New Results on $\gamma_v p \rightarrow p'\pi^+\pi^-$ Cross Sections in the Resonance Region With CLAS

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NSTAR 2017

The 11th International Workshop on the Physics of Excited Nucleons

August 20 - 23, Columbia, South Carolina

CLAS "e1e" experiment, E_{beam} = 2.039 GeV

The goal was to extract integral and single-differential cross sections of the reaction $\gamma_v\, p(n) \rightarrow p'(n')\pi^+ \pi^-$ for $1.3 < W < 1.8125$ GeV and $0.4 < Q^2 < 1.3$ GeV^2

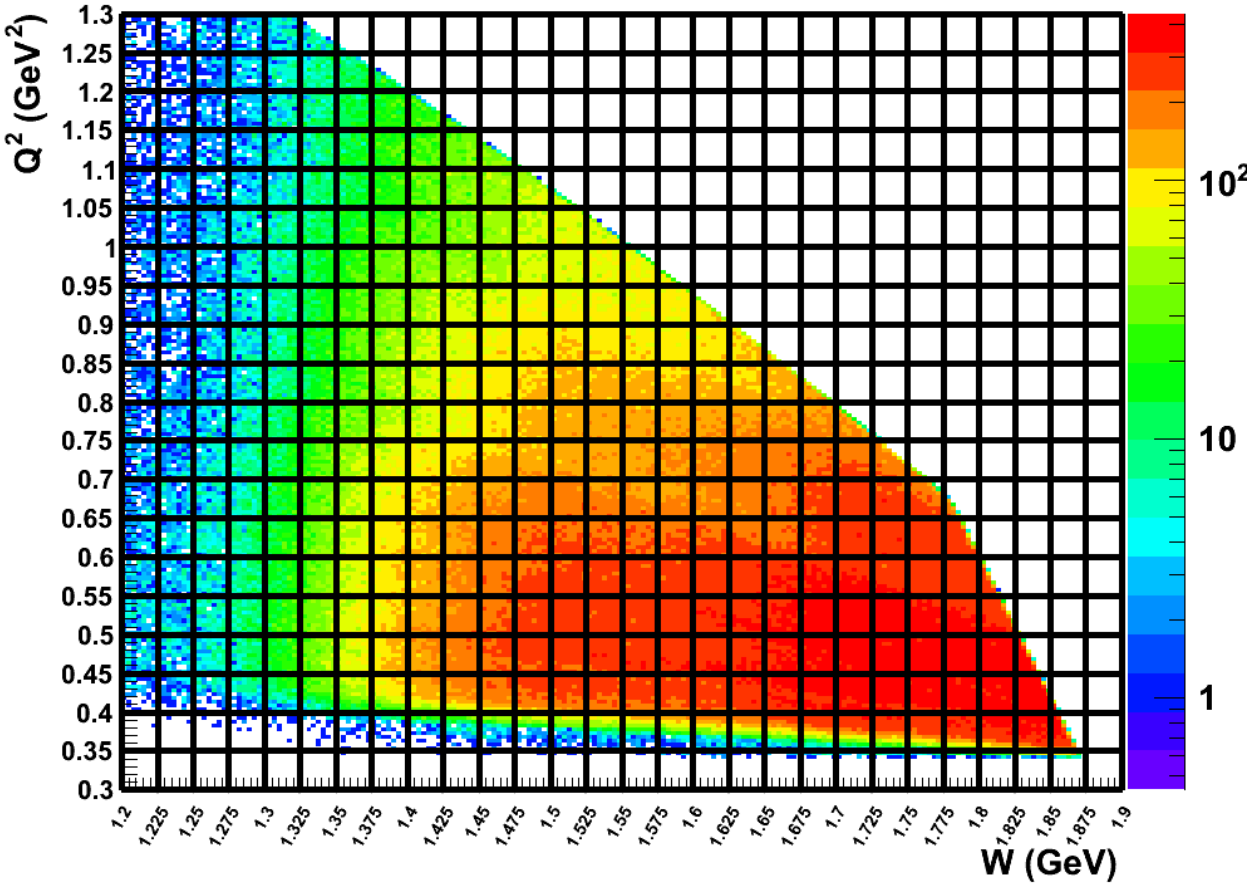
In the single-photon exchange approximation the virtual photoproduction cross section is connected with the experimental electron scattering cross section in the following way

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

Final hadrons are described by 5 independent variables

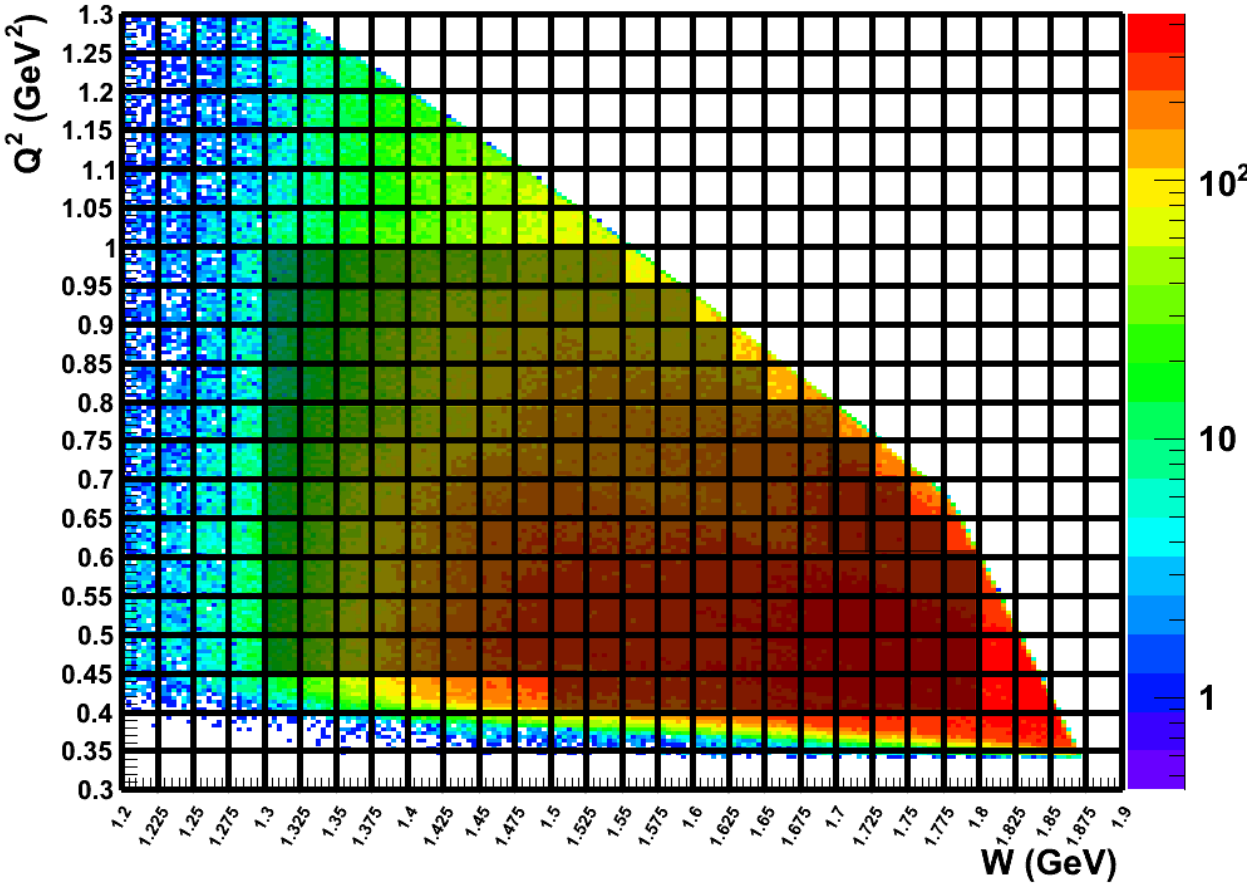
$$d^5\tau \;=\; dM_{\pi^+p}\,dM_{\pi^+\pi^-}\,d\Omega_{\pi^-}\,d\alpha_{[\pi^-p][\pi^+p']}$$

$N\pi^+\pi^-$ Electroproduction Kinematic Coverage



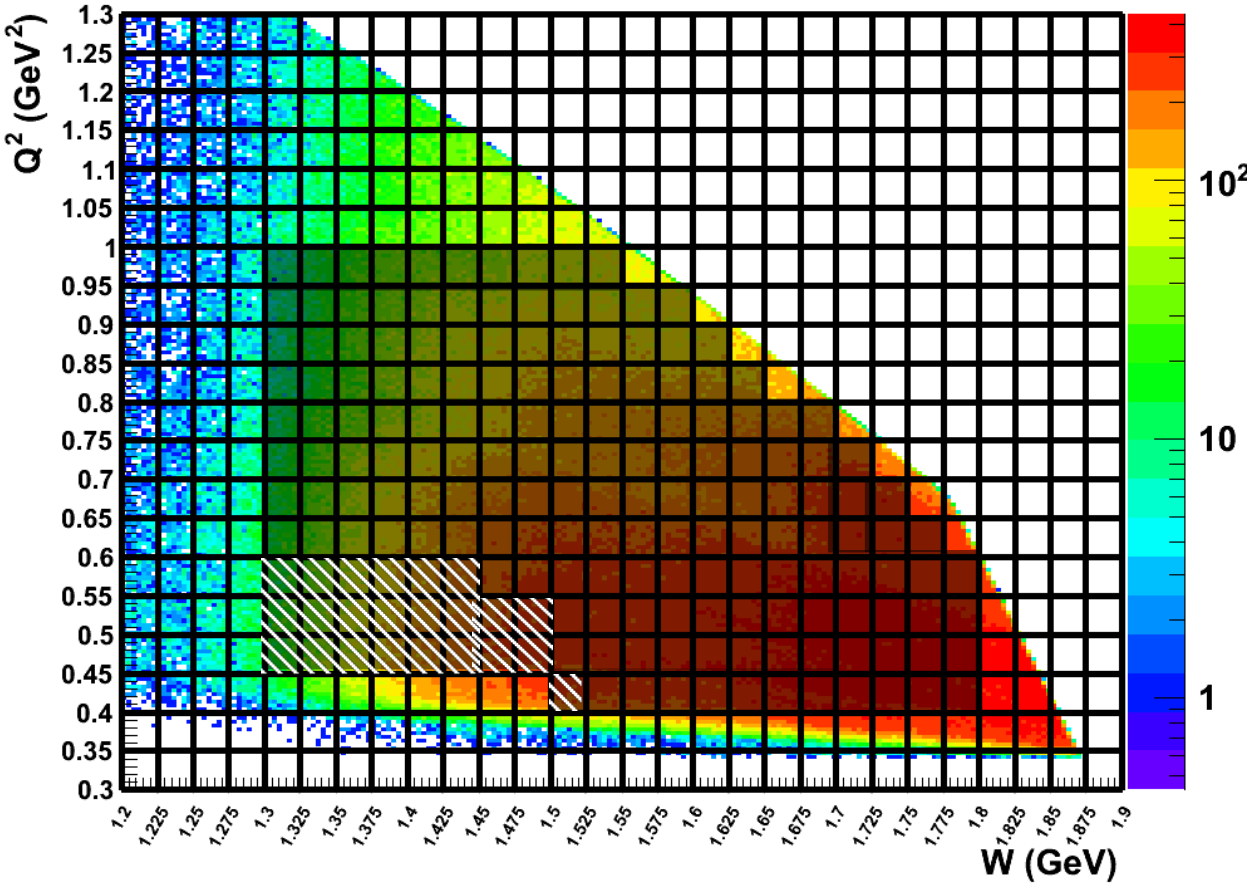
Yield of double-pion events over W and Q^2.

$N\pi^+\pi^-$ Electroproduction Kinematic Coverage



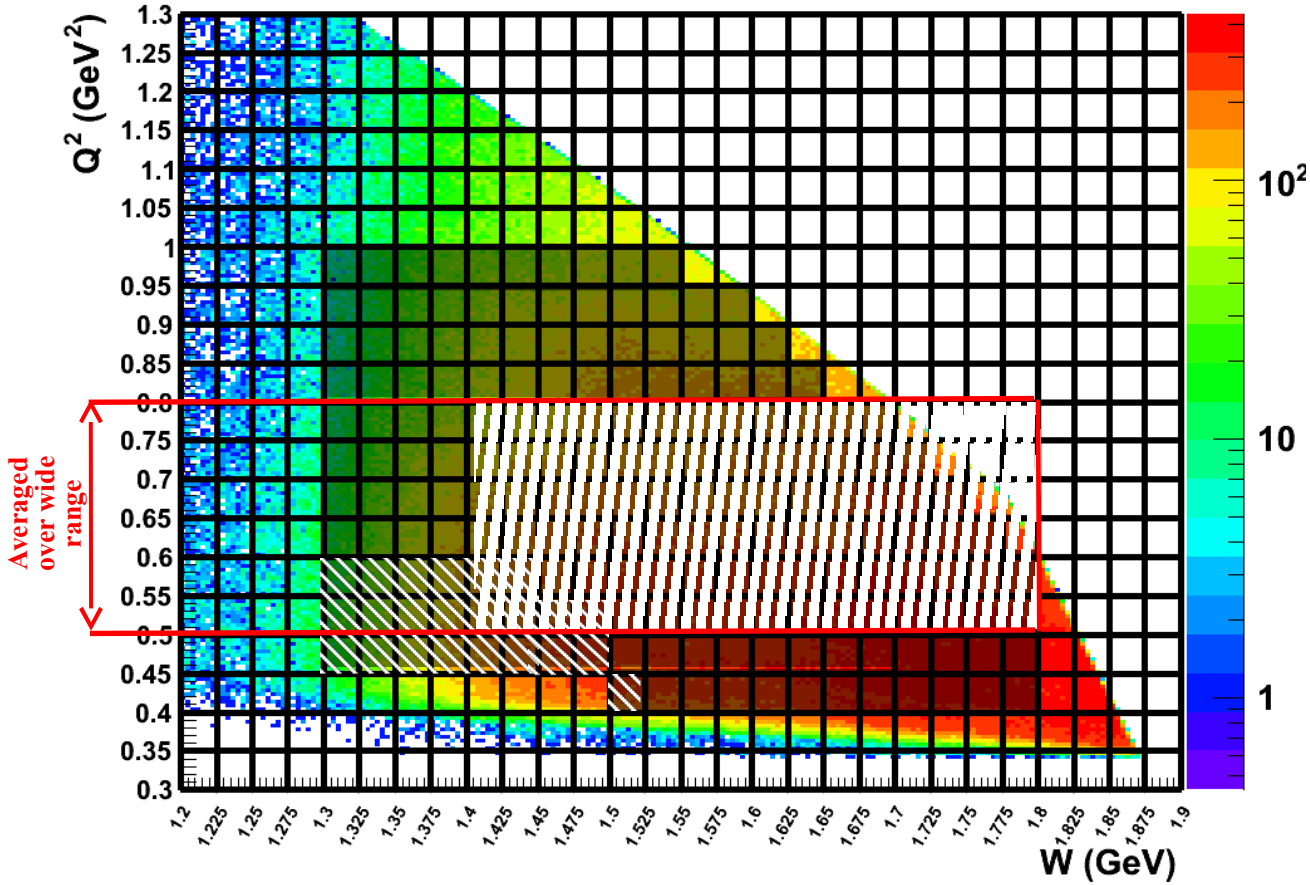
Shaded area corresponds to the region were cross sections were extracted.

$N\pi^+\pi^-$ Electroproduction Kinematic Coverage



Hatched area at low Q^2 stands for already published e1c data by G. Fedotov *et al.* Phys. Rev. C 79, 015204 (2009).

$N\pi^+\pi^-$ Electroproduction Kinematic Coverage



Hatched area at higher Q^2 stands for published data in one large Q^2 bin by M. Ripani et al. Phys. Rev. Lett. 91, 022002 (2003)

Importance of the Results

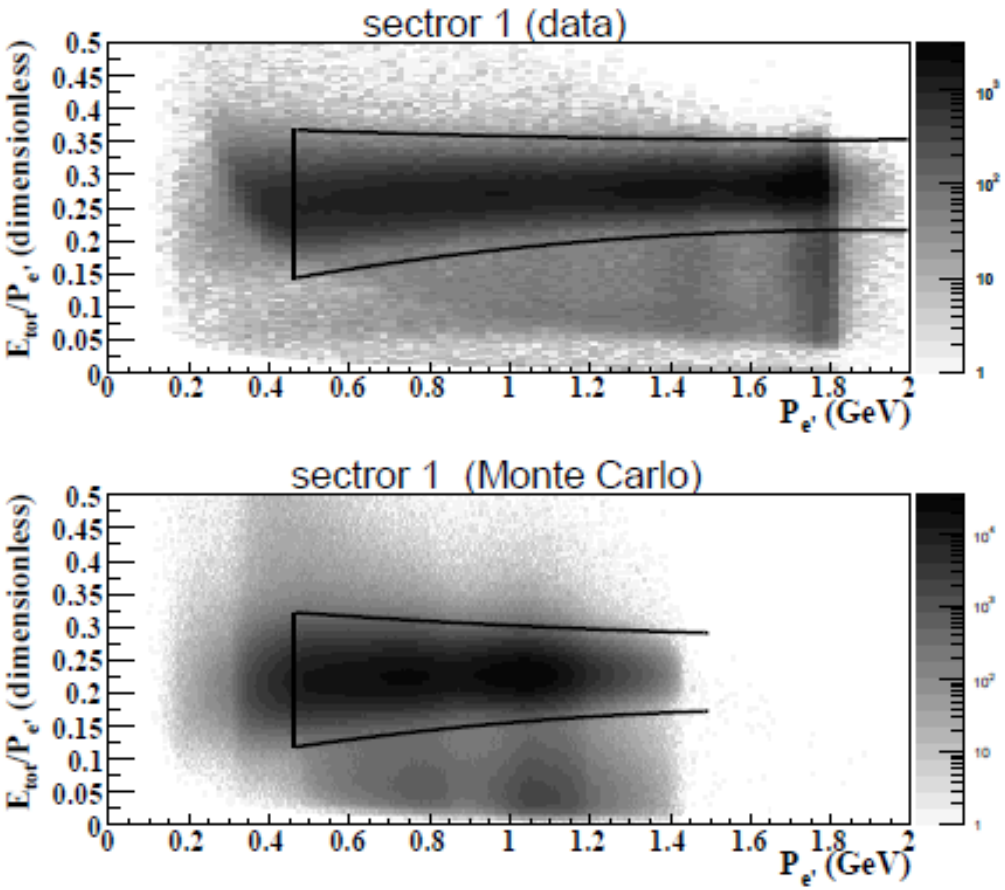
- Measurements were carried out in the so far unexplored kinematic region.
- Experimental statistics allowed to extract cross sections with very fine binning (Q^2-bins of six times smaller size than previously achieved).
- The results are of a great significance for nucleon resonance investigation, since many excited nucleon states with masses above 1.6 GeV are known to decay to the $N\pi\pi$ final state.

Selection of Double-Pion Events

Cuts	Data	Simulation
Fiducial	yes	yes
EC-cut	yes	yes
CC-cut	yes	no/yes
β vs. p	yes	yes
θ vs. p	yes	yes
Electron momentum correction	yes	no
Proton energy loss correction	yes	yes
Exclusivity cut	yes	yes

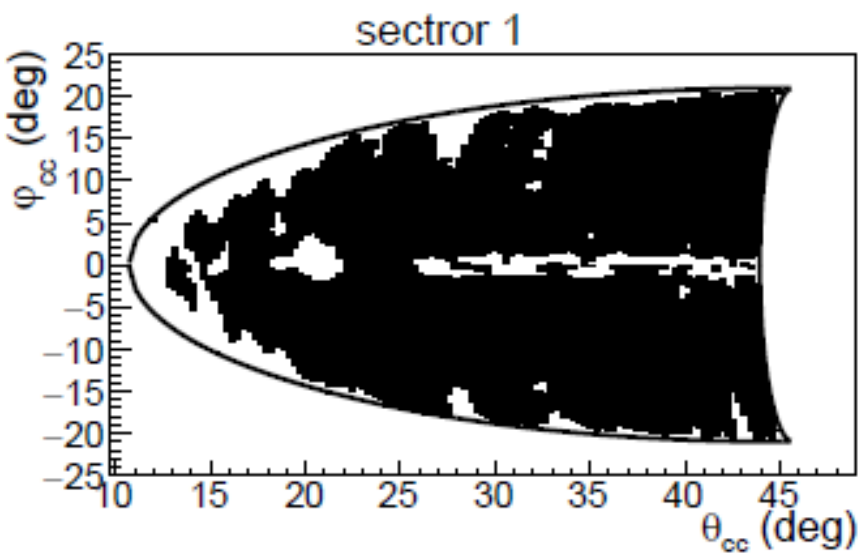
Electron Identification (EC cut)

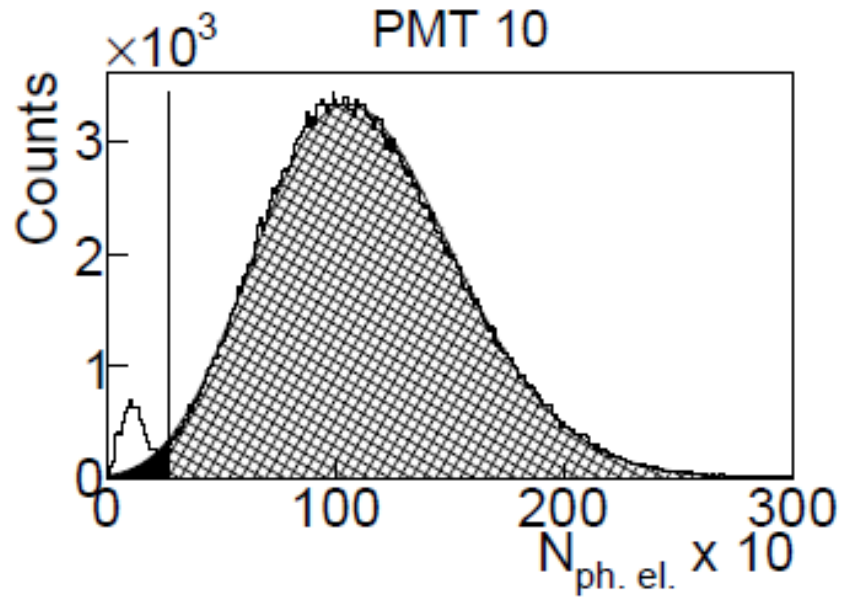
Electrons are identified by their coincident signals produced in the DC, CC, SC and EC detector elements as first in time particles.



- Total energy deposited in the electron calorimeter (EC) divided by electron momentum versus electron momentum.
- We identify events enclosed by the black curves as electrons.

Electron Identification (CC cut)



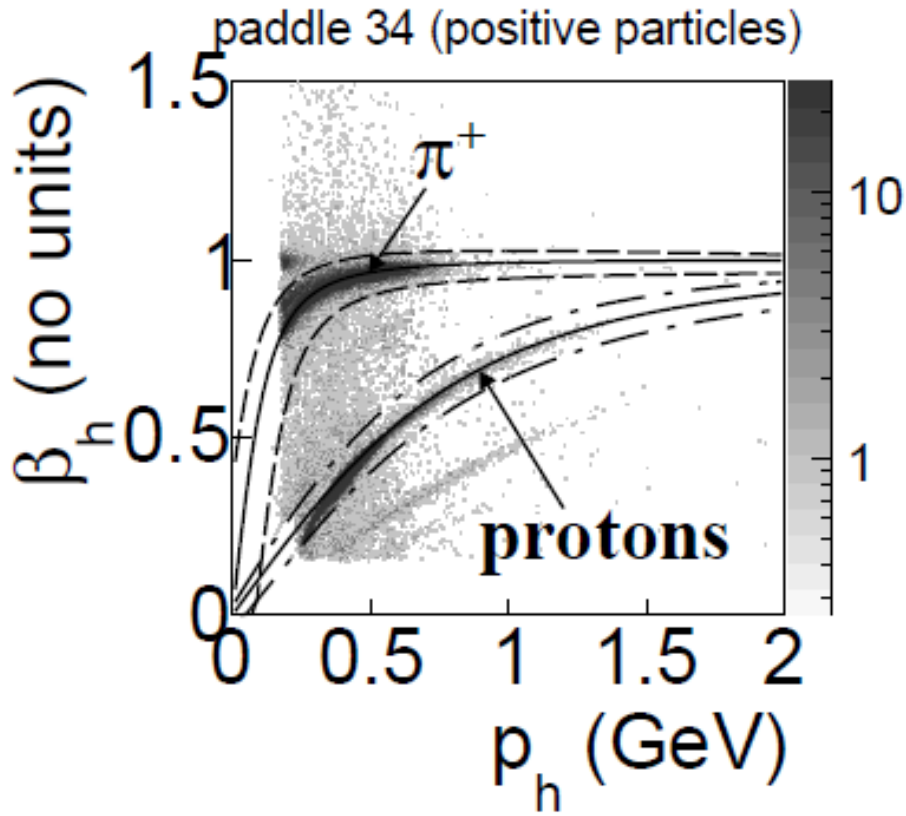


- Only efficient CC zones, shown by black in the left figure, were included into analysis.
- An addition correction factor was introduced to recover removed good events (shown by the black area in the right plot).

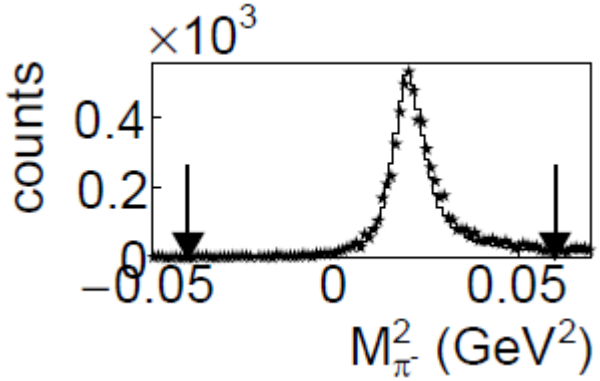
Hadron Identification

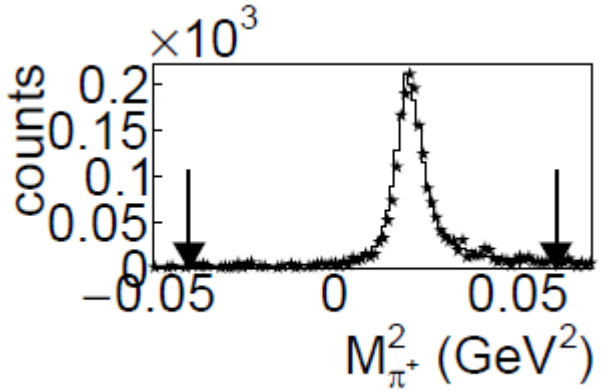
To identify hadrons information from the drift chambers (DC) and time-of-flight detector paddles (SC) are used.

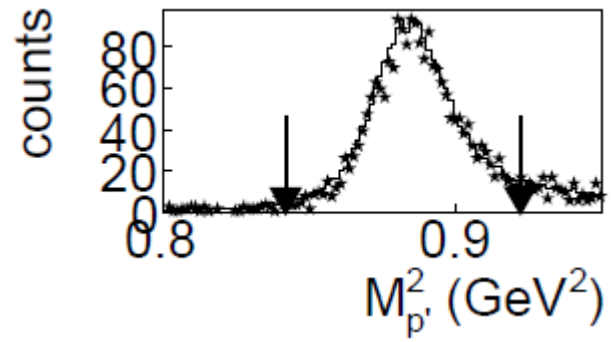
β versus momentum distribution snapshot for positively charged particles seen by ToF scintillator paddle 34 of CLAS sector one.
Black solid curves are theoretical calculations with exact hadron mass assumptions. Events between the two dashed and two dot-dashed curves are selected as π^+ and proton candidates, respectively.

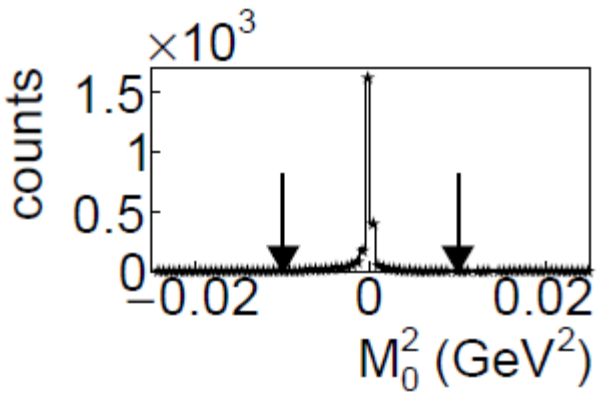


Topologies and Exclusivity Cuts









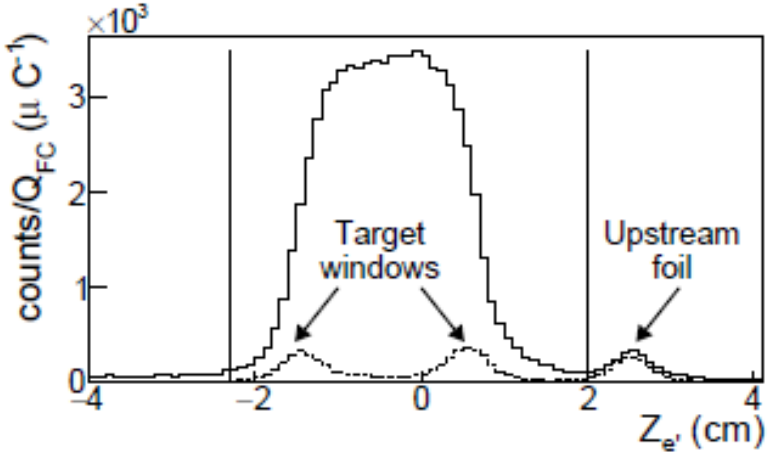
Topology	Statistics (%)
π^- missing	≈70
π^+ missing	≈10
proton missing	≈10
exclusive	≈10

For the first time for double-pion electroproduction all four topologies were combined together.

Three-pion background was taken into account according to the ratio of three-pion/double-pion cross sections taken from the paper: C. Wu et al., Eur. Phys. J. A23, 317 (2005).

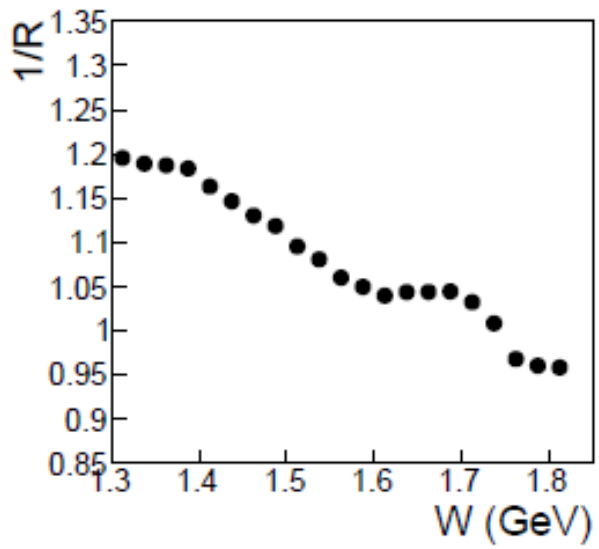
Corrections to the Cross Sections

- Empty target subtraction.

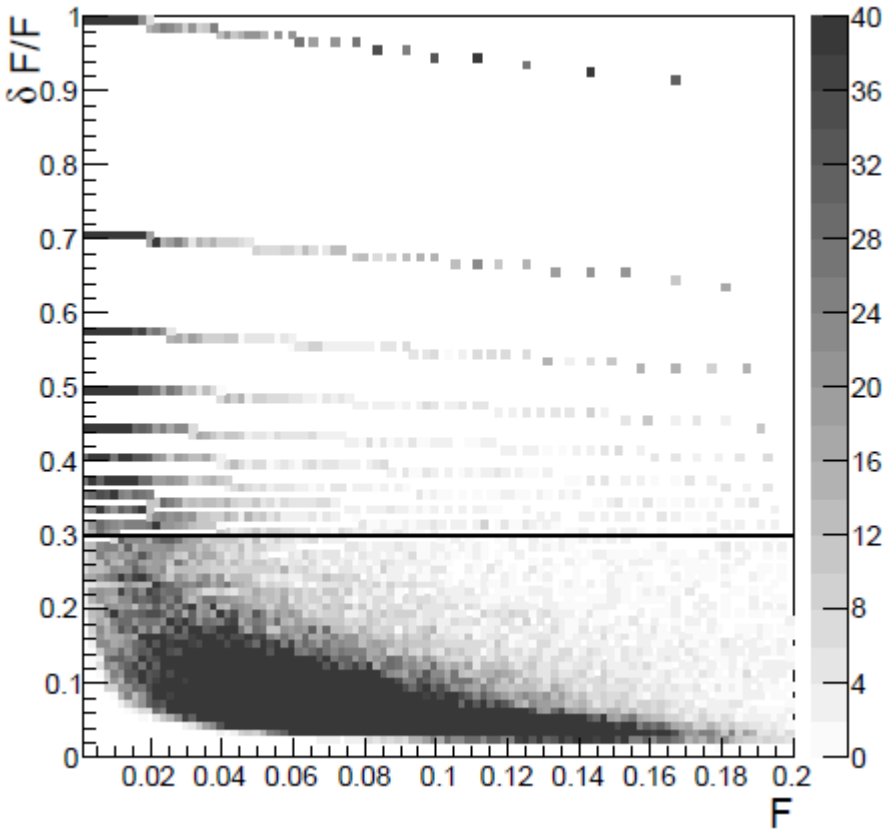


- Filling cells with zero acceptance by the advanced method using TWOPEG (CLAS12-NOTE-2017-001, arXiv:1703.08081) .

- Radiative corrections done according to the paper:(L. W. Mo and Y.-S. Tsai, Rev.Mod.Phys. 41, 205 (1969).



Empty Cells and Efficiency Error Cut



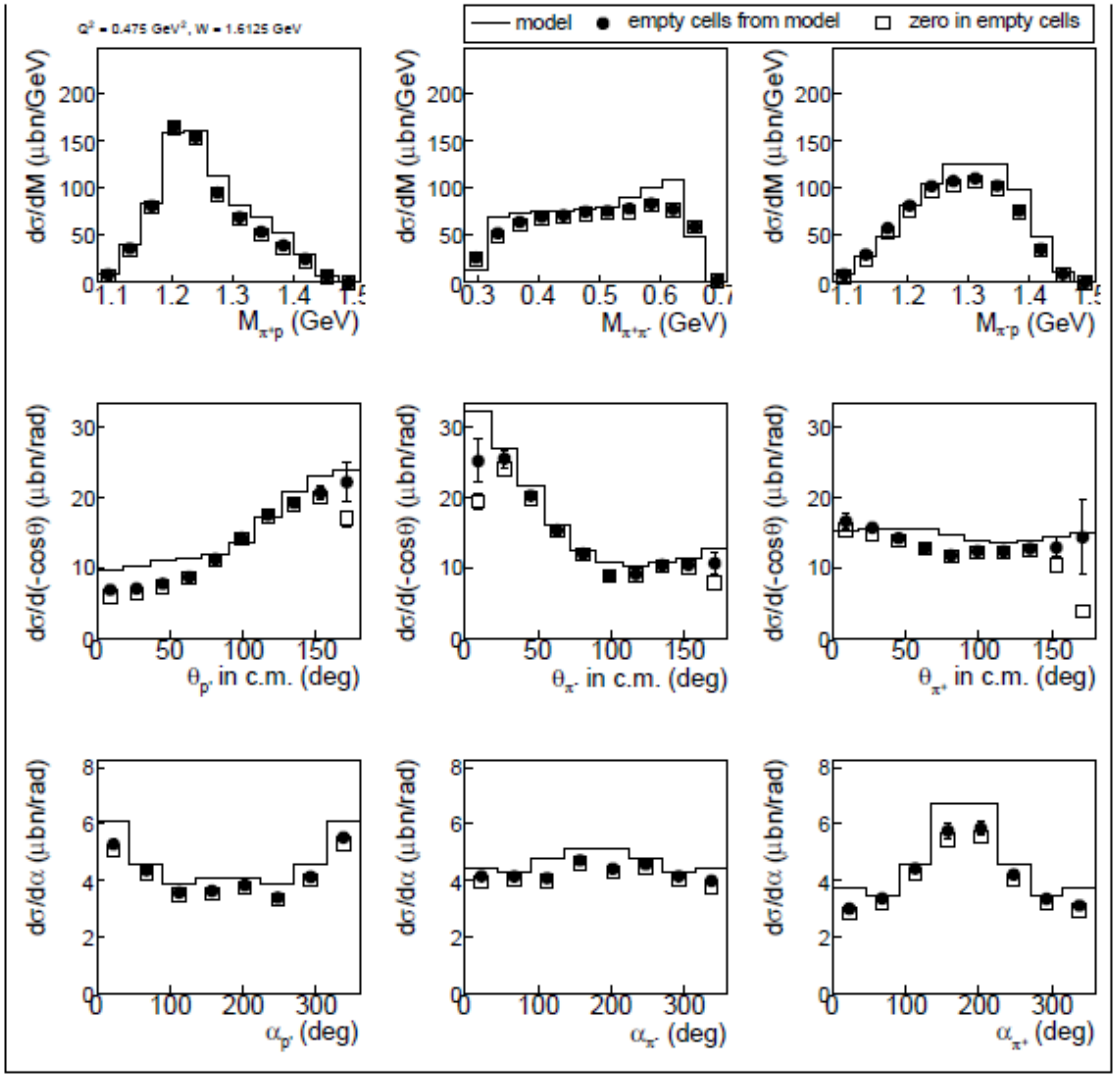
A kinematic cell is treated as empty if $N_{gen} > 0$ and $N_{rec} = 0$.

In addition to that the cells with relative efficiency error >30% also treated as empty.

The efficiency error was calculated according to the study B. Laforge and L. Schoeel, Nucl. Instrum. Meth. A394, 115 (1997).

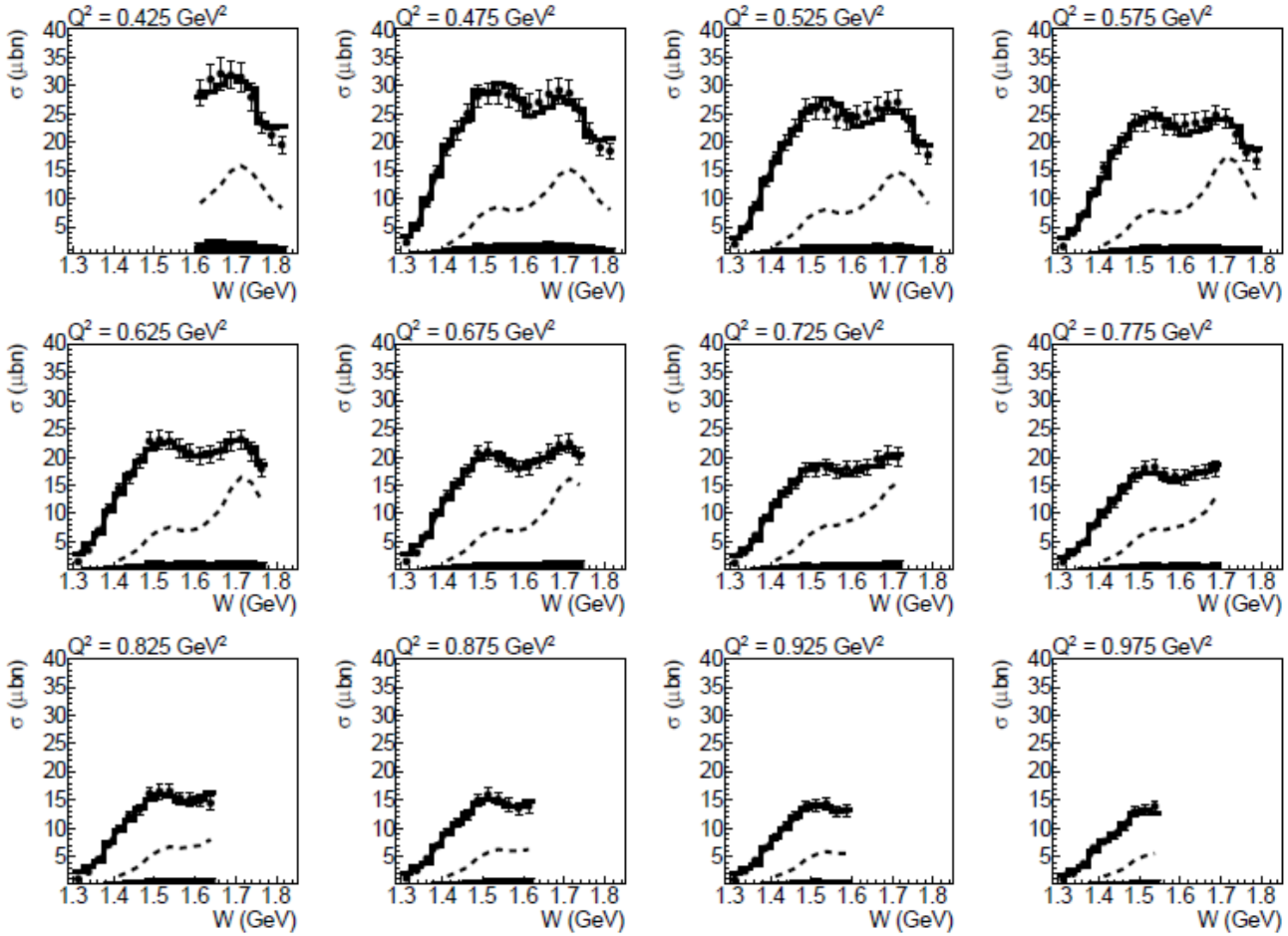
Filling Cells with Zero Acceptance

$Q^2 = 0.475\ GeV^2$, $W = 1.6125$ GeV



- Combination of all available topologies allows to minimize contributions from zones with zero acceptance.
- New advanced method to fill zones with zero acceptance based on TWOPEG .

W-Dependences of Integrated Cross Section



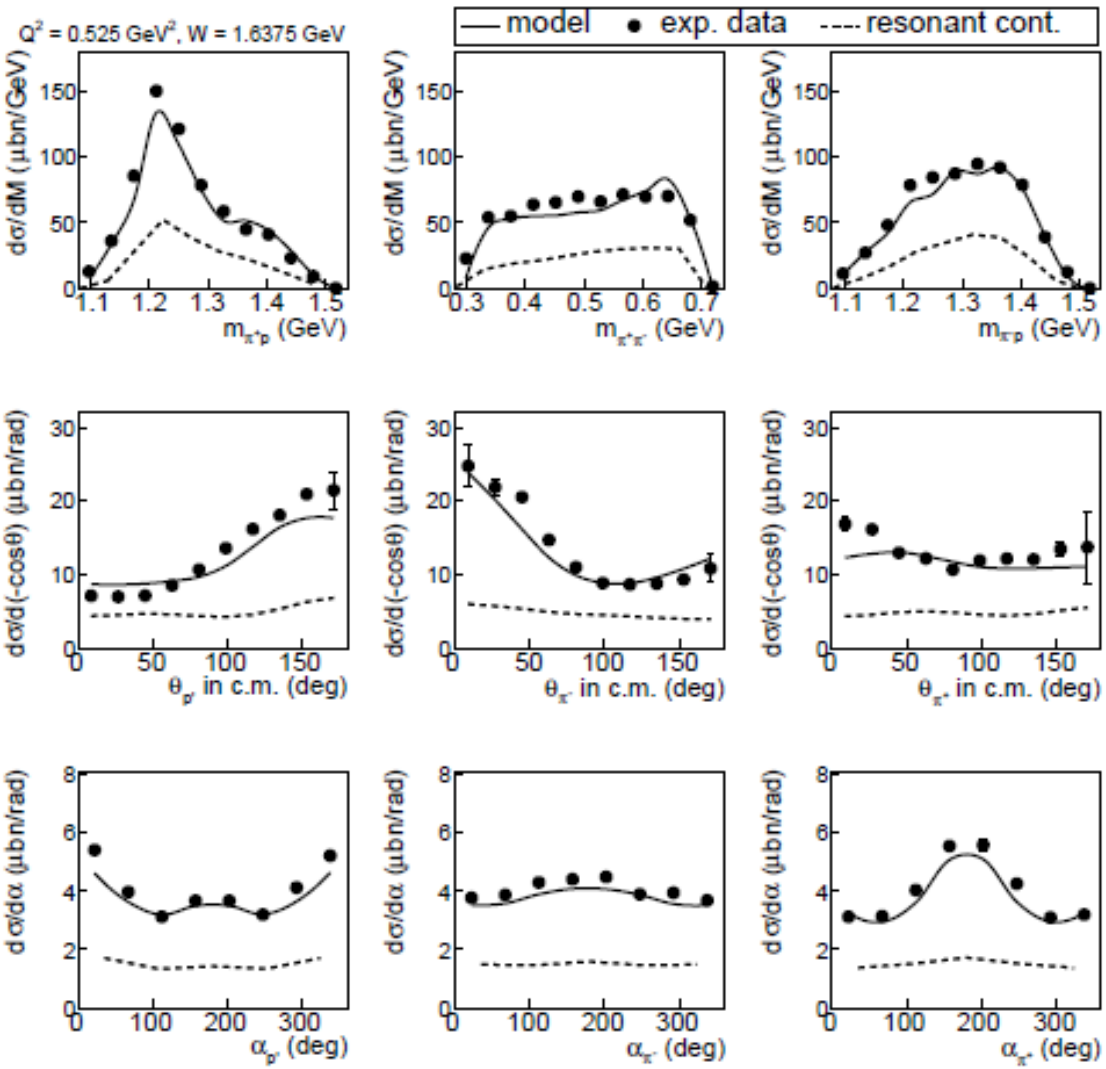
Symbols are for the extracted integral cross sections. Error bars correspond to the total uncertainty.

Solid curves are for the cross section estimated by TWOPEG.

Dashed curves are for the resonant contribution predicted by JM model.

Twelve bins in Q^2 are available.

Single-Differential Cross Sections



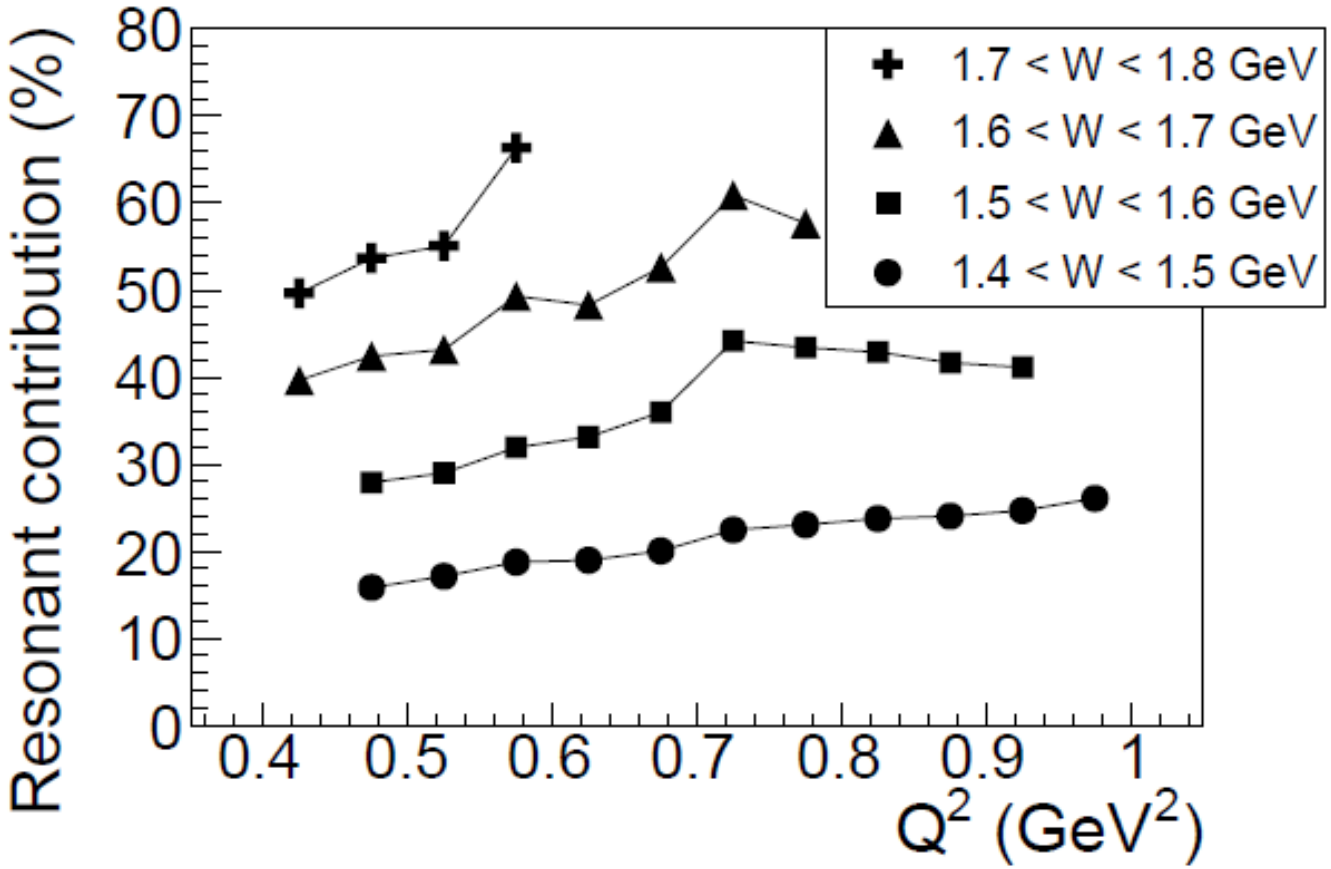
Symbols are for the extracted integral cross sections. Error bars correspond to the statistical uncertainty.

Solid curves are for the cross section estimated by TWOPEG.

Dashed curves are for the resonant contribution predicted by JM model.

Example is given for $W = 1.6375$ GeV and $Q^2 = 0.525$ GeV^2.

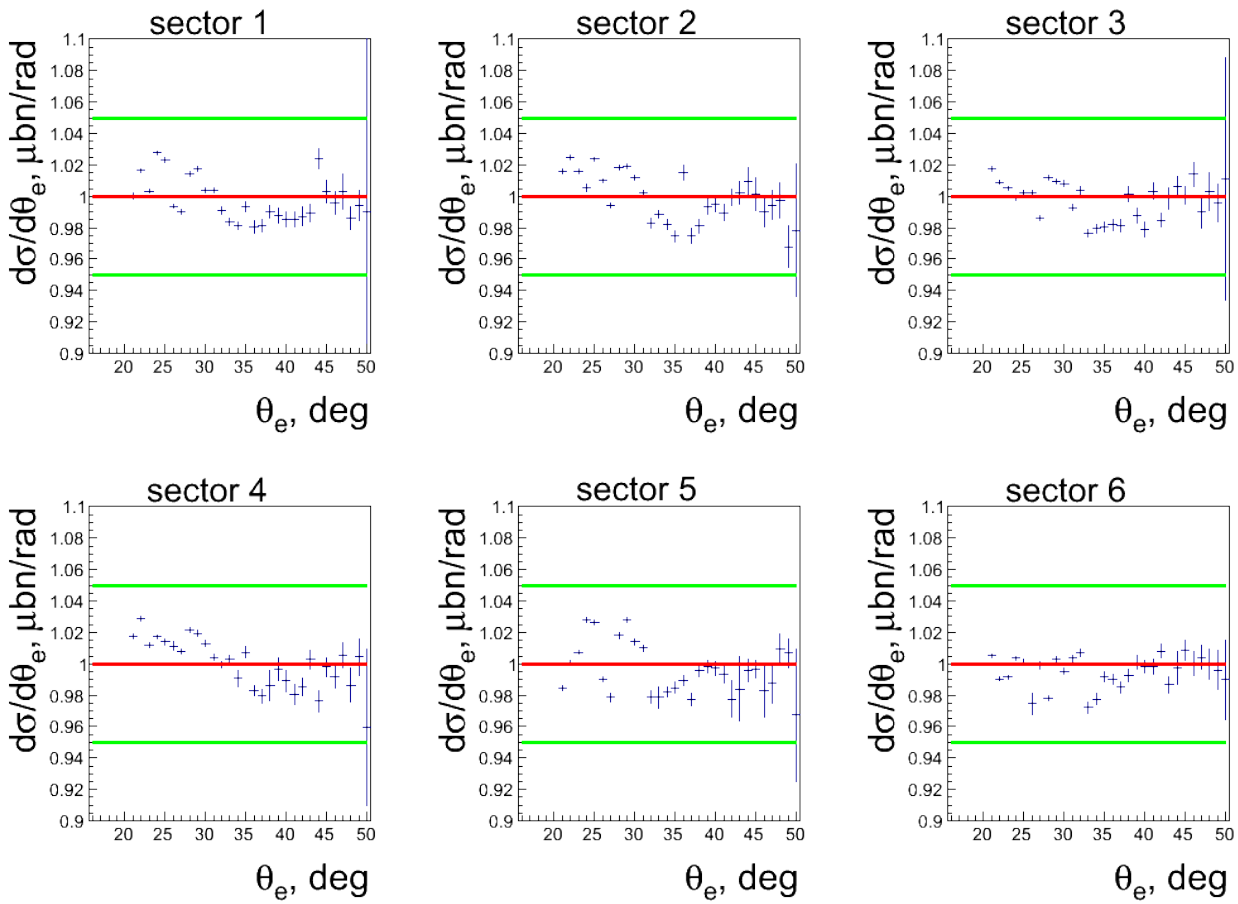
Relative Resonant Contribution



The relative resonant contribution to the cross section is found to range from 20% to 60% (depending on kinematical region) that advantages the extraction of resonance electrocouplings.

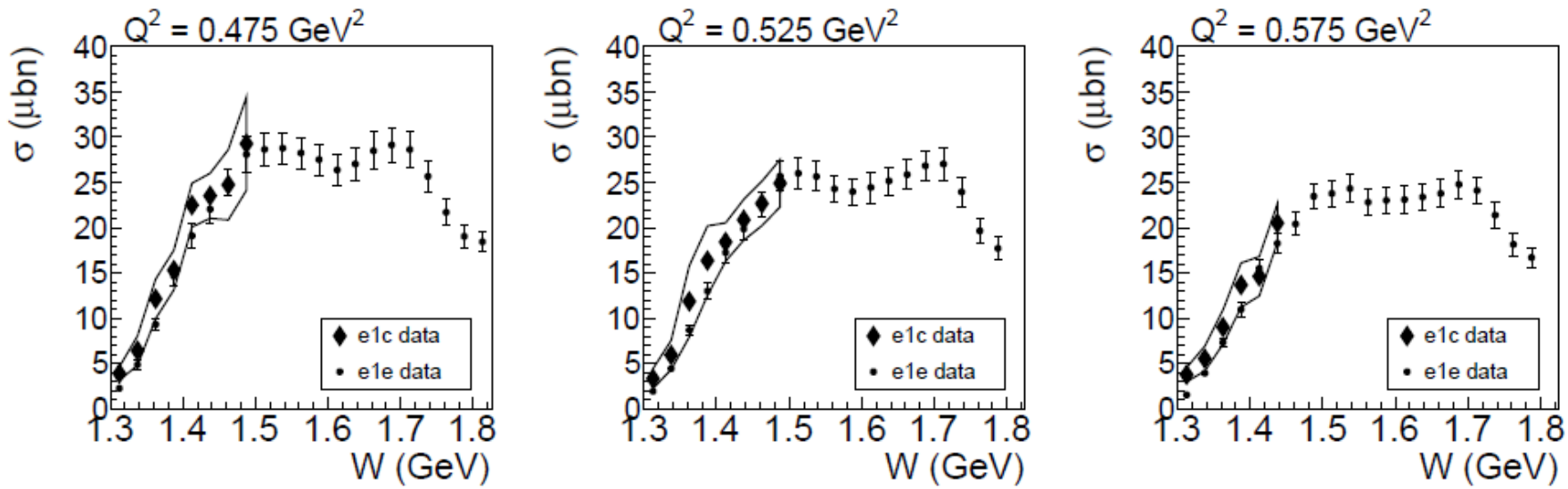
Cross Section Normalization Check

Ratio of the elastic cross section to the P. Bosted parameterization plotted versus θ_e. The parameterized cross sections are "radiated" and compared to the e1e elastic cross sections that are not corrected for radiative effects.



Good agreement in all 6 sectors

Comparison of Integrated Cross Sections with Existing Data



Circles represent published data (Fedotov *et al.*, PRC79, 015204 (2009)), while the diamonds represent the new e1e data. Good agreement within systematical uncertainties.

Conclusions

- The data on $\gamma_v p \rightarrow p'\pi^+\pi^-$ cross sections were obtained for W from 1.3 GeV to 1.825 GeV and Q^2 from 0.4 GeV^2 to 1 GeV^2.

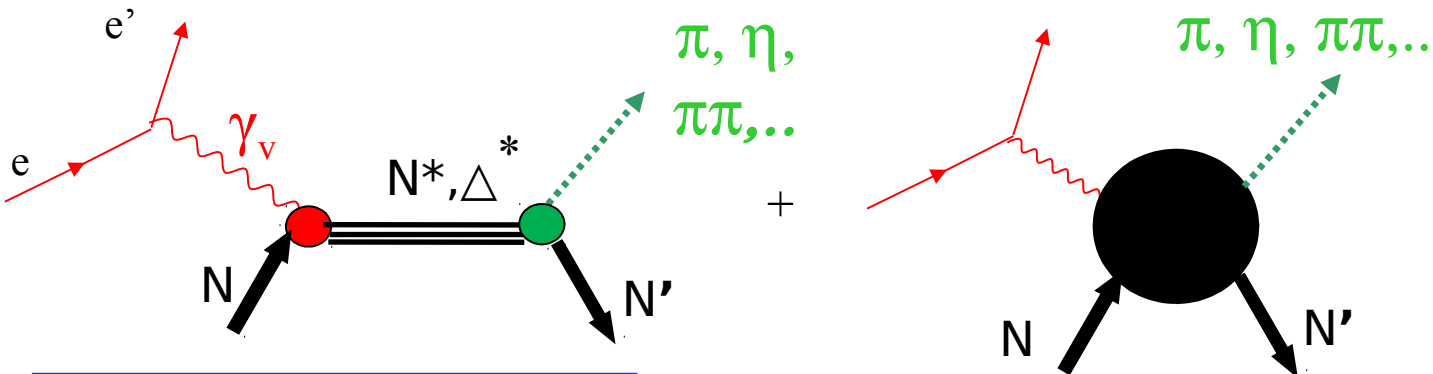
- Kinematic coverage and statistics exceed the previously available CLAS data and allow for a six times finer binning in Q^2.

- The results were obtained with advanced analysis procedure, i.e. the combination of all four available topologies was used, the map of empty cells was determined using the cut on the efficiency error, the contribution from the empty cells was accounted for by the advanced method using TWOPEG.

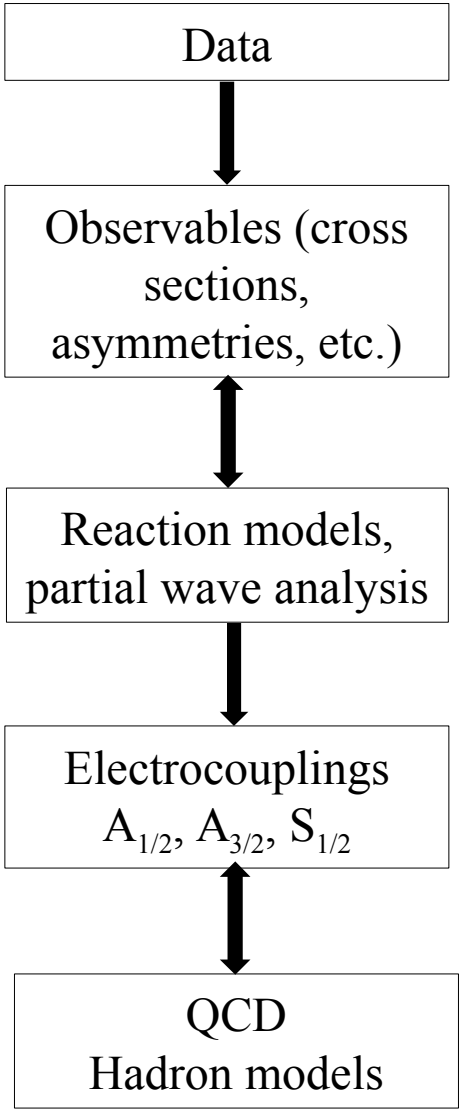
- The cross sections were preliminary interpreted within JM model. The revealed significant resonant contribution advantages the extraction of resonance parameters.

- The phenomenological analysis of this data will considerably extend the available information on the Q^2 evolution of the high lying N* (including new baryon state N'(1720)3/2$^+$) electrocouplings.

Extraction of $\gamma_v NN^*$ Electrocouplings from the Data

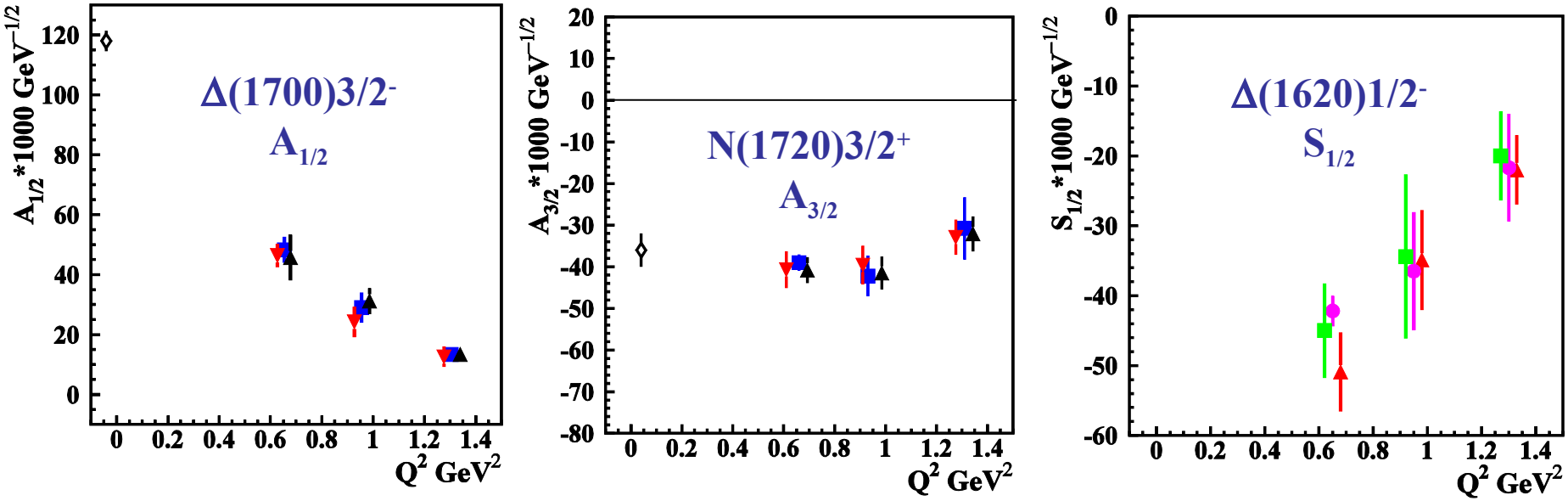


•$A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$



- **Separation of resonant/non-resonant contributions within the framework of reaction models; Breit Wigner ansatz for parameterization of resonant amplitudes; fit to the data.**
- **Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of N* parameters.**

Higher-Lying Resonance Electrocouplings



Independent fits in different W-intervals
green: 1.46<W<1.56 GeV
magenta: 1.56<W<1.66 GeV
red: 1.61<W<1.71 GeV
blue: 1.66<W<1.76 GeV
black: 1.71<W<1.81 GeV
result in self-consistent electrocouplings and hence offer sound evidence for their reliable extraction.

V. Mokeev *et al.*, Phys. Rev. C **93**, 025206

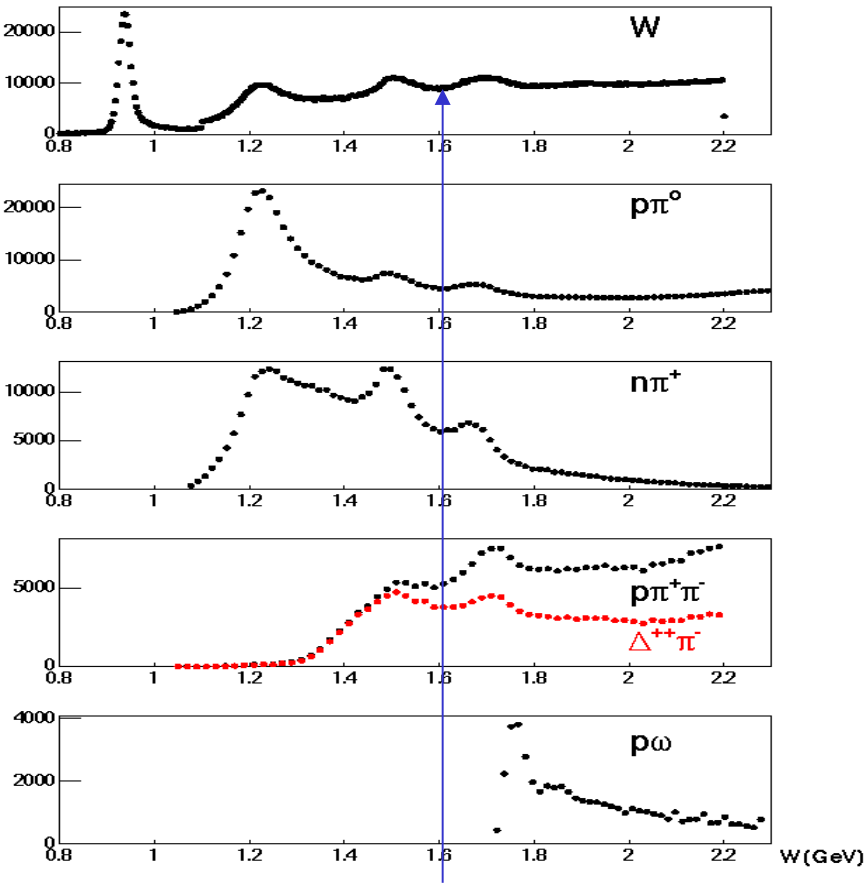
- The electrocouplings of the Δ(1620)1/2$^-$, N(1650)1/2$^-$, N(1680)5/2$^+$, Δ(1700)3/2$^-$, and N(1720)3/2$^+$ resonances were obtained at 0.5 GeV^2<Q^2<1.5 GeV^2, but just in three wide Q^2 bins.
- Improved information on their Q^2 evolution expected from the new e1e data collected in six times smaller Q^2 bins will provide further insight to the structure of orbital nucleon excitations with L=1.

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 $Q^2 < 4$ GeV^2



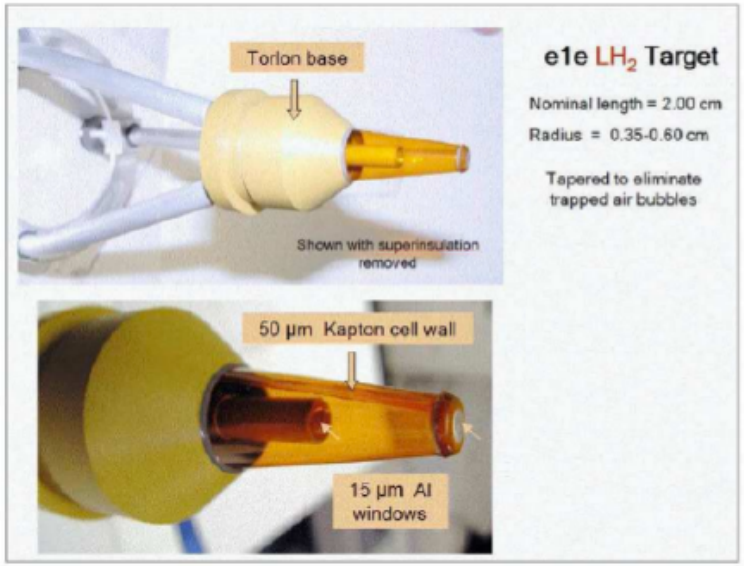
Branching Fractions in the 2nd and 3rd Resonance Regions

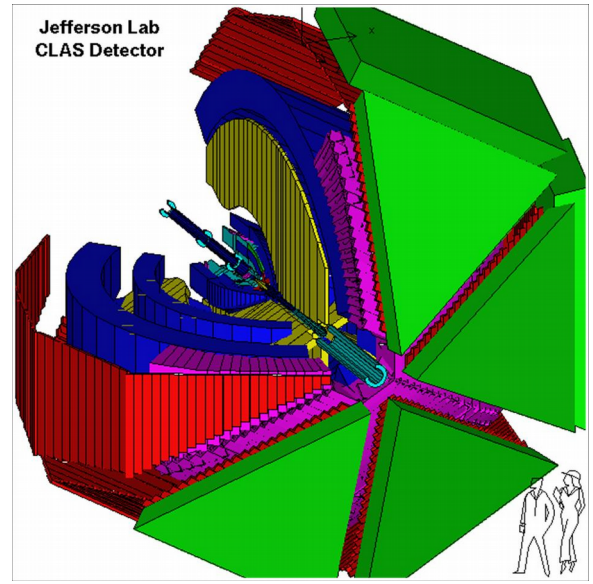
PDG values

State	$\eta_{N\pi}$	$\eta_{N\eta}$	$\eta_{N\pi\pi}$
$P_{11}(1440)$	0.55-0.75		0.3-0.4
$D_{13}(1520)$	0.55-0.65	0.0023	0.2-0.3
$S_{11}(1535)$	0.35-0.55	0.42	0.1-1.0
$S_{31}(1620)$	0.2-0.3		0.7-0.8
$S_{11}(1650)$	0.5-0.9	0.05-0.15	0.1-0.2
$F_{15}(1680)$	0.65-0.7		0.3-0.4
$D_{13}(1700)$	0.12		0.85-0.95
$D_{33}(1700)$	0.1-0.2		0.8-0.9
$P_{11}(1710)$	0.05-0.2	0.1-0.3	0.4-0.9
$P_{13}(1720)$	0.11	0.04	>0.7

Analysis of the e1e data measured with CLAS in Hall-B at JLab will be presented in this talk.

E1E target





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

$$ep \rightarrow e' p' \pi^+ \pi^-$$

New N'(1720)3/2$^+$ State and its Properties

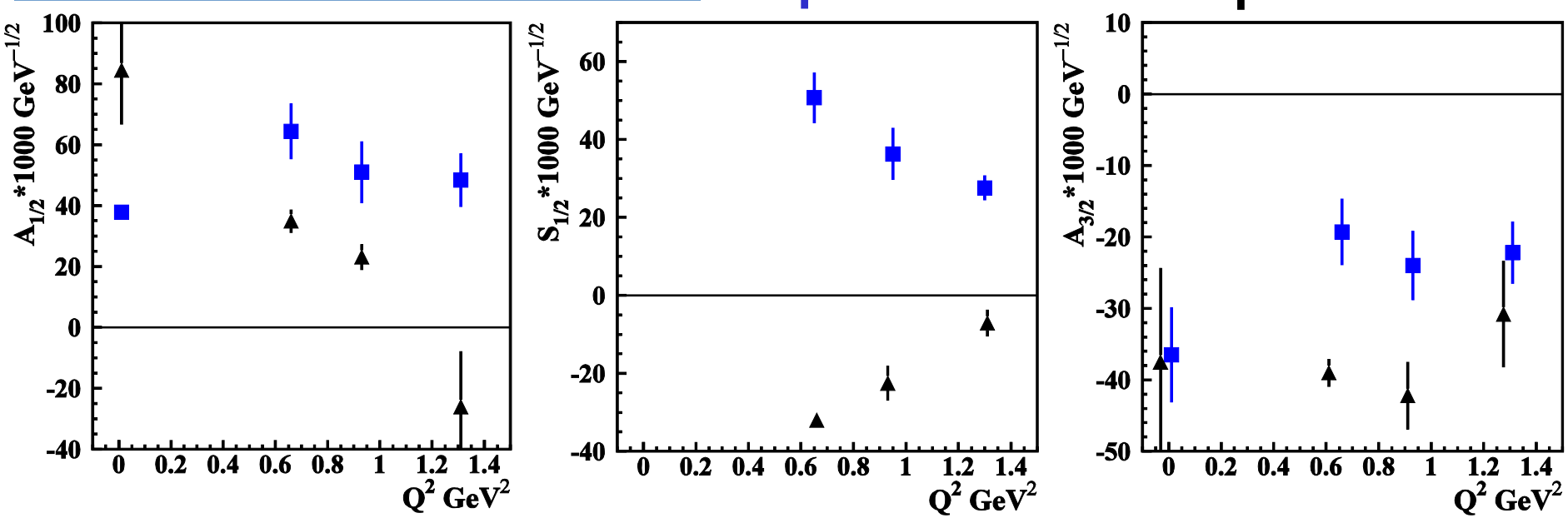
N* hadronic decays from JM15 that incorporates N'(1720)3/2$^+$

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

A successful description of $\pi^+\pi^-$p photo- and electro-production cross sections at Q^2=0, 0.65, 0.95, and 1.30 GeV^2 has been achieved by implementing a new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances that contribute at W~1.7 GeV, that allows us to claim the existence of a new N'(1720)3/2$^+$ state.

Mass: 1.715-1.735 GeV
Width: 120±6 MeV
N'(1720)3/2$^+$

Mass: 1.743-1.753 GeV
Width: 112±8 MeV
N(1720)3/2$^+$



New 2π Event Generator

- Based on JM15 and the newest data
- Written on C++
- Takes into account the cross section dependence on the beam energy
- Allows to obtain cross section values directly from the event generator (EG)
- EG generates phase space distributions and applies the cross section as weight to each event

List of data included:

Electroproduction

1) CLAS data at E_{beam} = 2.445, E_{beam} = 4 GeV

M. Ripani et al. [CLAS Collaboration], Phys. Rev. Lett. 91, 022002 (2003)
V. I. Mokeev et al. [CLAS Collaboration], Phys. Rev. C 86, 035203 (2012)

2) CLAS data at E_{beam} = 1.515 GeV

G. V. Fedotov et al. [CLAS Collaboration], Phys. Rev. C 79, 015204 (2009)

Photoproduction

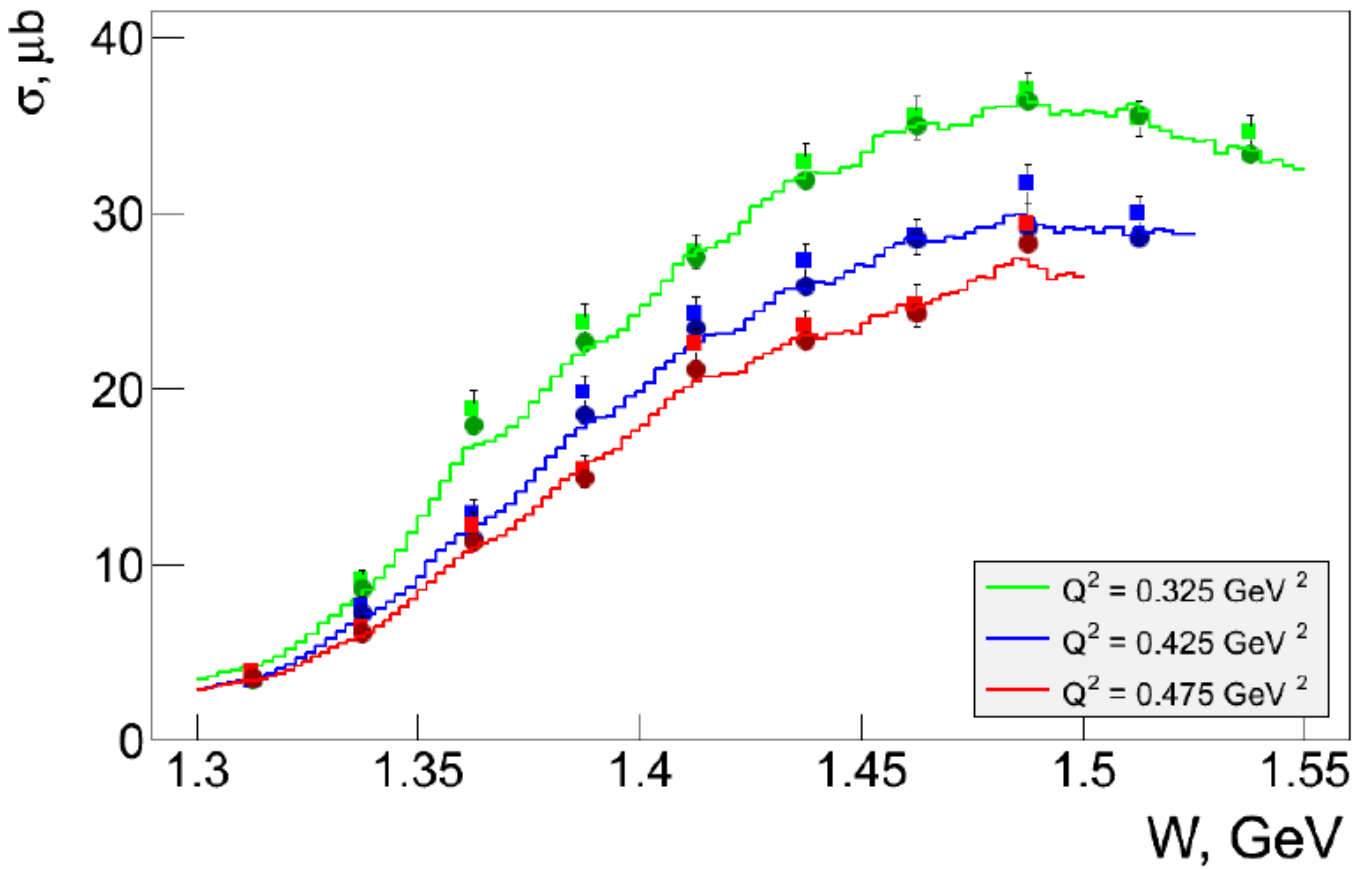
3) CLAS g11a experiment

E. Golovach et.al. CLAS ANALYSIS NOTE (under review)

4) SAPHIR Eur. Phys. J. A 23, 317 (2005).
ABBHM Collab., Phys. Rev. 175, 1669 (1968)

More information on new EG avaliable on Iu. Skorodumina's wiki page:
https://clasweb.jlab.org/wiki/index.php/NEW_2PI_EVENT_GENERATOR

New EG in Comparison with Experimental Data



- Squares – data (G. V. Fedotov *et al.*, Phys. Rev. C 79, 015204 (2009))
- Circles – model
- Curves – event generator

Kinematic Variables

$ep \to e' p' \pi^+ \pi^-$ **in single photon exchange approximation** $\gamma_v p \to p' \pi^+ \pi^-$

From experiment →

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

← **From JM model (fit to the data)**

Final hadrons are described by 5 independent variables

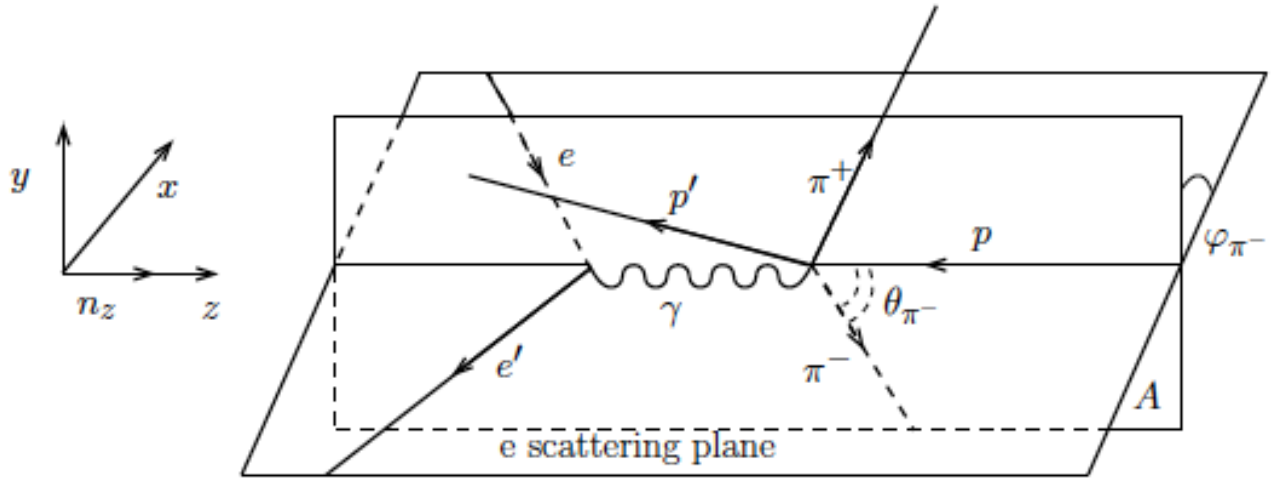
$$M_{\pi^+\pi^-}, M_{\pi^+ p}, \theta_p, \varphi_p, \alpha_p$$

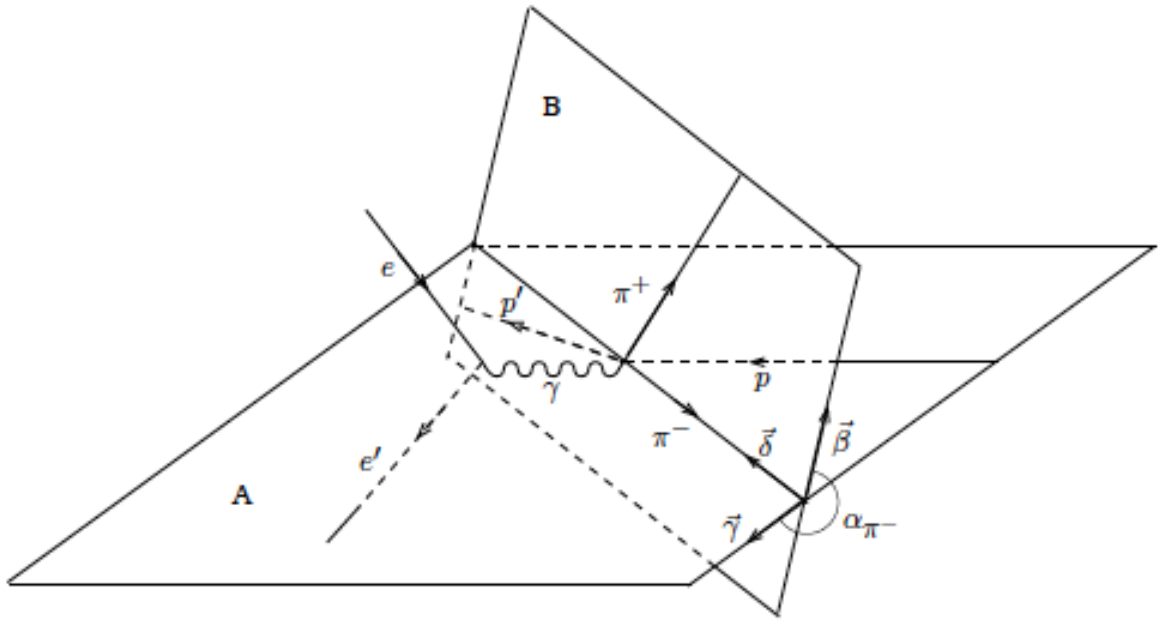
$$M_{\pi^+\pi^-}, M_{\pi^- p}, \theta_{\pi^+}, \varphi_{\pi^+}, \alpha_{\pi^+}$$

$$M_{\pi^+\pi^-}, M_{\pi^+ p}, \theta_{\pi^-}, \varphi_{\pi^-}, \alpha_{\pi^-}$$

All three sets of hadronic variables are used to extract cross sections. The difference between total cross sections obtained by integration over various sets of hadronic variables is interpreted as systematic uncertainty.

Definition of Final Hadron Angles





Cross Section Determination

$$\frac{d\sigma}{dW\,dQ^2 dM_{p\pi^+} dM_{\pi^+\pi^-} d\Omega d\alpha_{\pi^-}} = \frac{1}{F\cdot R}\frac{\left(\frac{\Delta N_{full}}{Q_{full}} - \frac{\Delta N_{empty}}{Q_{empty}}\right)}{\Delta W \Delta Q^2 \Delta\tau \left(\frac{l\rho N_A}{q_e M_H}\right)}$$

$$\Delta\tau = \Delta M_{p\pi^+}\Delta M_{\pi^+\pi^-}\Delta(-cos(\theta_{\pi^-}))\Delta\varphi_{\pi^-}\Delta\alpha_{\pi^-}$$

ΔN_{full} and ΔN_{empty} are the numbers of events inside a seven-dimensional bin for runs with hydrogen - and empty target, respectively. F is the efficiency determined by the Monte Carlo simulation. R is the radiative correction factor. Q_{full} and Q_{empty} are the integrated Faraday cup charges for runs with hydrogen - and empty target, respectively, and q_e is the elementary charge. ρ is the density of liquid hydrogen at T = 20 K. l is the length of the target (l = 2 cm). M_H is the molar density of the natural mixture of hydrogen and N_A is Avogadro's number. ΔW and ΔQ^2 are kinematical bins determined by the electron scattering kinematics. $\Delta\tau$ is the hadronic five-dimensional kinematic phase-space element.

Due to statistical limitations only single-fold differential cross sections were analyzed:

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \int \frac{d^5\sigma}{d^5\tau} d\tau^4_{M_{\pi^+\pi^-}}; \qquad d\tau^4_{M_{\pi^+\pi^-}} = dM_{\pi^+p} d\Omega_{\pi^-} d\alpha_{\pi^-}$$

$$\frac{d\sigma}{dM_{\pi^+p}} = \int \frac{d^5\sigma}{d^5\tau} d\tau^4_{M_{\pi^+p}}; \qquad d\tau^4_{M_{\pi^+p}} = dM_{\pi^+\pi^-} d\Omega_{\pi^-} d\alpha_{\pi^-}$$

$$\frac{d\sigma}{d(-cos\theta_{\pi^-})} = \int \frac{d^5\sigma}{d^5\tau} d\tau^4_{\theta_{\pi^-}}; \qquad d\tau^4_{\theta_{\pi^-}} = dM_{\pi^+\pi^-} dM_{\pi^+p} d\varphi_{\pi^-} d\alpha_{\pi^-}$$

$$\frac{d\sigma}{dM_{\alpha_{\pi^-}}} = \int \frac{d^5\sigma}{d^5\tau} d\tau^4_{\alpha_{\pi^-}}; \qquad d\tau^4_{\alpha_{\pi^-}} = dM_{\pi^+\pi^-} dM_{\pi^+p} d\Omega_{\pi^-}$$

$$d^5\tau = dM_{\pi^+\pi^-} dM_{\pi^+p} d\Omega_{\pi^-} d\alpha_{\pi^-}$$