``Single pion electroproduction off protons in the second and third resonance regions with CLAS"

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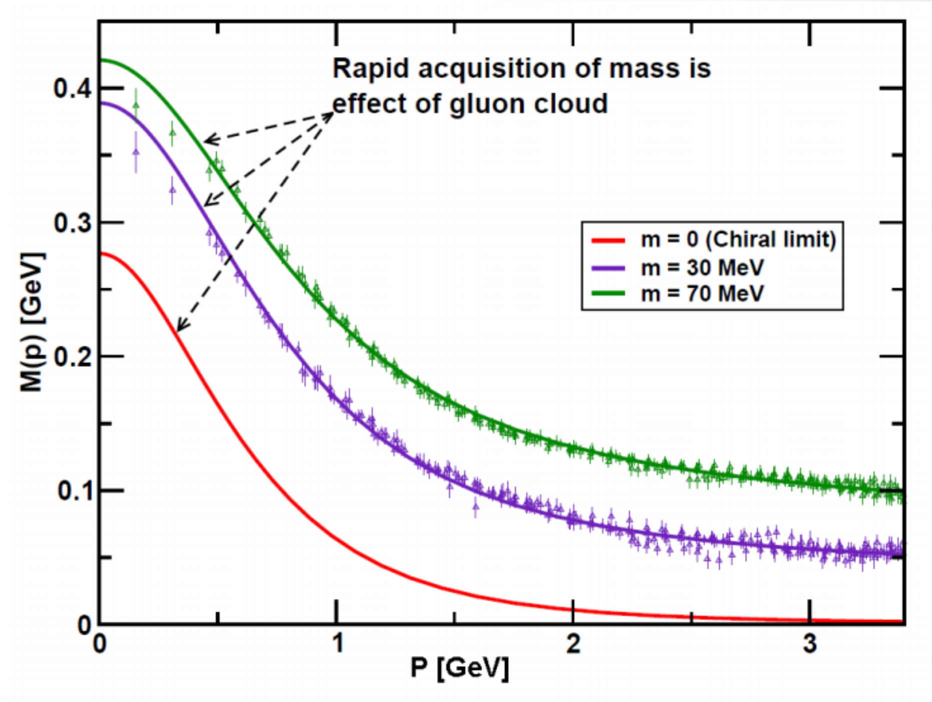
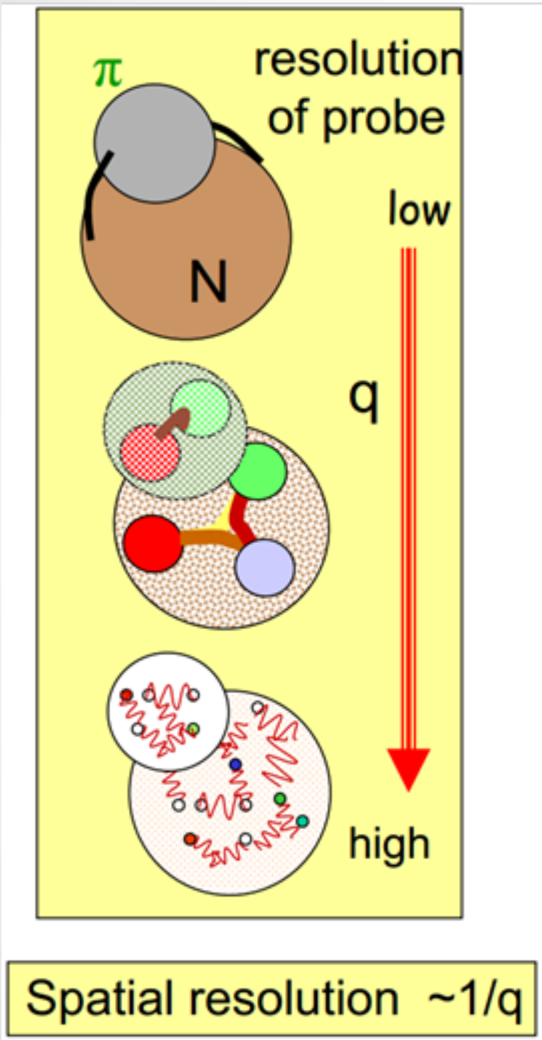
Motivation to study N*

- Particular feature of the strong interaction in perturbative regime is generation of effective degrees of freedom;
- Dressing of bare QCD quarks and $q\bar{q}$ pairs, coupled with gluon fields, generate dressed quarks with momentum dependent mass;
- More than 98% of dressed quark masses as well as their dynamical structure are generated non-perturbatively through dynamical chiral symmetry breaking (DCSB).
- The Higgs mechanism accounts for less than 2% of the nucleon & N* mass.



- Momentum dependence of the dressed quark mass reflects the transition from quark/gluon confinement to asymptotic freedom

Nucleon resonances



- N* electroproduction is proven to be an effective tool in exploration of excited nucleon state structure;
- Studies of Q^2 evolution of N^* electroproduction allows us to elucidate relevant degrees of freedom in N^* structure offering access to relevant degrees of freedom of the strong interaction, including dressed quark mass function;
- We already have results on the low lying resonances with mass below 1.6 GeV. However, states from third resonance region are less explored;
- We still have experimental data on
  - $N(1675)5/2^-$
  - $N(1680)5/2^+$
  - $N(1710)1/2^+$

  only from $\pi^+ n$ channel and at high photon virtuality $Q^2 > 2$ GeV^2.

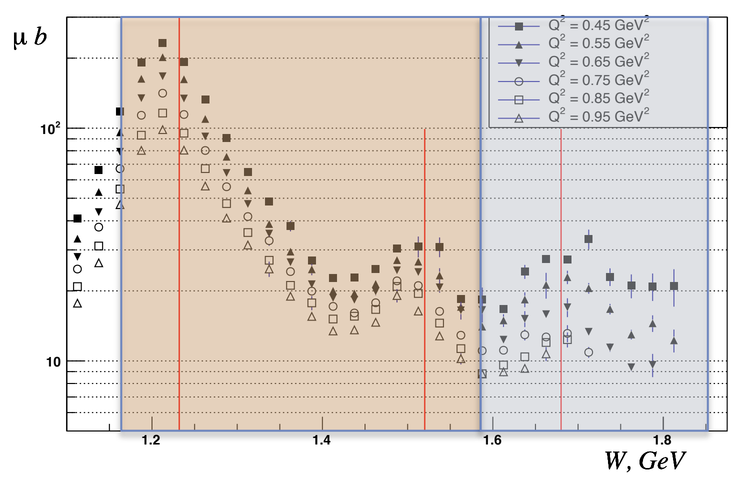
Nucleon resonances

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(1710)1/2+

I st resonance region

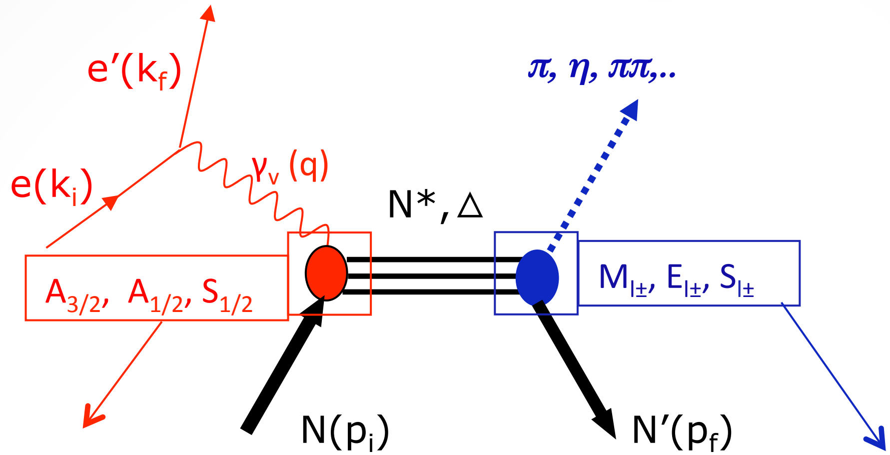
II nd resonance region

III rd resonance region



- For the first time electrocouplings of the resonances in the 3^{rd} resonance region will be available from π^0 electroproduction;
- 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.

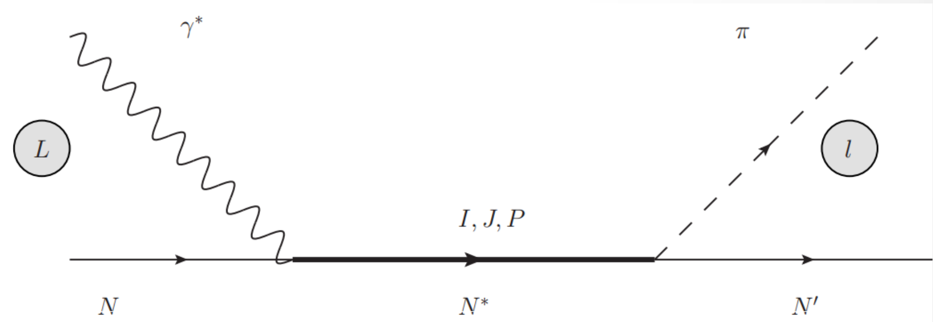
Resonant meson production



Helicity amplitudes

Meson production multipoles

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



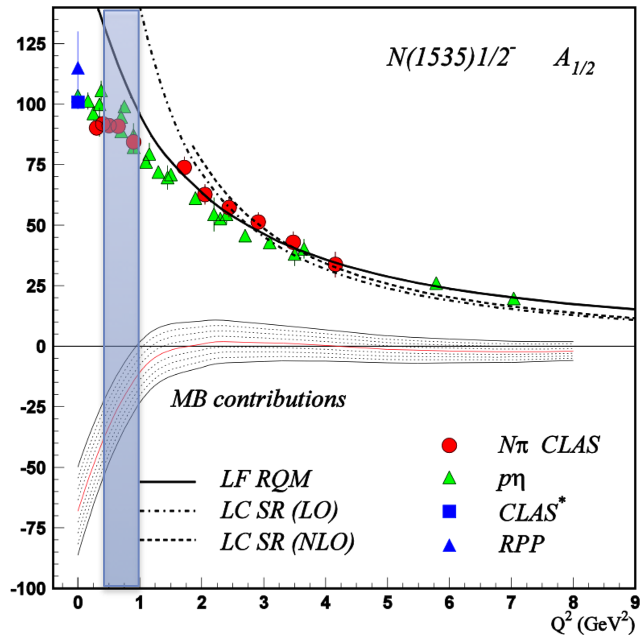
$$\Gamma_{em} = \frac{q^2_{\gamma CM}}{\pi} \frac{2M_p}{(2J+1)M_{N*}} (|A^2_{1/2}| + |A^2_{3/2}|)$$

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

At the photon point

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

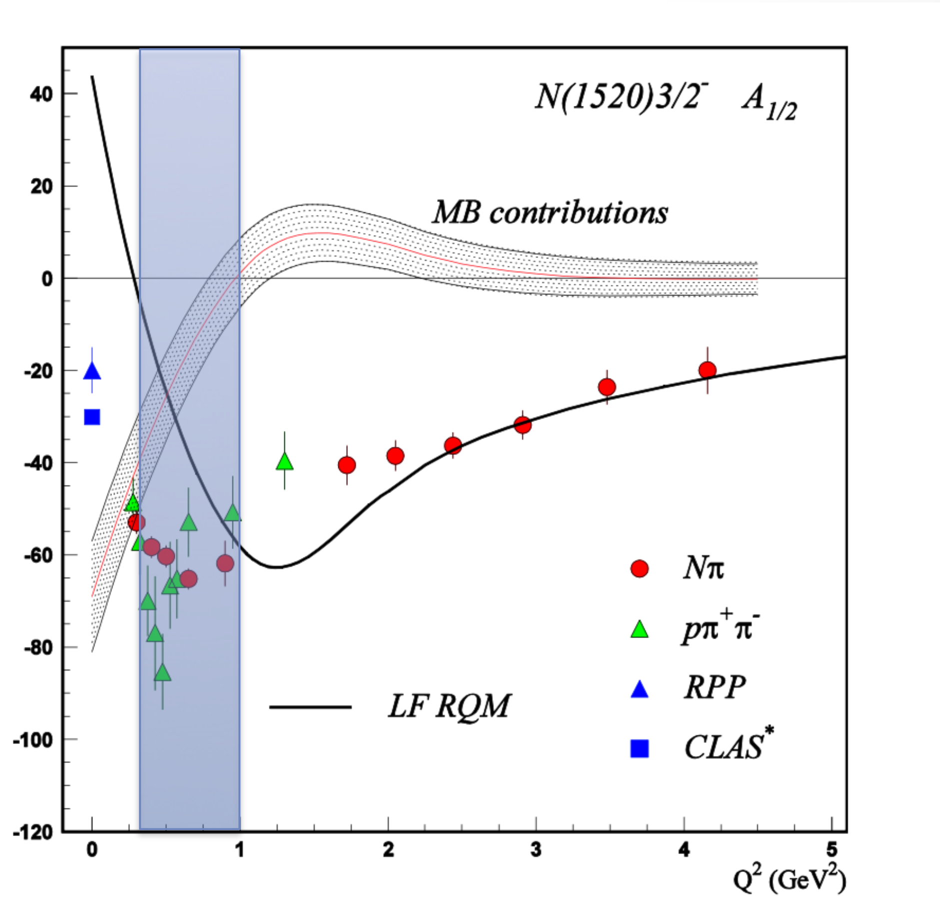
N(1535)1/2⁻



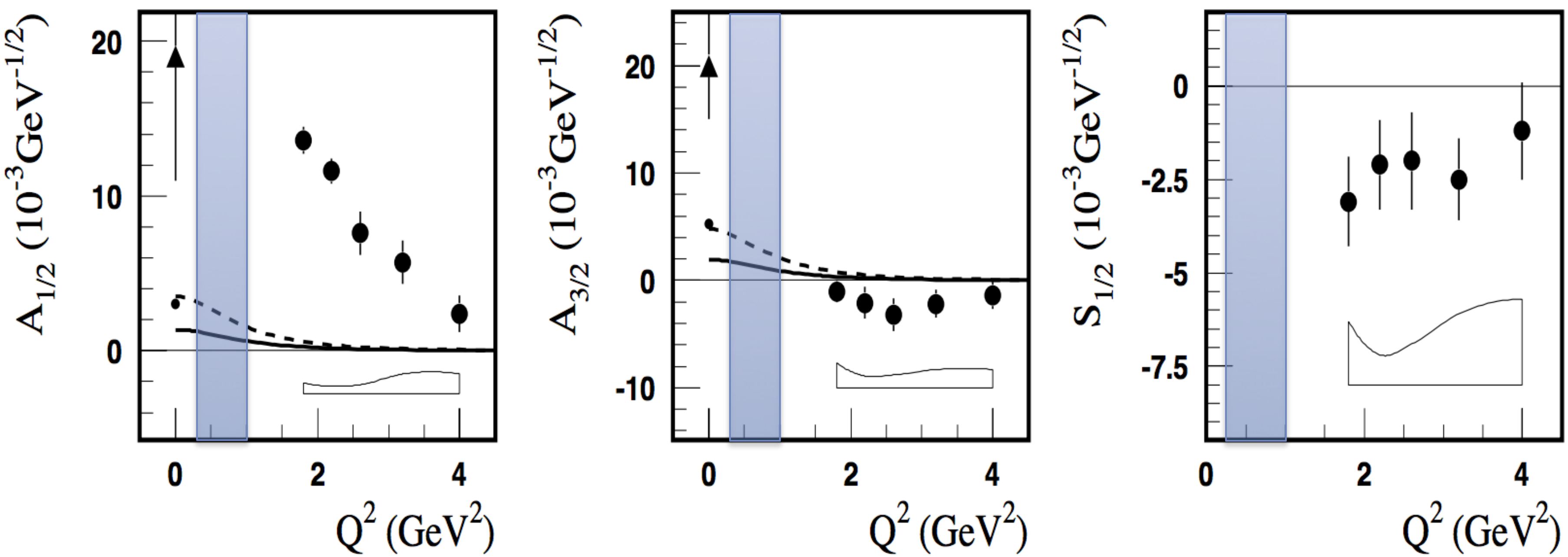
Consistent results between different exclusive channels will offer good test of this data; Presented data covers the region (see $A_{1/2}$) of combined contribution from MB cloud and quark core.

N(1520)3/2⁻

Presented data covers the region of possible transition from superposition of quark and MB degrees of freedom to the dominance of quark degrees of freedom.



$N(1675)5/2^-$

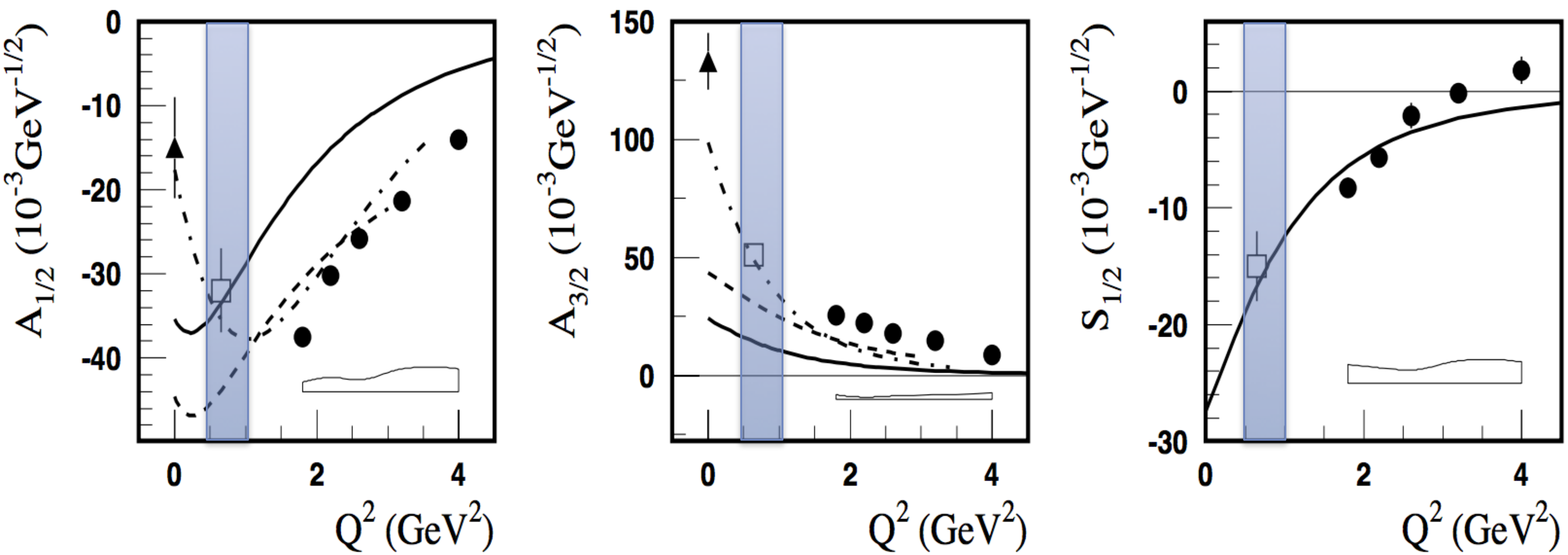


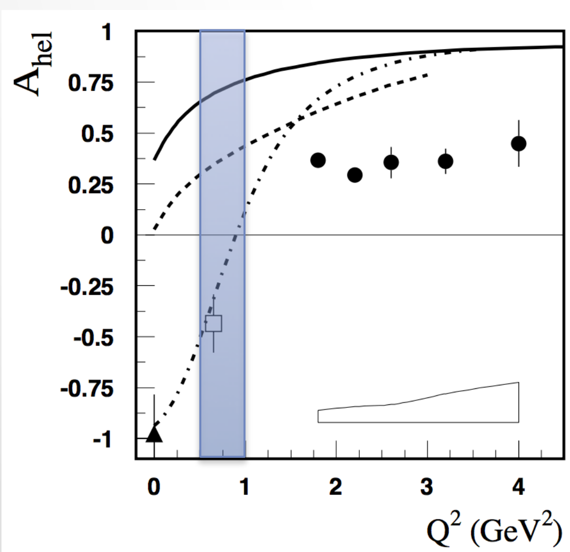
Lack of data in the region covered by this dataset;
Quark core contribution to the helicity amplitudes of the $N(1675)5/2^-$ are strongly suppressed (Moorhouse selection rules).
SQT results: $A_{1/2} = A_{3/2} = 0$
All the strength is generated from MB cloud=> prospects for direct access to MB

Plot from K. Park, I. Aznauryan,

Phys. Rev. C80, 055203 (2009)

N(1680)5/2+





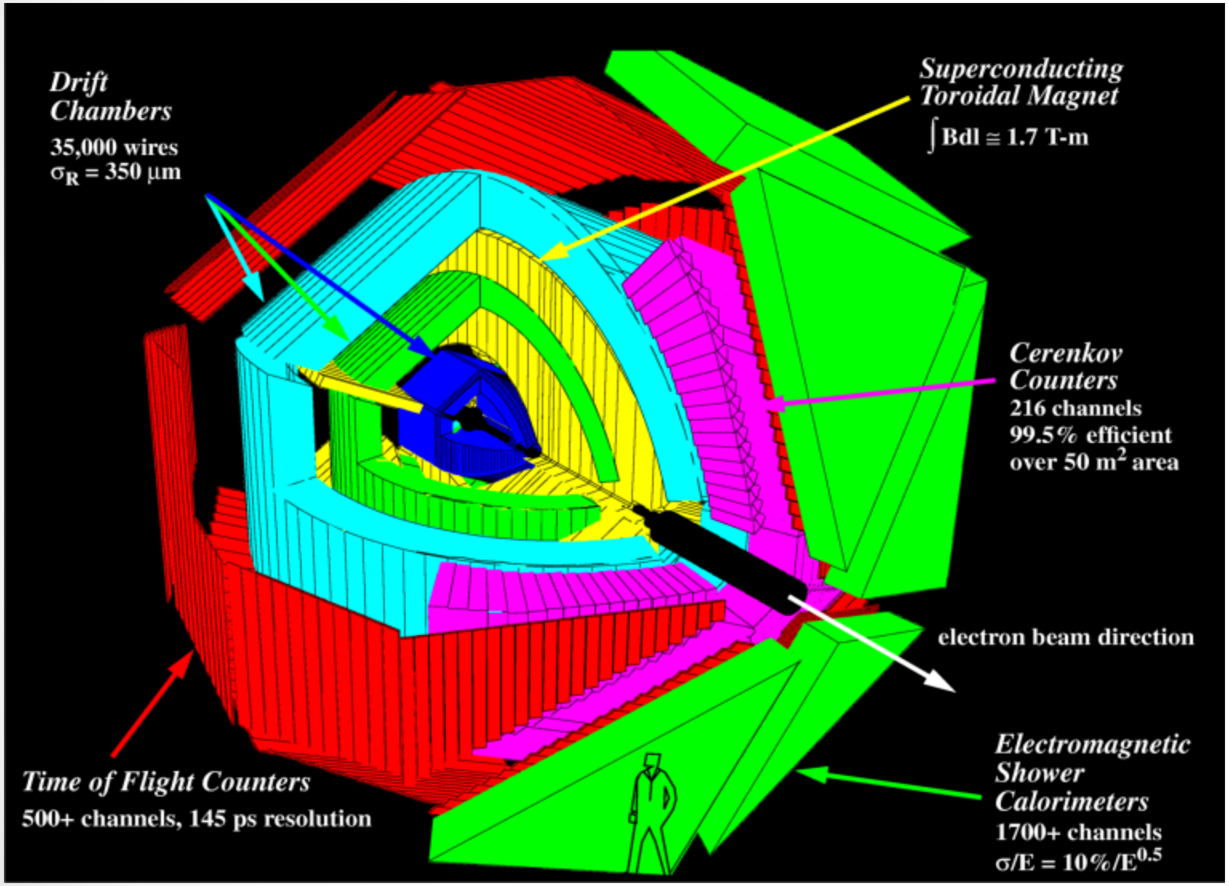
Lack of data in the region covered by this dataset;

Helicity asymmetry

$A_{hel} = (A^2_{1/2} - A^2_{3/2})/(A^2_{1/2} + A^2_{3/2})$

is expected to cross zero in the region covered by presented dataset

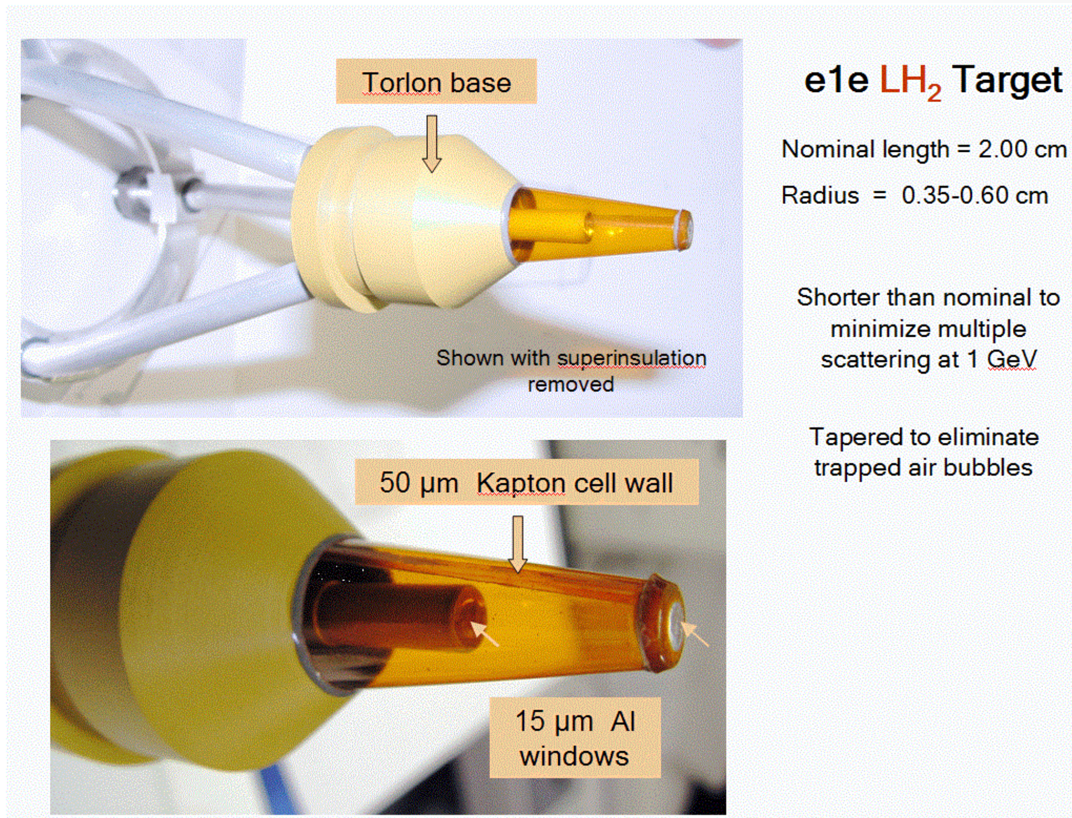
CLAS detector



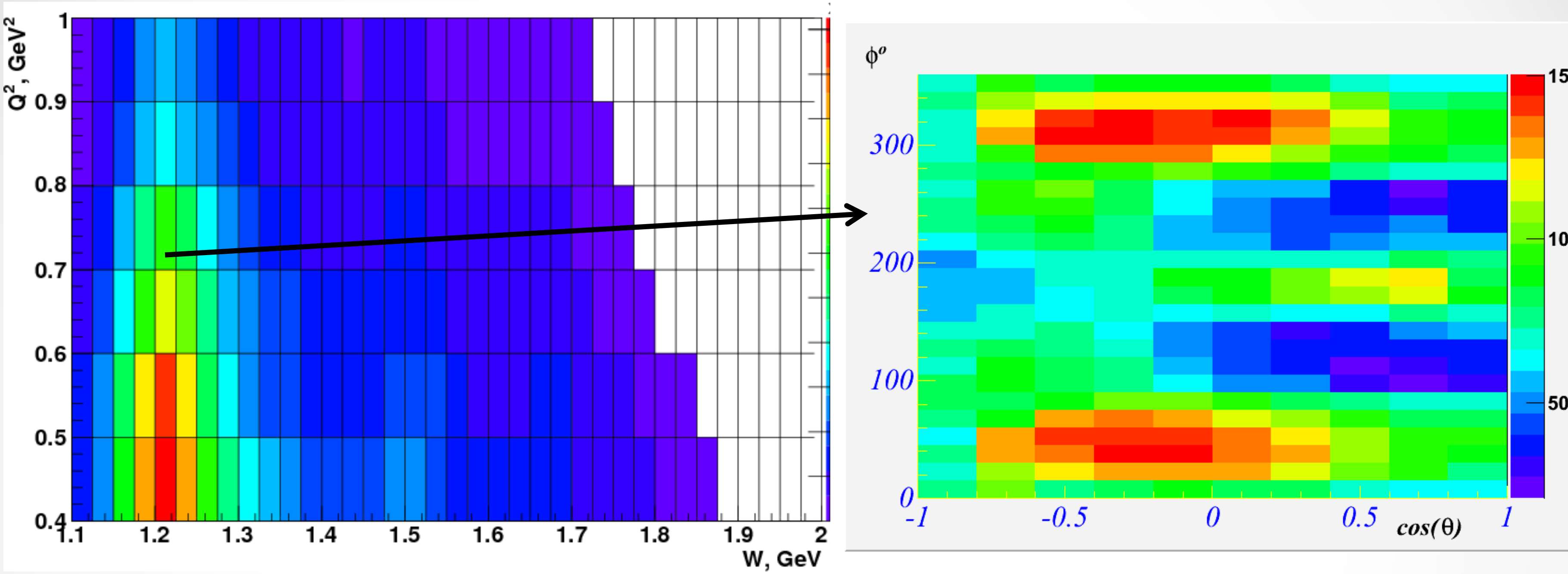
- 4π acceptance
- Possibility to detect multiple neutral and charged particles in the final state
- High energy and timing resolution

e1e run

Beam energy: 2.036 GeV
Beam polarization: ~ 70%
Target: Liquid Hydrogen
Number of triggers: $1.5*10^9$



Binning ep->epπ^0



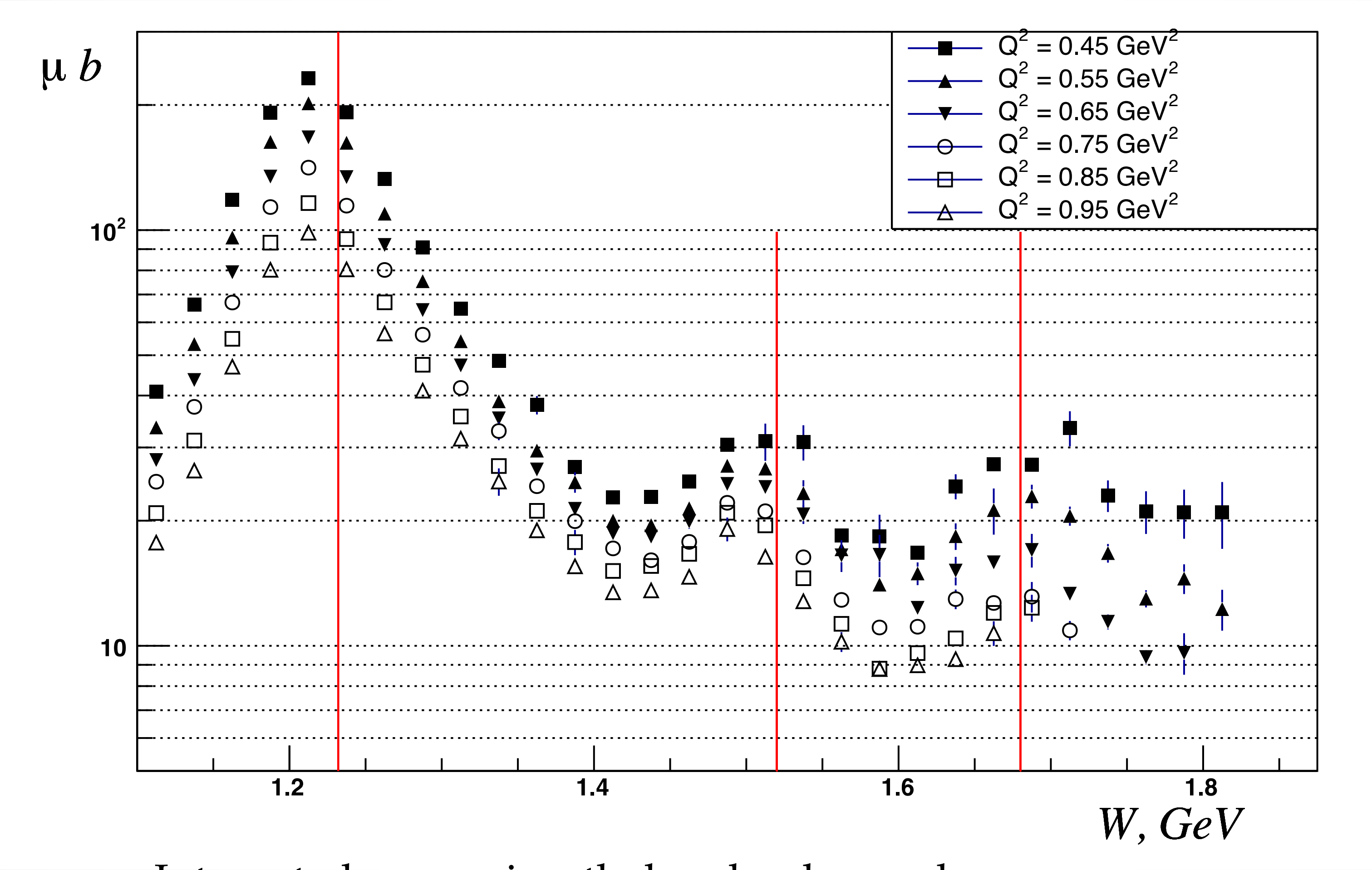
Wide kinematical coverage

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^o	24	0	360

Number of bins = 40320

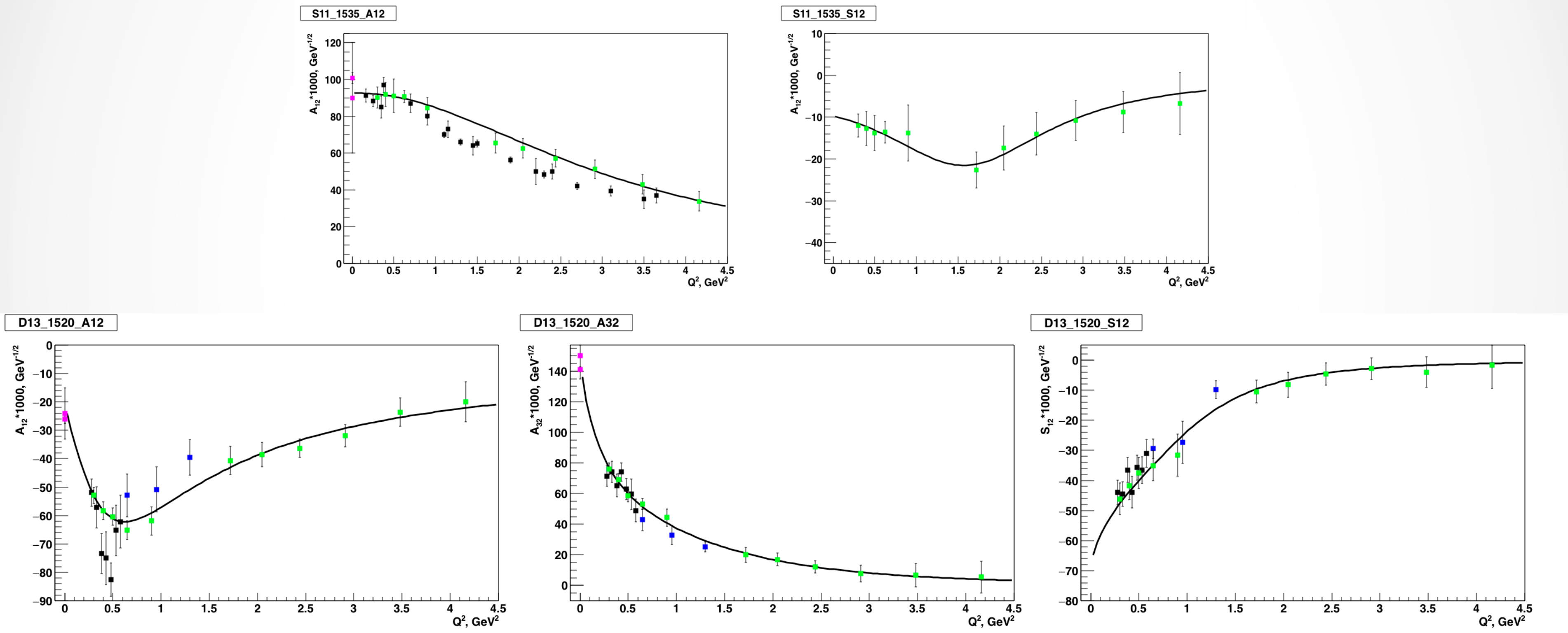
Cross section



Integrated over azimuthal and polar angles
Covering first, second and third resonance region
Three resonance regions are prominent in all 6 Q^2 bins

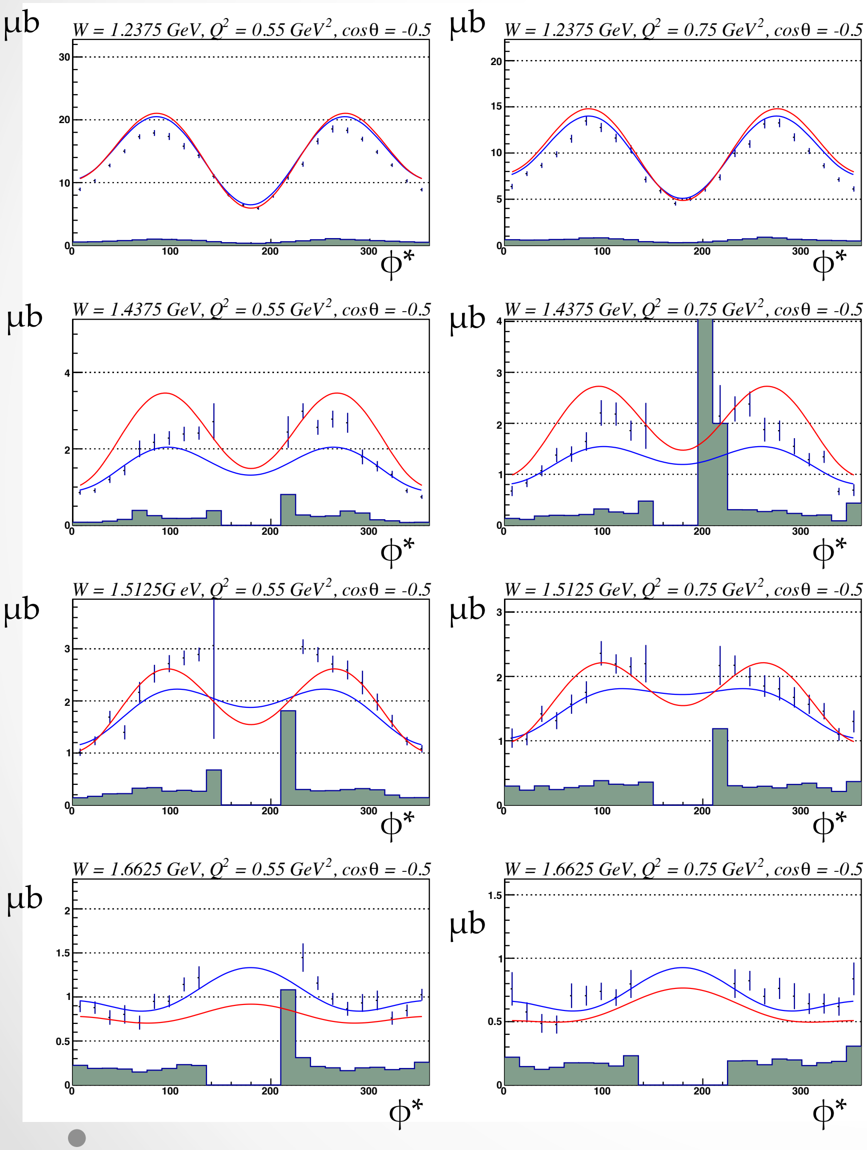
Interpolation of resonance parameters

- 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.GeV2 <Q2 < 5.0 GeV2 (userweb.jlab.org/~isupov/couplings/).



Polinomial fit to the available data

Cross section



Data
MAID07
JANR

MAID07: default parameters

JANR: code by I. Aznauryan with resonance form factors from the empiric fit to data by E. Isupov

- Reasonable agreement with models throughout the full kinematical range, good agreement in well known Δ region
- High statistics even at high W values
- Limited statistical and systematical uncertainties

Spikes in systematical error correspond to bins with low statistics

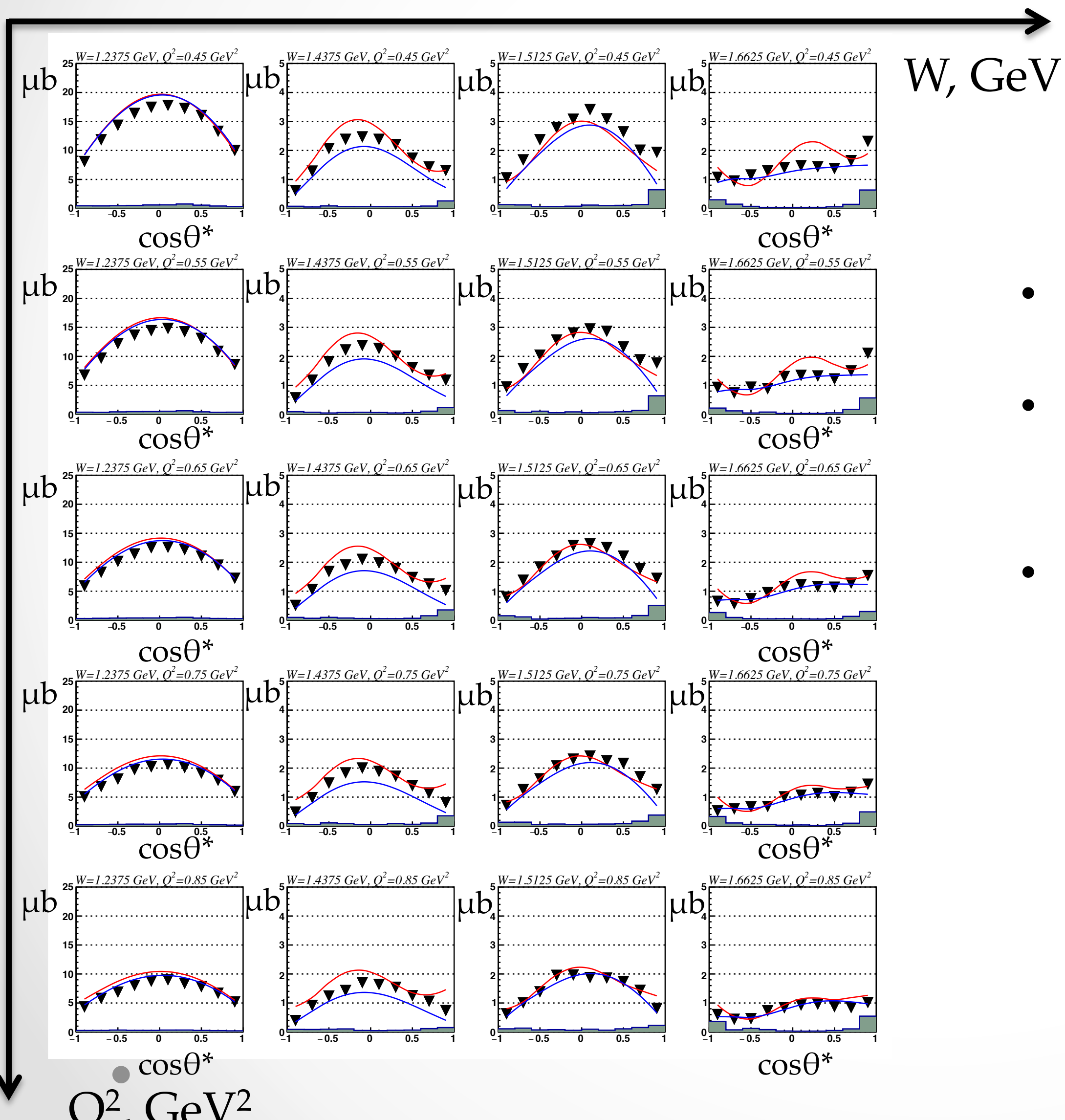
Structure functions

$$\frac{d\sigma}{d\Omega^*_{\pi^0}} = \frac{2W p_{\pi^o}}{W^2 - m_P^2}$$
$$(\sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT} sin^2\theta^*_{\pi^0} cos2\phi^*_{\pi^0} + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT} sin\theta^*_{\pi^0} cos\phi^*_{\pi^0} +$$
$$h\sqrt{2\epsilon_L(1-\epsilon)}\sigma_{LT'} sin\theta^*_{\pi^0} sin\phi^*_{\pi^0}), \quad (1.1)$$

Structure functions
$\sigma_T+\varepsilon\sigma_L$, σ_{TT} σ_{LT}
extraction is performed via
F(x) = A + Bcosϕ + Ccos2ϕ
fit to the measured cross section

σ_{LT}' will be discussed later

Structure functions

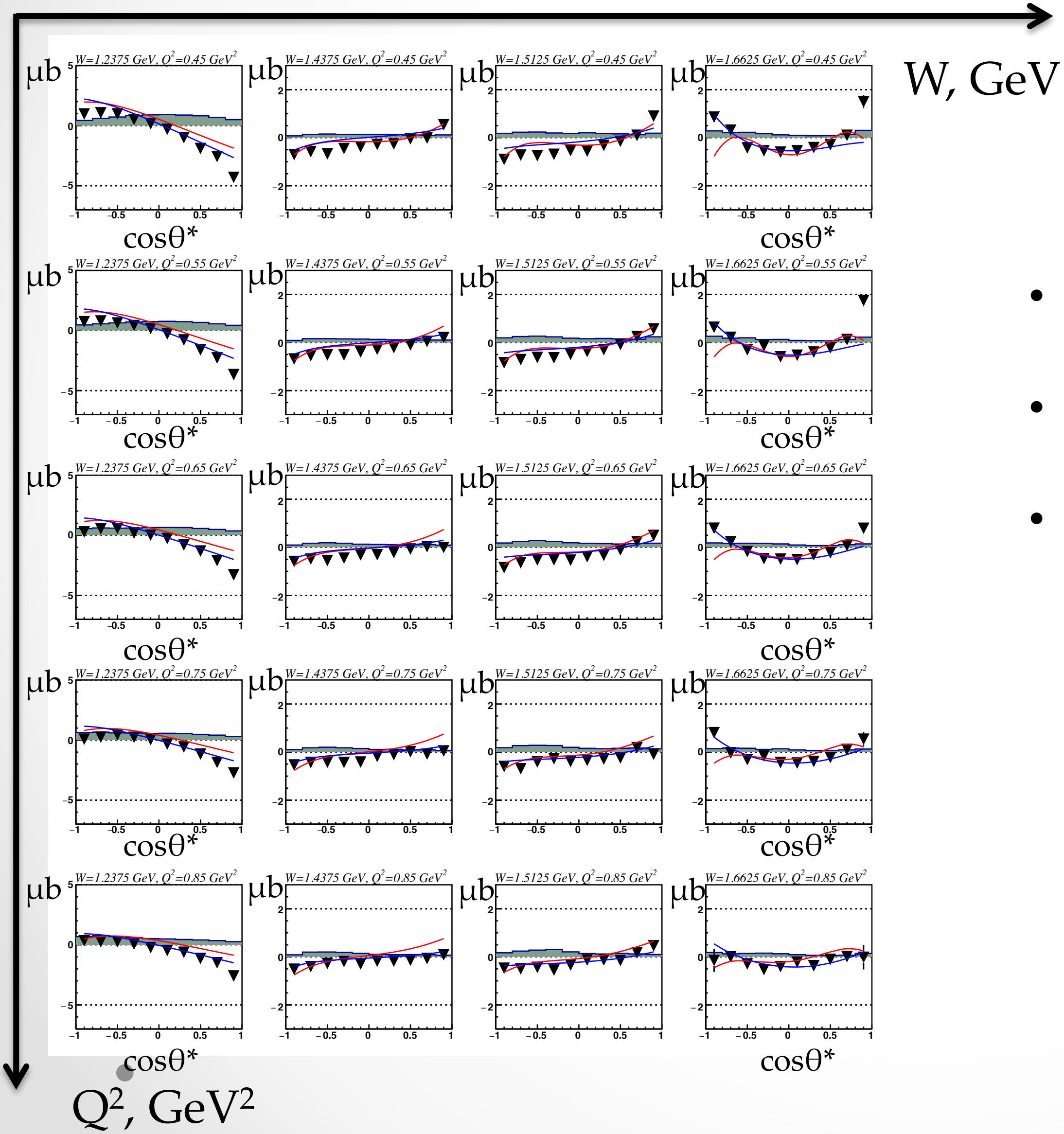


$\sigma_T + \varepsilon\sigma_L$

Data
MAID07
JANR

- Good agreement in the Δ region for both models;
- In the second resonance region JANR seems to have a minor advantage, especially at higher Q^2;
- In the third resonance regions both models should be further adjusted to the experimental data.

Structure functions

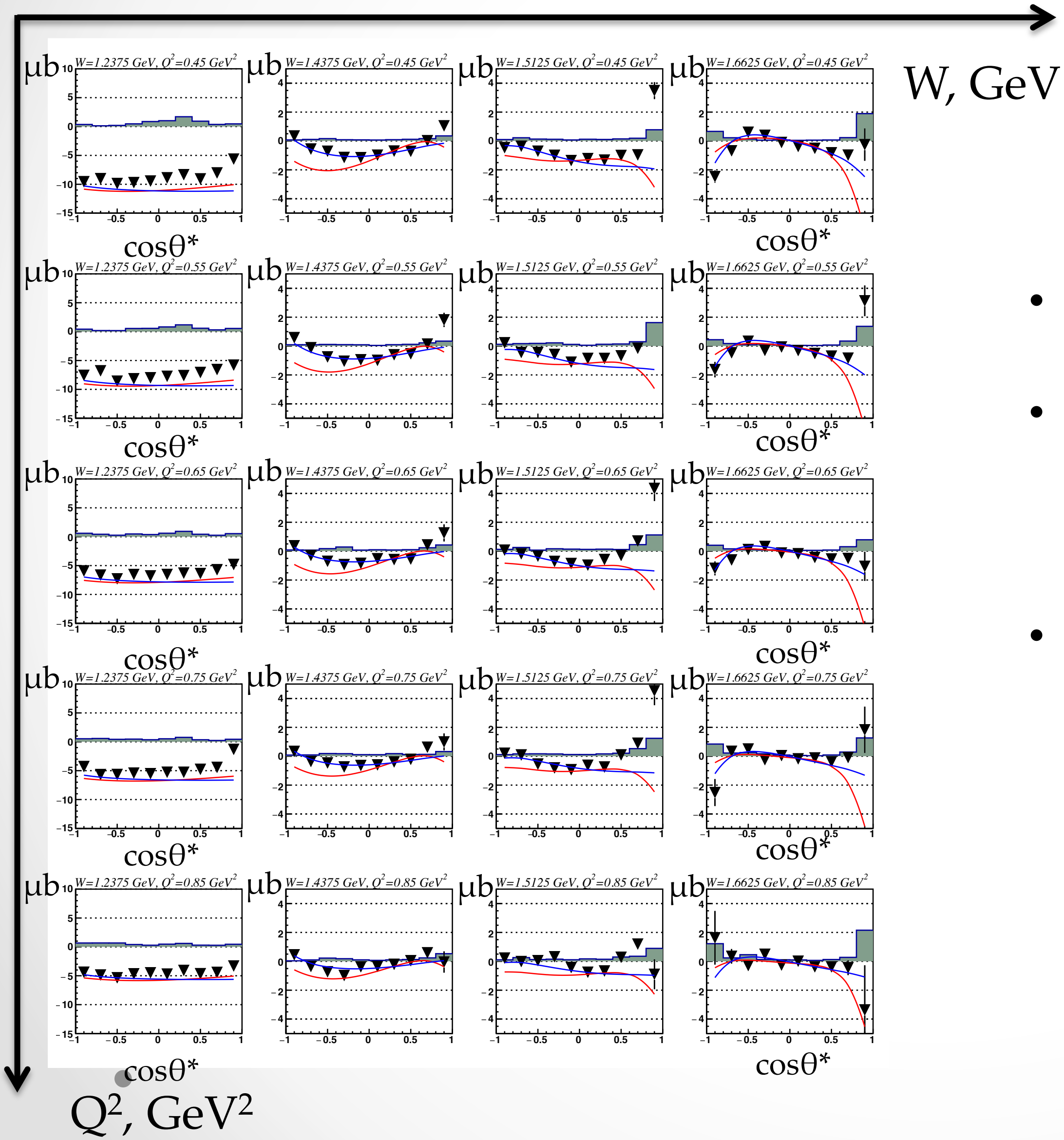


σ_{LT}

Data
MAID07
JANR

- Good agreement in the Δ region for both models;
- Good agreement in the second resonance region;
- Decent agreement in the third resonance region with discrepancy at extreme values of cosθ.

Structure functions



σ_{TT}

Data
MAID07
JANR

- Decent agreement in the Δ region for both models
- In the second resonance region MAID 07 seems to have some advantage, both models need to be further adjusted;
- In the third resonance regions MAID 07 seems to have some advantage, both models need to be adjusted.

Legendre multipoles

General equation:

$$\sigma_T + \epsilon\sigma_L = \sum_{i=0}^{2l} A_i P_i(cos\theta^*_\pi),$$

$$\sigma_{TT} = \sum_{i=0}^{2l-2} B_i P_i(cos\theta^*_\pi),$$

$$\sigma_{LT} = \sum_{i=0}^{2l-1} C_i P_i(cos\theta^*_\pi),$$

l = 1
l = 2
l = 3

Up to $l = 2$

$$\sigma_T + \varepsilon\sigma_L = A_0P_0(\cos\theta) + A_1P_1(\cos\theta) + A_2P_2(\cos\theta) + A_3P_3(\cos\theta) + A_4P_4(\cos\theta)$$

$$\sigma_{LT} = C_0P_0(\cos\theta) + C_1P_1(\cos\theta) + C_2P_2(\cos\theta)$$

$$\sigma_{TT} = B_0P_0(\cos\theta) + B_1P_1(\cos\theta)$$

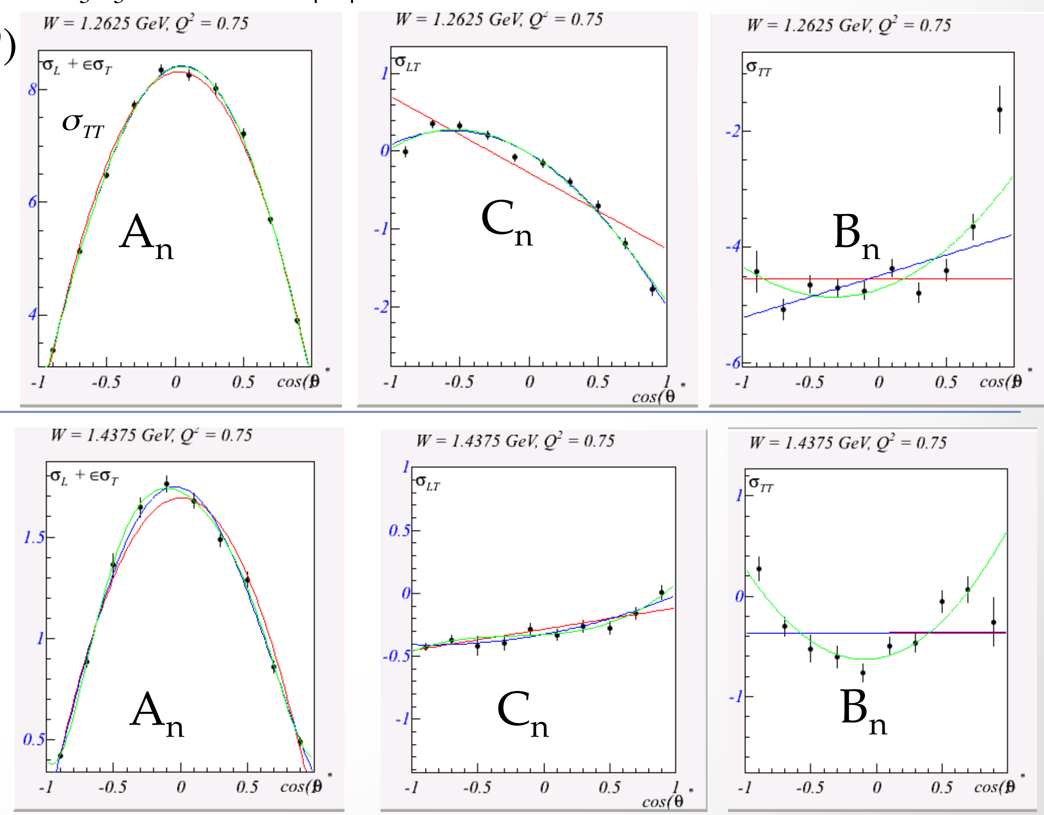
$$A_0P_0(\cos\theta) = A_0$$

$$A_1P_1(\cos\theta) = A_1\cos\theta$$

$$A_2P_2(\cos\theta) = \frac{1}{2}A_2(3\cos^2\theta - 1)$$

$$A_3P_3(\cos\theta) = \frac{1}{2}A_3(5\cos^3\theta - 3\cos\theta)$$

$$A_4P_4(\cos\theta) = \frac{1}{8}A_4(35\cos^4\theta - 30\cos^2\theta + 3)$$

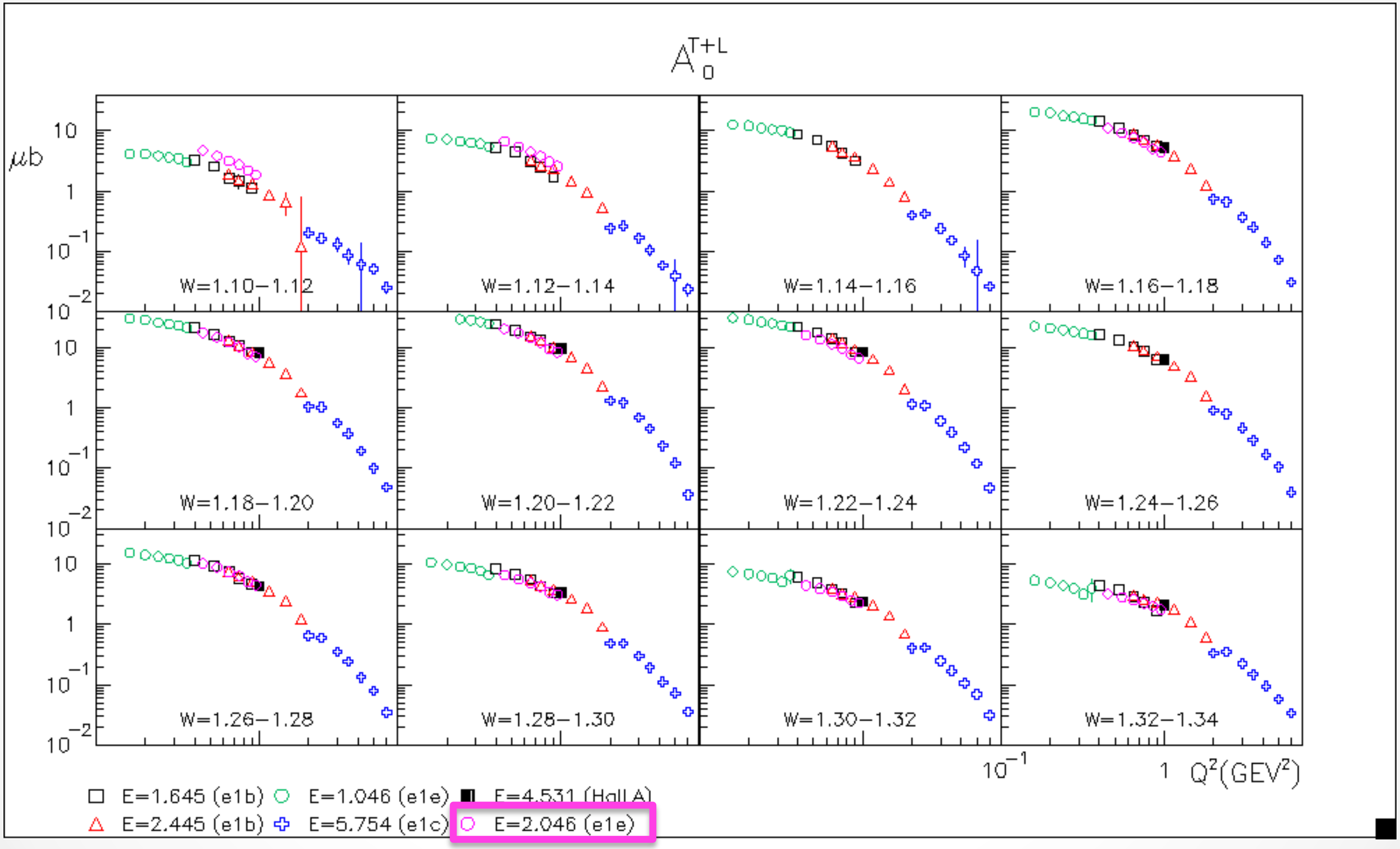


$l = 1$ does not work for C and B

$l = 2$ does not work for B

$l = 3$ works

Comparison to available data



- Results are consistent with previously available data in the Δ region and beyond

Sensitivity to individual resonances

1. Perform Legendre decomposition of the structure functions

$$\sigma_T + \epsilon\sigma_L = \sum_{i=0}^{2l} A_i P_i(cos\theta_\pi^*),$$

2. For each resonance we know corresponding pion multipoles

Resonance	Pion multipoles
$S_{11}(1535)$	E_{0+}, M_{0+}
$P_{11}(1440)$	M_{1-}, L_{1-}
$D_{13}(1520)$	E_{2-}, M_{2-}, L_{2-}
$D_{15}(1675)$	E_{2+}, M_{2+}, L_{2+}
$F_{15}(1680)$	E_{3-}, M_{3-}, L_{3-}

3. Express structure functions in terms of CGLN amplitudes:

$$\begin{aligned}\sigma_T &= |F_1|^2 + |F_2|^2 + 0.5sin^2\theta(|F_3|^2 + |F_4|^2) \\ &- Re(2cos\theta F_1^* F_2 \\ &- sin^2\theta(F_1^* F_4 + F2^* F_3 + cos\theta F3^* F_4)) \\ \sigma_L &= |F_5|^2 + |F_6|^2 + 2cos\theta Re(F_5^* F_6)\end{aligned}$$

4. CGLN amplitudes in terms of pion multipoles via derivatives of Legendre polynomials:

$$F_1 = \sum_{l\geqslant 0} \{(lM_{l+} + E_{l+})P'_{l+1} + [(l+1)M_{l-} + E_{l-}]P'_{l-1}\}$$

$$F_2 = \sum_{l\geqslant 1} [(l+1)M_{l+} + lM_{l-}]P'_l$$

$$F_3 = \sum_{l\geqslant 1} [(E_{l+} - M_{l+})P''_{l+1} + (E_{l-} + M_{l-})P''_{l-1}]$$

$$F_4 = \sum_{l\geqslant 2} (M_{l+} - E_{l+} - M_{l-} - E_{l-})P''_l$$

$$F_5 = \sum_{l\geqslant 0} [(l+1)L_{l+}P'_{l+1} - lL_{l-}P'_{l-1}]$$

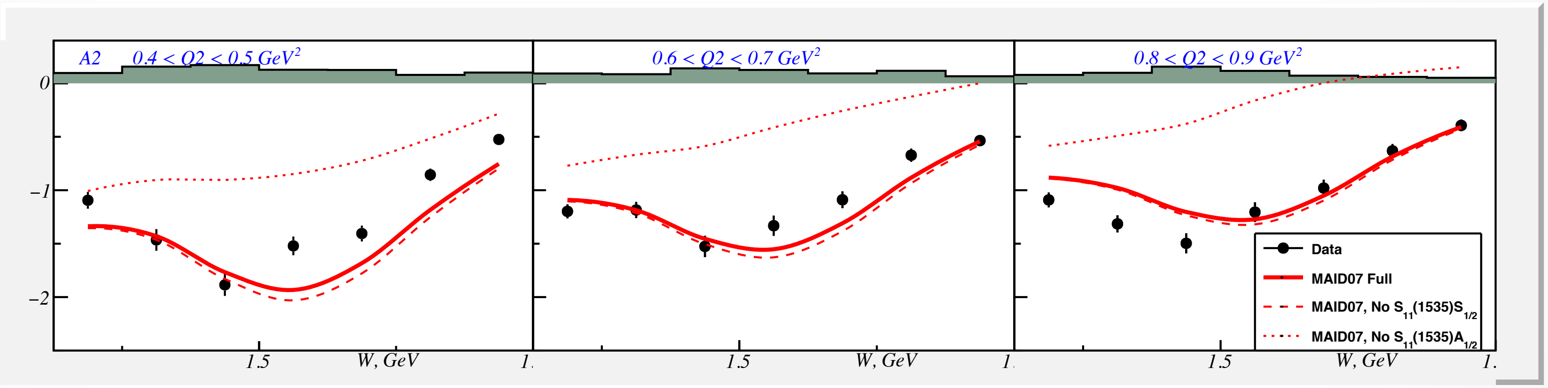
$$F_6 = \sum_{l\geqslant 1} [lL_{l-} - (l+1)L_{l+}]P'_l.$$

5. Determine which multipole (and resonance) could be expected in which A_i.
6. Repeat for all structure functions.

Individual Resonances

2nd resonance region

N(1535)1/2⁻

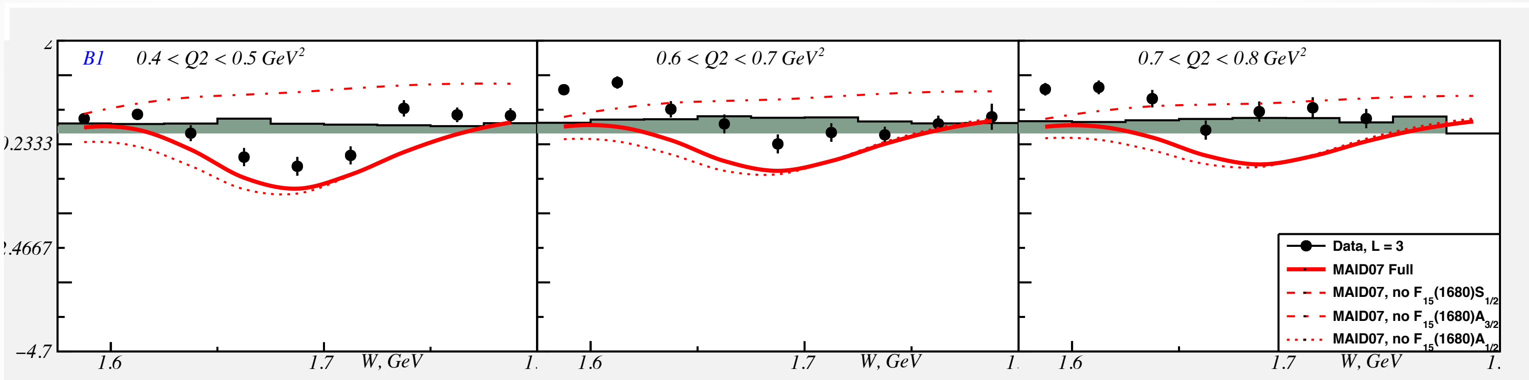


MAID07 is in good agreement with data in full Q^2 range
MAID07 is dominated by a $A_{1/2}$ amplitudes

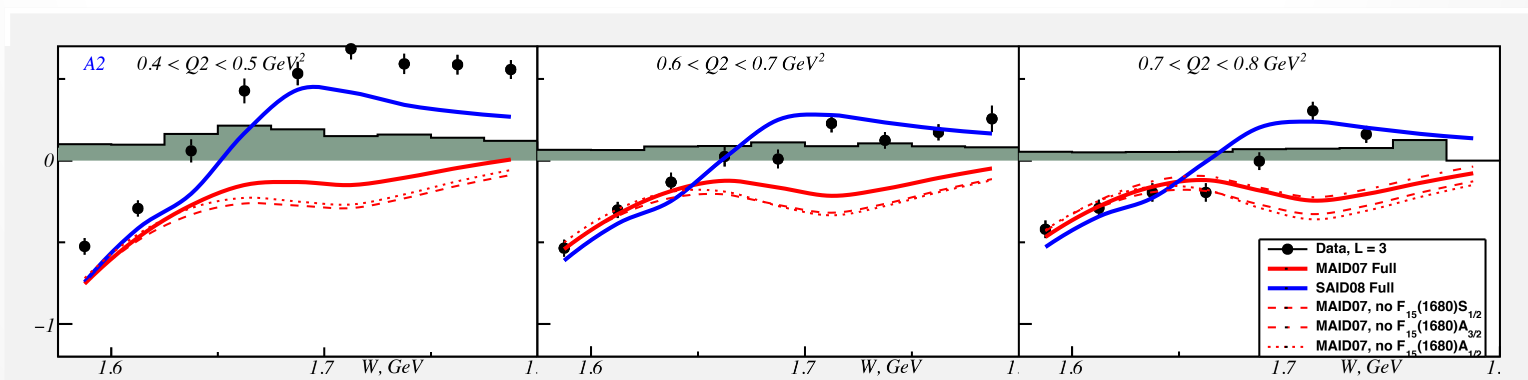
Individual Resonances

N(1680)5/2+

3rd resonance region



MAID is dominated by $A_{3/2}$
Good agreement at lower Q^2

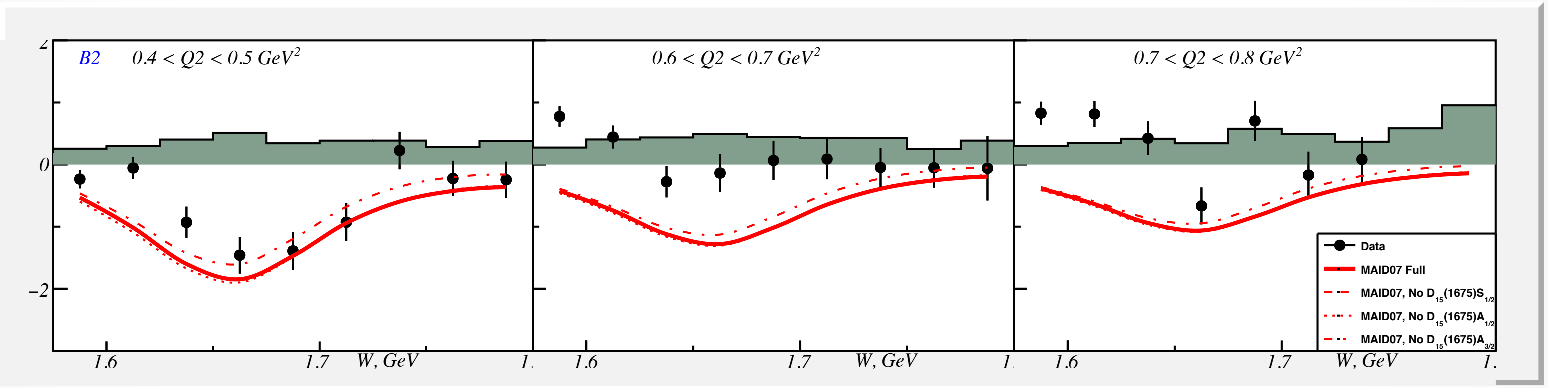


Good agreement with SAID
MAID has limited resonance contribution

Individual Resonances

3rd resonance region

N(1675)5/2-



Couplings are relatively weak, with a $A_{3/2}$ more prominent than others

Asymmetry

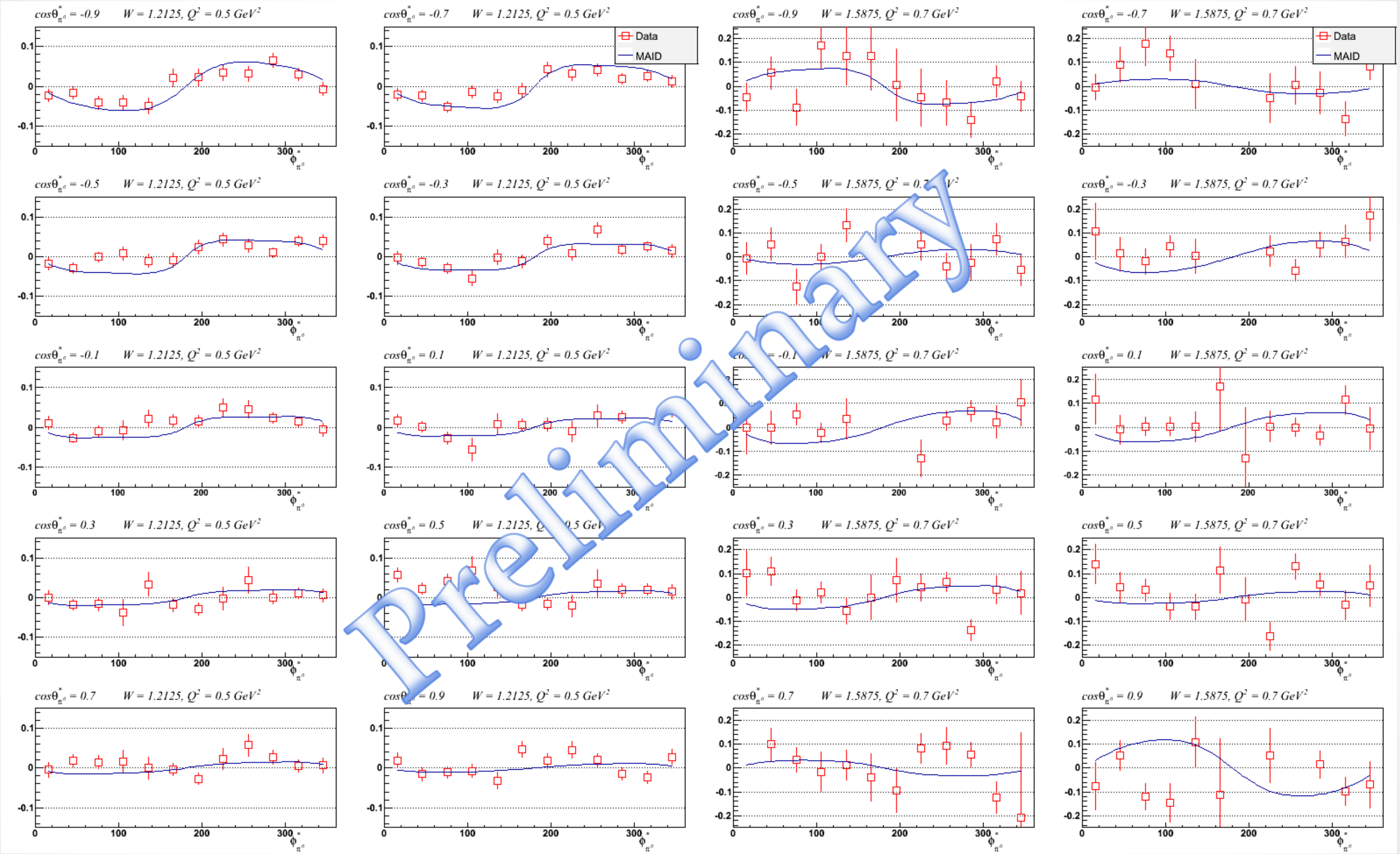
Reported data was taken with a longitudinally polarized beam => access to the single spin asymmetry

Access to interference terms between resonances, resonances and background and different background mechanisms.

Data binned in the following way (compared to the cross section measurements):
Δ W = 25 MeV (same);
Δ Q^2 = 0.2 GeV^2 (twice as wide);
$\Delta\cos\theta^*$ = 0.2 (same);
$\Delta\phi^*$ = 30 degrees (twice as wide).
Bin size is increased to reduce statistical uncertainty and pick up a weak signal.

$$A_{LT'}(W, Q^2, \cos\theta^*, \phi^*) = (N_+ - N_-)/(N_+ + N_-)$$

Asymmetry, comparison to MAID07



Increased binning allows to pick up a signal in the full W range

Structure functions

$$\frac{d\sigma}{d\Omega^*_{\pi^0}} = \frac{2W p_{\pi^o}}{W^2 - m_P^2}$$

$$(\sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT} sin^2\theta^*_{\pi^0} cos2\phi^*_{\pi^0} + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT} sin\theta^*_{\pi^0} cos\phi^*_{\pi^0} +$$

$$h\sqrt{2\epsilon_L(1-\epsilon)}\sigma_{LT'} sin\theta^*_{\pi^0} sin\phi^*_{\pi^0}), \quad (1.1)$$

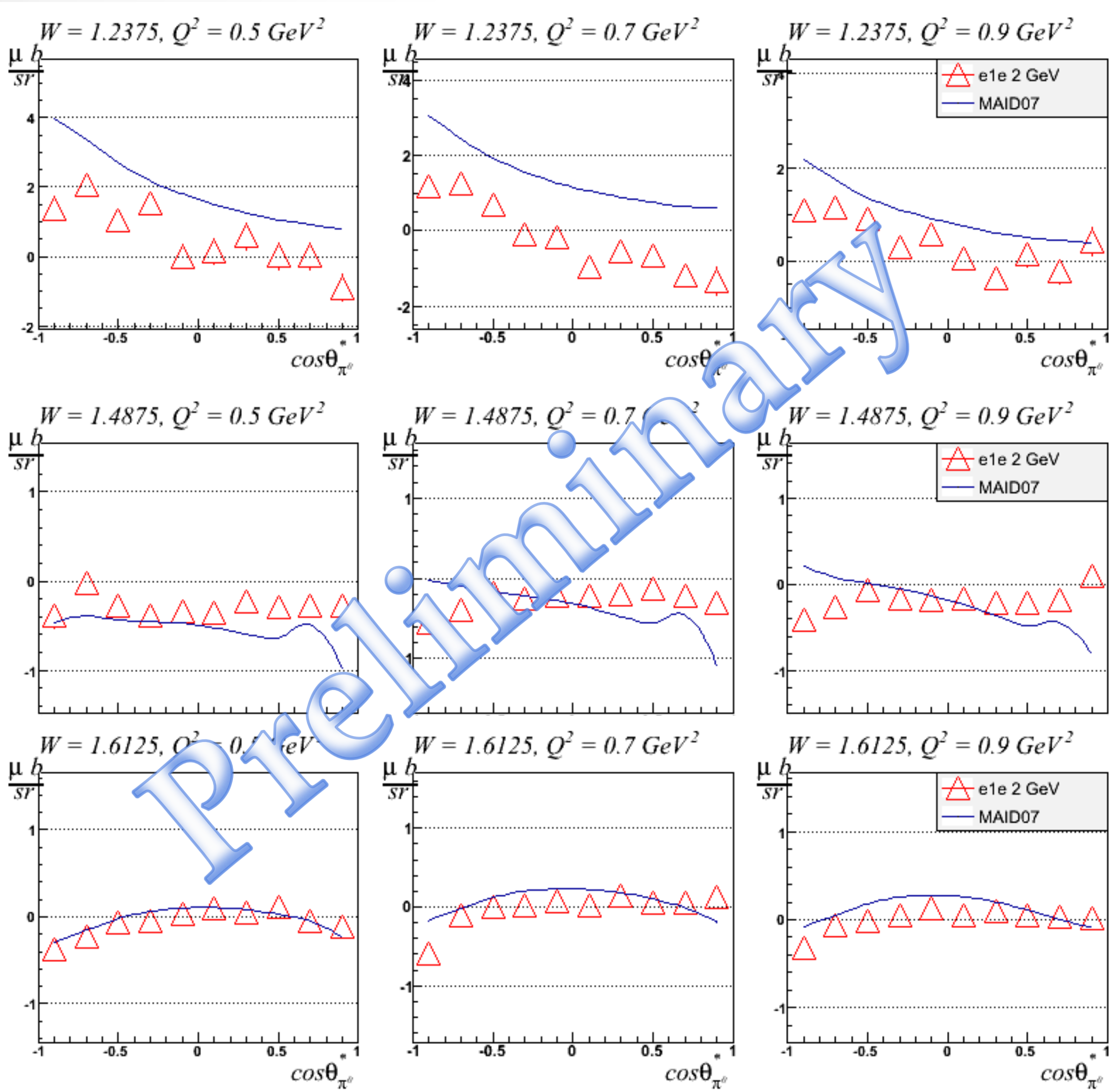
σ_{LT}':

$A_{LT'} = (\sqrt{}(2\varepsilon(1-\varepsilon))\ \sigma_{LT'} \sin\vartheta_{\pi 0}{}^* \sin\varphi_{\pi 0}{}^*)/(d\sigma/d\Omega^*_{\pi 0})$

↓

Measured from this dataset
as previously described

Results



$\sigma_{LT'}$

- This observable is sensitive to interference term, it may be that our knowledge on interference between resonance and non resonant contribution are incomplete;
- Relatively coarse Q^2 binning is important to pick up a small signal.

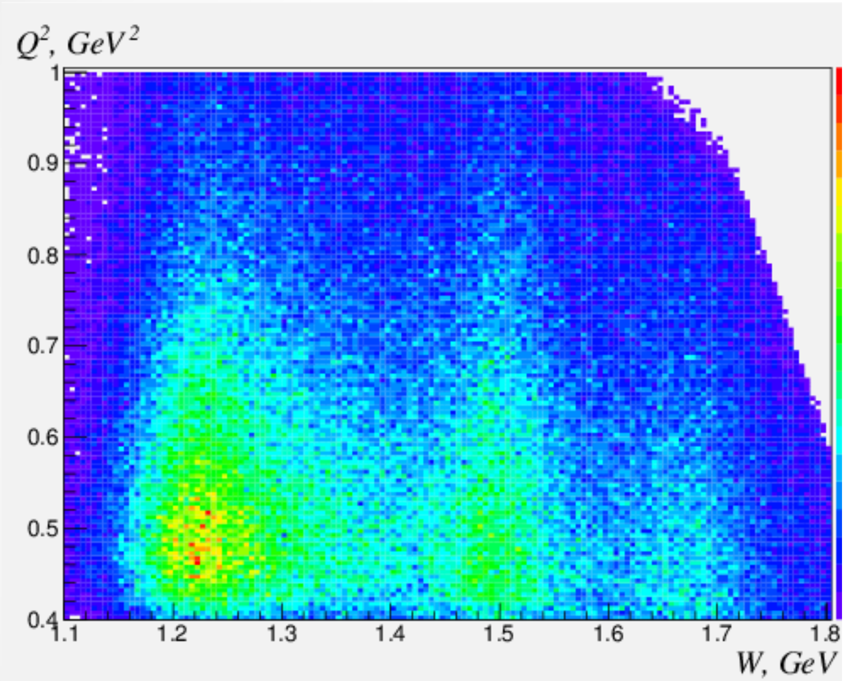
On the side: π^+n

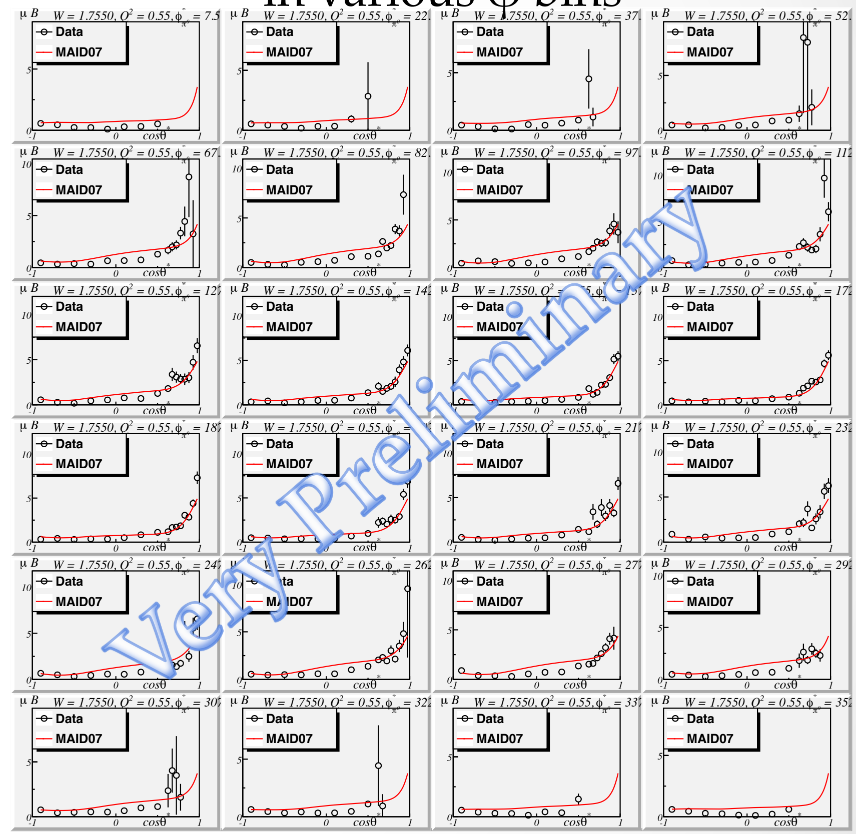
Kinematical coverage

Same dataset!

Results

Cross section as a function of cosθ* in various ϕ bins





Combined studies of π^+n and π^0p channels for the first time provide credible results on electrocouplings of N* states in the third resonance region with substantial Nπ decay.

- Fine bins at higher cosθ* allow to map out fast variation of cross section;
- High statistics even at high W.

Conclusion

- For the first time, differential π^0 electroproduction 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 $\sigma_T+\varepsilon\sigma_L$, σ_{TT}, σ_{LT} and $\sigma_{LT'}$ have been extracted;
- Comparison with models (MAID07, JANR) and multipole decomposition demonstrated data sensitivity to the contribution of individual resonances;
- Presented data is ready for the extraction of N* couplings within a framework of JANR;
- For the first time N* electrocouplings in the third resonance region will become available from a $p\pi^0$ channel;
- Comparison with previous data on low lying N* will validate reaction models used for electrocoupling extraction.
- This analysis will be complimented by the result from π^+n channel.