Measurements of $ep \to e'\pi^+\pi^-p'$ Cross Sections with CLAS at 1.40 GeV $< W <$ 2.0 GeV and 2.0 GeV^2 $< Q^2 <$ 5.0 GeV^2

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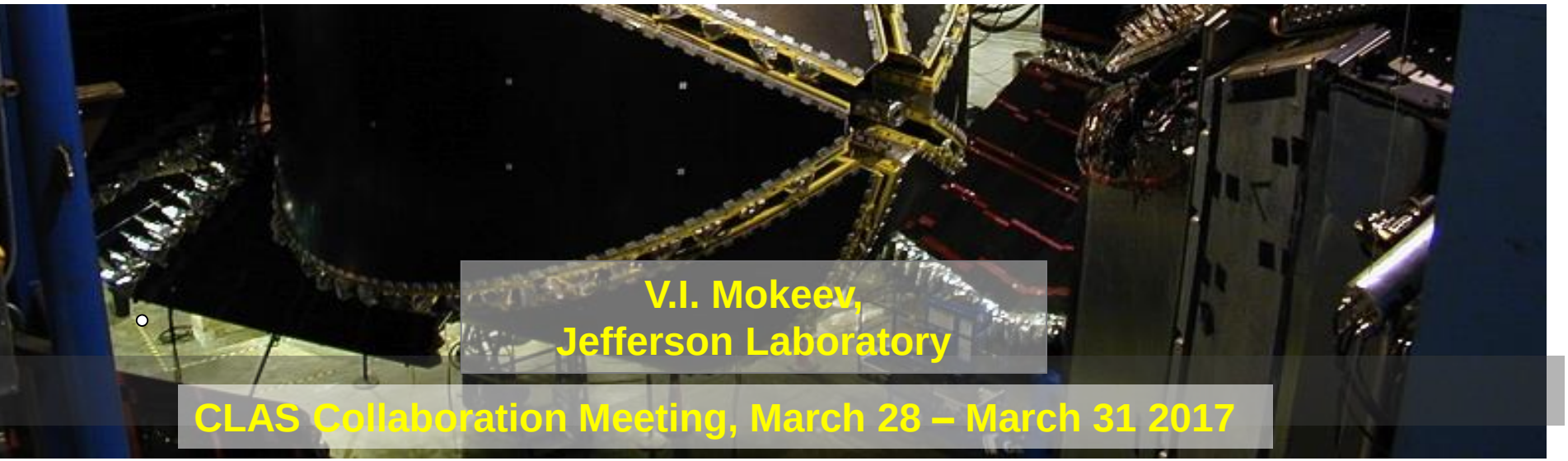
(Dated: March 20, 2017)

This paper reports new exclusive cross sections on $ep \to e'\pi^+\pi^-p'$ using the CLAS detector at Jefferson Laboratory. These results are presented for the first time at photon virtualities 2.0 GeV $< Q^2 <$ 5.0 GeV^2 in the center-of-mass energy range 1.4 GeV $< W <$ 2.0 GeV, which covers a large part of the nucleon resonance region. Using a model developed for the phenomenological analysis of electroproduction data, we see strong indications that the relative contributions from the resonant cross sections at $W <$ 1.74 GeV increase with Q^2. These data considerably extend the kinematic reach of previous measurements. Exclusive $ep \to e'\pi^+\pi^-p'$ cross section measurements are of particular importance for the extraction of resonance electrocouplings in the mass range above 1.6 GeV.

PACS numbers: 11.55.Fv, 13.40.Gp, 13.60.Le, 14.20.Gk



V.I. Mokeev,
Jefferson Laboratory

CLAS Collaboration Meeting, March 28 – March 31 2017

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

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

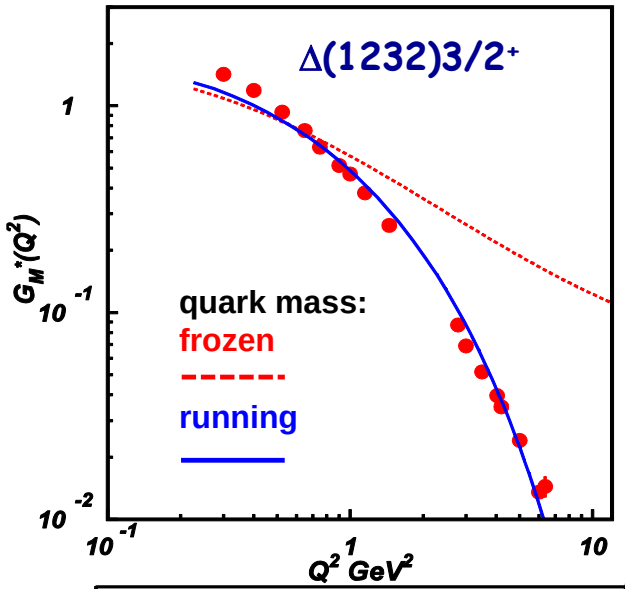
- γ_vNN* electrocouplings at photon virtualities up to 5.0 GeV^2 for most of the excited proton states through analyzing major meson electroproduction channels
- search for new the so-called ``missing" baryon states
- extend knowledge on N*-spectrum and on resonance hadronic decays from the data for photo- and electroproduction reactions, in particular, with multiple mesons in the final state

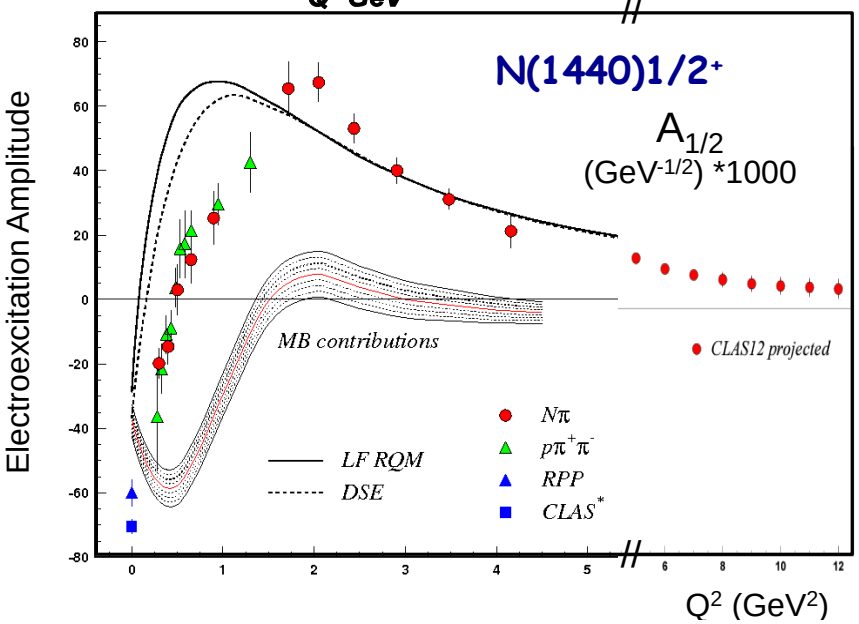
A unique source of information about the diverse manifestations of the strong QCD such as the origin of mass and mass-scales and how they work to generate the spectrum of hadrons as relativistic bound-systems of quarks and gluons

Review papers:

1. **I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).**
2. **I.G. Aznauryan et al., Int. J. Mod. Phys. E22, 133015 (2013).**
3. **C.D. Roberts, J. Phys. Conf. Ser. 706, 022003 (2016).**

Emergence and Distribution of Mass



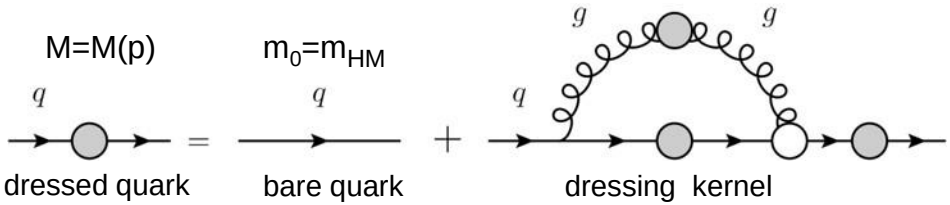


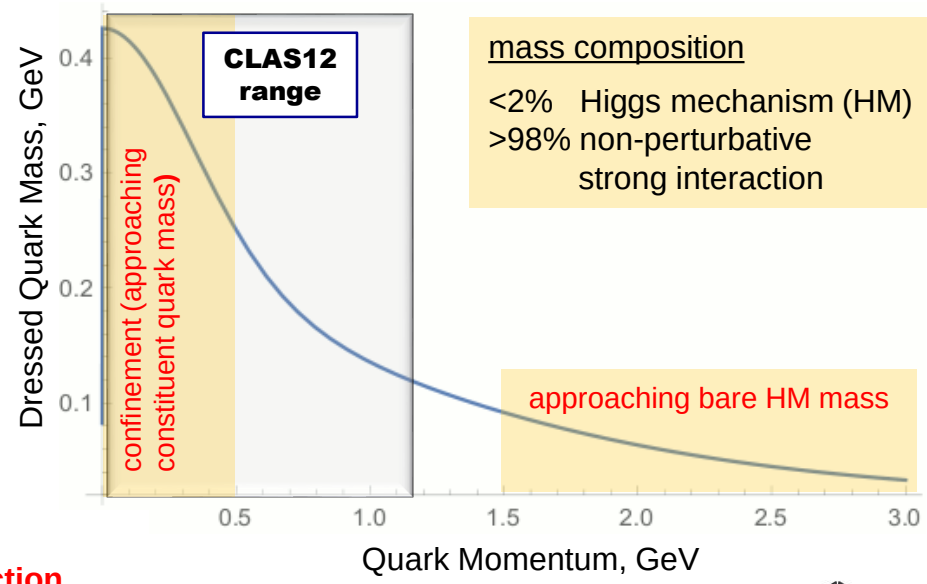
Successful description of Δ(1232)3/2⁺ and N(1440)1/2⁺ electroexcitation amplitudes with the same quark mass function suggest credible access to this key ingredient of strong QCD.

N* electroexcitation studies with CLAS/CLAS12 in Hall B will address the critical open questions:

How is >98% of visible mass generated, and how is it distributed within a hadron?

- **C.D.Roberts, Few Body Syst. 58,1 (2017).**
- **J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).**
- **J. Segovia et al., Few Body Syst. 55,1185 (2014).**



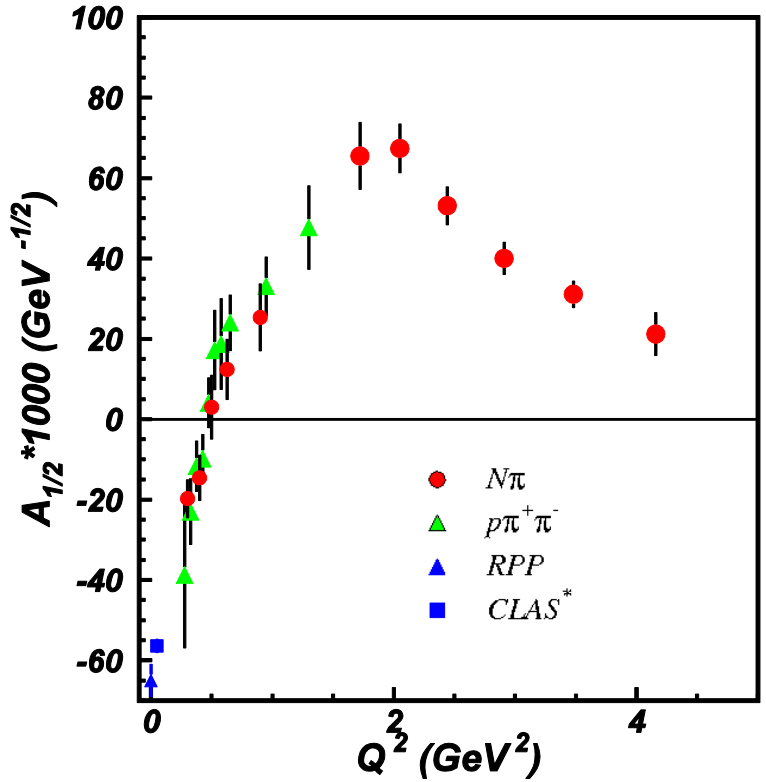


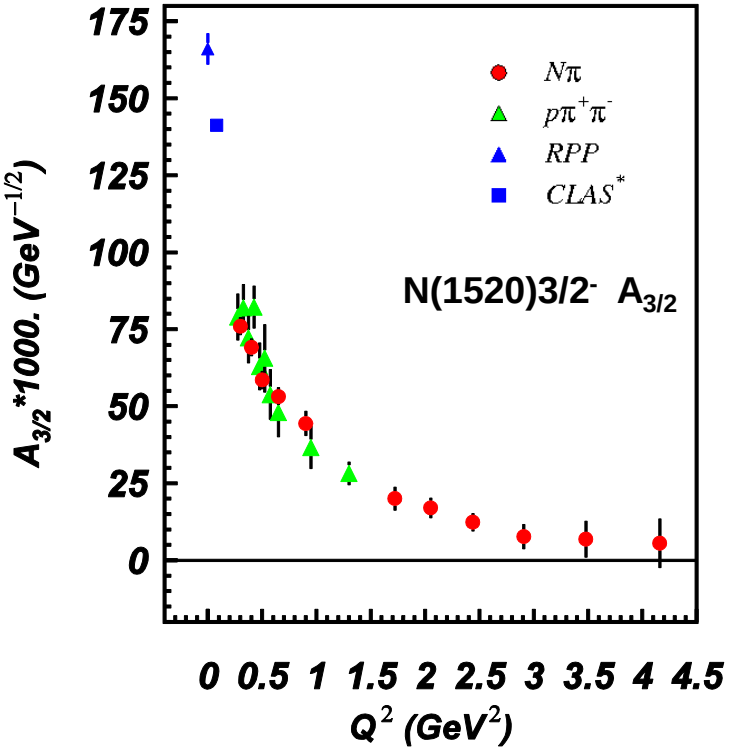
mass composition

<2% Higgs mechanism (HM)
>98% non-perturbative strong interaction

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

I.G. Aznauryan et al., Phys. Rev. C80, 055203 (2009).
V.I. Mokeev et al., Phys. Rev . C86, 035203 (2012).
K. Park et al., Phys. Rev. C91, 052014 (2015).
V.I. Mokeev et al., Phys. Rev . C93, 054016 (2016).





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

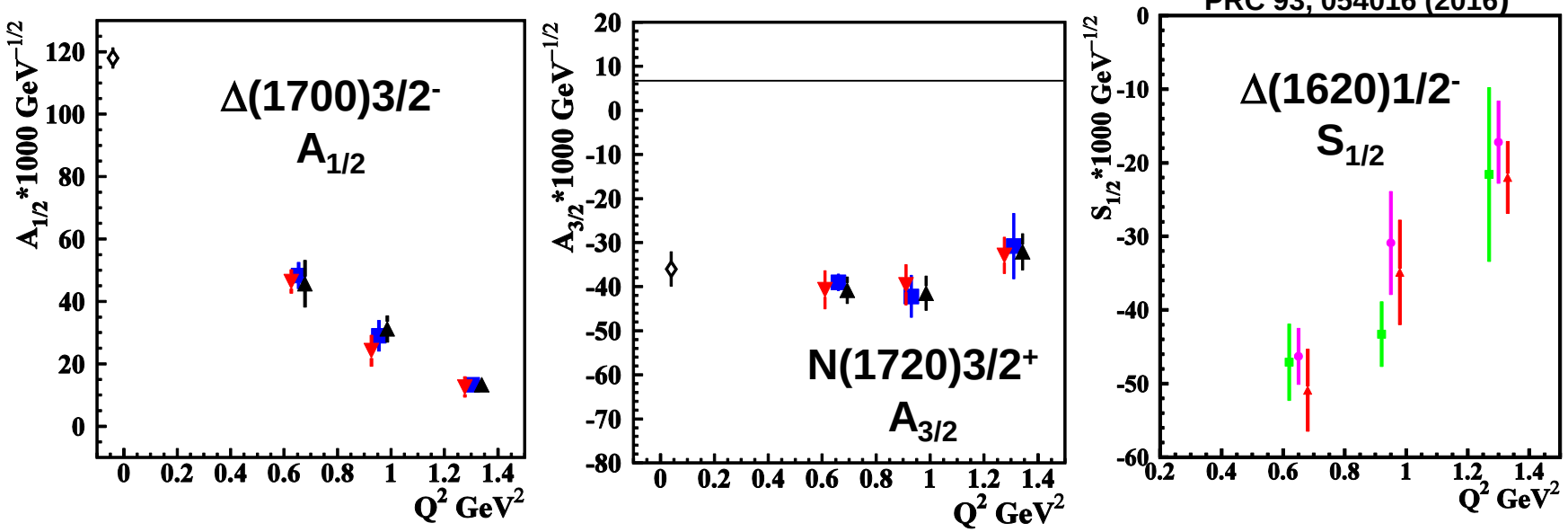
- **reliable electrocoupling extraction;**
- **capabilities of the reaction models to obtain resonance electrocouplings in independent analyses of these channels.**

Published in the recent edition of the PDG , Chin. Phys. C40, 100001 (2016).

Electrocouplings of the Resonances Formed by Three Quarks of Non-zero Orbital Momentum from the CLAS $\pi^+\pi^-$p Electroproduction Data

V.I. Mokeev and I.G. Aznauryan., Int. J. Mod. Phys. Conf. Ser. 26. 146080 (2014)

V.I. Mokeev et al., PRC 93, 054016 (2016)



Independent fits in different W-intervals:

green: 1.51<W<1.61 GeV **red: 1.61<W<1.71 GeV** **black: 1.71<W<1.81 GeV**
magenta: 1.56<W<1.66 GeV **blue: 1.66<W<1.76 GeV**

- **The $\pi^+\pi^-$p electroproduction is the major source of the information on electrocouplings of $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ which decay preferentially to the $N\pi\pi$ final states. $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$ resonances consists of 3 quarks with L=1, while $N(1720)3/2^+$ is formed by 3 quarks with L=2.**

- **The electrocouplings of $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances have become available from the $\pi^+\pi^-$p electroproduction off protons for the first time.**

- **Recent DSE studies revealed the critical importance of the data on electrocouplings of orbital-excited resonances in order to access to access full complexity of quark-gluon vertex dressing (slide # 3).**

New Opportunities in the N* Structure Exploration

New data set on exclusive $\pi^+\pi^-p$ electroproduction off protons cross sections measured with the CLAS at 1.4 GeV < W < 2.0 GeV and Q^2 from 2.0 GeV^2 to 5.0 GeV^2 will allow us:

- **determine electrocouplings of all prominent resonances in mass range up to 2.0 GeV and highest photon virtualities covered with 6.0 GeV electron beam;**

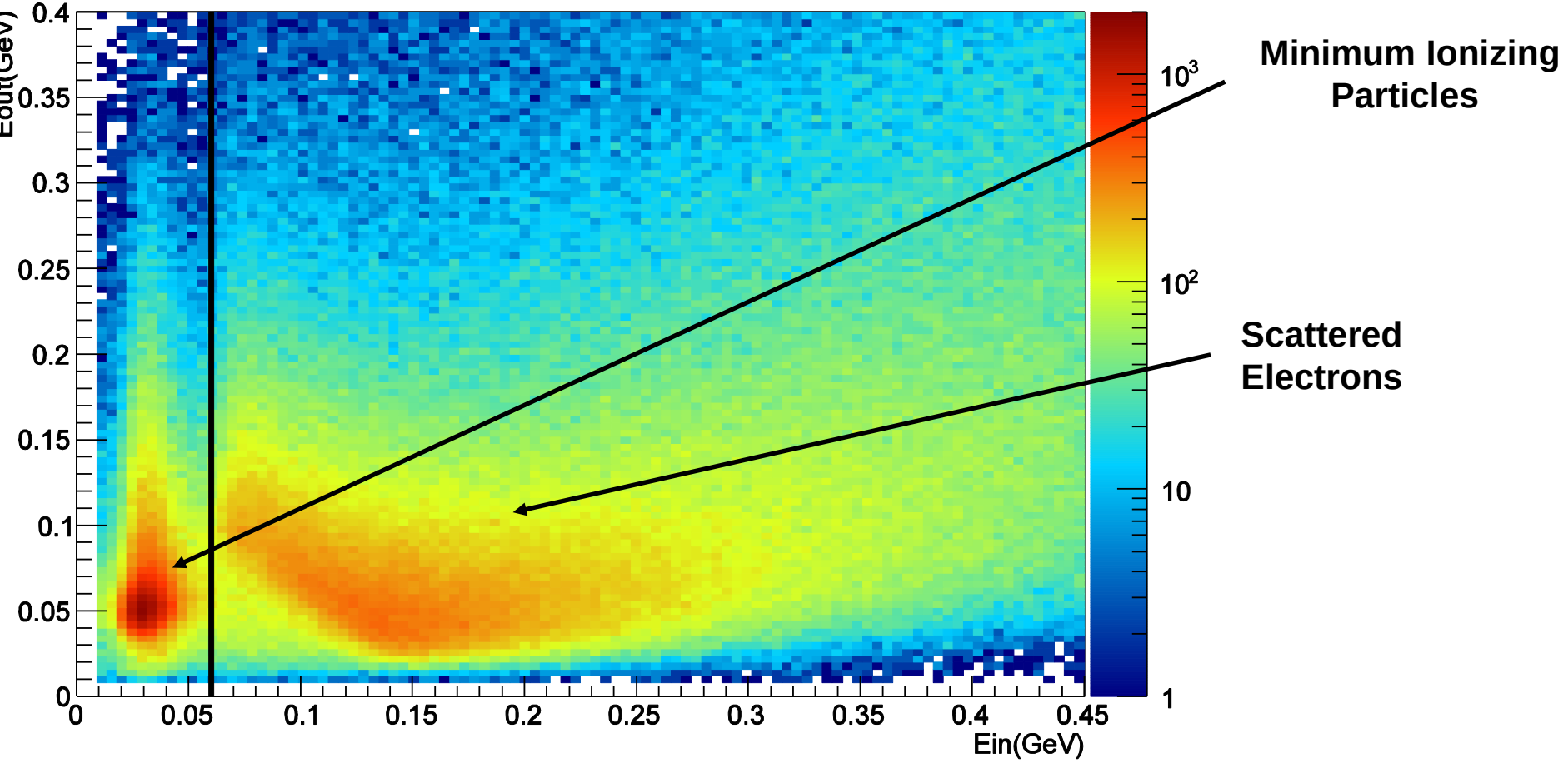
- **explore in detail the N* structure evolution at the distances where the transition from combined contribution of inner quark core and outer meson-baryon cloud to the dominance of the quark core component takes place;**

- **new data on electrocouplings of orbital-excited resonances are critical in order to map the full nonperturbative complexity of the quark-quark scattering kernel and test modern predictions of this fundamental quantity in the synergistic efforts between experimentalists and theorists under leadership by Dr. V.D. Burkert (Jlab) and Dr. C.D. Roberts (ANL).**

Experimental Parameters for e1-6 Run Period with CLAS

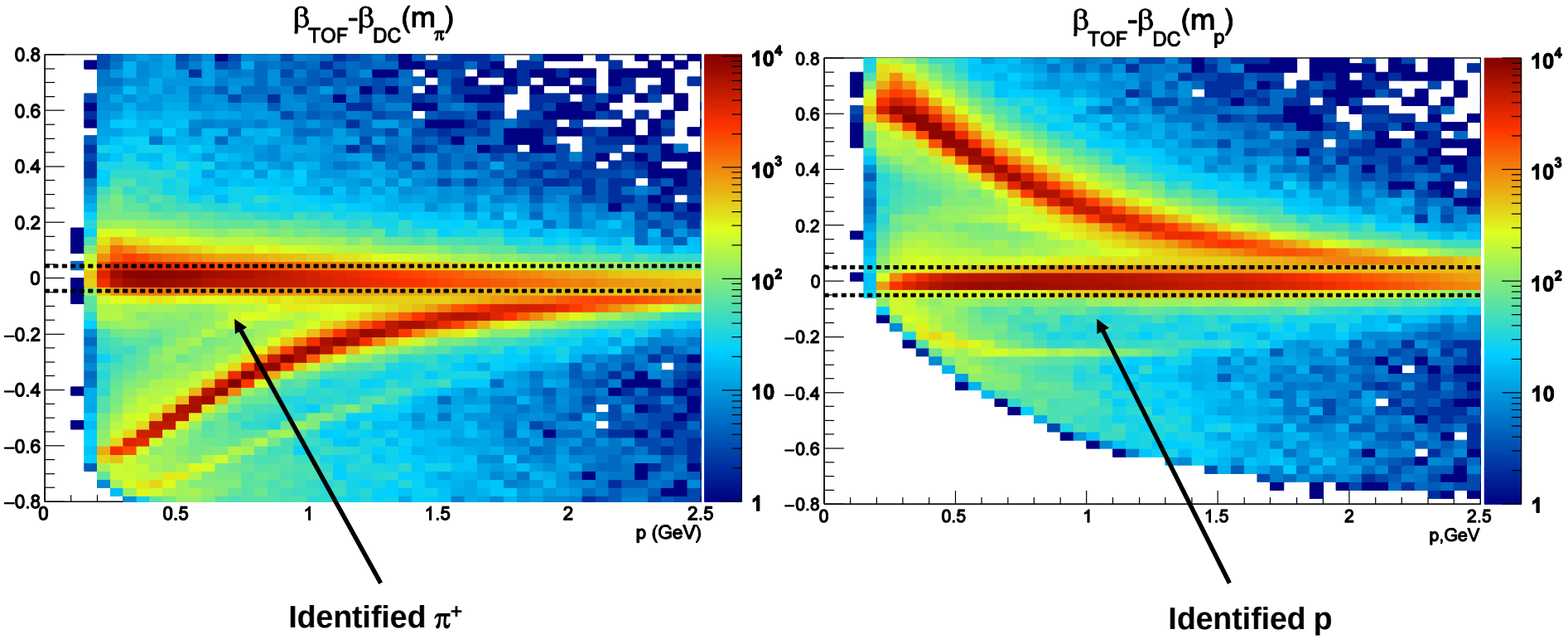
- Beam energy 5.75 GeV
- Beam current 7.0 nA (averaged)
- Liquid hydrogen target (5 cm long)
- Torus current 3375 A
- Mini-Torus current 3375 A
- Open trigger: above-threshold signal in CC + signal in EC

Electron Identification



- Specific electron signature in EC in the correlations E_{out} vs E_{in}
- Momentum-dependent 2.5σ cut for the quantity E_{dep}/P in EC
- Projected vertex should be on the LH target (z-vertex cut)

Positive Hadron Identification



- **Comparison between particle velocity determined from TOF β_{TOF} and from particle momentum measured with DC β_{DC} for certain assignment of the particle mass m_π/m_p**

- **In a case of correct particle ID, $\beta_{TOF}=\beta_{DC}$**

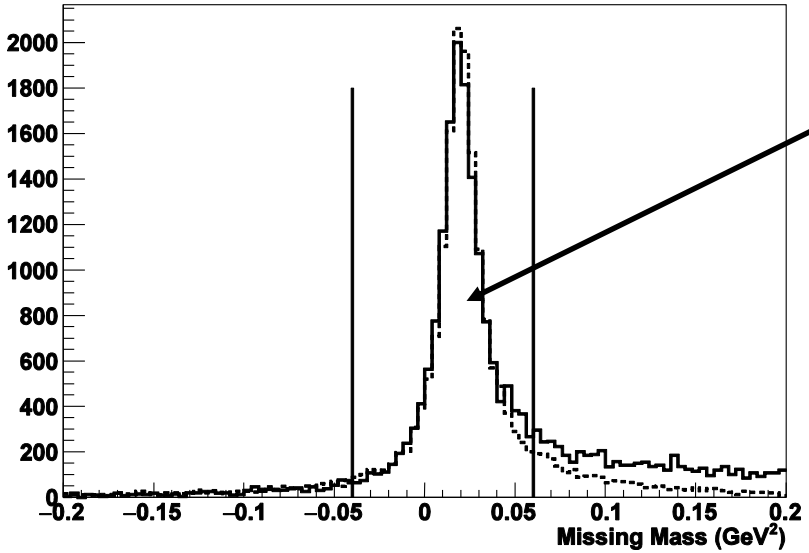
List of Selections/Corrections to Isolate $\pi^+\pi^-$p Events

- Electron ID
  - Calorimeter cuts
  - Cherenkov cut
  - Fiducial cuts
  - Zvertex cut
  - Momentum corrections
  - Zvertex corrections

Charged hadrons ID

- Beta vs Momentum cut
- Fiducial cuts
- Zvertex cut
- Theta vs p cuts
- Bad scintillators cut
- Momentum corrections for positive pion
- Energy loss corrections for proton

Exclusivity Cut & Kinematics Coverage

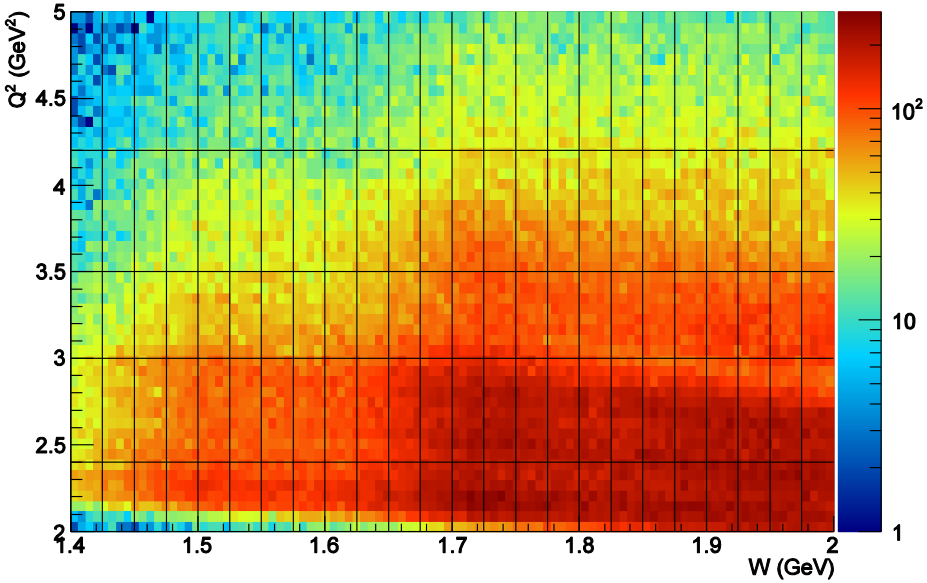


$\pi^+\pi^-p$ events

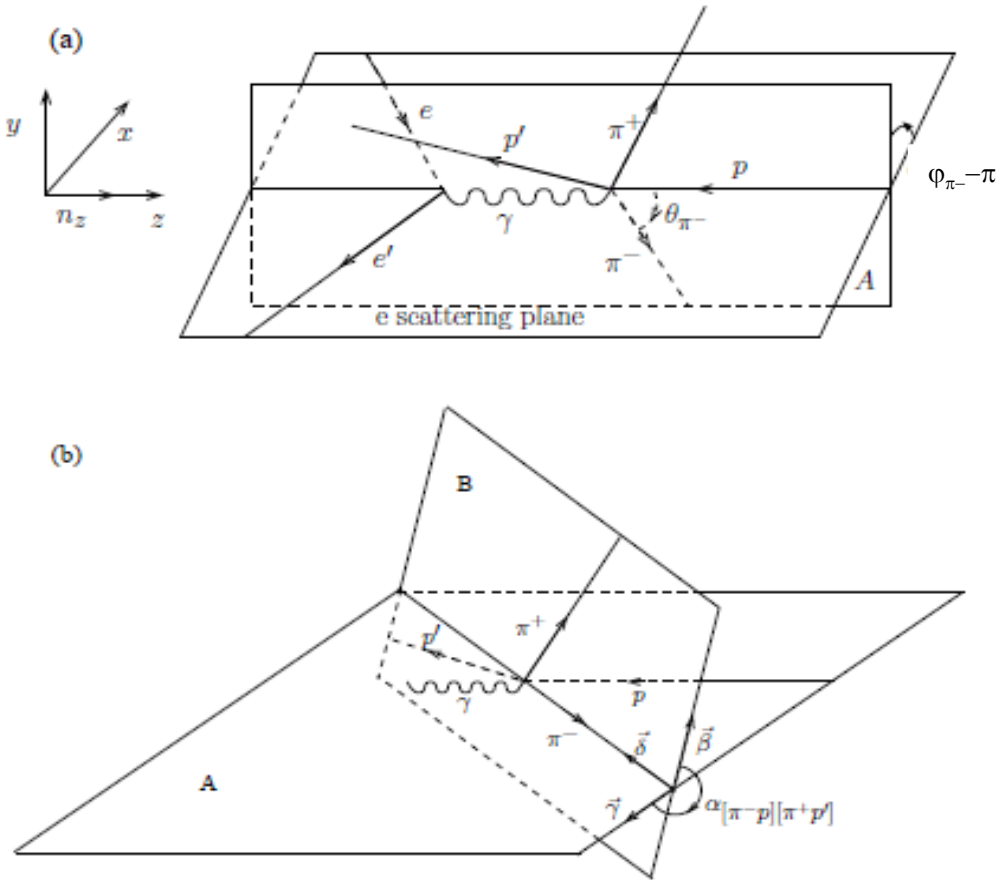
Data

MC simulation

336668 exclusive $\pi^+\pi^-p$ events events were selected.



ep→ e'$\pi^+\pi^-$p' Reaction Kinematics



Overall:
7 variables for ep→ e'$\pi^+\pi^-$p'

Five variables for the final $\pi^+\pi^-$p state :

- **Invariant masses of the two final hadron pairs: M_{ij}, M_{jk} ; i,j,k = π^+, π^-, p;**
- **Polar and azimuthal angles for the final hadron I θ_i, φ_i ;**
- **Angle $\alpha_{[p,i][j,k]}$ between two planes A and B shown in the bottom panel.**

Two variables for the initial γ_Vp state :

- **Four-momentum squared of the virtual photons $q_\mu{}^2 = -Q^2$;**
- **Invariant mass of the initial virtual-photon-proton (the final hadron system) W.**

Differential Cross Sections for $\pi^+\pi^-$p Electroproduction

7-fold differential ep→ e'$\pi^+\pi^-$p' cross section:

$$\frac{d^7\sigma}{dW\,dQ^2 d^5\tau} \qquad d^5\tau = d\,M_{ij}\,d\,M_{jk}\,d(-\cos\theta_i)\,d\varphi_i\,d\,\alpha_{[ip][jk]}$$

$$i,j,k = \pi^+,\pi^-,p$$

$$\frac{d^7\sigma}{dW\,dQ^2 d^5\tau} = \frac{\Delta N}{\varepsilon_{MC} RL\Delta W\Delta Q^2 \Delta^5\tau}$$

- **ΔN is the number of measured $\pi^+\pi^-$p events in 7d-bin;**
- **ε_{MC} and R stand for the detection efficiency available from MC simulation and radiative correction factor;**
- **L is the integrated luminosity**

one-photon exchange approximation for e scattering

$$\frac{d^7\sigma}{dW\,dQ^2 d^5\tau} = \Gamma_v \frac{d^5\sigma}{d^5\tau}$$

Virtual photon flux Γ_v is fully determined by e-scattering Kinematics.

Grid for 7-fold cross sections consists of 3606120 kin. independent cells populated with just 336668 $\pi^+\pi^-$p events , making possible evaluation of one-fold differential cross sections only.

Nine independent one-fold differential cross sections were obtained by integrating common 5-fold differential virtual photon cross sections over different sets of four Variables:

Invariant mass distributions:

$$\frac{d\sigma}{d\,M_{\pi^+\pi^-}} \quad \frac{d\sigma}{d\,M_{\pi^+ p}} \quad \frac{d\sigma}{d\,M_{\pi^- p}}$$

CM-polar-angle distributions:

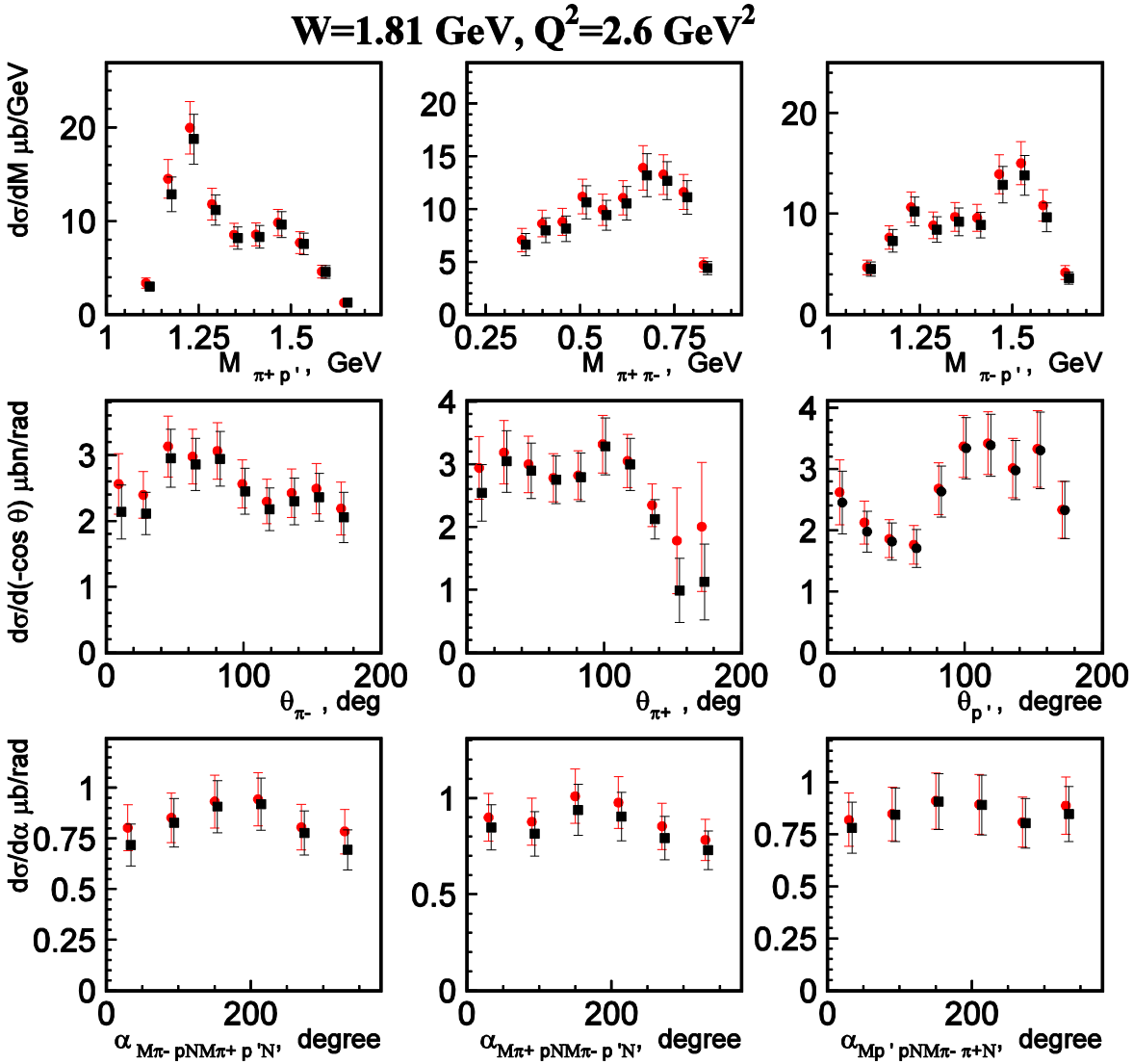
$$\frac{d\sigma}{d(-\cos\,\theta_{\pi^-})} \quad \frac{d\sigma}{d(-\cos\,\theta_{\pi^+})} \quad \frac{d\sigma}{d(-\cos\,\theta_p)}$$

CM-α-angle distributions:

$$\frac{d\sigma}{d\,\alpha_{[\pi^- p][\pi^+ p']}} \quad \frac{d\sigma}{d\,\alpha_{[\pi^+ p][\pi^- p']}} \quad \frac{d\sigma}{d\,\alpha_{[p' p][\pi^+\pi^-]}}$$

Statistical accuracy for one-fold differential cross sections in in range from 14% to 20 %

Interpolating 7-Fold $\pi^+\pi^-$p Electroproduction Cross Section into the Blind CLAS Areas



Cross sections in full acceptance

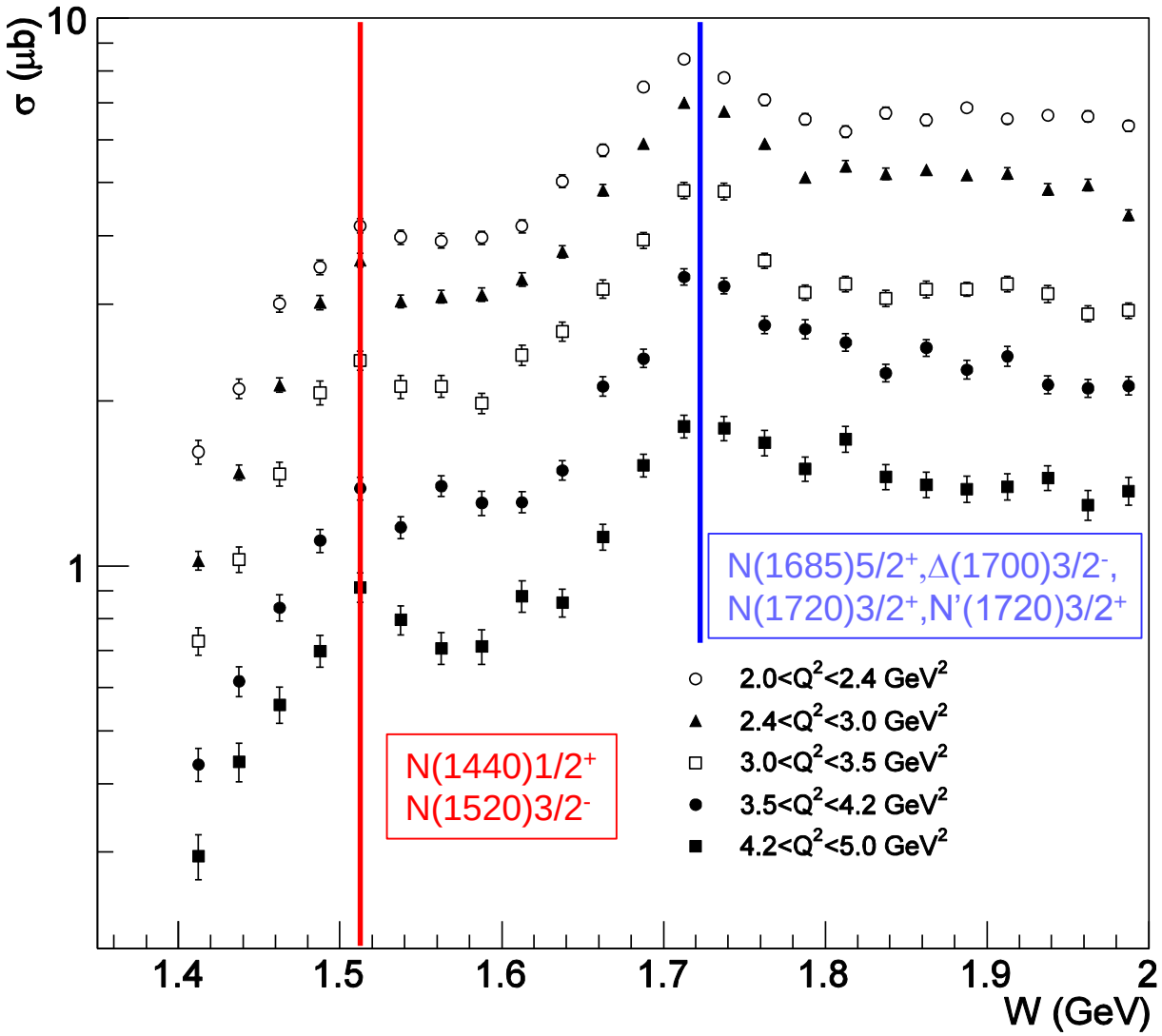
Cross sections within CLAS acceptance

Systematics uncertainties from 7d cross section interpolation into the blind CLAS areas are in range from 5 % to 10%

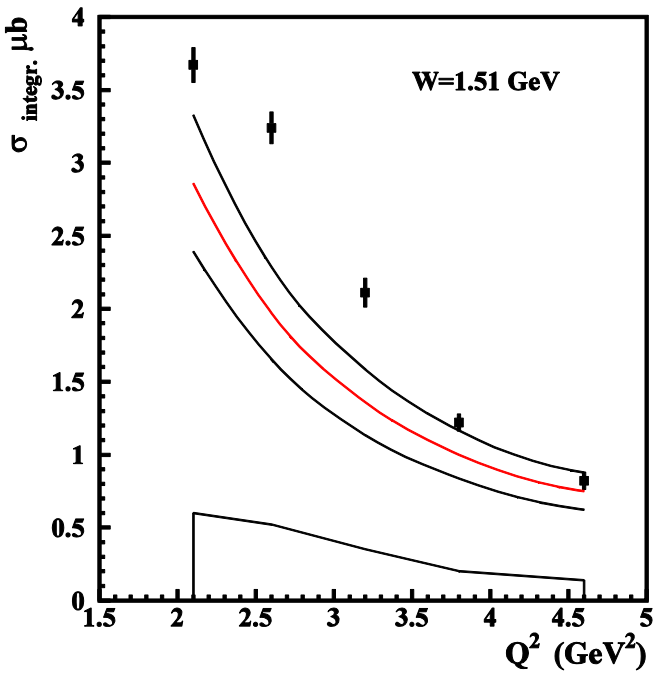
Fully Integrated Virtual Photon $\pi^+\pi^-p$ Cross Sections

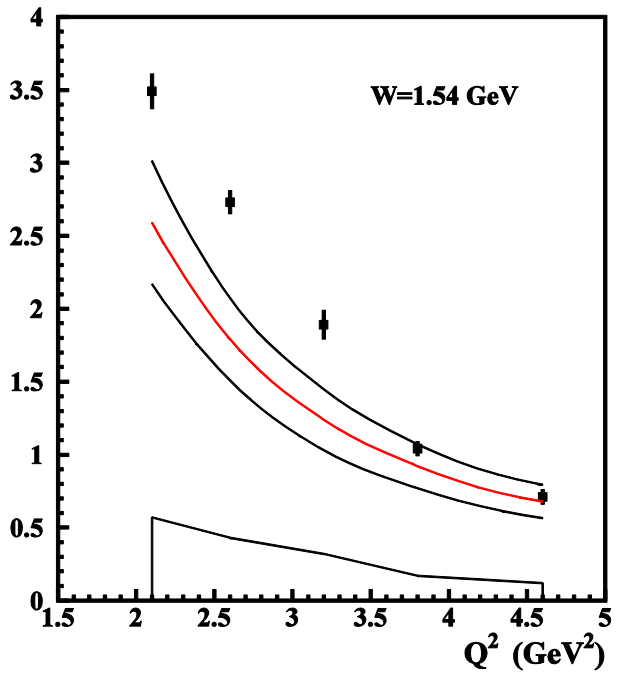
Systematics summary

Source of systematics	Uncertainty, %
Yield normalization	10.0
7d-cross section Interpolation into the blind areas	5.0-10.0
Missing mass cut	4.2
Hadron fiducial cuts	2.0
Hadron ID cuts	4.6
Radiative corrections	5.0
Detection efficiency	5.0
Total	**15.7**



Resonant Contributions to Fully Integrated $\pi^+\pi^-p$ Cross Sections





Resonant cross sections:

Central values

Uncertainty range

Data point error bars show the stat. Uncertainty

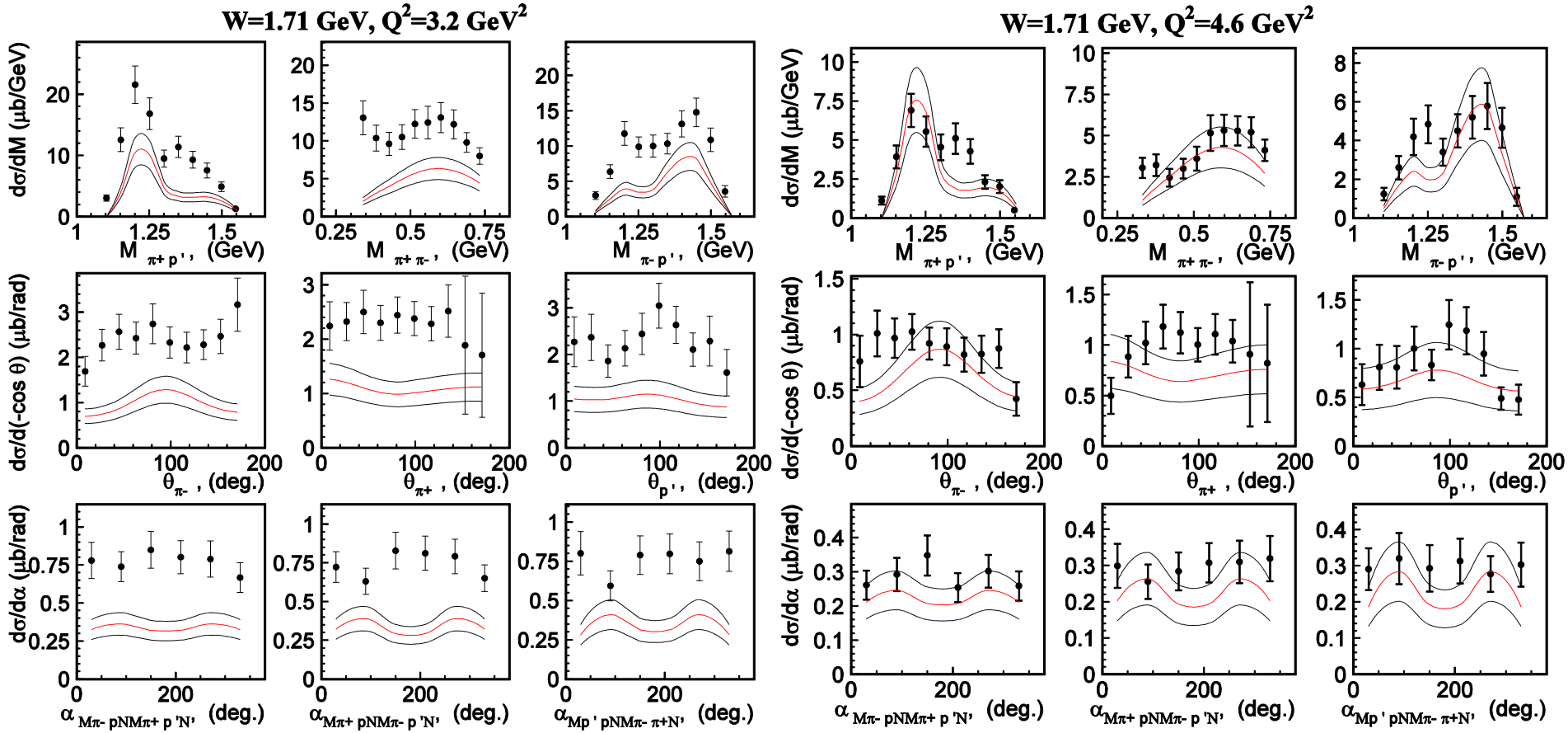
Bands on the bottom are the data syst. uncertainties

- **Resonant contributions were computed within the framework of unitarized Breit-Wigner ansatz employed in the JM model which allowed us to extract successfully resonance electrocouplings from the CLAS $\pi^+\pi^-p$ electroproduction off protons data.**

- **Resonance electrocouplings and $\pi\Delta$/ ρp decay widths were taken from the CLAS results (https://userweb.jlab.org/~mokeev/resonance_electrocouplings/, https://www.jlab.org/Hall-B/secure/e1/isupov/couplings/section1.html and references therein).**

The relative resonant contribution increases with photon virtuality.

Resonant Contributions to Differential $\pi^+\pi^-p$ Cross Sections



Sizable resonant contributions and distinctive shape difference for the resonant and full cross sections demonstrate the promising opportunity for extraction of resonance electrocouplings

Evolution of the Resonant Contributions

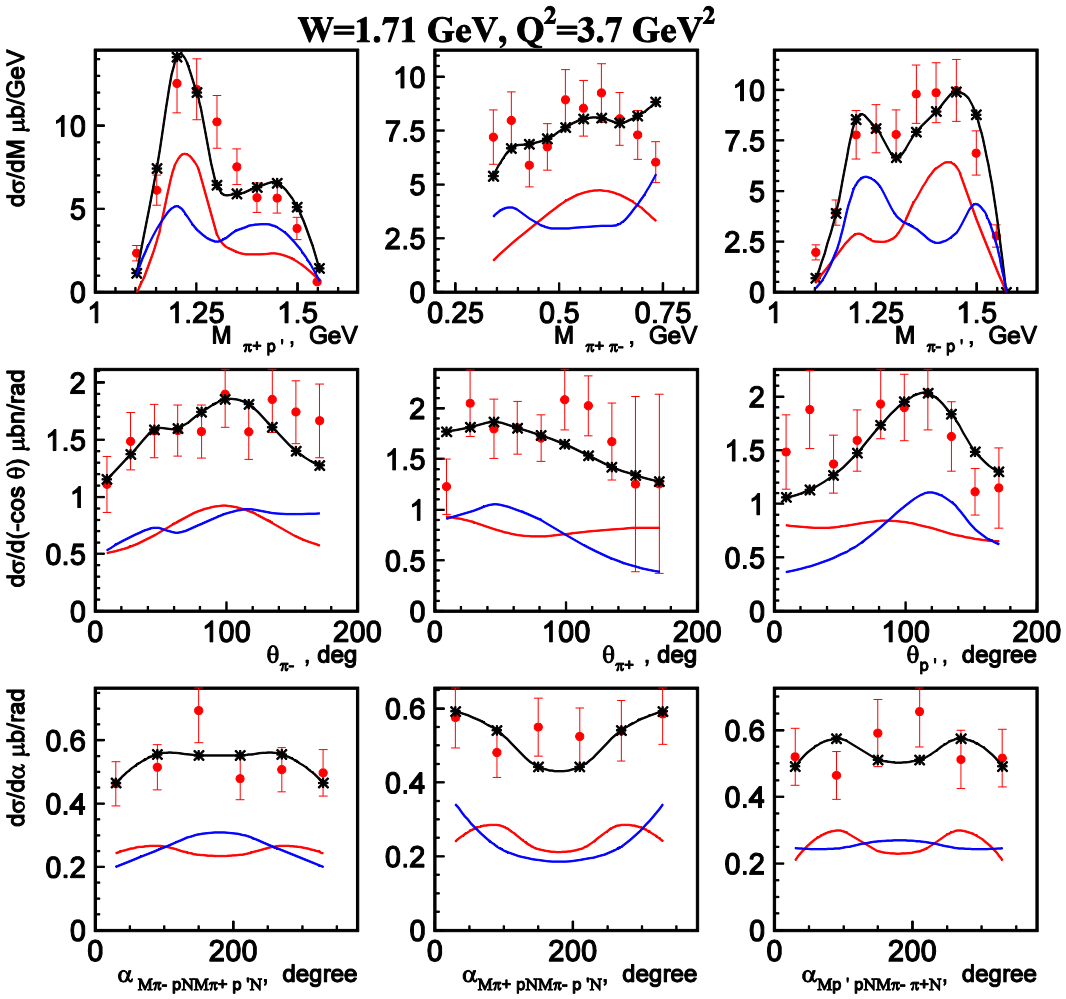
Ratio resonant part over full integrated cross sections averaged over three W-intervals:

- **1.41 GeV < W < 1.61 GeV – interpolation of $\gamma_v pN^*$ electrocouplings over Q^2;**
- **1.61 GeV < W < 1.74 GeV – extrapolation of $\gamma_v pN^*$ electrocouplings over Q^2;**
- **1.74 GeV < W < 1.82 GeV – mass range without well established resonances.**

Q^2, GeV^2	$1.41 < W < 1.61$, GeV	$1.61 < W < 1.74$, GeV	$1.74 < W < 1.82$, GeV
2.1	0.650 ± 0.033	0.570 ± 0.034	0.200 ± 0.019
2.6	0.570 ± 0.029	0.500 ± 0.028	0.180 ± 0.010
3.2	0.550 ± 0.029	0.490 ± 0.029	0.190 ± 0.017
3.8	0.660 ± 0.034	0.620 ± 0.034	0.210 ± 0.014
4.6	0.750 ± 0.041	0.790 ± 0.049	0.240 ± 0.017

A substantial decrease of the resonant contribution over full cross section ratio at 1.74 GeV < W < 1.82 GeV is suggestive for the contribution from ``missing" baryon states not included in the current evaluation of the resonant contribution.

Outlook: Representative Example of the Differential Cross Section Description with the Updated JM17 model



Full JM17 Model:
Resonant & Non-resonant contributions

Good data description at
1.40 GeV < W < 2.00 GeV and
2.0 GeV² < Q² < 4.2 GeV² with
χ^2/d.p. < 1.4

Full

Resonant part

Non-resonant part

The data description at W ~1.7 GeV requires the contribution from new candidate-state N'(1720)3/2⁺ at 2.0 GeV²< Q² < 4.0 GeV², supporting strong evidence for this new state from combined analyses of the CLAS $\pi^+\pi^-$p photo-/electroproduction data at Q²<1.5 GeV² (V.I.Mokeev et al., Eur. Phys. J. Web Conf. 113, 01013 (2016)).

Conclusions and Outlook

- **Nine independent one-fold differential and fully integrated $\pi^+\pi^-p$ electro-production off protons cross sections have become available for the first time at 1.4 GeV<W<2.0 GeV and photon virtualities 2.0 GeV^2 < Q^2 < 5.0 GeV^2. The paper for PRC are under the CLAS Collaboration review.**

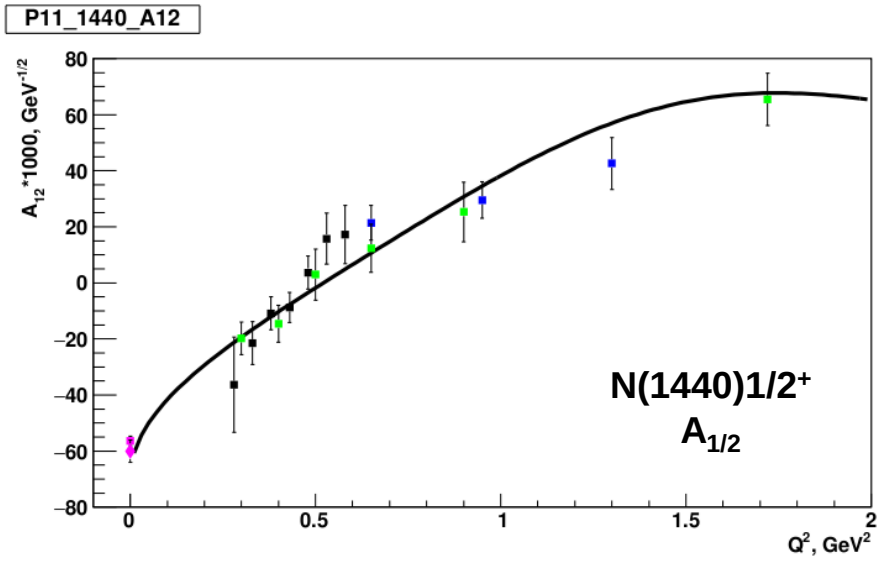
- **Analysis of the resonant contributions to the measured cross sections revealed growth of the resonant fraction in full cross sections with Q^2 and distinctive differences in the shapes of the resonant and full cross sections, suggesting good prospects for extraction of $\gamma_v pN^*$ electrocouplings for most N* with masses up to 2.0 GeV from the new data set.**

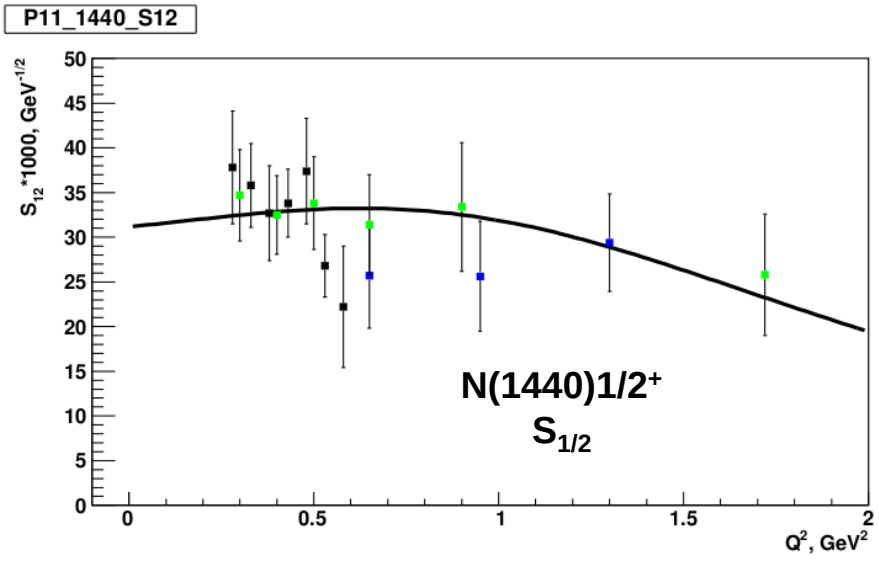
- **Promising opportunity to explore the N* structure at the distances where the transition from combined contribution of meson-baryon cloud and quark core to the quark core dominance takes place.**

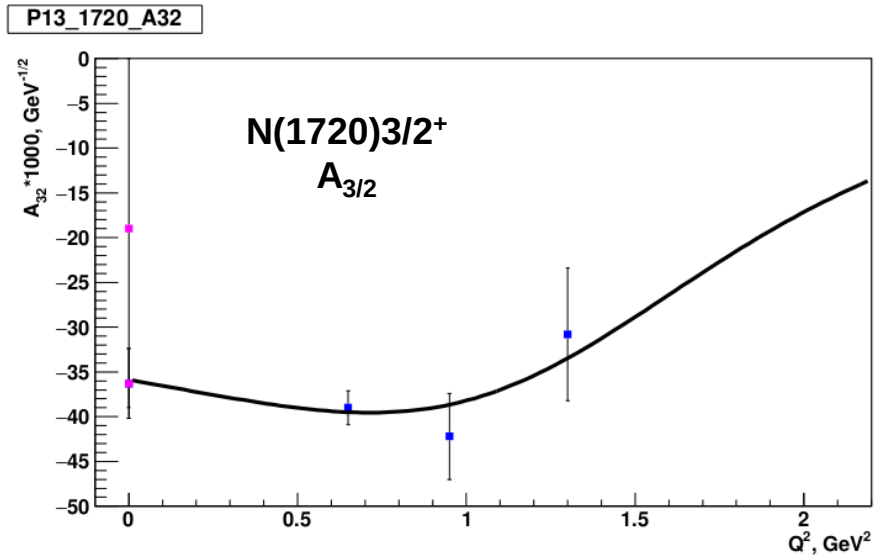
- **Data on $\gamma_v pN^*$ electrocouplings for high lying N* (M>1.6 GeV) with inner core of orbital-excited three quarks (L_{3q} >0) open prospect to explore complexity of dressed quark-gluon vertex and quark correlations for di-quarks of different quantum numbers in synergistic efforts between experimentalists and theorists offering a unique access to the essence of the strong QCD dynamics.**

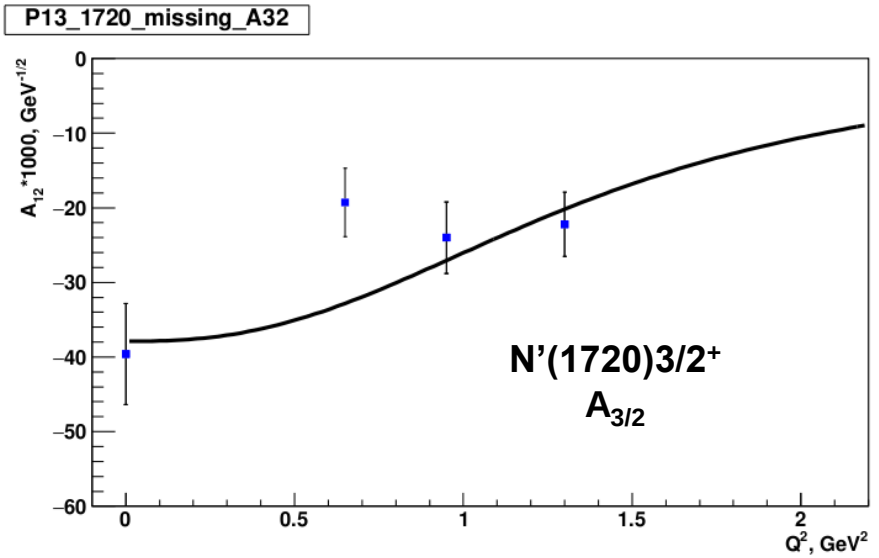
Back - up

Interpolation/Extrapolation of the CLAS Results on $\gamma_v pN^*$ electrocpouplings







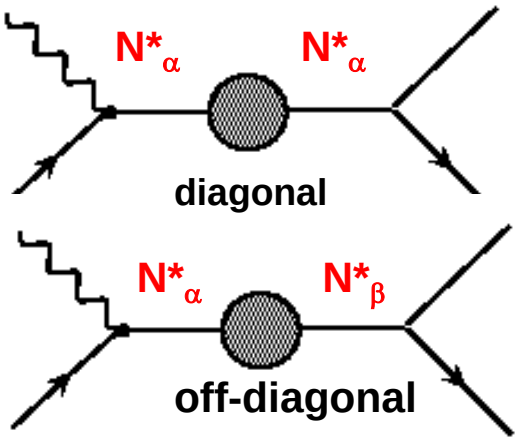


- **The CLAS results on $\gamma_v pN^*$ electrocouplings for the excited states in mass range up to 1.8 GeV are interpolated/extrapolated at 0.GeV^2 <Q^2 < 5.0 GeV^2 (userweb.jlab.org/~isupov/couplings/).**
- **The Fortran code for computation of the interpolated electrocoupling values are available upon request (E.L.Isupov, isupov@jlab.org)**

Resonant Contributions to Exclusive, Semi- Inclusive, and Inclusive Processes

Resonant amplitude in exclusive $\gamma p \to MB$ channel :

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



- α,β label the N* states included, sum over repetitive α and β is assumed.
- Resonance electroproduction $f_{\alpha\,\gamma p}$ and hadronic decay $f_{\beta\,MB}$ amplitudes are related to the $\gamma_v pN^*$ electrocouplings and partial N* hadronic decay width Γ_β (V.I. Mokeev, et al., PRC 86, 035203 (2012))

Inverse of the unitarized resonant propagator:

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

$N(1535)1/2^- \leftrightarrow N(1650)1/2^-$
$N(1520)3/2^- \leftrightarrow N(1700)3/2^-$
$N'(1720)3/2^+ \leftrightarrow N(1720)3/2^+$

Accounting for the transition between the same and different N* states makes the resonant amplitude consistent with the restrictions imposed by a general unitarity condition ⟹ the most advanced version of the Breit-Wigner ansatz.

The resonant contribution to semi-inclusive and inclusive processes can be evaluated by summing up the described above resonant amplitudes over all contributing meson-baryon channels.