Exclusive $\pi^0 p$ electroproduction off protons in the resonance region at photon virtualities 0.4 GeV^2 ≤ Q^2 ≤ 1 GeV^2

UCONN
UNIVERSITY OF CONNECTICUT

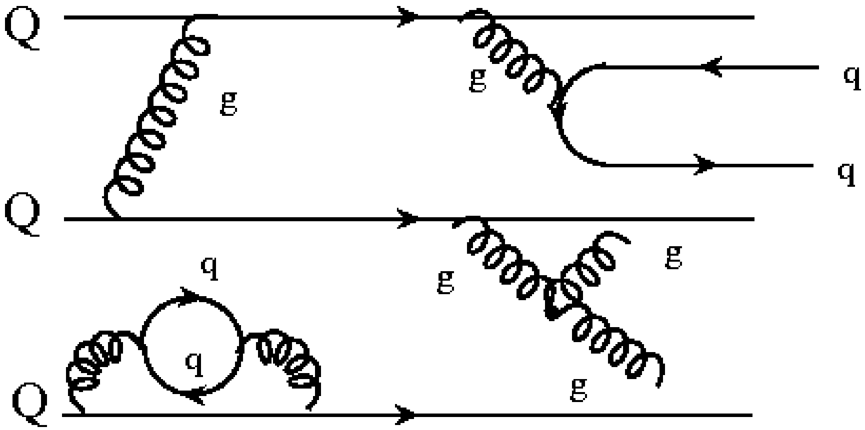
Nikolay Markov,
University of Connecticut

Outline

- Introduction
- Particle Identification
- Corrections
- Cross section
- Systematical uncertainties
- Results
- Conclusion

Nucleons as the Building Blocks of Hadronic Matter

Nucleons and atomic nuclei account for most of the visible mass in the Universe



Three valence current quarks (Q) embedded in a sea of gauge gluons (g) and quark+antiquark pairs

Particular features of nucleon structure:
- the current quarks and gauge gluons are in permanent creation/annihilation processes;
- relativistic objects moving with velocities comparable with the velocity of light;
- quarks and gluons are always confined inside the hadrons; they are never free.

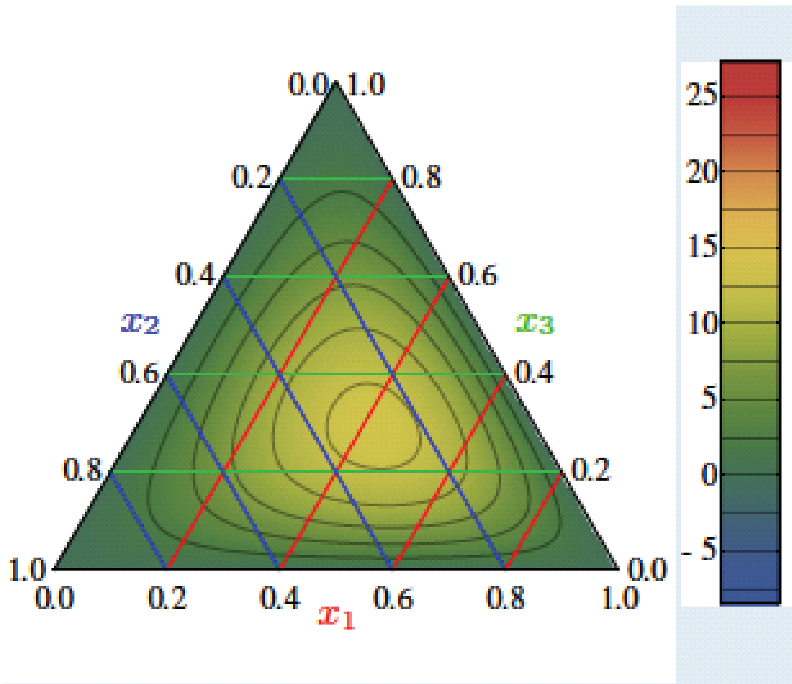
Such a complex composite system should possess a spectrum of excited states.

Understanding the nature of quark-gluon confinement requires combined studies of the ground and excited nucleon states.

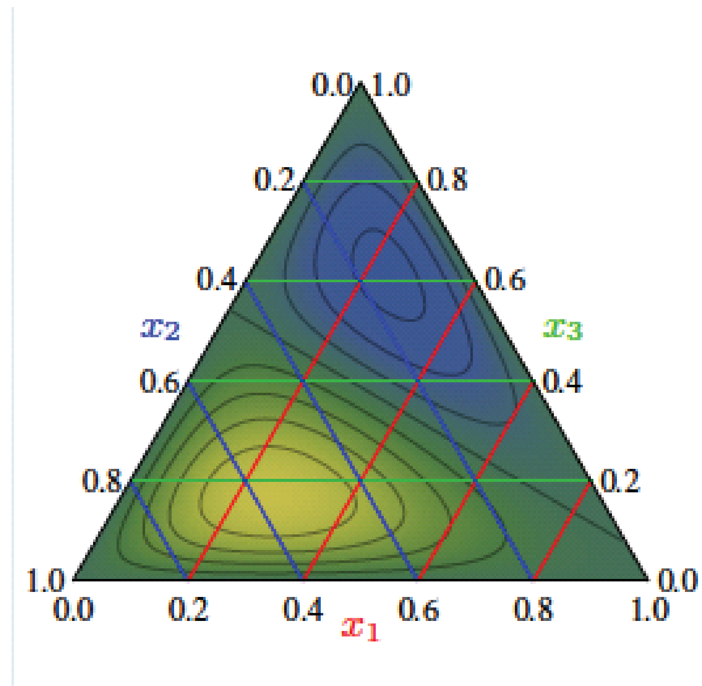
Quark Distributions in the Ground and Excited Nucleons Constrained by the Data on Elastic and Transition N→N* Form Factors

I.V. Anikin, V.M. Braun, N. Offen, Phys. Rev. D92, 014018 (2015).
V.M. Braun et al., Phys. Rev D89, 094511 (2014).

Ground Nucleon



N(1535)$_{1/2}^{-}$

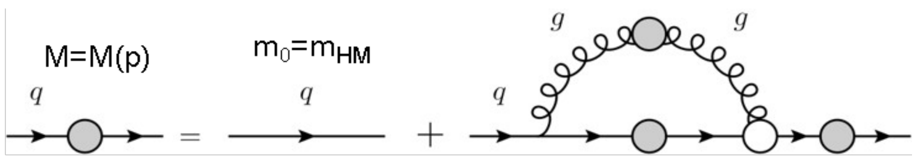


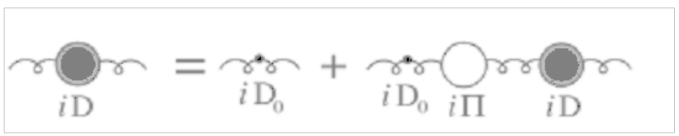
x_i stands for the momentum fraction of i-th valence quark

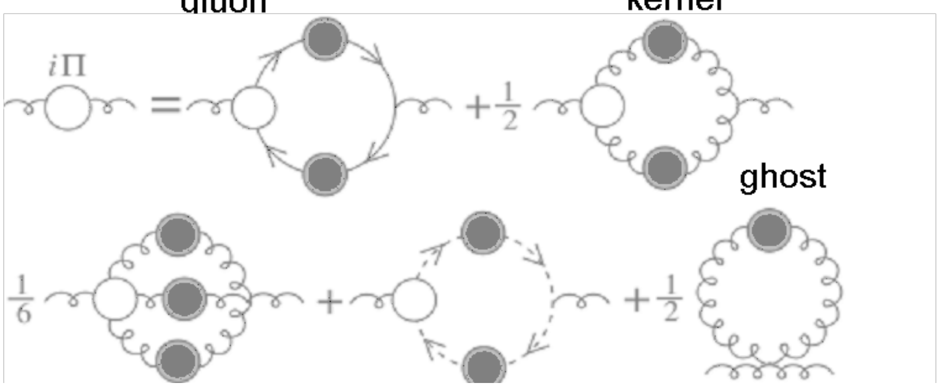
Studies of the nucleon elastic and transition p→N(1535)$_{1/2}^{-}$ EM form factors revealed the differences for the Quark Distribution Amplitudes in the nucleon and its chiral partner N(1535)$_{1/2}^{-}$.

Excited Nucleon States and Insight into Strong QCD Dynamics

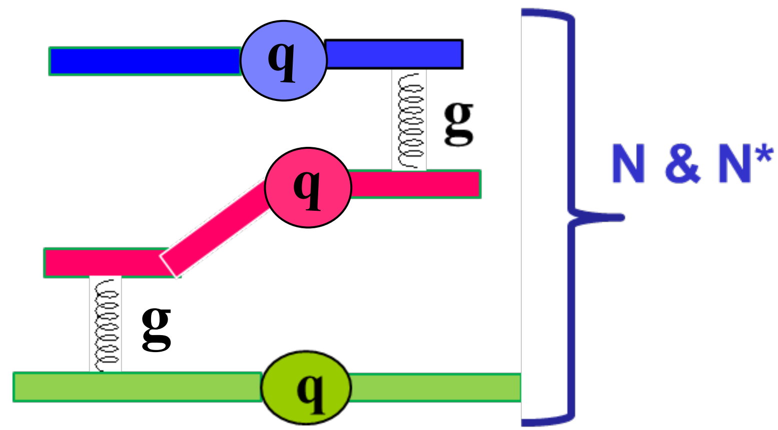
Emergence of Dressed Quarks and Gluons
D. Binosi et al, Phys. Rev. D95, 031501 (2017)



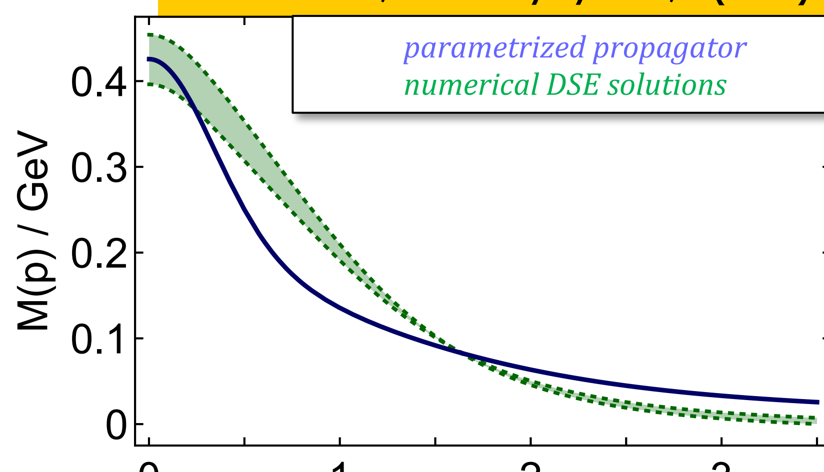




Dressed Quark Borromeo Binding in Baryons
Ch. Chen et al, Phys. Rev. D97, 034016 (2018)



Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)

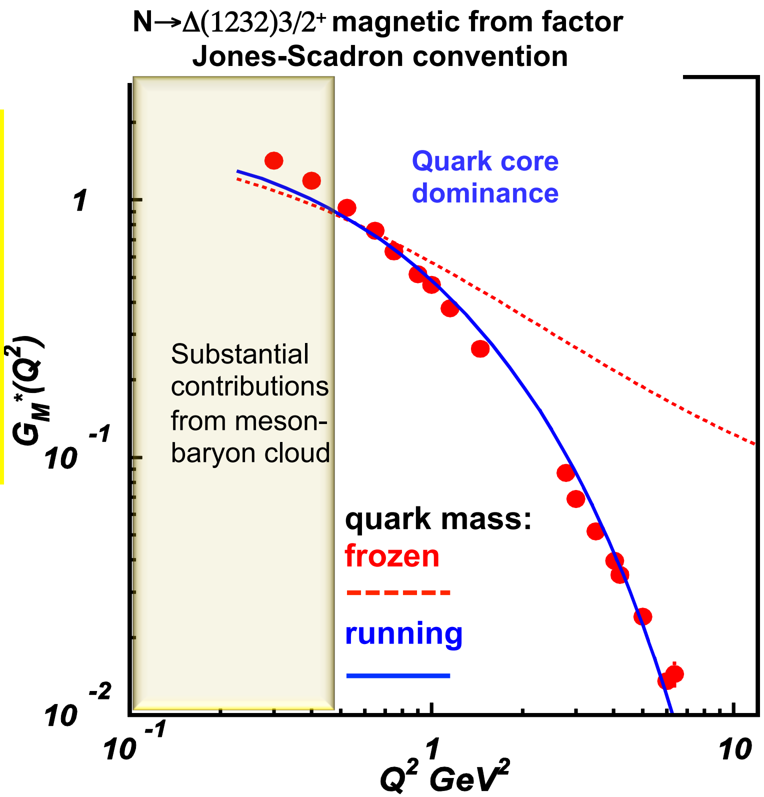


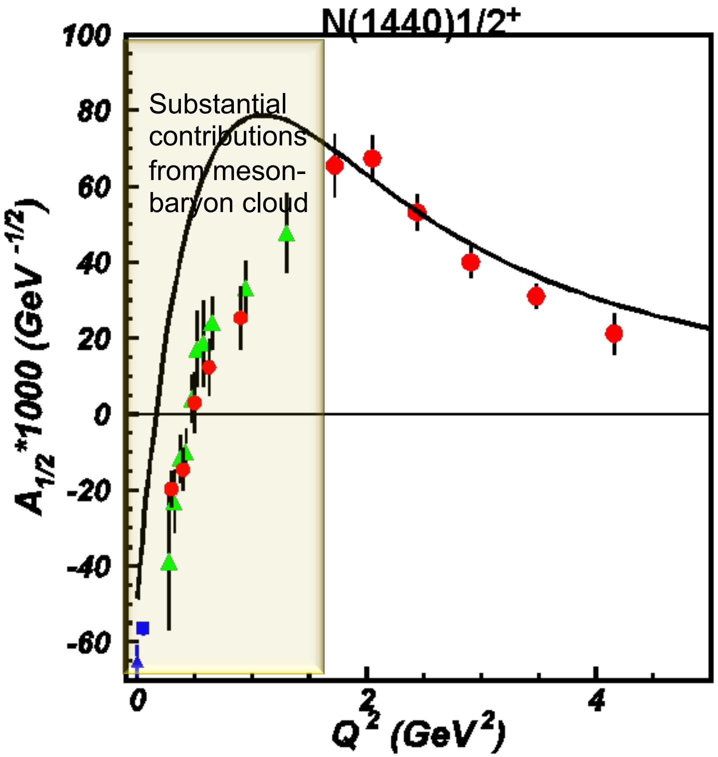
N* structure studies address:

- **Nature of > 98% of hadron mass**
- **Confinement and color charge emergence from QCD**

From resonance electrocouplings to the hadron mass generation

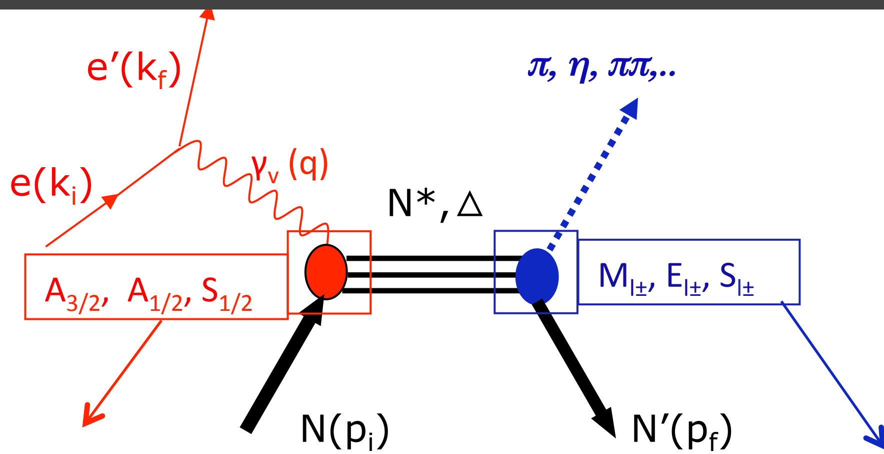
Dyson-Schwinger Equations (DSE):
- **J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015).**
- **J. Segovia et al., Few Body Syst. 55, 1185 (2014).**





- ***Dressed quark mass is running with momentum***
- Good description of the first spin-isospin-flip and radial excited resonance electrocouplings at Q^2>2.0 GeV^2 with the same dressed quark mass function validates relevance of dressed quark with dynamically generated mass in the structure of the ground and excited nucleons.
- Both elastic nucleon form factors and $g_v pN^*$ electrocouplings data for all prominent resonances of different structure are needed in order to map-out dressed quark mass function.

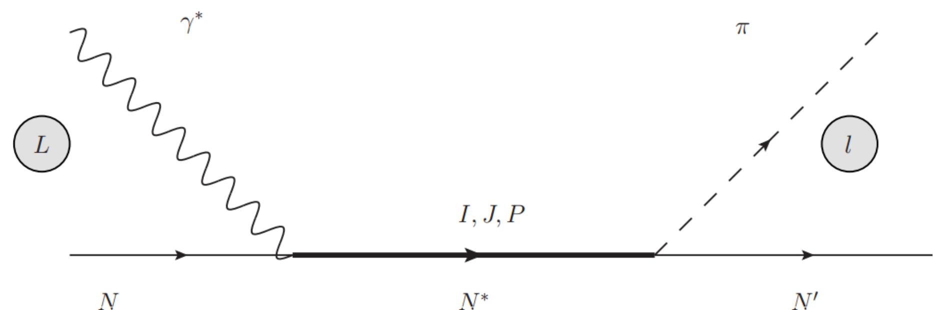
Resonance meson production



Helicity amplitudes

Meson production multipoles

Amplitude	Υ	N
$A_{1/2}$	$s_z = 1$ →	⟸ $s_z = -1/2$
$A_{3/2}$	$s_z = 1$ →	⟹ $s_z = 1/2$
$S_{1/2}$	$s_z = 0$ →	⟸ $s_z = 1/2$



$$\Gamma_{em} = \frac{q^2_{\gamma CM}}{\pi} \frac{2M_p}{(2J+1)M_{N*}} (|A^2_{1/2}| + |A^2_{3/2}|)$$

At the photon point

$$\sigma(M_{N*}) = \frac{\pi}{q^2_\gamma}(2J+1)Br(N^* \to \pi N)\frac{\Gamma_{em}}{\Gamma_{tot}(M_{N*})}$$

$E_{l\pm}$, $M_{l\pm}$, $S_{l\pm}$
where *l* is an orbital momentum of the pion

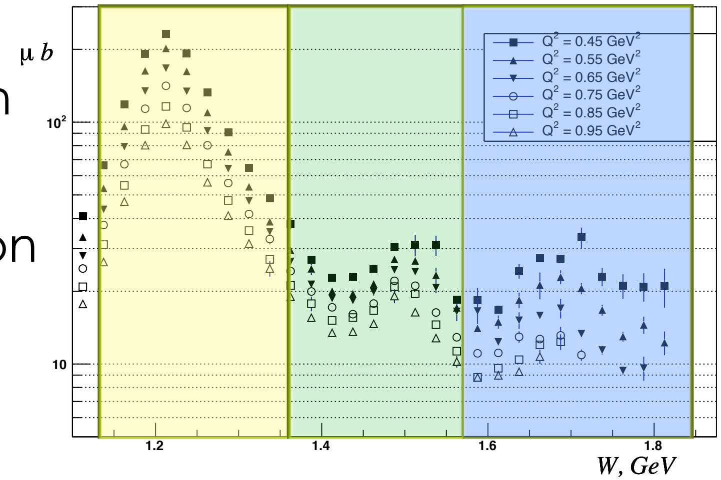
Coverage of the Resonance region

Δ (1232)3/2+
N(1440)1/2+
N(1520)3/2-
N(1535)1/2-
N(1650)1/2-
N(1675)5/2-
N(1680)5/2+
N(1710)1/2+
Δ(1620) 1/2-
Δ(1700) 3/2-

I st resonance region

II nd resonance region

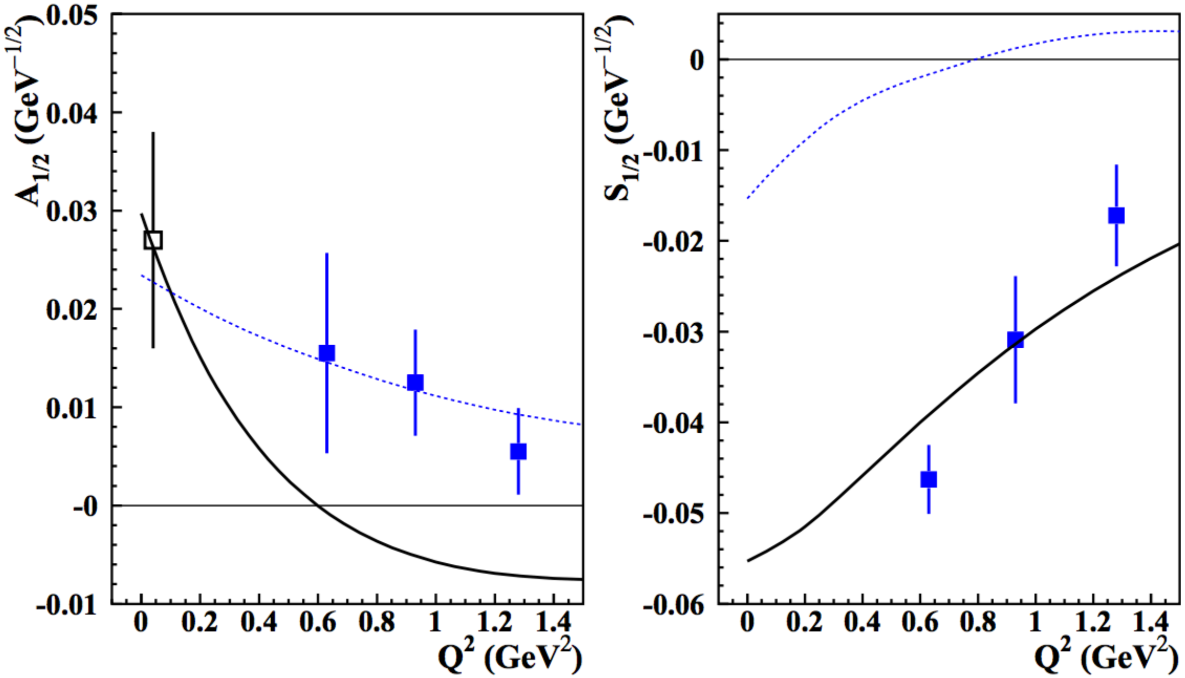
III rd resonance region



Integrated over angles

- For the first time electrocouplings of the resonances in the 2nd and 3rd resonance regions will be available from $\pi^0 p$ electroproduction off protons;
- For the first time electrocouplings of Δ resonances in the 3rd resonance regions will become available from $\pi^0 p$ exclusive channel, which is the most sensitive to the contributions from the Δ states;
- This study is concentrated on the area of moderate Q^2, where MB and quarks degrees of freedom are both important;
- There is an overlap between this data and previous results on low lying resonant states (W < 1.6 GeV), allowing to check procedures of extracting N* parameters.

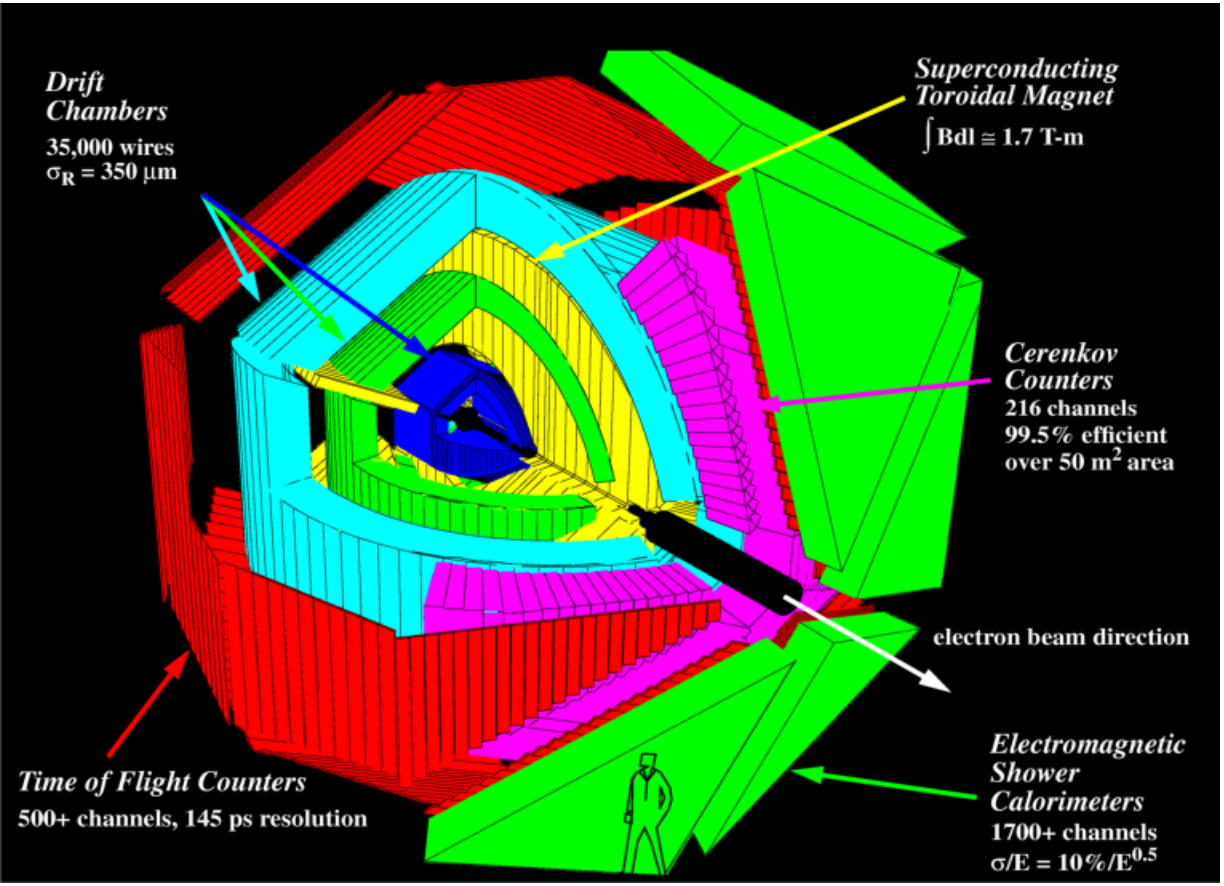
Peculiarities of the Δ(1620) 1/2⁻



Data points: V. Mokeev et al, Phys Rev c93, 025706(2016)
blue line: M. Ronninger and B. Ch. Metsch, Eur. Phys J. A 49, 8(2012).
black line: E. Santopinto and M.M. Giannini, Phys. Rev. C 86,065202 (2012).

- Obtained from 2 pion channel (BF to N π π around 80%);
- Only N* that is dominated by the longitudinal $S_{1/2}$ amplitude for 0.5 GeV^2 < Q^2 < 1.5 GeV^2
- hypercentral constituent quark model and Bethe-Salpeter approach describe only one of two amplitudes

Experiment



- 4π acceptance
- Possibility to detect multiple neutral and charged particles in the final state
- High energy and timing resolution

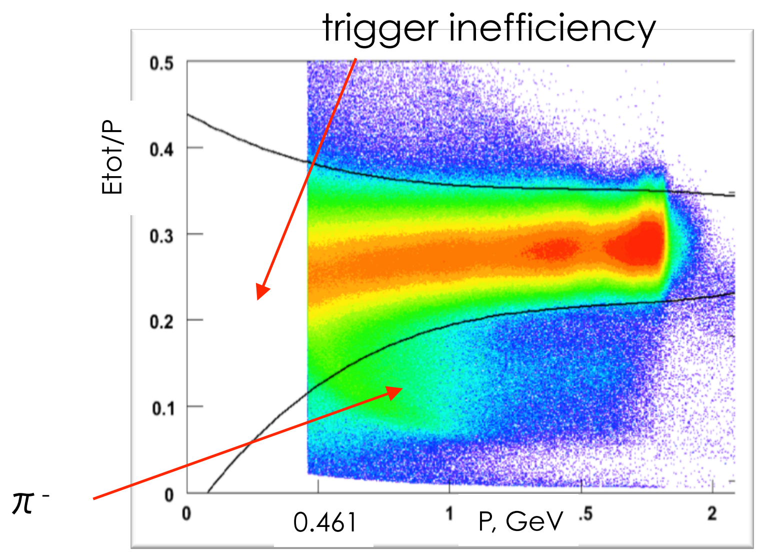
- Beam energy: 2.036 GeV
- Beam polarization: ~ 70%
- Target: Liquid Hydrogen
- Number of triggers: $1.5*10^9$
- Number of $ep\pi^0$ events: 10M

Data analysis

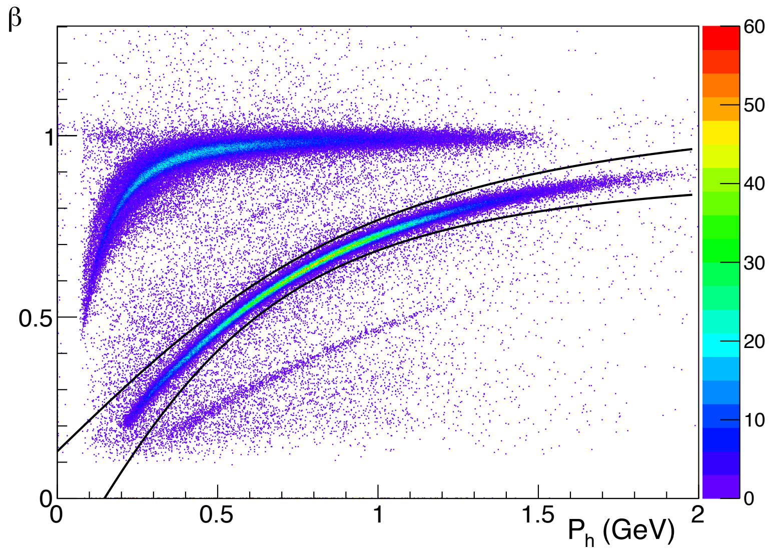
- Particle ID
- Acceptance correction
- Radiative corrections
- Bin centering corrections
- Normalization
- Systematical uncertainties

Particle ID

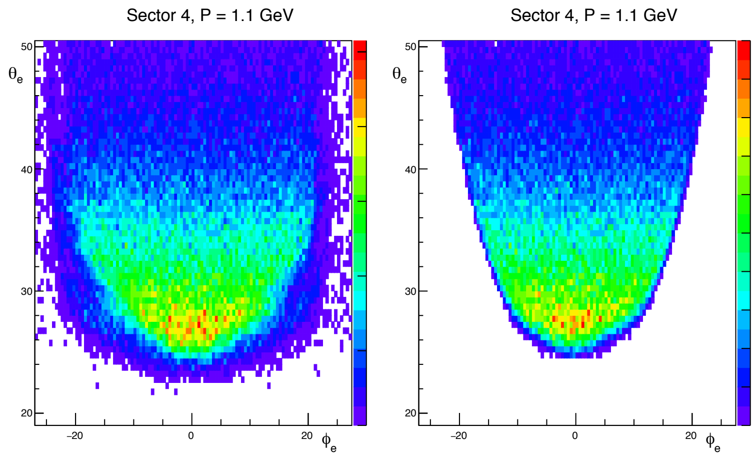
e π^- separation



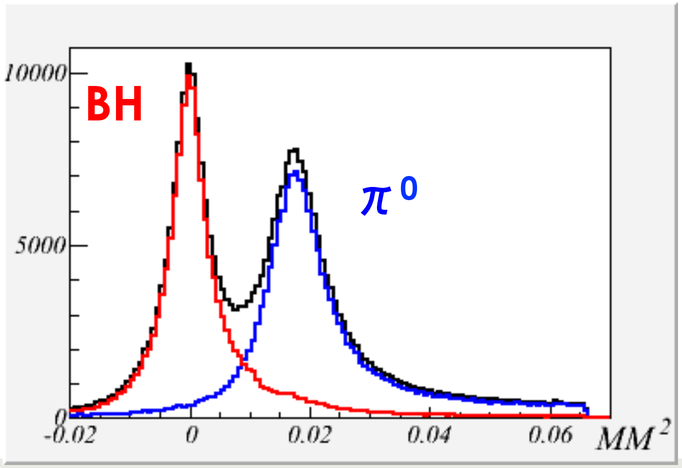
Proton identification



Fiducial cuts

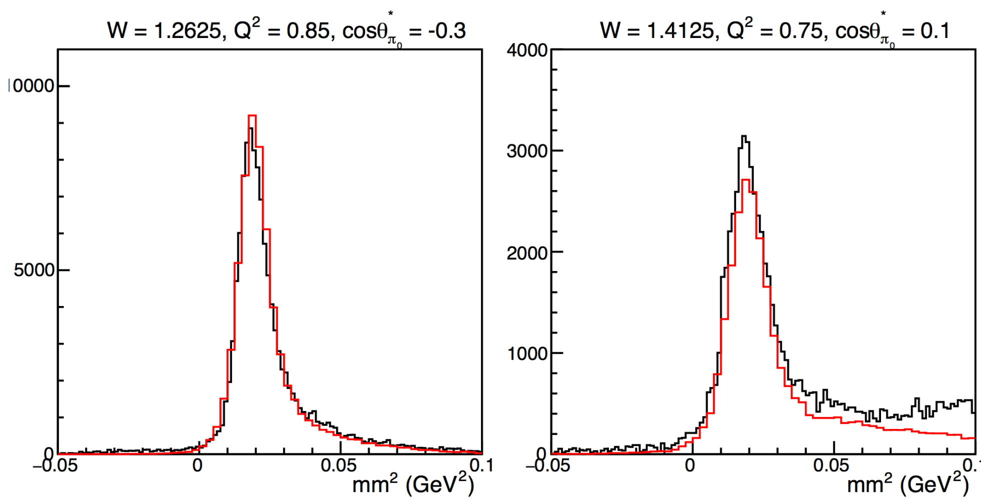


Final event selection



Simulation and acceptance correction

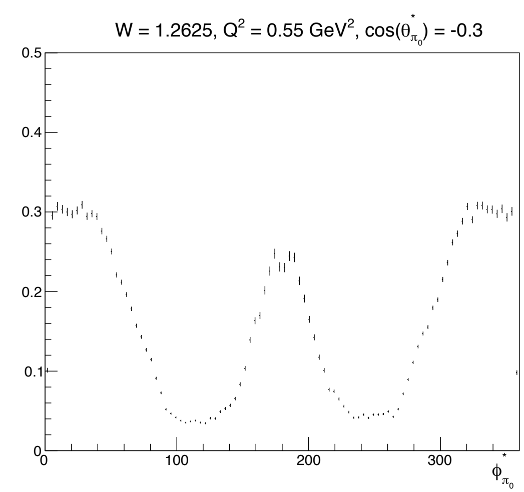
aao_rad code is used to generate radiated ep π^0 events
gsim is a GEANT simulation of the CLAS detector
recsis is a reconstruciton code, same as used for the data reconstruction



Data
Sim

Acc = Rec/Gen

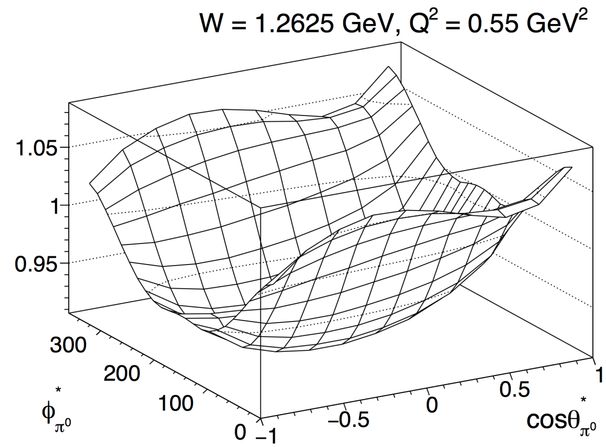
Sample acceptance correction

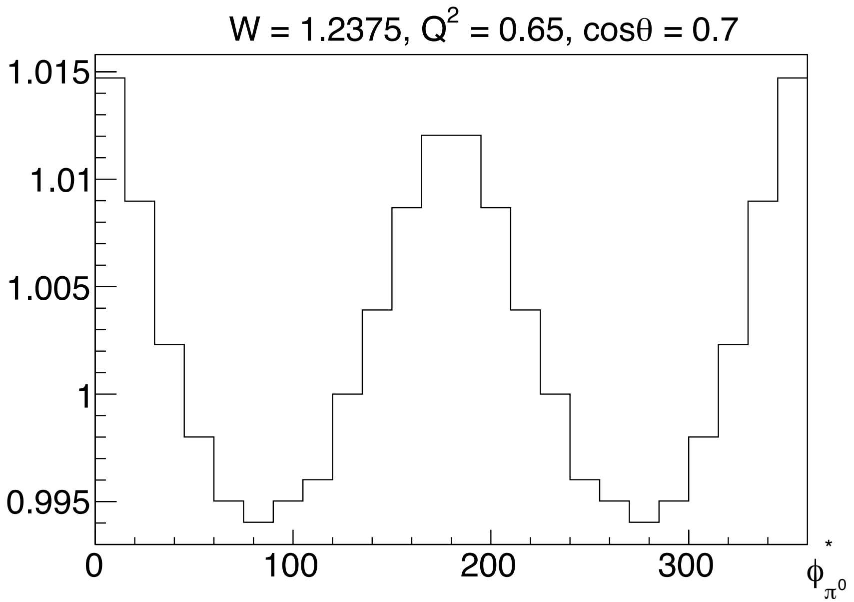


Corrections

Radiative corrections to the cross sections are are calculated exactly for the single pion electroproduction off the proton using the EXCLURAD approach developed in

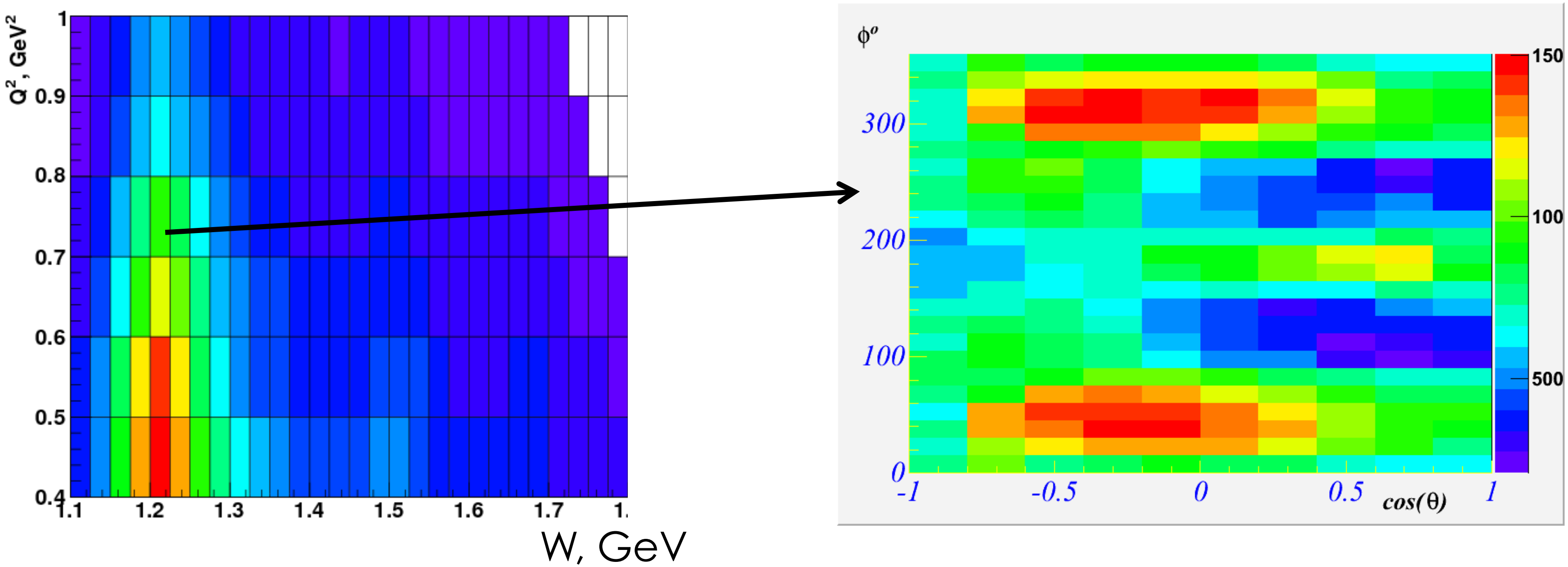
A. Afanasev, I. Akushevich, V. Burkert, K. Joo, Phys.Rev. D, 66 074004 (2002).





Bin centering correction to account for the difference between the value of the cross section in the center of the bin and average value.

Kinematical coverage



Wide kinematical coverage

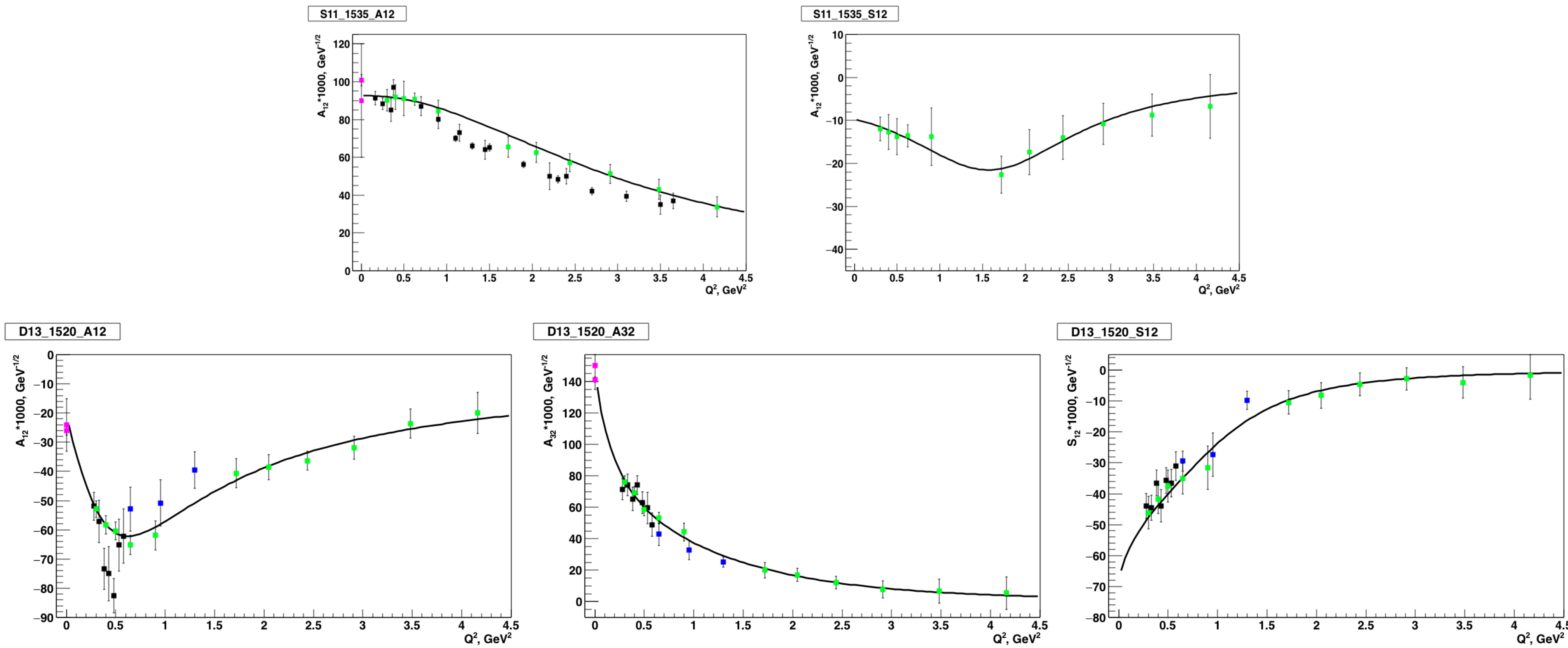
Nearly full angular coverage

	Bin size	Number of bins	Low edge	High edge
W	25 MeV	28	1.1	1.8
Q^2	0.1 GeV^2	6	0.4	1.0
$\cos\theta^*_{\pi^0}$	0.2	10	-1	1
$\phi^*_{\pi^0}$	15°	24	0	360

Number of bins = 40320

Interpolation of resonance parameters

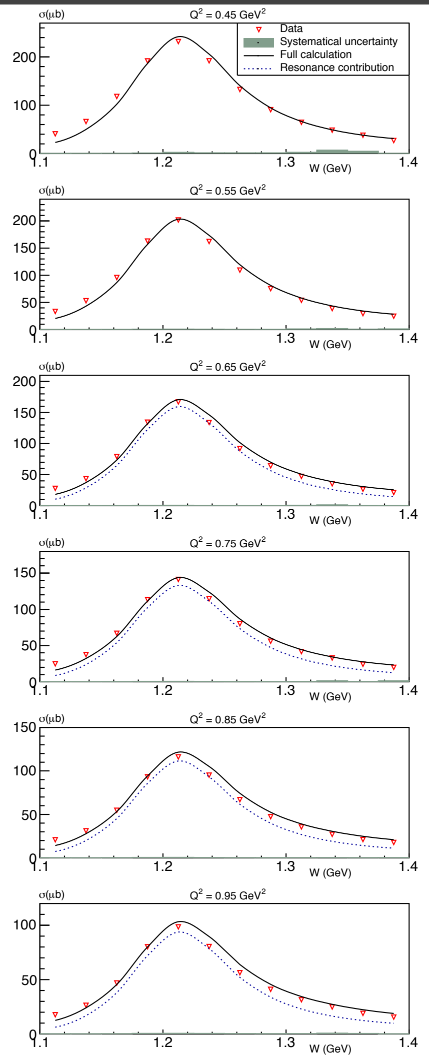
The CLAS results on $\gamma_v pN^*$ electrocouplings for the excited states in mass range up to 1.8 GeV are interpolated/extrapolated at 0 GeV^2 <Q^2 < 5.0 GeV^2 (userweb.jlab.org/~isupov/couplings/).



Polinomial fit to the available data

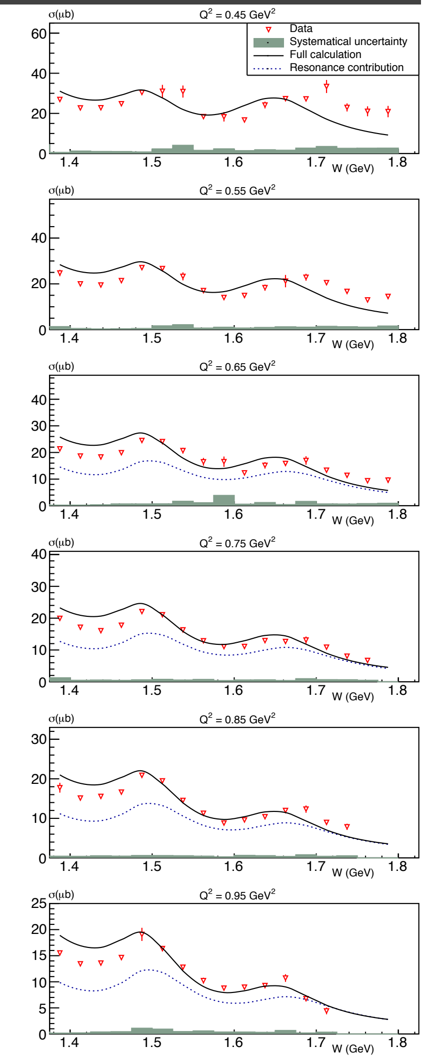
E.L. Isupov, Mosc. State U and UCONN

Cross section



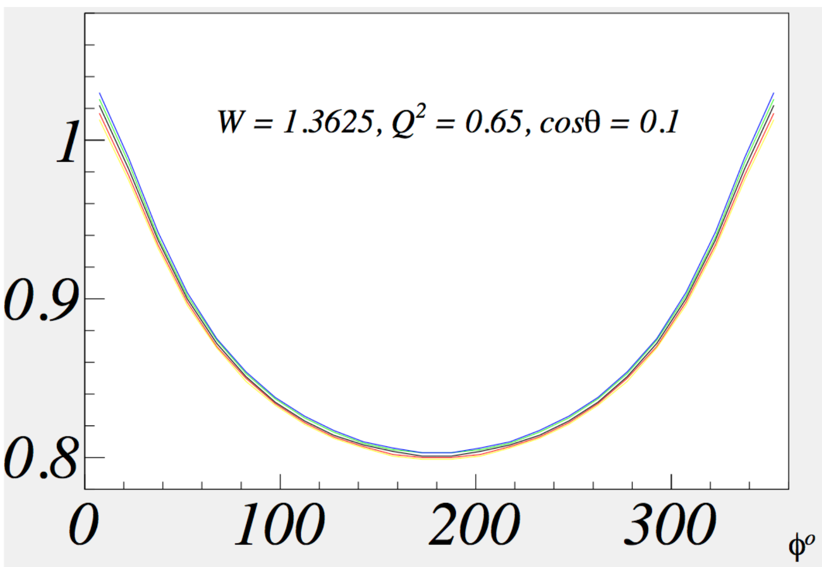
Model: code by I. Aznauryan with resonance electrocouplings from the empiric fit to data on resonance electrocouplings from CLAS results on $g_v pN^*$ electrocouplings (userweb.jlab.org/~isupov/couplings/).

- Model captures the major features throughout the full kinematical range, good agreement in well known Δ region
- Sizable resonant contributions
- High statistics even at high W values



Systematical uncertainties

Radiative correction



Cut	Uncertainty
Sampling fraction	1.49%
Electron fiducial cut	3.80%
Proton identification	2.44%
Proton fiducial cuts	4.1%
m_x^2 cut	2.56%
$\Delta\theta_1$ cut	0.68%
$\Delta\theta_2$ cut	0.77%
$\Delta\phi_{CMS}$ cut	1.92%
Normalization	5%
Total	8.7%

Structure functions

Model: code by I. Aznauryan with resonance electrocouplings from the empiric fit to data CLAS results on $g_v pN^*$ electrocouplings.

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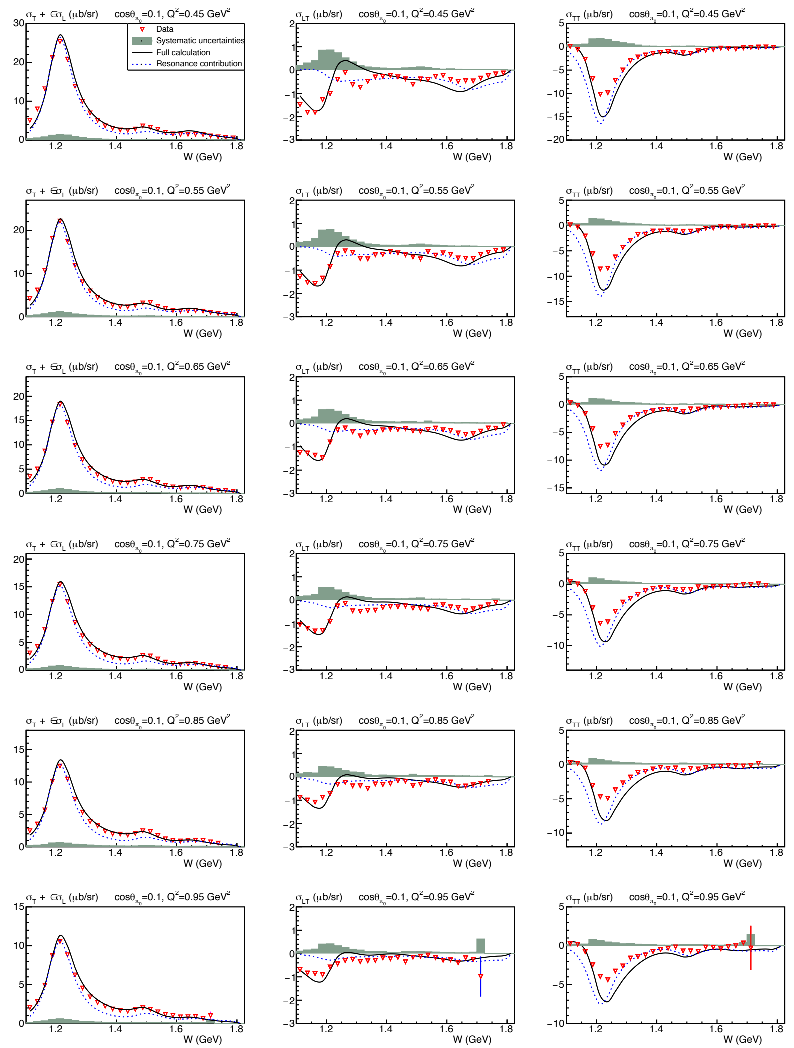
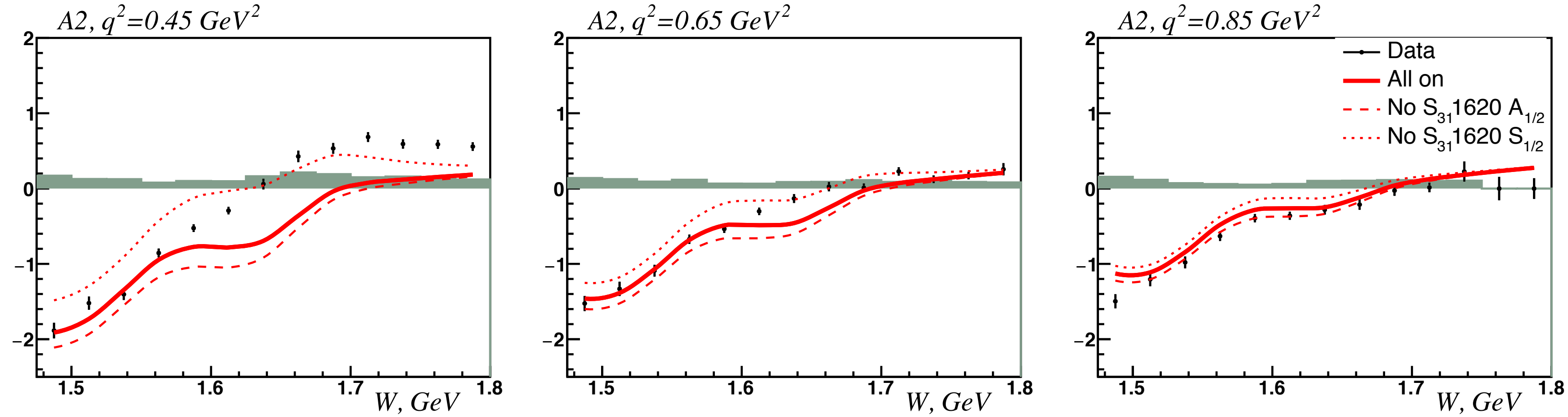


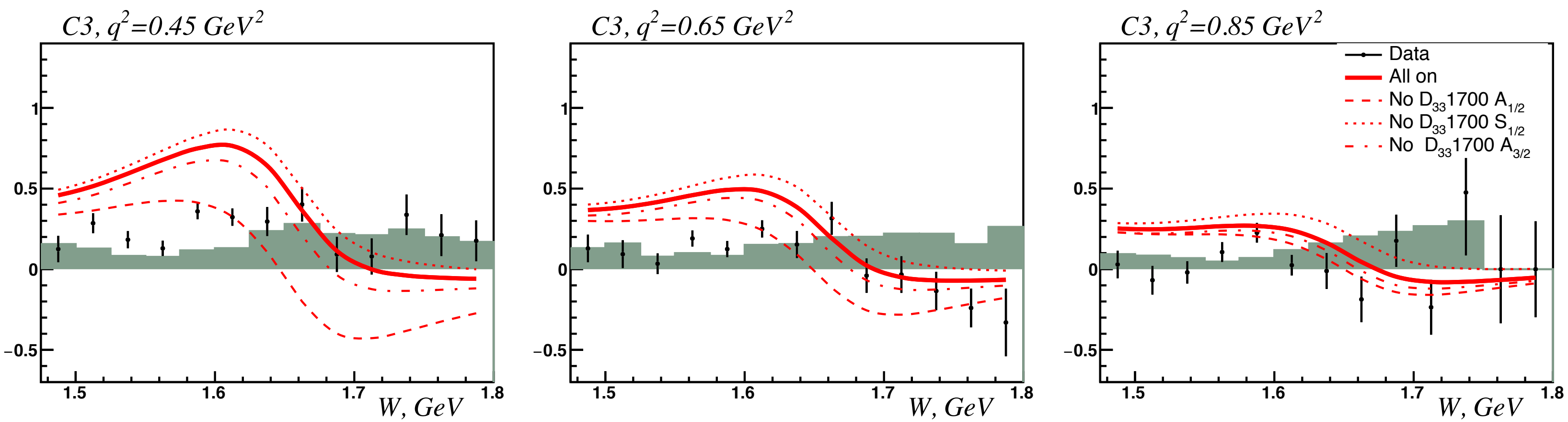
Sensitivity to Resonances

$S_{31}(1620)$



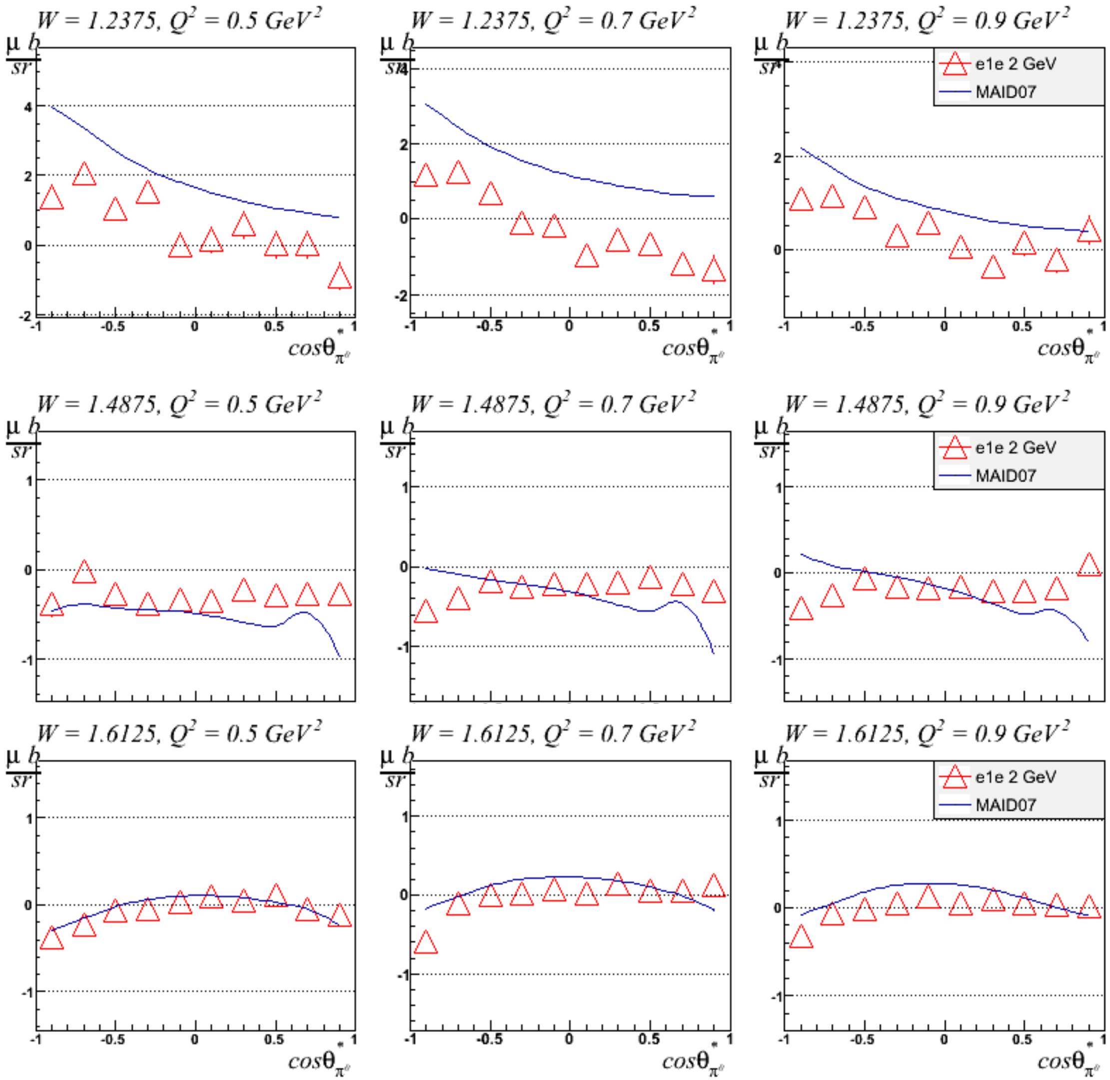
Very sensitive to $S_{1/2}$ at low Q^2
Hint to overestimation at low Q^2

$D_{33}(1700)$



Very sensitive to the $A_{1/2}$

Polarization Observables



$$\frac{d\sigma_{LT'}}{d\cos\theta^*_{\pi^0 CM}}$$

- This observable is sensitive to interference between different resonances, resonances and background and between different background terms;
- Relatively coarse Q^2 binning is important to pick up a small signal.

Conclusion

- For the first time, differential π^0 electroproduction off protons cross section and beam spin asymmetry are measured in wide Q^2 (0.4 – 1.0 GeV^2) and W (1.1 – 1.8 GeV) range;
- Exclusive electroproduction structure functions $d\sigma_U/d\Omega_{\pi^0 CM}$, $\sigma_{TT}/d\Omega_{\pi^0 CM}$, $\sigma_{LT}/d\Omega_{\pi^0 CM}$ and $\sigma_{LT'}/d\Omega_{\pi^0 CM}$ and Legendre moments have been extracted;
- Comparison with JANR model and multipole decomposition demonstrated data sensitivity to the contribution of individual resonances for both N* and Δ* resonances in the second and third third resonance region;
- Measured observables provided information needed for extraction of the resonance electrocouplings in the second and third resonance regions from $\pi^0 p$ electroproduction off protons data for the first time.
- Combined studies of $p\pi^0$ and $\pi^+ n$ exclusive electroproduction will allow us to determine electrocouplings of N* and Δ* in the third resonance region for all states with substantial single pion decays.