The Strangeness Physics Program at CLAS

Nucleon Resonance Studies

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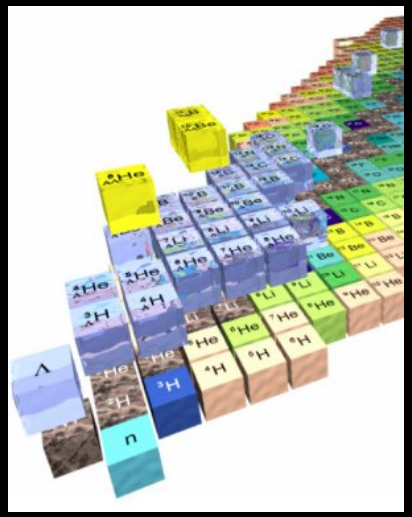
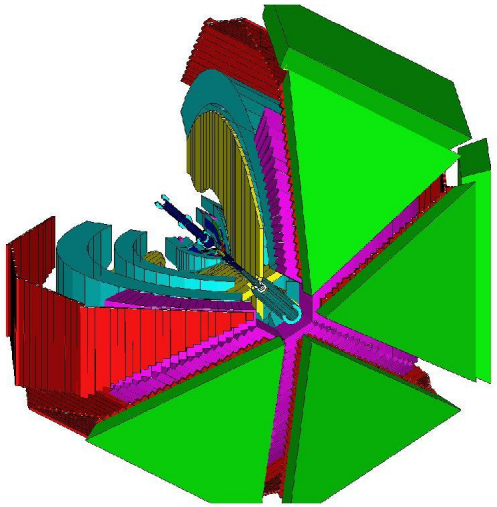


Outline:

- Introduction & Landscape
- CLAS Strangeness Program
- CLAS $\gamma^{(*)}p \rightarrow KY$ Data
- Theoretical Progress & Plans
- Summary & Conclusions

Introduction

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



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

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

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

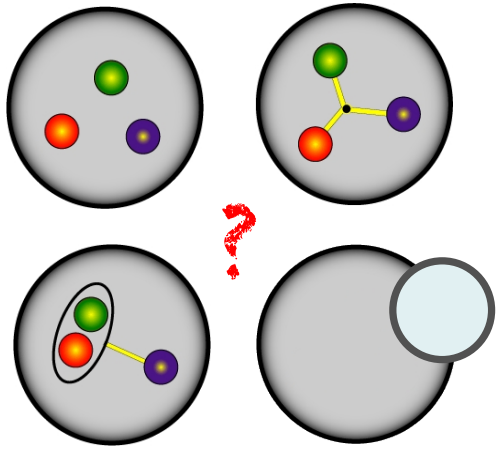
- Different final states provide complementarity due to the different couplings and mix of resonant/non-resonant process.

- The constituent quark model predicts a spectrum of states, many of which have not been seen experimentally.

  - N studies dominated by pionic channels*

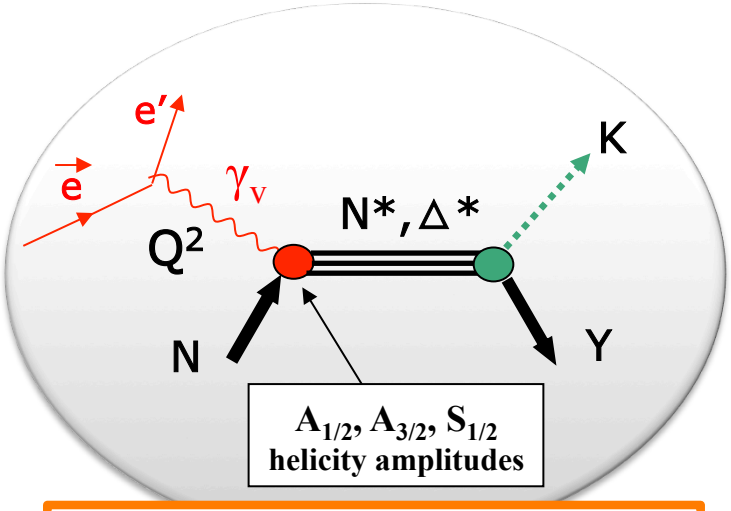
  - KY channels important contributors in resonance region

  - Study of the N spectrum and N* structure vs. distance scale reflects the underlying d.o.f. of the nucleon*

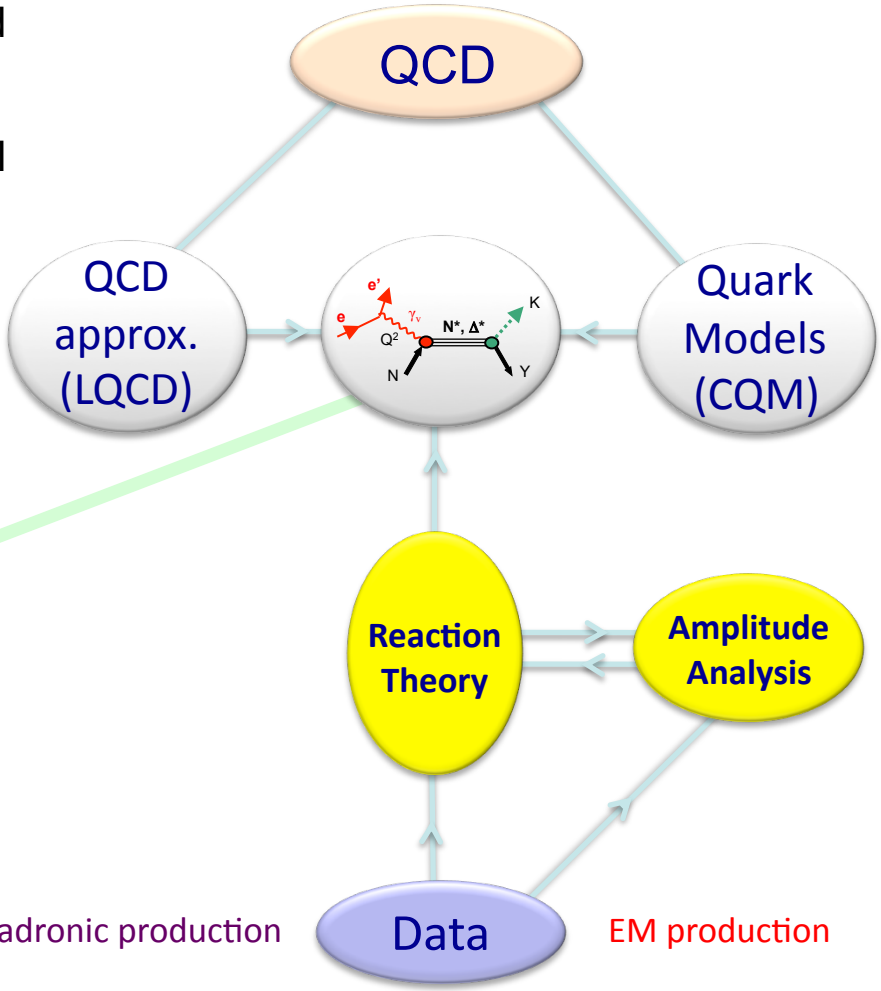


Experimental Search for New States

- Measurements of γN / $\gamma^* N$ cross sections and spin observables in wide kinematic range needed to extend our understanding.
- Engagement of both experimental and theoretical groups essential to complete sound analyses to extract the physics.



Compare electrocoupling parameters



- Multi-lab experimental program:

JLab, BESIII, ELSA, GRAAL, LEPS, MAMI

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)	****	-
N*(1720)	***	1–15	-	Δ*(1920)	***	2.1
N*(1900)	**	0–10	-	Δ*(1930)	***	-
N*(1990)	**	-	-	Δ*(1940)	*	-
				Δ*(1950)	****	-
				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)]

Bonn-Gatchina coupled-channels fits

CLAS Strangeness Program

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

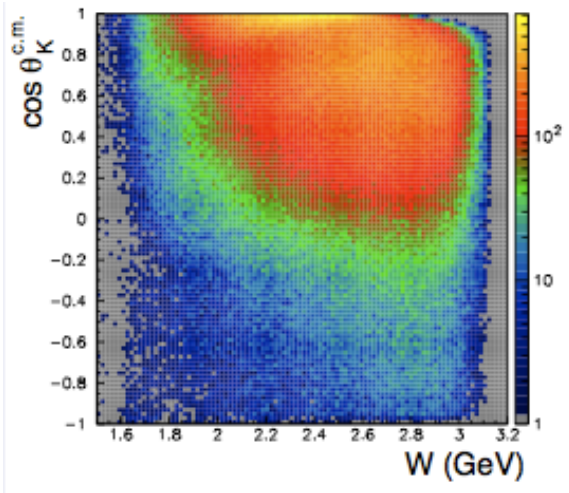


Photo- and electroproduction experiments

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)*
- New focus on "complete" experiments

Complete Experiments: γN → KY

Full cross section can be written in terms of 16 experimental observables

$$\frac{1}{\sigma_0}d\sigma(\theta,\phi) = 1 + \Sigma\cdot[P_L^\gamma\cos 2\phi - P_y^T\cdot P_{y'}^\Lambda] + T\cdot[P_y^T - P_L^\gamma\cdot P_{y'}^\Lambda\cos 2\phi] + P\cdot[P_{y'}^\Lambda - P_L^\gamma\cdot P_y^T\cos 2\phi]$$
$$+ E\cdot[-P_c^\gamma\cdot P_z^T - P_L^\gamma\cdot P_x^T\cdot P_{y'}^\Lambda\sin 2\phi] + F\cdot[P_L^\gamma\cdot P_z^T\sin 2\phi + P_c^\gamma\cdot P_x^T\cdot P_{y'}^\Lambda]$$
$$+ G\cdot[P_c^\gamma\cdot P_x^T + P_L^\gamma\cdot P_z^T\cdot P_{y'}^\Lambda\sin 2\phi] + H\cdot[-P_L^\gamma\cdot P_x^T\sin 2\phi - P_c^\gamma\cdot P_z^T\cdot P_{y'}^\Lambda]$$
$$+ C_{x'}\cdot[P_c^\gamma\cdot P_{x'}^\Lambda - P_L^\gamma\cdot P_y^T\cdot P_{z'}^\Lambda\sin 2\phi] + C_{z'}\cdot[P_c^\gamma\cdot P_{z'}^\Lambda + P_L^\gamma\cdot P_y^T\cdot P_{x'}^\Lambda\sin 2\phi]$$
$$+ O_{x'}\cdot[P_L^\gamma\cdot P_{x'}^\Lambda\sin 2\phi + P_c^\gamma\cdot P_y^T\cdot P_{z'}^\Lambda] + O_{z'}\cdot[P_L^\gamma\cdot P_{z'}^\Lambda\sin 2\phi - P_c^\gamma\cdot P_y^T\cdot P_{x'}^\Lambda]$$
$$+ L_{x'}\cdot[P_z^T\cdot P_{x'}^\Lambda + P_L^\gamma\cdot P_x^T\cdot P_{z'}^\Lambda\cos 2\phi] + L_{z'}\cdot[P_z^T\cdot P_{z'}^\Lambda - P_L^\gamma\cdot P_x^T\cdot P_{x'}^\Lambda\cos 2\phi]$$
$$+ T_{x'}\cdot[P_x^T\cdot P_{x'}^\Lambda - P_L^\gamma\cdot P_z^T\cdot P_{z'}^\Lambda\cos 2\phi] + T_{z'}\cdot[P_x^T\cdot P_{z'}^\Lambda + P_L^\gamma\cdot P_z^T\cdot P_{x'}^\Lambda\cos 2\phi]$$

- Not all observables are independent *[Chiang and Tabakin, PRC 55, 2054 (1997)]*
- Need only 8 (carefully chosen) observables to separate amplitudes at any given W.
- With full experimental decomposition of the reaction amplitudes, it is expected that models can then determine the N* content of the reactions.

CLAS γN → KY Program

Photon Beam		Target			Recoil			Target – Recoil								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_o		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

γp

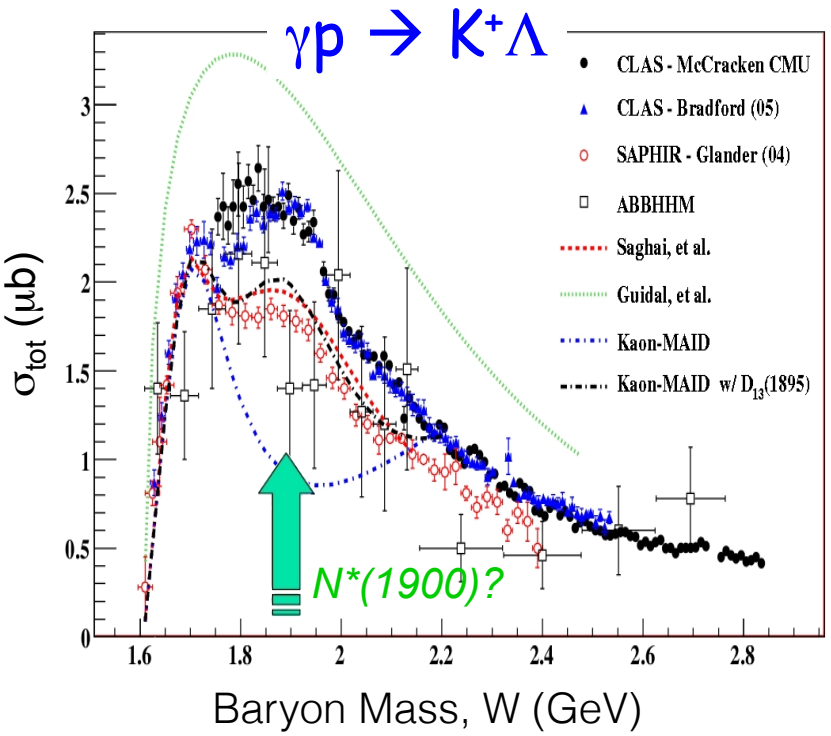
- Circularly polarized photons/unpolarized target
  - GI / GII
- Linearly polarized photons/unpolarized target
  - G8
- Polarized beam/longitudinal-transverse target
  - FROST

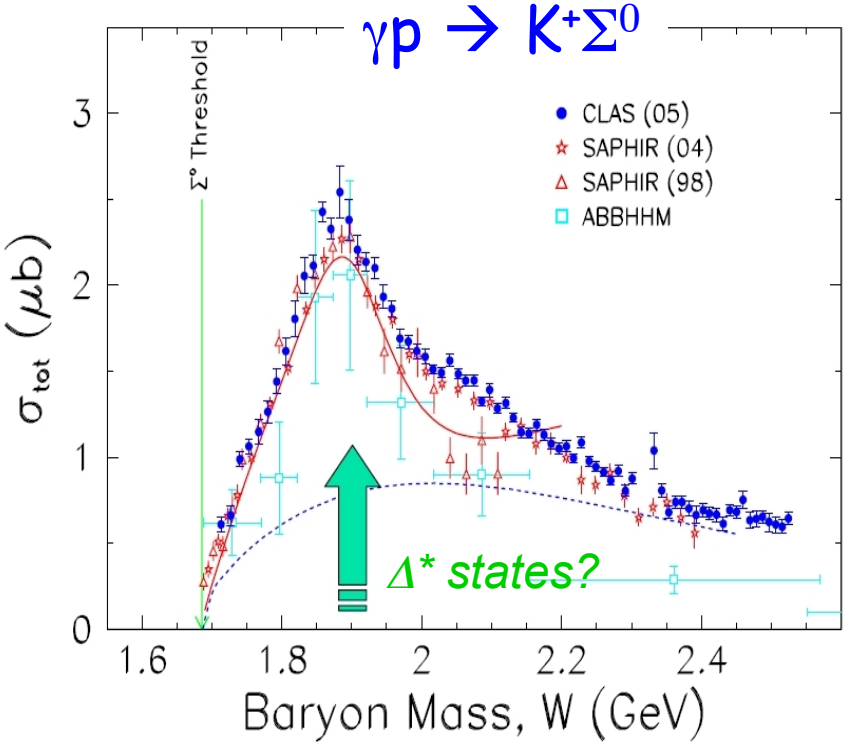
γn

- Polarized beam/longitudinally polarized target
  - G13
- Polarized beam/longitudinal-transverse target
  - HD-ICE

Data collection complete; analysis in progress

Total Cross Sections $\gamma p \rightarrow K^+ Y$



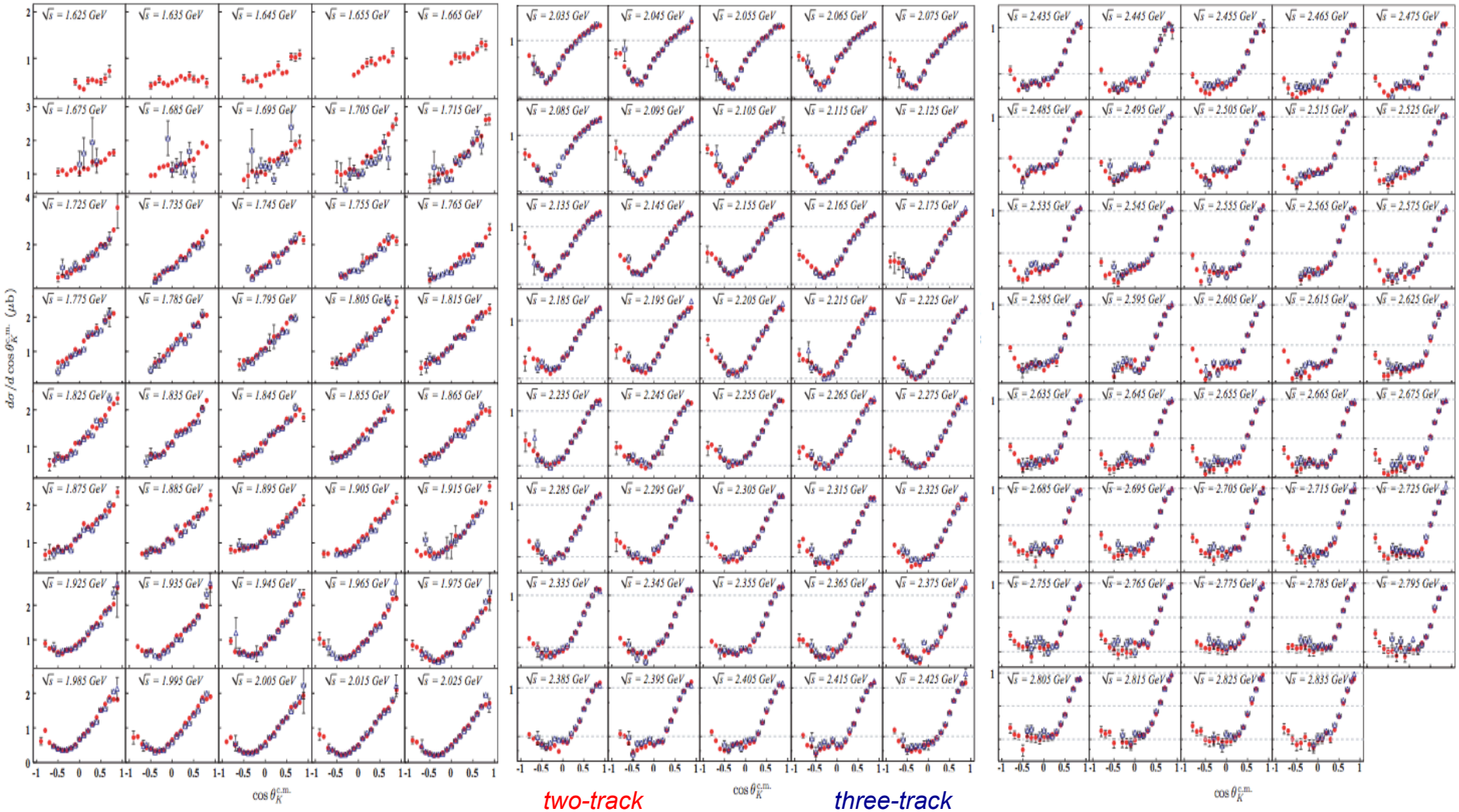


[Bradford et al., PRC 73, 035202 (2006)]

- Dominated by t-channel exchange
- Core N* set $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$
- Data show 2nd structure at ~1.9 GeV
- Models suggest $D_{13}(1900)$ or $P_{13}(1900)$

- Dominated by s-channel exchange
- No PDG states listed with N* → KΣ
- Typically use same core set of N* from KΛ
- Structure at 1.9 GeV from Δ* states?

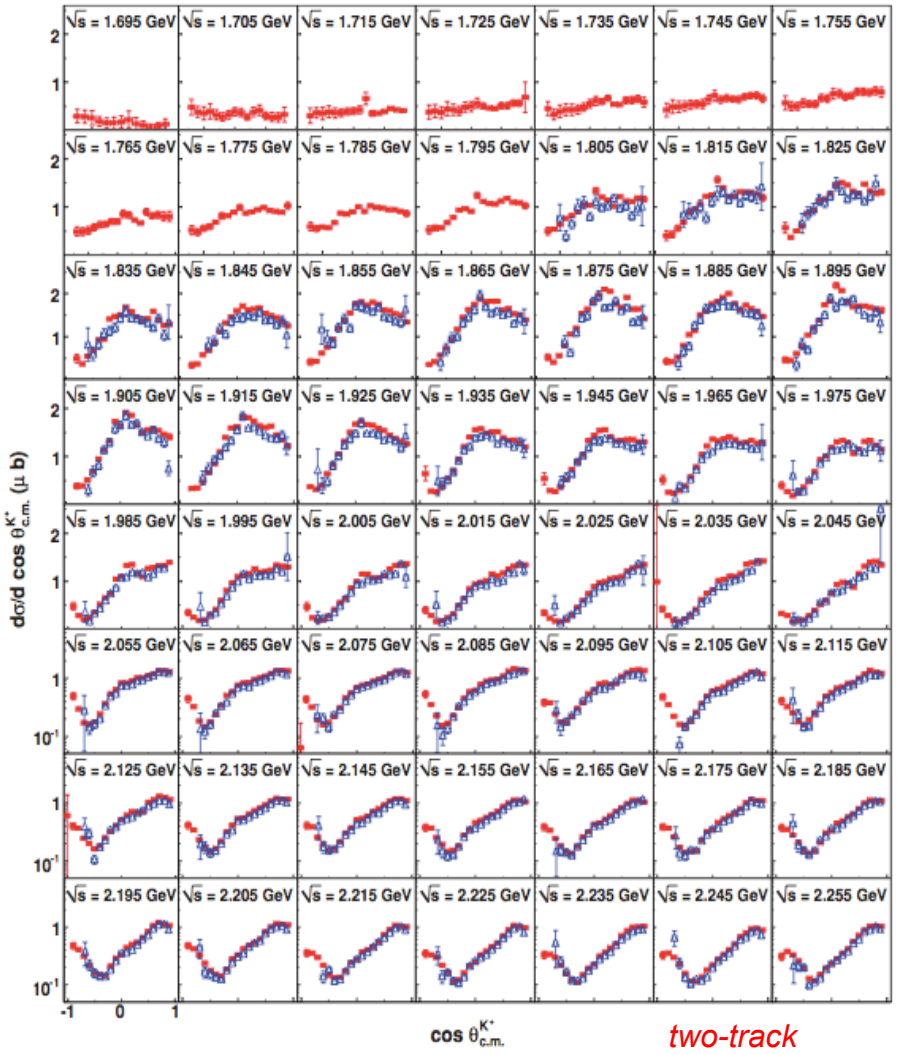
Differential Cross Sections $\gamma p \rightarrow K^+\Lambda$



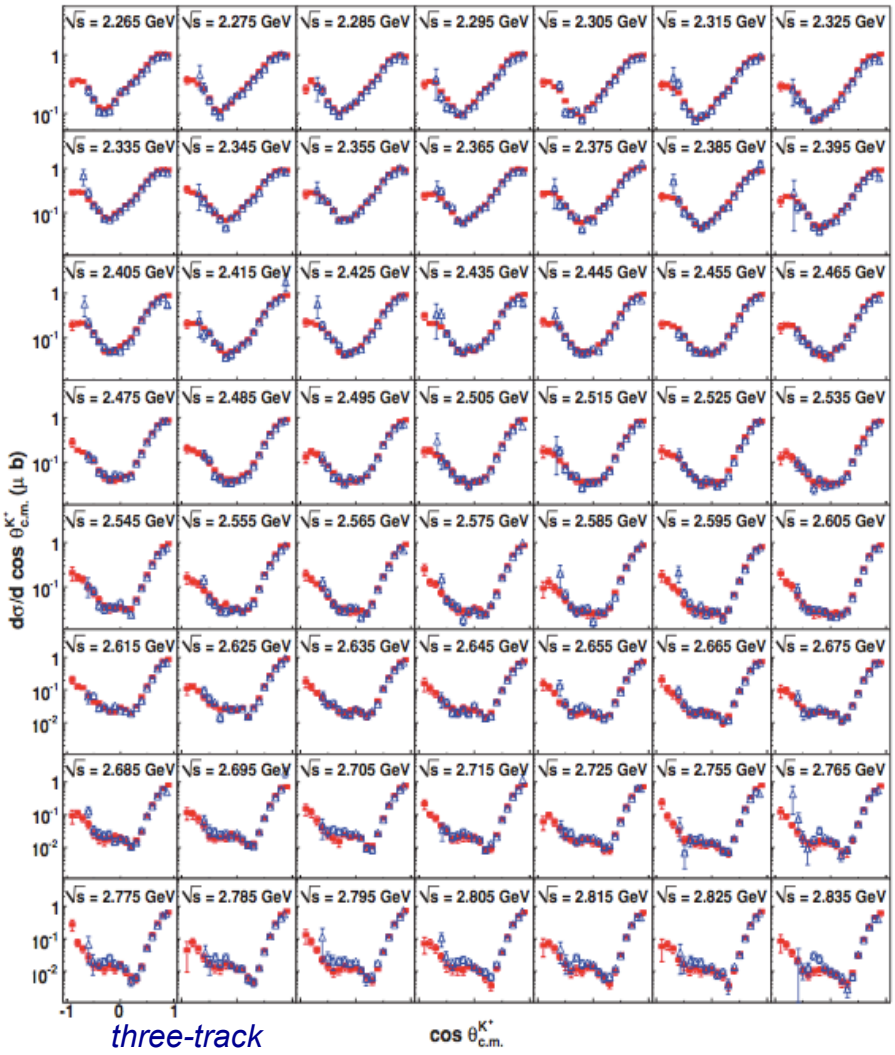
[McCracken et al., PRC 81, 025201 (2010)]

W: 1.625 – 2.835 GeV

Differential Cross Sections $\gamma p \rightarrow K^+\Sigma^0$



two-track

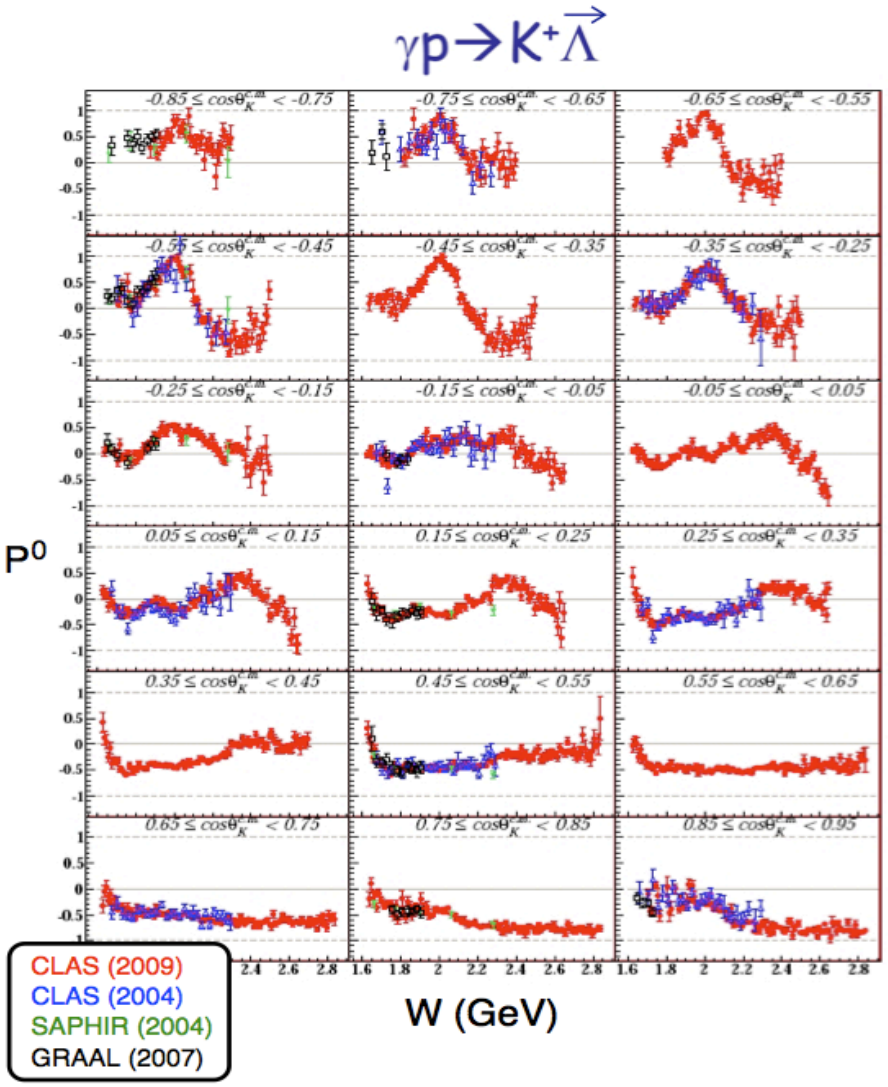


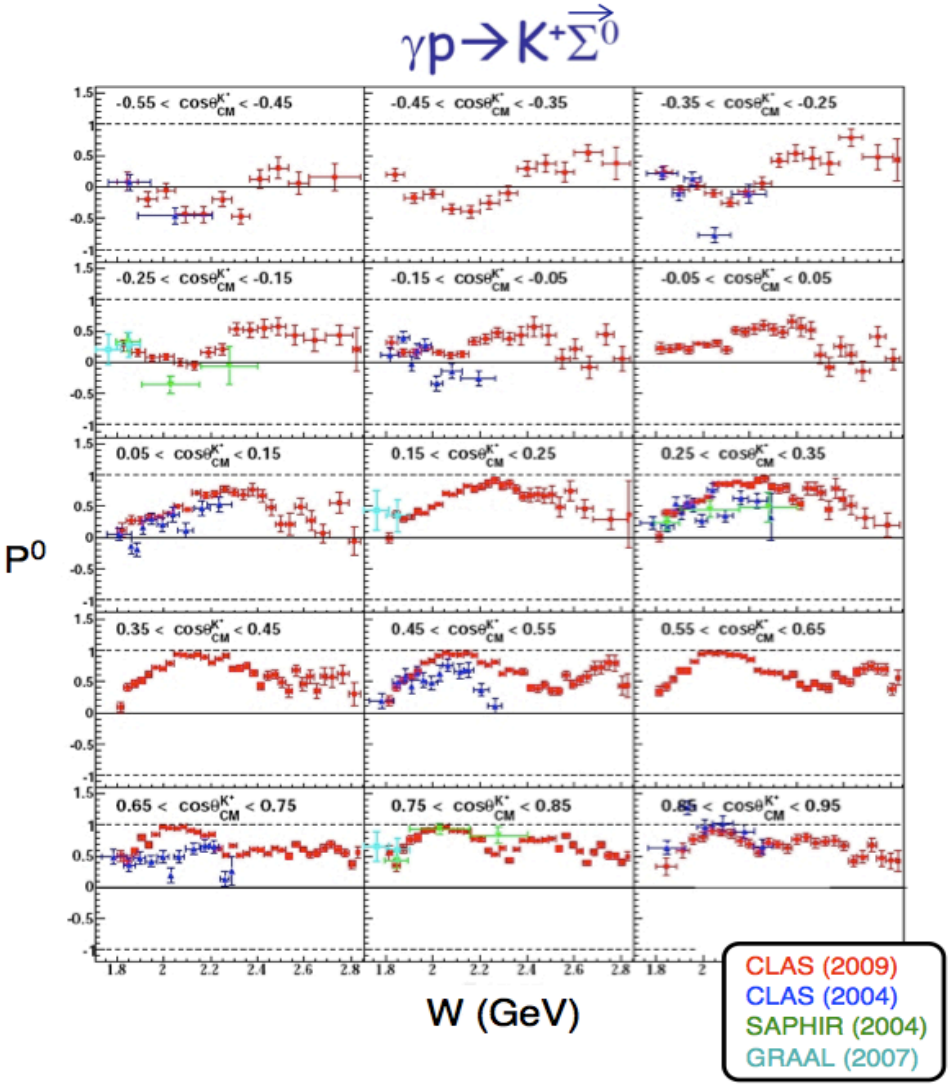
three-track

[Dey et al., PRC 82, 025202 (2010)]

W: 1.695 – 2.835 GeV

Recoil Polarization

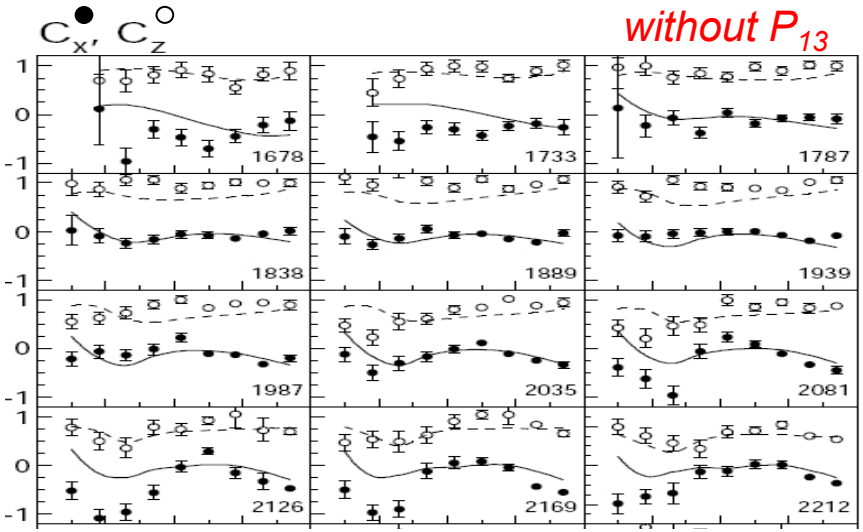


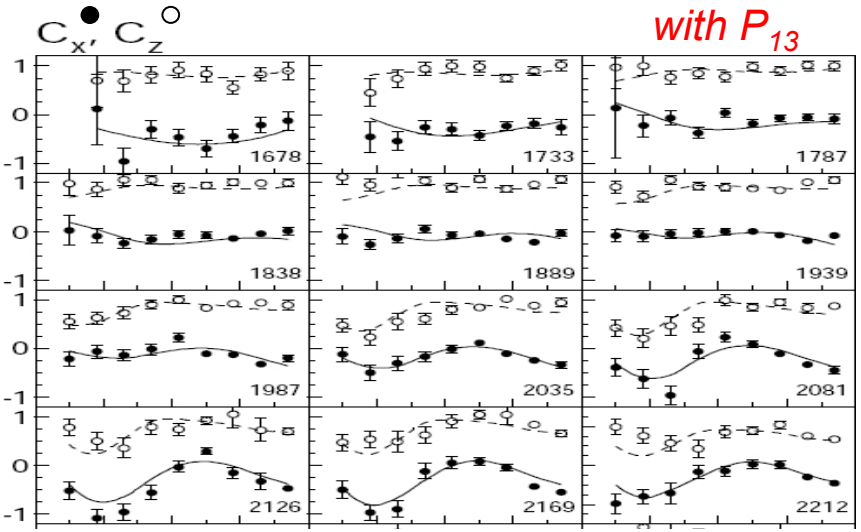


[McCracken et al., PRC 81, 025201 (2010)]

[Dey et al., PRC 82, 025202 (2010)]

Transferred Polarization $\vec{\gamma}_c p \rightarrow K^+\vec{\Lambda}$





[Bradford et al., PRC 75, 035205 (2007)] $\cos\theta_K^*$

not predicted in diquark model $\cos\theta_K^*$

- Fits from Bonn-Gatchina coupled-channel model established $P_{13}(1900)$

  [Nikonov et al., PLB 662, 245 (2008)] *($M = 1915 \pm 60$ MeV, $\Gamma = 180 \pm 40$ MeV)*

- State confirmed in covariant isobar model analysis – single channel $\gamma p \rightarrow K^+\Lambda$

  [Mart & Kholili, PRC 86, 022201 (2012)]

- Confirmed in effective Lagrangian calculation of $\gamma p, \gamma^* p \rightarrow K^+\Lambda$ data

  [Maxwell, PRC 85, 034611 (2012)]

State may be ready for promotion to **** assignment and to become the first baryon resonance observed and confirmed in EM meson production

Electroproduction Data

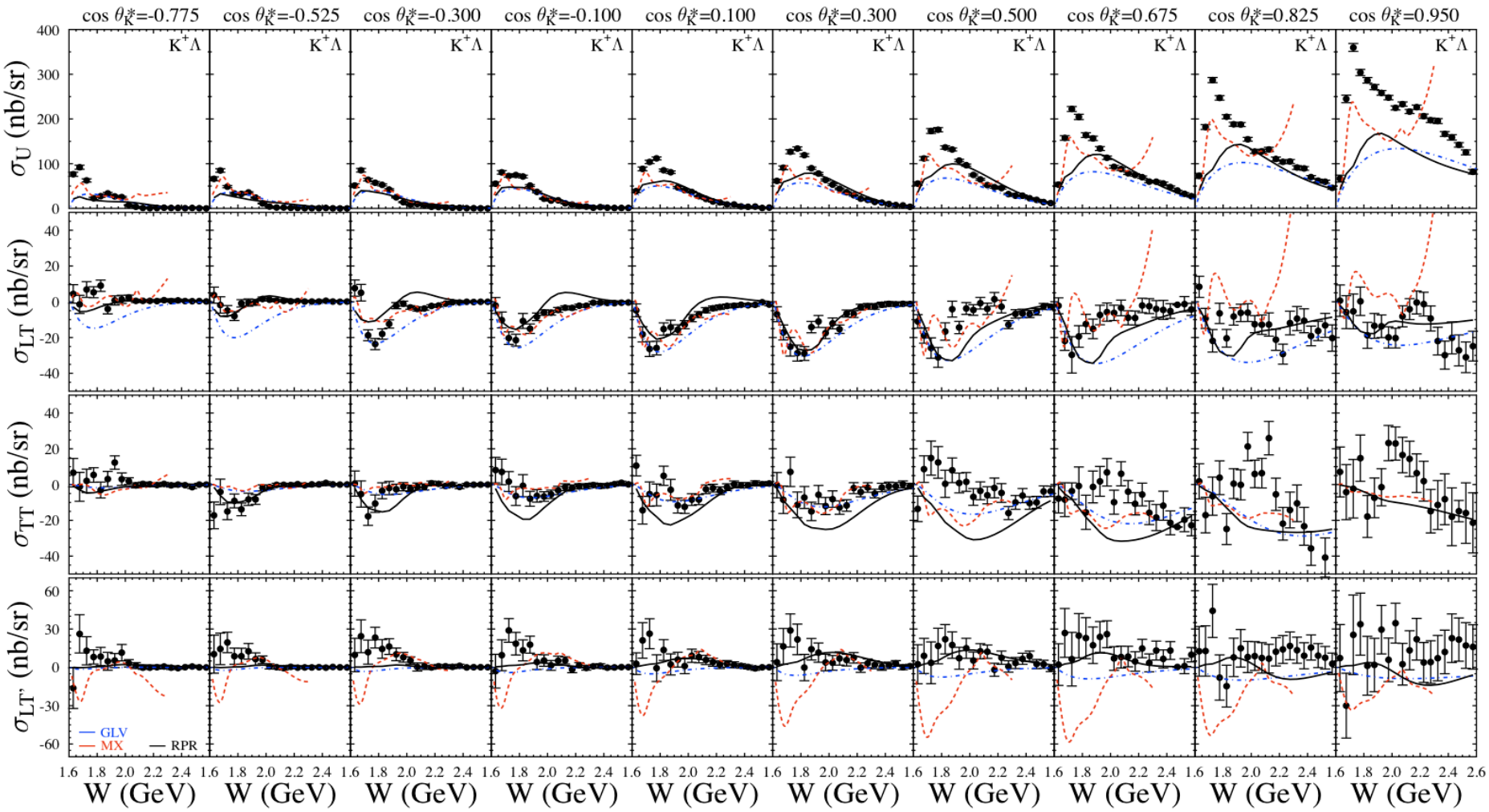
- CLAS photoproduction data sets have been used extensively in coupled-channel fits and "advanced" single-channel models.
  - *Electroproduction data have not been employed on the same scale.*
  - *Inclusion of electroproduction data in these fits is underway.*
- The electroproduction data have several critical roles to play:
  - *Studies of finite Q^2 processes are sensitive to both L and T photo-couplings.*

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

  - *The LT and TT structure functions provide signatures of interfering partial wave strengths that can differentiate among production mechanisms.*
  - *The structure functions are particularly useful to gain control over the parameterization of the background diagrams.*
  - *The Q^2 dependence of the data gives access to the γ^*NN^* transition FFs.*

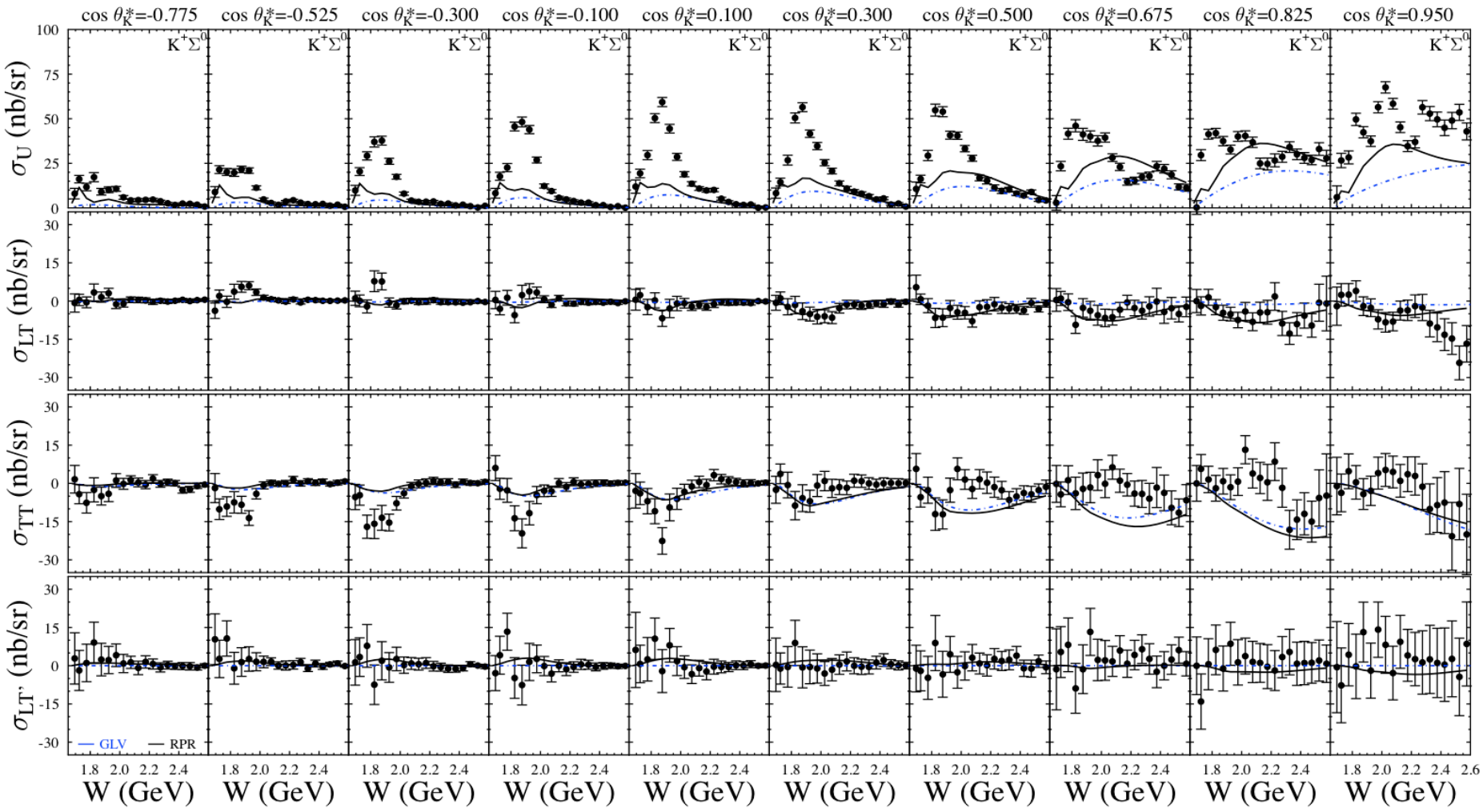
The electroproduction data provide constraints on the production amplitudes complementary to the photoproduction data.

$K^+\Lambda$ 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



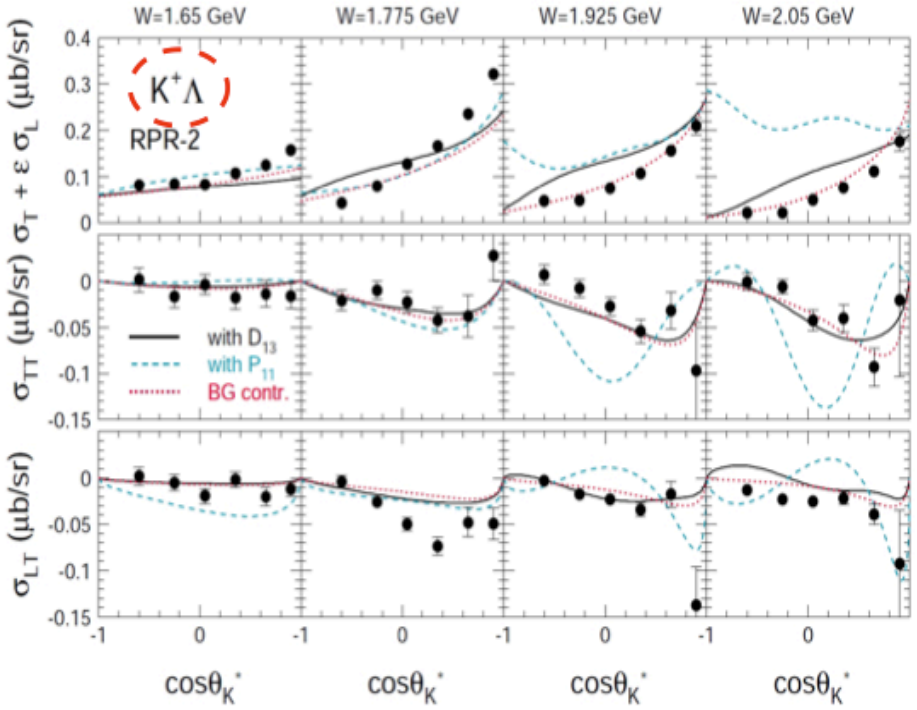
E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2 *[Carman et al., PRC 87, 025204 (2013)]*

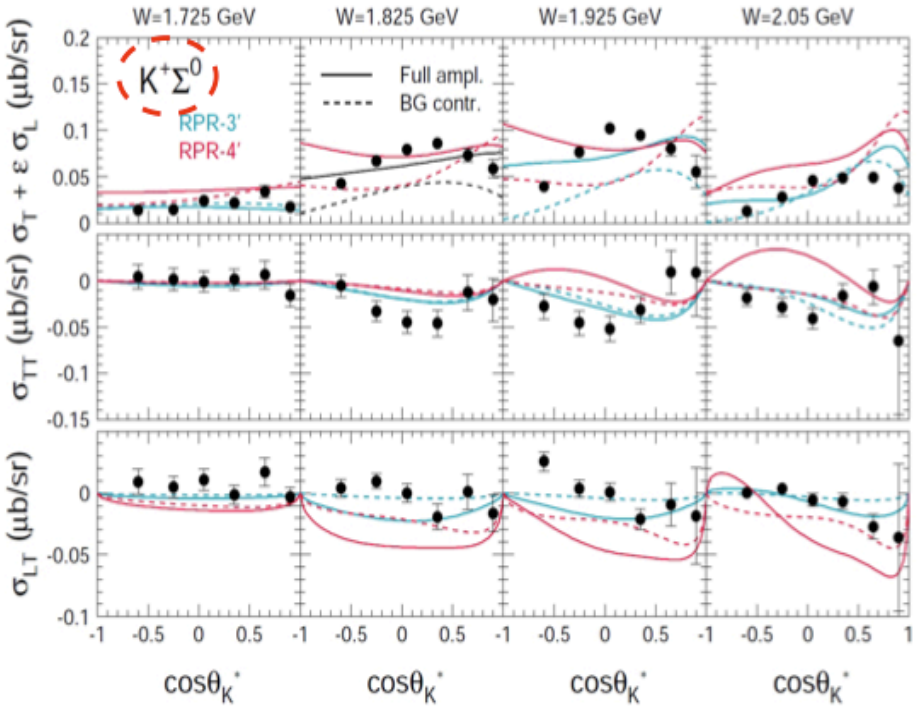
Electroproduction Predictions

$$\mathcal{M}_{RPR} = \sum_{\mathcal{K}} \left(\gamma \; (\gamma K \mathcal{K}) \; K \;\; \alpha_{\mathcal{K}}(t) \;\; p \; (p\mathcal{K}Y) \; Y \right)_{Regge} + \sum_{R} \left(\gamma \; (\gamma pR) \; R \; (RKY) \; K \;\; p \;\; Y \right)_{Feyn}$$

Regge + Resonance Model

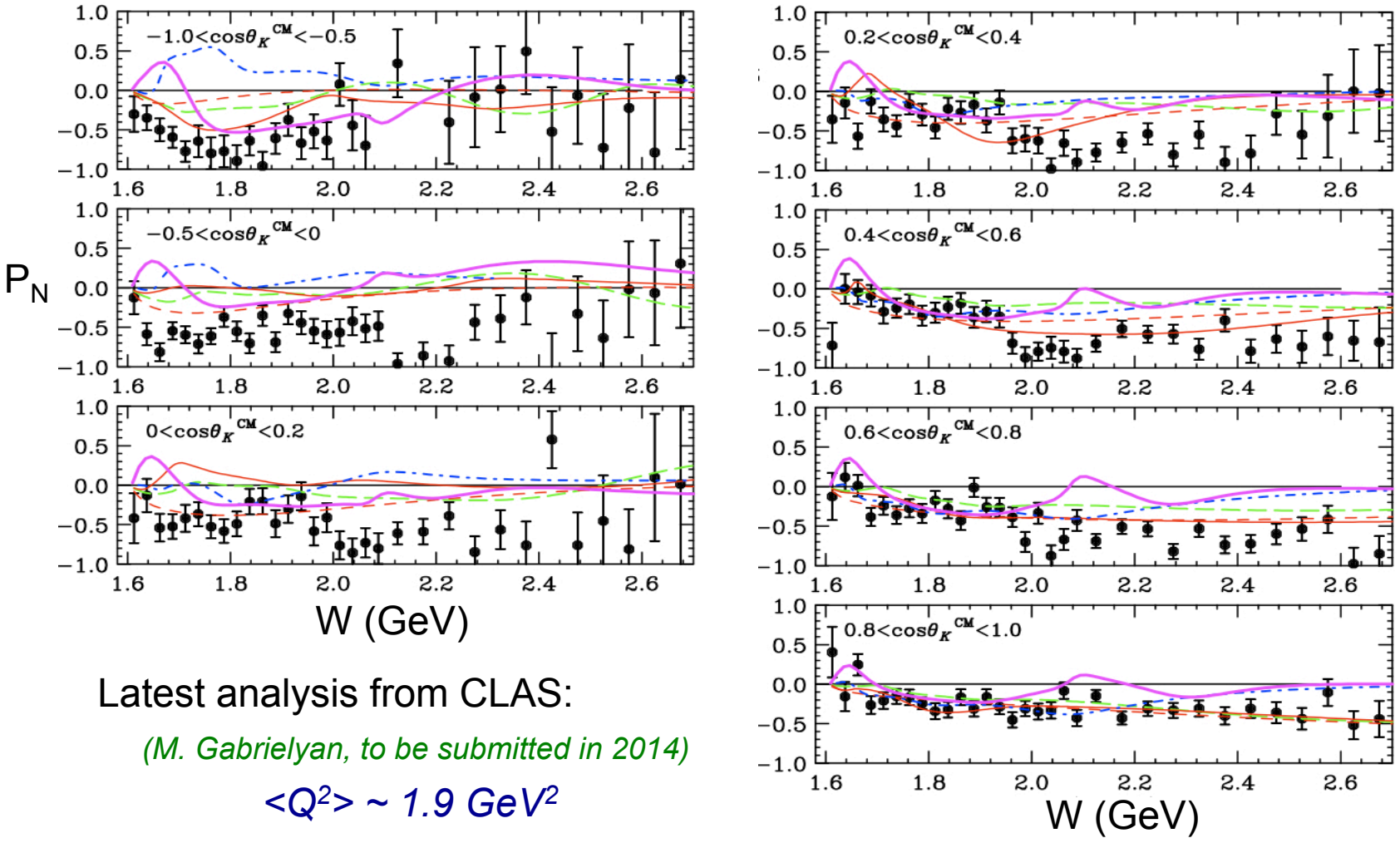
[Corthals et al., PLB 656, 185 (2007)]





- Rule out P_{11} and D_{13} assignments for N* state at 1900 MeV

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



Latest analysis from CLAS:

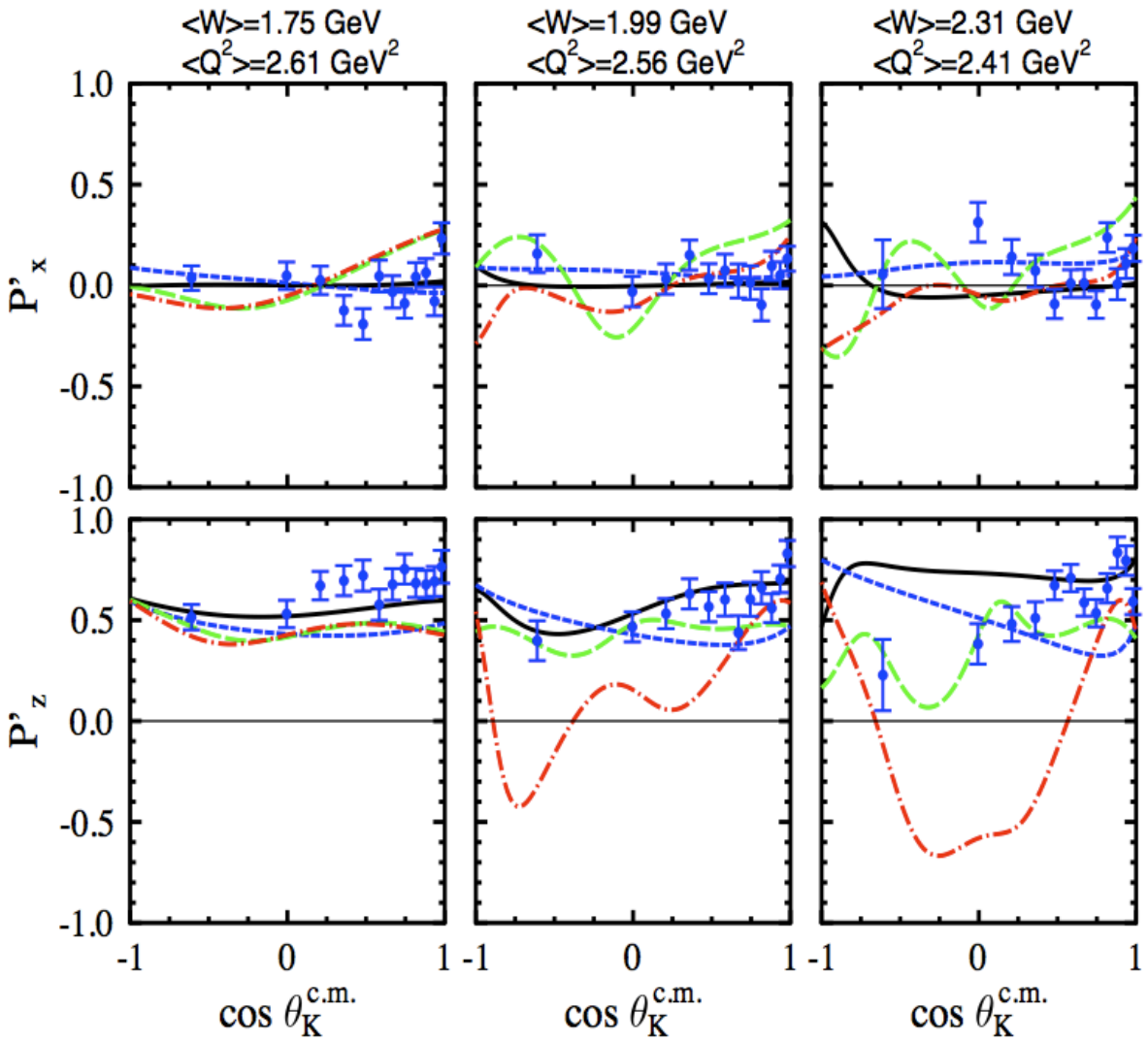
(M. Gabrielyan, to be submitted in 2014)

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

Kaon-Maid *Maxwell* *RPR-2007* *RPR-2011 (solid-full, dash-NR)*

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 – MB

Regge Model – GLV

RPR w $P_{11}(1900)$ - Ghent

RPR 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)]

Theory Ambiguities $N^* \rightarrow K^+\Lambda$

- PDG status for 30 years: Core set of states: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$
  Recent emergence of: $P_{13}(1900)$ *(from γp fits)*

- Coupled-Channel Model (Bonn): *[Anisovich et al., EPJA 48, 15 (2012)]*
  Most relevant: $S_{11}(1650)$, $P_{11}(1710)$, $D_{13}(1895)$, $P_{13}(1900)$
  Other required states: $P_{13}(1720)$, $P_{11}(1880)$, $S_{11}(1895)$, $F_{15}(2000)$, $D_{13}(2150)$, $G_{17}(2190)$

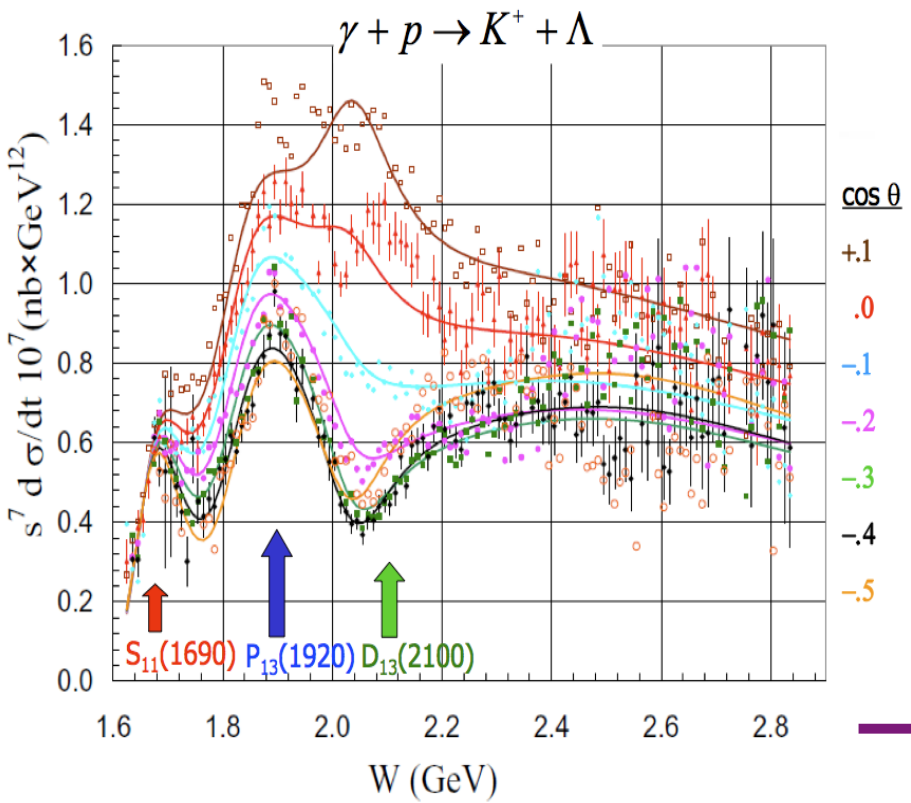
- Coupled-Channel Model (EBAC): *[Kamano et al., PRC 88, 035209 (2013)]*
  Most relevant: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1900)$
  Other required states: $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $P_{13}(1720)$

- Isobar Model (Mart): *[Mart and Kholili, PRC 86, 022201 (2012)]*
  Most relevant: $S_{11}(1650)$, $P_{13}(1720)$, $P_{11}(1880)$, $P_{13}(1900)$, $D_{13}(2080)$

- Models agree in some respects but full consistency is lacking:
  - Include electroproduction data in fits – sensitivity beyond γp data alone! --

N* → K⁺Λ Amplitude Analysis

[Schumacher & Sargsian, PRC 83, 025207 (2011)]



- Compute coherent total amplitude:

$$|A(m,\cos\theta_K^*)|^2 = |\Psi_S(\tfrac{1}{2},\tfrac{1}{2}) + \Psi_P(\tfrac{3}{2},\tfrac{1}{2}) + \Psi_P(\tfrac{3}{2},\tfrac{3}{2}) + \Psi_D(\tfrac{3}{2},\tfrac{1}{2}) + \Psi_D(\tfrac{3}{2},\tfrac{3}{2})|^2$$

- Fit to observed angular distributions:

$$s^7\left(\frac{d\sigma}{dt} = \frac{(hc)^2}{64\pi}\frac{1}{s}\frac{1}{k^2}|A|^2\right)$$

- Test various resonance sets vs. mass
- Free parameters: mass, width, couplings

- Reasonable correspondence with Bonn-Gatchina/EBAC fits:

- cross section fits allow dominant N states to be "seen"*
- confirm P-wave character for state at 1.9 GeV
- other contributions could be investigated including spin observables

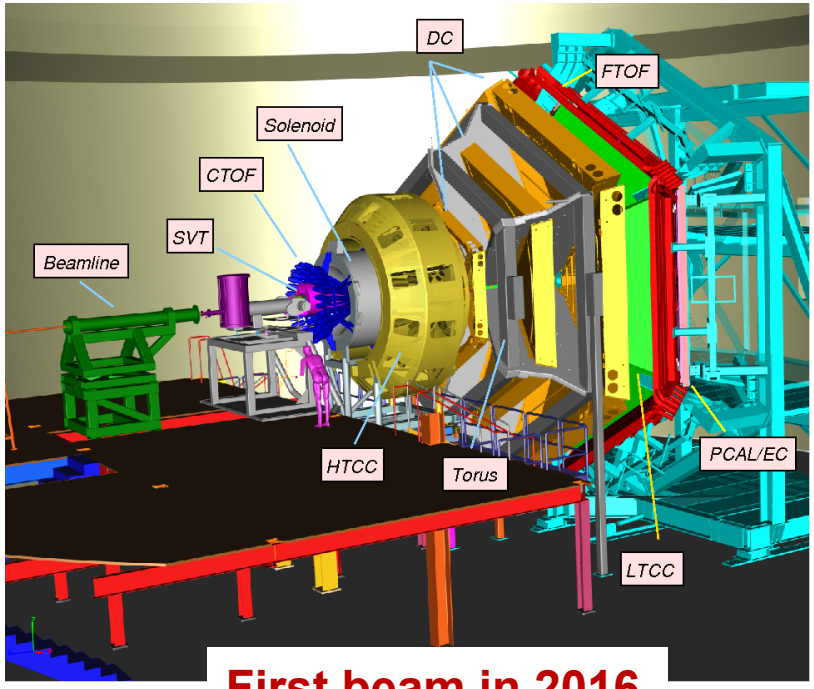
New KY Proposal for CLAS12

- Measure exclusive $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction cross sections from an unpolarized proton target with polarized electron beam.

$$E_b = 11\ GeV,\ Q^2 = 4 - 12\ GeV^2,\ W = 1.6 - 3.0\ GeV,\ \cos\theta_K^* = [-1{:}1]$$

- Key Motivations:
  - *Study spectrum and structure of high-lying baryon states at high Q^2.*
  - *Develop reaction models for extraction of electrocoupling amplitudes that incorporate transition from M-B to quark-gluon degrees of freedom.*
  - *KY data needed to provide independent information for high-mass states inaccessible with $N\pi$ final states.*

Submitted to PAC42



First beam in 2016

Summary/Conclusions

- **The CLAS strangeness physics program:**
  - Designed to measure cross sections and all combinations of beam, target, and recoil polarization states.
    - *Precision data – broad kinematic coverage*
    - *Program includes "complete" experiments on both proton and neutron targets*
  - CLAS data dominates the world's strangeness physics database for both photo- and electroproduction cross sections and spin observables.
- **Main points from this talk:**
  - CLAS KY data has played an important role in understanding the N* spectrum.
    - *Strong evidence for $P_{13}(1900)$ (missing quark model state) established*
    - *Photo- and electroproduction data are complementary to constrain models*
  - Progress in developing advanced dynamical coupled-channels models.
    - *Dominant N* states coupling to KY determined; consistency issues to be understood*
    - *Initial focus on photoproduction data; electroproduction data fits planned*
  - The N* → KY experimental program will continue with CLAS12 to study the spectrum and structure of N* states for Q^2 up to 12 GeV^2.

BACKUP SLIDES

CLAS ep Data Set Overview

#	Run	E_b (GeV)	Trig.
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. transfer
  - *W=1.6-2.7 GeV, $<Q^2>$=1.9 GeV^2*
  - *to be submitted (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 from pol. transfer data
  - *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*

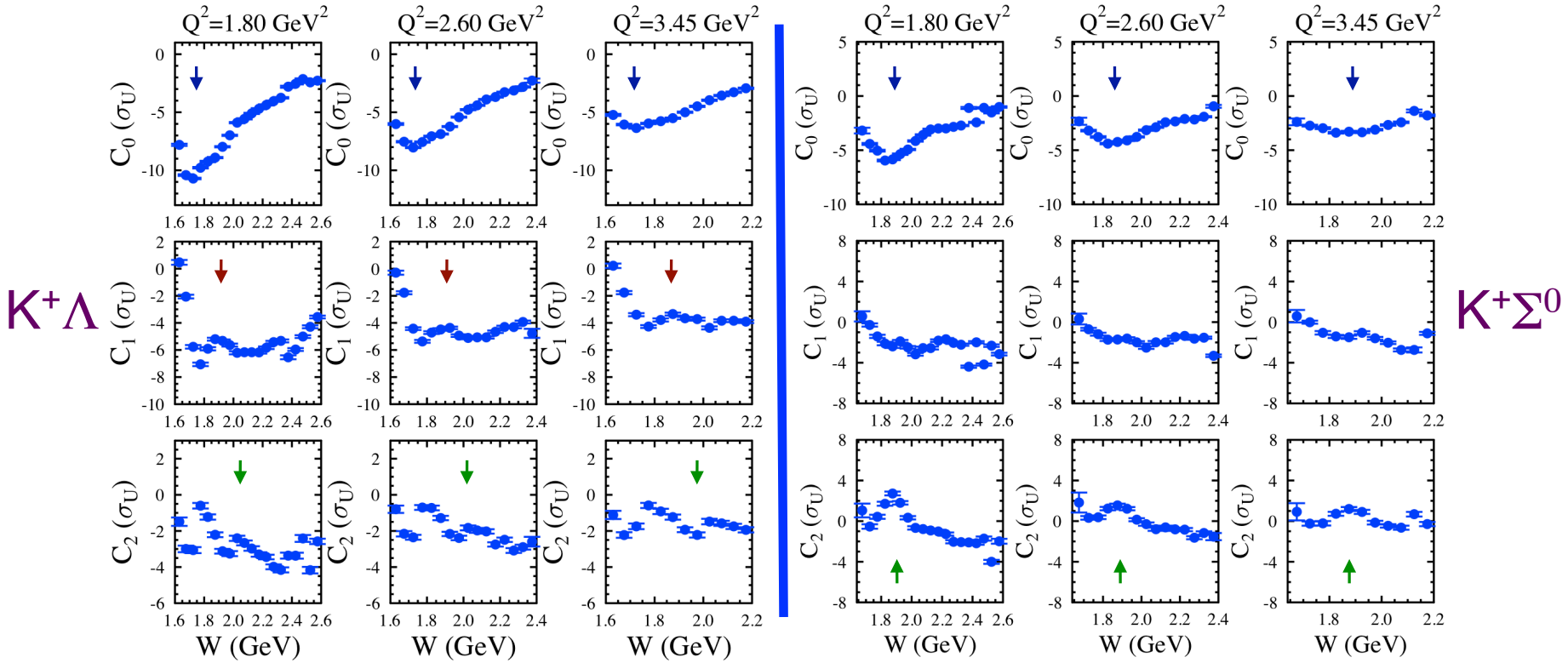
  [Nasseripour et al., PRC 77, 065208 (2008)]
- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil pol. transfer
  - *W=thr-2.6 GeV, Q^2=1.6-2.6 GeV^2*

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

Legendre Analysis

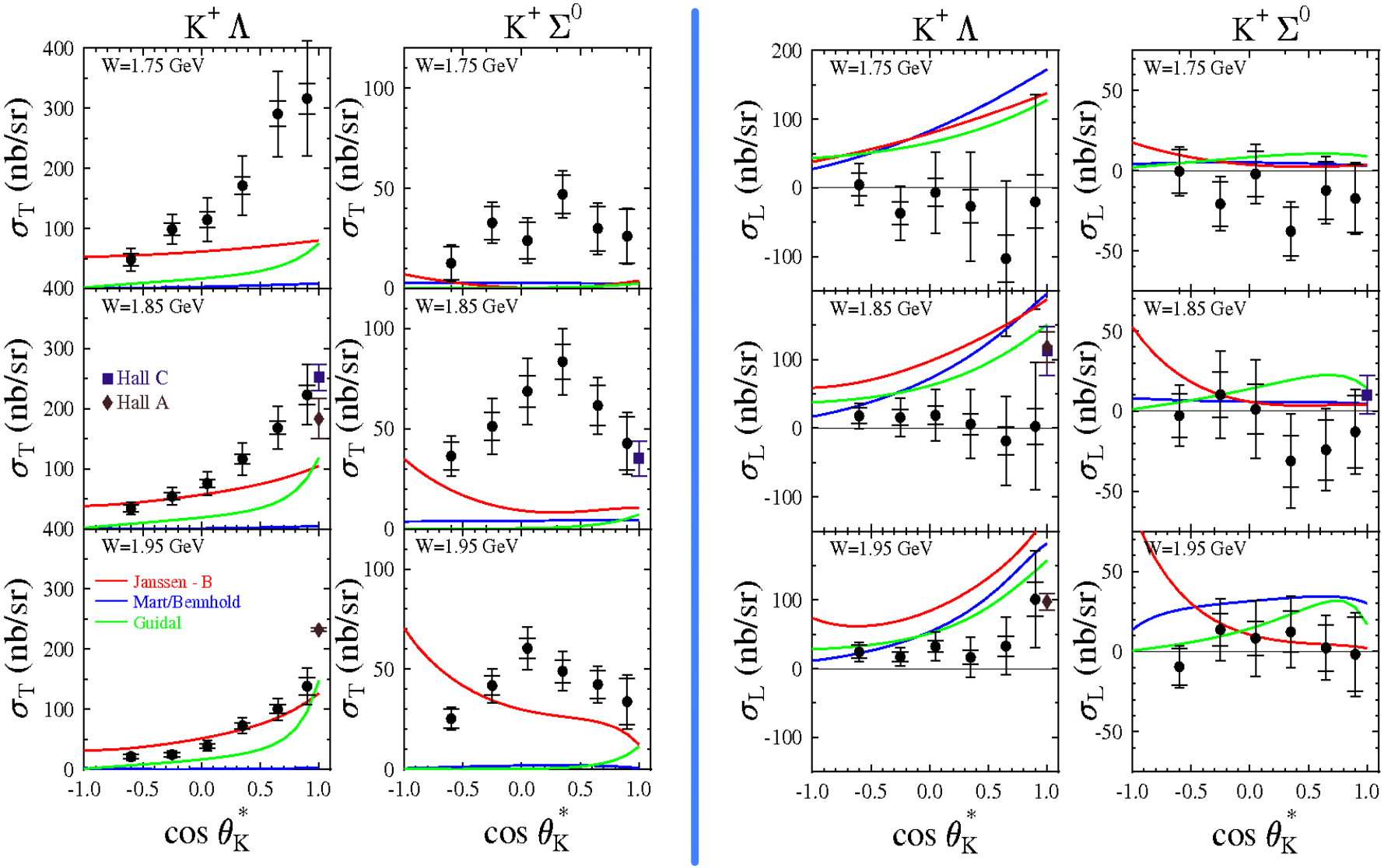
Coherent Legendre fit:

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



- 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 models are needed for the extraction of the *N** parameters.

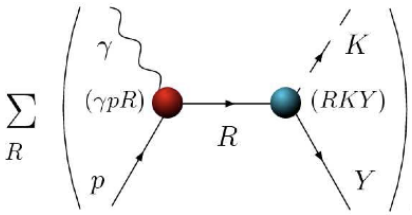
L/T Separation

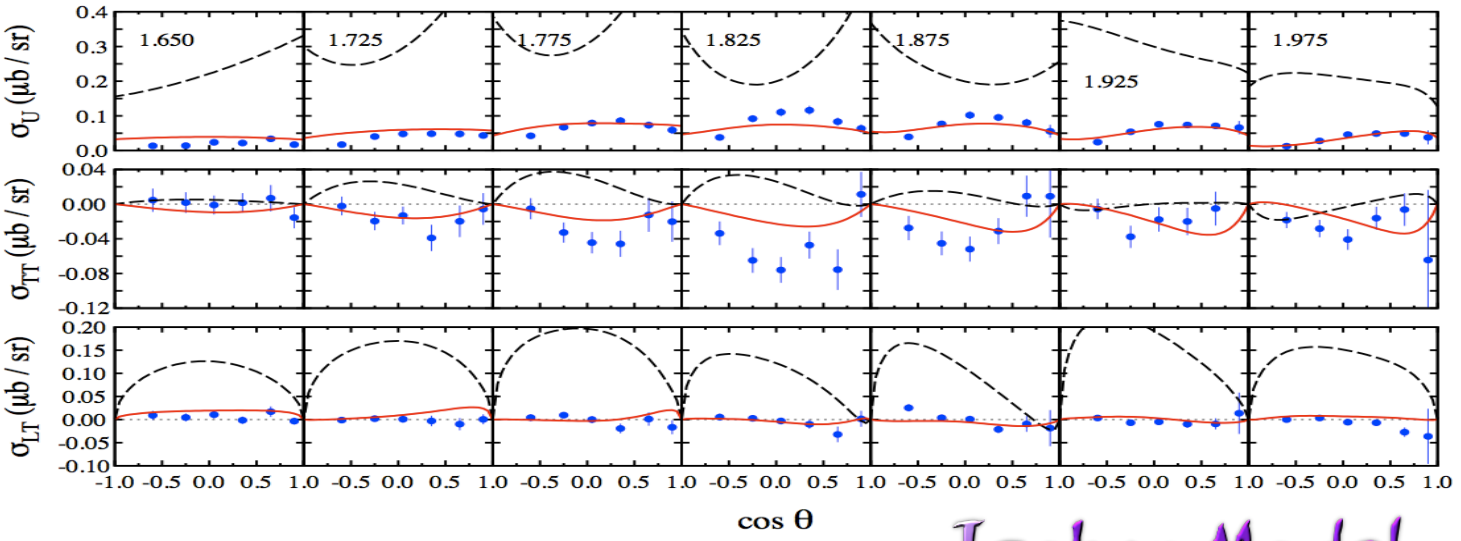


[Ambrozewicz et al., PRC 75, 045203 (2007)]

Structure Function Fits

$K^+\Lambda$

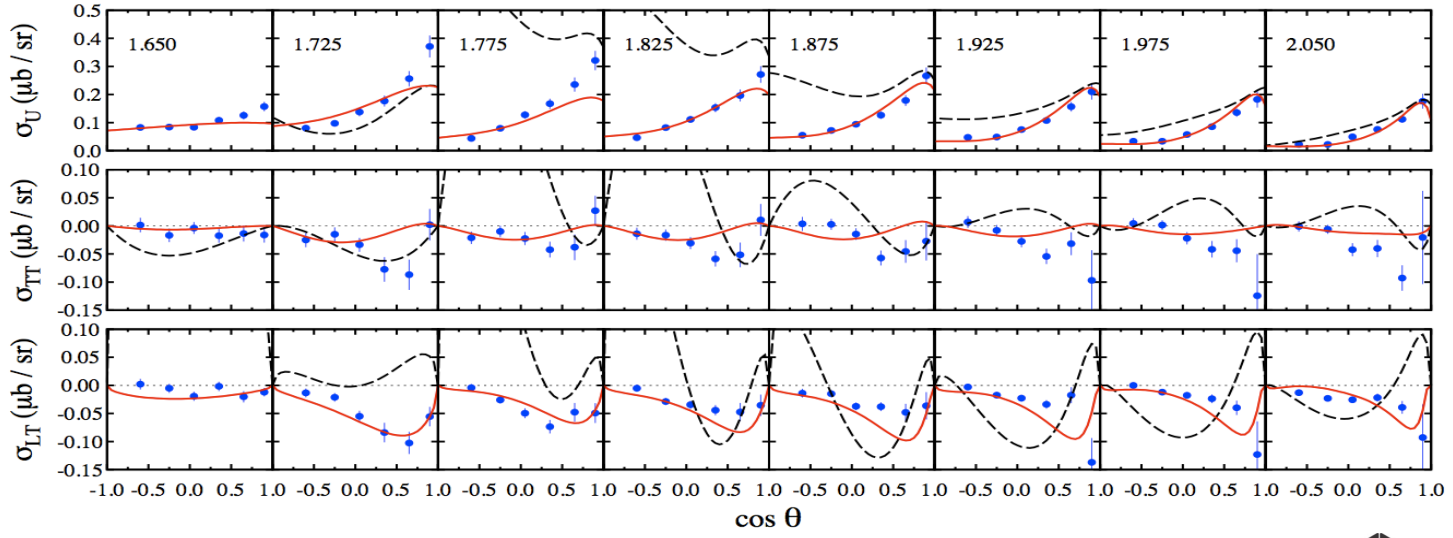




[Mart, EPJ Web Conf. 3, 07002 (2010)]

Isobar Model

$K^+\Sigma^0$



KAON-MAID
New fits

(includes only PDG states)