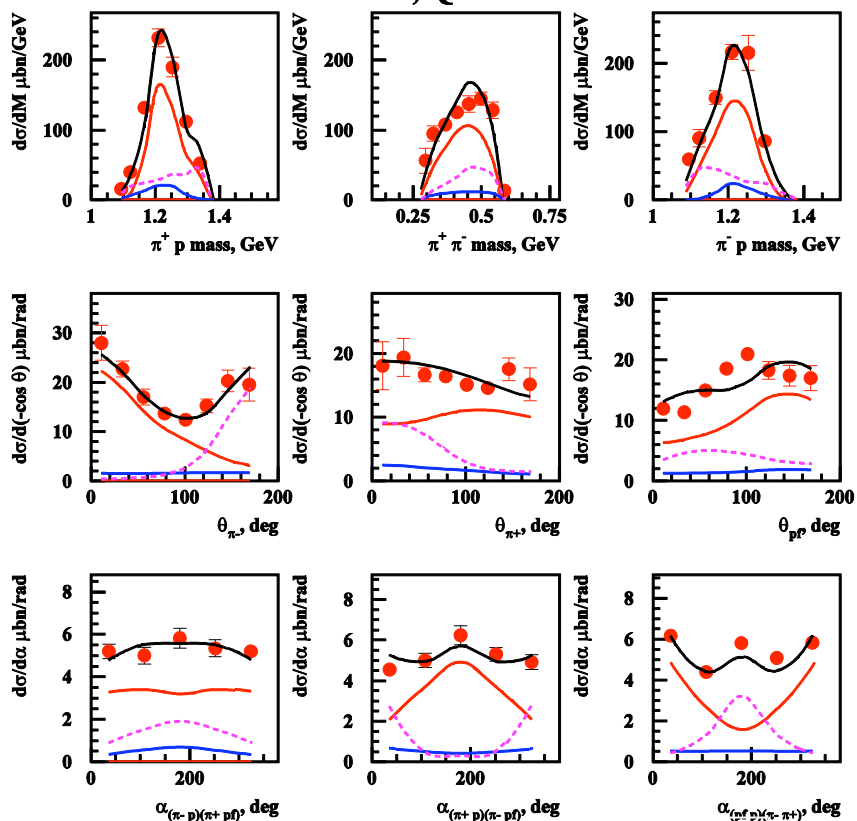
The CLAS Data on $\pi^+\pi^-p$ Differential Cross Sections and their Fit within the Framework of Meson-Baryon Model JM

G.V.Fedotov et al, PRC 79 (2009), 015204
 $1.30 < W < 1.56$ GeV; $0.2 < Q^2 < 0.6$ GeV²

M.Ripani et al, PRL 91 (2003), 022002
 $1.40 < W < 2.30$ GeV; $0.5 < Q^2 < 1.5$ GeV²

$W=1.5125$ GeV, $Q^2=0.375$ GeV²

$W=1.71$ GeV, $Q^2=0.65$ GeV²



— full JM calc.
 — $\pi^+\Delta^0$
 — $\rho\rho$
 - - - $\pi^+ N^0(1680) F_{15}$
— $\pi^-\Delta^{++}$
 - - - 2π direct
— $\pi^+ N^0(1520) D_{13}$



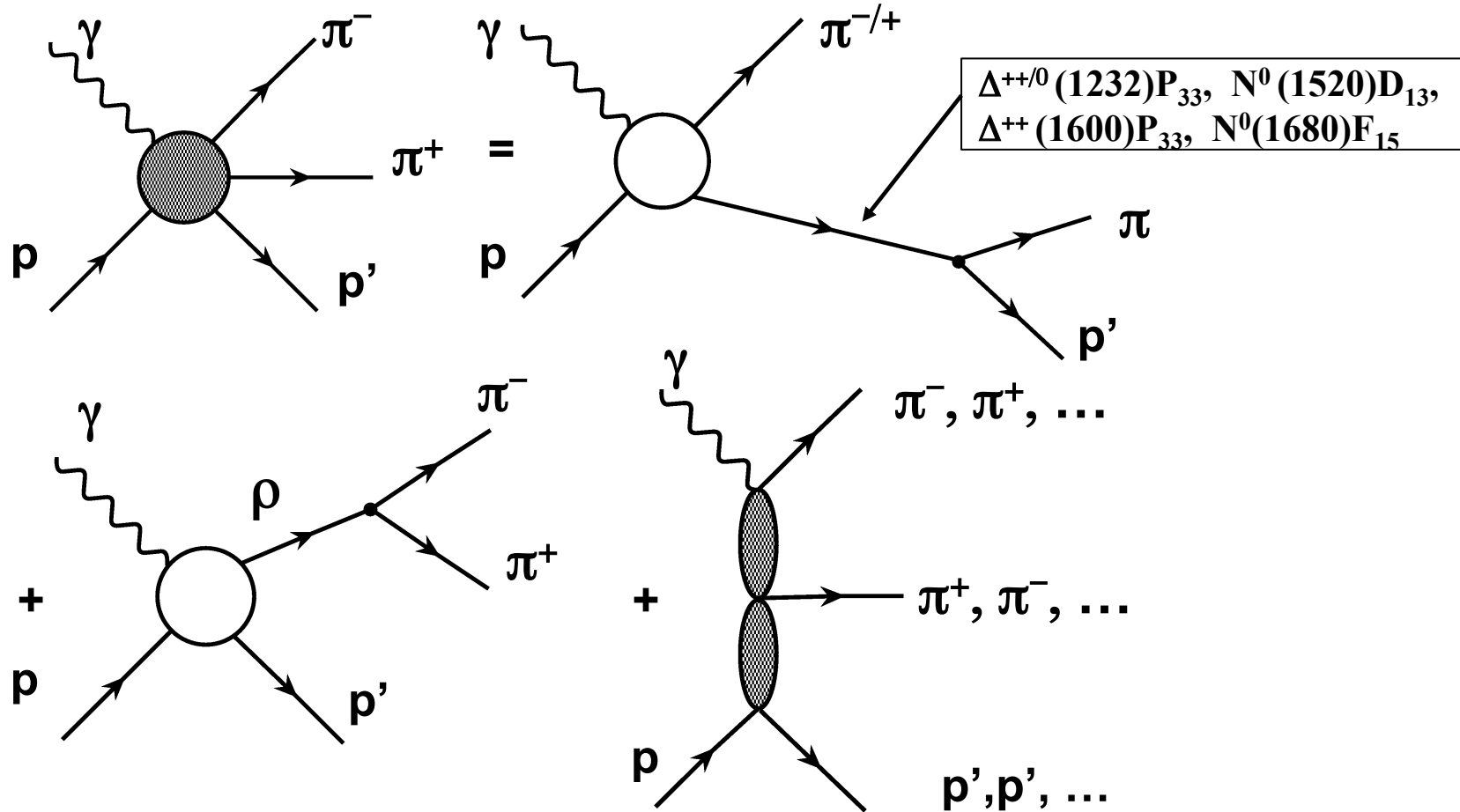
The Data Driven JM Model. Basic Ingredients.

- Coherent superposition of $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, $\rho\rho$, $\pi^+ N^0(1520)D_{13}$, $\pi^-\Delta^{++}(1600)P_{33}$, $\pi^+N^0(1680)F_{15}$ meson-baryon channels and direct 2π production amplitudes without formation of unstable hadrons in the intermediate states.
- Resonant amplitudes described by unitarized Briet-Wigner ansatz and contribute to $\pi\Delta$ and $\rho\rho$ channels only. All N^* -states of 4-star RPP status are included.
- Current conserving, reggeized Born terms plus extra-contact terms for description of non-resonant $\pi\Delta$ amplitudes. The absorptive ansatz for phenomenological ISI & FSI treatment.
- Diffractive ansatz for non-resonant $\rho\rho$ amplitudes accounting for ρ -line shrinkage in N^* -excitation region.
- The amplitudes of $\pi^+ N^0(1520)D_{13}$ channel are derived from those of $\pi\Delta$ channel implementing γ_5 -matrix to $p\text{-}\pi\text{-}N^0(1520)D_{13}$ vertex with magnitudes fit to the data.
- The amplitudes of $\pi^-\Delta^{++}(1600)P_{33}$, $\pi^+ N^0(1680)F_{15}$ channels are parameterized by contact terms with magnitudes fit to the data.
- Parameterizations of direct 2π production amplitudes were established examining the correlations between the shapes of their contributions to different 1-fold differential cross sections.

Major objectives: extraction of $\gamma_V NN^*$ electrocouplings and $\pi\Delta$, $\rho\rho$ decay widths fitting all available observables of $\pi^+\pi^-p$ exclusive channel.



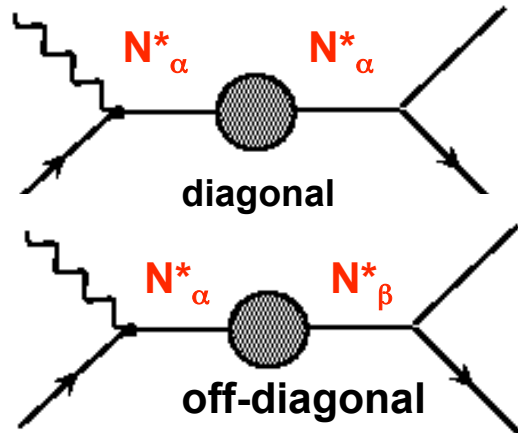
$\pi^+\pi^-p$ Electroproduction Amplitudes in the JM Model



1. V.I.Mokeev, V.D. Burkert, et al., (CLAS Collaboration) Phys. Rev. C86, 035203 (2012).
2. V.I.Mokeev, V.D. Burkert, et al., Phys. Rev. C80, 045212 (2009).
3. M.Ripani, V.I.Mokeev et al., Nucl. Phys. A672, 220 (2000).

Unitarized Breit-Wigner Ansatz for Resonant Amplitudes

Resonant amplitude : $T_{\gamma p \rightarrow MB}^{res} = f_{\beta MB} S_{\alpha\beta} f_{\alpha\gamma p}$



Inverse of the JM unitarized N^* propagator:

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

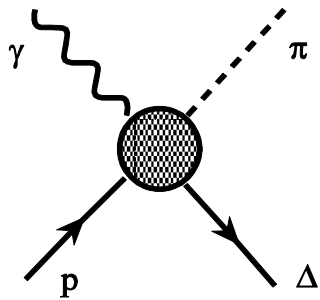
Off-diagonal transitions incorporated into the full resonant amplitudes of the JM model:

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

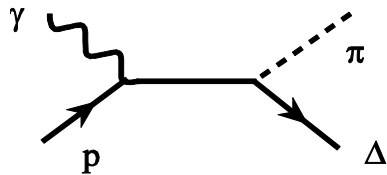
Full resonant amplitude of unitarized Breit-Wigner ansatz is consistent with restrictions imposed by a general unitarity condition.

Non-resonant Contributions to $\pi\Delta$ Channels

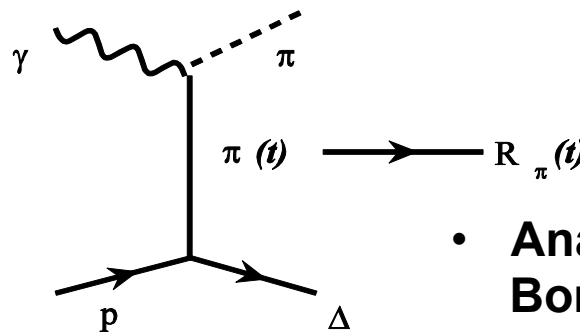
Minimal set of current conserving
Born terms:



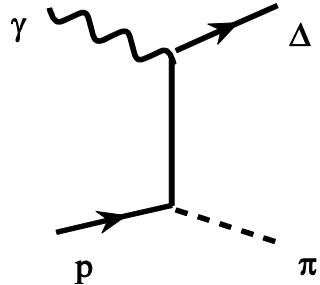
contact



nucleon term



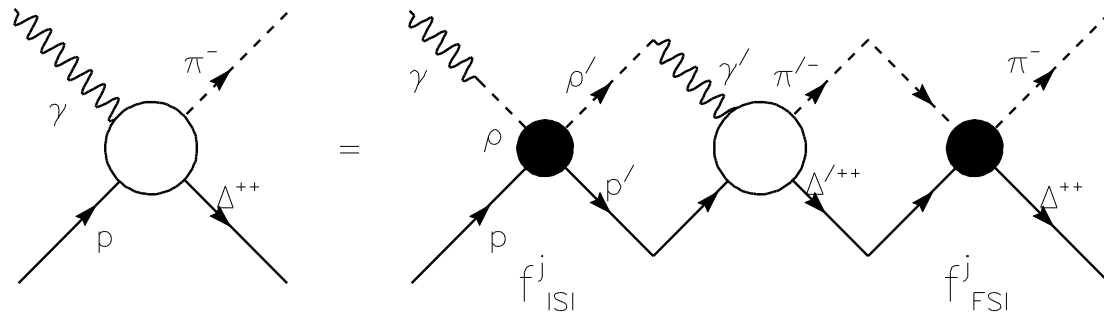
pion in flight



delta in flight

- Analytical expressions for the Born terms can be found in Refs. 2,3 in the slide #7.
- Born terms were reggiezed as described in Refs. 2,3 in the slide # 7.
- Extra contact term was added to parameterize the contributing processes beyond Born terms. See Ref. 2 in the slide # 7.

Accounting for the ISI & FSI in $\pi\Delta$ Channels



Absorptive ansatz proposed in **K.Gottfried, J.D.Jackson, Nuovo Cimento 34, 736 (1964)** and developed for the use in the JM model in **M.Ripani et al., Nucl Phys. A672, 220 (2000)**.

Non-resonant parts of $\pi\Delta$ amplitudes computed from tree diagrams $T_{\lambda\mu}^{J tree}$ are multiplied by the absorptive factors in the initial and final states f_{ISI}^J, f_{FSI}^J :

$$T_{\lambda\mu}^{J full} = f_{ISI}^J T_{\lambda\mu}^{J tree} f_{FSI}^J$$

$$\lambda = \lambda_\gamma - \lambda_p$$

$$\mu = -\lambda_\Delta$$

$$f_{ISI}^J = \langle \lambda_\rho \lambda_p | S^J | \lambda_\rho \lambda_p \rangle^{1/2}$$

$$f_{FSI}^J = \langle \pi \lambda_\Delta | S^J | \pi \lambda_\Delta \rangle^{1/2}$$

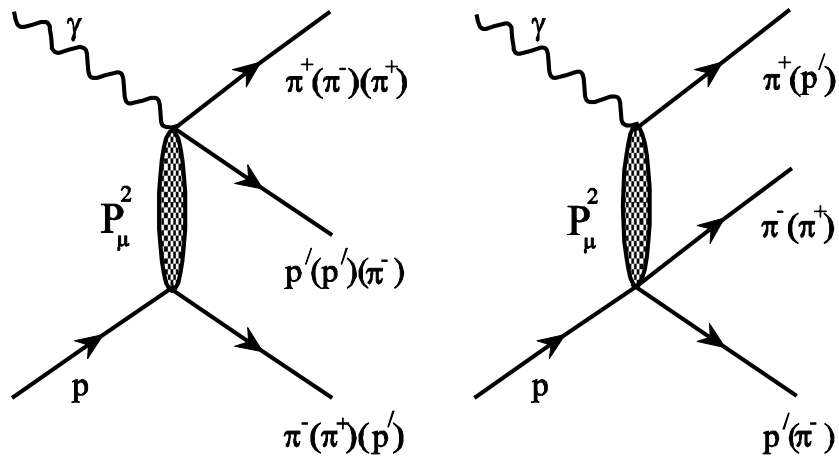
$$S = 1 + 2iT$$

Possible improvement: absorptive ansatz can be replaced by the results of coupled channel analyses on the ratio R : $\pi\Delta$ (photo) electroproduction amplitudes accounting for FSI $T_{\pi\Delta}^{J full}$ over their values computed from tree diagrams $T_{\pi\Delta}^{J tree}$:

$$R = \frac{T_{\lambda\mu}^{J full}}{T_{\lambda\mu}^{J tree}} \quad T_{\lambda\mu}^{J full} = T_{\lambda\mu}^{J tree} R$$

Parameterization of Direct 2π Production Amplitudes Based on the CLAS Data Description.

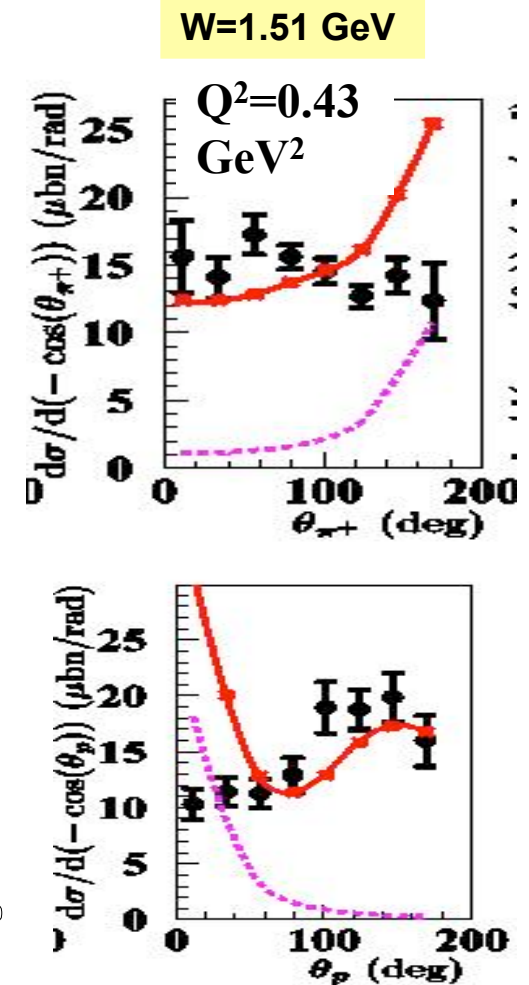
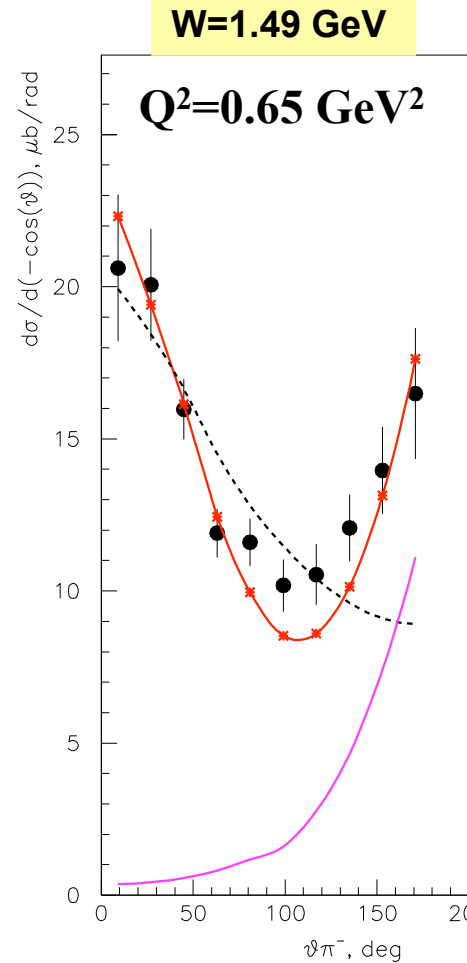
data descriptions achieved with 2π direct production mechanisms described as:
 phase space
 ——— exchange mechanisms:



$$M_d = A(W, Q^2) \varepsilon_\mu^\gamma \bar{U}_{p'} \gamma_\mu U_p *$$

$$\frac{1}{W^4} e^{b(P_\mu^2 - P_{\mu\min}^2)} (PP_2)$$

Further improvements in description of direct 2π production mechanisms were implemented.



Contributions of 2π direct production described by exchange processes

Direct 2π Production Mechanisms in the Current Version of the JM13 Model

$$A(W, Q^2) \varepsilon_\mu(q_\gamma) \bar{U}_{p'}(P_{p'}) \gamma^\mu U_p(P_p)^* e^{b(t_1 - t_{1\max})} (P_2 P_3) \{ \alpha_1(W) e^{b(t_2 - t_{2\max})} + \alpha_2(W) e^{b(t_3 - t_{3\max})} \}$$

$$t_1 = (q_\gamma - P_1)^2$$

$$t_2 = (P_p - P_3)^2$$

$$t_3 = (P_p - P_2)^2$$

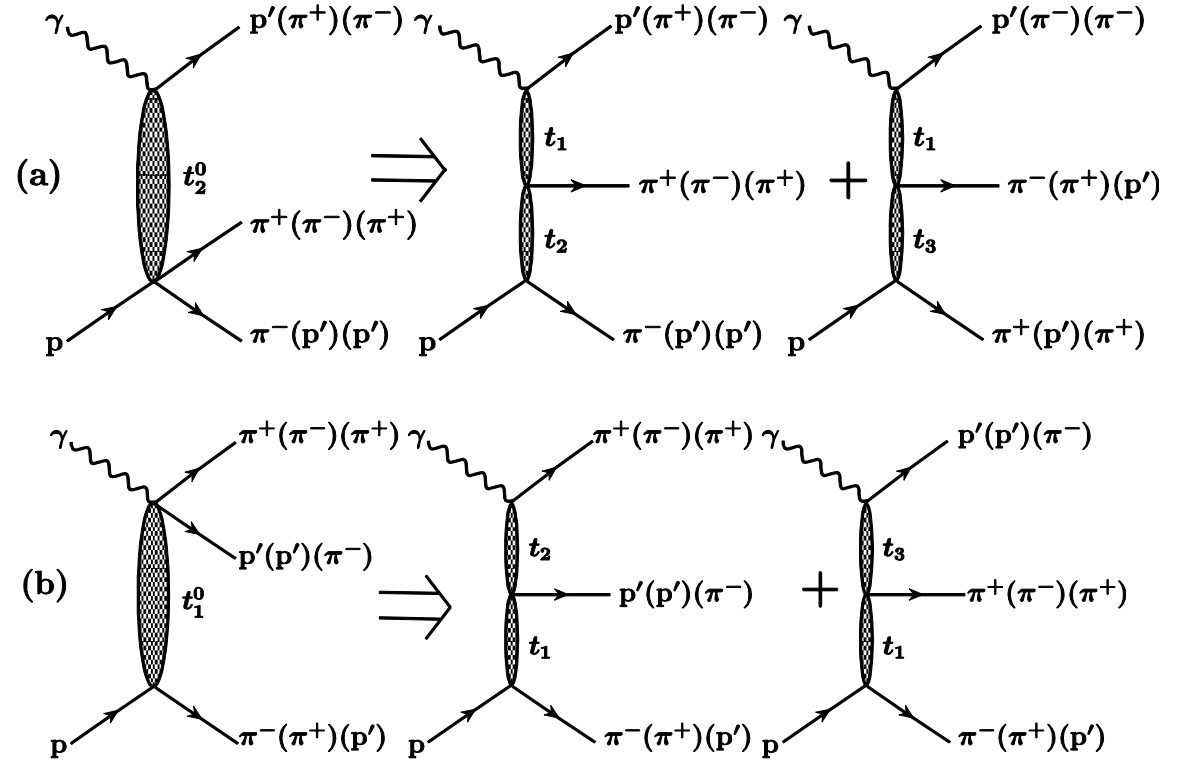
$$A(W, Q^2) \varepsilon_\mu(q_\gamma) \bar{U}_{p'}(P_{p'}) \gamma^\mu U_p(P_p)^* e^{b(t_1 - t_{1\max})} (P_1 P_2) \{ \alpha_1(W) e^{b(t_2 - t_{2\max})} (t_2 - t_{2\max}) + \alpha_2(W) e^{b(t_3 - t_{3\max})} \}$$

$$t_1 = (p_p - P_3)^2$$

$$t_2 = (q_\gamma - P_1)^2$$

$$t_3 = (q_\gamma - P_2)^2$$

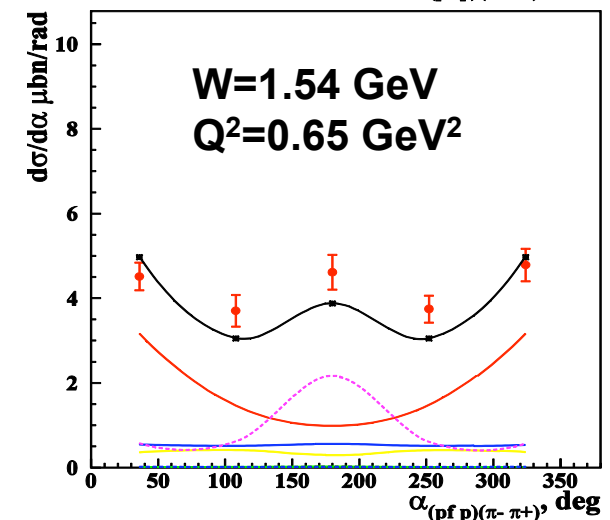
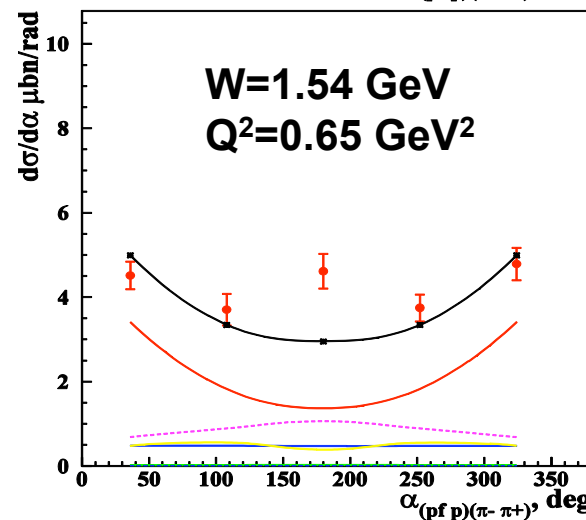
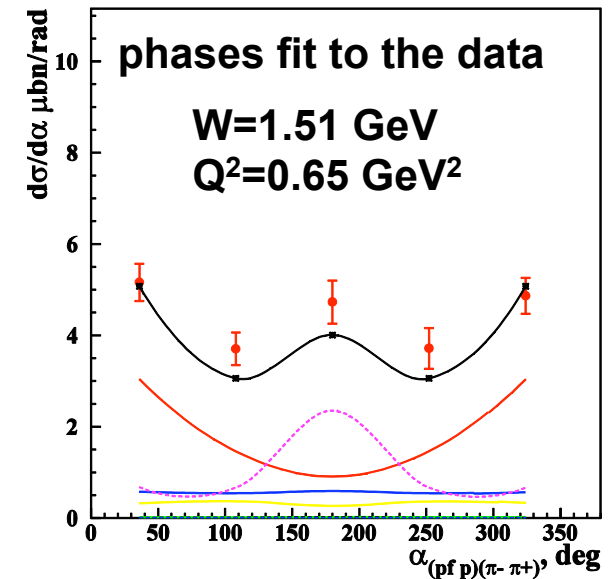
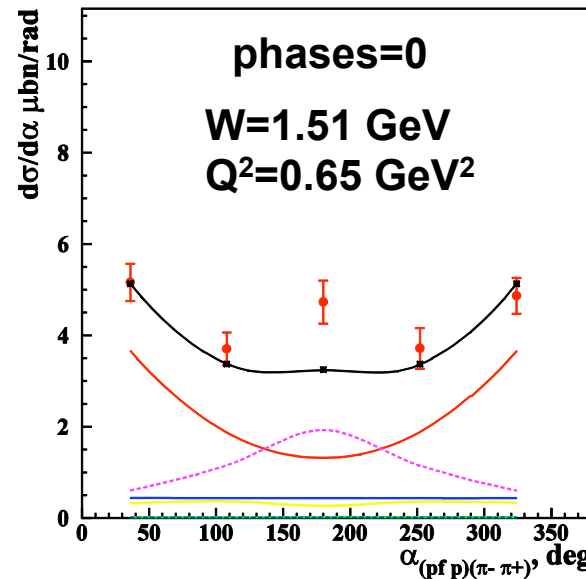
The details on amplitude parameterization are in Ref 2, slide #7.



Examples of the CLAS data description achieved employing the direct 2π production mechanisms depicted above can be found in the slide #5

The Phases of Direct 2π Production Amplitudes from the CLAS data on α -angular distributions

phase implementation allowed us to improve description of all differential cross sections, in particular α -angular distributions



Summary of the CLAS $\pi^+\pi^-p$ Electroproduction Data Analysis within the JM Model

Good description of all available data at $W < 1.8$ GeV and $0.25 < Q^2 < 1.5$ GeV² was achieved with $\chi^2/\text{d.p.} < 3.0$.

Major restriction: considerable contributions from the mechanisms parameterized phenomenologically without access to explicit meson-baryon or quark-gluon processes behind the phenomenology.

Further model developments: the JM's non-resonant mechanisms can be improved by using $2 \rightarrow 2$, $2 \rightarrow 3$, and $3 \rightarrow 3$ amplitudes describing electroproduction of the intermediate/final states and generated from the effective Lagrangians of the ANL-Osaka dynamical coupled-channel model (H. Kamano et al., [arXiv:1305.4351\[nucl-th\]](https://arxiv.org/abs/1305.4351), to appear in PRC).



Fitting Procedures and Uncertainty Estimates

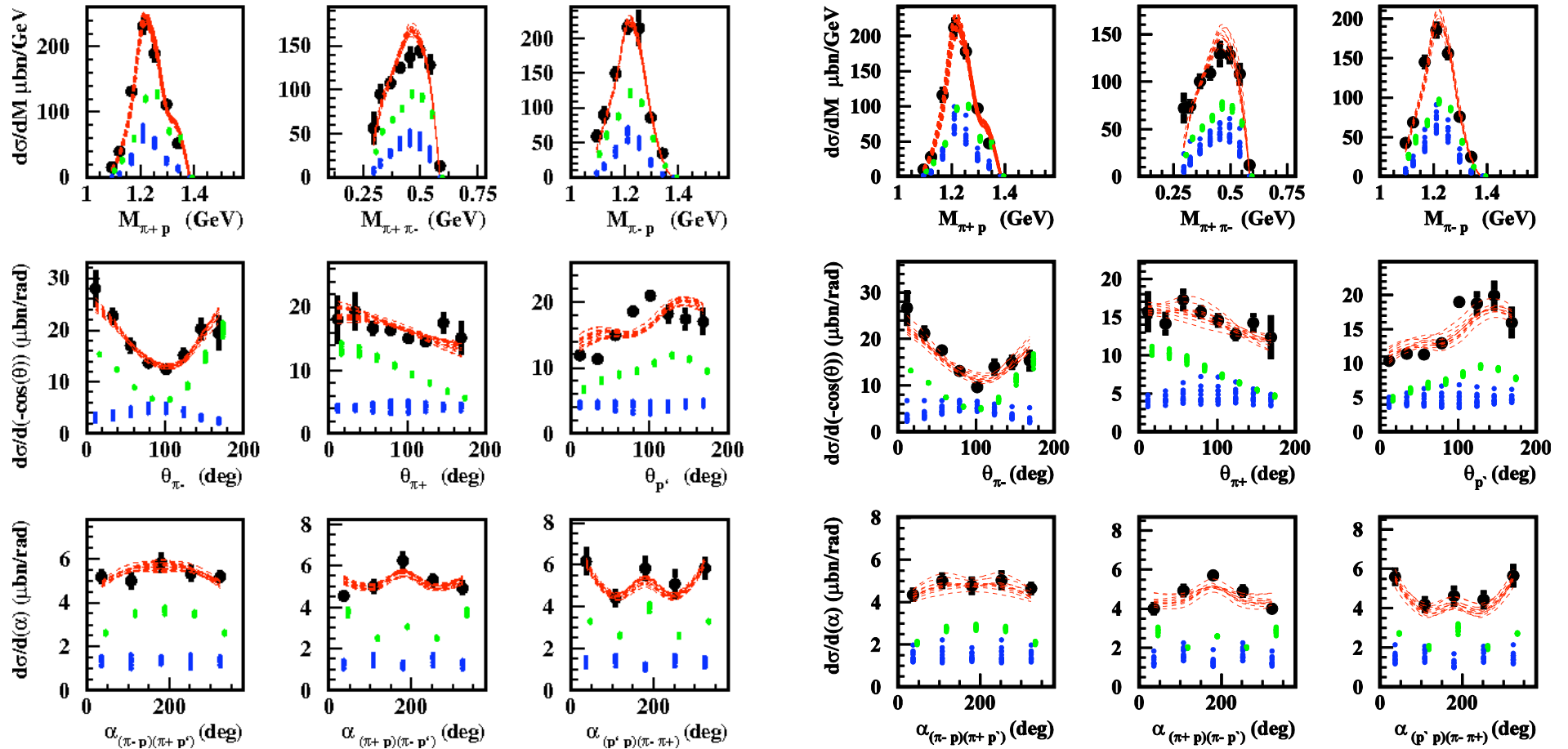
Simultaneous non-restricted variation of the following resonant/non-resonant JM model parameters according to the normal distribution:

- $\gamma_V NN^*$ electrocouplings with σ -parameter equal to 30% from their initial values;
 - $\pi\Delta$ and ρp hadronic decays for the N^* -states under studies with σ -parameters, that cause total N^* width 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.
- $\chi^2/d.p.$ fit of nine 1-fold diff. cross sections in each bin of W and Q^2 . Closest to the data computed cross sections were selected with $\chi^2/d.p. < \chi^2/d.p._{thr.}$, which was defined so that selected in the fit cross sections should be inside the uncertainties for most of the data points.
 - Mean values of N^* parameters resulting to the selected in the fit computed cross 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, $Q^2=0.38$ GeV²

$W=1.51$ GeV, $Q^2=0.43$ GeV²



Reliable isolation of the resonant cross sections is achieved




— full cross sections within the JM model

● resonant part

● non-resonant part

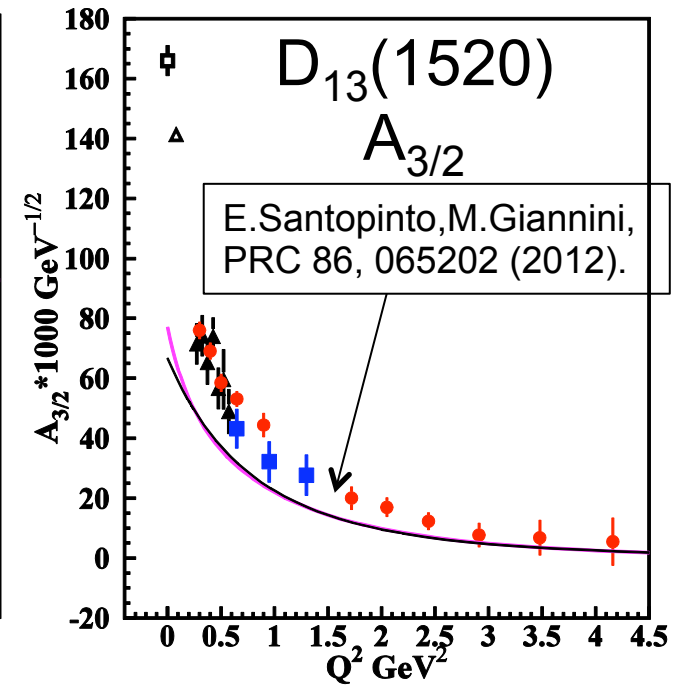
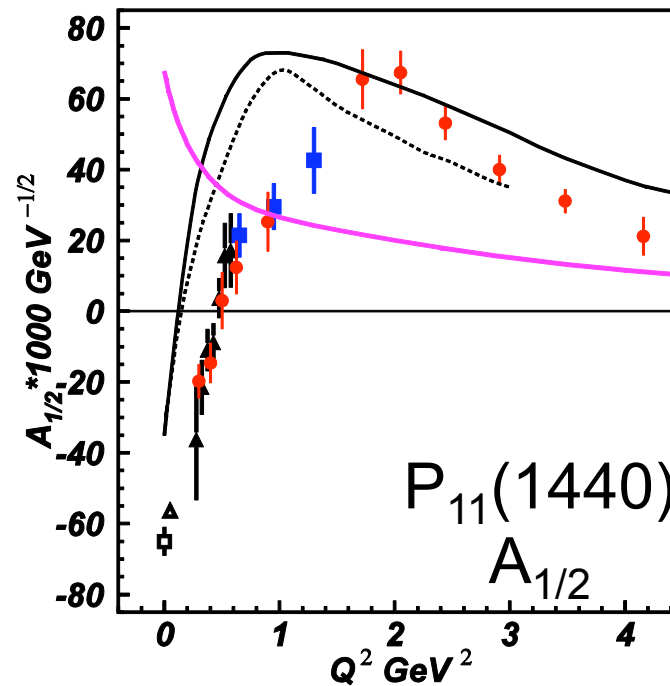
The $P_{11}(1440)$ and $D_{13}(1520)$ Electrocouplings from the CLAS $N\pi$ and $N\pi\pi$ Data

CLAS data:

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

Light Front quark models:

- I.G.Aznauryan, PRC 76, 025212 (2007).
- S.Capstick and B.D.Keister, PRD 51, 3598 (1995).



Meson-Baryon dressing:
(absolute values)

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

Consistent results on $P_{11}(1440)$ and $D_{13}(1520)$ electrocouplings determined independently from $N\pi$ and $\pi^+\pi^-p$ electroproduction strongly support reliable electrocoupling extraction.

Access to bare $\gamma_V NN^*$ electrocouplings is needed in order to compare extracted from the data N^* parameters with the results of quark models and the Dyson-Schwinger Equations of QCD. LQCD will allow us to confront dressed N^* -parameters with expectations on full PW amplitudes evaluated starting from the QCD Lagrangian.



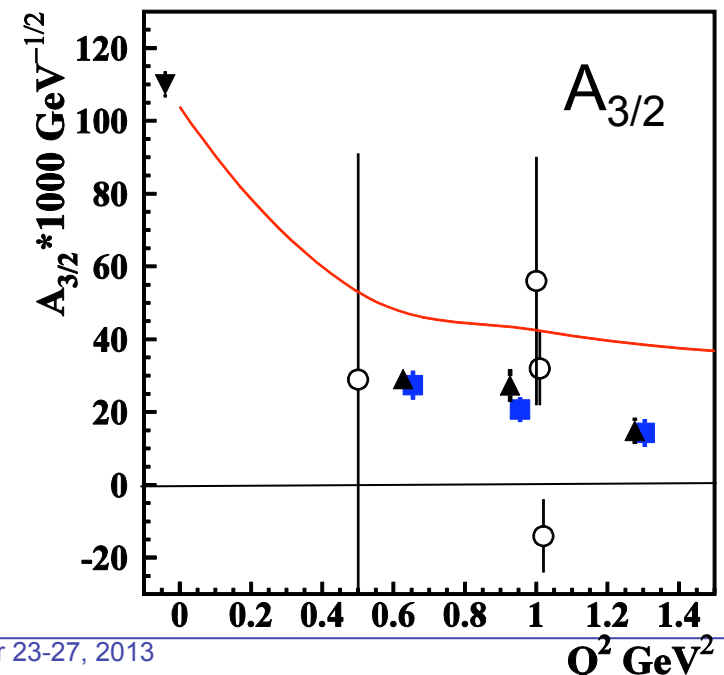
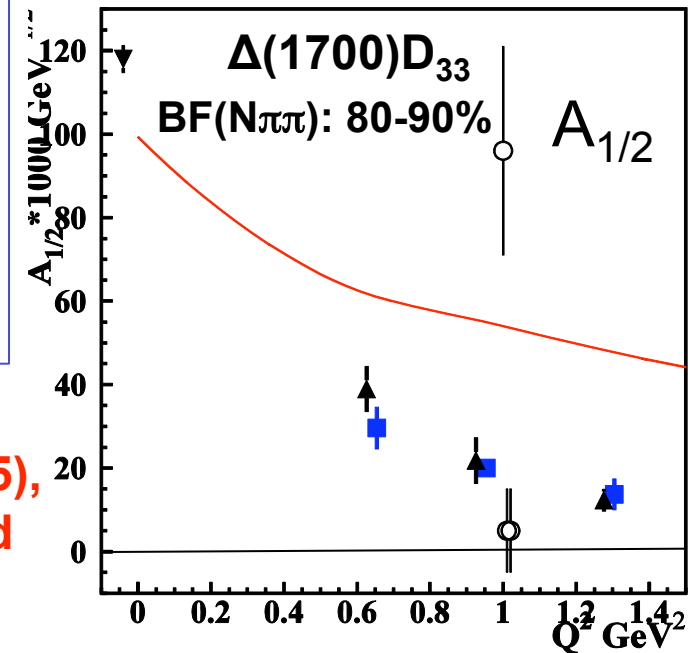
High lying resonance electrocouplings from the $\pi^+\pi^-\rho$ CLAS data analysis

<p>$N\pi$ world V.D.Burkert, et al., PRC 67, 035204 (2003).</p>	<p>$N\pi\pi$ CLAS preliminary N^* hadr. coupl. are varied fixed D_{33} (1700) hadr. couplings</p>	<p>$N\pi$ $Q^2=0$, CLAS M.Dugger, et al., PRC 79,065206 (2009).</p>
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- $\pi^+\pi^-\rho$ electroproduction channel provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy.

- for the first time they were determined varying both electrocouplings and $\pi\Delta$, $\rho\rho$ hadronic decay widths of all aforementioned resonances.

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



Hadronic Decays of $D_{33}(1700)$ -state from the CLAS $\pi^+\pi^-p$ Electroproduction Data

	Analysis of the CLAS $\pi^+\pi^-p$ electroproduction data (preliminary)	RPP results ¹
Total decay width, MeV	342±40	200-400
$\pi\Delta$ Branching Fraction, %	68-100	30-60
$\rho\rho$ Branching Fraction, %	1.5-10	30-55

¹ Review of Particle Physics, Phys. Rev. D86, (2012).

- Restriction: N^* hadronic parameters should be the same at different photon virtualities Q^2 .
- The CLAS $\pi^+\pi^-p$ electroproduction data extended available knowledge on hadronic decays of high-mass resonances.

Conclusions and Outlook

- **High quality $\pi^+\pi^-p$ electroproduction data from the CLAS allowed us to determine electrocouplings of most resonances in the mass range $W < 1.8$ GeV and at photon virtualities $Q^2 < 1.5$ GeV² for the first time.**
- **Consistent results on electrocouplings of $P_{11}(1440)$ and $D_{13}(1520)$ states obtained from independent analyses of $N\pi/N\pi\pi$ channels confirmed reliable extraction of these fundamental quantities and capability of the JM model for the reliable extraction of resonance parameters.**
- **The resonant/non-resonant amplitudes of the meson-baryon channels derived from the fit of the $\pi^+\pi^-p$ electroproduction data can be employed in a global multi-channel analyses of meson photo-, electro-, and hadroproduction data.**
- **Electrocouplings of most N^* -states in mass range up to 2.0 GeV will be determined in few years from independent analyses of $N\pi$ and $N\pi\pi$ electroproduction at $Q^2 < 5.0$ GeV², allowing us to explore the evolution of resonance structure with the excited state quantum numbers at the distances where the transition to dominance of quark degrees of freedom occurs.**



Outlook

- Extension of the JM model with a goal of determining N^* parameters at the pole singularities. Help from the experts in coupled channel approaches is appreciated.



Back up



CEBAF Large Acceptance Spectrometer

Torus magnet

6 superconducting coils

Liquid D₂ (H₂)target +

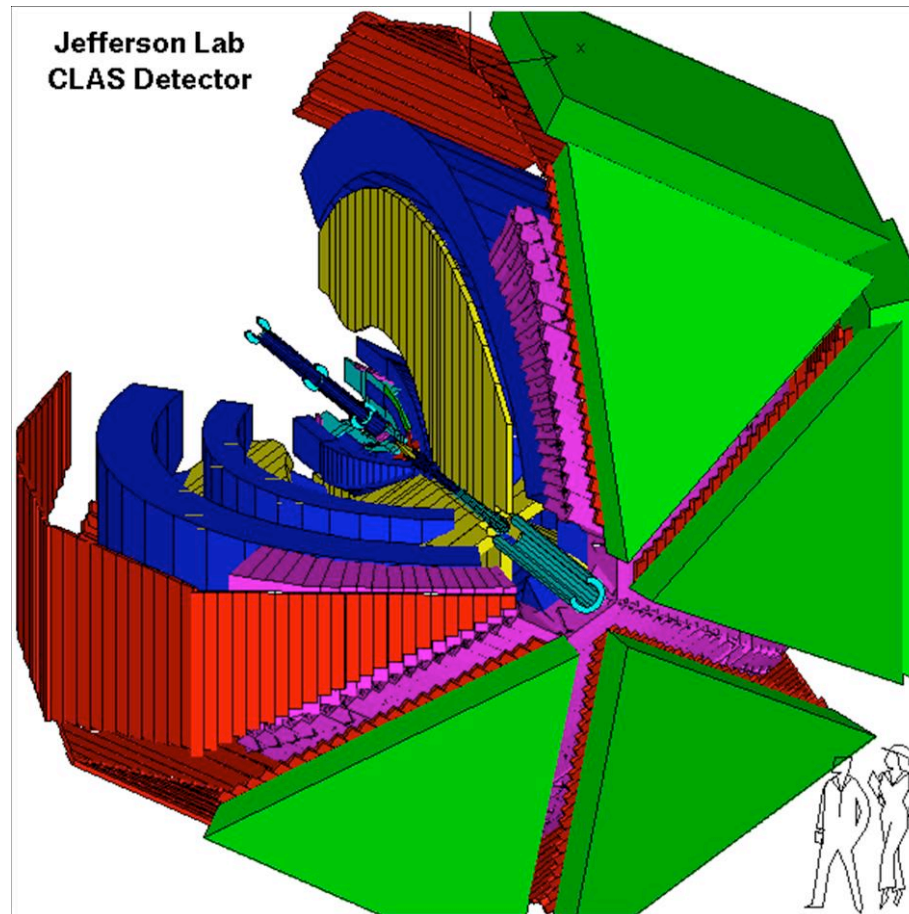
γ start counter; e minitorus

Drift chambers

argon/CO₂ 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 $Q^2 < 5.0$ GeV².



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	1.1-1.40 1.1-1.55 1.1-1.7	0.15-0.40 0.3-0.6 1.7-4.2	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega, A_b$
π^0p	1.1-1.40 1.1-1.7 1.1-1.7	0.15-0.40 0.4-0.7 0.75-6.0	$d\sigma/d\Omega$ $d\sigma/d\Omega, A_b, A_t, A_{bt}$ $d\sigma/d\Omega$
ηp	1.5-2.0	0.2-4.0	$d\sigma/d\Omega$
$K^+\Lambda$	1.65-2.35 1.65-2.35	0.65-2.55 1.4-2.6	$d\sigma/d\Omega$ P'
$K^+\Sigma^0$	1.7-2.1 1.8-2.5 1.7-2.6	0.5-2.55 1.5-3.50 1.8-3.50	$d\sigma/d\Omega$ P' $d\sigma/d\Omega$
$\pi^+\pi^+p$	1.3-1.6 1.4-2.1	0.2-0.6 0.5-1.5	Nine 1-fold differential cross sections

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

The data are available in the CLAS Physics Data Base:

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



Non-resonant contributions in $\rho\rho$ meson-baryon channel

Diffractive ansatz from J. D. Bjorken, PRD3, 1382 (1971).

$$T_{diff} = iA e^{bt}$$

Good approximation for $t < 1.0 \text{ GeV}^2$;
at larger t full $\rho\rho$ amplitudes are dominated by N^*

$$t = (\mathbf{P}_{p'} - \mathbf{P}_{\gamma'})^2$$

$b = b(L_{fluct})$ from D.G.Cassel et al, PRD 24, 2878 (1981).

Special approach allowing us to account for r-line shrinkage at $W < 1.8 \text{ GeV}$:

$$A(W, Q^2) = A(Q^2) (1 - e^{-(W-1.41)/D})$$

$$L = 0.77 \text{ GeV} \quad A = 12$$
$$D_\lambda = 0.30 \text{ GeV} \quad D = 0.25 \text{ GeV}$$

$$A(Q^2) = \frac{A_0}{(1 + Q^2 / \Lambda^2(W))}$$

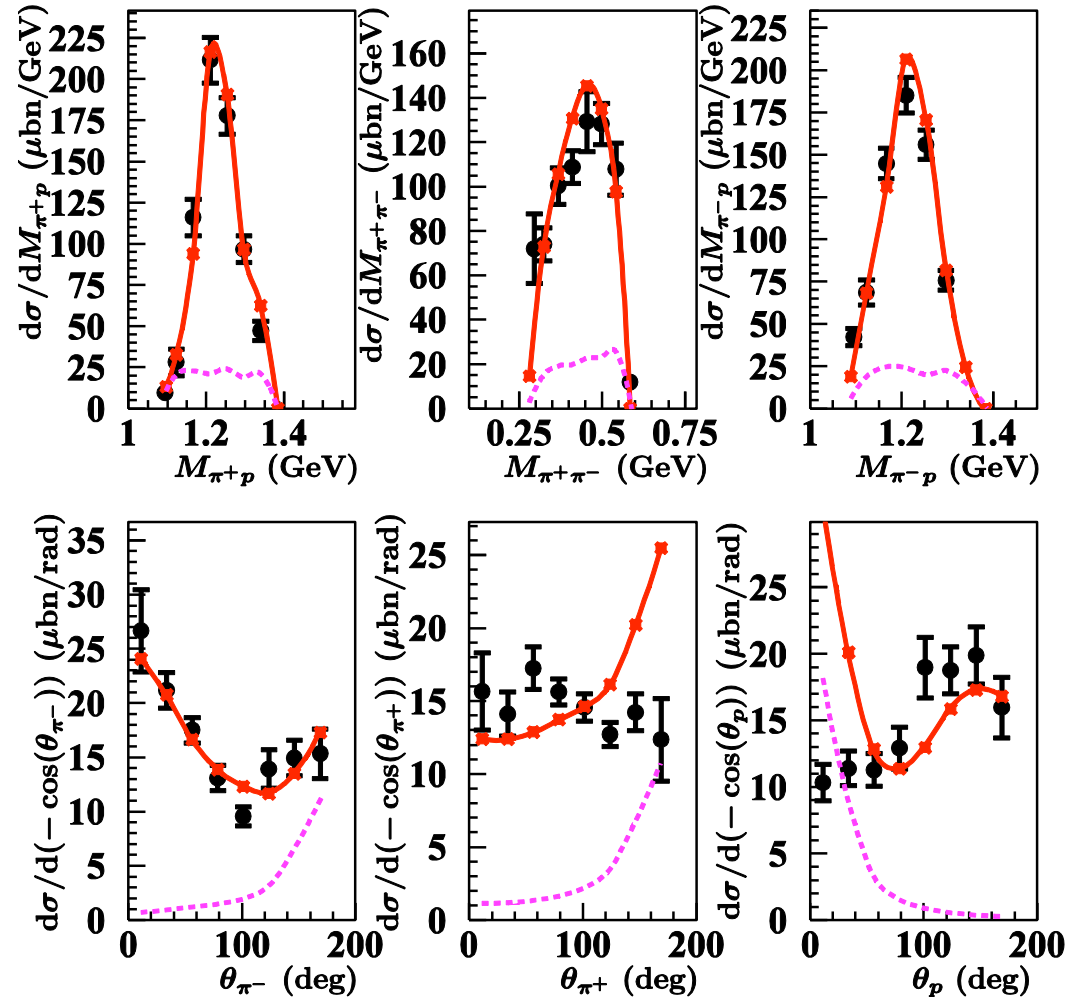
$$\Lambda(W) = \Lambda_0 (1 - e^{-(W-1.41)/D_\lambda})$$

**See details in:
N.V.Shvedunov et al, Phys of
Atom. Nucl. 70, 427 (2007).**

Need for Further Improvements in Description of Direct 2π Production

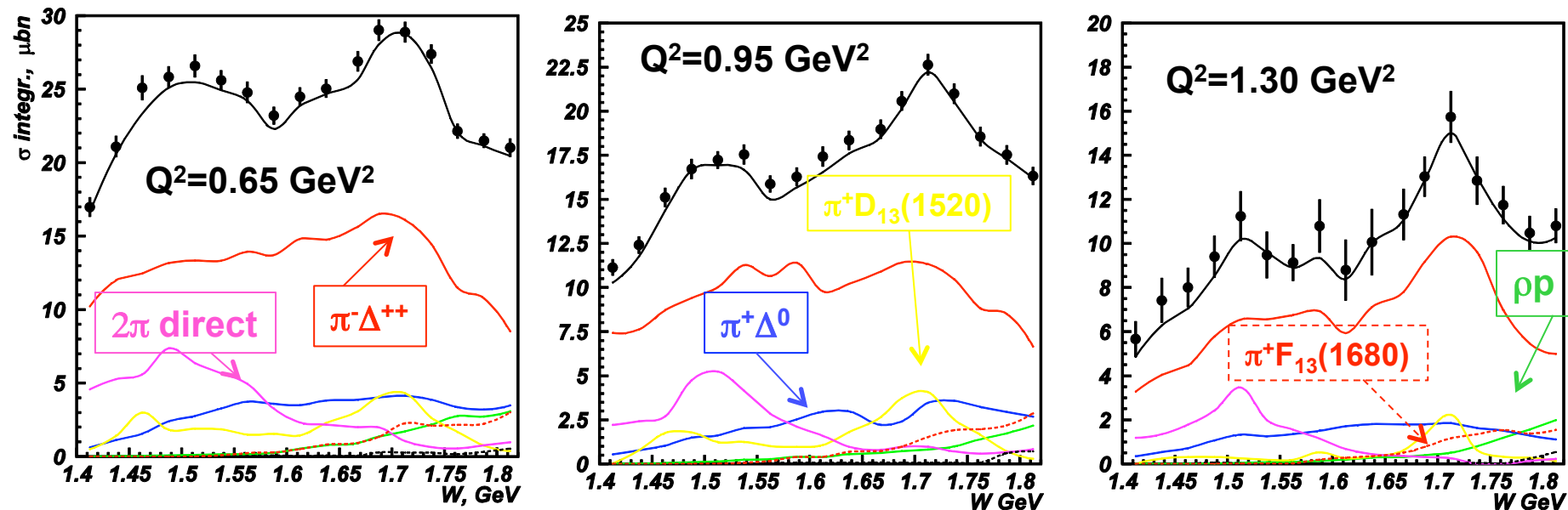
— full JM
 - - - 2π direct

W=1.51 GeV Q²=0.43 GeV²



failure in description of angular distributions is related to the shortcomings in parameterization of direct 2π production

Integrated Cross Sections of the Meson-Baryon Channels Contributing to $\pi^+\pi^-p$ Electroproduction



- $\pi^-\Delta^{++}$ 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 .
- The meson-baryon channels incorporated into the JM model becomes relevant in the following W -areas:

Channel	$\pi^-\Delta^{++}$	$\pi^-\Delta^0$	$\pi^-\text{D}_{13}(1520)$	$\pi^-\text{F}_{15}(1680)$	$\pi^-\text{P}_{33}(1600)$	$\rho\rho$	2π direct
W , GeV	>1.21	>1.21	>1.45	>1.60	>1.70	>1.70	>1.21

- 2π direct production decreases substantially at W from 1.5 to 1.7 GeV offering an indication for sizable transition amplitudes between the final $\pi^+\pi^-p$ state and open meson-baryon channels.

Fitting Procedures

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

- $\gamma_V NN^*$ electrocouplings with σ -parameter equal to 30% from their initial values, taken from interpolation of the CLAS/world data;
 - $\pi\Delta$ and ρp hadronic decays decomposed over LS p.w for part of N^* 's with σ -parameters, that cause total N^* width float slightly above RPP ranges;
 - magnitudes of complementary contact terms in $\pi\Delta$ isobar channels; magnitudes of the $\pi^+D_{13}^0(1520)$, $\pi^+F_{15}^0(1685)$, $\pi^-P_{33}^{++}(1620)$ isobar channel amplitudes; magnitudes of direct 2π production mechanisms ; the respective σ -parameters were chosen 10 -30 % from the starting magnitude values
- $\chi^2/d.p.$ fit of nine 1-fold diff. cross sections in each bin of W and Q^2 were carried out . Closest to the data calculated cross sections were selected with $\chi^2/d.p. < \chi^2/d.p._{thr.}$ The $\chi^2/d.p._{thr.}$ were defined so that selected in the fit calculated cross sections are inside the uncertainties of measured cross sections for a major part of the data points.

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



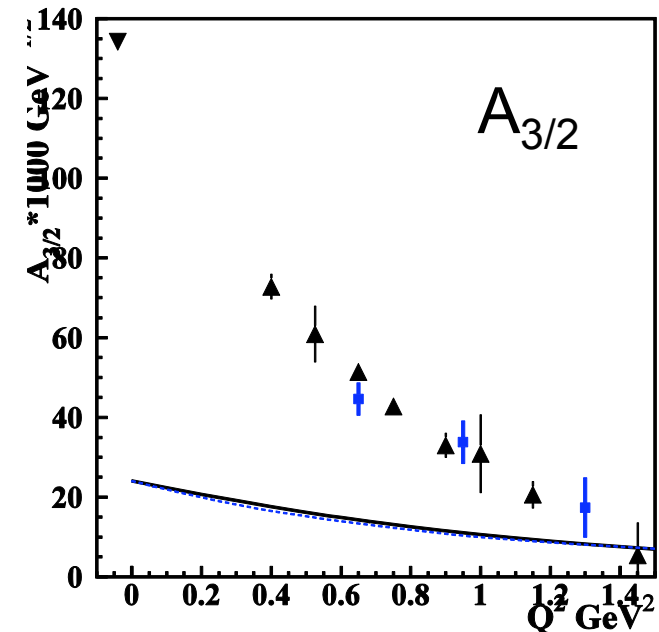
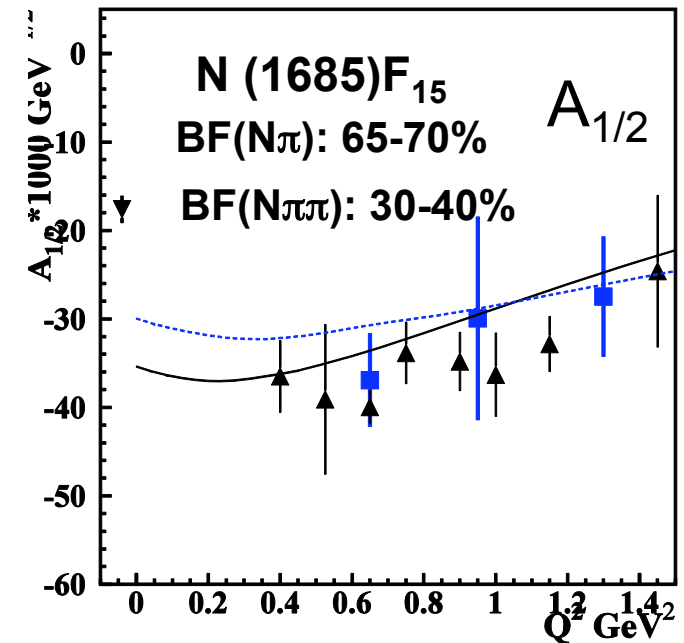
MAID analysis of $N\pi$ electroproduction
L.Tiator et al., Eur. Phys. J. Spec. Top.
198, 141 (2011).

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

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

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

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



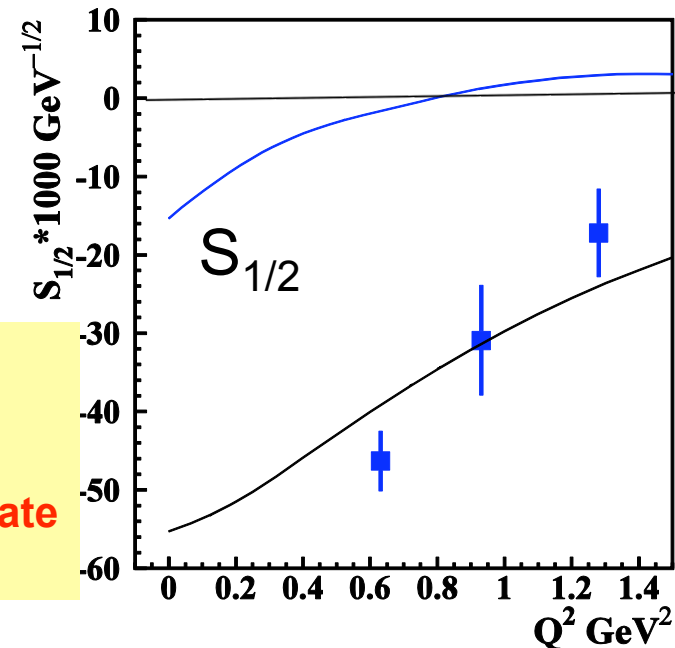
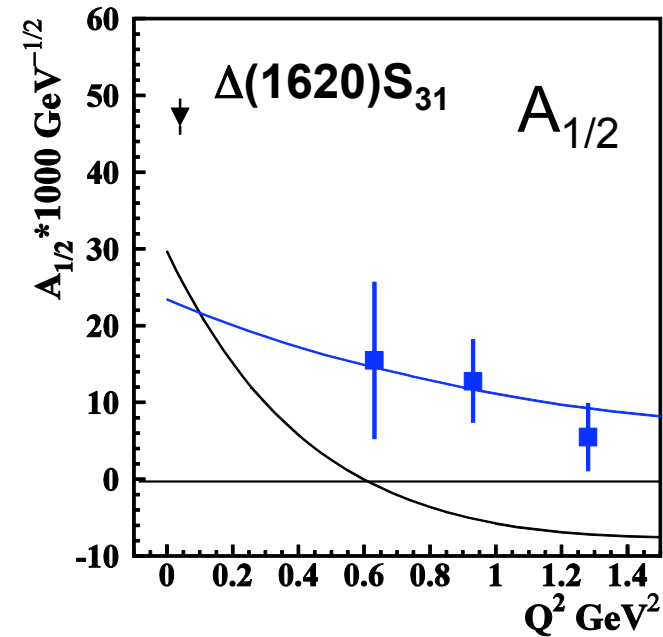
High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

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

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

Only known N^* -state with dominant longitudinal electroexcitation at $Q^2 > 0.5 \text{ GeV}^2$.

- The studies of elastic form factors, partonic structure functions, and transition $\gamma_\nu NN^*$ -electrocouplings of all prominent resonances are needed in order to explore the mechanisms of the ground and excited nucleon state formation from quarks and gluons.



Signals from N^* states in the CLAS KY electroproduction data

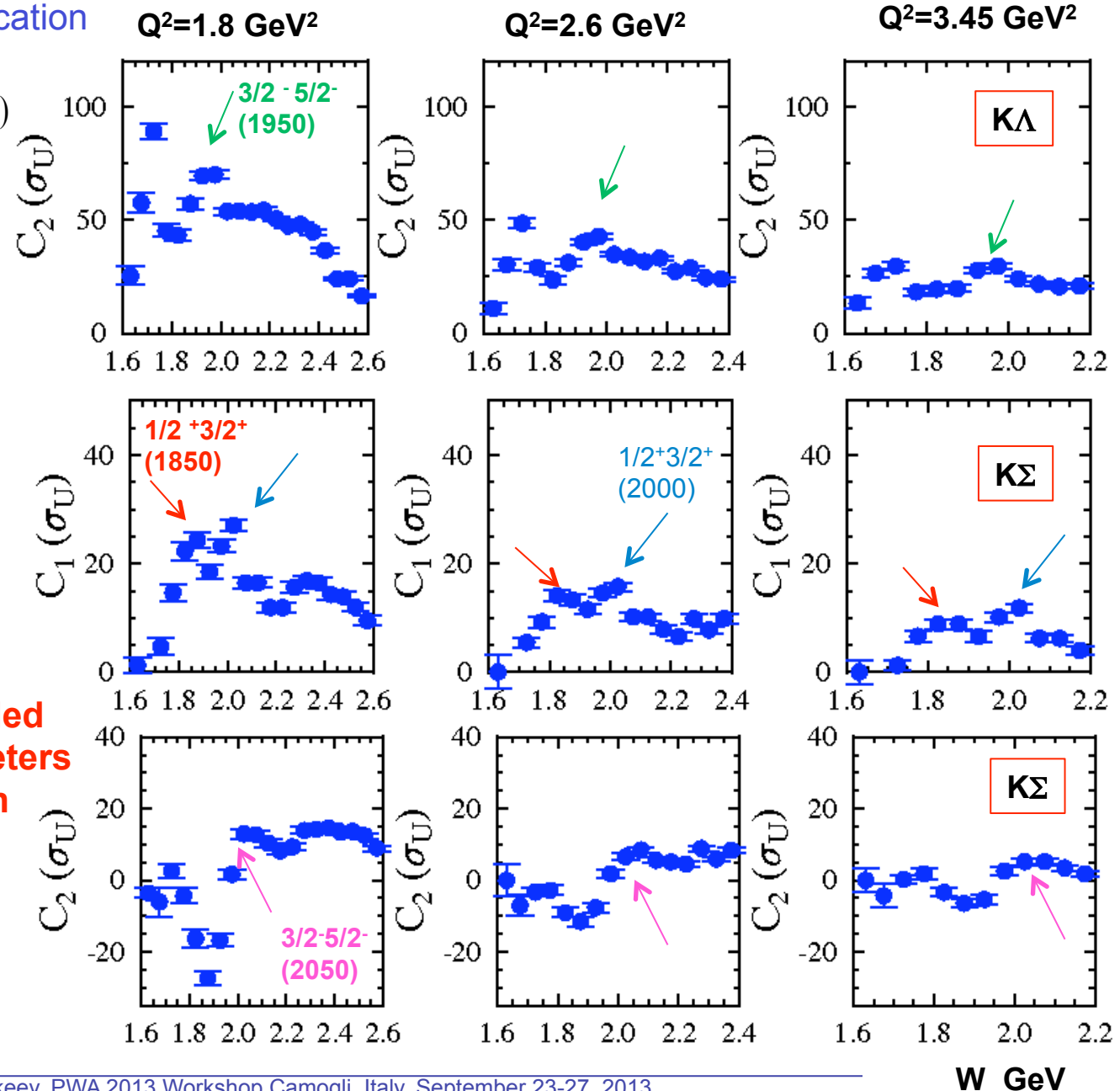
D.Carman, private communication

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

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

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



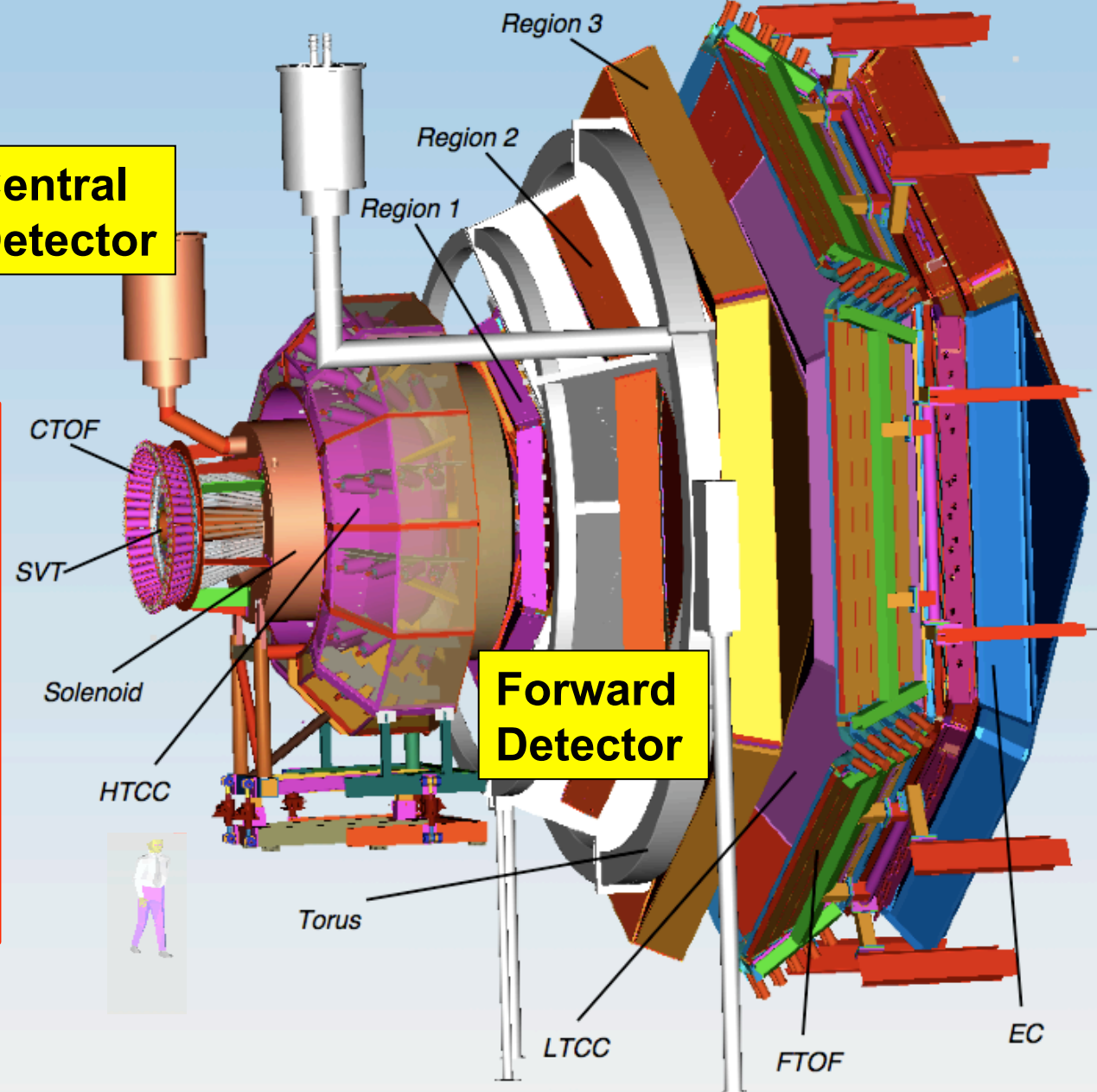
CLAS12

**Central
Detector**

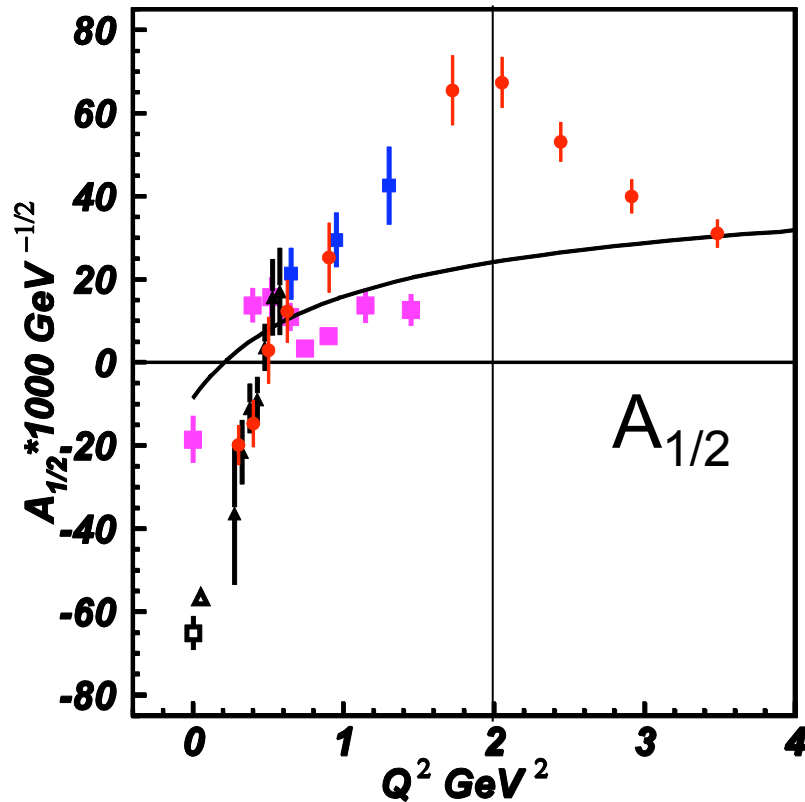
CLAS12 supports a broad program in hadronic physics.

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 .**



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



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

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

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

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

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

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

Consistent results on the quark core contribution from:

— DSEQCD.



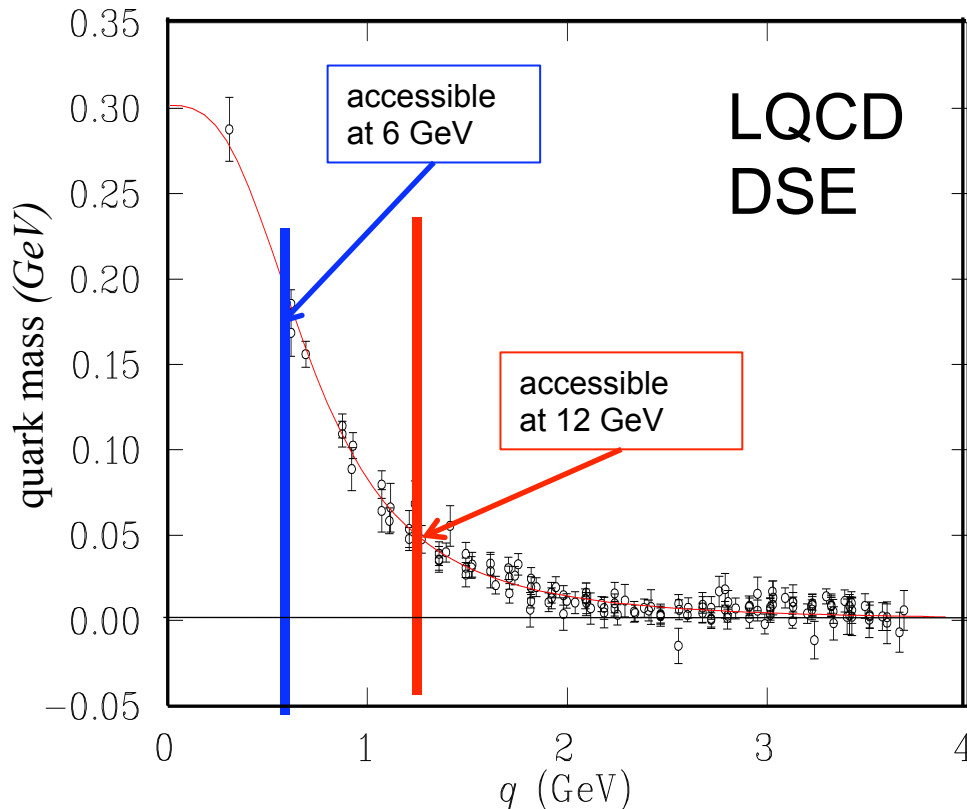
global meson photo-, electro-, and hadroproduction data analysis within EBAC/ Argonne-Osaka approach.

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

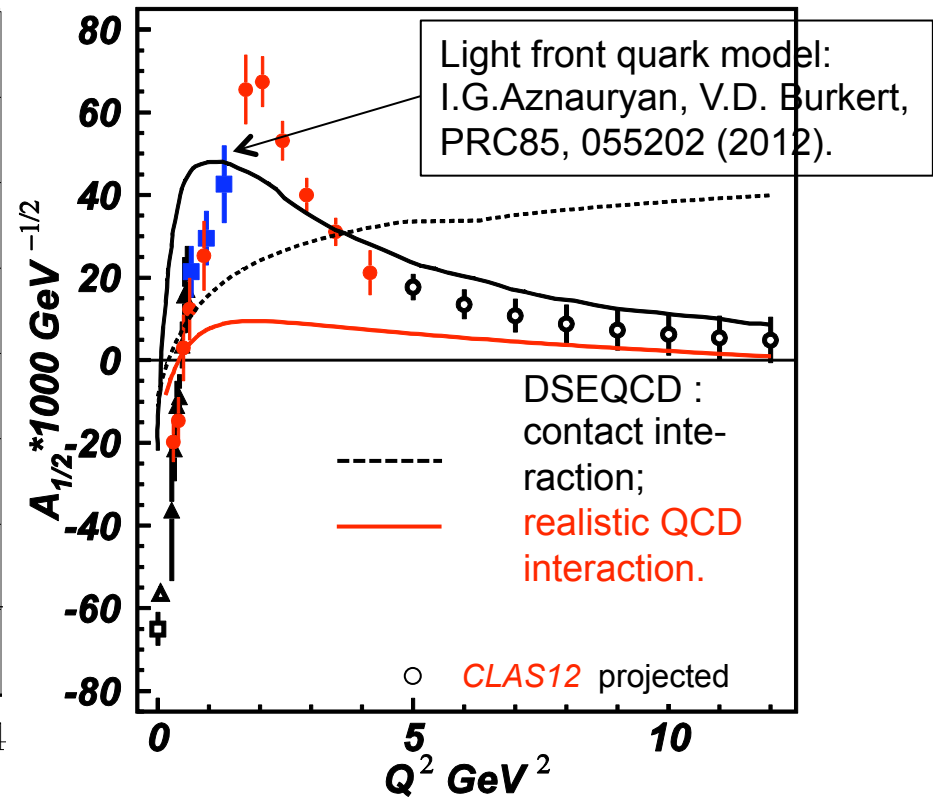
Resonance Transitions with the CLAS12

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 $Q^2=12\text{GeV}^2$.



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



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.

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

- I. G. Aznauryan, A. Bashir, V. Braun, S.J. Brodsky, V.D. Burkert, L. Chang, Ch. Chen, B. El-Bennich, I.C. Cloët, P.L. Cole, R.G. Edwards, G.V. Fedotov, M.M. Giannini, R.W. Gothe, F. Gross, Huey-Wen Lin, P. Kroll, T.-S.H. Lee, W. Melnitchouk, V.I. Mokeev, M.T. Peña, G. Ramalho, C.D. Roberts, E. Santopinto, G F. de Teramond, K. Tsushima, D.J. Wilson

27 authors – 99 pages

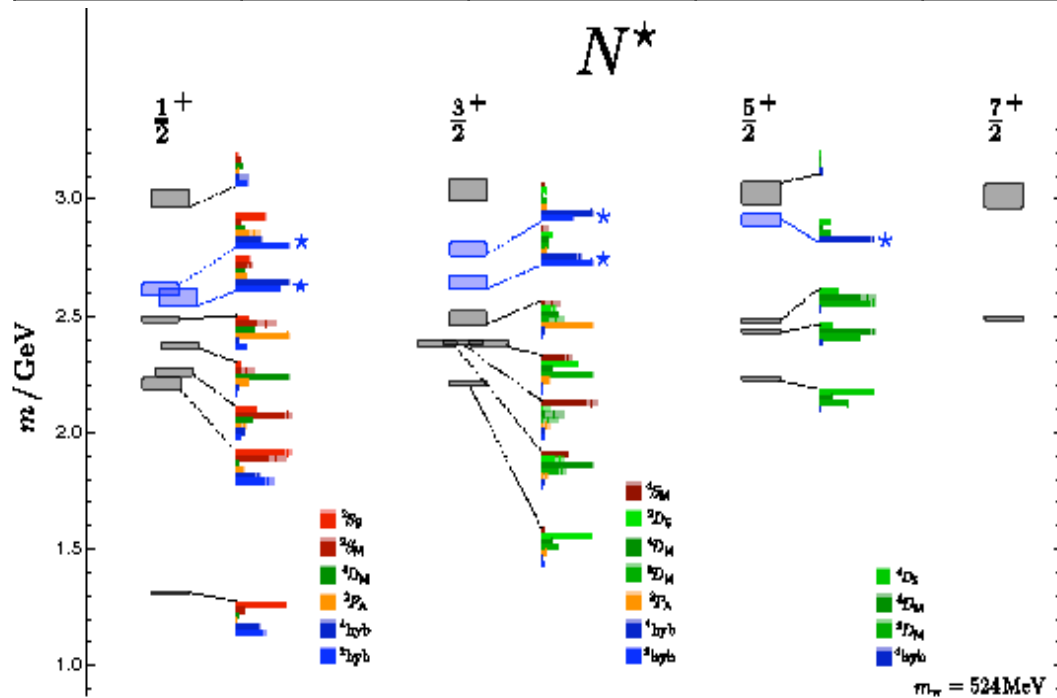
- Will be published in Int. J. Mod. Phys. E22, 1330015 (2013).

<http://arxiv.org/abs/1212.4891>

Why studies of ground and excited nucleon states combined are needed?

Di-quark J_π	Ground state	P_{11} $\frac{1}{2}^+(1440)$	S_{11} $\frac{1}{2}^-(1535)$	S_{11} $\frac{1}{2}^-(1650)$
0^+	77%			
1^+	23%	100%		
0^-			51%	43%
1^-			49%	57%

Di-quark content of ground and N^* states from DSEQCD with vector x vector interaction, C.D.Roberts et al., AIP Conf. Proc. 1432, 309 (2012).



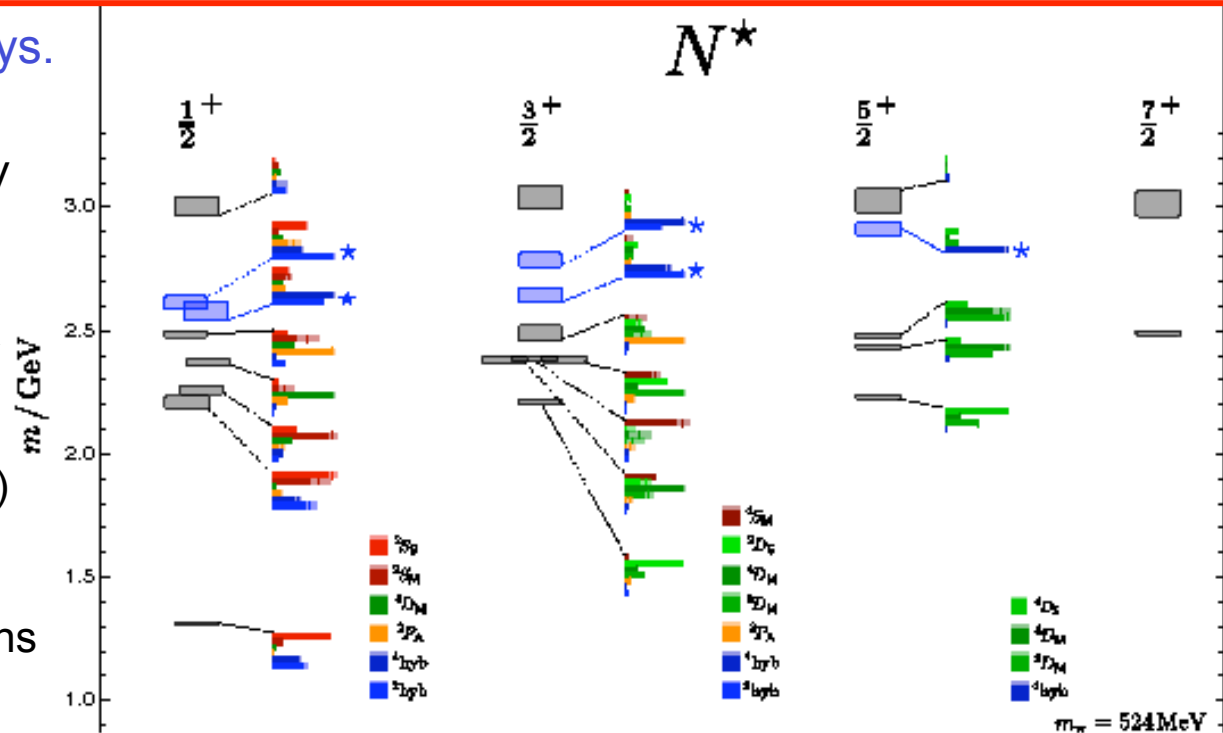
N^* spectrum and structure from LQCD, J.J.Dudek, R.G.Edwards, Phys. Rev. D85, 054016 (2012).

- N^* states of different quantum numbers offer complementary information on mechanisms of baryon generation from quarks and gluons.
- N^* electrocouplings allow us to explore strong regime of QCD at larger transverse distances with larger α_s than the ground state form factors.

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 $\gamma_V NN^*$ electrocouplings, which reflects presence of the hybrid component.**



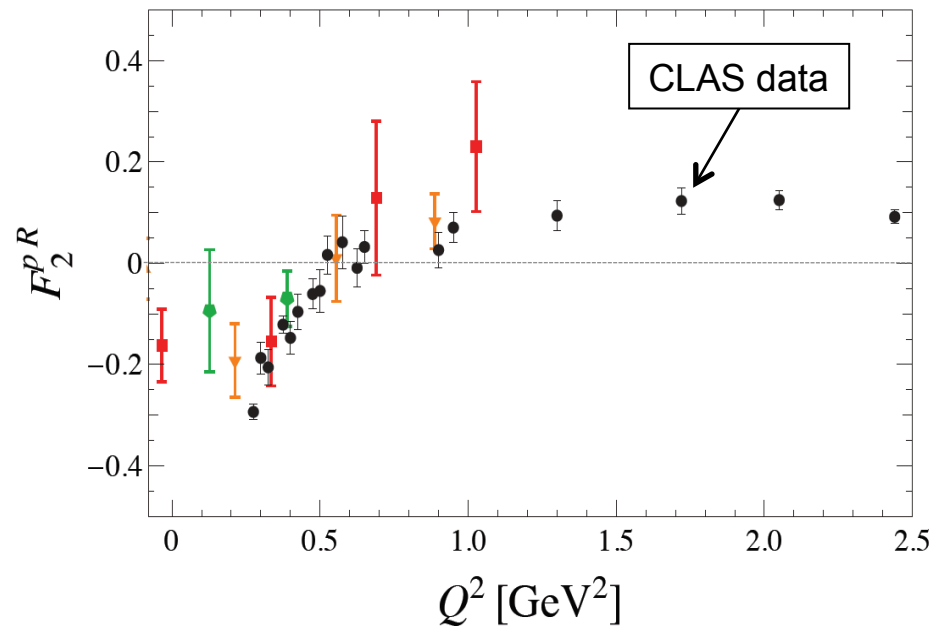
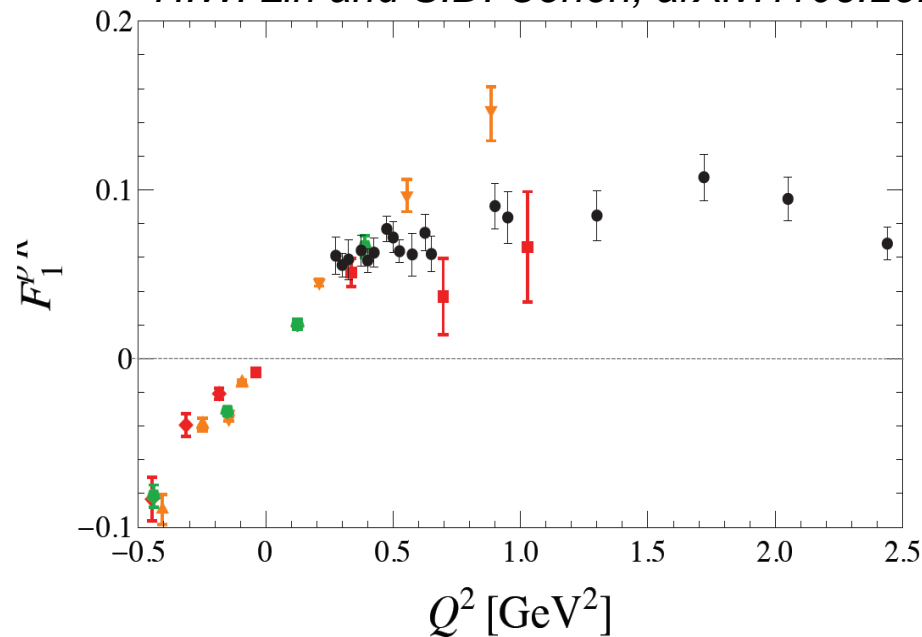
Transition $N-P_{11}(1440)$ form factors in LQCD

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

$$A_{1/2}, S_{1/2} \Rightarrow F_1^*, F_2^*$$

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

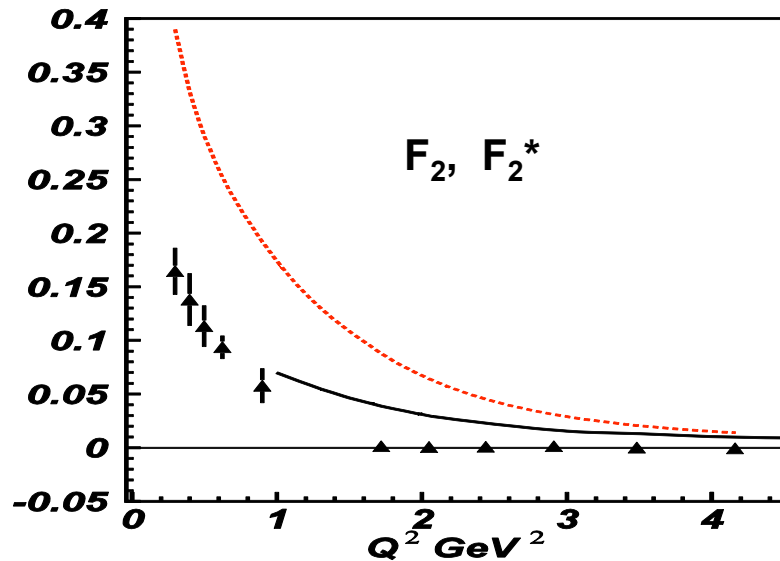
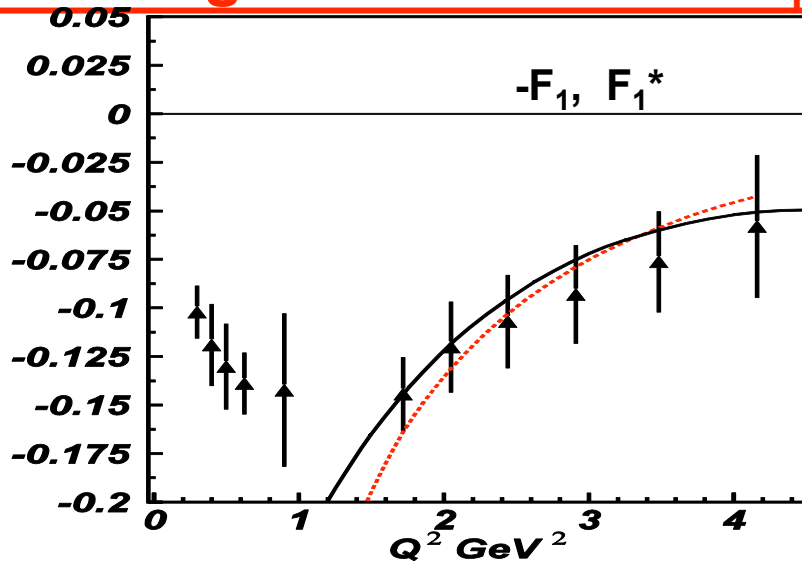
$$M_\pi = 390, 450, 875 \text{ MeV}$$
$$L \text{ box} = 3.0, 2.5, 2.5 \text{ f}$$



• 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:

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

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

$1/2^+ \rightarrow 1/2^-$ 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^* $p \rightarrow S_{11}(1535)$ 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.

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]

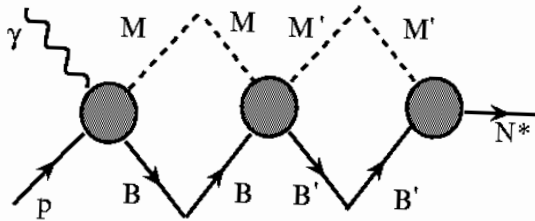
1. D.S. Carman et al., (CLAS Collaboration), Phys. Rev. C79, 065205 (2009).
2. R. Nasseripour et al., (CLAS Collaboration), Phys. Rev. C77, 065208 (2008).
3. P. Ambrozewicz et al., (CLAS Collaboration), Phys. Rev. C75, 045203 (2007).
4. D.S. Carman et al., (CLAS Collaboration), Phys. Rev. Lett. 90, 131804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



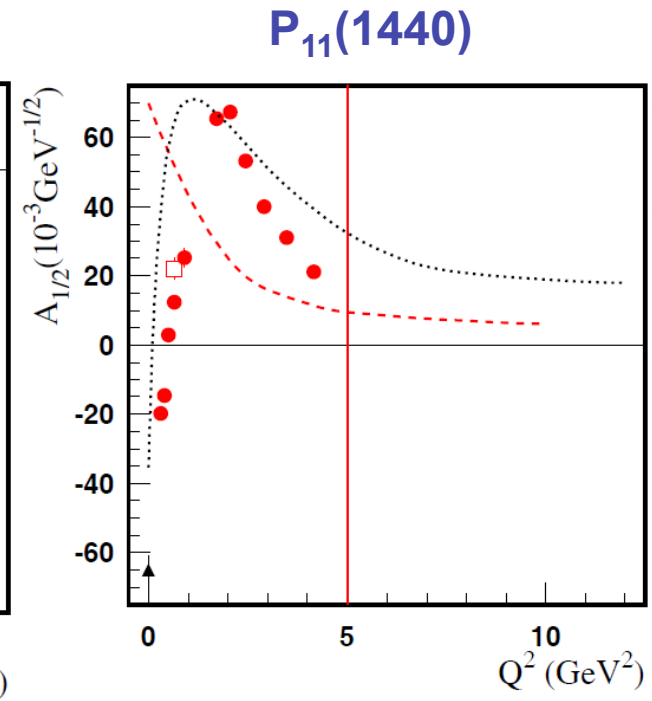
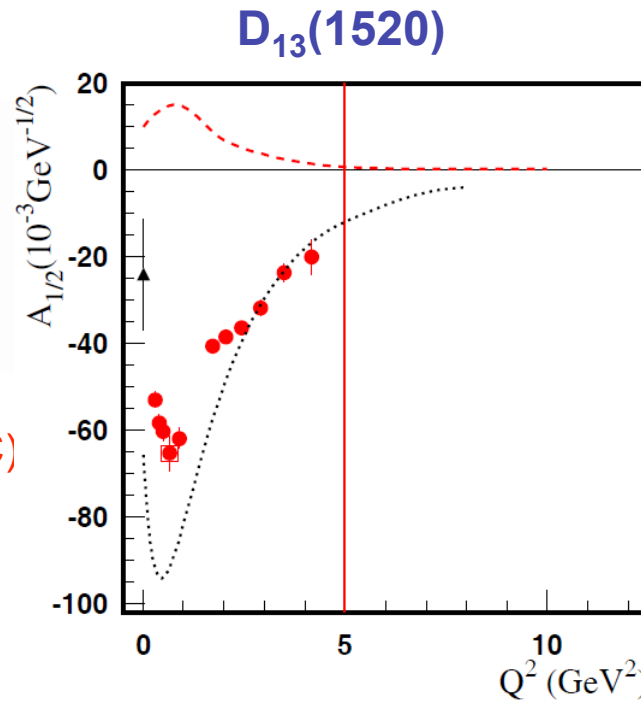
$\gamma_V NN^*$ Electrocouplings: A Unique Window into the Quark Structure

Meson-Baryon Dressing



--- absolute meson-baryon cloud amplitudes (EBAC)

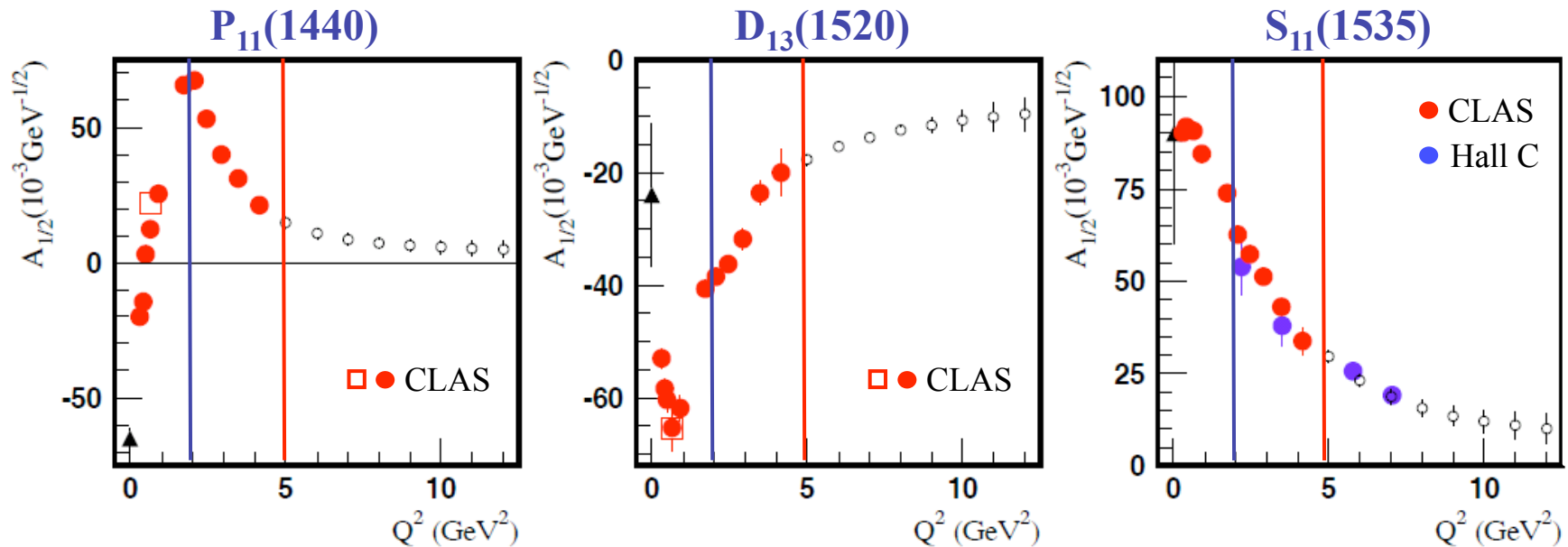
..... quark core contributions (constituent quark models)



CLAS: $N\pi$ and $N\pi/N\pi\pi$ combined

Data on $\gamma_V NN^*$ electrocouplings from E12-09-003 experiment ($Q^2 > 5 \text{ GeV}^2$) will afford for the first time direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent N^* formation.

Anticipated N^* Electrocouplings from data on $N\pi$ & $N\pi\pi$ electroproduction



Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- Examples of **published and projected results** obtained within 60d for three prominent excited proton states from analyses of $N\pi$ and $N\pi\pi$ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, ...
- This experiment will – for the foreseeable future – be **the only experiment** that can provide data on $\gamma_N N^*$ electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N^* studies up to Q^2 of 12 GeV^2 .

Studies of the N*-Structure in Exclusive Meson Electroproduction

Our experimental program 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 electro-production channels independently and in global multi-channel analyses.

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

The non-perturbative strong interaction represents the most important part of the Standard Model that we have yet to explore. These are only known fundamental processes for which relevant degrees of freedom accessible in the measurements can be very different with respect to those entered in the basic QCD Lagrangian.

