Nucleon Structure Studies Via Exclusive KY Electroproduction

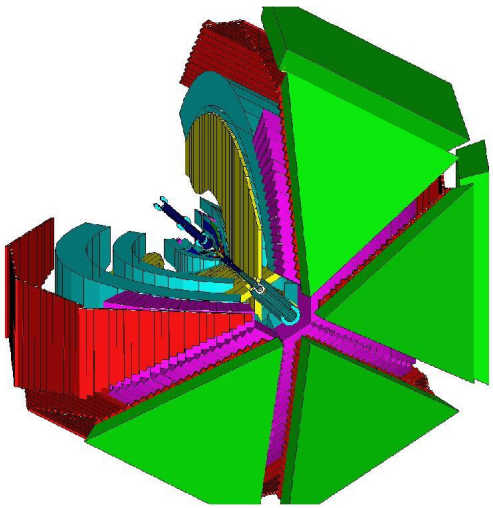
Daniel S. Carman
Jefferson Laboratory

Outline

- N* Spectrum & Structure
- Relevance of KY Data
- CLAS $\gamma_v p \rightarrow KY$ Measurements
- CLAS12 N* → KY Experiment
- Concluding Remarks

CLAS N* Program

The *N** program is one of the key physics foundations of Hall B



- CLAS was designed to measure γN and $\gamma_v N$ cross sections and spin observables over a broad kinematic range for exclusive reaction channels

$$\pi N,\ \omega N,\ \phi N,\ \eta N,\ \eta' N,\ \pi\pi N$$

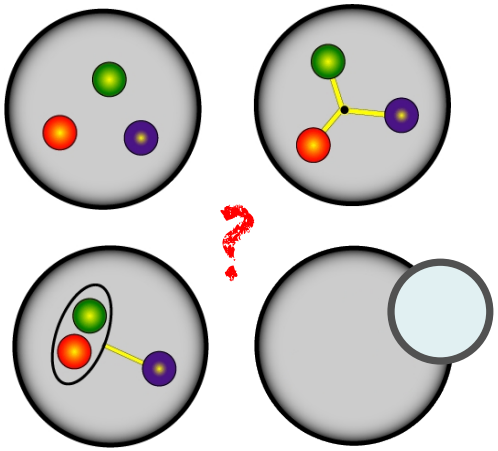
$$KY,\ K^*Y,\ KY^*$$

- Consistent interpretation of N properties from different exclusive channels with different couplings and backgrounds offers model independent support for findings*

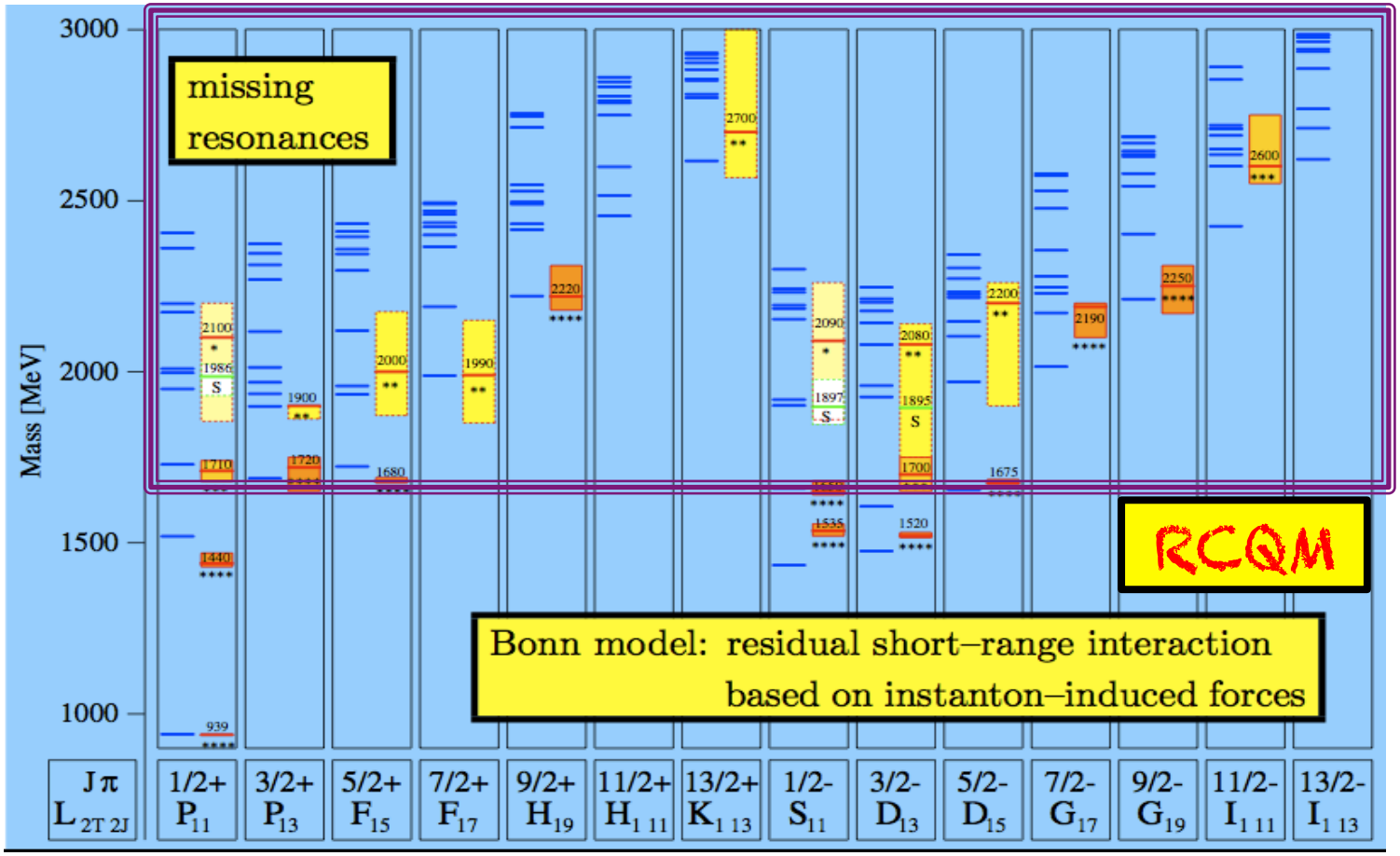
- The program goal is to study the ***spectrum*** of states and their associated ***structure*** vs. distance scale through studies of the Q^2 evolution of the $\gamma_v NN^*$ electrocouplings

  - Probe the underlying degrees of freedom of the nucleon

  - Study the non-perturbative strong interaction that generates N of different quantum numbers from quark and gluons*



N* Spectrum



missing N states*

Nππ, KY

sensitive to higher mass states

[Löring, Metsch, Petry, Eur. Phys. J. A 10, 395 (2001)]

- Recent LQCD predictions support CQM

[Dudek, Edwards, PRD 85, 054016 (2012)]

N*,Δ* → KY Landscape

Old

N* → KY				Δ* → KΣ		
State	Rating	BR % (KΛ)	BR % (KΣ)	State	Rating	BR % (KΣ)
N*(1650)	****	3–11	-	Δ*(1700)	****	-
N*(1675)	****	< 1	-	Δ*(1750)	*	-
N*(1680)	****	-	-	Δ*(1900)	**	-
N*(1700)	***	< 3	-	Δ*(1905)	****	-
N*(1710)	***	5–25	-	Δ*(1910)	****	9
N*(1720)	***	1–15	-	Δ*(1920)	***	2.1
N*(1875)	***	-	-	Δ*(1930)	***	-
N*(1900)	***	0-10	5	Δ*(1940)	**	-
N*(1990)	**	-	-	Δ*(1950)	****	-
N*(2000)	**	-	-	Δ*(2000)	**	-

[Beringer et al. (PDG), PRD 86, 010001 (2012)]

New

N* → KY				Δ* → KΣ		
State	Rating	BR % (KΛ)	BR % (KΣ)	State	Rating	BR % (KΣ)
N*(1650)	****	10±5	-	Δ*(1620)	****	-
N*(1675)	****	-	-	Δ*(1700)	****	-
N*(1680)	****	-	-	Δ*(1750)	*	-
N*(1700)	***	-	-	Δ*(1900)	**	5±3
N*(1710)	***	23±7	-	Δ*(1905)	****	-
N*(1720)	****	-	-	Δ*(1910)	****	9±5
N*(1875)	***	4±2	15±8	Δ*(1920)	***	4±2
N*(1880)	**	2±1	17±7	Δ*(1930)	***	-
N*(1895)	**	18±5	13±7	Δ*(1940)	***	-
N*(1900)	**	16±5	5±2	Δ*(1950)	****	0.4±0.1
N*(1990)	**	-	-	Δ*(2000)	**	-
N*(2000)	**	-	-			

[Anisovich et al., EPJ A 48, 15 (2012)]

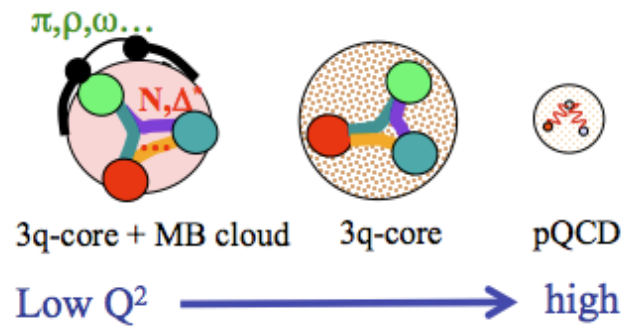
Essentially nothing is known regarding N*,Δ* states for M > 2 GeV

Nucleon Structure

- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only

  - *Low Q^2:* *structure well described by adding an external MB cloud to inner quark core* ($Q^2 < 5\ GeV^2$)

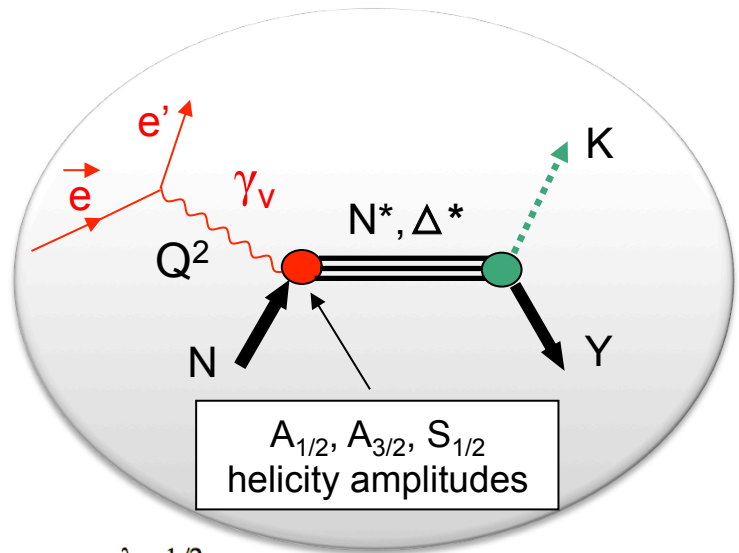
  - *High Q^2:* *quark core dominates; transition from confinement to pQCD regime* ($Q^2 > 5\ GeV^2$)

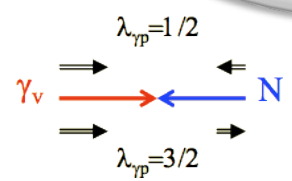


- Electroproduction at high Q^2 probes the quark core of the excited N* resonances through the $\gamma_v NN^*$ electrocoupling amplitudes

  - *The electrocouplings probe the mass function and structure of the dressed quarks vs. distance scale*

- Comparison of theory predictions to data test our understanding of the strong interaction dynamics vs. distance scale





$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

Electroproduction Data

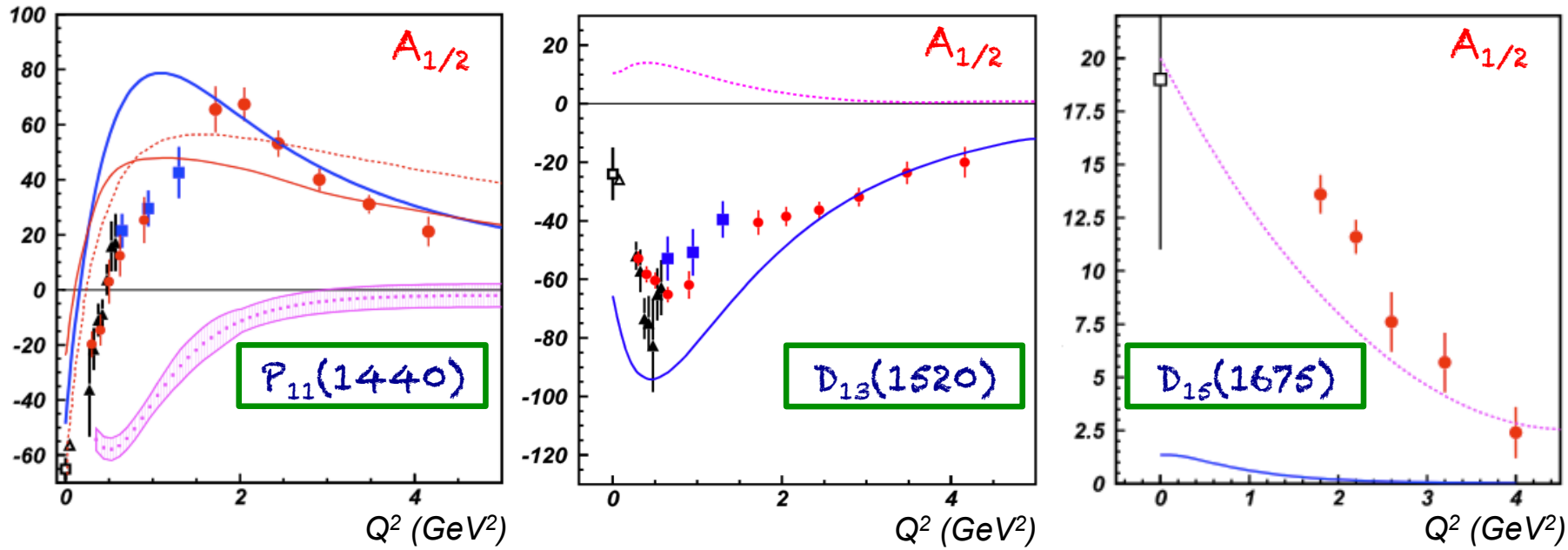
- Photoproduction data sets have been used extensively in coupled-channel fits and "advanced" single-channel models

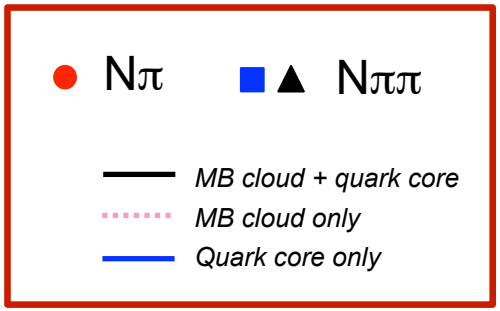
Photoproduction allows us to identify new states but tells us little about their nature

- Electroproduction data allows for:
  - *The Q^2 dependence of the data gives access to the $\gamma_v NN^*$ transition form factors - our source of information on N* structure*
  - *Promising in the search for new baryon states, since ratio of resonant to non-resonant contributions increases with Q^2*
  - *Effective tool to explore the existence of new N* states examining the data description with Q^2-independent resonance masses and hadronic decay widths*

The electroproduction data provide constraints on the production amplitudes complementary to the photoproduction data

Lower-Lying N* States



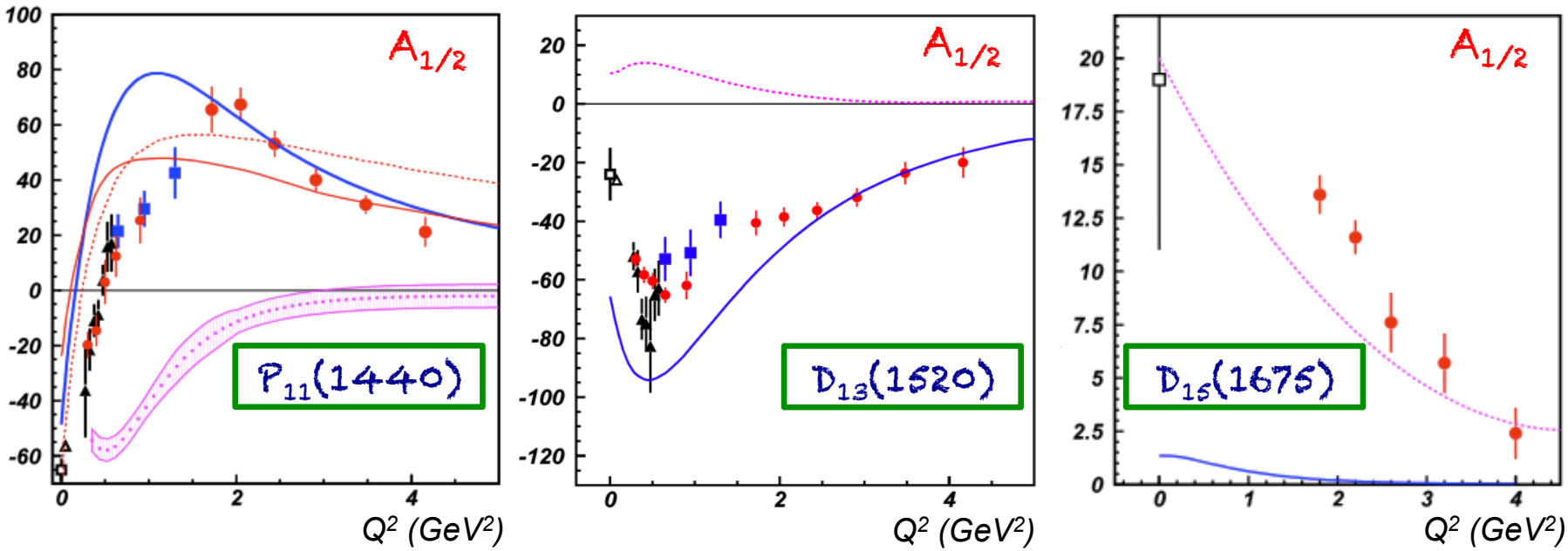


- Studies of $\gamma_v NN^*$ electrocouplings for different N* states at lower Q^2 reveals different interplay between quark core and MB cloud

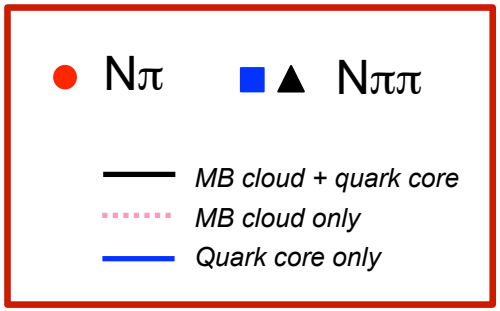
  - *Important to study states of different quantum numbers vs. distance scale*

[Aznauryan et al., PRC 80, 055203 (2009)]
[Mokeev et al., PRC 86, 035203 (2012)]
[Park et al., PRC 91, 045203 (2015)]

Lower-Lying N* States



- Good agreement of the extracted N* electrocouplings from both the Nπ and Nππ exclusive channels:
  - *Compelling evidence for the reliability of the results*
  - *Channels have very different mechanisms for the non-resonant background*

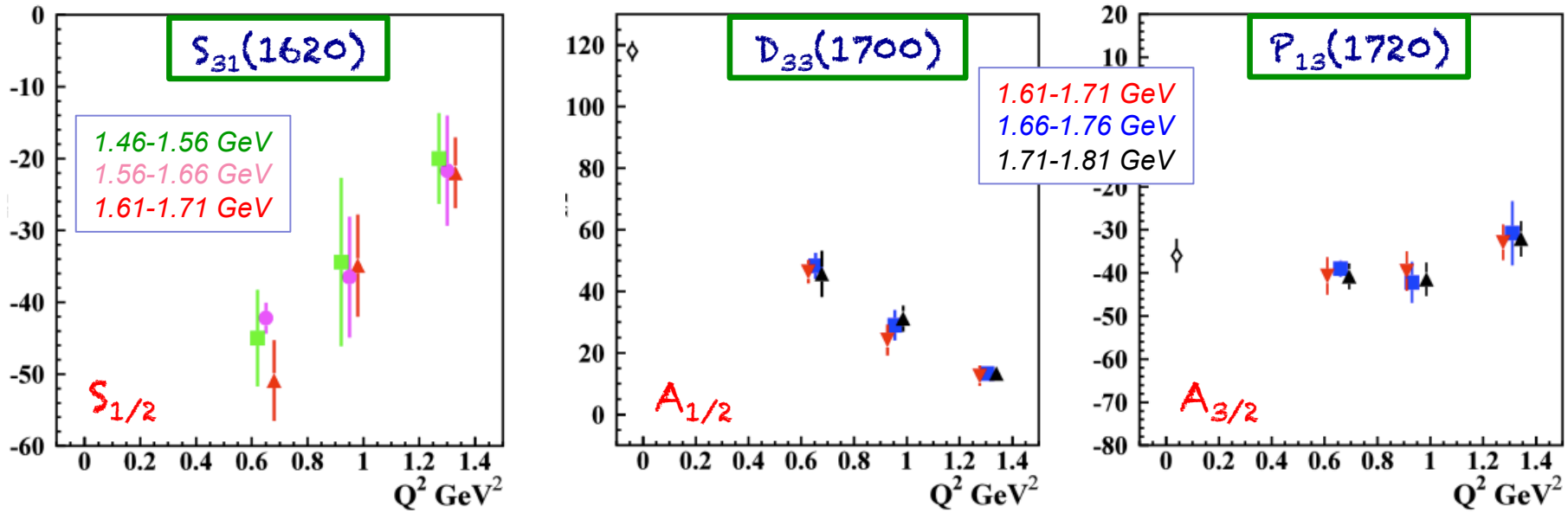


- Structure studies of low-lying N* states (M < 1.7 GeV) have advanced due to agreement of results from independent analysis of the Nπ and Nππ final states

Higher-Lying N* States

- Nππ channel provided the first results on higher-lying states up to 1.7 GeV:

  $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1680)$, $D_{33}(1700)$, $P_{33}(1720)$



[Mokeev, Aznauryan, Int. J. Mod. Phys. Conf. Ser. 26, 1460080 (2014)]

- Many high-lying N* states (M > 1.6 GeV) decay mainly to Nππ with much smaller strength to Nπ

Data from the KY channels is critical to provide an independent extraction of the electrocoupling amplitudes for the high-lying N* states

CLAS Strangeness Program

- The initial thrust of the CLAS measurement program focused on exclusive production of ground-state Λ and Σ hyperons

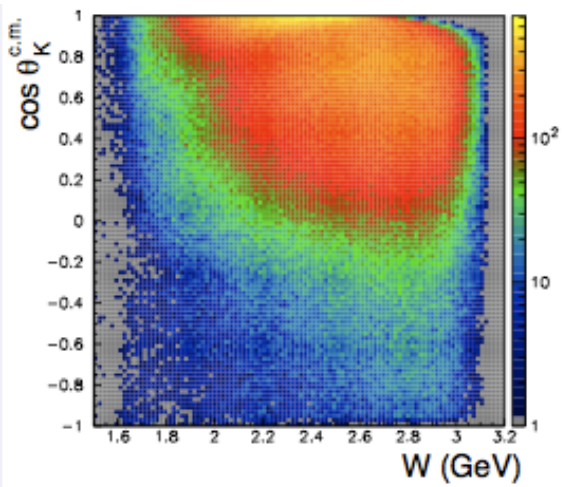


Photo- and electroproduction experiments

W: 1.6 – 3.0 GeV *cos $\theta_K^{c.m.}$: [-1: 1]*

Q^2: 0 – 4.5 GeV^2 *E_b: up to 6 GeV*

- *Provide extensive database of cross sections for model fits*

- Measurement of hyperon polarizations: *recoil, transferred*
  - *Λ polarization "self-analyzing" via decay frame angular distribution*

- Program has grown to include studies of:
  - *vector meson production (K*Y)*
  - *excited hyperon production (KY*)*
  - *semi-inclusive hyperon processes (YX)*
  - *"complete" experiments in photoproduction (γp and γn)*

CLAS KY Data Set Overview

#	Run	E_b (GeV)	Trig. (M)
1	e1c	2.567	900
2	e1c	4.056	370
3	e1c	4.247	620
4	e1c	4.462	420
5	e1d	4.817	300
6	e1-6	5.754	4500
7	e1f	5.499	5000
8	e1g	3.178	2500

- $K^+\Lambda$ recoil pol.
  - *W=1.6-2.7 GeV, $<Q^2>$=1.9 GeV^2*
    [Gabrielyan et al., PRC 90, 035202 (2014)]

Publications:

- $K^+\Lambda$ beam-recoil pol. transfer
  - *W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2*
    [Carman et al., PRL 90, 131804 (2003)]
- $K^+\Lambda$ σ_L/σ_T ratio
  - *W=1.72-1.98 GeV, Q^2~0.7 GeV^2*
    [Raue & Carman, PRC 71, 065209 (2005)]
- $K^+\Lambda$, $K^+\Sigma^0$ separated structure functions
  - *W=thr-2.4 GeV, Q^2=0.5-2.8 GeV^2*
  - σ_U, σ_{LT}, σ_{TT}, σ_L, σ_T - $K^+\Lambda$, $K^+\Sigma^0$
    [Ambrozewicz et al., PRC 75, 045203 (2007)]
  - *W=thr-2.6 GeV, Q^2=1.4-3.9 GeV^2*
  - σ_U, σ_{LT}, σ_{TT}, $\sigma_{LT'}$ – $K^+\Lambda$, $K^+\Sigma^0$
    [Carman et al., PRC 87, 025204 (2013)]
- $K^+\Lambda$ fifth structure function $\sigma_{LT'}$
  - *W=1.6-2.1 GeV, Q^2=0.65, 1.0 GeV^2*
    [Nasseripour et al., PRC 77, 065208 (2008)]
- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil pol. transfer
  - *W=thr-2.6 GeV, Q^2=1.6-2.6 GeV^2*
    [Carman et al., PRC 79, 065205 (2009)]

Formalism: KY Electroproduction

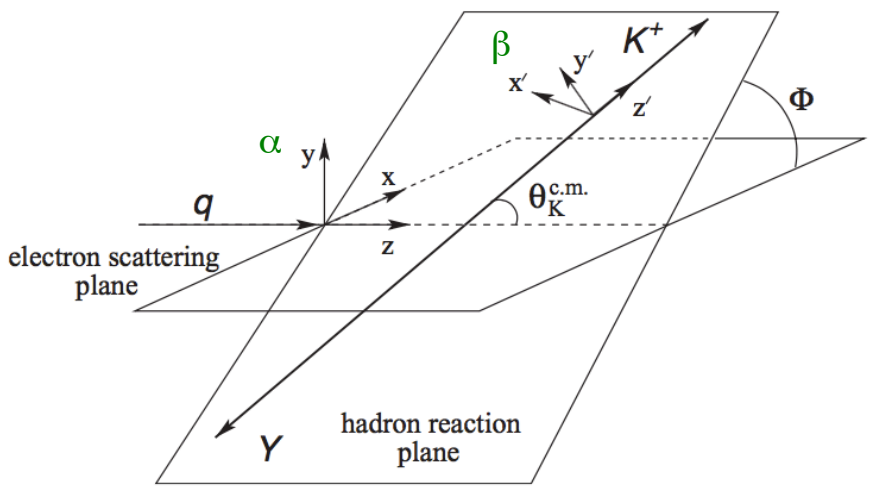
$$\frac{d\sigma}{d\Omega_{e'}d\Omega_K^* dE_{e'}} = \Gamma_v \frac{d\sigma_v}{d\Omega_K^*}$$

36 independent response functions

$$\frac{d\sigma_v}{d\Omega_K^*} = \mathcal{K}\sum_{\alpha,\beta} S_\alpha S_\beta \Big[R_T^{\beta\alpha} + \epsilon R_L^{\beta\alpha} + \sqrt{\epsilon(1+\epsilon)}({}^c R_{LT}^{\beta\alpha}\cos\Phi + {}^s R_{LT}^{\beta\alpha}\sin\Phi)$$
$$+ \epsilon({}^c R_{TT}^{\beta\alpha}\cos 2\Phi + {}^s R_{TT}^{\beta\alpha}\sin 2\Phi) + h\sqrt{\epsilon(1-\epsilon)}({}^c R_{LT'}^{\beta\alpha}\cos\Phi + {}^s R_{LT'}^{\beta\alpha}\sin\Phi) + h\sqrt{1-\epsilon^2}R_{TT'}^{\beta\alpha}\Big]$$

[Knochlein, Dreschel, Tiator, Z. Phys. A 352, 327 (1995)]

polarization components



$$P_{x'}^0 = \frac{\mathcal{K}}{\sigma_0}\left(\sqrt{\epsilon(1+\epsilon)}R_{LT}^{x'0}\sin\Phi + \epsilon\, R_{TT}^{x'0}\sin 2\Phi\right)$$

$$P_{y'}^0 = \frac{\mathcal{K}}{\sigma_0}\left(R_T^{y'0} + \epsilon R_L^{y'0} + \sqrt{\epsilon(1+\epsilon)}R_{LT}^{y'0}\cos\Phi + \epsilon R_{TT}^{y'0}\cos 2\Phi\right)$$

$$P_{z'}^0 = \frac{\mathcal{K}}{\sigma_0}\left(\sqrt{\epsilon(1+\epsilon)}R_{LT}^{z'0}\sin\Phi + \epsilon R_{TT}^{z'0}\sin 2\Phi\right)$$

$$P'_{x'} = \frac{\mathcal{K}}{\sigma_0}\left(\sqrt{\epsilon(1-\epsilon)}R_{LT'}^{x'0}\cos\Phi + \sqrt{1-\epsilon^2}R_{TT'}^{x'0}\right)$$

$$P'_{y'} = \frac{\mathcal{K}}{\sigma_0}\sqrt{\epsilon(1-\epsilon)}R_{LT'}^{y'0}\sin\Phi$$

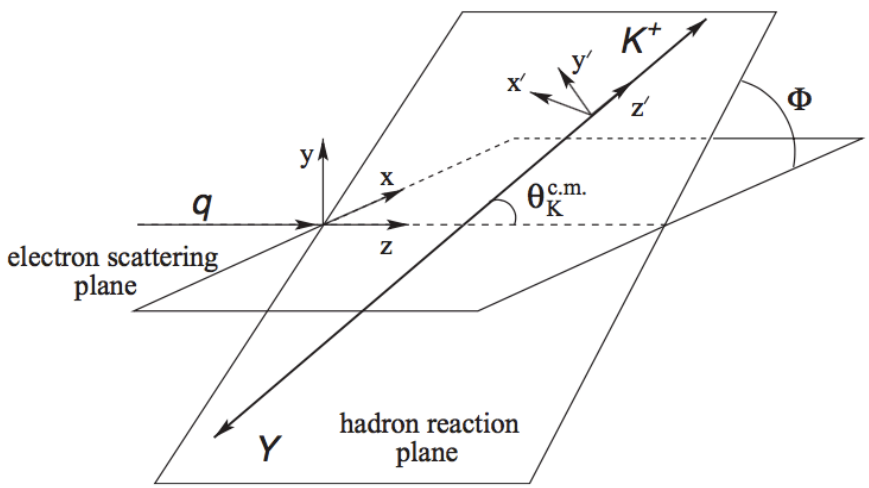
$$P'_{z'} = \frac{\mathcal{K}}{\sigma_0}\left(\sqrt{\epsilon(1-\epsilon)}R_{LT'}^{z'0}\cos\Phi + R_{TT'}^{z'0}\right)$$

Formalism: KY Electroproduction

$$\frac{d\sigma_v}{d\Omega_K^*} = \sigma_T + \epsilon\sigma_L + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + \epsilon\sigma_{TT}\cos 2\Phi + h\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\Phi$$

$$\sigma_i = f(Q^2, W, \cos\theta_K^*)$$

Φ Integrated polarization components



$$\mathcal{P}^0_{x'} = 0$$

$$\mathcal{P}^0_{y'} = \frac{R_T^{y'0} + \epsilon R_L^{y'0}}{R_T^{00} + \epsilon R_L^{00}}$$

$$\mathcal{P}^0_{z'} = 0$$

recoil

$$\mathcal{P}'_{x'} = \frac{\sqrt{1-\epsilon^2}R_{TT'}^{x'0}}{R_T^{00} + \epsilon R_L^{00}}$$

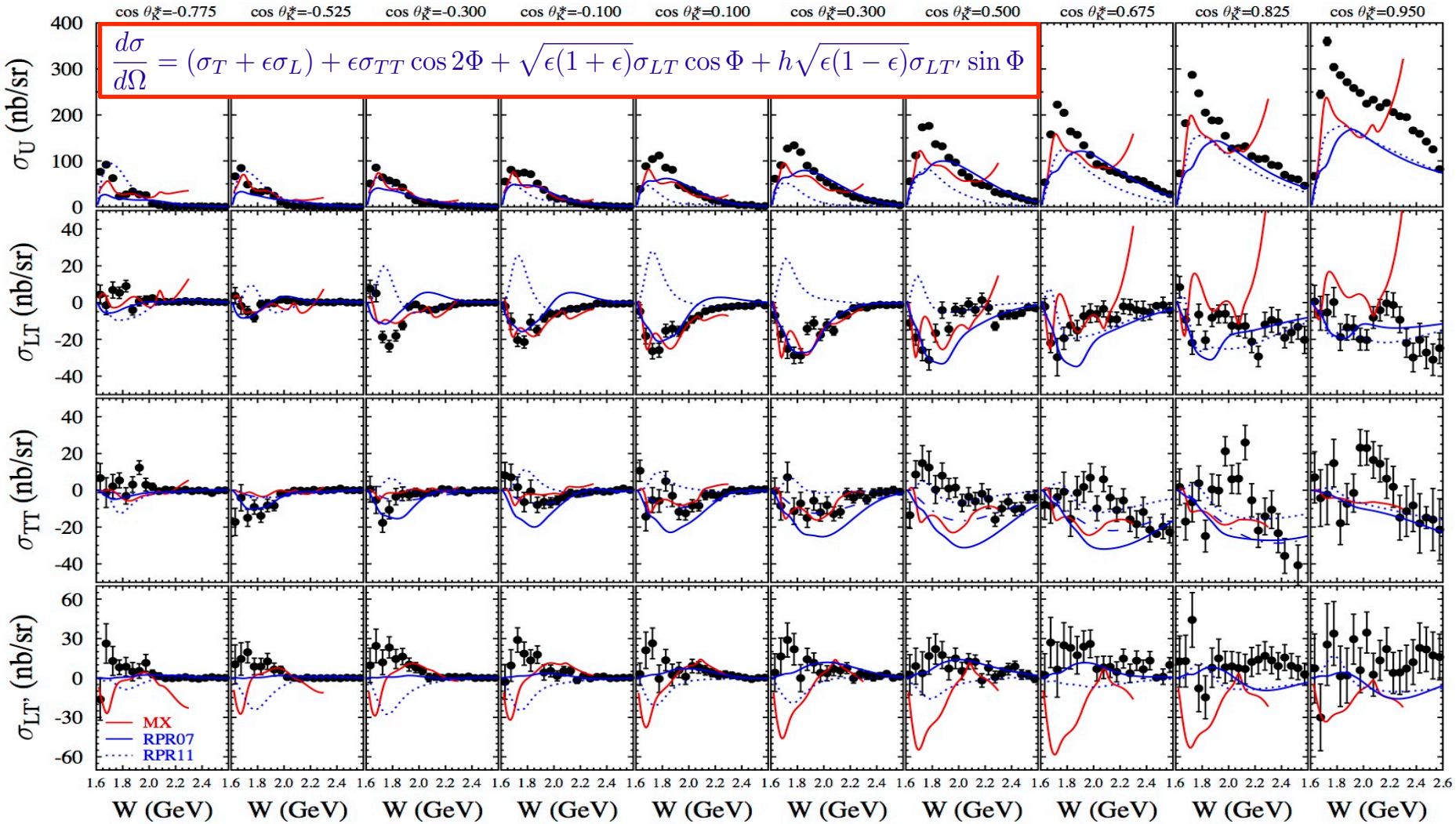
$$\mathcal{P}'_{y'} = 0$$

$$\mathcal{P}'_{z'} = \frac{\sqrt{1-\epsilon^2}R_{TT'}^{z'0}}{R_T^{00} + \epsilon R_L^{00}}$$

transferred

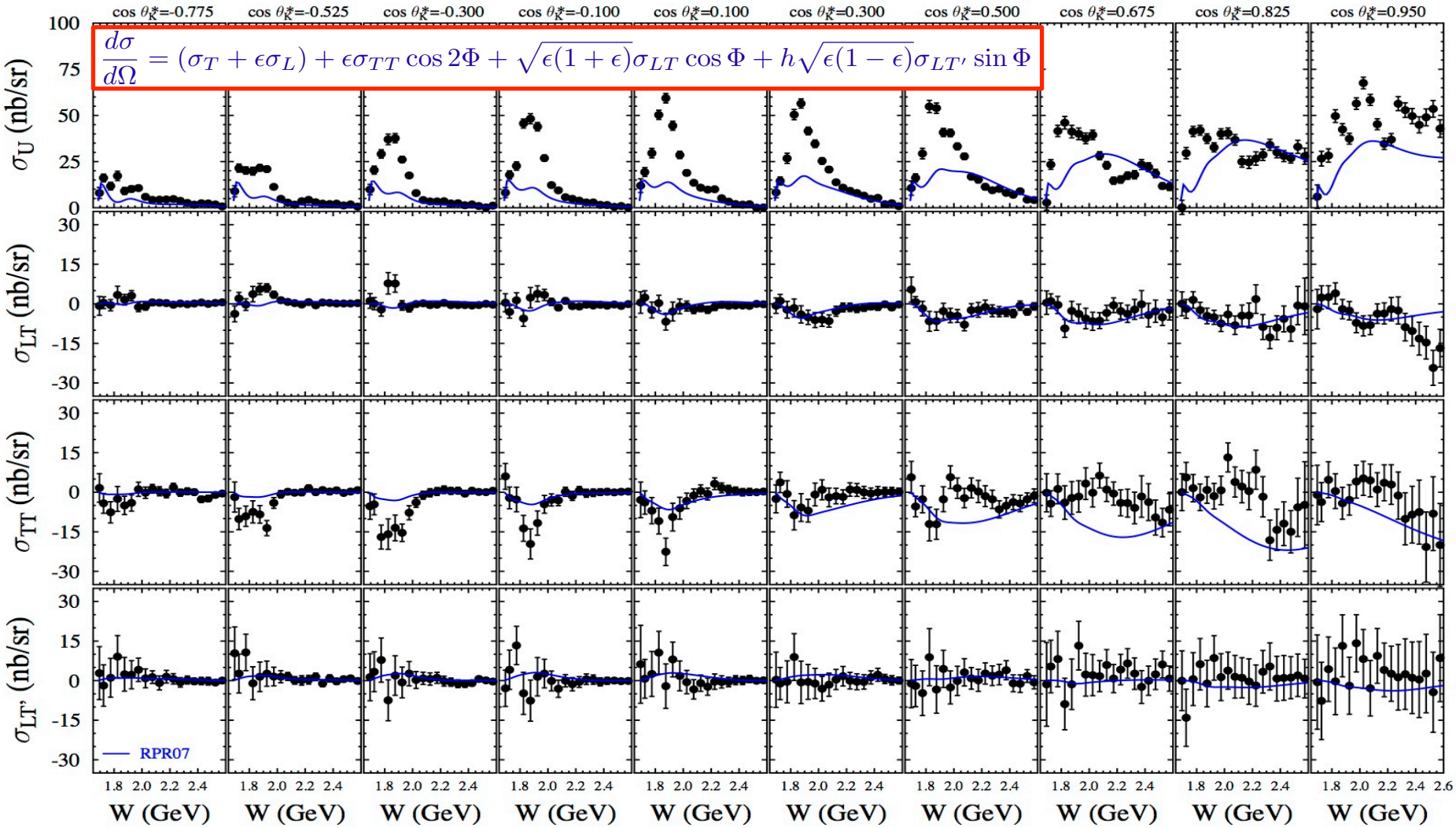
[Carman et al., PRL 90, 131804 (2003)]

$K^+\Lambda$ Structure Functions



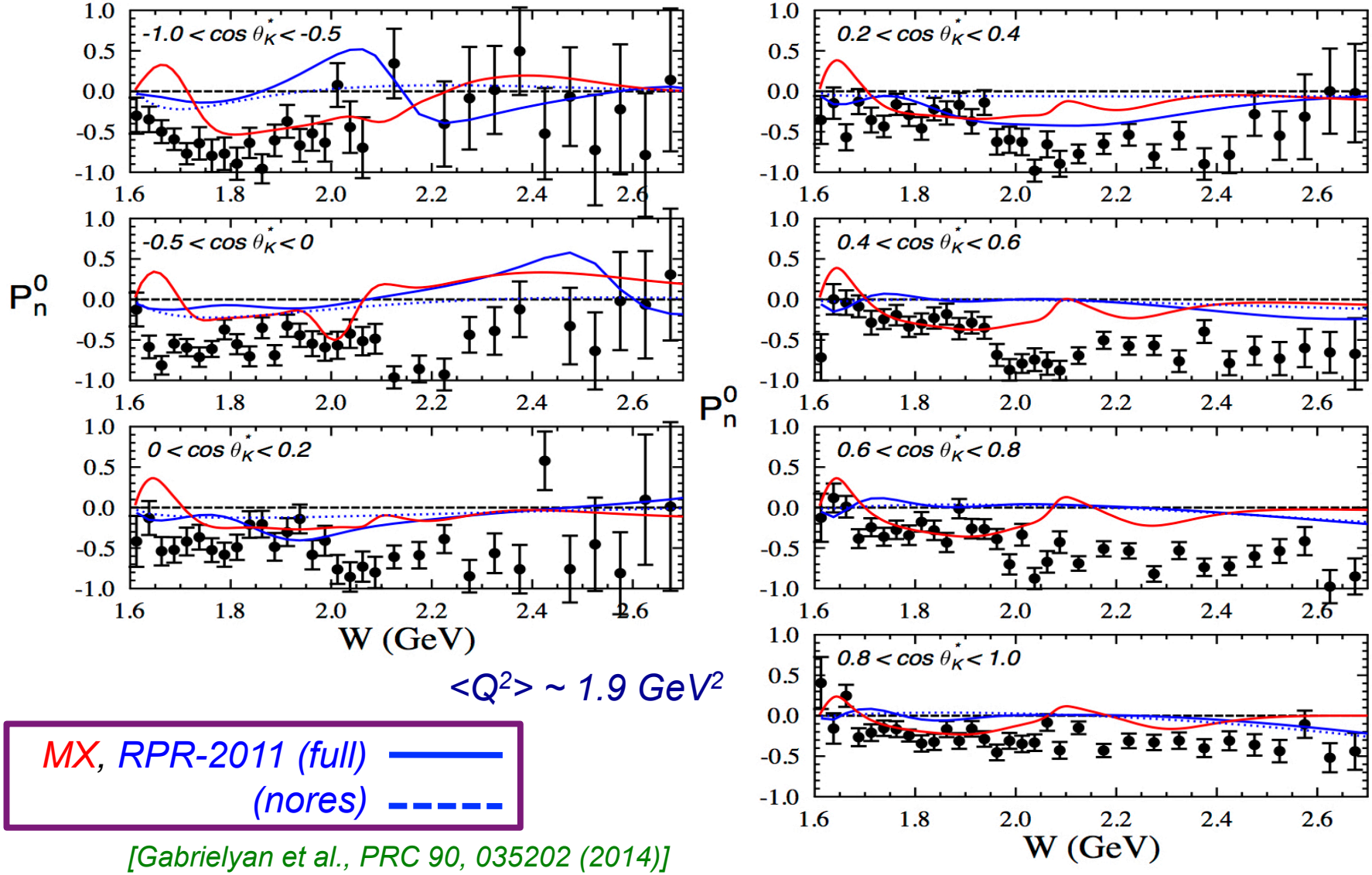
E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *[Carman et al., PRC 87, 025204 (2013)]*

$K^+\Sigma^0$ Structure Functions



E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *[Carman et al., PRC 87, 025204 (2013)]*

Recoil Polarization $ep \rightarrow e'K^+\vec{\Lambda}$

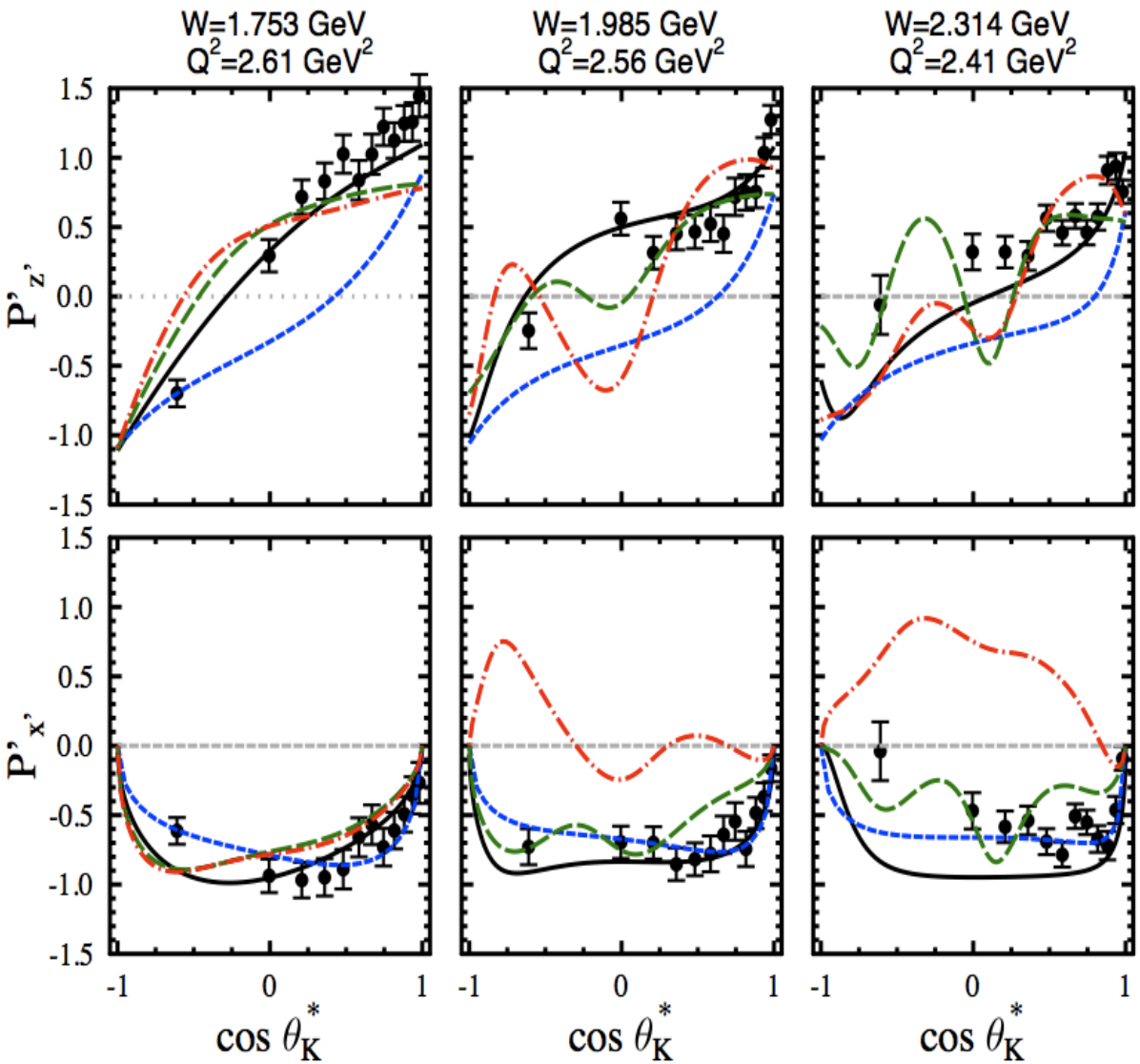


$\langle Q^2 \rangle \sim 1.9\ GeV^2$

MX, RPR-2011 (full) ——
(nores) - - - -

[Gabrielyan et al., PRC 90, 035202 (2014)]

Transferred Polarization $\vec{e}p \rightarrow e'K^+\vec{\Lambda}$



5.754 GeV
Summed over Q^2, Φ

- Data not included in fits
- Rule out $P_{11}(1900)$ assignment
- $D_{13}(1900)$ not ruled out via P' data but with S.F. data

Isobar Model – Mart
Regge Model – GLV
RPR07 w $P_{11}(1900)$ - Ghent
RPR07 w $D_{13}(1900)$ - Ghent

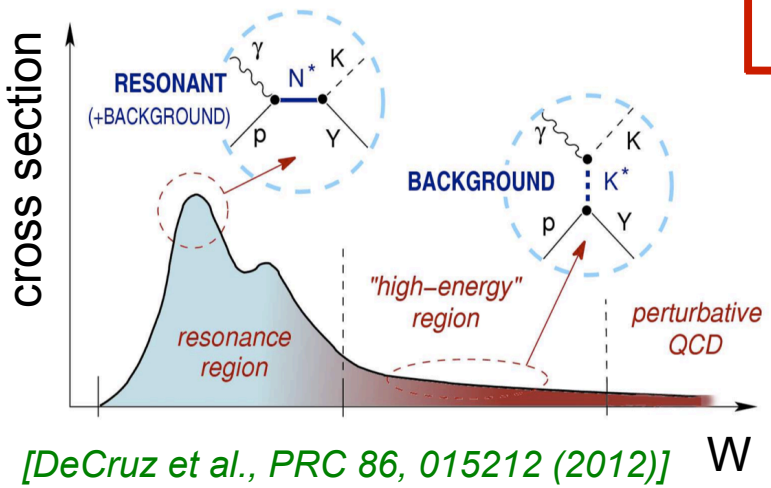
RPR background + $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$

[Carman et al., PRC 79, 065205 (2009)]

KY Reaction Model

- At present there is no reaction model that adequately describes the KY electroproduction data in the resonance region

A model that describes the data well is necessary to extract the electrocoupling parameters from the existing lower Q^2 CLAS data and the expected higher Q^2 CLAS12 data



[DeCruz et al., PRC 86, 015212 (2012)]

Work is underway to develop the RPR model

- Update RPR electrocoupling parameters
- Refit model to CLAS γp and $\gamma_v p$ data:

  $W \rightarrow 2.6$ GeV, $Q^2 \rightarrow 4$ GeV^2

- Extend model to CLAS12 kinematics:

  $W \rightarrow 3$ GeV, $Q^2 \rightarrow 12$ GeV^2

Background:

- *Exchange of K(494)/K*(892) Regge trajectories*
- *Parameterized by 3 coupling strengths/2 phases*
- *Background tuned to high-energy data and CLAS data in resonance region*

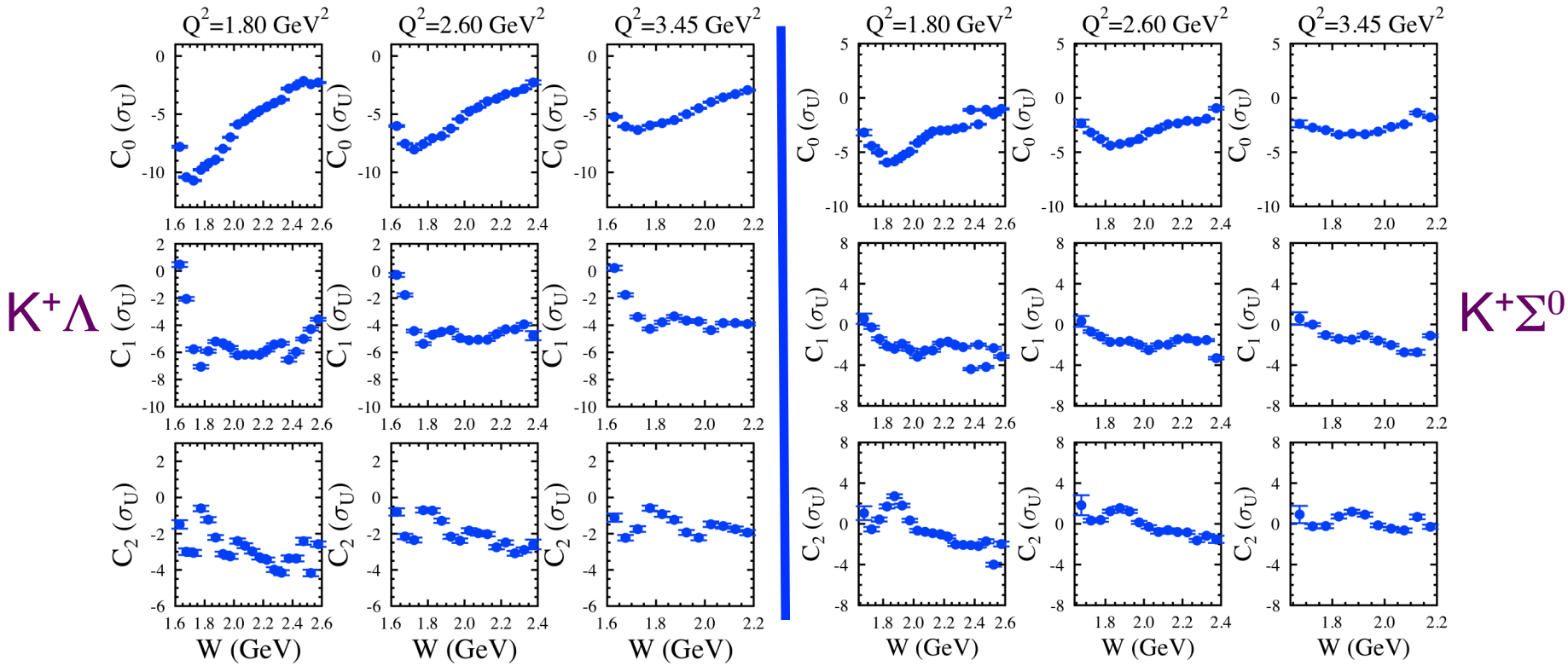
Resonances:

- *Standard isobar model N* states with J=1/2, 3/2, 5/2*
- *EM form factors from Bonn CQM*
- *11 s-channel resonance candidates with W < 2 GeV*
- *Fit model to world γp data over full angular range*
- *Model not constrained by CLAS electroproduction data*

Legendre Analysis $ep \rightarrow K^+Y$

Coherent Legendre fit:

$$\frac{d\sigma}{d\Omega_K^*} = \left[\sum_{L=0}^{2} C_L(Q^2, W) P_L(\cos\theta_K^*)\right]^2 + C_x^2$$



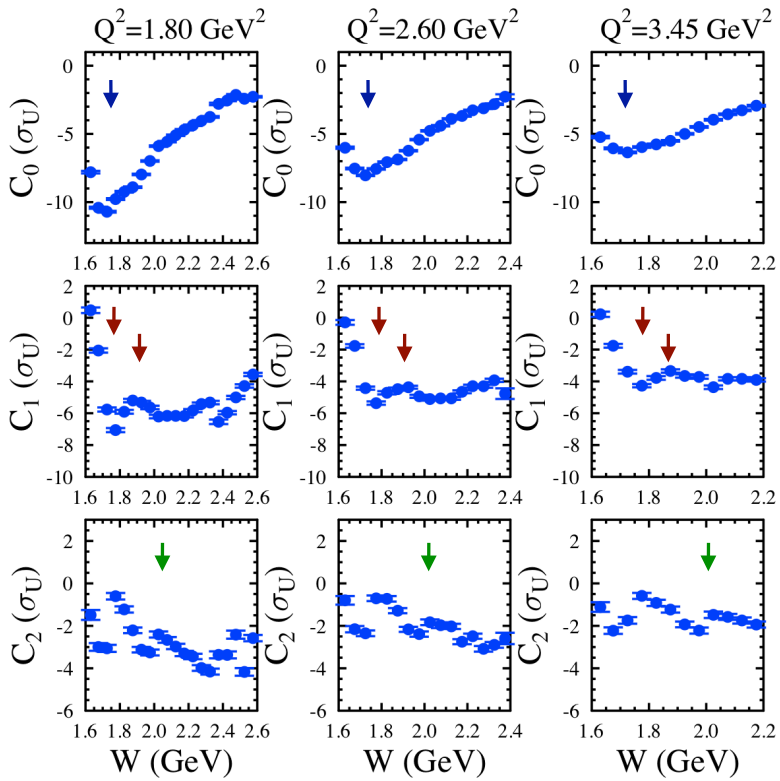
- Structures in *W* dependence of C_L moments at the same *W* in all Q^2 bins are consistent with *s*-channel resonance contributions. *[Carman et al., PRC 87, 025204 (2013)]*
- Reaction model is needed for the extraction of the *N** parameters.

Legendre Analysis ep → K^+Y

Coherent Legendre fit:

$$\frac{d\sigma}{d\Omega_K^*} = \left[\sum_{L=0}^{2} C_L(Q^2,W)P_L(\cos\theta_K^*)\right]^2 + C_x^2$$

$K^+\Lambda$



S-wave state at 1650 MeV

P-wave states at 1700, 1900 MeV

D-wave state at 2000 MeV

- Consistency of dominant N* → $K^+\Lambda$ couplings with advanced models

… again a complete reaction model is needed for a proper analysis

CLAS12 N* Program

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Burkert, Mokeev, Stoler, Joo, Gothe, Cole	*Carman, Mokeev, Gothe*

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

  E_b = 11 GeV, Q^2 = 3 → 12 GeV^2, W → 3.0 GeV, cos θ_m* = [-1:1]

- Key Motivations:
  - *Study spectrum and structure of all prominent N* states vs. Q^2 up to 12 GeV^2.*

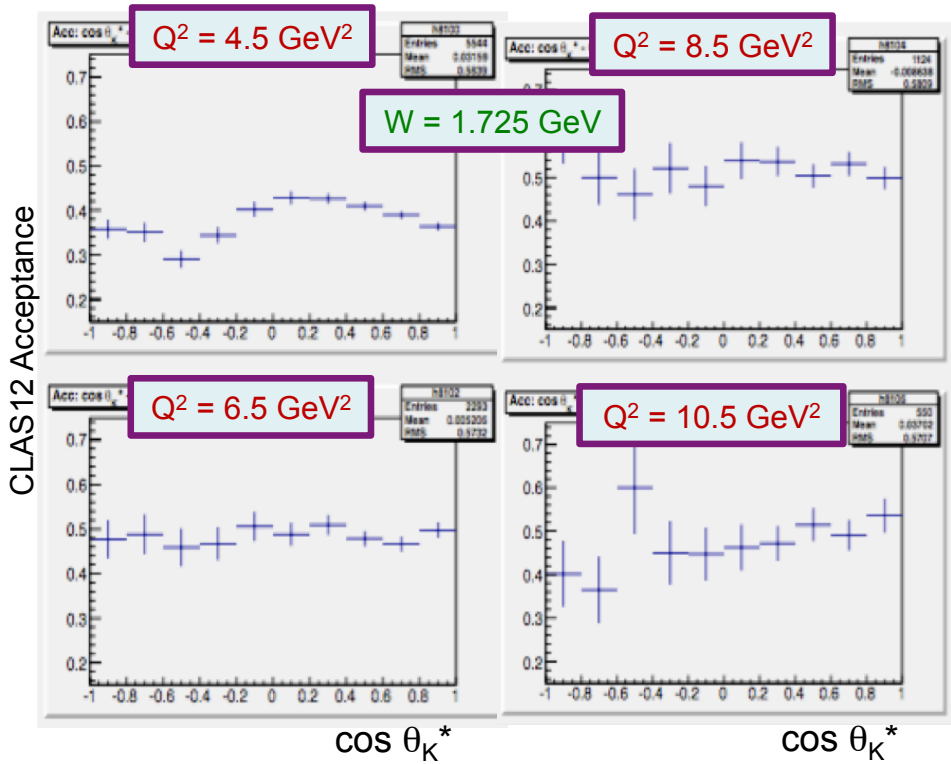
    A unique opportunity to explore the nature of confinement that is responsible for >98% of resonance masses and the emergence of N states from QCD*

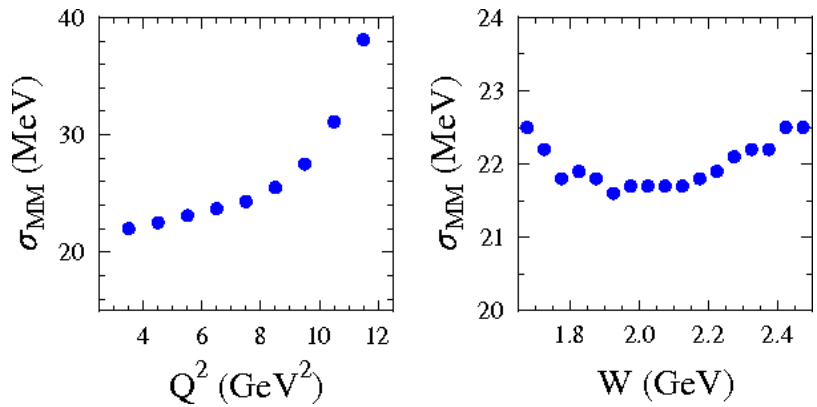
  - *KY data complement the $N\pi\pi$ data as independent information for high-mass states inaccessible with $N\pi$ final states*

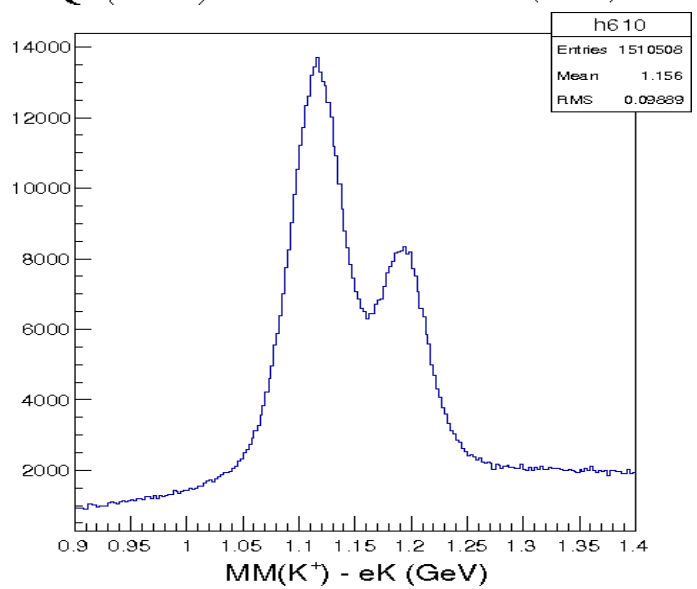
    Urgent need: Develop reaction models to extract electrocouplings that incorporate the transition from M-B to q-G degrees of freedom

CLAS12 KY Experiment Details

$$e + p \rightarrow e' + K^+ + Y \quad @\ 11\ \mathrm{GeV}$$

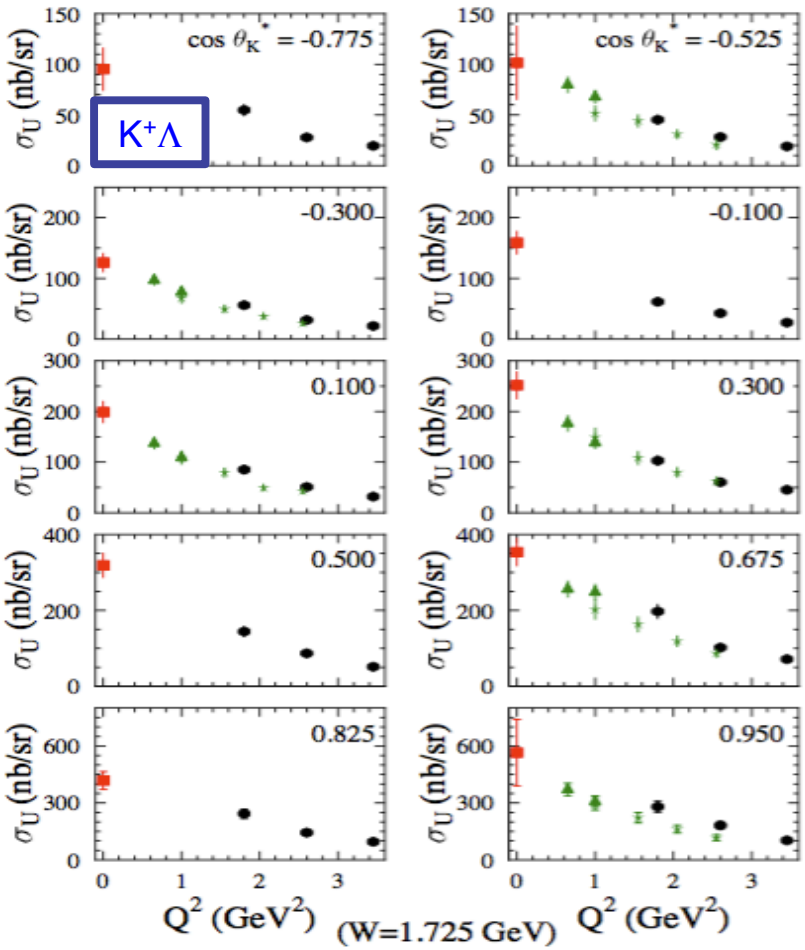


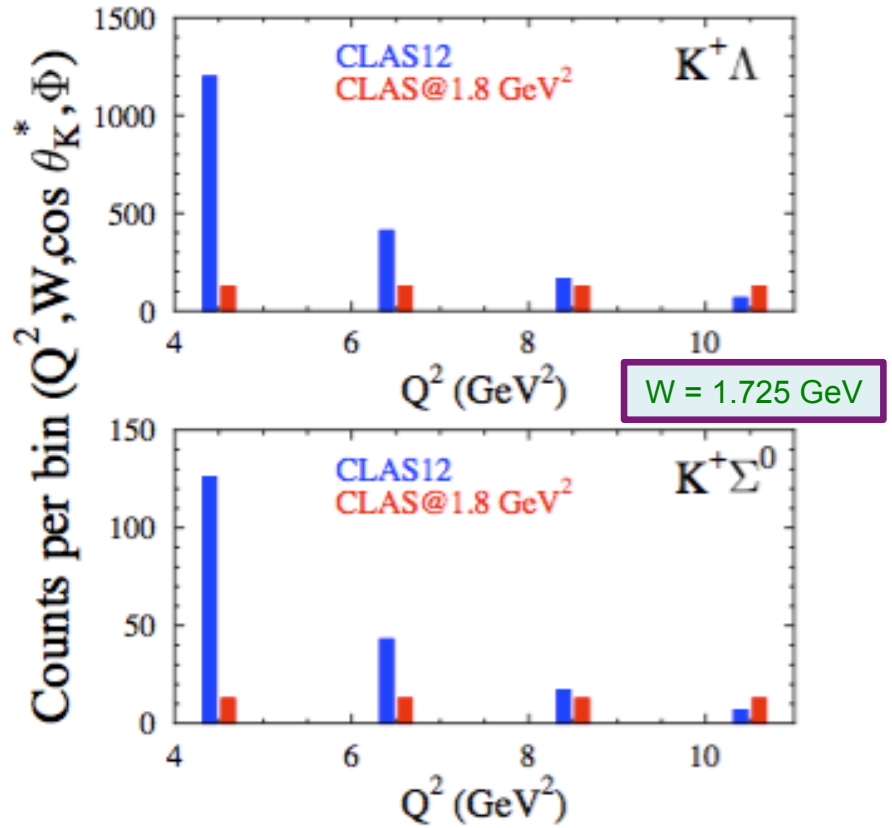




Typical CLAS12 e'K⁺ acceptance e'K⁺ ≈ 50%

KY Yield Estimates





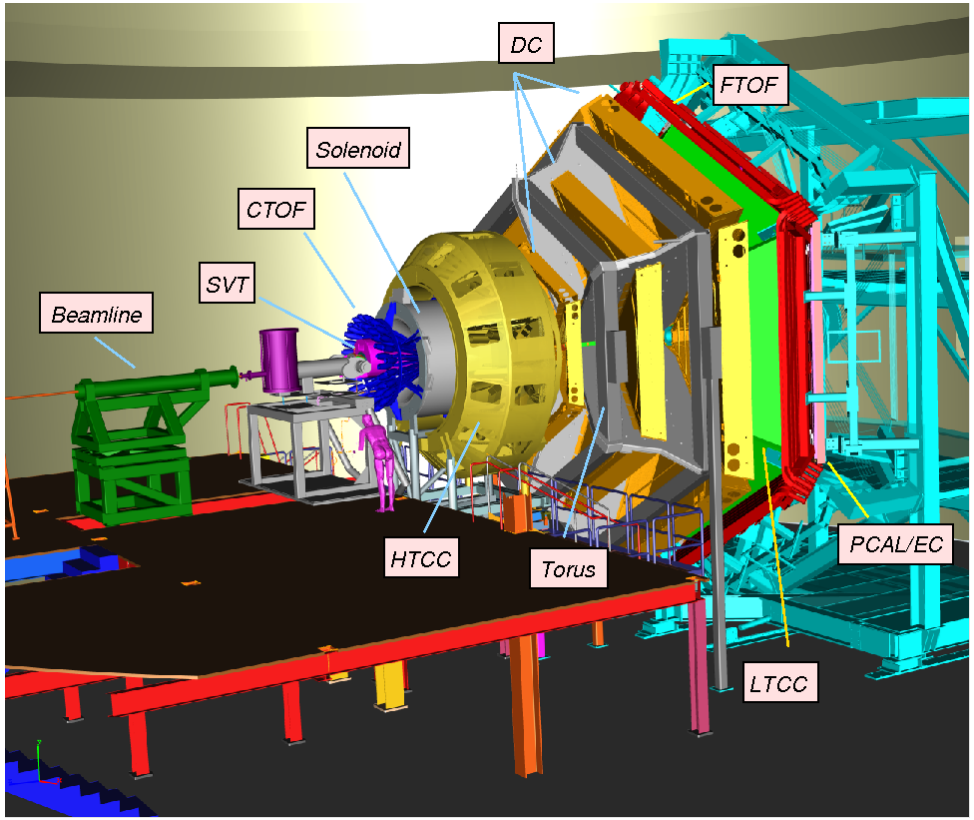
$$\frac{d\sigma}{d\Omega} = \frac{1}{\mathcal{L}} \cdot \frac{N}{ACC \cdot (\Delta Q^2 \Delta W \Delta \cos\theta_K^* \Delta\Phi)} \cdot \frac{1}{\Gamma_v} \cdot \frac{1}{t}$$

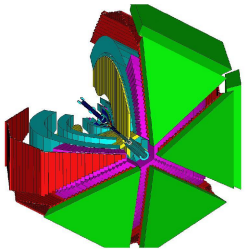
$$\frac{d\sigma}{d\Omega_K^*} = \frac{\mathcal{C}_1}{(\mathcal{C}_2 + Q^2)}$$

$$\mathcal{L} = 1 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}, t = 80\ \mathrm{days}, \mathrm{ACC\ from\ fastMC},\ \mathrm{full\ field}$$

$$\Delta Q^2 \Delta W \Delta \cos\theta_K^* \Delta\Phi = 1.0\ \mathrm{GeV}^2 \cdot 50\ \mathrm{MeV} \cdot 0.2 \cdot 45^\circ$$

CLAS12 Spectrometer



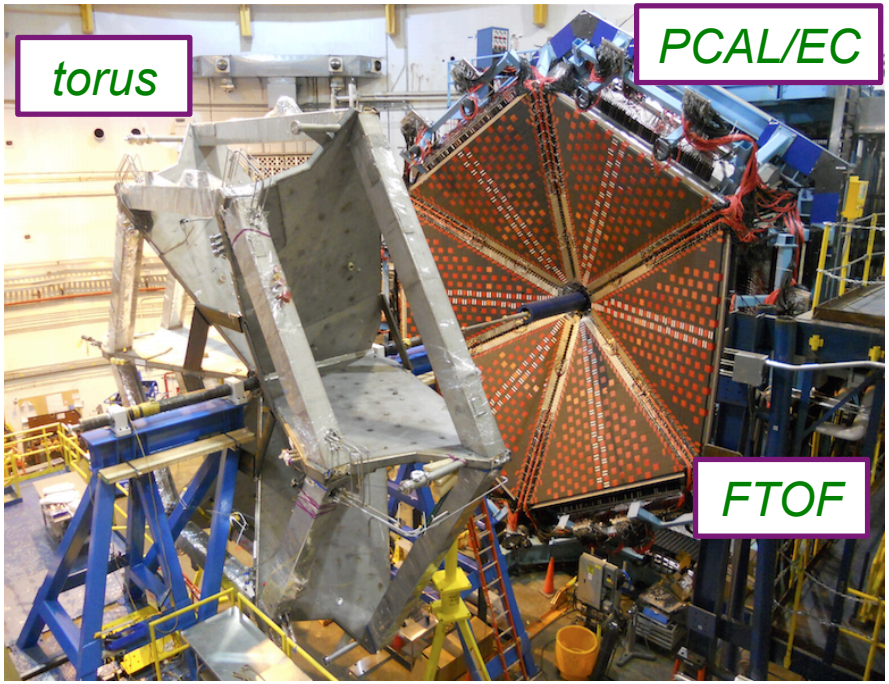


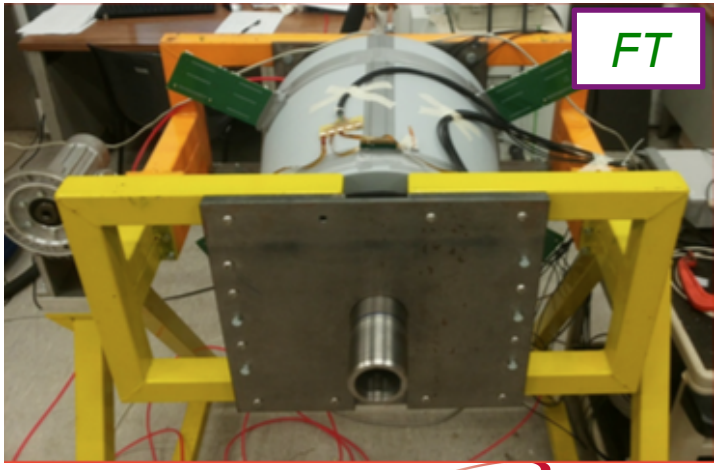
CLAS Spectrometer: 1997 - 2012

CLAS12 Specifications

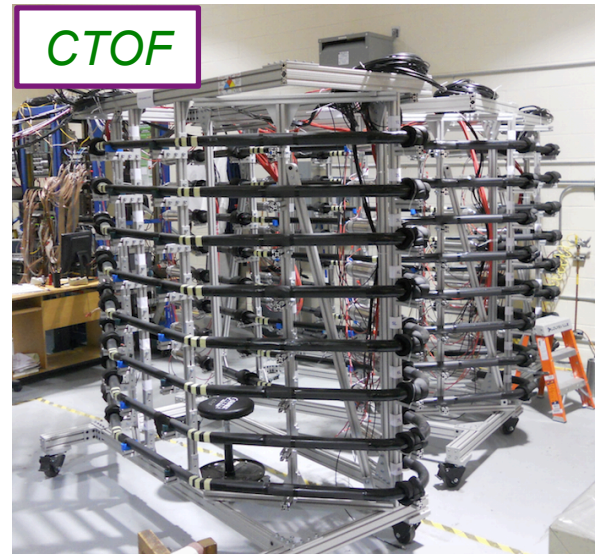
	Forward	Central
Angular coverage	5° – 35°	35° – 135°
Momentum resolution	$\delta p/p < 1\%$	$\delta p/p < 5\%$
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ
PID:		
π/K	4σ to 2.8 GeV	3σ to 0.6 GeV
K/p	4σ to 4.8 GeV	3σ to 1.0 GeV
π/p	4σ to 5.4 GeV	3σ to 1.2 GeV
Calorimeter resolution	$\sigma_E \sim 0.1\sqrt{E}$	
Luminosity	10^{35} cm^{-2}s^{-1}	

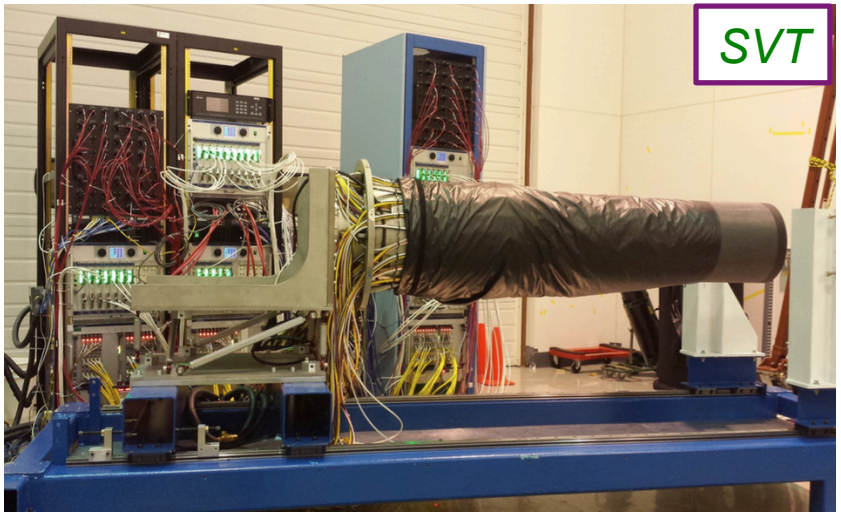
CLAS12 Photographs





CLAS12 Photographs





Concluding Remarks

- **The study of N* states is one of the key foundations of the Hall B physics program with CLAS:**
  - CLAS has provided a dominant amount of precision data (cross sections and pol. observables) for the $N\pi$, $N\eta$, KY, and $N\pi\pi$ channels Q^2 from 0 to 4.5 GeV^2
  - Electrocouplings of most N* states < 1.7 GeV were extracted from these data for the first time for the non-strange MB final states
- **The CLAS12 N* program will extend these studies to Q^2 up to 12 GeV^2:**
  - These studies will allow for insight into the strong interaction dynamics of dressed quarks and their confinement in baryons over a broad Q^2 range
  - These data will address the most challenging and open problems of the Standard Model on the nature of hadron mass, quark-gluon confinement, and the emergence of the N* states from QCD

Exciting time as CLAS12 begins its physics program in early 2017