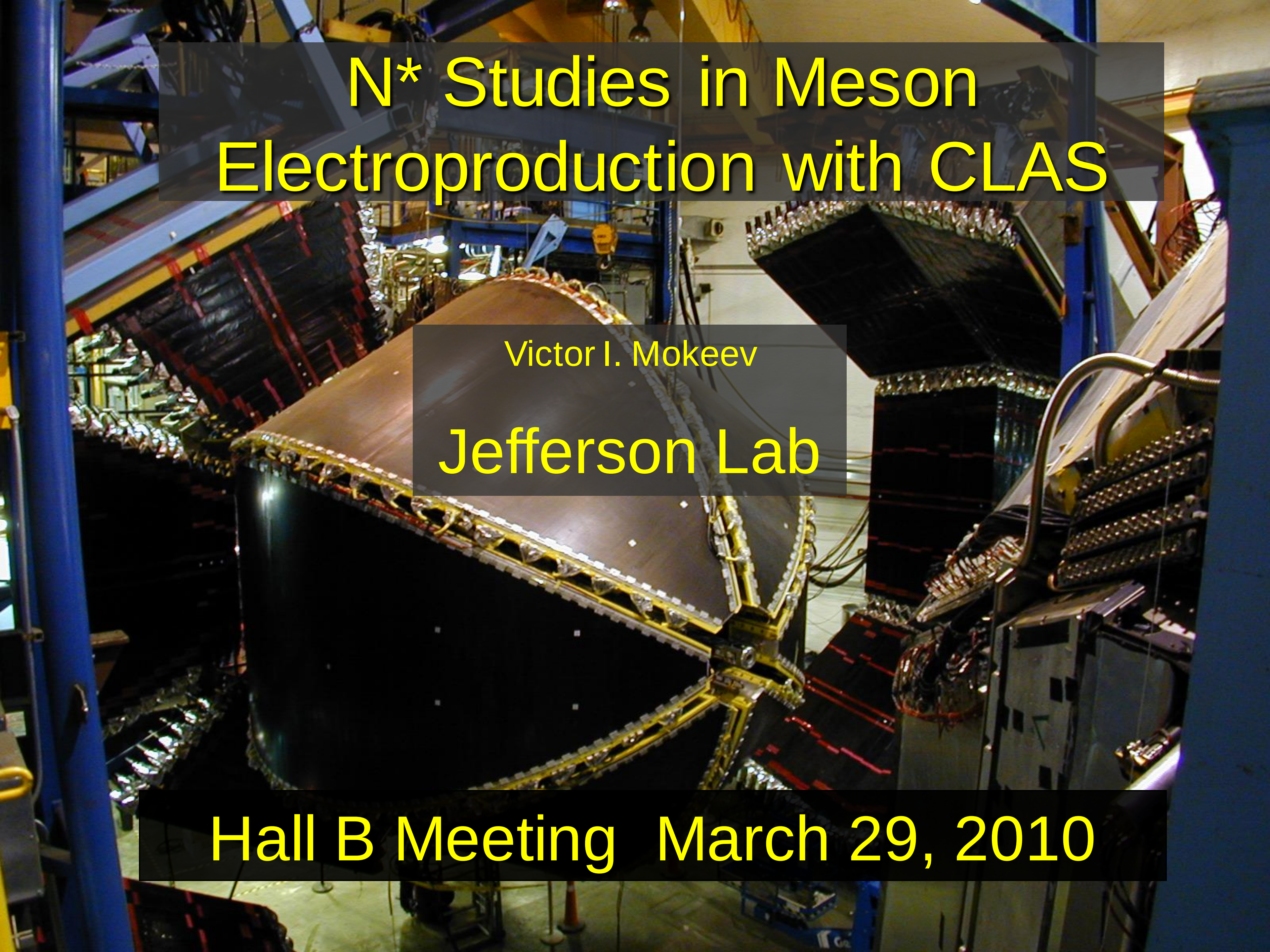

N* Studies in Meson Electroproduction with CLAS

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Jefferson Lab

Hall B Meeting March 29, 2010

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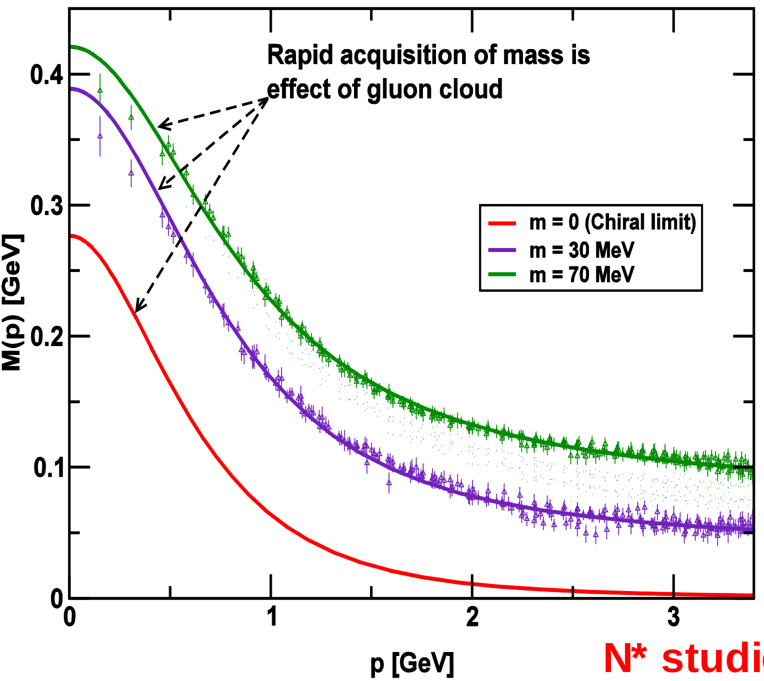
- Introduction
- Analysis tools for evaluation of N* electrocouplings
- New insights into the low lying N* structure from our studies on the $N\pi$ & $N\pi\pi$ CLAS data
- Preliminary results on the studies of high lying proton states (M>1.6 GeV)
- Conclusions and outlook

Primary objectives in the studies of N* structure with CLAS

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 almost all excited proton states analyzing major meson electroproduction channels combined

This comprehensive information allows us to:

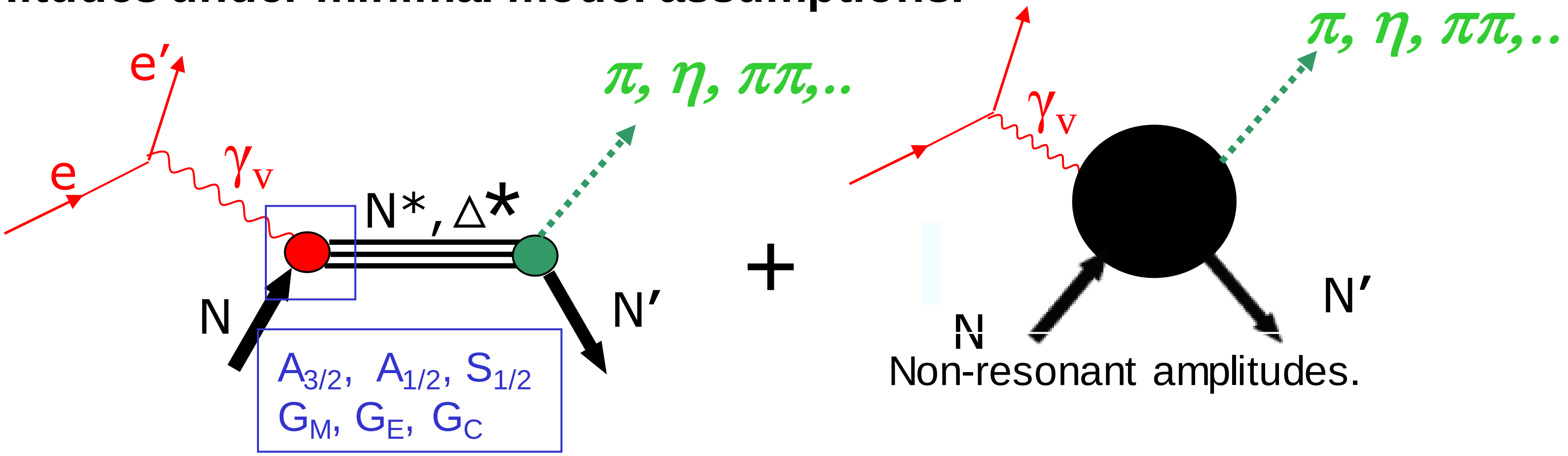


- **pin-down active degrees of freedom in N* structure at various distances;**
- **study the non-perturbative strong interactions which are responsible for nucleon formation and their emergence from QCD;**
- **uniquely access to the origin of more than 97% of nucleon mass generated through dynamical chiral symmetry breaking, and to the behavior of the running strong coupling in the confinement regime.**

N* studies are of key importance for the exploration of non-perturbative strong interactions and quark/gluon confinement

How N* electrocouplings can be accessed

- **Isolate the resonant part of production amplitudes by fitting the measured observables within the framework of reaction models, which are rigorously tested against data.**
- **N* electrocouplings can then be determined from resonant amplitudes under minimal model assumptions.**



Consistent results on N* electrocouplings obtained in analyses of various meson channels (e.g. πN, ηp, $\pi\pi N$) *with entirely different non-resonant* amplitudes will show that they are determined reliably

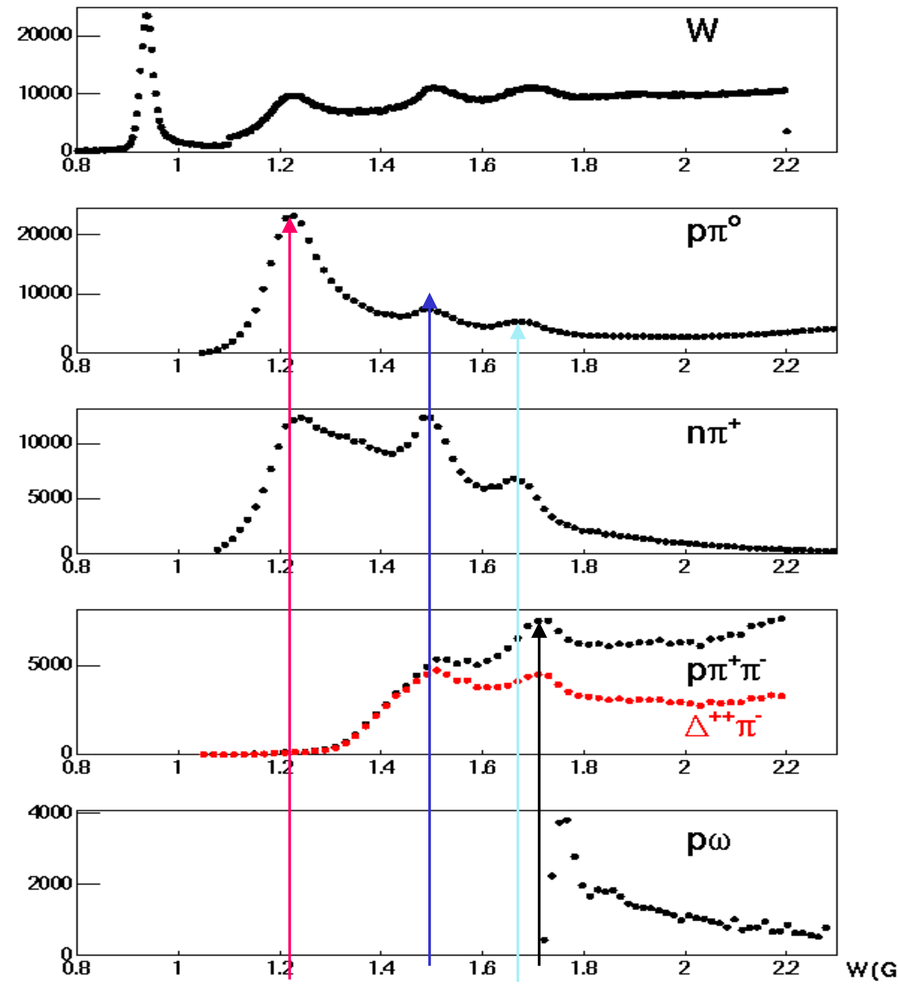
Advanced coupled-channel analysis methods are being developing at EBAC: H.Kamano *et al.*, PRC80, 065203 (2009); N.Suzuki, T.Sato and T-S.H.Lee , arXiv:0910.1742[nucl-th]

Why Nπ/Nππ electroproduction channels are important

- Nπ/Nππ channels are the two major contributors in N* excitation region;
- these two channels combined are sensitive to almost all excited proton states;
- they are strongly coupled by πN→ππN final state interaction;
- may substantially affect exclusive channels having smaller cross sections, such as ηp,KΛ, and KΣ.

Therefore knowledge on Nπ/Nππ electro production mechanisms is key for the entire N* Program

CLAS data on meson electroproduction at $Q^2 < 4.0$ GeV²



$N\pi$ CLAS data at low & high Q^2

Number of data points > 119,000, W < 1.7 GeV

Observable	Q^2 [GeV²]	Number of Data points
$d\sigma/d\Omega(\pi^0)$	0.35-1.6	31 018
$d\sigma/d\Omega(\pi^+)$	0.25-0.65 1.7-4.3	13 264 33 000
$A_e(\pi^0)$	0.40 0.65	956 805
$A_e(\pi^+)$	0.40 0.65 1.7 - 4.3	918 812 3 300
$d\sigma/d\Omega(\eta)$	0.375 0.750	172 412

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).

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

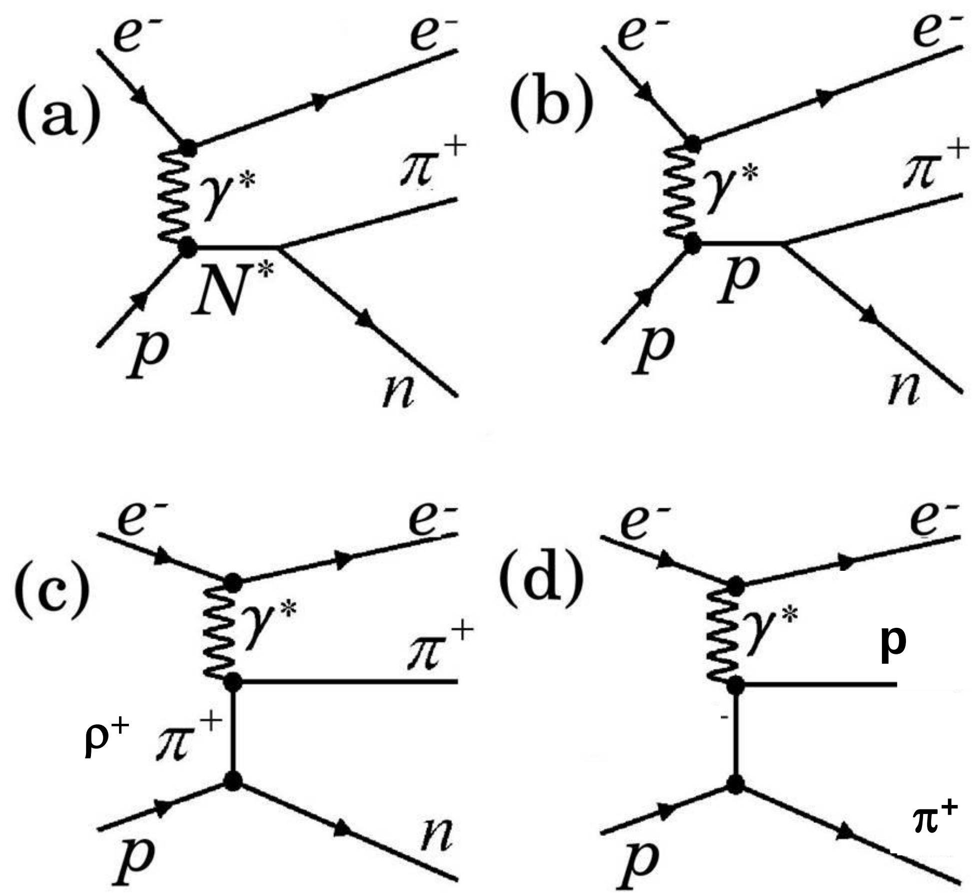
full data set in:
http://clasweb.jlab.org/physicsdb/

Unitary Isobar Model (UIM) for Nπ electroproduction

Non-resonant contributions were described by gauge invariant Born terms:

- pole/reggeized meson *t*-channel exchange;
- *s*- and *u*-nucleon terms.

Final-state πN rescattering was taken into account through the K-matrix approximation



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

Fixed-*t* Dispersion Relations for invariant Ball amplitudes (Devenish &Lyth)

$\gamma^* p \rightarrow N\pi$

Dispersion relations for 6 invariant Ball amplitudes:

17 UnsubtractedDispersion Relations

$$Re B_i^{(\pm,0)}(s,t,Q^2)\left[Re B_3^{(+,0)}(s,t,Q^2)\right] = R_i^{(v,s)}(Q^2)\left(\frac{1}{s-m_N^2}+\frac{\eta_i\eta^{(+,-,0)}}{u-m_N^2}\right) + \frac{P}{\pi}\int_{s_{thr}}^{\infty} Im B_i^{(\pm,0)}(s',t,Q^2)\left(\frac{1}{s'-s}+\frac{\eta_i\eta^{(+,-,0)}}{s'-u}\right)ds'$$

(i=1,2,4,5,6)

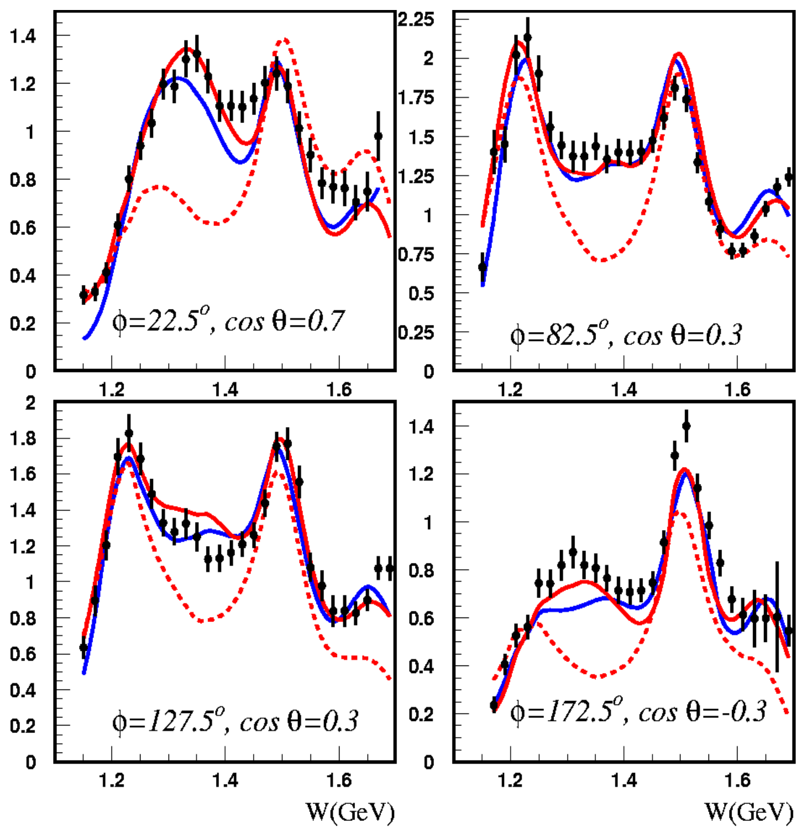
1 Subtracted Dispersion Relation

$$Re B_3^{(-)}(s,t,Q^2) = R_3^{(v)}(Q^2)\left(\frac{1}{s-m_N^2}+\frac{1}{u-m_N^2}\right) - eg\frac{F_\pi(Q^2)}{t-m_\pi^2} + f_{sub}(t,Q^2) + \frac{P}{\pi}\int_{s_{thr}}^{\infty} Im\ B_3^{(-)}(s',t,Q^2)\left(\frac{1}{s'-s}+\frac{1}{s'-u}\right)ds'$$

Fits to Nπ diff. cross sections & structure functions

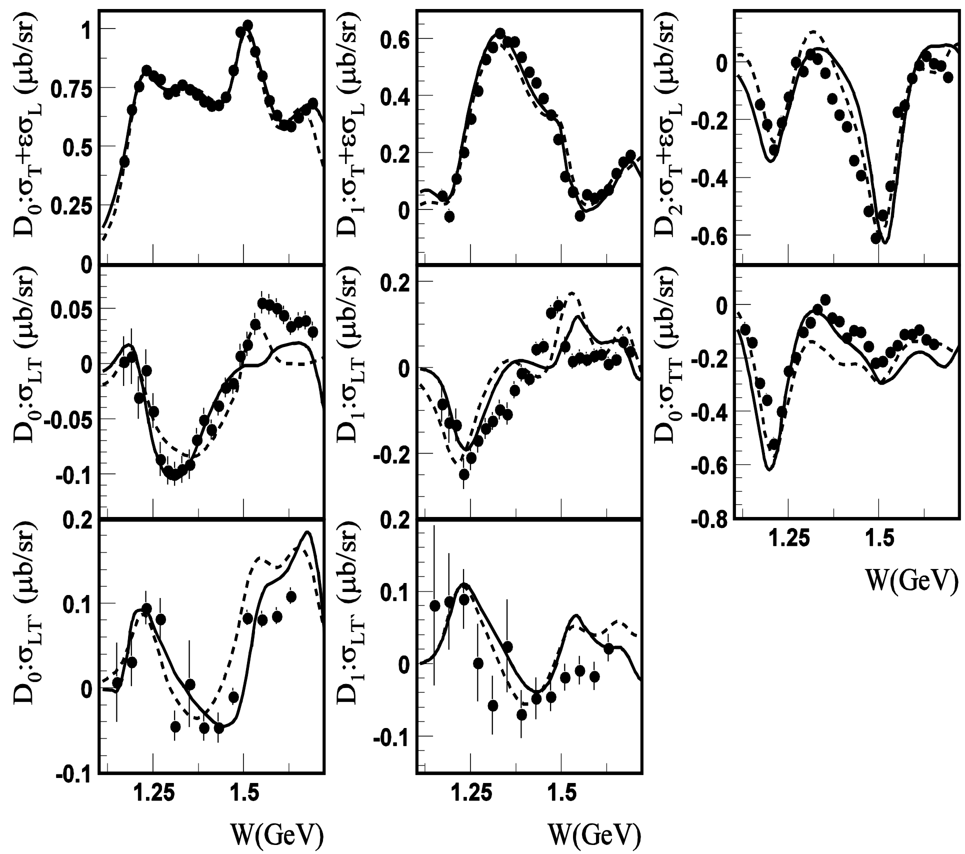
Q^2=2.05 GeV^2

DR
DR w/o P11
UIM



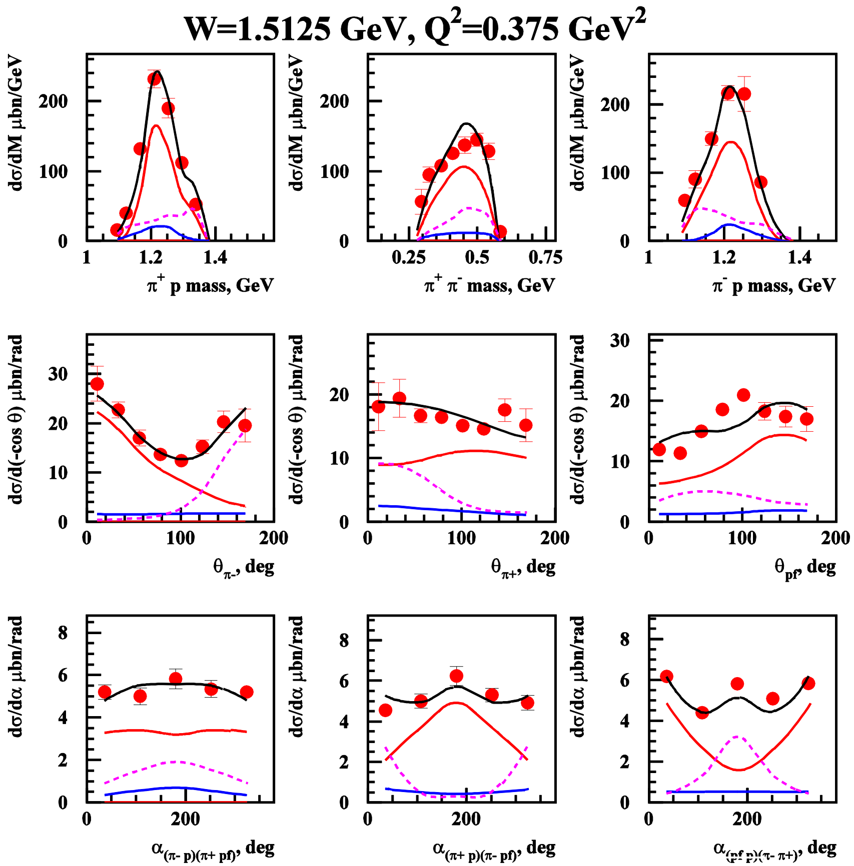
Q^2=2.44 GeV^2

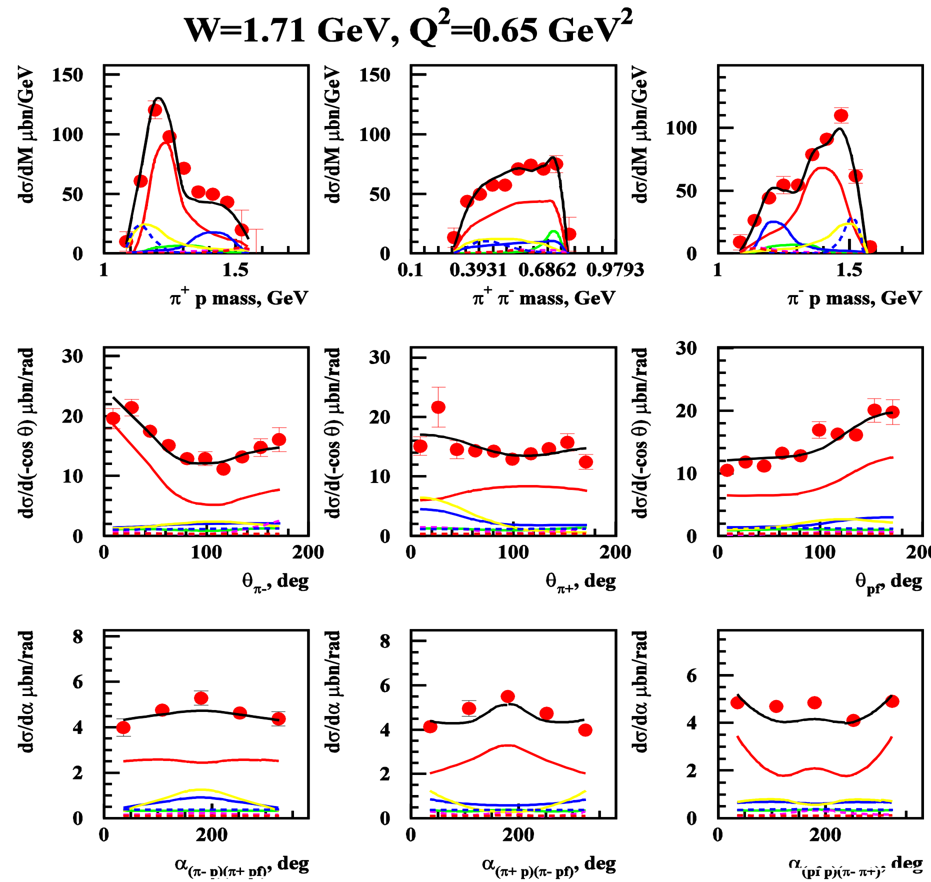
DR
UIM



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

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



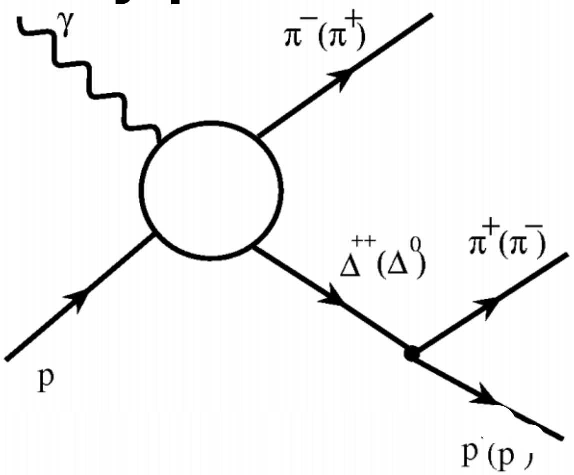


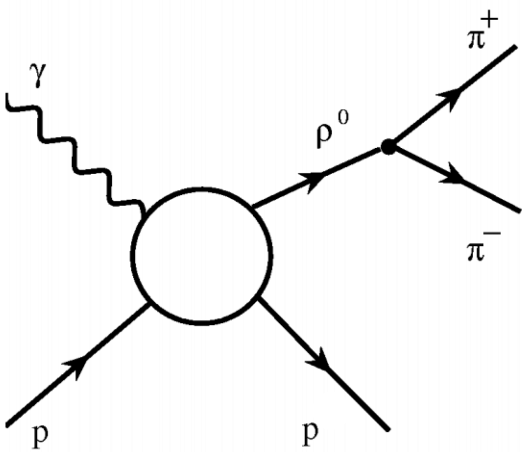
full JM calc. — $\pi^+\Delta^0$ — ρp — $\pi^+F^0_{15}(1685)$

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

JLAB-MSU meson-baryon model (JM) for $N\pi\pi$ electroproduction.

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 & ISI treatment .**
- **Extra $\pi\Delta$ contact term.**

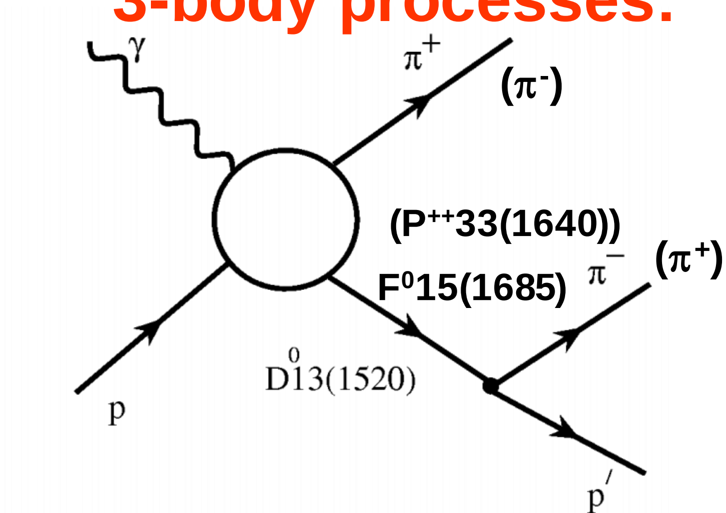
$\rho^0 p$

- **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.**

JM09 version: Unitarized BW ansatz for resonant amplitudes: I.J.R.Aitchison NP A189 (1972), 417

continued

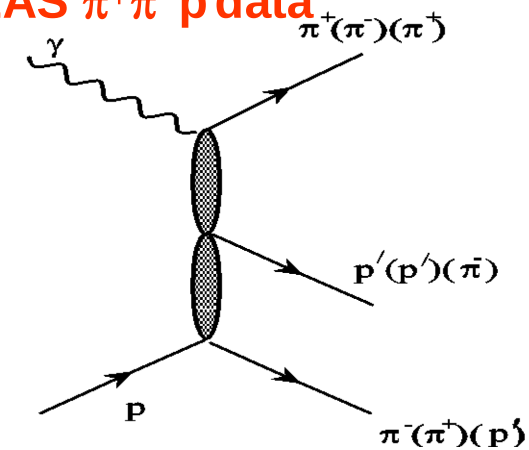
3-body processes:

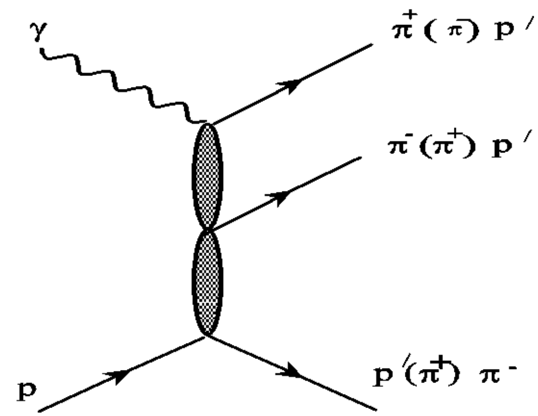


Isobar channels included:

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

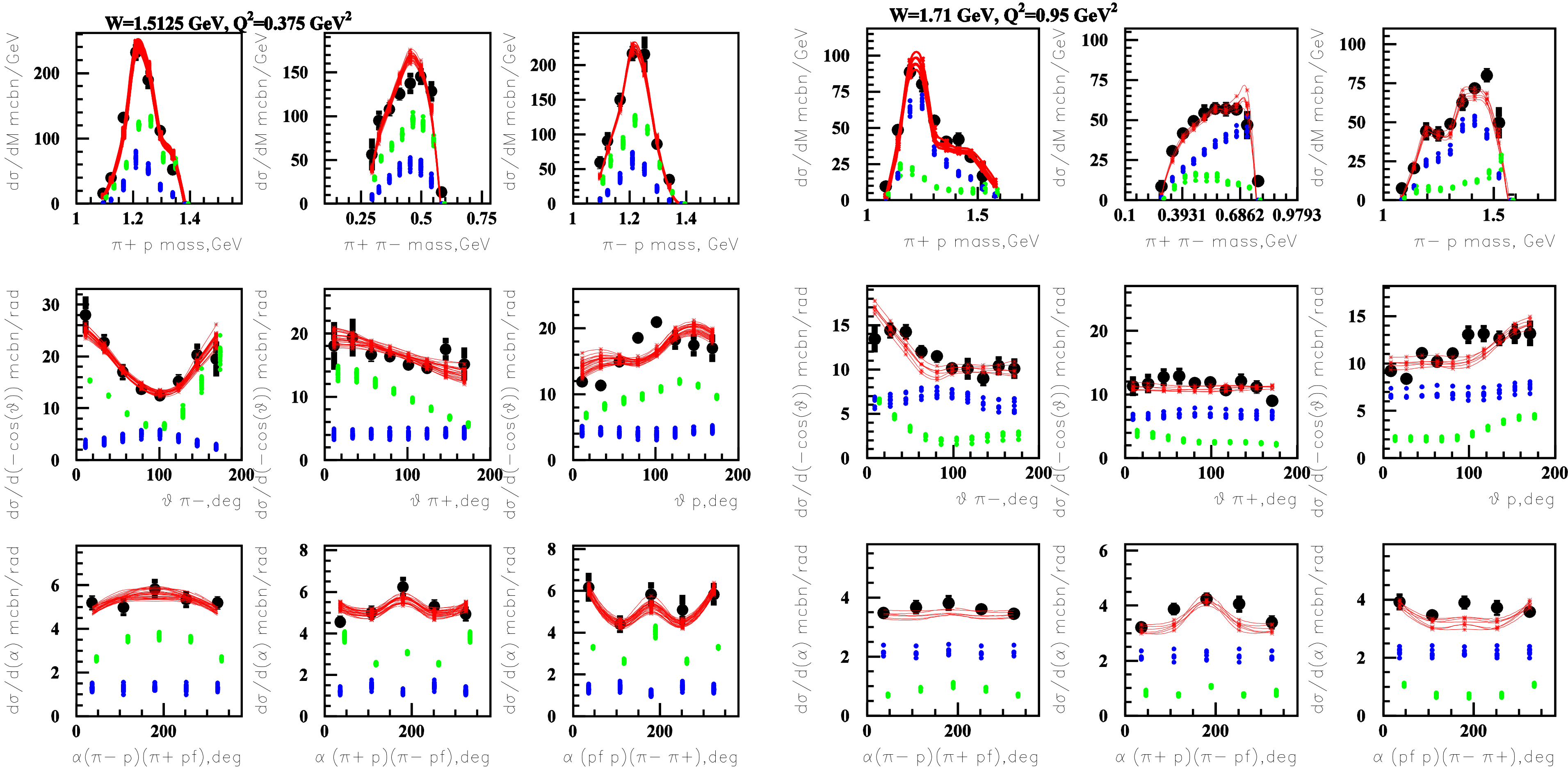
Direct 2π production required by unitarity and confirmed in analysis of the CLAS $\pi^+\pi^-$p data





V. Mokeev, V .Burkert, J. Phys. 69, 012019 (2007);
V. Mokeev *et al*., Phys. Rev. C80, 045212 (2009).

Resonant & non-resonant parts of Nππ cross sections as determined from the CLAS data fit within the framework of JM model



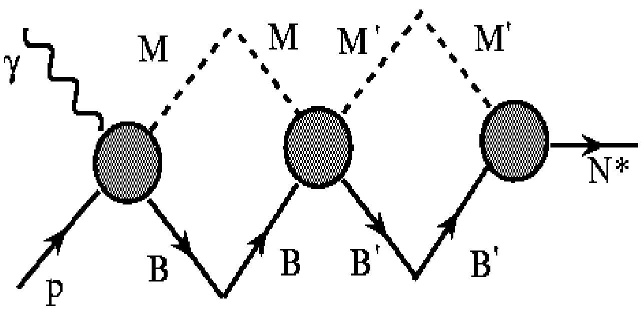
full cross sections

resonant part

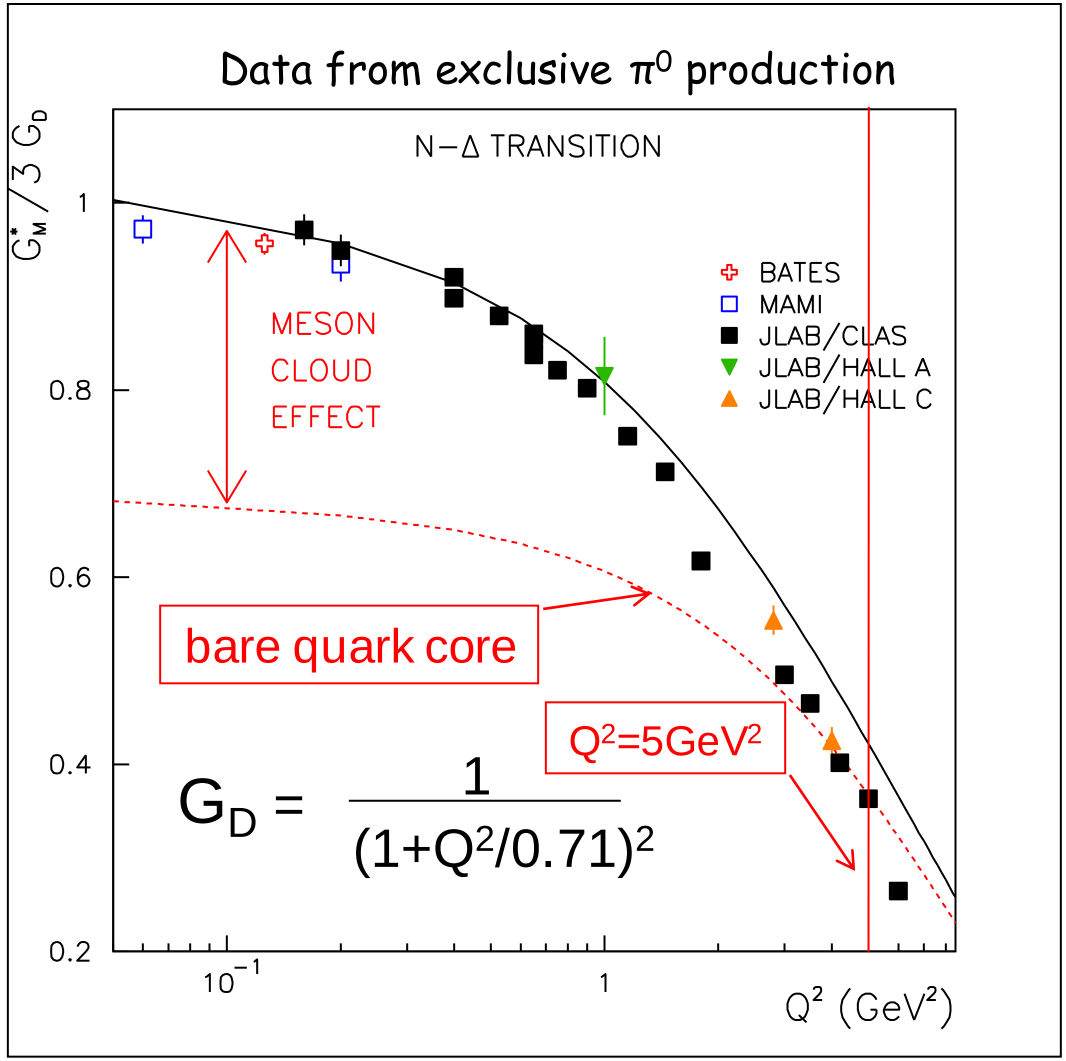
non-resonant part

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

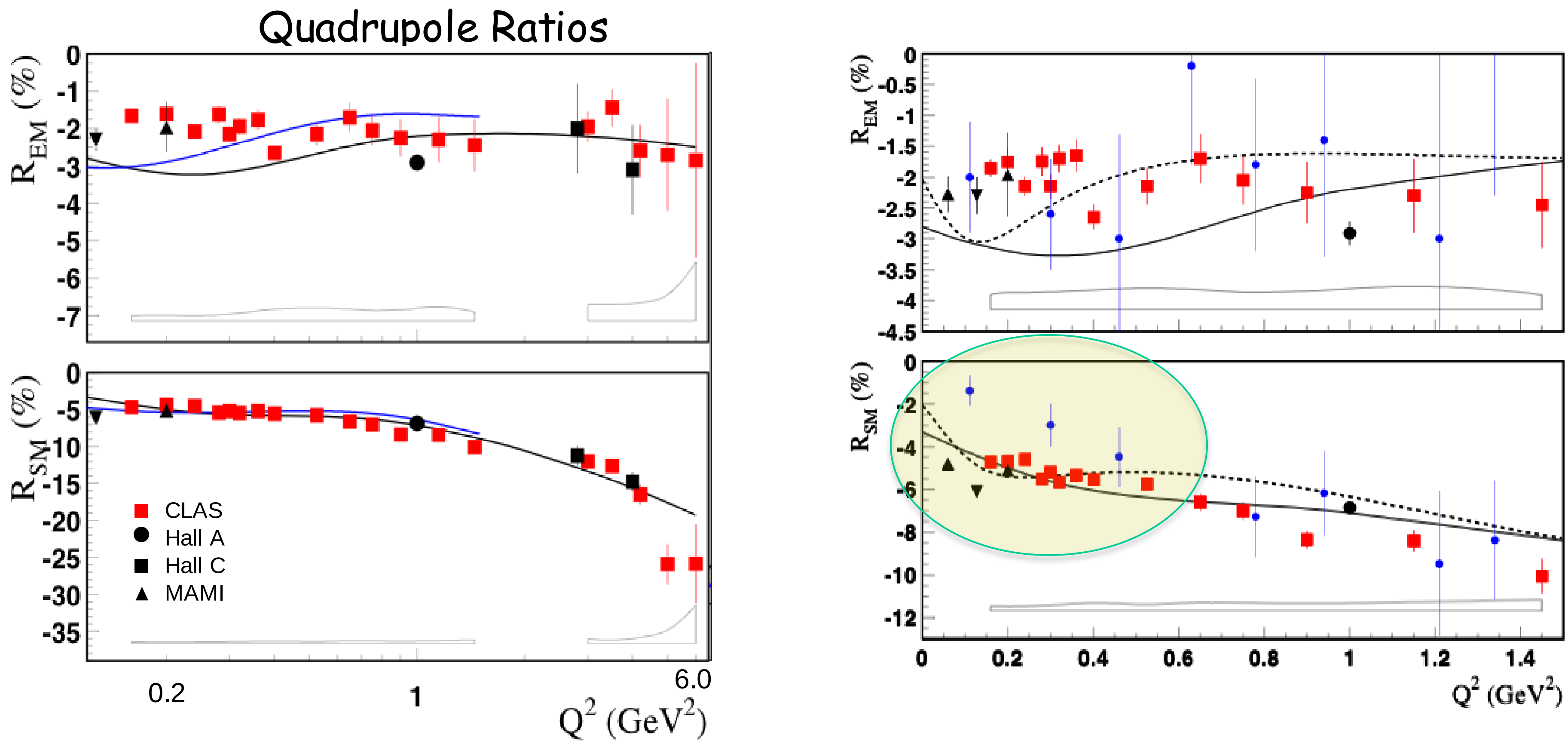
- One third of G^*_M at low Q^2 is due to contributions from meson-baryon (MB) dressing:



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 the wf.

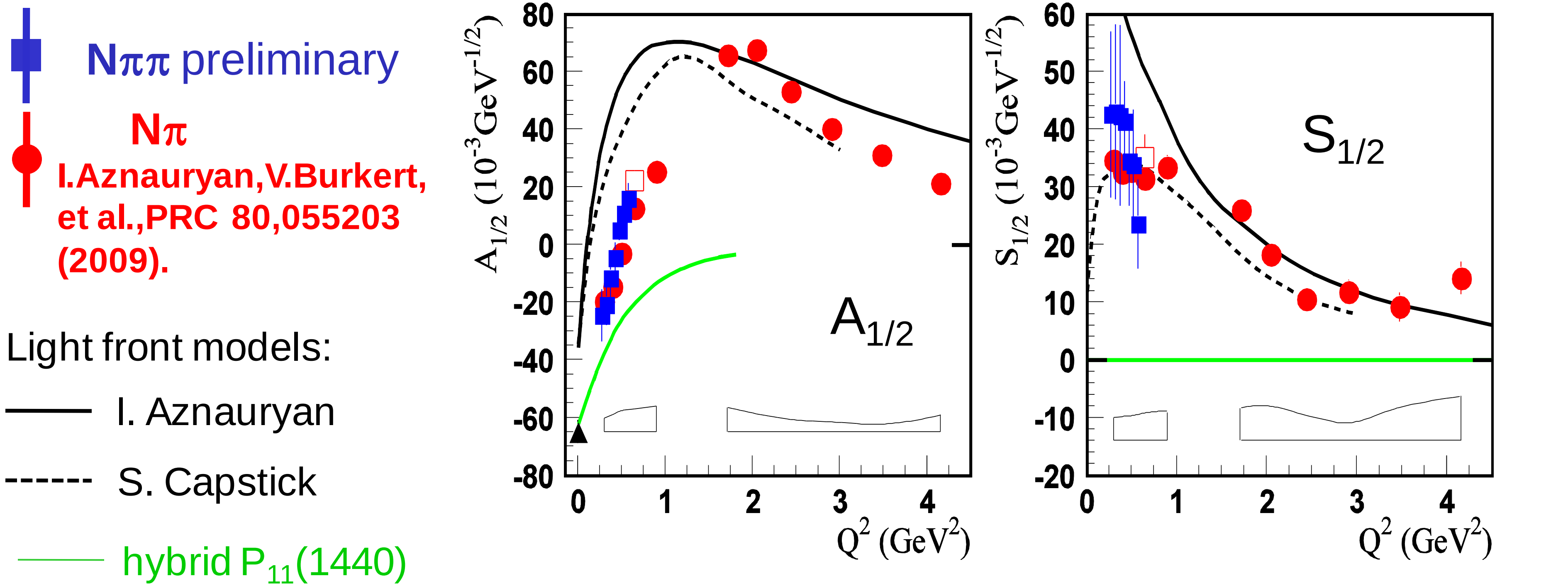


Q^2 dependence of NΔ Transition amplitudes



- No sign for onset of asymptotic behavior, $R_{EM} \rightarrow +100\%$, $R_{SM} \rightarrow$ const.
- R_{EM} remains negative and small, R_{SM} becoming more negative with Q^2.
- Meson-baryon contributions needed to describe multipoles.
- LQCD shows same trend as data but discrepancies for R_{SM} at low Q^2

$P_{11}(1440)$ electrocouplings from the CLAS data on Nπ/Nππ electroproduction



- **Good *agreement* between the electrocouplings obtained from the *Nπ and Nππ channels*: Reliable measurement of the electrocouplings.**
- **The data are sensitive to quark model expectations, allowing us to rule out hypothesis of hybrid nature of $P_{11}(1440)$.**

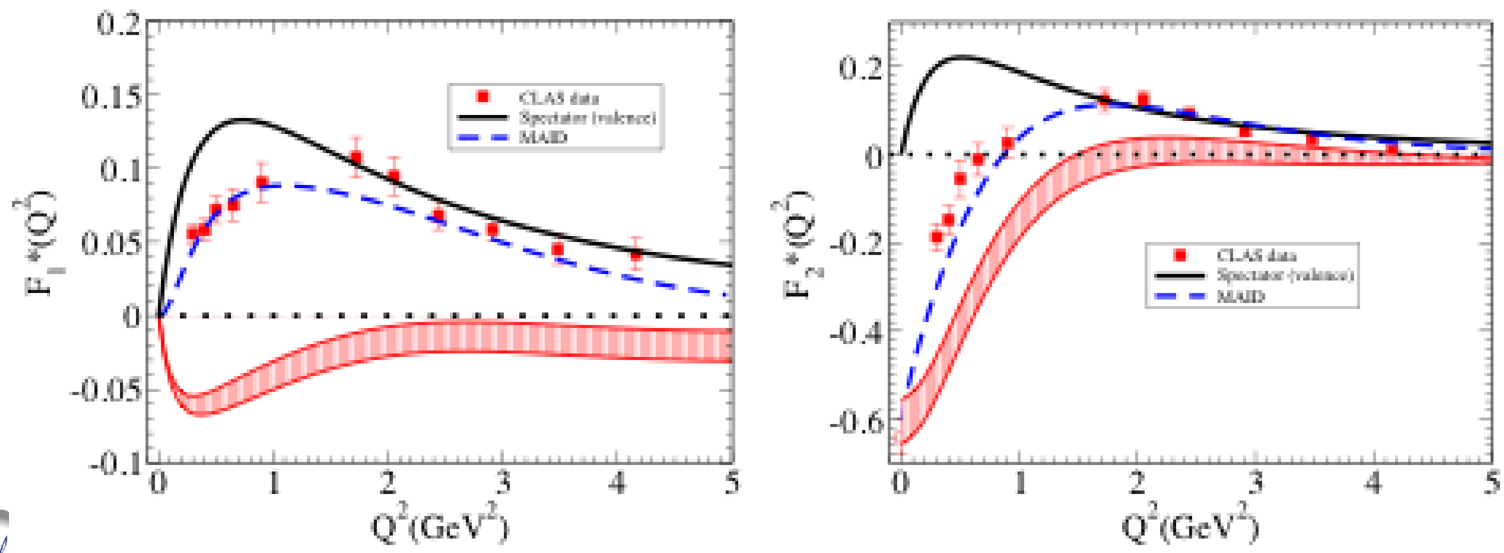
Valence quark distribution for $\gamma_v p \rightarrow P_{11}(1440)$

G. Ramalho and K.Tsushima, arXiv:1002.3386

- Use valence quark model; based on covariant spectator formalism (F. Gross).

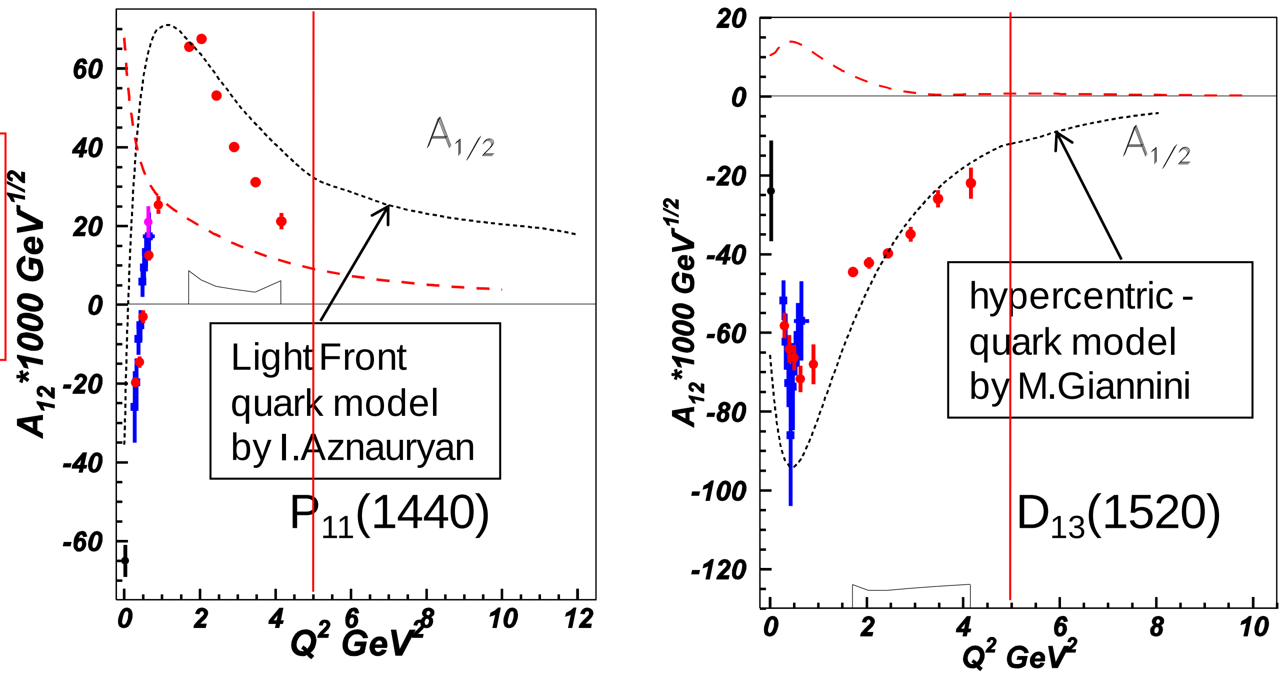
Baryon is described as a quark-diquark system with the 0 and 1 spin states (consistent with DSE kernel), and acts as spectator. Photon interacts with isolated quark in impulse approximation.

- Model parameter adjusted to fit the nucleon form factor and Delta data. No new parameter adjusted for the $NP_{11}(1440)$ transition form factors.
- Agreement at high Q^2 where meson cloud should be small, support the structure of P11(1440) core as three quarks in first radial excitation



Meson-baryon dressing / Quark core contributions in the $A_{1/2}$ electrocouplings of the $P_{11}(1440)$ & $D_{13}(1520)$ states.

Estimates from EBAC for the MB dressing (absolute values): B.Julia-Diaz *et al*., PRC 76, 5201 (2007).

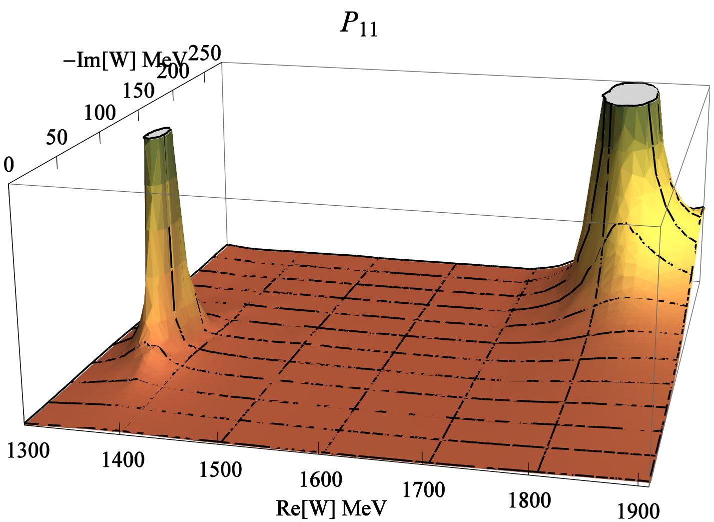


•MB dressing effects have substantial contribution to N* electrouplings at Q^2<1.0 GeV^2 and gradually decrease with Q^2;

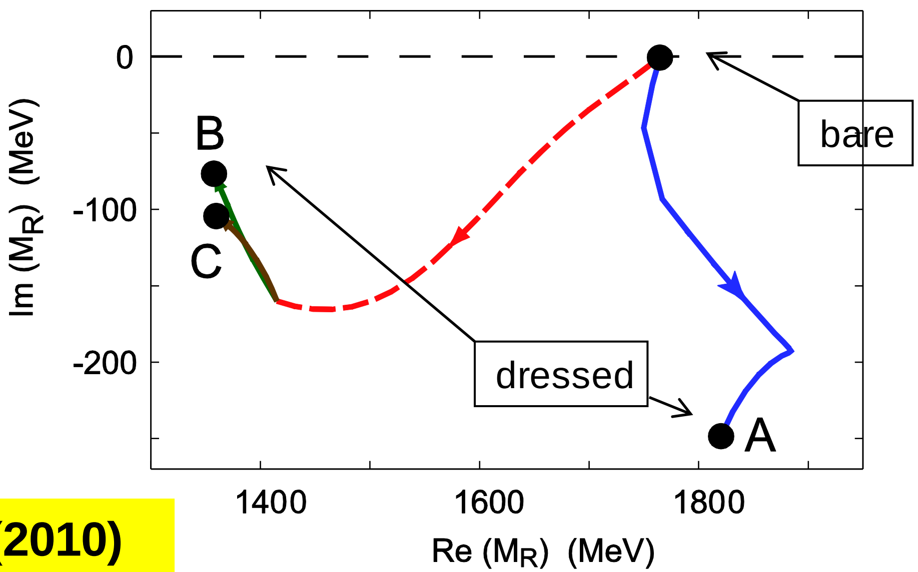
•Contribution from dressed quarks increases with Q^2 and are expected to be dominant at Q^2>5.0 GeV^2;

•**$A_{1/2}$ amplitude of $D_{13}(1520)$ state is dominated by quark contributions at Q^2>2.0 GeV^2. These data can be used, e.g., together with DSE analyses in order to chart momentum dependence of running dressed quark mass.**

Impact of MB dressing on spectrum of P_{11} excited proton states. EBAC global analysis.



Pole evolution in P11 πN amplitudes as MB dressing increases from zero to full strength



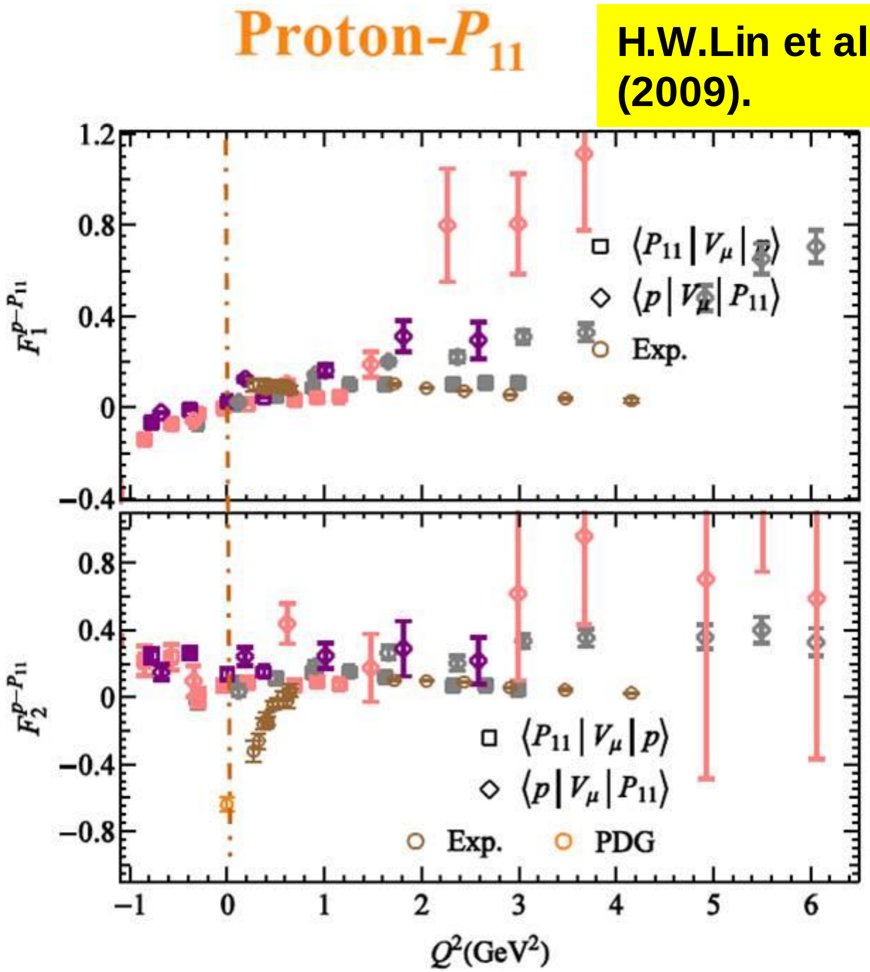
N.Suzuki et al.,PRL 104, 043202 (2010)

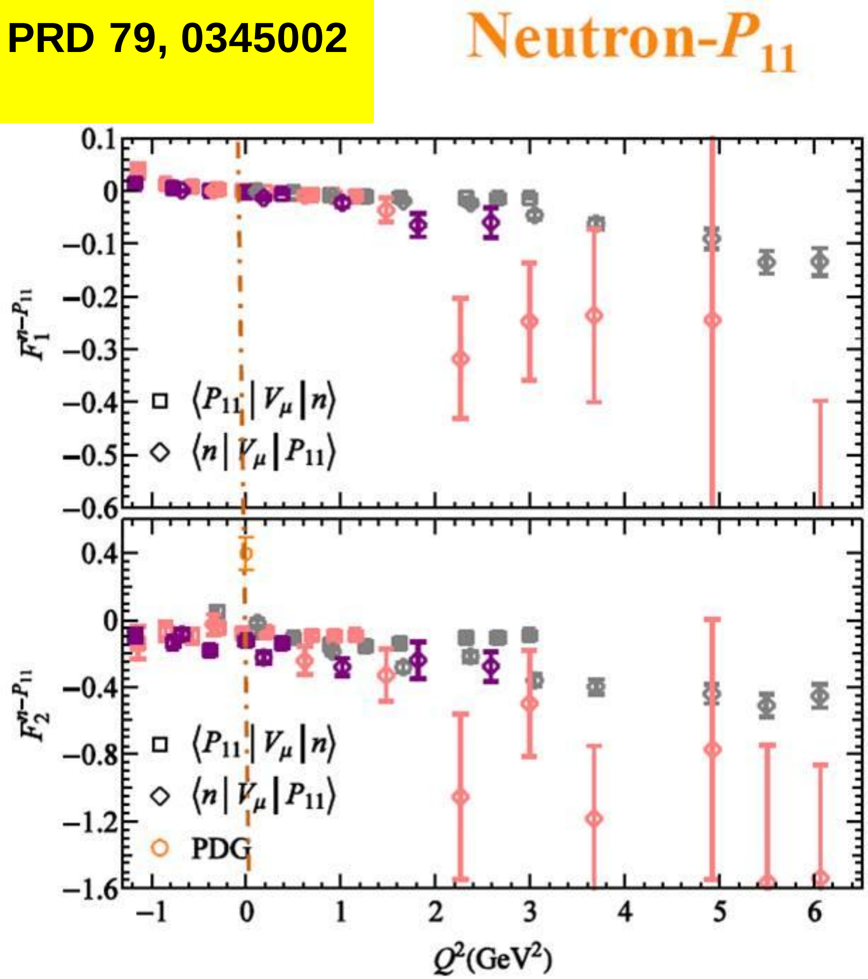
Single bare pole or quark core creates three resonant poles being dressed by MB cloud. Two of them at lower masses correspond to P_{11}(1440), third generates resonance ~1.8 GeV mass.

Puzzle with P_{11}(1440) mass in quark models is solved? DSE evaluation of bare P_{11}(1440) mass are in progress by I.Cloet and C.Roberts

$\gamma_v NP_{11}(1440)$ electrocouplings from LQCD. Lattice group at JLAB Theory Center

H.W.Lin et al., PRD 79, 0345002 (2009).

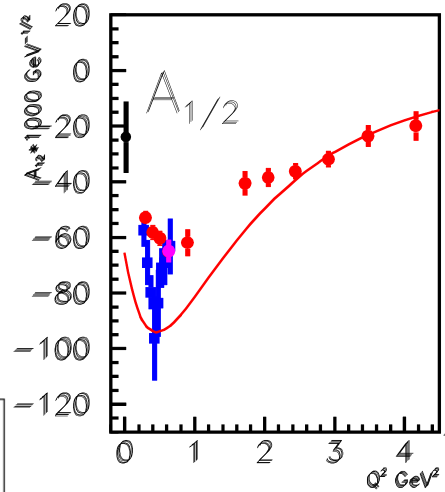


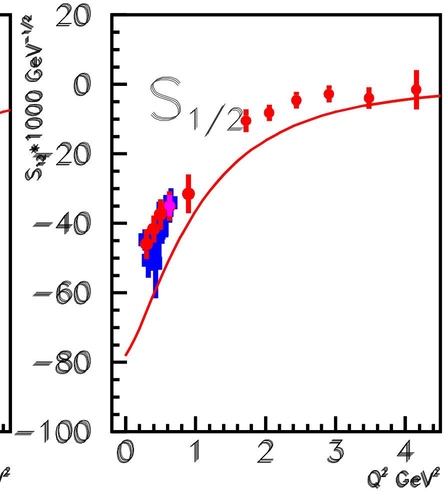


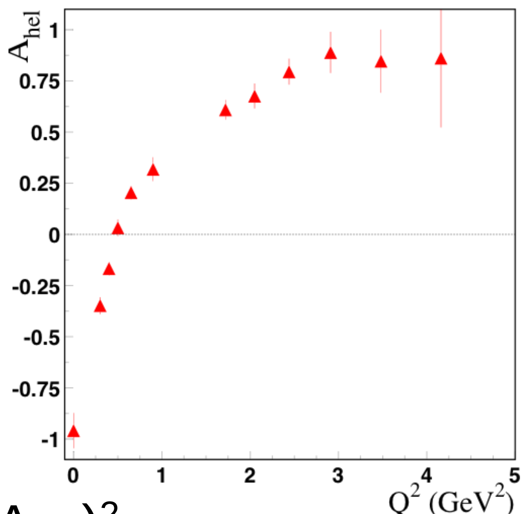
Trend in the data behavior is well reproduced by LQCD with m_π=450 MeV (red points), except F_2 form factor at Q^2<1.0 GeV^2

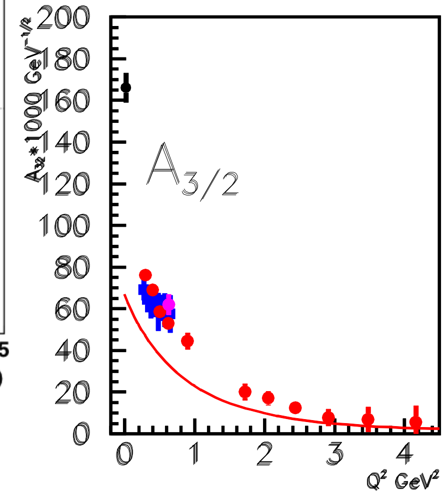
$D_{13}(1520)$ electrocouplings from the CLAS data on $N\pi/N\pi\pi$ electroproduction

- **electrocouplings as determined from the $N\pi$ & $N\pi\pi$ channels are in good agreement overall**
- **indications for contributions from both quark core and MB cloud**







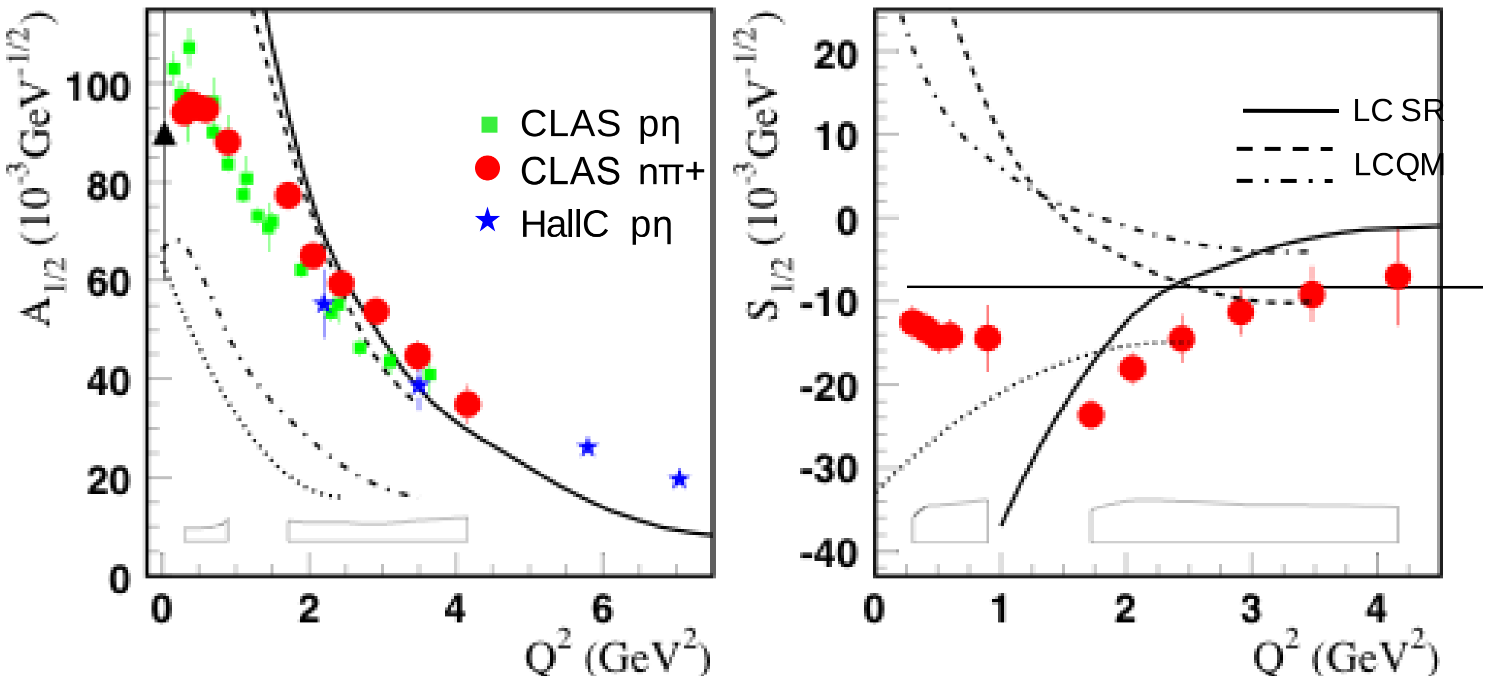


error bars include systematic uncertainties

M.Giannini/ E.Santopinto hyper-centric CQM

$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

γpN(1535)S_{11} electrocouplings

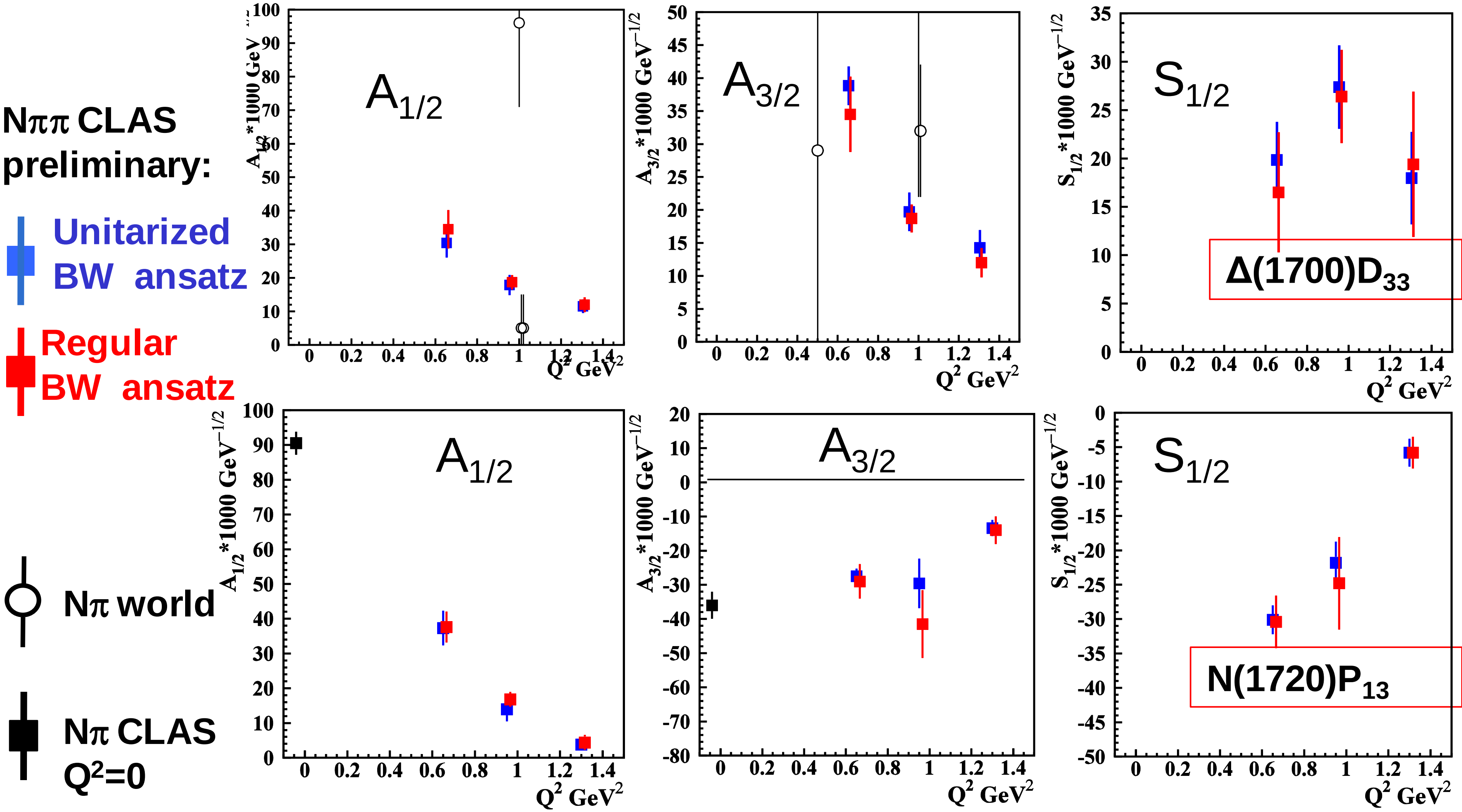


Analysis of pη channel assumes $S_{1/2}$=0
Branching ratios: $\beta_{N\pi} = \beta_{N\eta} = 0.45$

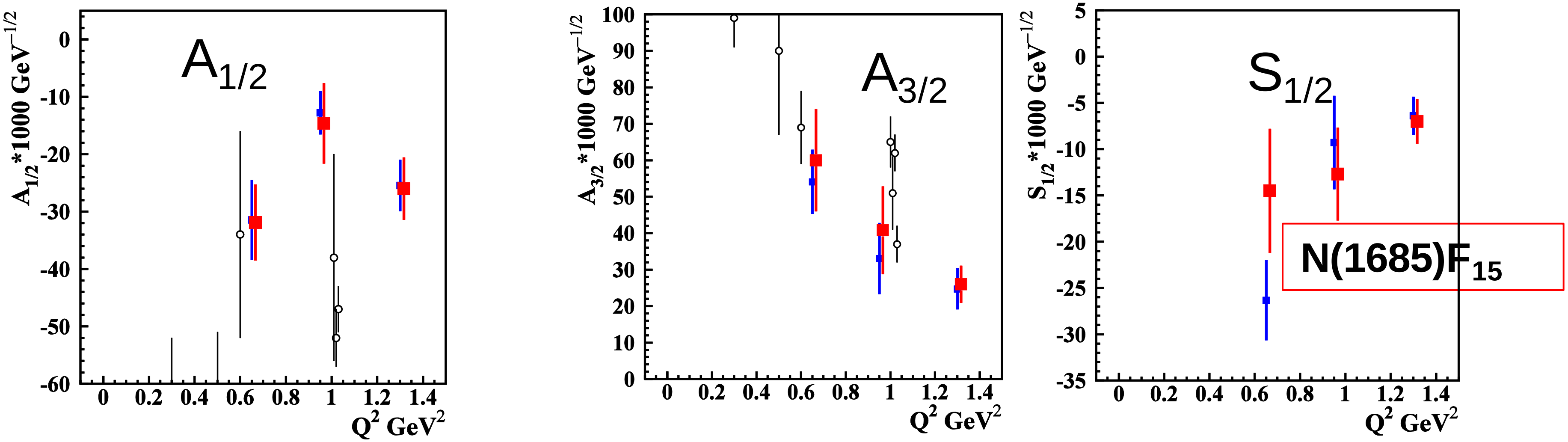
$$D_0^{LT} = \frac{|q|}{K} Re(E_{0+}S_{1-}^* + S_{0+}M_{1-}^*).$$

- **$A_{1/2}$ (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**

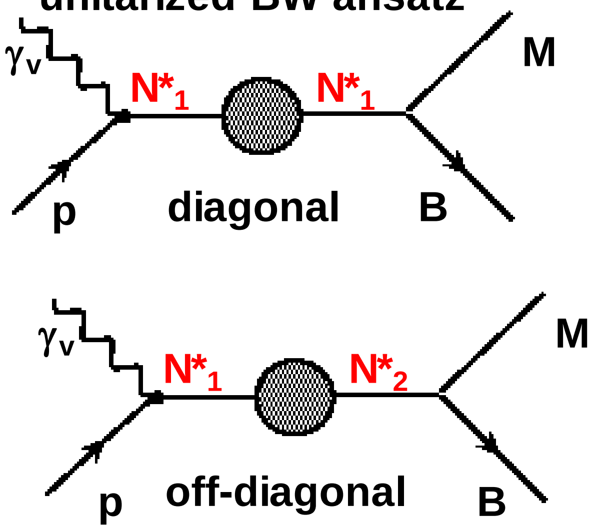
High lying resonance electrocouplings from Nππ CLAS data analysis

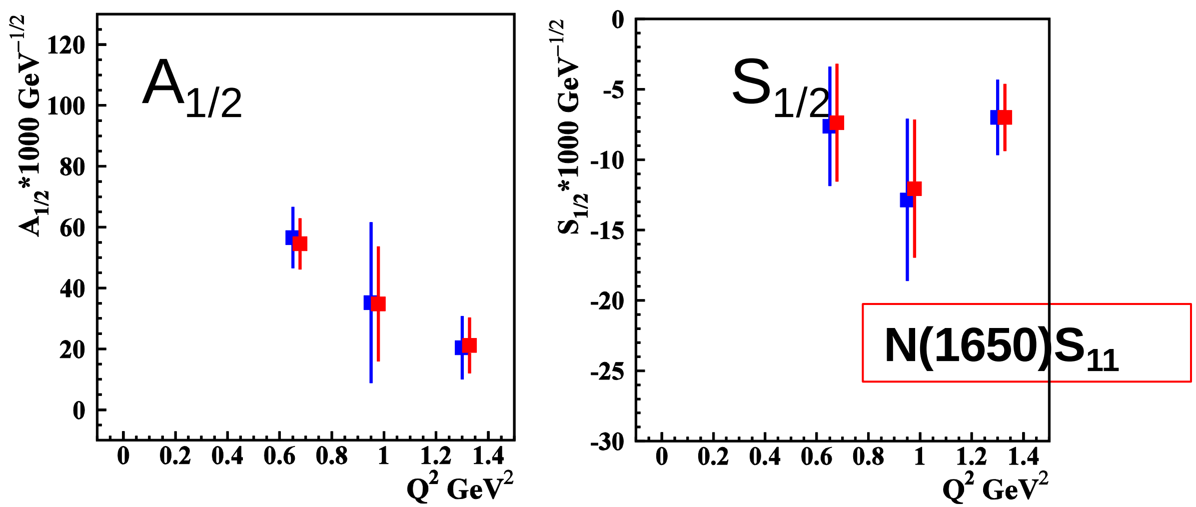


High lying resonance electrocouplings from Nππ CLAS data analysis



The amplitudes of unitarized BW ansatz





The CLAS $\pi^+\pi^-p$ data offer sufficient constraints for the extraction of $\gamma_v NN^*$ electrocouplings.

1^{st} through 3^{rd} nucleon resonance regions

State	$\beta_{N\pi}$	$\beta_{N\eta}$	$\beta_{N\pi\pi}$
$\Delta(1232)P_{33}$	0.995		
$N(1440)P_{11}$	0.55-0.75		0.3-0.4
$N(1520)D_{13}$	0.55-0.65		0.4-0.5
$N(1535)S_{11}$	0.35-0.55	0.45-0.60	<0.1
$N(1620)S_{31}$	0.20-0.30		0.7-0.8
$N(1650)S_{11}$	0.60-0.95	0.03-0.10	0.1-0.2
$N(1685)F_{15}$	0.65-0.70		0.3-0.4
$\Delta(1700)D_{33}$	0.1-0.2		0.8-0.9
$N(1720)P_{13}$	0.1-0.2	0.01-0.15	> 0.7

- $N\pi$ and $N\pi\pi$ for $P_{11}(1440)$,$D_{13}(1520)$,$S_{11}(1650)$,$F_{15}(1685)$
- $N\pi$ and $N\eta$ for $S_{11}(1535)$
- $N\pi\pi$ for $D_{33}(1700)$ and $P_{13}(1720)$

N* hadronic parameters derived from the CLAS $\pi^+\pi^-p$ data fit

$P_{13}(1720)$

	Γ_{tot}, MeV	$\Gamma_{\pi\Delta}$, MeV	$\Gamma_{\rho p}$, MeV	M,GeV
Regular BW ansatz	135±12	1.53±1.05	114±12	1.743±0.006
Unitarized BW ansatz before improvements	176±19	26±3.78	131±21	1.745±0.004
Unitarized BW ansatz after improvements	113±3.4	10.9±1.40	82.9±3.26	1.744±0.007

$3/2^+(1720)$ candidate state

	Γ_{tot}, MeV	$\Gamma_{\pi\Delta}$, MeV	$\Gamma_{\rho p}$, MeV	M,GeV
Regular BW ansatz	86±5	44±5.5	6.25±1.62	1.727±0.003
Unitarized BW ansatz before improvements	86±11	44±11	5.85±1.27	1.727±0.004
Unitarized BW ansatz after improvements	107±12	61±12	0.63±0.21	1.725±0.006

Conclusions and outlook

- **Phenomenological analyses of a large body of observables measured in π^+n, π^0p, ηp and $\pi^+\pi^-p$ electroproduction channels allowed us to determine electrocouplings for almost all well established N*'s with masses <1.8 GeV. Electrocouplings of low lying N*'s (M<1.6 GeV) were obtained at photon virtualities $0.2<Q^2<5.0$ GeV^2 from $N\pi$ channels and at $Q^2<0.6$ GeV^2 also from $\pi^+\pi^-p$ channel, while for high lying states (M>1.6 GeV) they were determined at $0.5<Q^2<1.5$ GeV^2 from $\pi^+\pi^-p$ channel.**

- **Consistent results on $\gamma_v NN^*$ electrocouplings obtained from various meson electroproduction channels with entirely different non-resonant contributions offer an evidence for reliable electrocoupling measure and for credible evaluation of resonant/non-resonant contributions .**

- **In near term future $\pi^+\pi^-p$ electroproduction data will be available at $2.0<Q^2<5.0$ GeV^2, allowing us to determine electrocouplings for a major part of excited proton states up to highest photon virtualities accessible with 5 GeV beam. g11 $\pi^+\pi^-p$ photoproducton data will extend considerably our knowledge of mechanisms contributing to this exclusive channel.**

Conclusions and outlook

- **Derived from the data fit information on amplitudes/cross sections of various mechanisms in $N\pi$ & $N\pi\pi$ electroproduction will be utilized in a global coupled channel analysis developing by EBAC.**
- **Phenomenological analyses of $\gamma_v NN^*$ electrocouplings at $Q^2<5.0$ GeV^2 revealed substantial contributions from both meson-baryon and quark degrees of freedom. MB dressing of N*'s were determined by EBAC from a global fit of πN scattering and $N\pi$ electroproduction reactions. MB contributions decrease with Q^2 and at $Q^2>5.0$ GeV^2 quark degrees of freedom are expected to dominate.**
- **First exploratory attempts to describe $\gamma_v NN^*$ electrocouplings within the LQCD framework (JLAB Lattice Group, Univ. of Regensburg) showed promising potential for LQCD to understand N* formation in non-perturbative quark/gluon interactions starting from the QCD Lagrangian.**

Conclusions and outlook

- **Analyses of $\gamma_v NN^*$ electrocouplings at $Q^2>2.0$ GeV^2 within the framework of DSE approaches (ANL, Univ. of Washington) will allow us to address two central issues in the physics of non-perturbative strong interactions: a) generation of >97 % of nucleon/N* masses through dynamical chiral symmetry breaking; b) explore a behavior of QCD β-function in confinement regime**

Hall B at Jefferson Lab has unique, best in the world opportunities to explore non-perturbative strong interactions at large and intermediate x_B and their emergence from QCD through combined analysis of the data on γvNN^* electrocouplings and comprehensive experimental information on the ground state structure from DIS inclusive and semi-inclusive and from fully exclusive GPD 's structure functions. LQCD and DSE offer two independent and complementary QCD-based theoretical frameworks allowing us to achieve these challenging objectives.

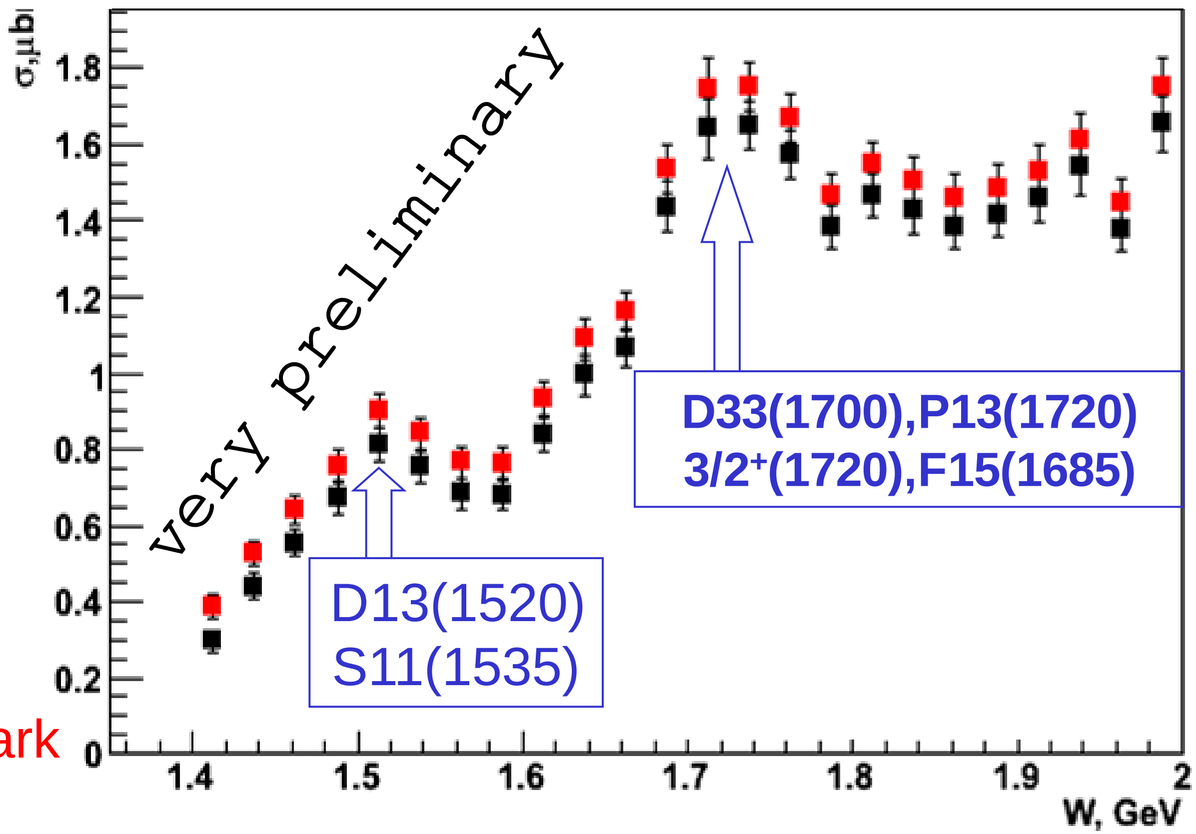
Back-up

Resonance signals in 2π electroproduction at high Q^2.

After 12 GeV Upgrade CLAS12 will be only facility foreseen worldwide, capable to study electrocouplings for full spectrum of N*'s at Q^2 from 5.0 to 10 GeV^2.

Access to constituent quark structure and interactions through quark core excitation in N*'s for the first time.

Fully integrated 2π cross section at Q^2 from 4.5 to 5.2 GeV^2



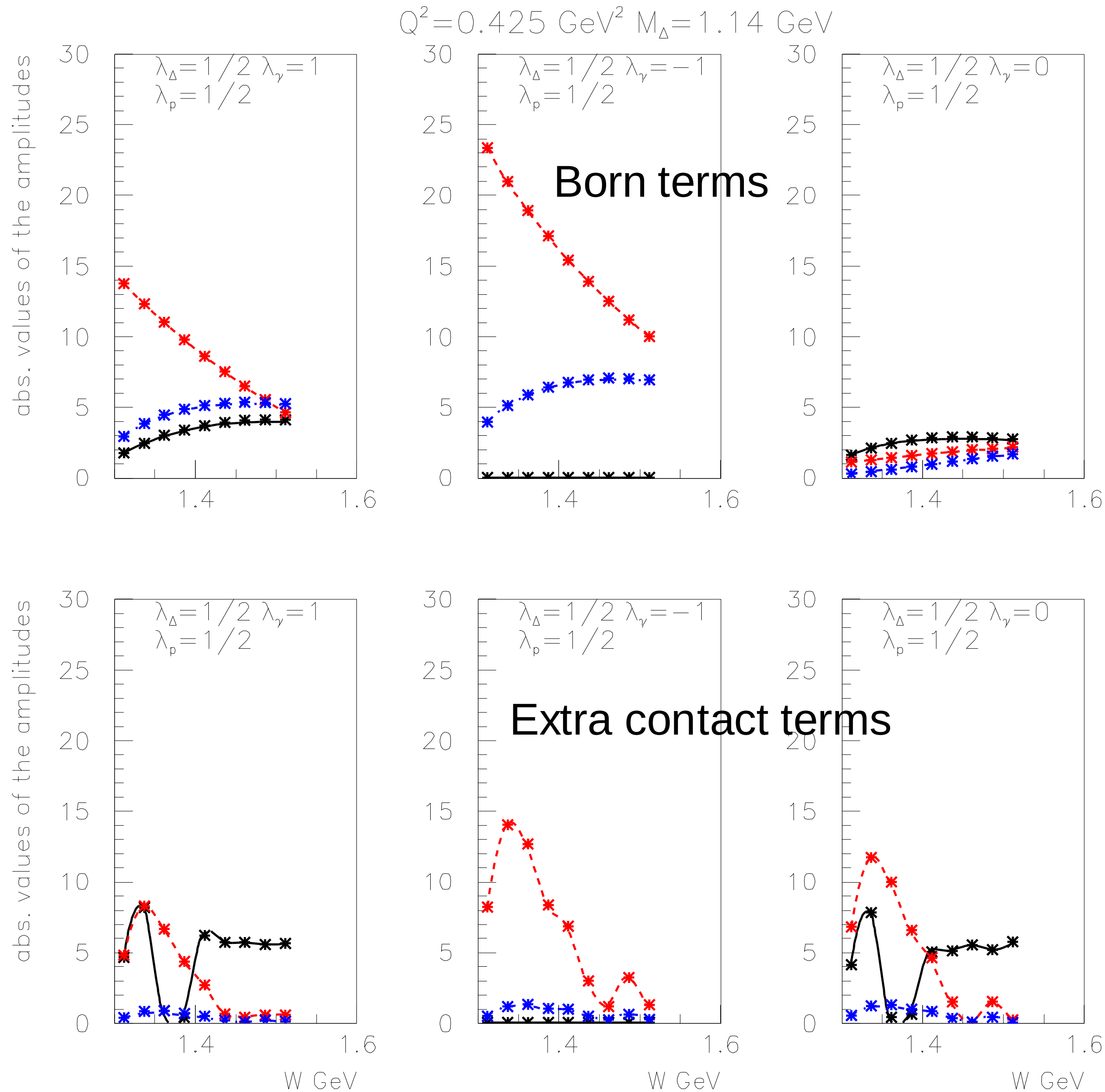
Evidence for substantial N* contributions

Input for Nπ/Nππ coupled channel analysis : partial waves of total spin J for non-resonant helicity amplitudes in $\pi^-\Delta^{++}$ isobar channel

J	
black line	**1/2**
red line	**3/2**
blue line	**5/2**

$$\langle \lambda_f | T^J | \lambda_\gamma \lambda_p \rangle = \int \frac{2J+1}{2} \langle \lambda_f | T | \lambda_\gamma \lambda_p \rangle \bullet d^J_{\mu\nu}(\theta_f) \sin\theta_f \, d\theta_f$$

Will be used for N* studies in coupled channel approach developing by EBAC.



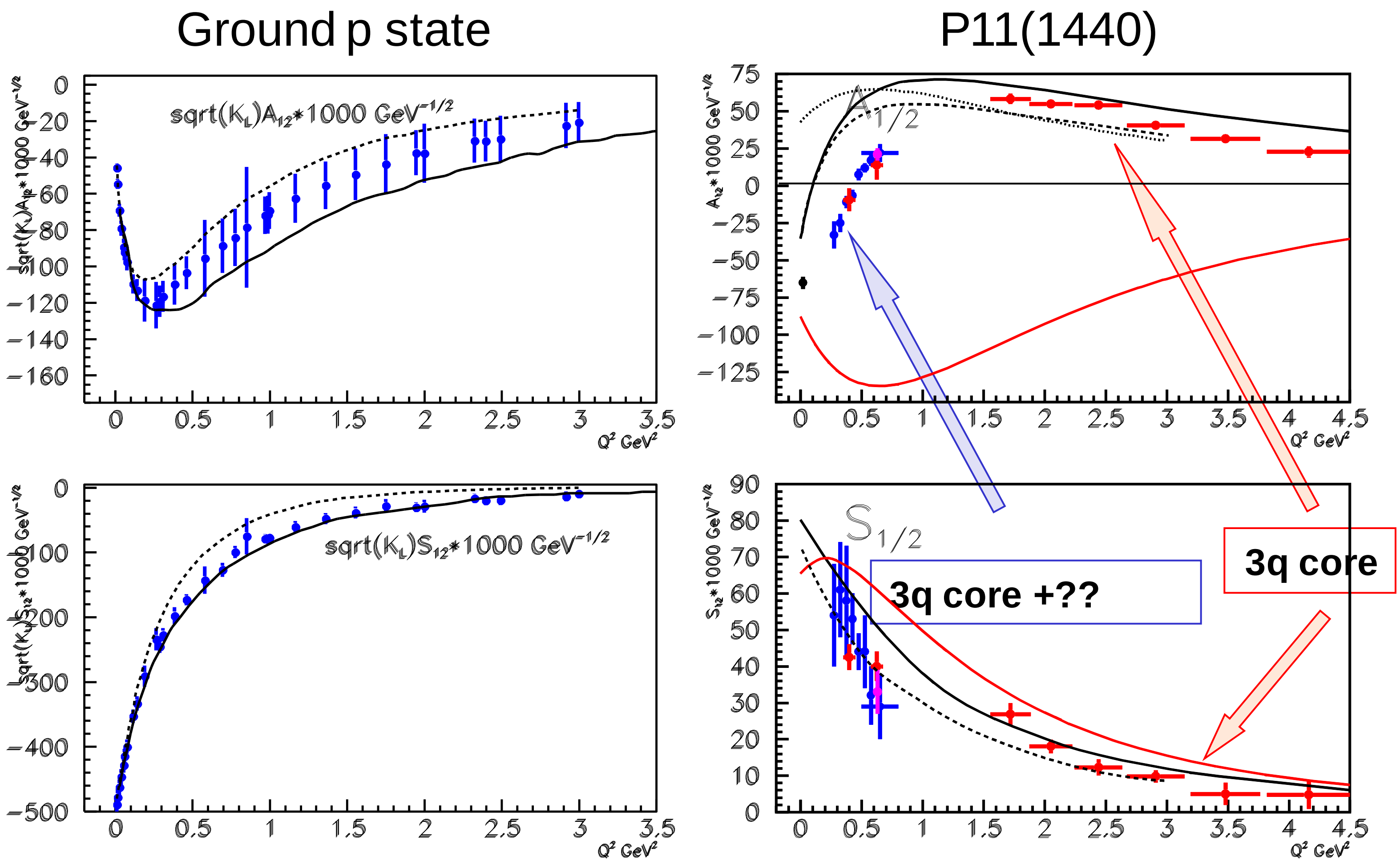
Ground state and P11(1440) electrocouplings & quark model expectations

S.Capstick light cone (LC) model (dashed line)

B.Metsch Bethe-Salpeter model (dotted line)

I.Aznauryan LC model (solid black line)

M.Giannini/ E.Santopinto hyper-centric CQM (solid red line)



P11(1440) electrocouplings at Q^2>2.0 GeV^2 are consistent with substantial contribution from 3-quarks in first radial excitation, while at Q^2<0.6 GeV^2 additional contributions become evident.

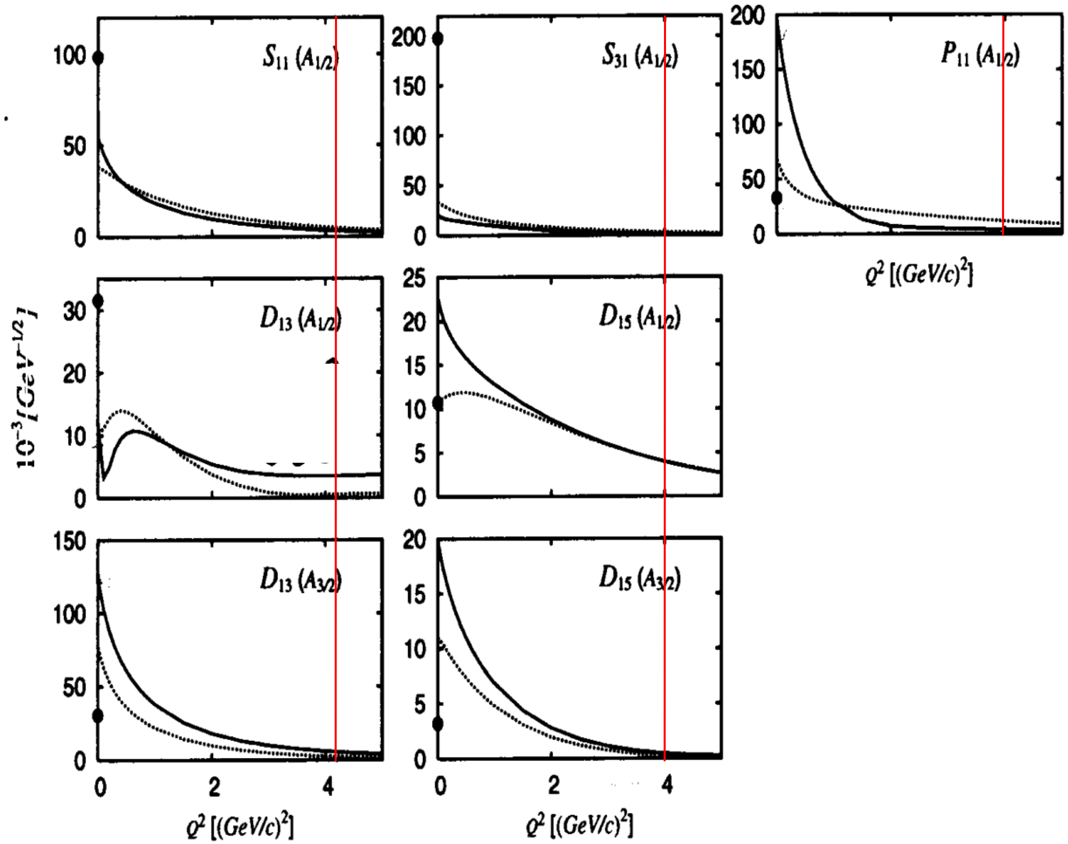
New regime in N* excitation at high Q^2

- the photons of high virtuality penetrate meson-baryon cloud and interact mostly to quark core

- data on N* electrocouplings at high Q^2 allow us to access quark degrees of freedom, getting rid of meson-baryon cloud.

- can be obtained at $5<Q^2<10$ GeV^2 after 12 GeV Upgrade with CLAS12 for majority of N* with masses less then 3.0 GeV

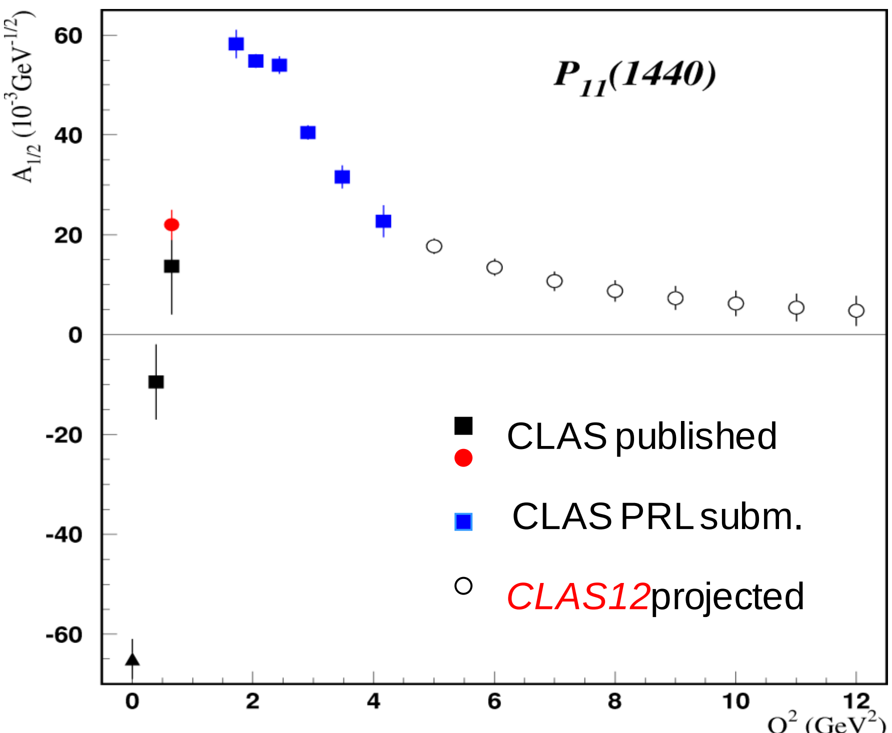
EBAC calculations for meson-baryon cloud of low lying N*'s.

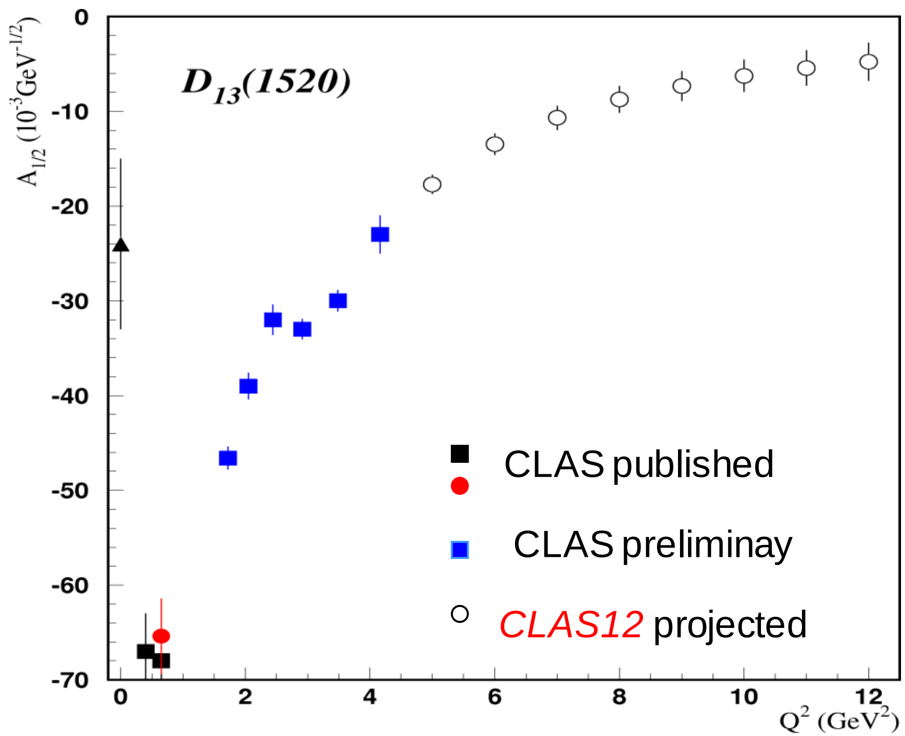


B.Julia-Diaz, T-S.H.Lee, et.al, Phys. Rev. C77, 045205 (2008).

CLAS12 Projections for N* Transitions

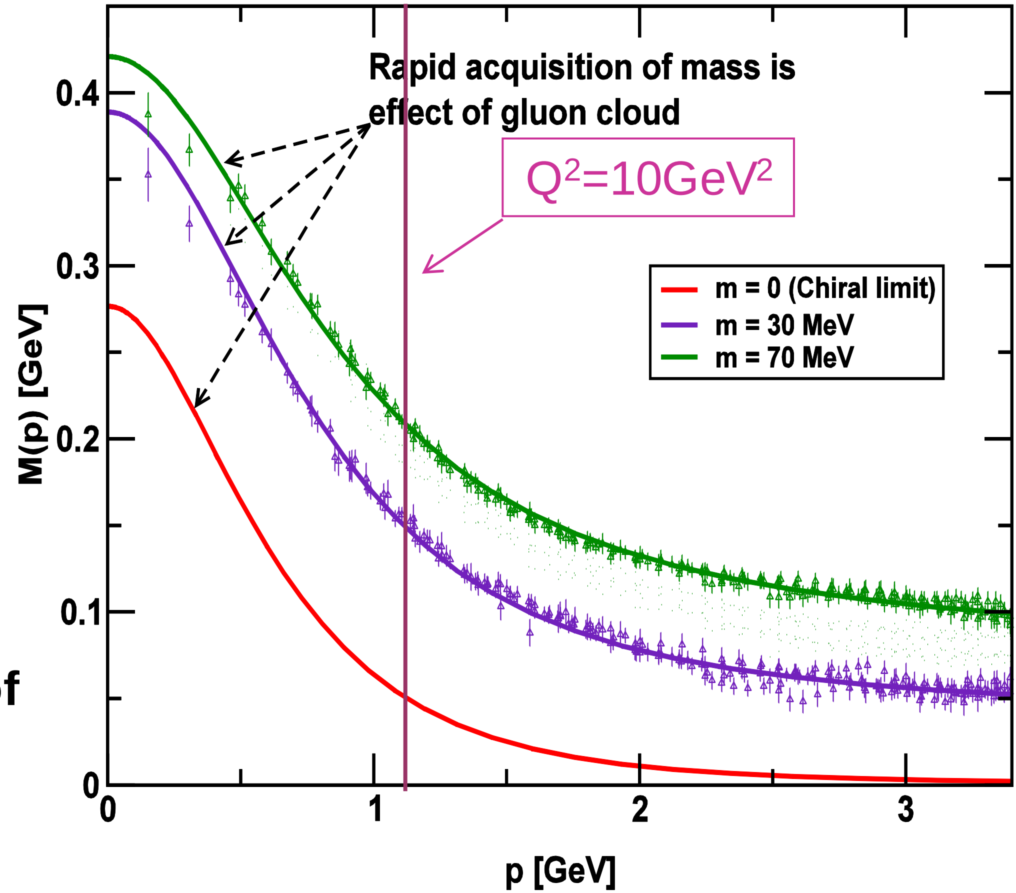
For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the Q^2 regime of 5 GeV^2 to 10 GeV^2, where the quark degrees of freedom are expected to dominate.





Physics objectives in the N* studies with CLAS12

- **explore the interactions between the dressed quarks, which are responsible for the formation for both ground and excited nucleon states.**
- **probe the mechanisms of light current quark dressing, which is responsible for >97% of nucleon mass.**



Approaches for theoretical analysis of N* electrocouplings: LQCD, DSE, relativistic quark models. See details in the White Paper of EmNN* JLAB Workshop, October 13-15, 2008: http://www.jlab.org/~mokeev/white_paper/

DSE: lines and LQCD: triangles

Q^2 = 10 GeV^2 = (p times number of quarks)^2= 10 GeV^2→ p = 1.05 GeV

Parallel sessions #9,13 of GHP09 Workshop

Nucleon Resonance Studies with CLAS12

D. Arndt[4], H. Avakian[6], I. Aznauryan[11], A. Biselli[3], W.J. Briscoe[4], **V. Burkert[6]**,
V.V. Chesnokov[7], **P.L. Cole[5]**, D.S. Dale[5], C. Djalali[10], L. Elouadrhiri[6], G.V. Fedotov[7],
T.A. Forest[5], E.N. Golovach[7], **R.W. Gothe*[10]**, Y. Ilieva[10], B.S. Ishkhanov[7],
E.L. Isupov[7], **K. Joo[9]**, T.-S.H. Lee[1,2], **V. Mokeev*[6]**, M. Paris[4], K. Park[10],
N.V. Shvedunov[7], G. Stancari[5], M. Stancari[5], S. Stepanyan[6], **P. Stoler[8]**,
I. Strakovsky[4], S. Strauch[10], D. Tedeschi[10], M. Ungaro[9], R. Workman[4],
and the CLAS Collaboration

JLab PAC 34, January 26-30, 2009
Approved for 60 days beamtime

http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.

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Idaho State University (ID, USA)[5], Jefferson Lab (VA, USA)[6],
Moscow State University (Russia)[7], Rensselaer Polytechnic Institute (NY, USA)[8],
University of Connecticut (CT, USA)[9], University of South Carolina (SC, USA)[10],
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JLab PAC 34, January 26-30, 2009

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University of Regensburg (Germany)[8],
and University of Washington (WA, USA)[9]

Open invitation.

List is open to any and all who wish to participate!