Strangeness Physics at CLAS in the 6 GeV Era

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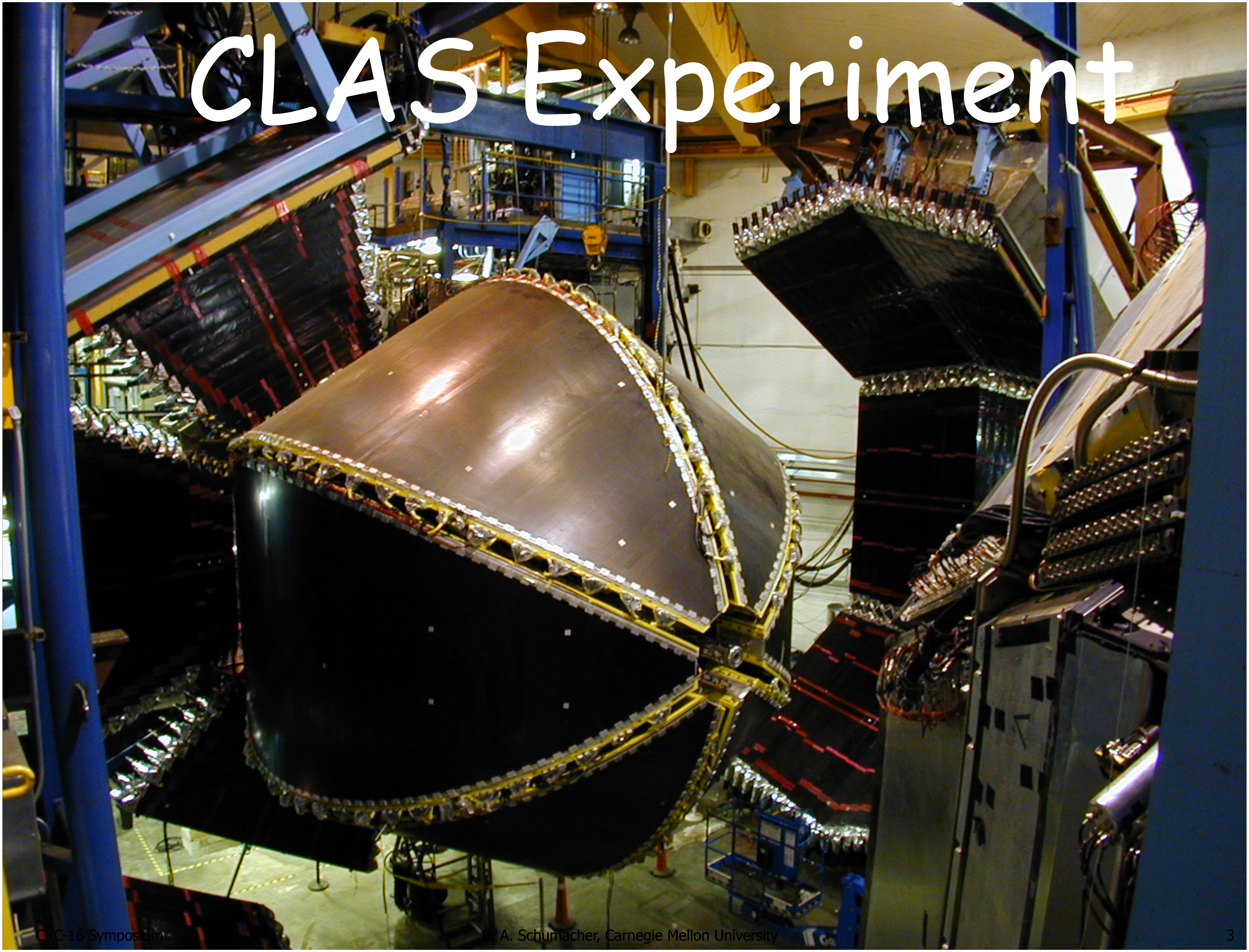
Outline /Overview

- The N^* spectrum of states via hyperon photo- and electro- production
- Dimensional scaling of $K\Lambda$ photoproduction
- Excited Y^* cross sections measured at CLAS
  - $\Sigma^0(1385)$ ($J^P = 3/2^+$); $\Lambda(1405)$ ($J^P = 1/2^-$); $\Lambda(1520)$ ($J^P = 3/2^-$)
- Structure of the $\Lambda(1405)$: $\Sigma\,\pi$ line shapes; J^P
- Strangeness suppression in exclusive electro-production
- Cascade photoproduction
- Brief outlook to future work

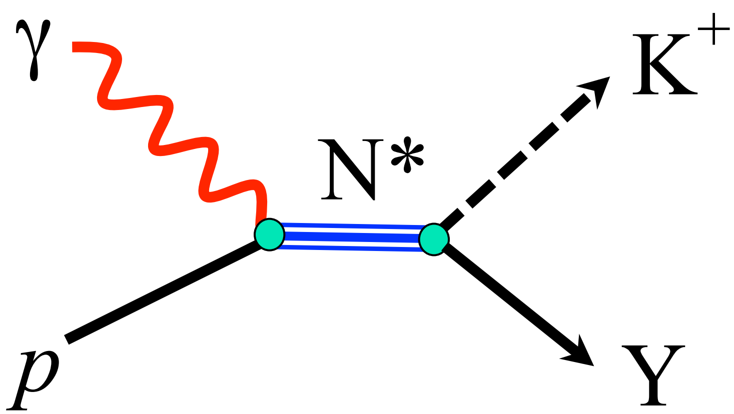
CLAS Experiment



CLAS Experiment

- Photoproduction:
  - Targets: unpolarized LH_2, polarized p, & HD-ice
  - Beams: unpolarized, circular, linear, to ~5 GeV
  - Reconstructed $K^+ p \pi^- (\pi^0)$ or $K^+ \pi^+ \pi^- (n)$
  - 20×10^9 triggers → 1.41×10^6 $KY\pi$ events in g11a
- Electroproduction:
  - Q^2 from ~0.5 to ~3 $(GeV/c)^2$
  - Structure functions separations from ϕ-dependencies, Rosenbluth and beam-helicity

The N* Spectrum
Photoproduction



Strangeness in N* Physics: Status

Table 8. Star rating suggested for baryon resonances and their decays. Ratings of the Particle Data Group are given as *; additional stars suggested from this analysis are represented by ★; (*) stands for stars which should be removed.

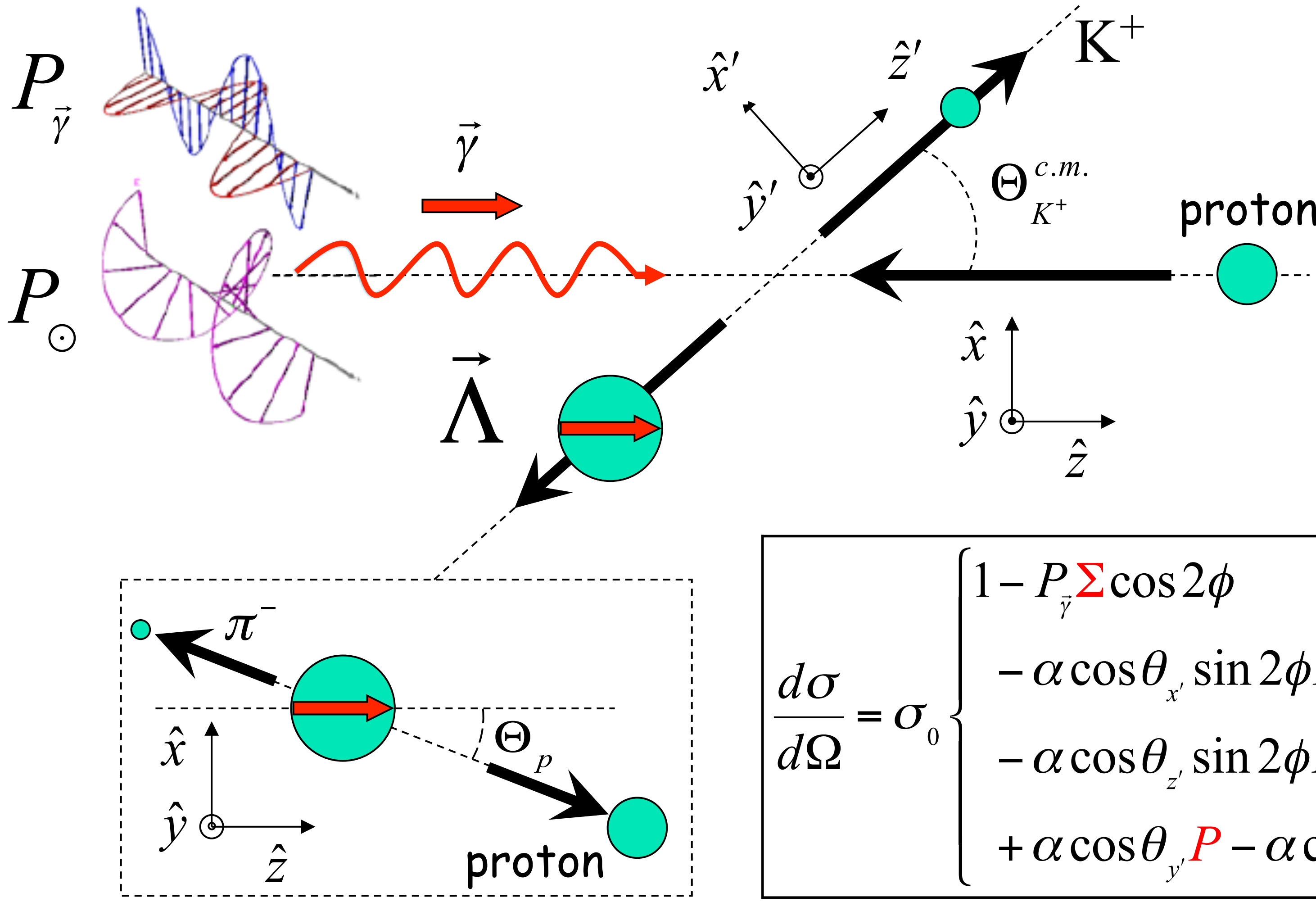
		all	πN	γN	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\sigma$
	$N(1440)\frac{1}{2}^+$	****	****	***★	(*)			***	★★★
	$N(1710)\frac{1}{2}^+$	***	***	***	**★	★★★	★★	*(*)	
	$N(1880)\frac{1}{2}^+$	★★	★	★		★★	★		
	$N(1535)\frac{1}{2}^-$	****	****	****	****			*	
S_{11}	$N(1650)\frac{1}{2}^-$	****	****	***	*★★	***	**	**(*)	
	$N(1895)\frac{1}{2}^-$	★★	★	★★	★★	★★	★		
	$N(1720)\frac{3}{2}^+$	****	****	****	****	**	**	***	
P_{13}	$N(1900)\frac{3}{2}^+$	**★	**	★★★	★★	★★★	★★	★★	
	$N(1520)\frac{3}{2}^-$	****	****	****	***			****	
	$N(1700)\frac{3}{2}^-$	**★	**	**	*	*(*)	*	**★	
D_{13}	$N(1875)\frac{3}{2}^-$	★★★	★	★★★		★★★	★★		★★★
	$N(2150)\frac{3}{2}^-$	★★	★★	★★		★★		★★	
	$N(1680)\frac{5}{2}^+$	****	****	****	*			**(*)	★★
	$N(1860)\frac{5}{2}^+$	★	★	★					
	$N(2000)\frac{5}{2}^+$	**★	*(*)	★★	★★	★★	★		
	$N(1675)\frac{5}{2}^-$	****	****	***(*)	*	*		***(*)	★
	$N(2060)\frac{5}{2}^-$	★★★	★★	★★★	★		★★		
	$N(1990)\frac{7}{2}^+$	**	*(*)	★★					
G_{17}	$N(2190)\frac{7}{2}^-$	****	****	**★		★★			
	$N(2220)\frac{9}{2}^+$	****	****						
	$N(2250)\frac{9}{2}^-$	****	****						
	$\Delta(1910)\frac{1}{2}^+$	****	****	*★			*★	*★	
	$\Delta(1620)\frac{1}{2}^-$	****	****	***				****	
	$\Delta(1900)\frac{1}{2}^-$	**	**	*★			*★	*★	
	$\Delta(1232)\frac{3}{2}^+$	****	****	****					
	$\Delta(1600)\frac{3}{2}^+$	***	***	**★				***	
	$\Delta(1920)\frac{3}{2}^+$	***	***	*★			*★★	**	
	$\Delta(1700)\frac{3}{2}^-$	***	***	***				**	
	$\Delta(1940)\frac{3}{2}^-$	*	*	★★				|★ from $\Delta\eta$|	
	$\Delta(1905)\frac{5}{2}^+$	****	****	****			*★★	**(**)	
	$\Delta(1950)\frac{7}{2}^+$	****	****	***			*★★	**★	

A. V. Anisovich (BoGa) et al., Eur.Phys. J. A **48**, 15 (2012)

- Role of JLab/CLAS strangeness physics in unraveling properties of N* and Δ states?
- Worldwide effort to determine resonance poles, branching fractions, helicity couplings, etc.
- Bottom line: "Stars" & new resonances added to world database

Define the Spin Observables

(for unpolarized nucleon)



$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ \begin{array}{l} 1 - P_{\vec{\gamma}} \Sigma \cos 2\phi \\ -\alpha \cos\theta_{x'} \sin 2\phi P_{\vec{\gamma}} O_{x'} - \alpha \cos\theta_{x'} P_{\odot} C_{x'} \\ -\alpha \cos\theta_{z'} \sin 2\phi P_{\vec{\gamma}} O_{z'} - \alpha \cos\theta_{z'} P_{\odot} C_{z'} \\ + \alpha \cos\theta_{y'} P - \alpha \cos\theta_{y'} P_{\vec{\gamma}} T \cos 2\phi \end{array} \right\}$$

Theory: Bonn Gatchina Model

(One of a few models on the market)

- Coupled channels (K-matrix) framework
  - Input: from π N, K N elastic; γ N, π N inelastic to $\pi^{\pm 0}$ N, ηN, η'N, $K^{\pm 0}$ Y, $\pi\pi$ N
    - Use ALL experimental channels, including the strangeness channels & spin observables
  - Partial Wave Analysis
    - First extract each J^P wave
    - Fit N* and Δ resonance pole parameters

Short list of References:

A. Sarantsev, V. Nikonov, A. Anisovich, E. Klempt, U. Thoma; Eur. Phys. J. A **25**, 441 (2005)

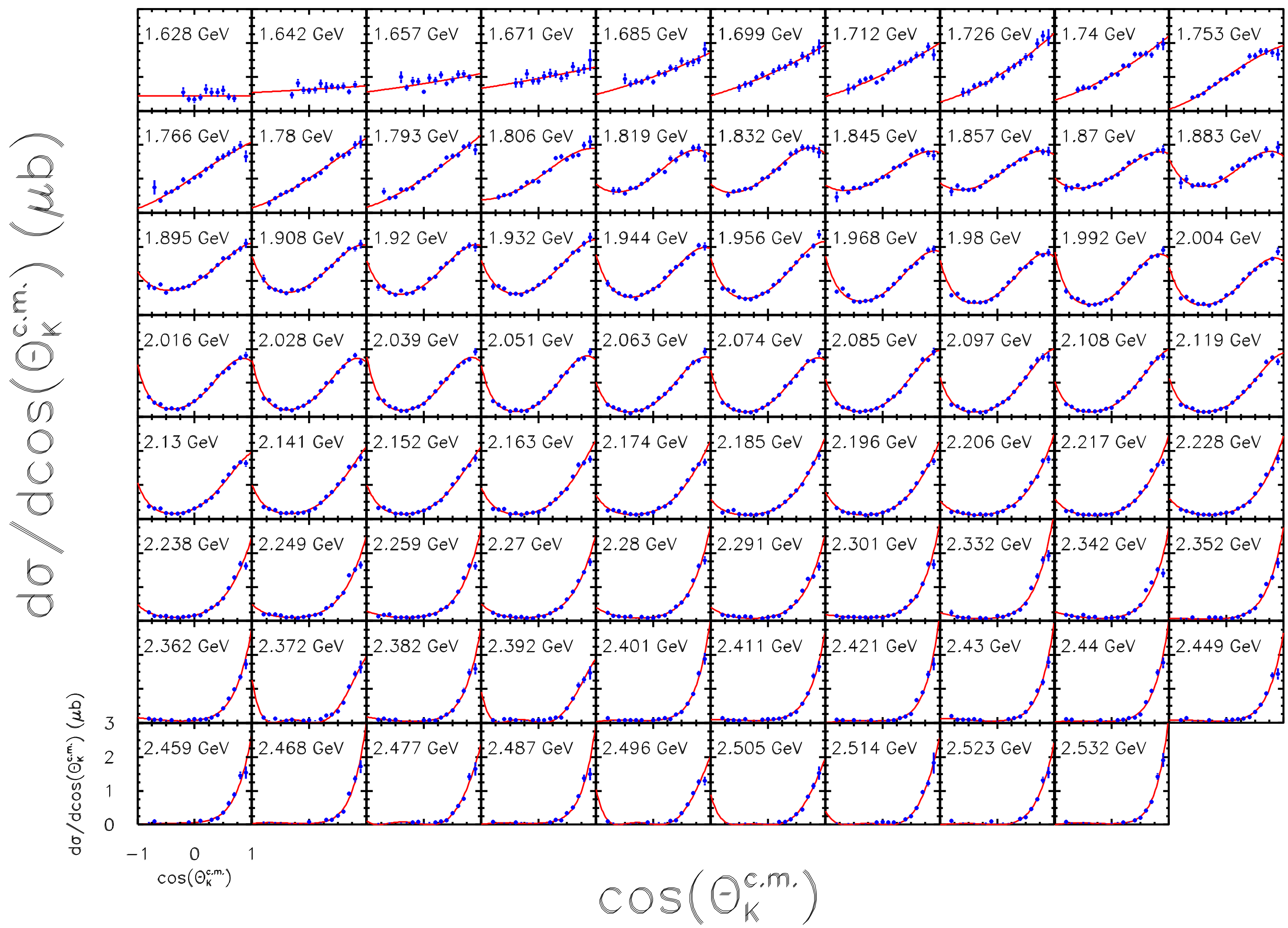
A.V. Anisovich *et al.*, Eur. Phys J. A **25** 427 (2005); Eur. Phys J. A **24,** 111 (2005);

V. A. Nikonov *et al.*, Phys Lett. B **662**, 246 (2008).

A. Anisovich, E. Klempt, V. Nikonov, A. Sarantsev, U. Thoma; Eur. Phys. J. A **47**, 153 (2011).

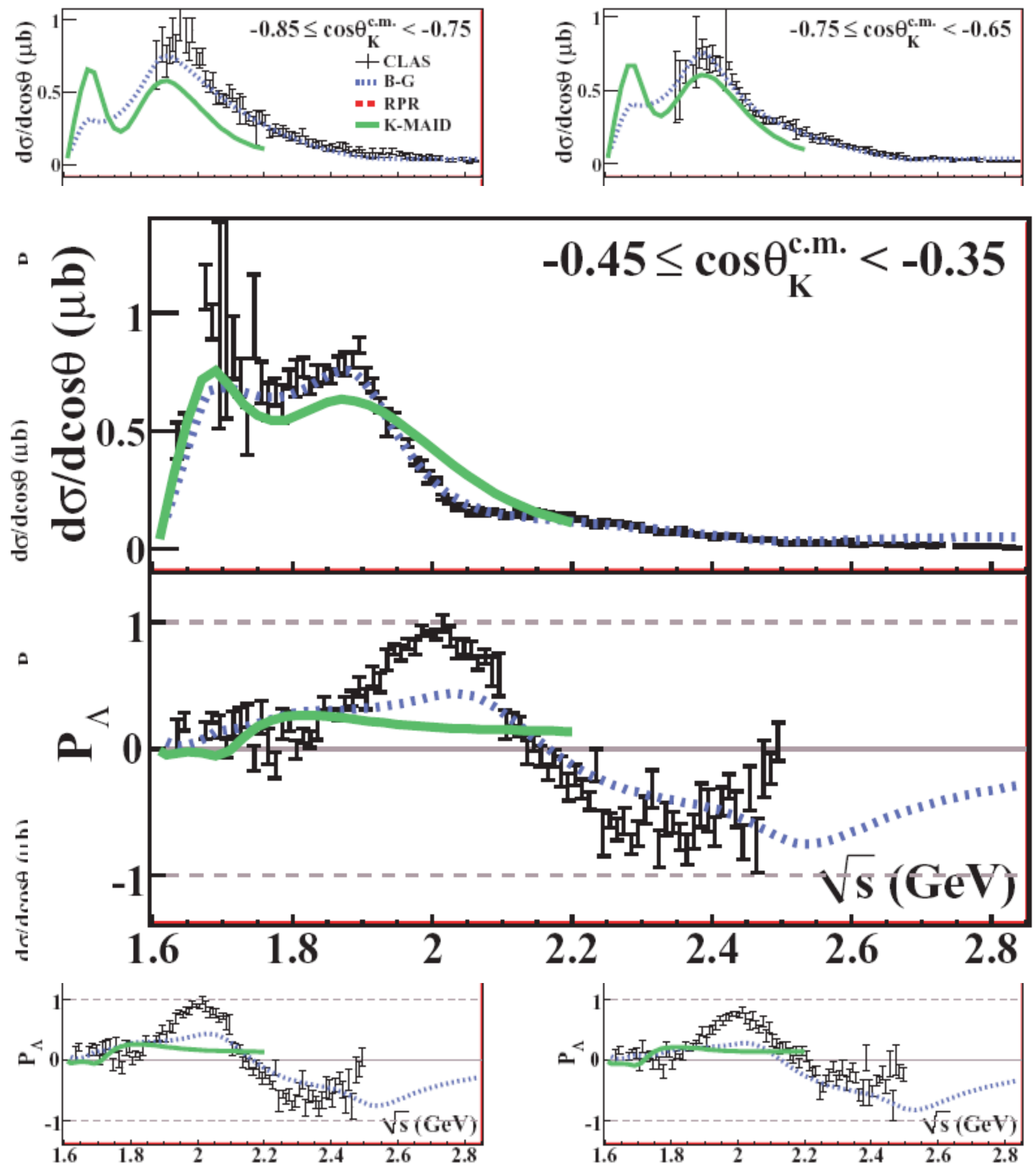
γp→K⁺Λ: cross section

R. Bradford *et al.*, Phys.Rev. C **73**, 035202 (2006)



- Forward peaking indicates t-channel processes at high W
- Angular dependence at lower W consistent with s- and u-channel processes.

γp→K⁺$\vec{\Lambda}$: recoil polarization P



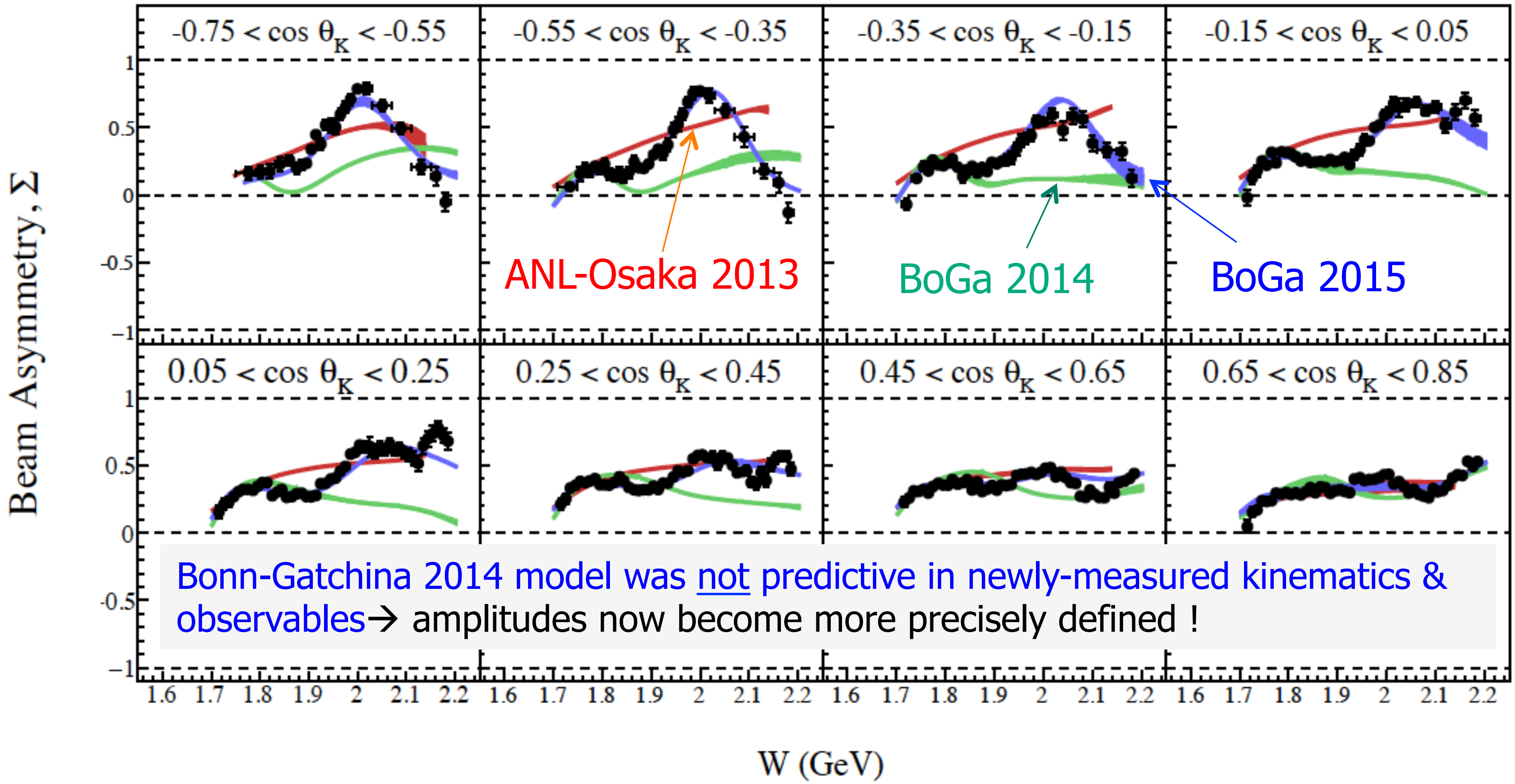
- Kaon-MAID model (green)
  - F.X. Lee *et al.*, Nucl. Phys. **A695**, 237 (2001).
  - Single-channel BW resonance fits
  - No longer up-to-date
- Bonn-Gatchina model (blue)
  - Multi-channel, unitary, BW resonance fit
  - Large suite of N* contributions
  - Was not predictive for recoil polarization → amplitudes became more precisely defined !

A.V. Sarantsev et al., Eur. Phys. J., A **25**, 441 (2005).

M. McCracken et al, (CLAS) Phys. Rev. C **81**, 025201 (2010).

$\gamma p \rightarrow K^+\Lambda$: Beam Asymmetry Σ

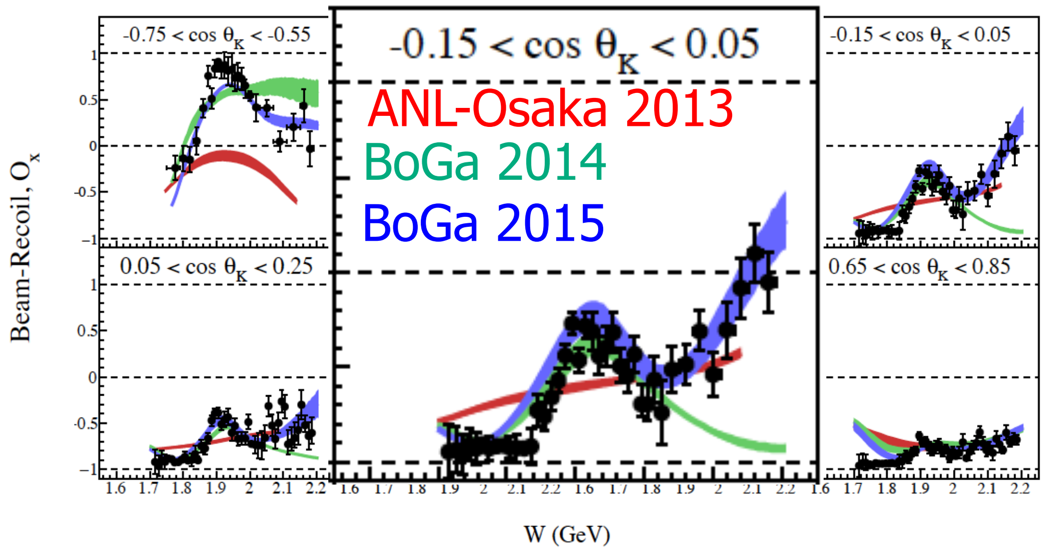
$$\frac{d\sigma}{d\Omega_{K^+}} = \frac{d\sigma}{d\Omega_{K^+}}\bigg|_{unpol.} \left\{1 + \Sigma P_\gamma \cos 2\phi\right\}$$



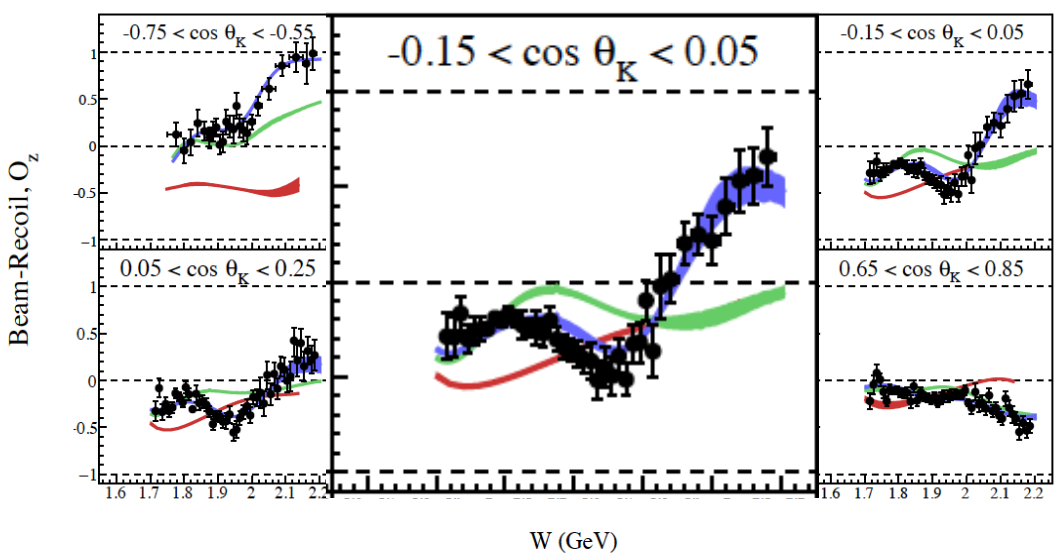
Bonn-Gatchina 2014 model was not predictive in newly-measured kinematics & observables→ amplitudes now become more precisely defined !

C.A. Paterson et al. (CLAS Collaboration) submitted for publication, 2016

$\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$ Beam-Recoil O_x and O_z



O_x



O_z

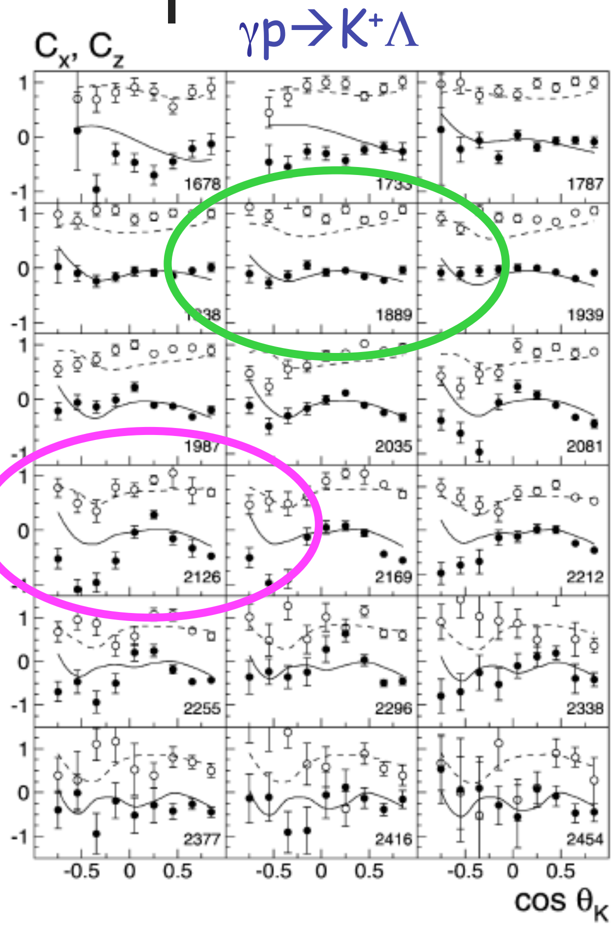
Bonn-Gatchina 2014 model was not predictive in newly-measured kinematics & observables:

The model is descriptive but not predictive: lots of high quality data needed to pin down the resonance content of the reaction.

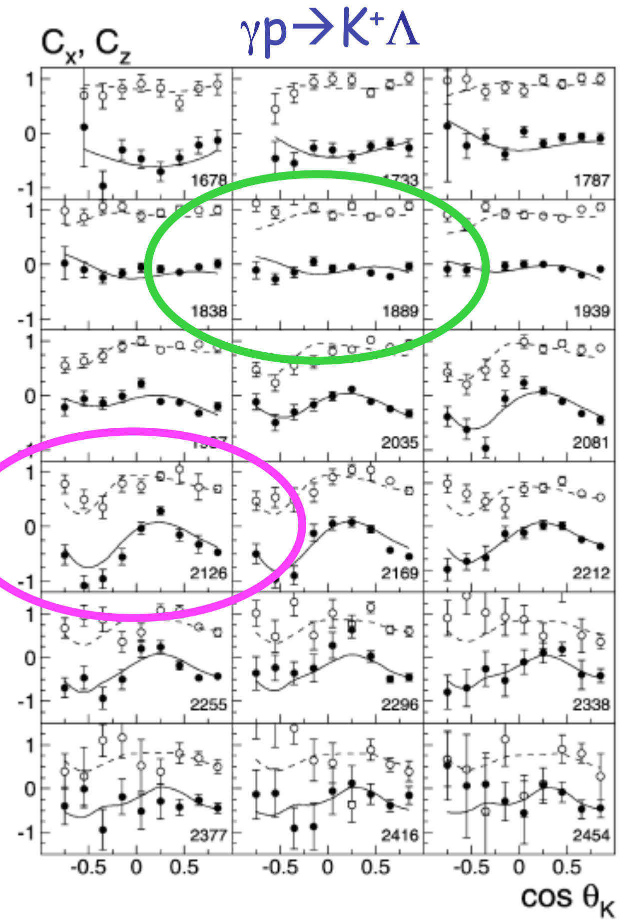
→ amplitudes now become more precisely defined !

C.A. Paterson et al. (CLAS Collaboration) to be published, 2016

$\vec{\gamma} p \to K^+ \vec{\Lambda}$ Beam-Recoil C_x and C_z

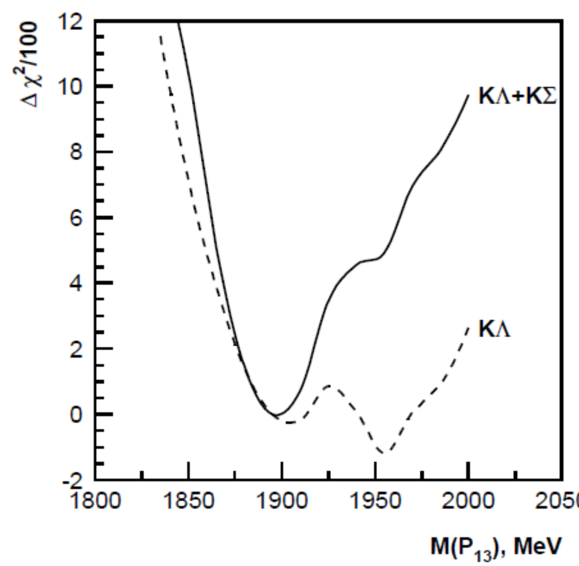


C_xC_z without N*(1900)P_{13}



C_xC_z with N*(1900)P_{13}

- Nikanov *et al.*'s refit of Bonn-Gatchina coupled-channel isobar model
- mix includes: S_{11}-wave, $P_{13}(1720)$, $P_{13}(1900)$, $P_{11}(1840)$
- $K^+\Sigma^0$ cross sections also better described with $P_{13}(1900)$



R. Bradford *et al.*, (CLAS Collaboration) Phys. Rev. C **75**, 035205 (2007).
V. A. Nikanov *et al.*, Phys Lett. B **662**, 246 (2008).
see also: A.V. Anisovich *et al.*, Eur. Phys J. A **25** 427 (2005).

CLAS Output vs. the World

TABLE II. Measurements performed by the different experiments.

Experiment	Ref(s)	Final State	W range (GeV)	Σ	P	C_x	C_z	T	O_x	O_z
CLAS g11	[12]	$K\Lambda$	1.62–2.84		⋆					
	[13]	$K\Sigma^0$	1.69–2.84		⋆					
CLAS g1c	[9, 11]	$K\Lambda$	1.68–2.74		⋆	⋆	⋆			
	[9, 11]	$K\Sigma^0$	1.79–2.74		⋆	⋆	⋆			
LEPS	[14]	$K\Lambda$	1.94–2.30	⋆						
	[14]	$K\Sigma^0$	1.94–2.30	⋆						
GRAAL	[15, 16]	$K\Lambda$	1.64–1.92	⋆	⋆			⋆	⋆	⋆
	[15]	$K\Sigma^0$	1.74–1.92	⋆	⋆					
CLAS g8		$K\Lambda$	1.71–2.19	⋆	⋆			⋆	⋆	⋆
		$K\Sigma^0$	1.75–2.19	⋆	⋆			⋆	⋆	⋆

Spin Observables with linear and circular polarized photons

Hyperon recoil polarization components are easy to measure: competitive advantage over non-strange baryon channels

C.A. Paterson et al. (CLAS Collaboration) submitted for publication , 2016

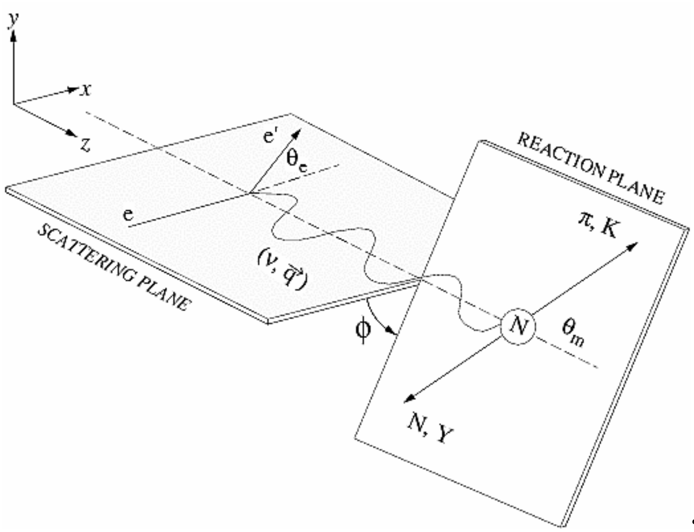
Lots more could be said…

- Omit results for Σ photoproduction
- Omit discussion of photoproduction reactions on the neutron (deuteron), which accesses the isospin dependence of photon coupling.

Strangeness and the N* Spectrum of States - Electroproduction

Structure Functions

For unpolarized target & polarized e⁻ beam:



$$\frac{d^4\sigma}{dQ^2 dW\, d\Omega_K} = \Gamma(Q^2, W) \times \frac{d\sigma}{d\Omega_K}\left(Q^2, W, \Theta_K, \varepsilon, \phi\right)$$

Virtual photon flux

Meson cross section

$$\frac{d\sigma}{d\Omega_K} = \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \cos(2\phi) + \sqrt{2\varepsilon_L(\varepsilon+1)}\,\sigma_{LT} \cos(\phi) + h\sqrt{2\varepsilon_L(1-\varepsilon)}\,\sigma_{LT'}$$

Transverse

Transverse-transverse interference

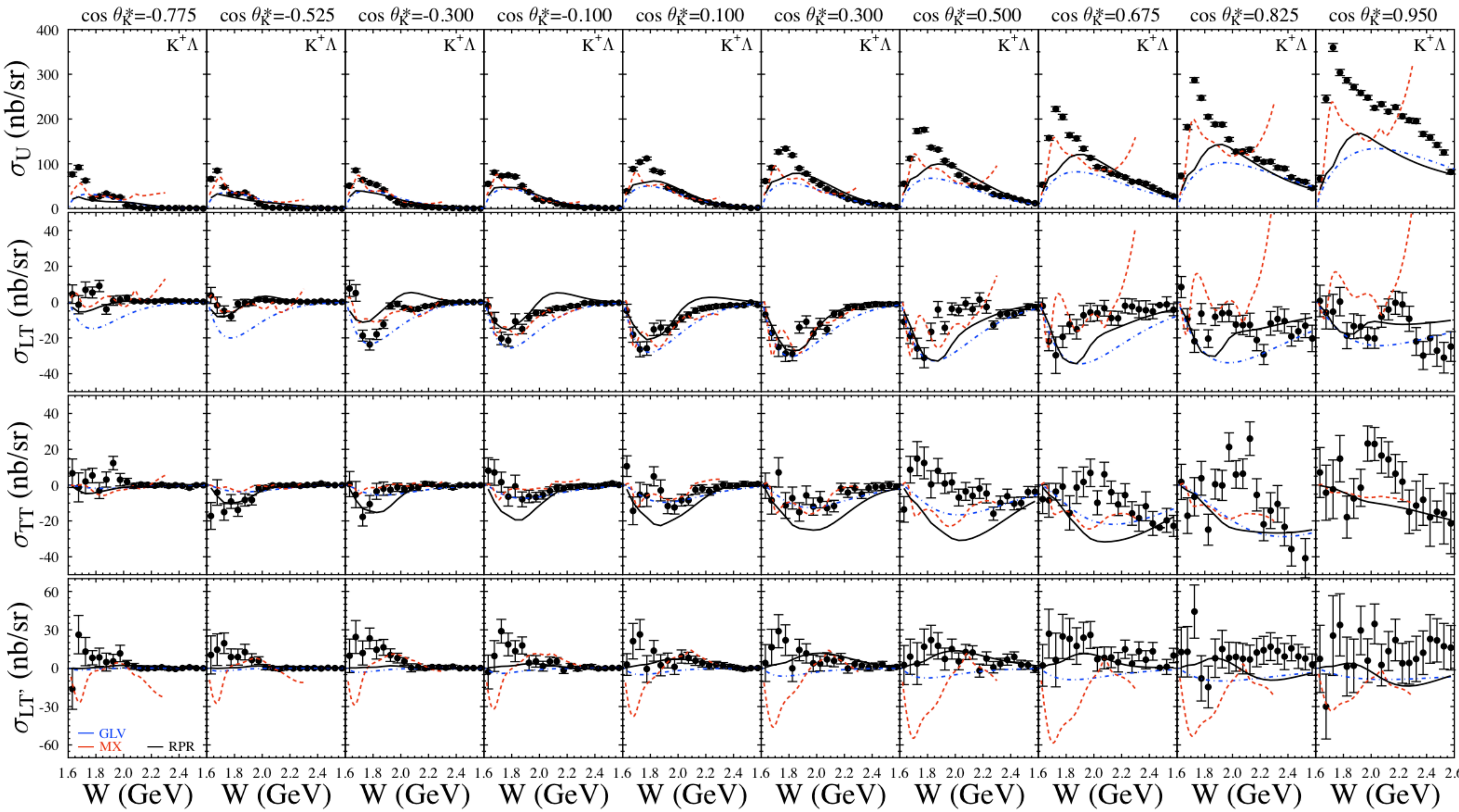
Helicity structure

σ_u
"Unseparated"

Longitudinal (sensitive to J=0± exchange in t-channel: kaons, diquarks)

Transverse-longitudinal interference

K⁺Λ Structure Functions



E = 5.5 GeV, W: thr – 2.6 GeV, Q² = 1.80, 2.60, 3.45 GeV² [Carman *et al.*, PR C **87**, 025204 (2013)]

CLAS *ep* Data Set Overview

#	Period	E_b (GeV)	Events (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 polarization
  - *W=1.6-2.7 GeV, $\langle Q^2\rangle$=1.9 GeV^2*
    [Gabrielyan *et al.*, PR C **90**, 035202 (2014)]

Publications:

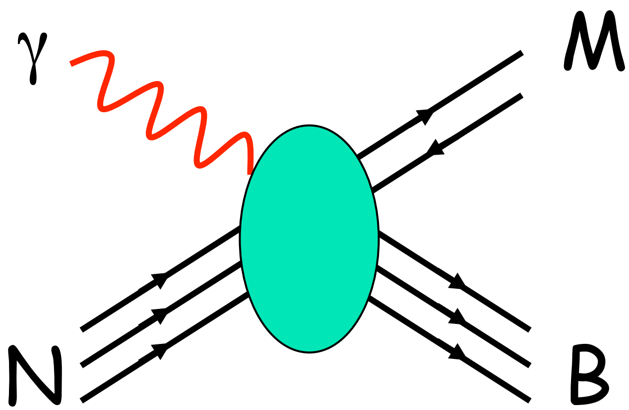
- $K^+\Lambda$ beam-recoil pol. transfer
  - *W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2*
    [Carman *et al.*, PRL **90**, 131804 (2003)]
- $K^+\Lambda$ σ_L/σ_T ratio from pol. transfer data
  - *W=1.72-1.98 GeV, Q^2~0.7 GeV^2*
    [Raue & Carman, PR C **71**, 065209 (2005)]
- $K^+\Lambda$, $K^+\Sigma^0$ separated 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.*, PR C **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.*, PR C **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.*, PR C **79**, 065205 (2009)]

Dimensional Scaling of $K\Lambda$

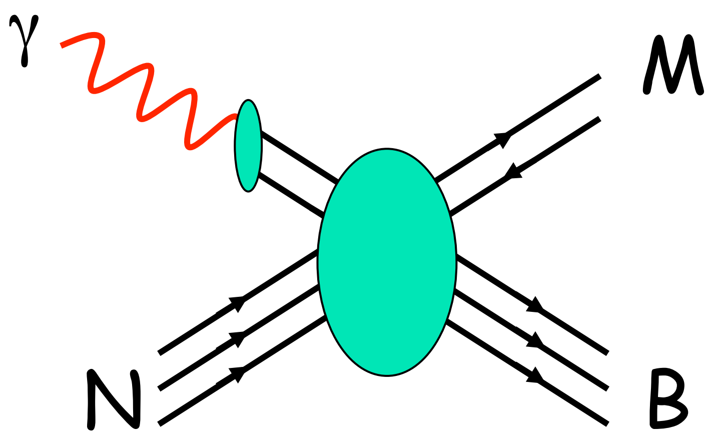
Publication: Scaling and Resonances in Elementary $K^+\Lambda$ Photo-production, R.A.Sch. and M.M. Sargsian Phys.Rev.C**83** 025207 (2011).

Constituent-Counting Scaling

$$\frac{d\sigma}{dt} = f\left(\frac{t}{s}\right)s^{2-n}$$



n=9

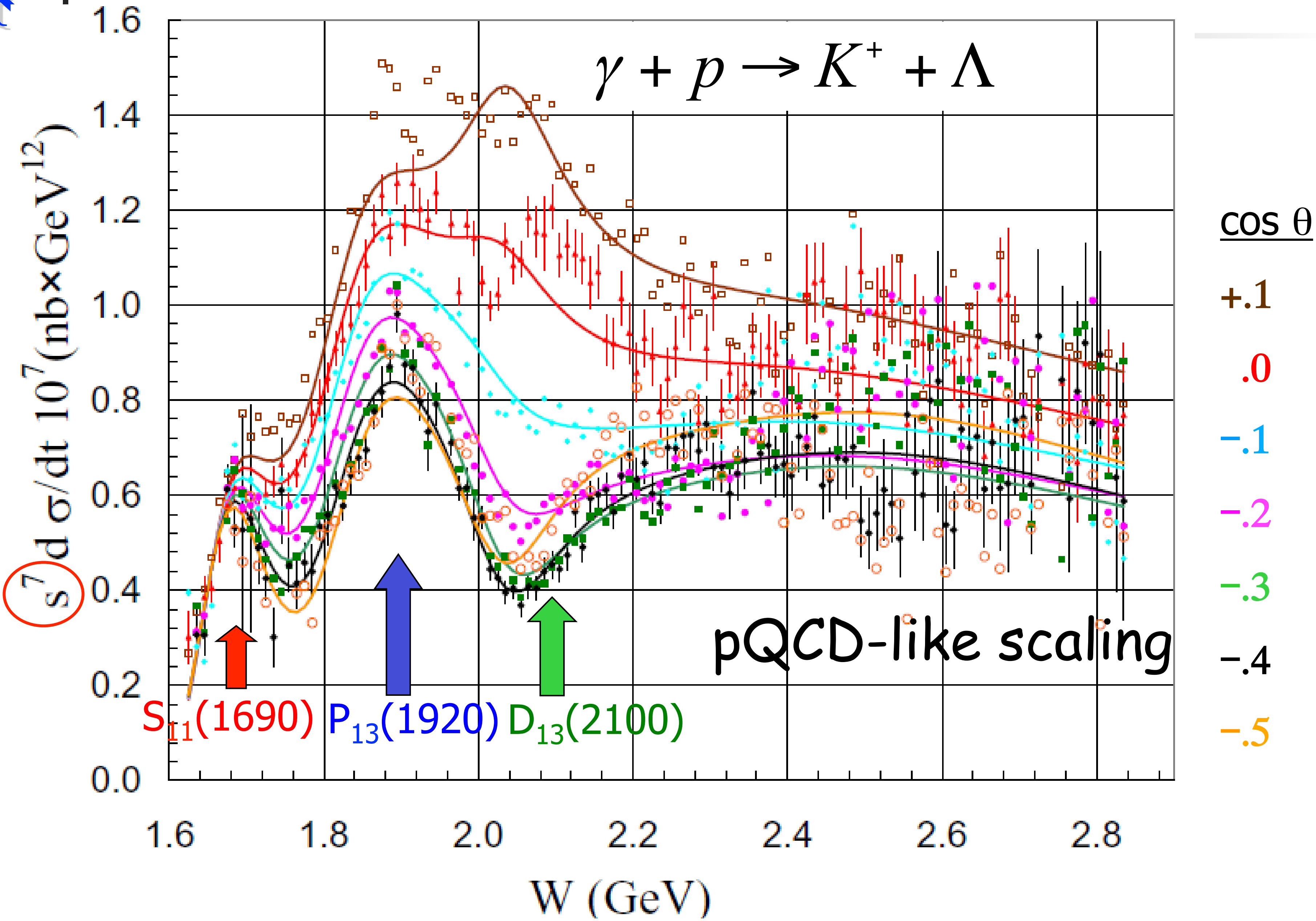


n=10

- Constituent counting rules for exclusive scattering
- Valid for $s \to \infty$ and t/s fixed
  - $t/s \sim \cos(\theta_{cm})$ as $s \to \infty$
- n = number of point-like constituents
- Follows from pQCD… but also other models
- Does it work for $K\Lambda$?

S. J. Brodsky and G. R. Farrar, PRL **31**, 1153 (1973)

Resonance Fit to Scaled Cross Section

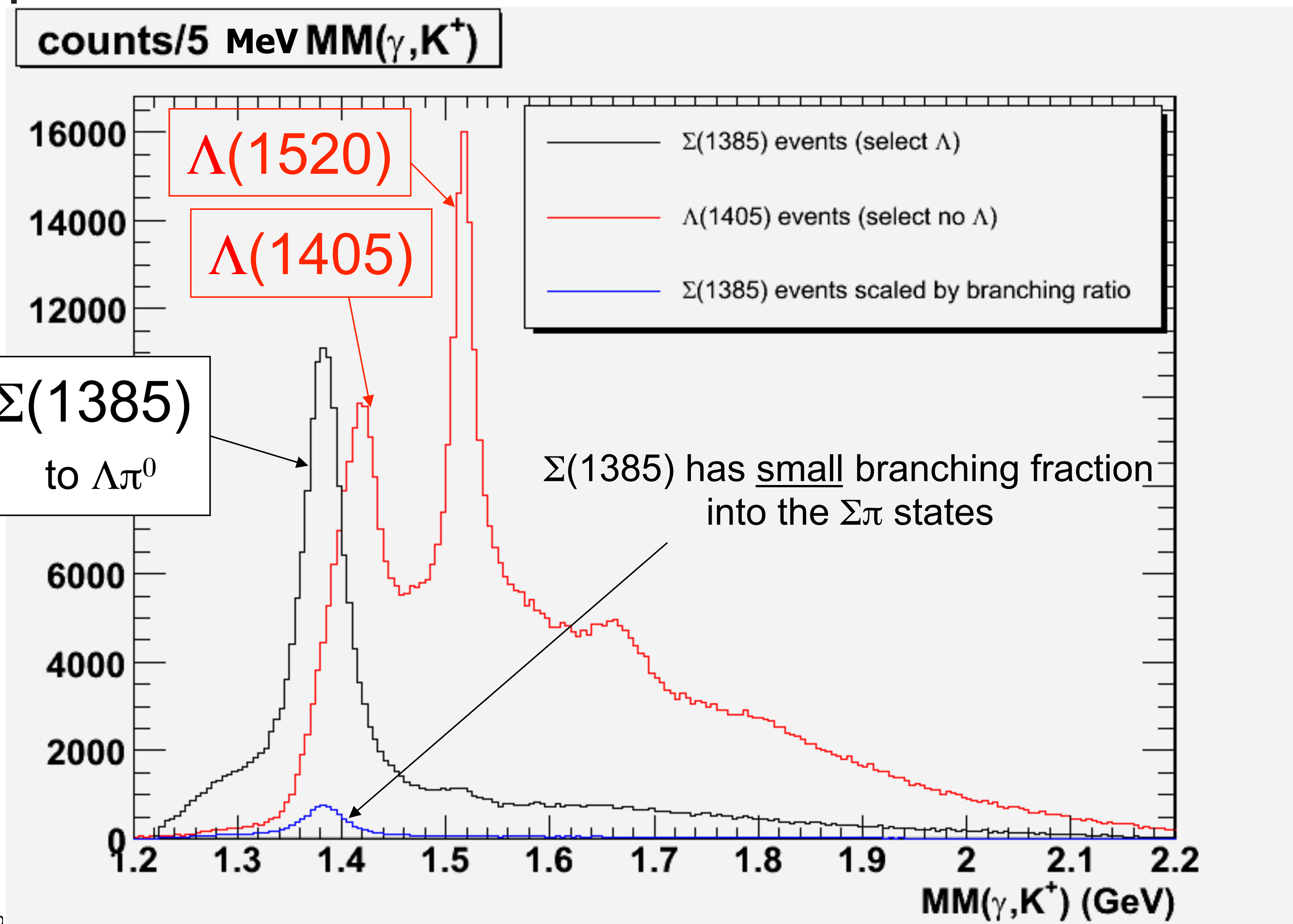


R.A. Sch. and M.M. Sargsian Phys. Rev. C **83** 025207

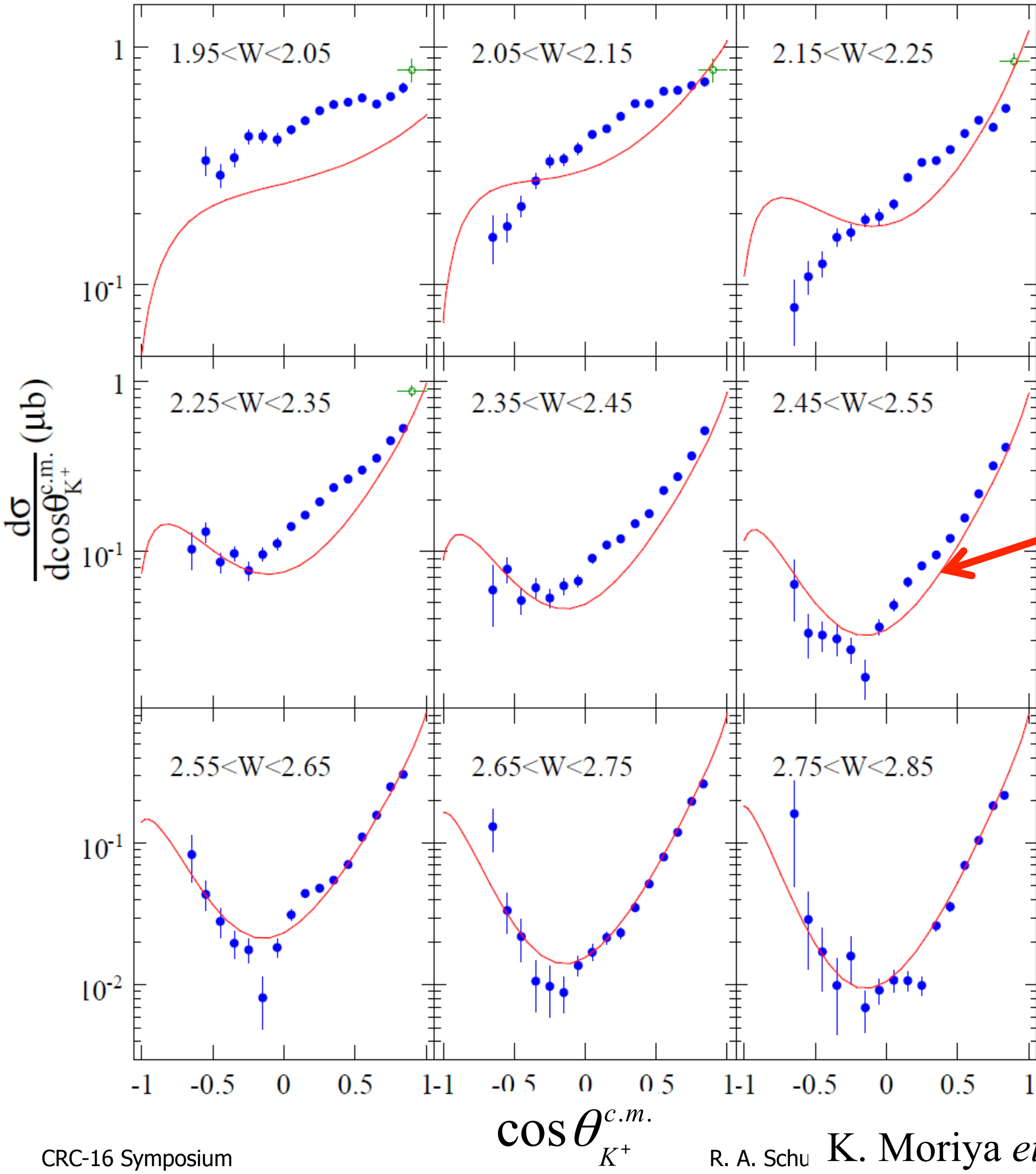
Excited Y* Cross Sections

Publication: Differential Photoproduction Cross Sections of $\Sigma^0(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$, K. Moriya *et al.* (CLAS Collaboration), Phys. Rev. C **88**, 045201 (2013).

Detect $K^+ p\pi^-(\pi^0)$ or $K^+\pi^+\pi^-(n)$



Differential $\Sigma^0(1385)$ Cross Section

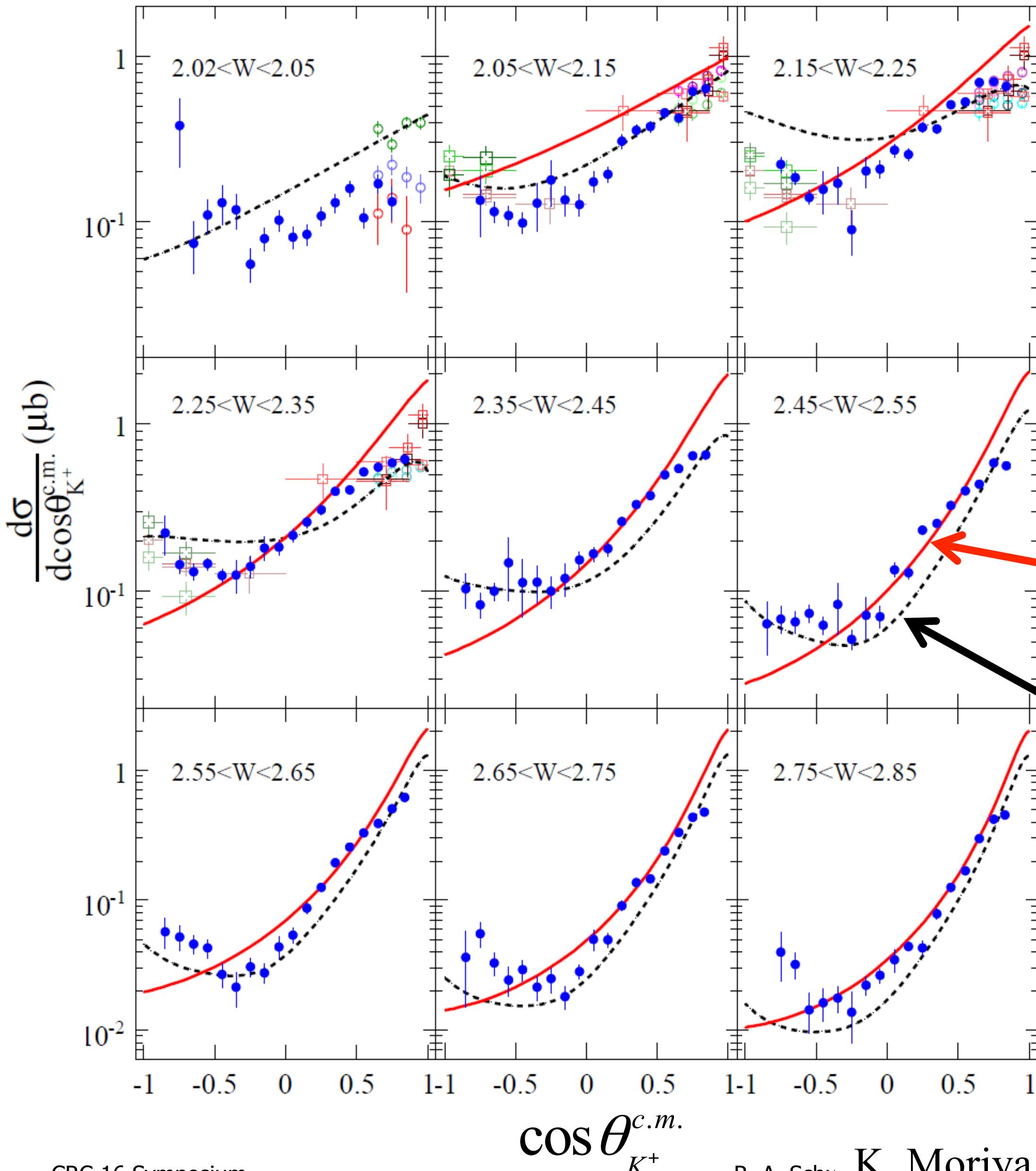


- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
- Experiment: see t-channel-like forward peaking & u-channel backward rise
  - Agreement with LEPS
- Theory by Oh et al.[1]: contact term dominant; included four high-mass N^* and Δ resonances
  - Prediction was fitted to preliminary CLAS total cross section (years ago)

1. Y. Oh, C. M. Ko, K. Nakayama, Phys. Rev. **C 77**, 045204 (2008)

K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

Differential Λ(1520) Cross Section

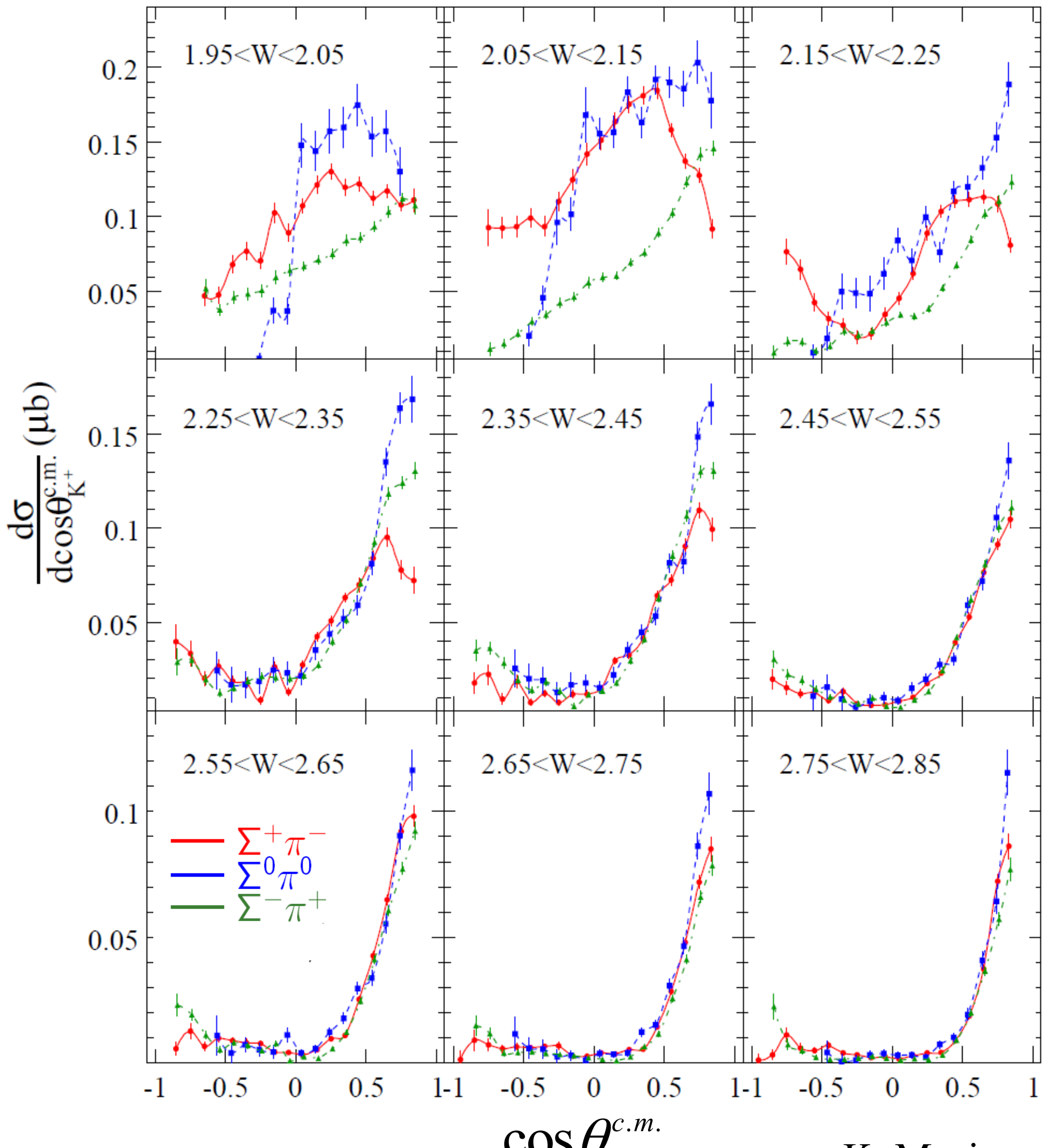


- $\gamma + p \rightarrow K^+ + \Lambda(1520)$
- Experiment: see t-channel-like forward peaking & u-channel backward rise
  - Agreement with LEPS[1,2]
- Theories:
  - Nam & Kao[3]: contact term dominant; no K^* or u-channel exchanges
  - He & Chen[4]: K^* and $N(2080)D_{13}$ $J^P=3/2^-$ added

1. H. Kohri et al. (LEPS) Phys Rev Lett **104**, 172001 (2010)
2. N. Muramatsu et al. (LEPS) Phys Rev **103**, 012001 (2009)
3. S.I. Nam & C.W. Kao, Phys. Rev. **C 81**, 055206 (2010)
4. J. He & X.R. Chen, Phys. Rev. **C 86**, 035204 (2012)

K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

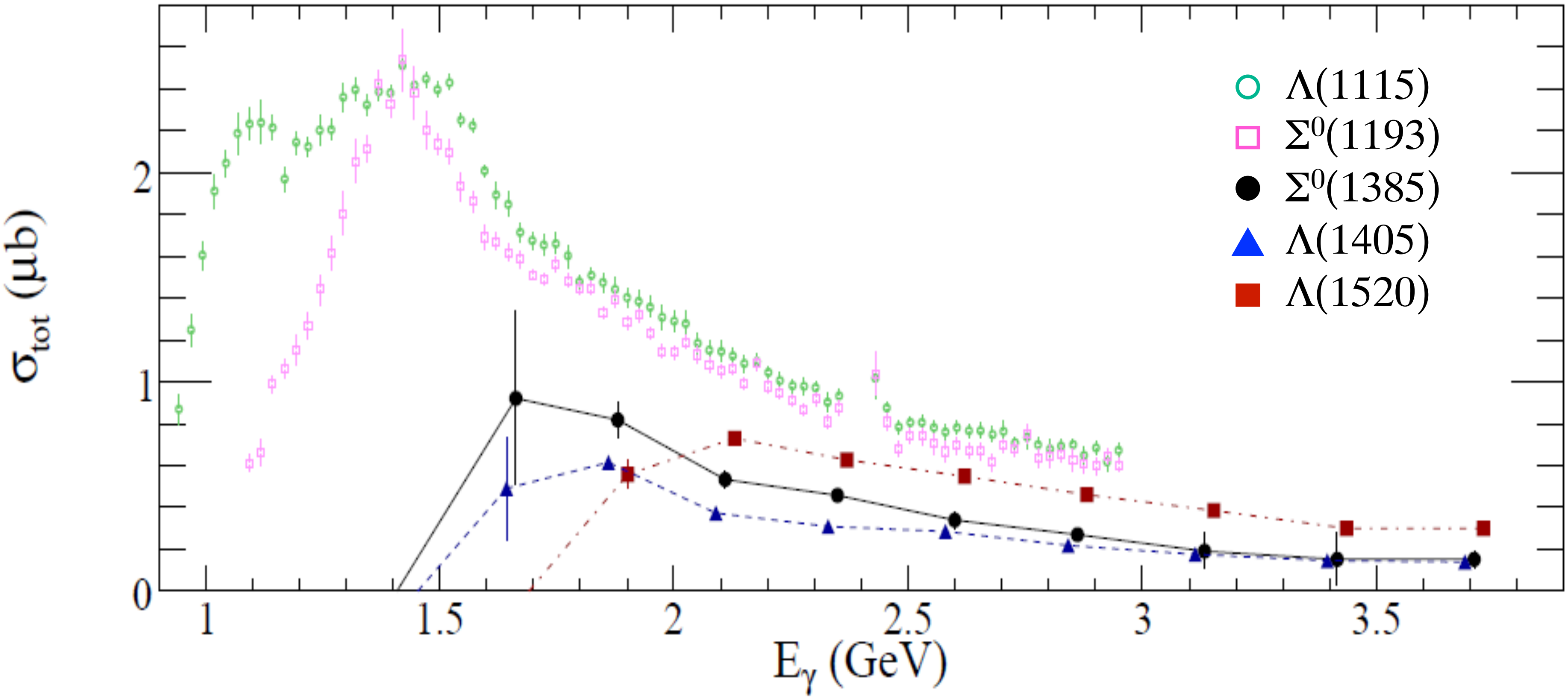
Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Experiment: first-ever measurements
- Low W: See strong isospin dependence
  - Charge channels differ
  - WHY?!?
- High W: See t-channel-like forward peaking & u-channel backward rise at high W
- Channels merge together at high W

K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

Total Cross Sections Comparison



- $\gamma + p \rightarrow K^+ + Y^{(*)}$
- All three Y^*s have similar total cross sections
- Ground state Λ and Σ^0 are comparable to Y^* in size[1]

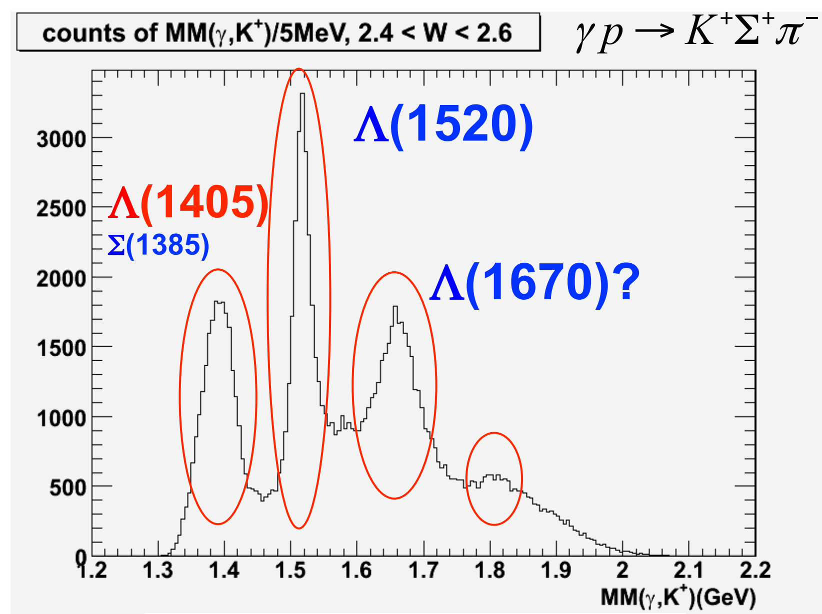
1. R. Bradford et al. (CLAS) Phys. Rev. **C 73**, 035202 (2006)
K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

$\Lambda(1405)$ Structure

Publications: Measurement of the $\Sigma\pi$ Photo-production Line Shapes Near the $\Lambda(1405)$, K. Moriya *et al.* (CLAS Collaboration), Phys. Rev. C **87**, 035206 (2013);
Isospin Decomposition of the Photoproduced $\Sigma\pi$ System near the $\Lambda(1405)$, R. A. Sch. & K. Moriya, Nucl. Phys A **914**, 51 (2013) .

What "is" the Λ(1405)?

- An issue since its prediction/discovery
  - Dynamically generated resonance, via unitary meson-baryon channel coupling
    - R. Dalitz & S.F.Tuan, Phys. Rev. Lett. **2**, 425 (1959), Ann. Phys. **10**, 307 (1960).
    - Chiral unitary models (present-day theoretical industry!)
  - SU(3) singlet 3q state, $\mathrm{I} = 0, J^P = ½^-$
  - $\bar{K}N$ sub-threshold state
    - Recent first Lattice QCD result: J. Hall *et al.*, Phys Rev Lett **114**, 132002 (2015)
  - Signal may be a mix of $\mathrm{I} = 0$ and $\mathrm{I} = 1$ states



(γ,K) Missing Mass (GeV)

Chiral Unitary Models

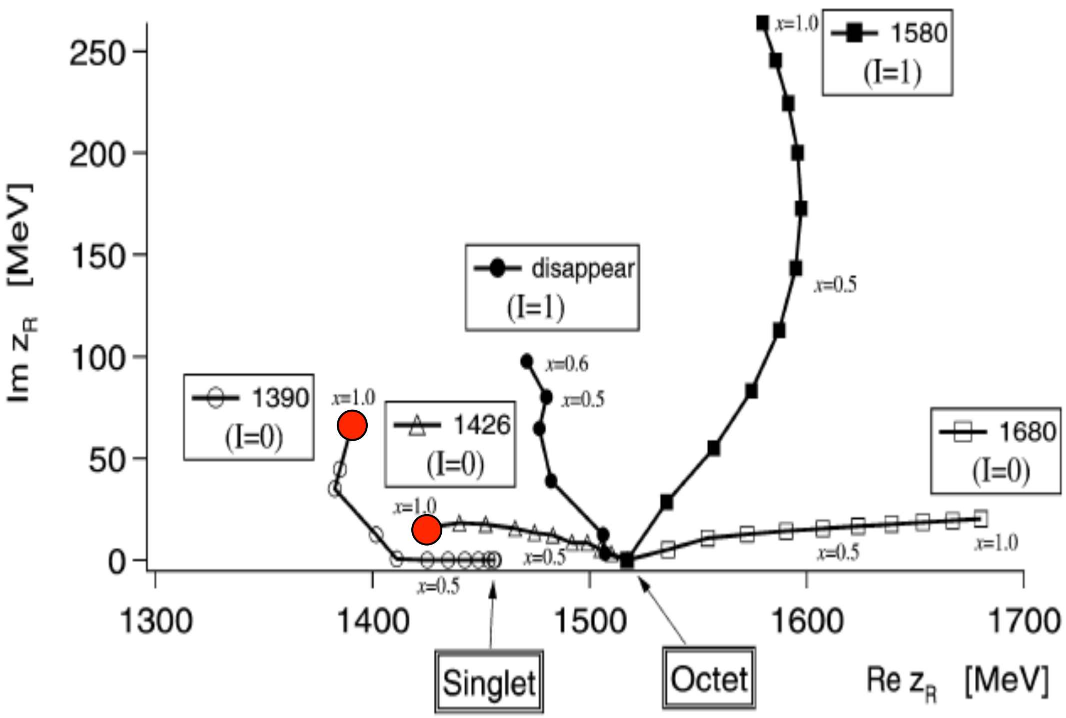
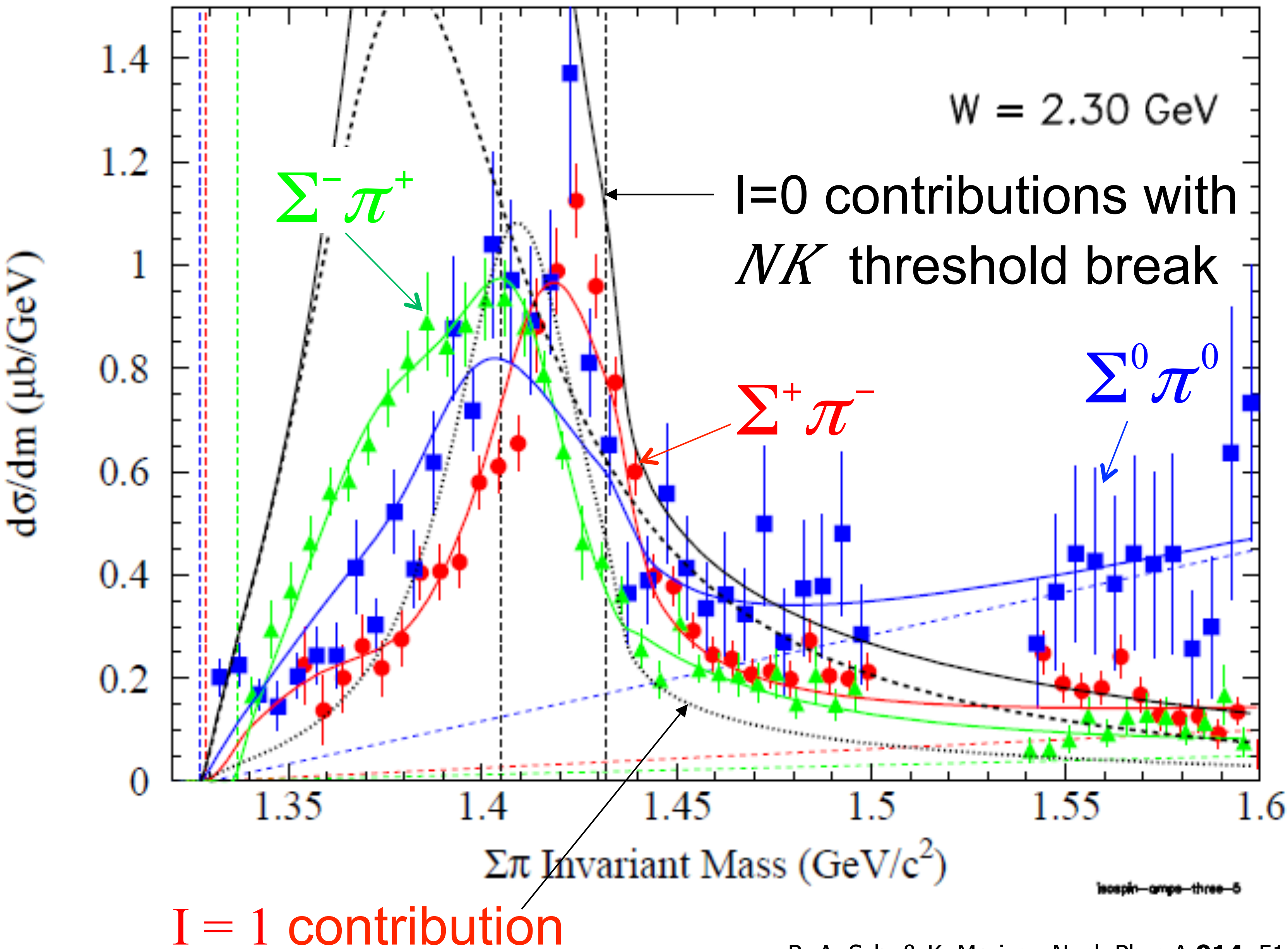


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

- SU(3) baryons irreps $1+8_s+8_a$ combine with 0^- Goldstone bosons to generate:
- Two octets and a singlet of $\frac{1}{2}^-$ baryons generated dynamically in SU(3) limit
- SU(3) breaking leads to two $S=-1$ $I=0$ poles near 1405 MeV
  - ~1420 mostly KN
  - ~1390 mostly $\pi\Sigma$
- Possible weak $I=1$ pole also predicted

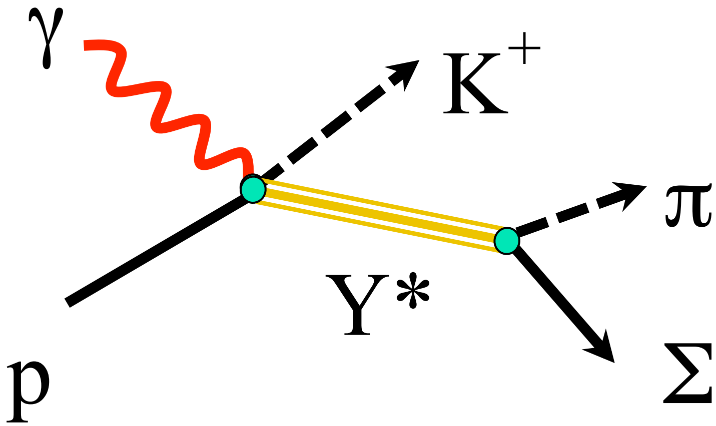
D. Jido, J.A. Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A **725,** 181 (2003)
J.A. Oller, U.-G. Meissner Phys. Lett B **500**, 263 (2001).

Example at W=2.30 GeV



R. A. Sch. & K. Moriya, Nucl. Phys A **914**, 51 (2013)

Isospin Interference



Final Σ π state

$$\left|I, I_3\right\rangle = \left|0,0\right\rangle, \left|1,0\right\rangle$$

$$|t_I|^2 \equiv |\langle I, 0|\hat{T}^{(I)}|\gamma p\rangle|^2$$

Three charge combinations:

$$|T_{\pi^-\Sigma^+}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 - \frac{2}{\sqrt{6}}|t_0||t_1|\cos\phi_{01},$$

$$|T_{\pi^0\Sigma^0}|^2 = \frac{1}{3}|t_0|^2,$$

$$|T_{\pi^+\Sigma^-}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 + \frac{2}{\sqrt{6}}|t_0||t_1|\cos\phi_{01}.$$

What "is" the $\mathrm{I} = 1$ piece?

- $\mathrm{I} = 1$ resonance? $\mathrm{I} = 1$ continuum amplitude?
- L. Roca and E. Oset model[1]:
  - Possible $\mathrm{I}=1$ resonance in vicinity of $N\bar{K}$ threshold
- B.-S. Zou et al. model[2]:
  - $\Sigma\left(\frac{1}{2}\right)^{-}$ is a $\left|[ud][us]\bar{s}\right\rangle$ state: part of a new nonet
- No interference seen in $\Lambda(1520)$ mass range: therefore it's not a continuum amplitude
- More investigation needed ! Can BGO-OD do this?

1. L. Roca, E. Oset "On the isospin 0 and 1 resonances from $\pi\Sigma$ photoproduction data" Phys. Rev. C **88** 055206 (2013).
2. Bing-Song Zou "Five-quark components in baryons", Nucl Phys A 835 199 (2010).

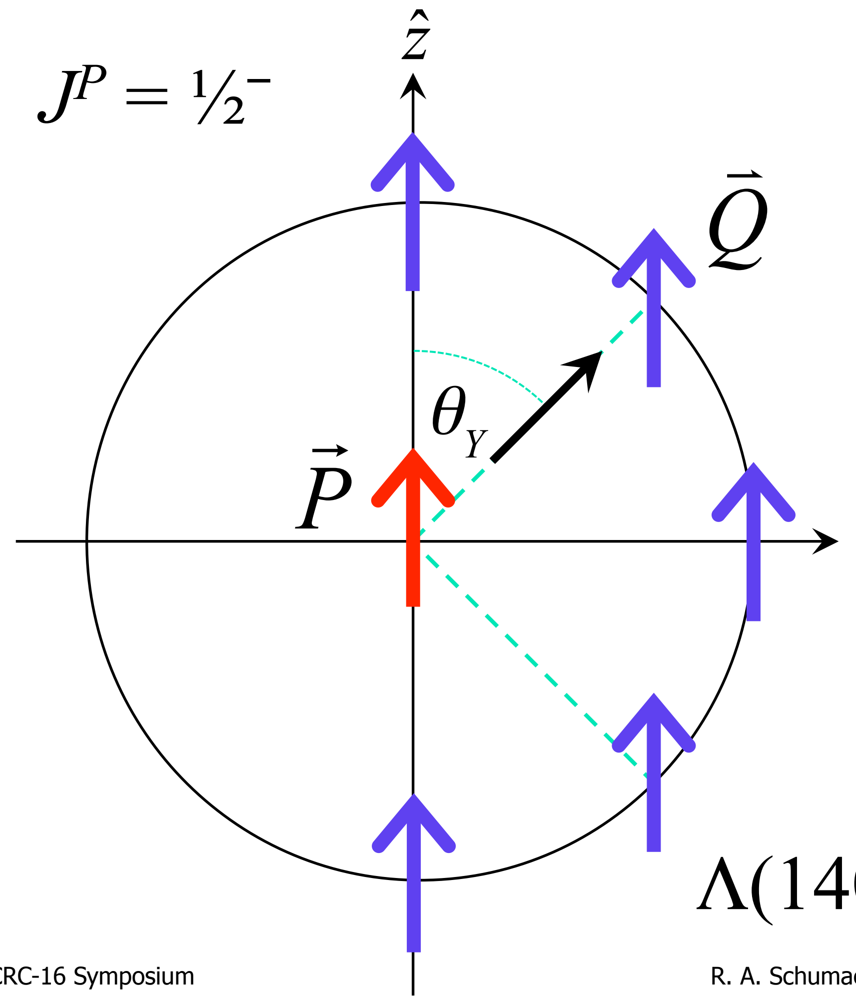
Spin and Parity of $\Lambda(1405)$

Publication: Spin and Parity of the $\Lambda(1405)$ Baryon, K. Moriya *et al.* (CLAS Collaboration), Phys. Rev. Lett. **112**, 082004 (2014).

S-wave, P-wave Scenarios

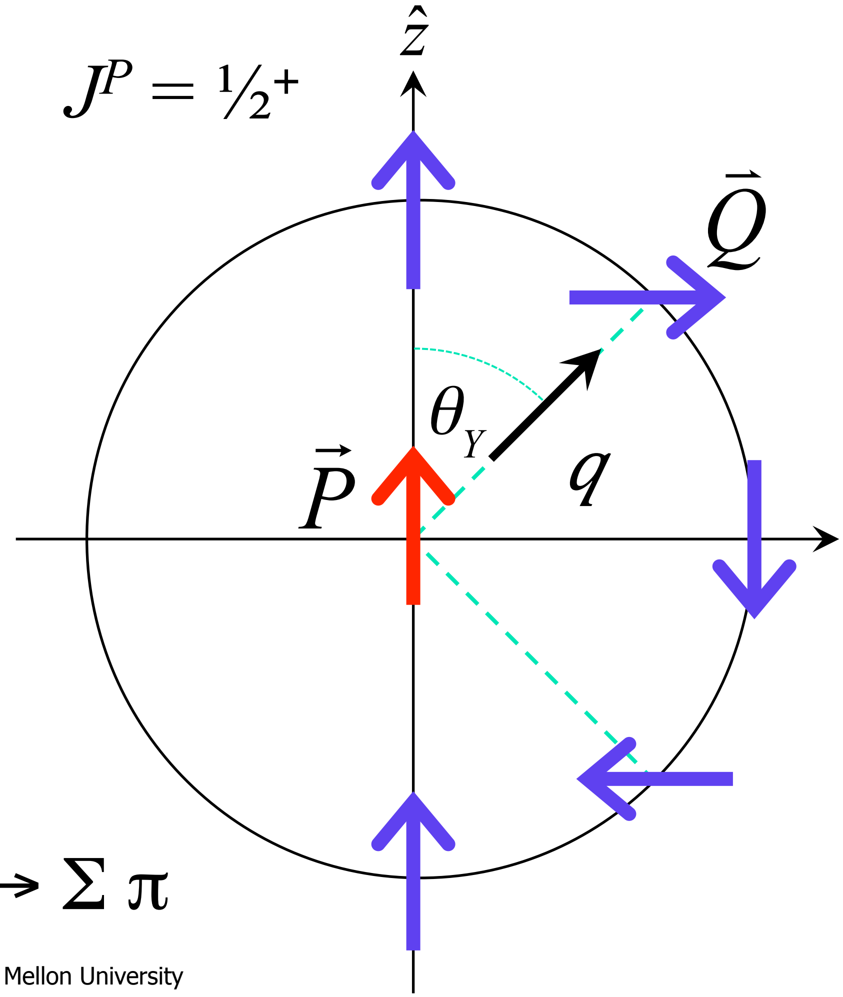
L=0 (s-wave)

$$\vec{Q} = \vec{P}$$



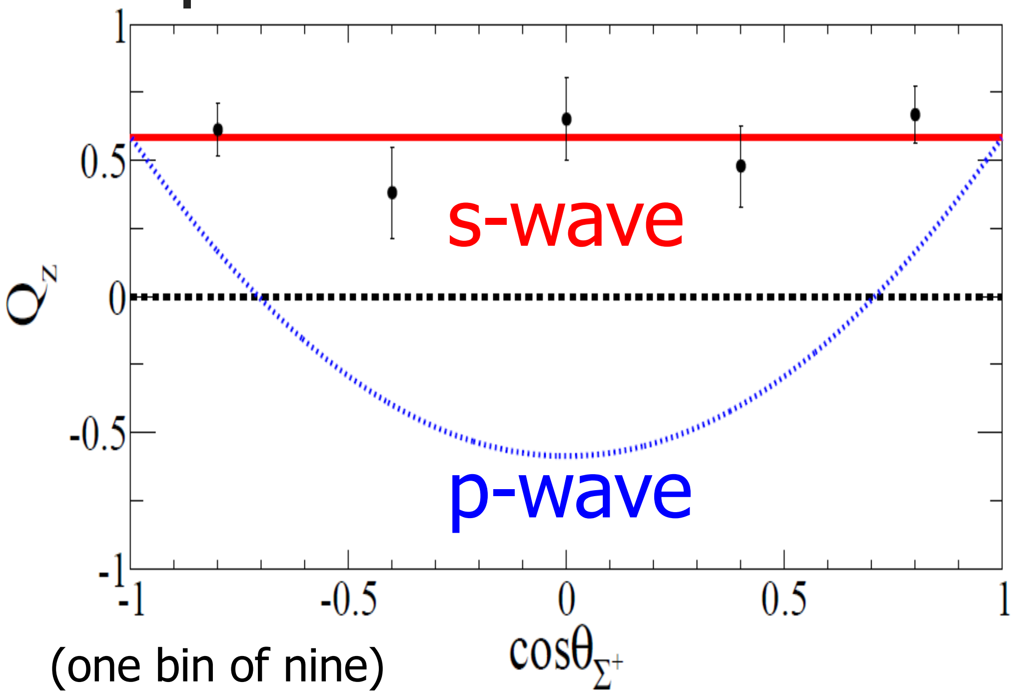
L=1 (p-wave)

$$\vec{Q} = -\vec{P} + 2(\vec{P} \bullet \hat{q})\hat{q}$$



$$\Lambda(1405) \rightarrow \Sigma\,\pi$$

Parity and Spin of $\Lambda(1405)$



(one bin of nine)

- Polarization axis is along $\hat{z} = \hat{\gamma} \times \hat{K}$
- Used W = 2.35 to 2.85 GeV, $\cos\theta_K^{c.m.} > 0.6$
- Decay $\Lambda(1405) \to \Sigma^+ \pi^-$ is isotropic (p=0.5), so $J \to 1/2$
- Weak decay asymmetry for Σ^+ is $\alpha = -0.98$ (big!)
- Decay is s-wave,

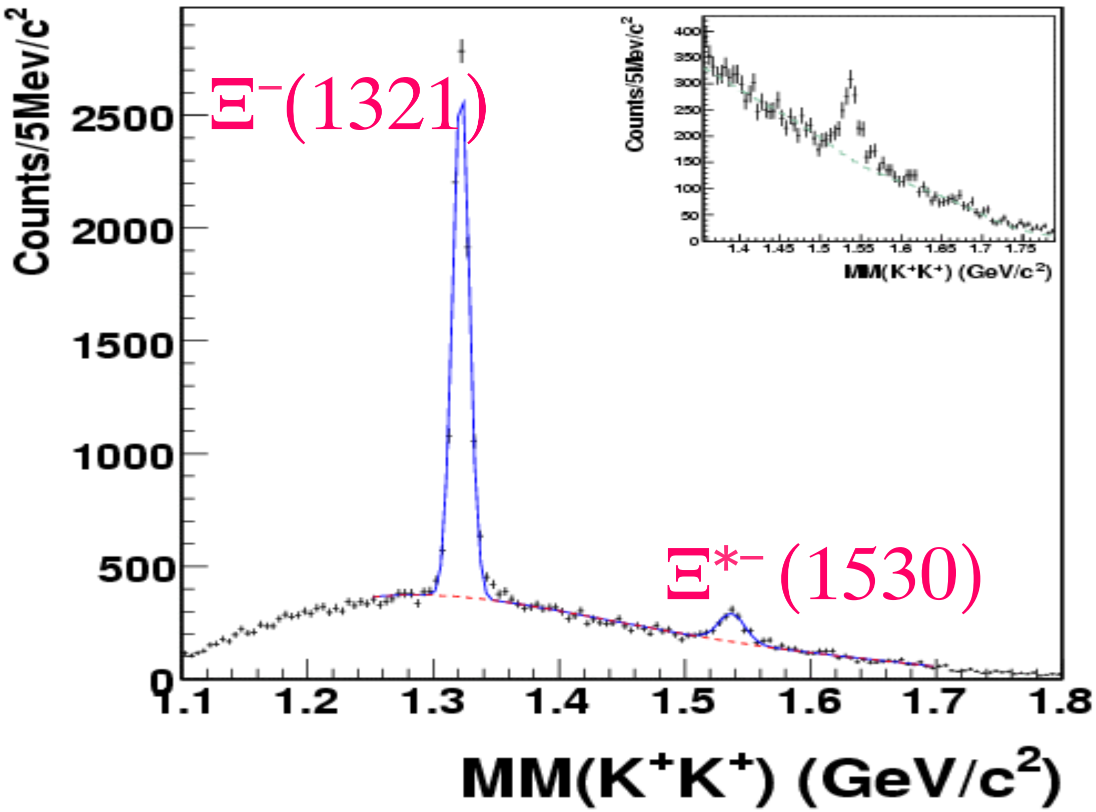
$$\Rightarrow P = \text{"}negative\text{"}$$

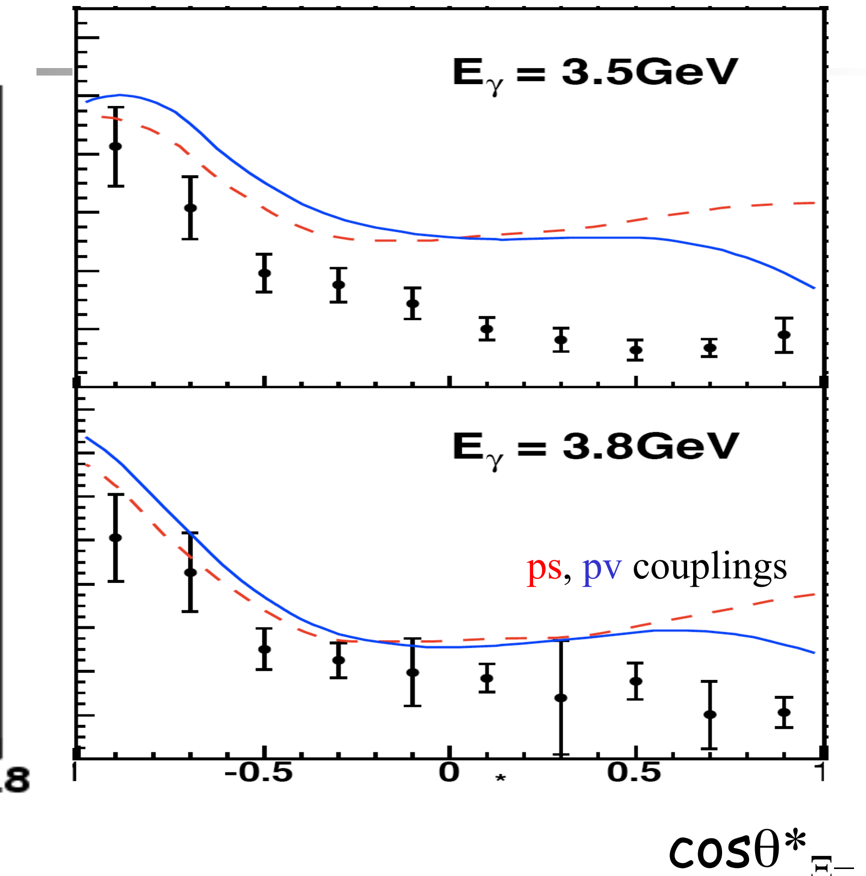
$J^P = ½^-$ confirms quark model expectation

and the $\Lambda(1405)$ is produced ~ +45% polarized

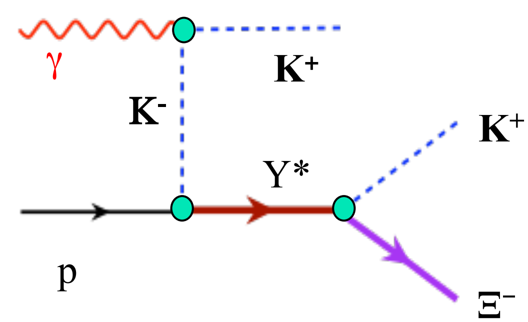
Strangeness -2: Where are the Excited Cascades?

$\Xi^{-(*)}$ Production: $S = -2$ physics





- Detect via $\gamma\, p \rightarrow K^+K^+(\Xi^-)$
- Only two narrow states seen: $\Xi(1321)$, $\Xi(1530)$
- Other states? Failed searches (g12 group)…



L. Guo et.al. Phys Rev C **76** 025208 (2007)

J. Goetz UCLA thesis, 2010

CLAS/g12 data set

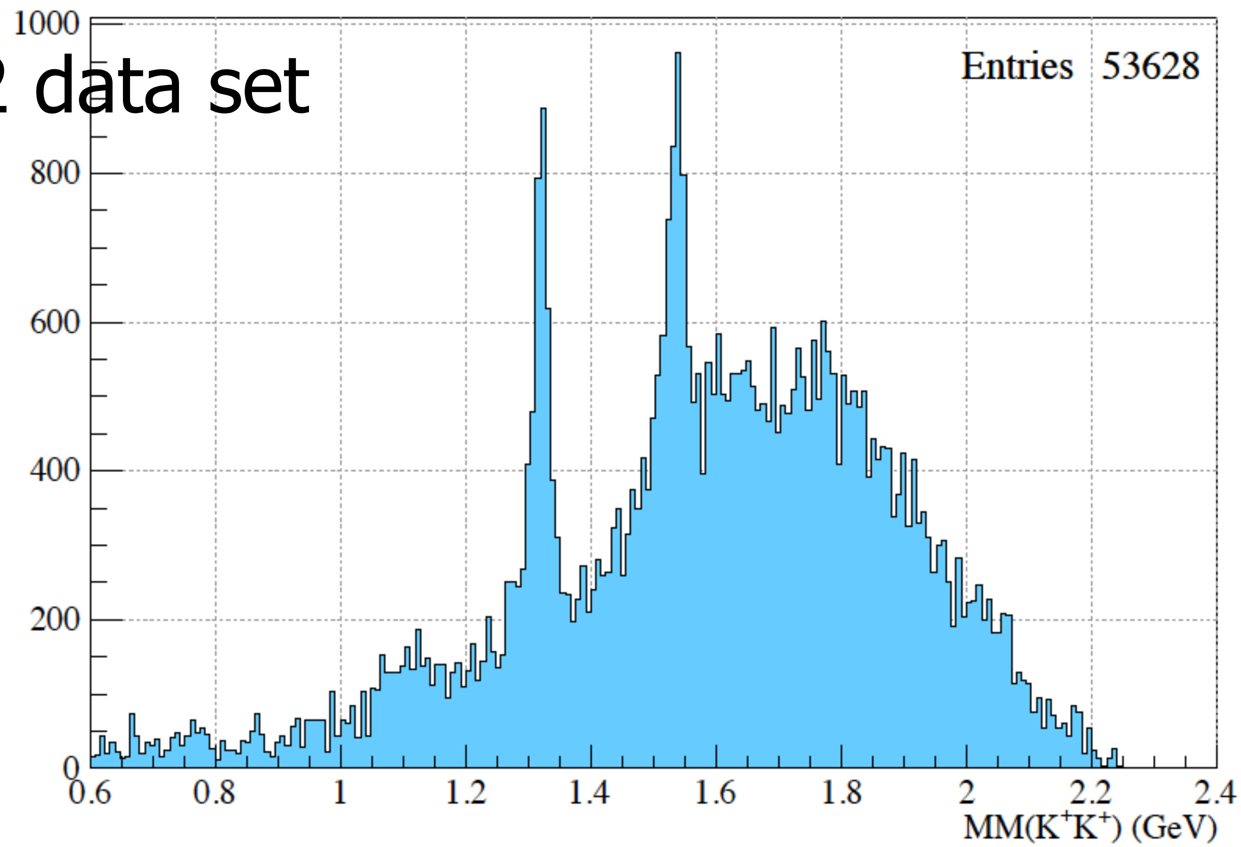
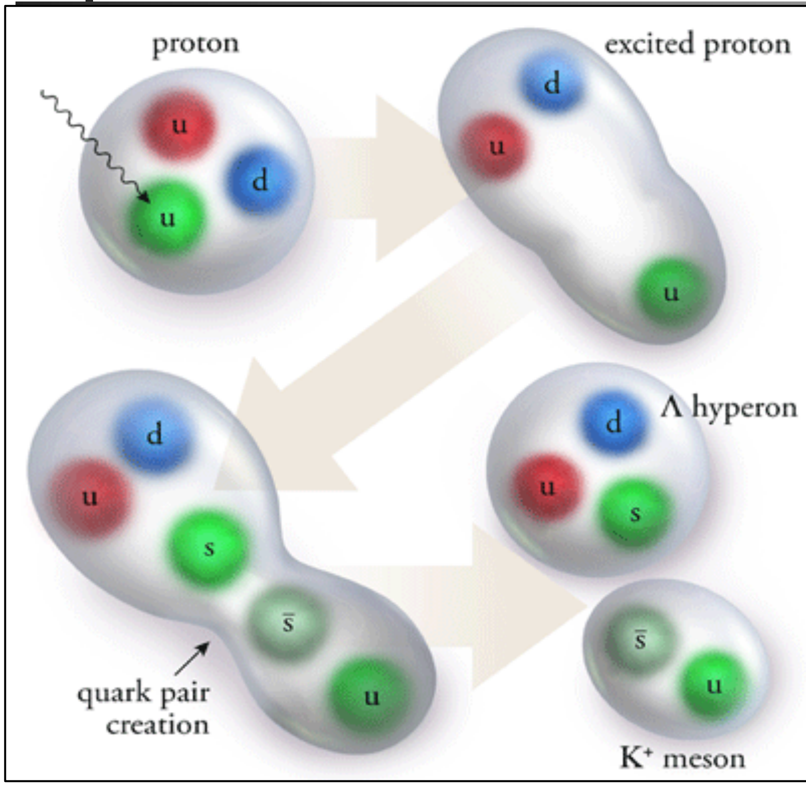


Figure 3.39: Missing mass off K^+K^+ in the reaction $\gamma p \rightarrow K^+K^+\pi^0 X^-$ with cuts as described in Tables 3.2 and 3.3. The $\Xi^-(1320)$ and $\Xi^-(1530)$ signals peak at 1320.9 ± 0.4 and 1535.3 ± 0.6 MeV.

Strangeness Suppression in $q\bar{q}$ Creation in Exclusive Reactions

Publication: M. D. Mestayer, K. Park *et al.* (CLAS Collaboration), Phys. Rev. Lett. **113**, 152004 (2014).

$K^+\Lambda : \pi^+n : \pi^0p$ Electroproduction Ratios



Ratio	$s\bar{s}$ / $d\bar{d}$	$u\bar{u}$ / $d\bar{d}$
$K^+\Lambda/\pi^+n$	0.19 ± 0.03	-
$K^+\Lambda/\pi^0p$	0.22 ± 0.07	-
$K^+\Lambda/\pi^0p$	0.28 ± 0.07	-
π^0p/π^+n	-	0.74 ± 0.18

- Motivation:
  - Quark model picture of quark-pair creation and flux-tube breaking: does it apply in the low-energy exclusive limit?
- Measurements:
  - Ratio of processes in which only one $q\bar{q}$ pair is produced: an $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$, respectively
  - In quark-model picture, meson ratios are proportional to the relative production rates of $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$
- Physics conclusion:
  - Ratio of $s\bar{s}$ pair creation relative to $u\bar{u}$ or $d\bar{d}$ is suppressed ~0.2 – 0.3
  - Consistent with high-energy results when 100's of particles are produced

The Future

JLab Hall B / CLAS12

Baseline equipment

Forward Detector (FD)

- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter

Central Detector (CD)

- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

Beamline

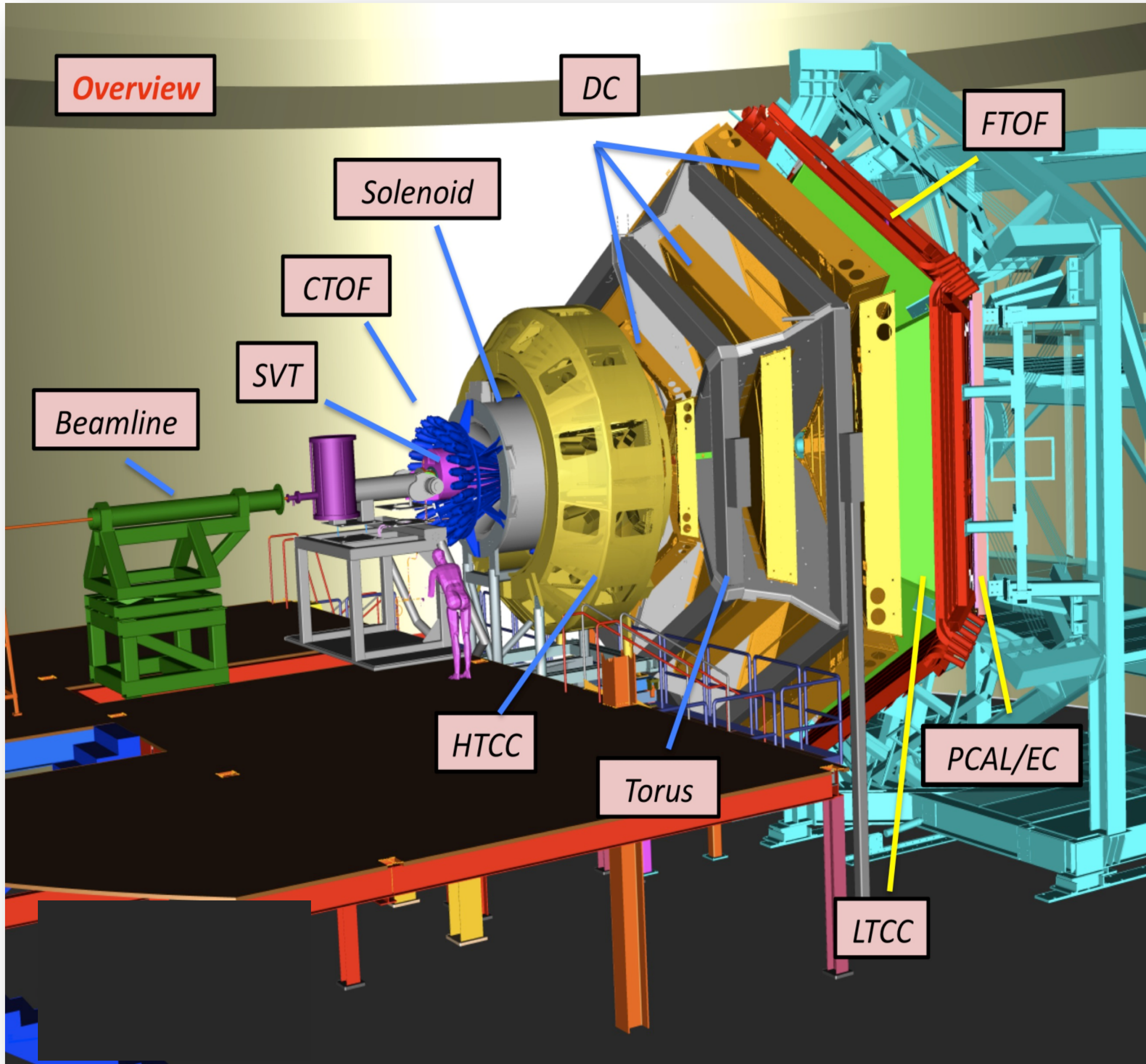
- Polarized target (transv.)
- Moller polarimeter
- Photon Tagger

Upgrades to the baseline

Under construction

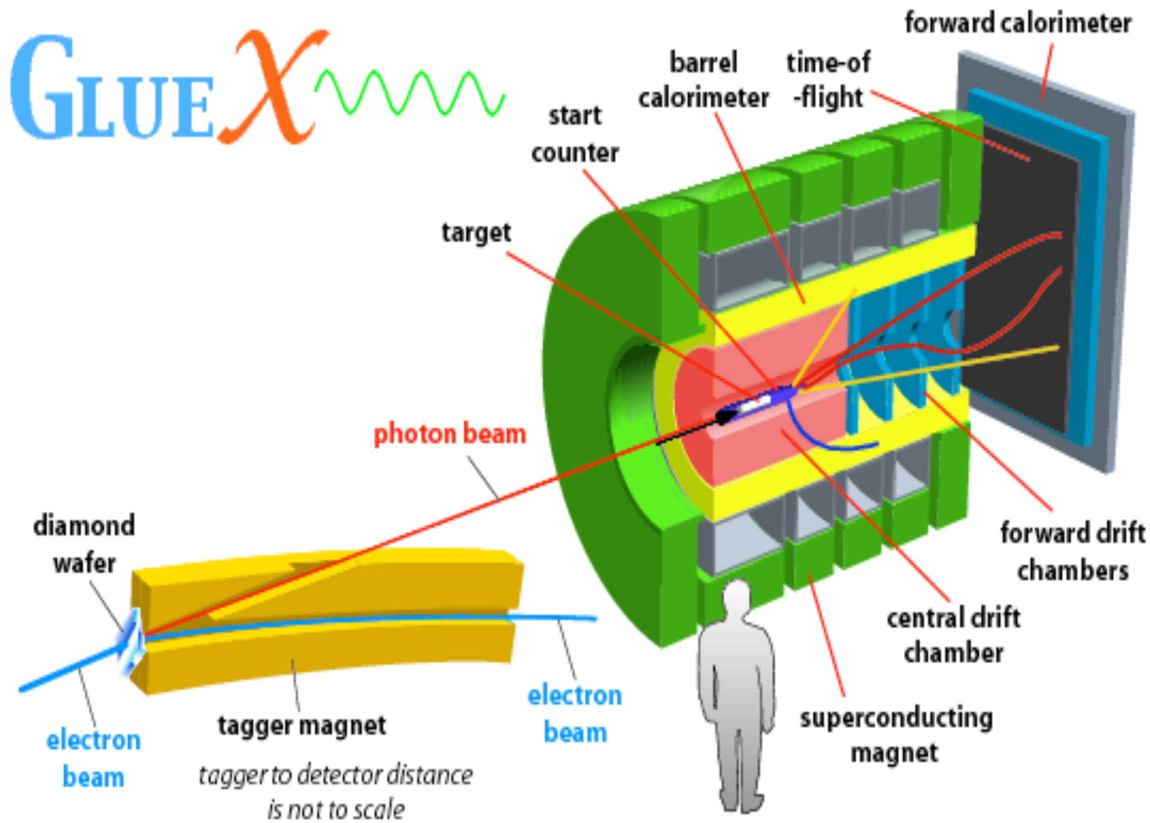
- MicroMegas
- Central Neutron Detector
- Forward Tagger
- RICH detector (1 sector)
- Polarized target (long.)

6/19/14



Jlab Hall D/GlueX

- Real photon beam centered at 9 GeV
- Liquid hydrogen target
- Reconstruct both charged and neutral particles over large angular range
- Hermetic detector within solenoid magnetic field
- Meson & Baryon spectroscopy: search for new and exotic states



Topics not addressed today:

- K* photoproduction
  - Publication: Cross Sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ Reactions, W. Tang, K. Hicks *et al.* (CLAS) Phys. Rev. C **87**, 065204 (2013).
- Hypernuclear electroproduction
  - Halls A & C, Nakamura, Hashimoto, Markowitz, Tang, et al.
- Reactions on neutron (deuteron) targets (g13, g14…)

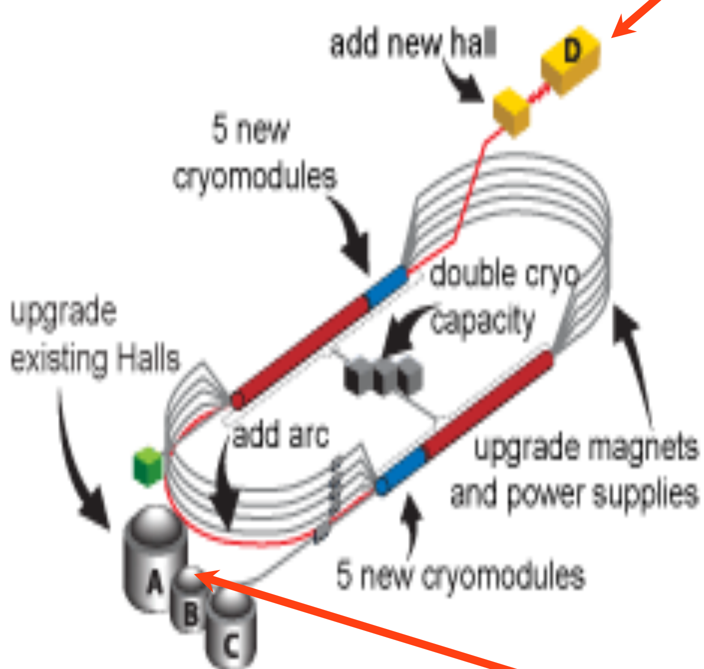
Summary/Conclusions

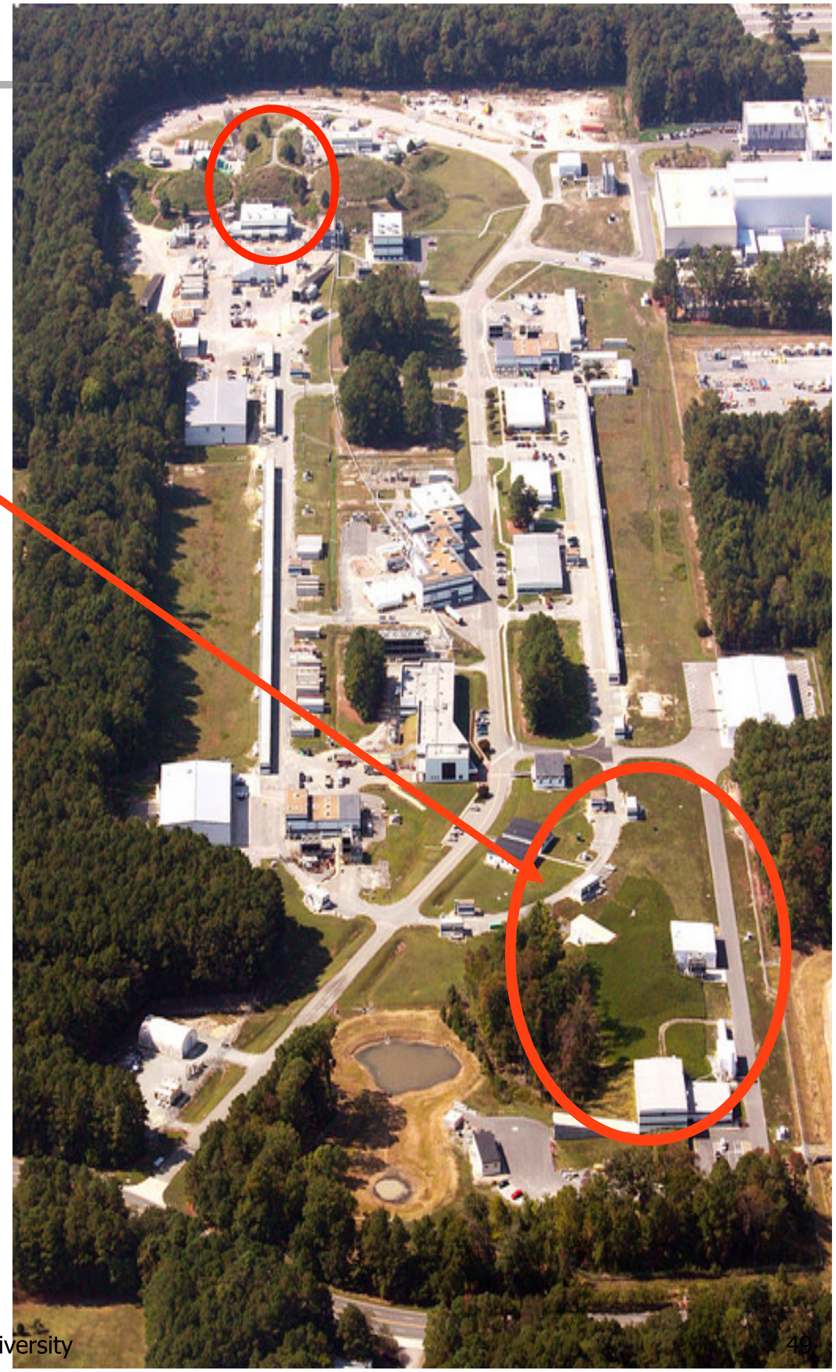
- Hyperon photo- and electro-production used to pin down N^* spectrum above 1.6 GeV
- Y^* cross sections compared; $\Lambda(1405)$ "weird"
- Interference effects in $\Lambda(1405)$ line shapes in $\Sigma\pi$ demonstrated
- Direct J^P measurement for $\Lambda(1405)$ made: $\frac{1}{2}^-$
- Cross section "scaling" demonstrated
- Strangeness "suppression" seen in exclusive
- The future is at CLAS12 and GlueX

Supplemental Slides

Jefferson Lab

- Located in Newport News, Virginia
- Ran for ~14 yrs at 6 GeV in Halls A, B, C
- Upgrading to 12 GeV, new Hall D

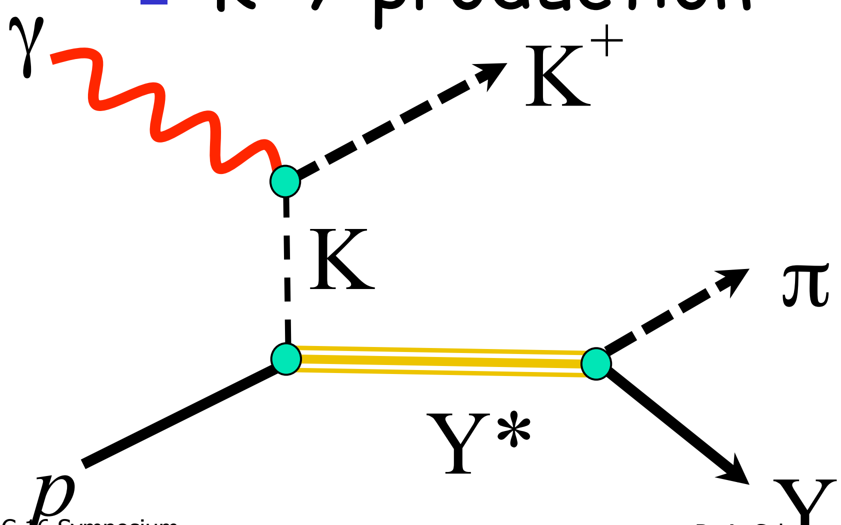


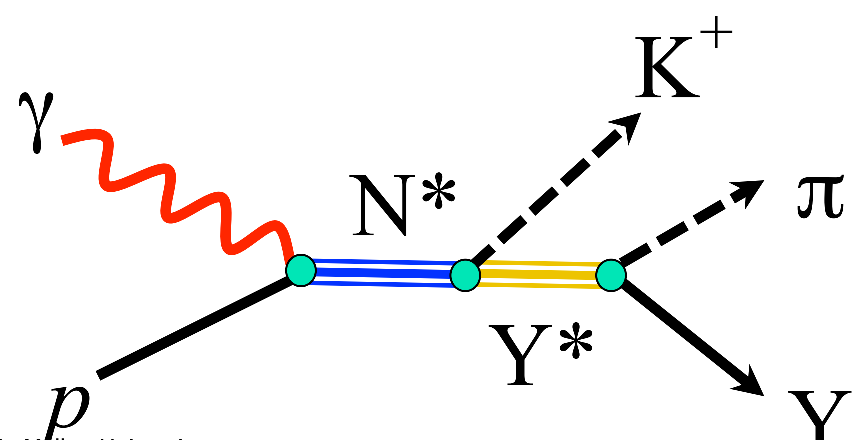


- Most Y, Y* publications from Hall B
  - Upgrading as CLAS12 for 12 GeV

Outline /Overview

- Excited Y* cross sections measured at CLAS
  - $\Sigma^0(1385)$ ($J^P = 3/2^+$) in $\Lambda\pi^0$ channel
  - $\Lambda(1405)$ ($J^P = 1/2^-$) in 3 $\Sigma\pi$ channels
  - $\Lambda(1520)$ ($J^P = 3/2^-$) in 3 $\Sigma\pi$ channels
- Isospin interference in $\Lambda(1405)$: line shapes
- Spin & parity J^P of the $\Lambda(1405)$
- First Electro-production of $\Lambda(1405)$
- K*Y production





$\gamma p \rightarrow K^+\Lambda$: beam asymmetry Σ

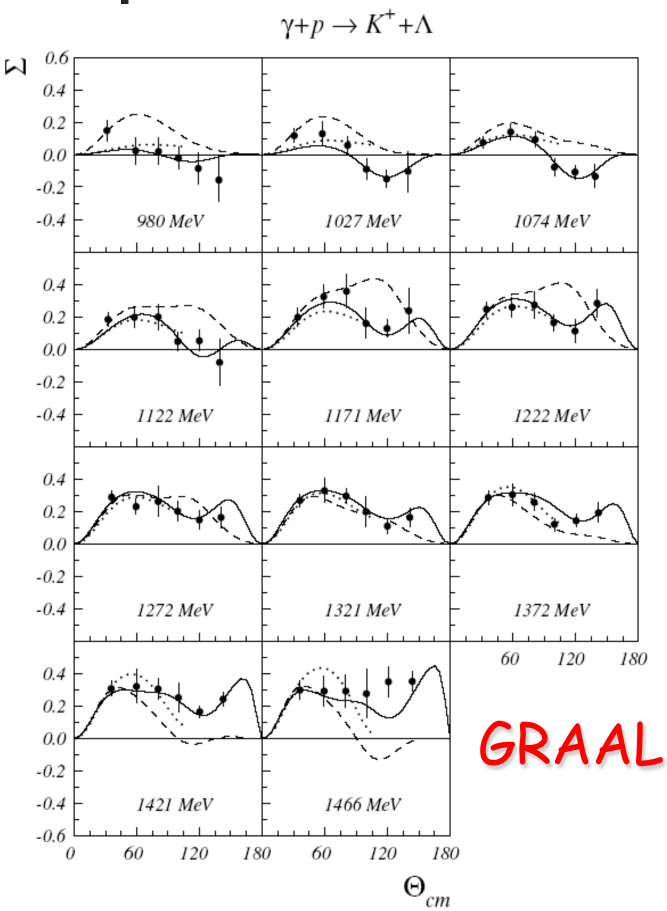


Fig. 14. Angular distributions of the beam asymmetries Σ for $\gamma p \rightarrow K^+\Lambda$ and γ-ray energies ranging from t 1500 MeV. Data are compared with the new solutions of the BCC (solid line), SAPCC (dashed line) and GRP models.

GRAAL

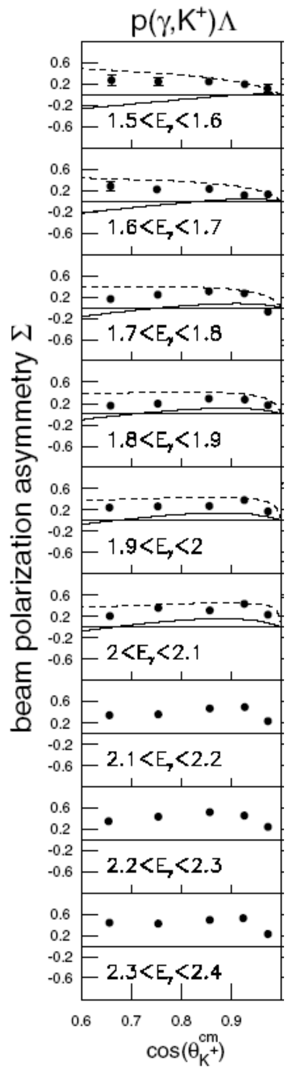


FIG. 3. Beam polarization asymmetries for the $p(\vec{\gamma}, K^+)\Lambda$ (left) and $p(\vec{\gamma}, K^+)\Sigma^0$ (right) reactions as a function of $\cos(\theta^{c.m.}_{K^+})$ for different photon-energy bins. The error bars are ... s using ... anssen ... mental

LEPS

$$\frac{d\sigma}{d\Omega_{K^+}} = \left.\frac{d\sigma}{d\Omega_{K^+}}\right|_{unpol.} \left\{1 + \Sigma P_\gamma \cos 2\phi\right\}$$

GRAAL threshold range,
E_γ < 1.5 GeV

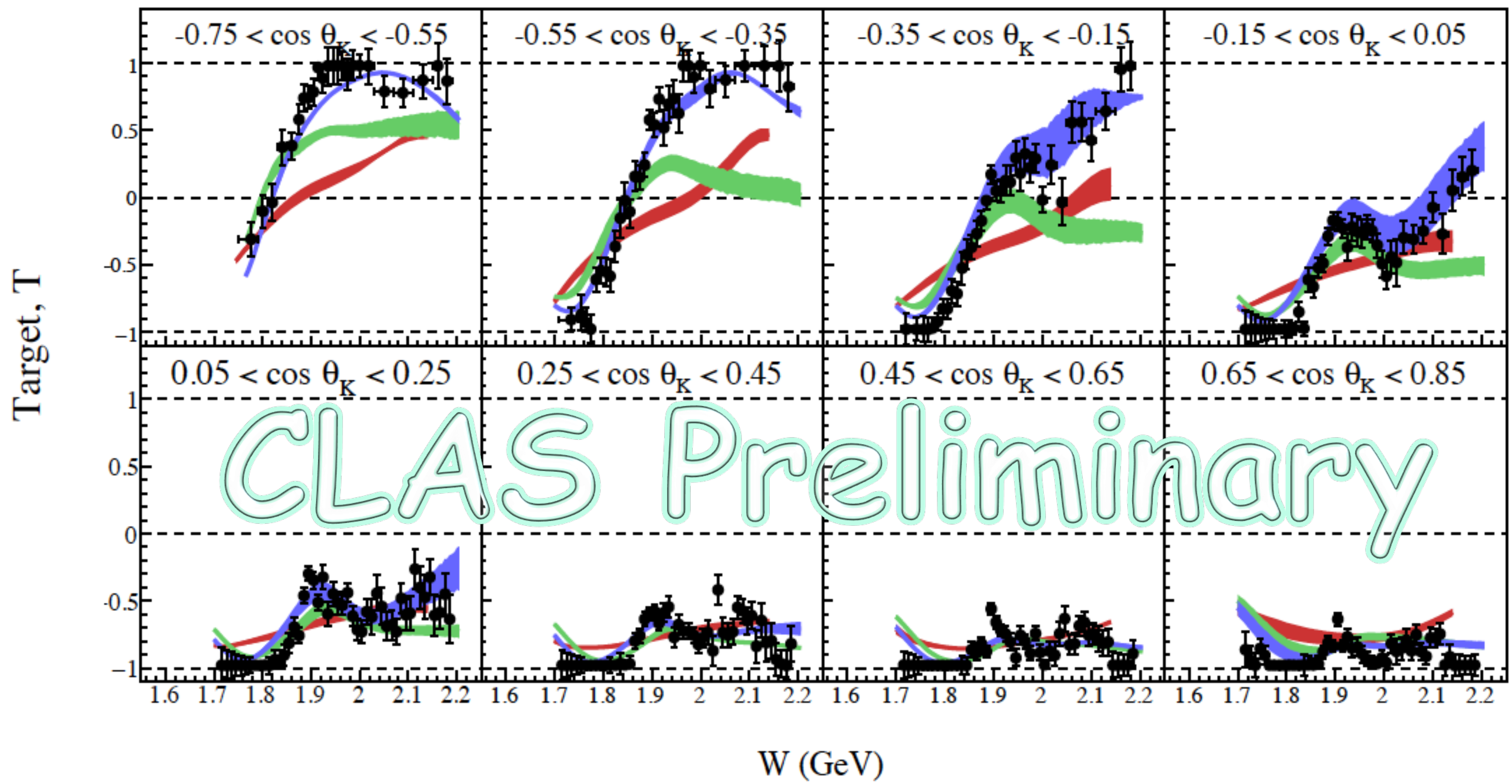
LEPS 1.5 < E_γ < 2.4 GeV

The trends are consistent:
Σ is smooth and featureless
at all energies and angles.

R. G. T. Zegers *et al.* (LEPS) Phys. Rev. Lett. **91**, 092001 (2003).

A. Lleres *et al.* (GRAAL) Eur. Phys. J. A **31**, 79 (2007).

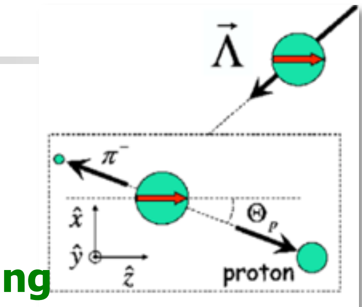
$\gamma p \rightarrow K^+\Lambda$: target asymmetry T



Bonn-Gatchina 2014 model was not predictive in newly-measured kinematics & observables

C.A. Paterson et al. (CLAS Collaboration) to be published, 2016

Pseudoscalar Meson Photoproduction



4 Complex amplitudes: **16** real polarization observables.

Complete measurement with at least **8** suitably chosen observables.

πN has large cross section but in **KY** recoil is **self- analysing**

πN: recoil target γ

KY: γ target recoil

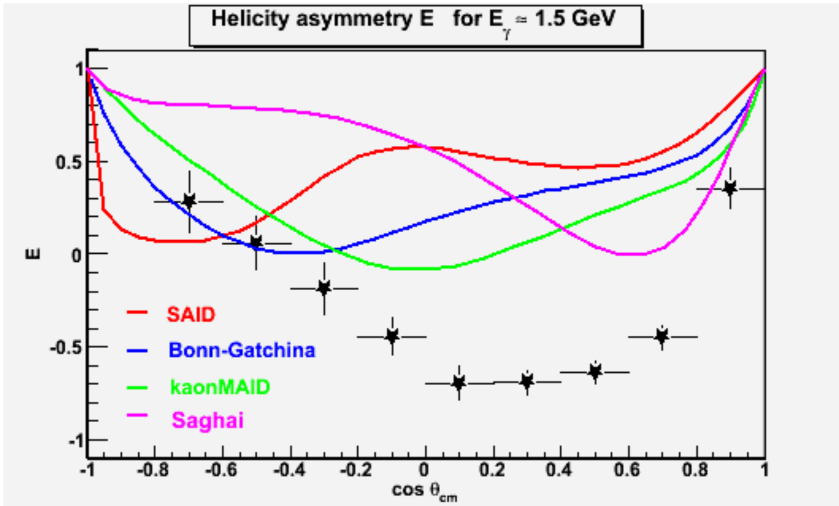
Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;-;-\}$	S
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$T d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;y;-\}$	
$P d\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{-;-;y\}$	
$G d\sigma/dt$	$2\,\mathrm{Im}(b_1b_3^*+b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_3^*-b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_3^*+b_2b_4^*)$	$\{C;z;-\}$	
$F d\sigma/dt$	$2\,\mathrm{Im}(b_1b_3^*-b_2b_4^*)$	$\{C;x;-\}$	
$O_x d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_4^*-b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z d\sigma/dt$	$-2\,\mathrm{Im}(b_1b_4^*+b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_x d\sigma/dt$	$2\,\mathrm{Im}(b_1b_4^*-b_2b_3^*)$	$\{C;-;x'\}$	
$C_z d\sigma/dt$	$-2\,\mathrm{Re}(b_1b_4^*+b_2b_3^*)$	$\{C;-;z'\}$	
$T_x d\sigma/dt$	$2\,\mathrm{Re}(b_1b_2^*-b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_z d\sigma/dt$	$2\,\mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
$L_x d\sigma/dt$	$2\,\mathrm{Im}(b_1b_2^*+b_3b_4^*)$	$\{-;z;x'\}$	
$L_z d\sigma/dt$	$2\,\mathrm{Re}(b_1b_2^*+b_3b_4^*)$	$\{-;z;z'\}$	

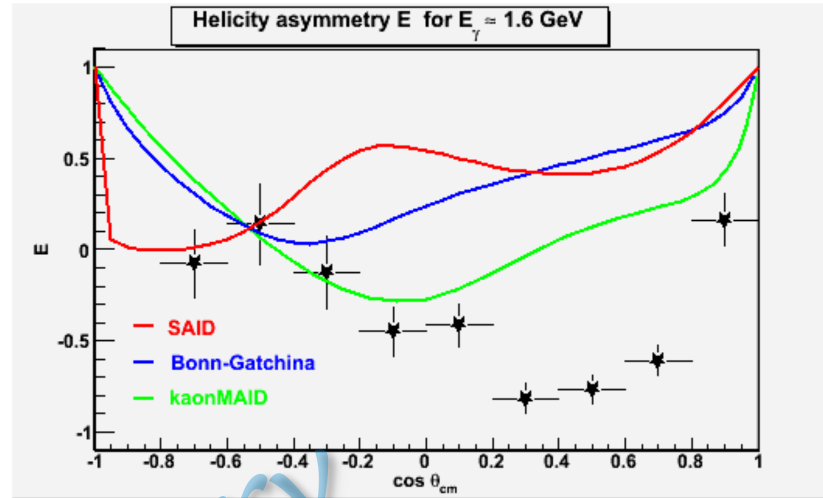
I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

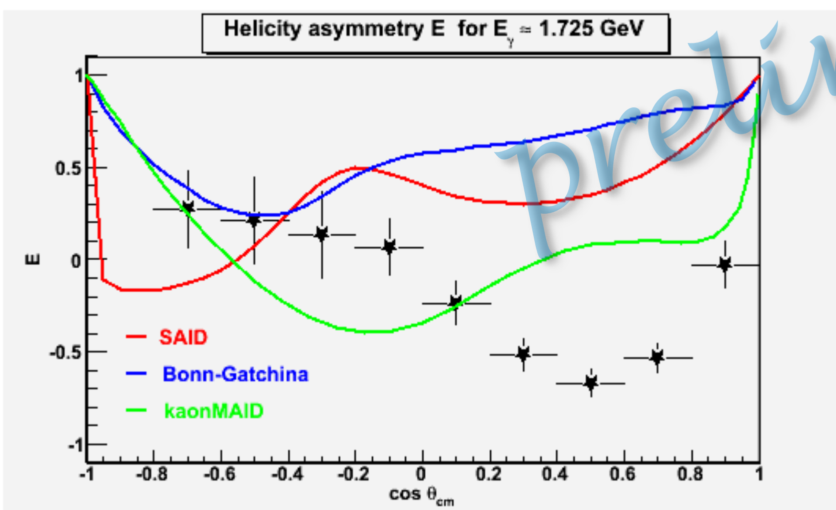
circc polarized photons — longitudinally polarized target

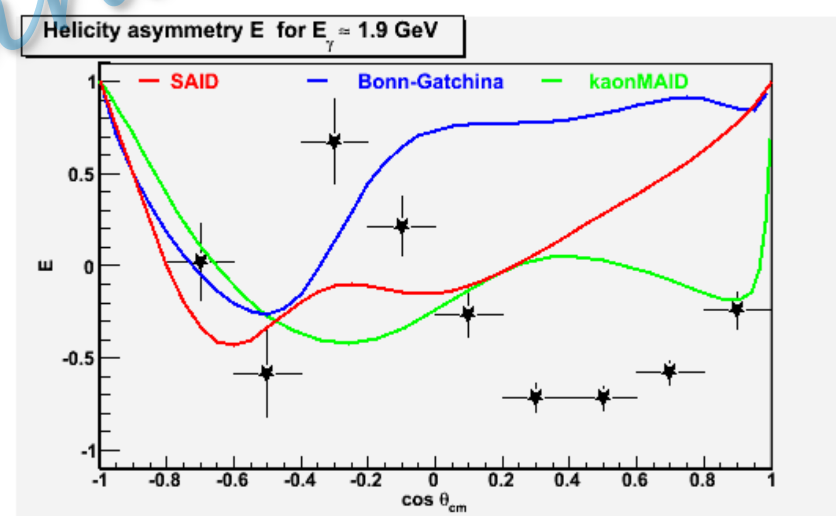
linearly polarized photons — transversely polarized target

γp→K⁺Λ : helicity asymmetry E



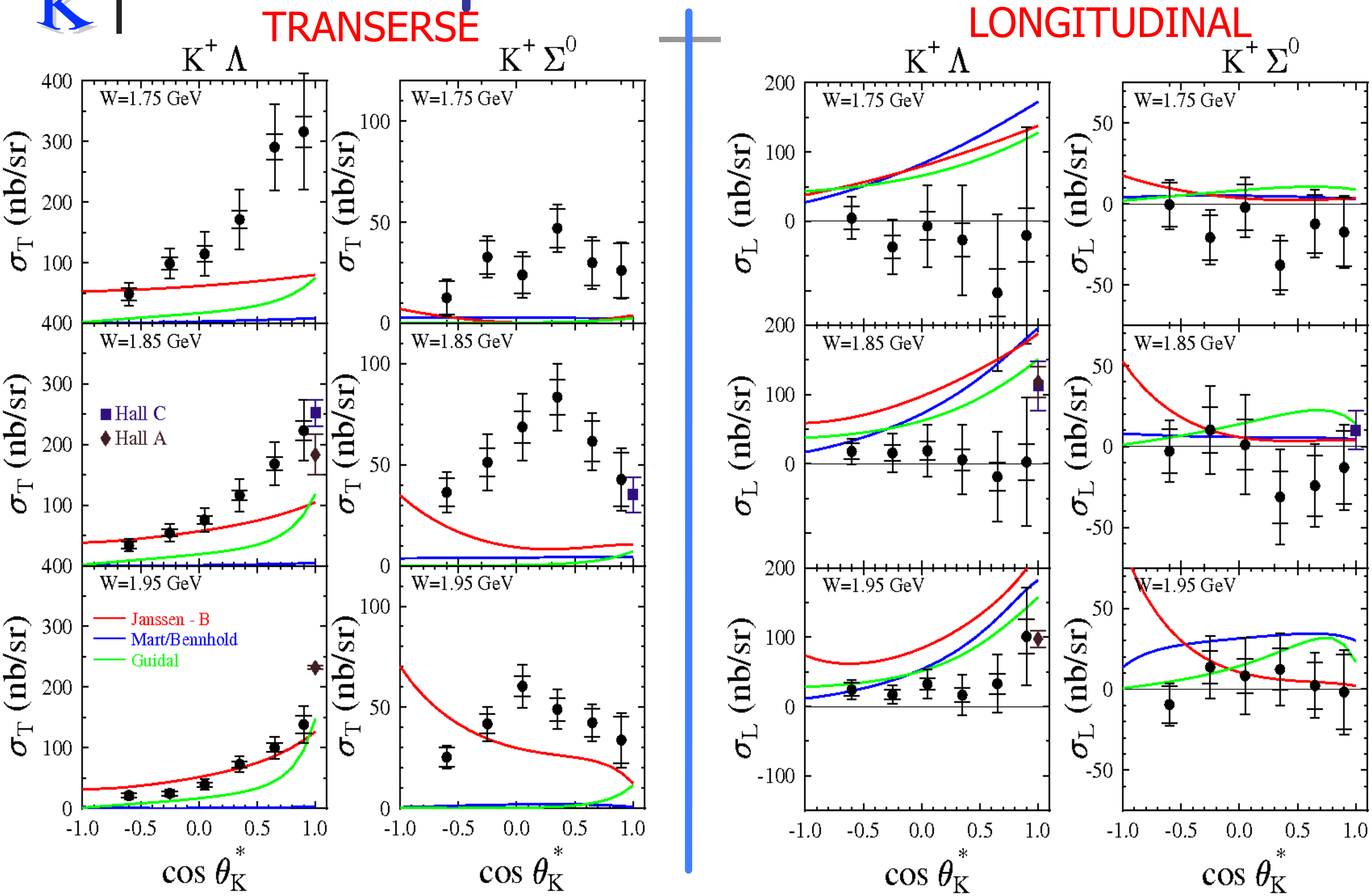






preliminary

L/T Separation



[P. Ambrozewicz *et al.,* PR C **75,** 045203 (2007)]

Seeking New S=0 Baryons via Mesons off the Proton:

published, acquired, FroST(g9b)

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z	CLAS run Period
$p\pi^0$	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)									g1, g8, g9
$n\pi^+$	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)									g1, g8, g9
$p\eta$	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)									g1, g11, g8, g9
$p\eta'$	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)									g1, g11, g8, g9
$p\omega$	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)									g11, g8, g9
$K^+\Lambda$	✔ (published)	✓ (acquired)	✓ (FroST)	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)	✓ (FroST)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (acquired)	✓ (acquired)	✔ (published)	✔ (published)	g1, g8, g11
$K^+\Sigma^0$	✔ (published)	✓ (acquired)	✓ (FroST)	✔ (published)	✓ (acquired)	✓ (FroST)	✓ (acquired)	✓ (FroST)	✓ (FroST)	✓ (FroST)	✓ (acquired)	✓ (acquired)	✓ (acquired)	✓ (acquired)	✔ (published)	✔ (published)	g1, g8, g11
$K^{0*}\Sigma^+$	✔ (published)										✓ (acquired)	✓ (acquired)			✓ (acquired)	✓ (acquired)	g1, g8, g11

Source: V. D. Burkert

Seeking New S=0 Baryons via Mesons off the Neutron:

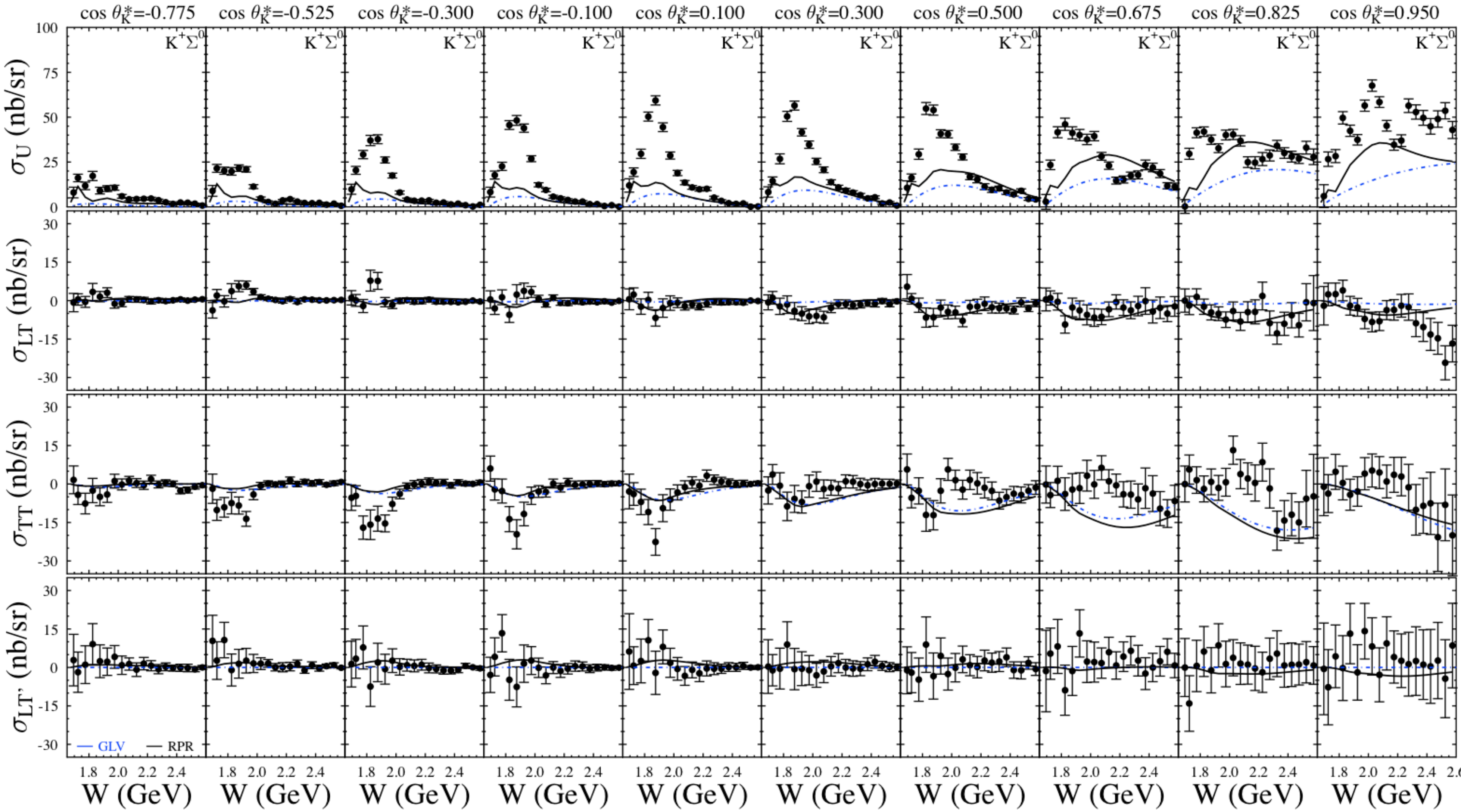
published, acquired, HD-ice

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z	CLAS run Period
$p\pi^-$	✔	✓	✓		✓	✓	✓	✓									g2, g10, g13, g14
$p\rho^-$	✓	✓	✓		✓	✓	✓	✓									g2, g10, g13, g14
$K^0\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	g13, g14
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	g13, g14
$K^+\Sigma^-$	✓	✓	✓		✓	✓	✓	✓									g10, g13, g14
$K^{0*}\Sigma^0$	✓	✓															g10, g13

The combination of all of these measurements on proton and neutron targets represents an extremely powerful tool in the search for new baryon states.

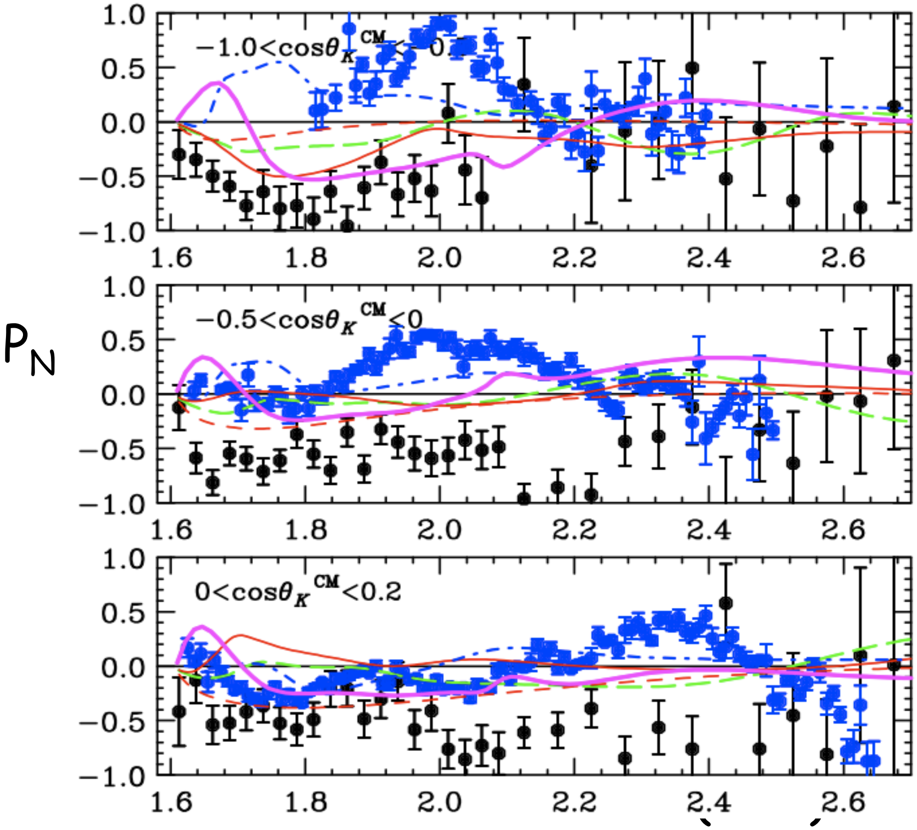
Source: V. D. Burkert

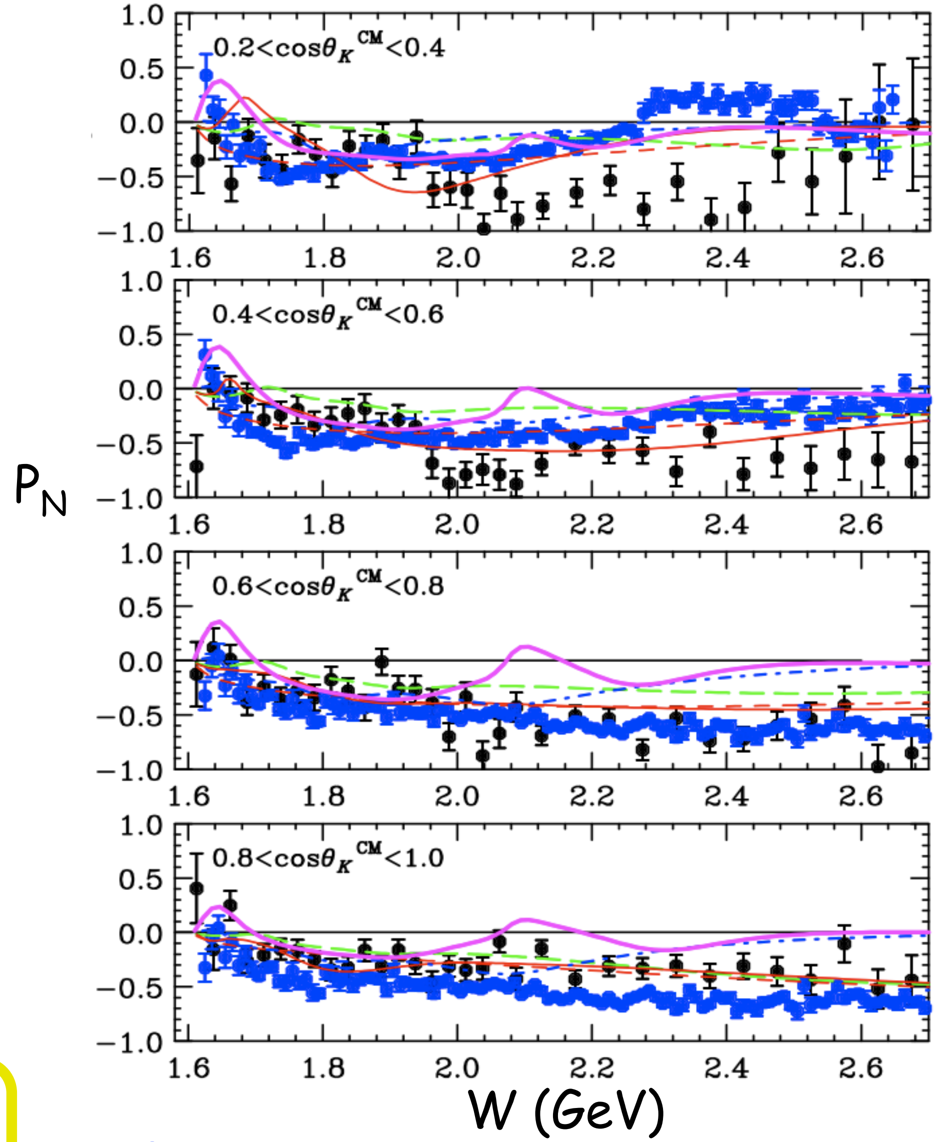
$K^+\Sigma^0$ Structure Functions



E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV² [Carman *et al.*, PR C **87**, 025204 (2013)]

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





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

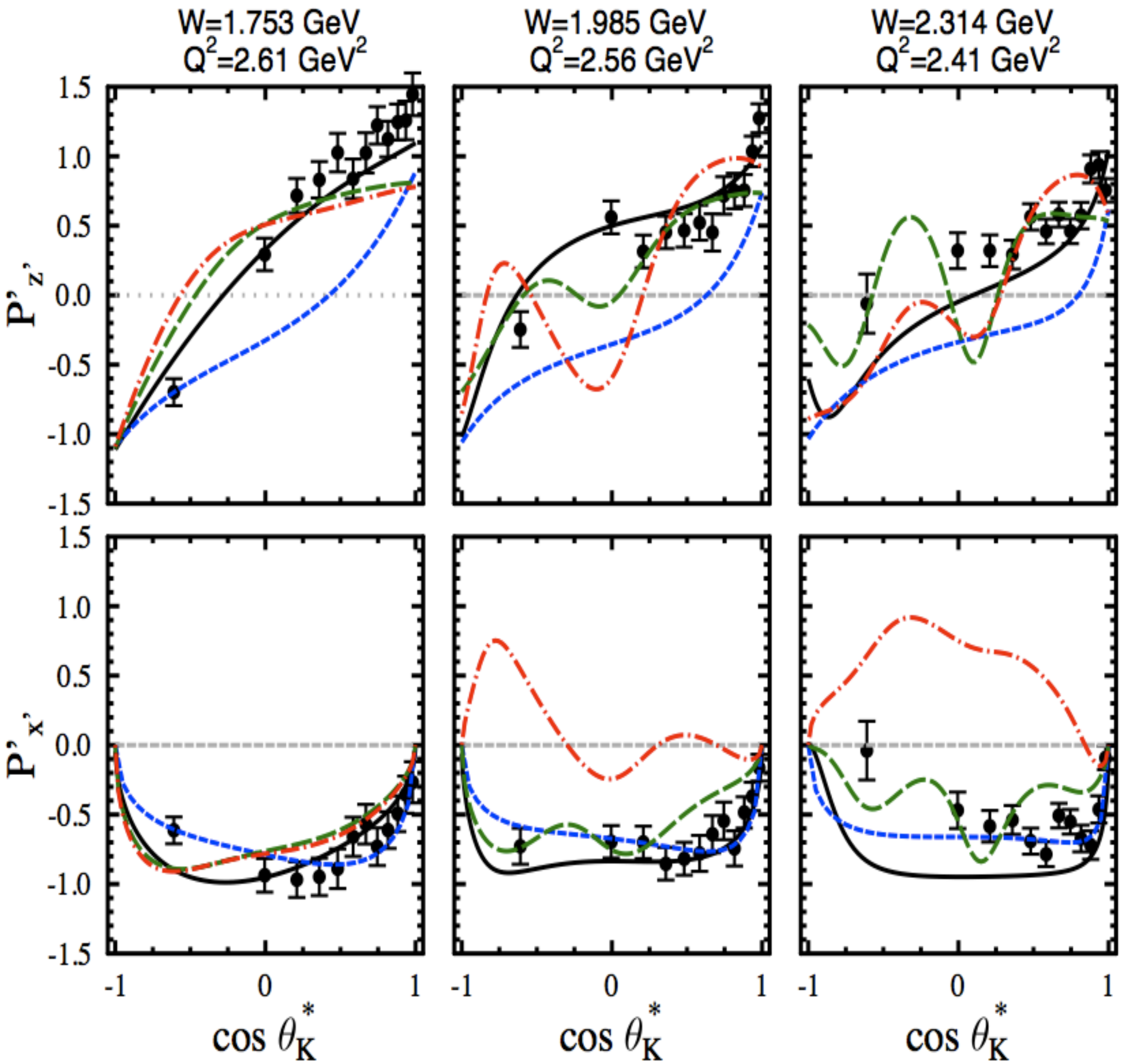
[Gabrielyan *et al.*, PR C **90**, 035202 (2014)]

Kaon-Maid *Maxwell* *RPR-2007*

RPR-2011 (solid-full, dash-NR)

● [McCracken *et al.*, PR C **81**, 025201 (2010)]

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



5.754 GeV
Summed over Q^2, Φ

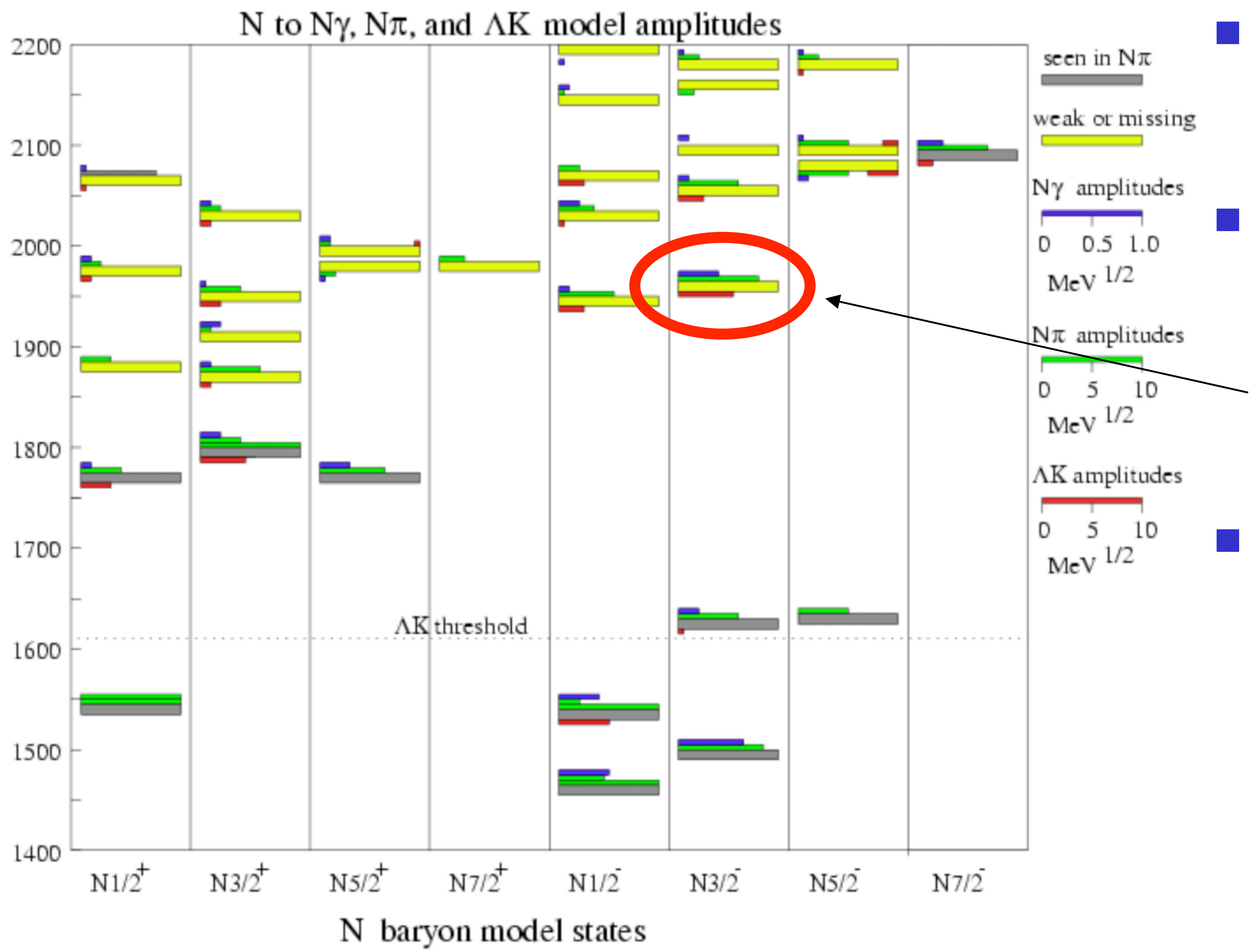
- Data not included in fits
- Rule out $P_{11}(1900)$ assignment
- $D_{13}(1900)$ not ruled out via P′ data but with S.F. data

Isobar Model – Mart
Regge Model – GLV
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)]

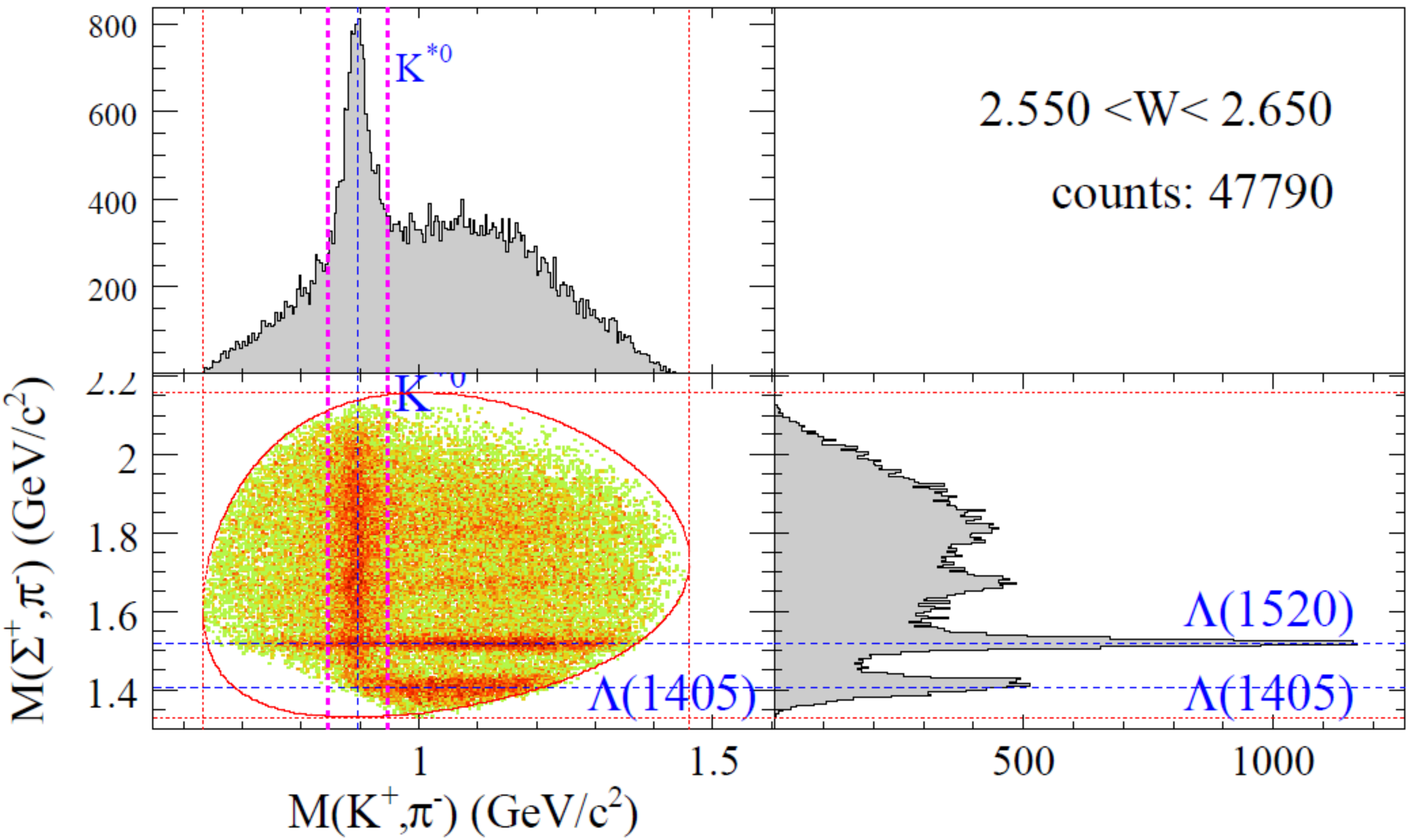
N* Baryons: Seen & "Missing"



- Relativized CQM
  - Classify oscillator-model states by I, J, P
- Consistent with observation of a "missing" N* state in $K^+\Lambda$
- PDG2013 now lists the "**" $N(2150)\ 3/2^-\ D_{13}$

S. Capstick and W. Roberts, Phys. Rev. **D58**, (1998).

Events in $K^+\Sigma^+\pi^-$ Final State

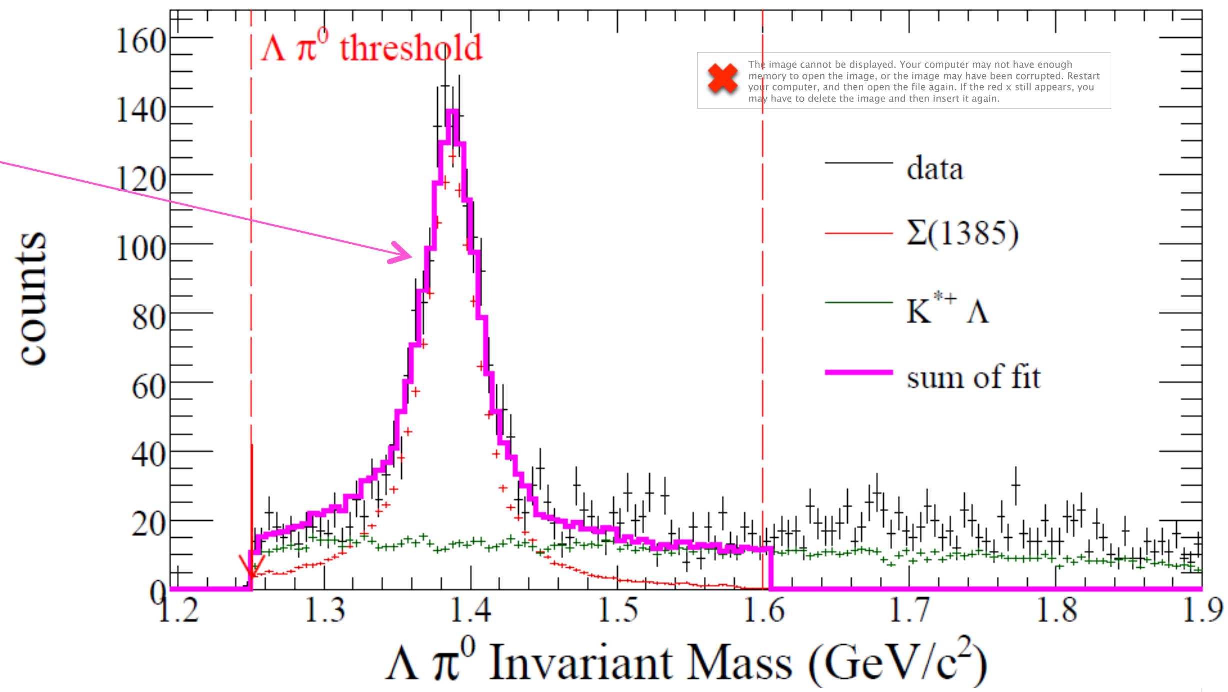


K* overlap must be subtracted in some W bins

Yields for $\Sigma^0(1385)$

- Use the dominant $\Lambda\pi^0$ decay mode (88%)
- Select Λ in $p\pi^-$ invariant mass;
- Select π^0 via $K^+\Lambda$ missing mass
- Fit to $\Lambda\pi^0$ channel
- Remove other channels ($K^*\Sigma$) by incoherent fits with Monte Carlo templates

$\Sigma^0(1385)$ in one energy and angle bin



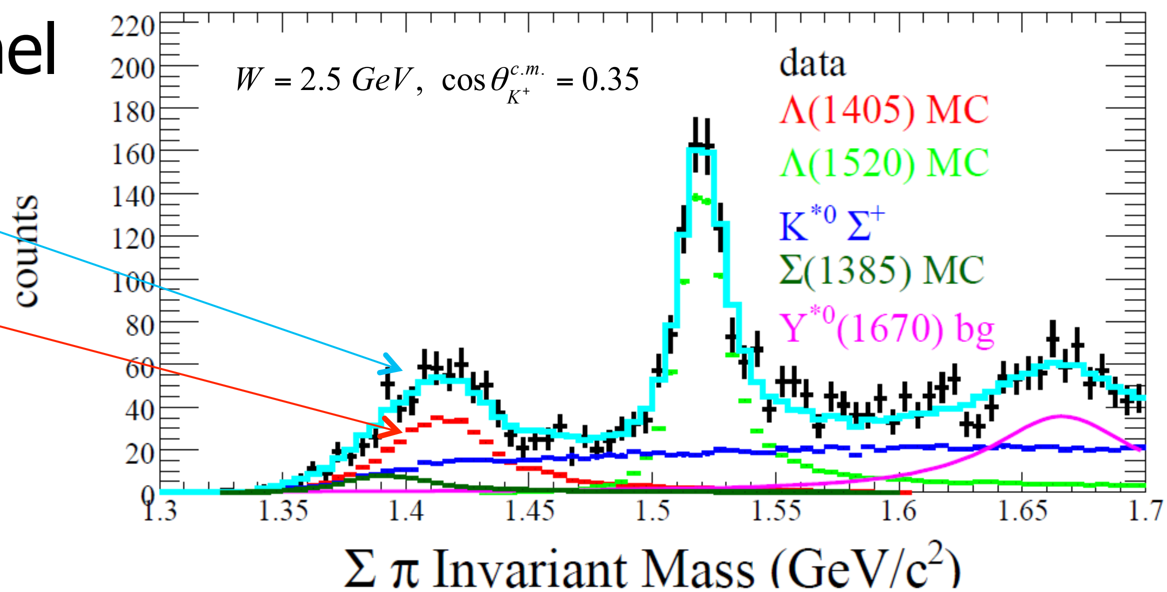
Yields for Λ(1405) & Λ(1520)

- Reconstruct and select ground state $\Sigma^{\pm}$ states
- Remove $\Sigma^0(1385) \rightarrow \Sigma^{\pm}\pi^{\mp}$ (6% each) by scaling down contribution from dominant $\Lambda\pi$ channel
- Separate other channels ($K^*\Sigma$, K^+Y^*) by incoherent fits with Monte Carlo templates and Breit-Wigner functions

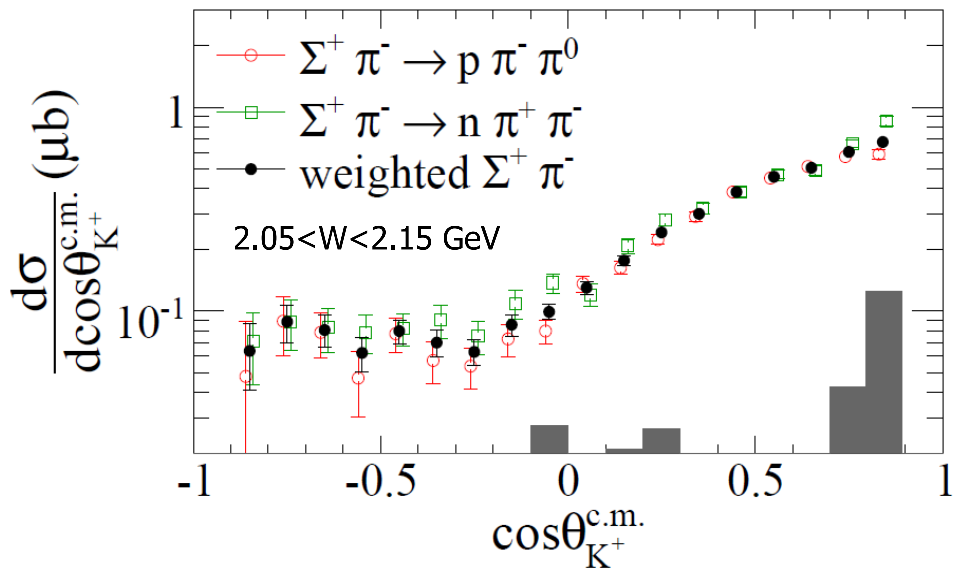
Fit to $\Sigma^+\pi^-$ channel

Total fit result

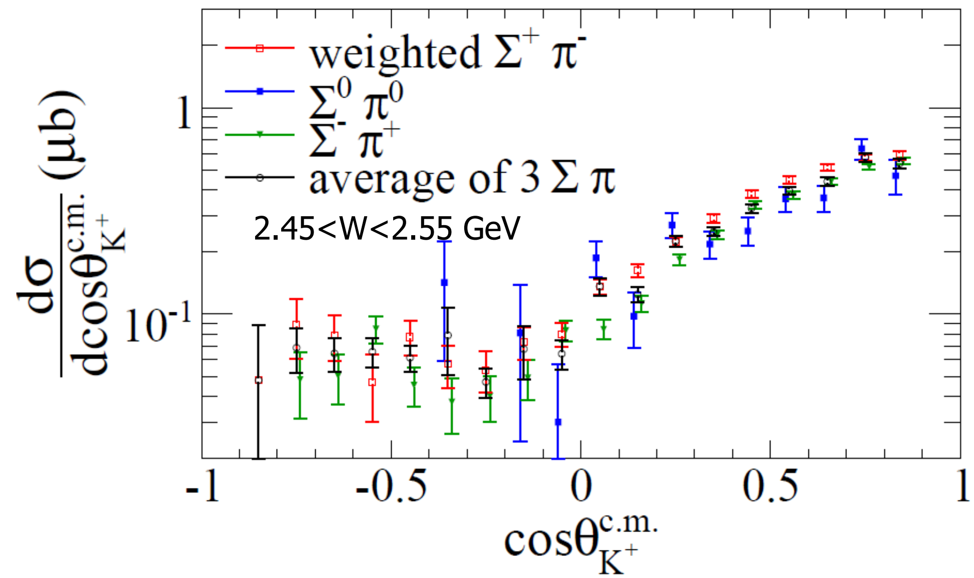
Iterated Λ(1405) line shape



Differential Λ(1520) Cross Section



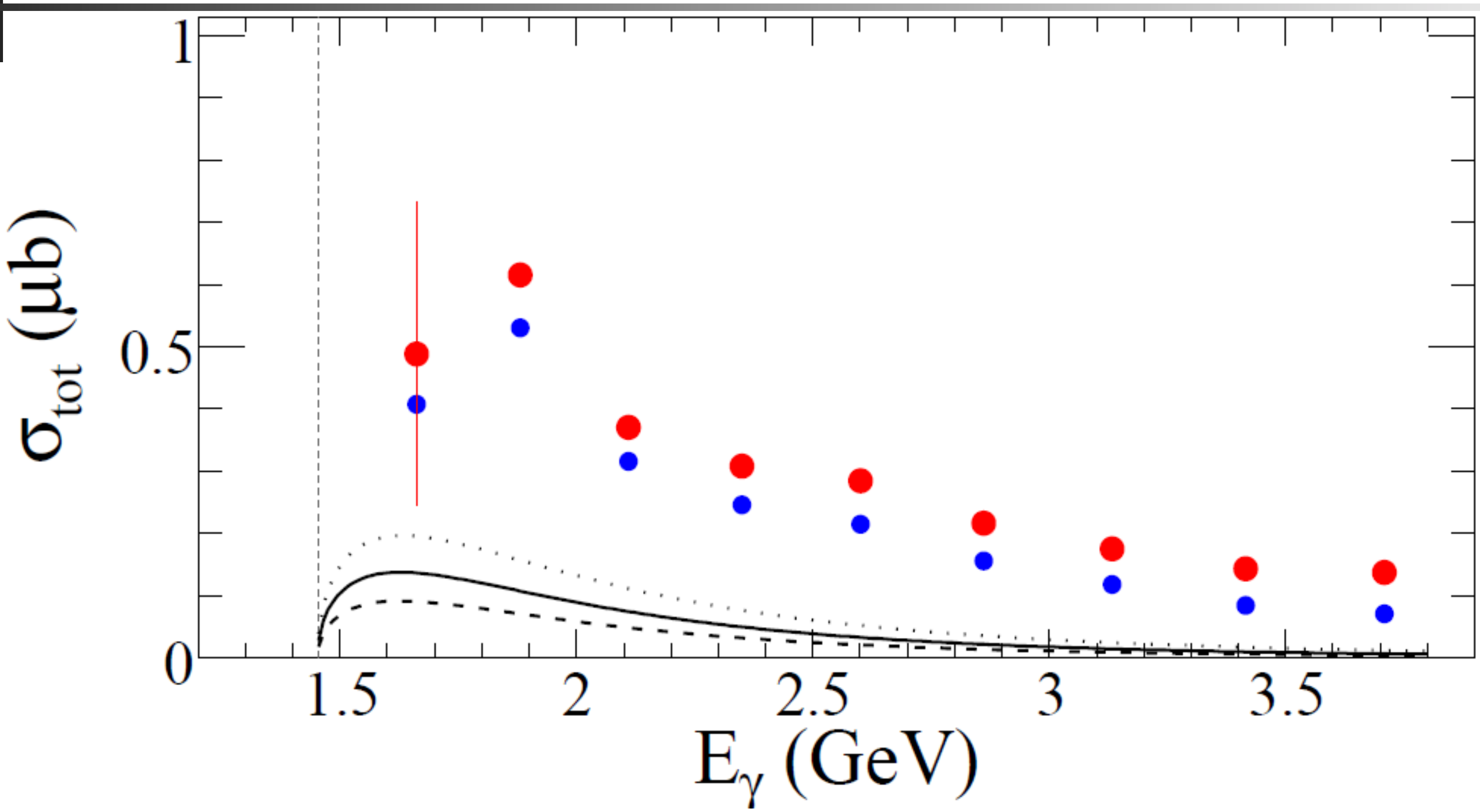
Agreement between $\Sigma^+\pi^-$ decay modes: tests acceptance consistency



Agreement among $\Sigma^+\pi^-$, $\Sigma^0\pi^0$, $\Sigma^-\pi^+$ decay modes: tests acceptance consistency

- $\gamma + p \to K^+ + \Lambda(1520)$
- Good agreement among Σπ decay modes
- Corrected with 42% branching fraction to Σπ

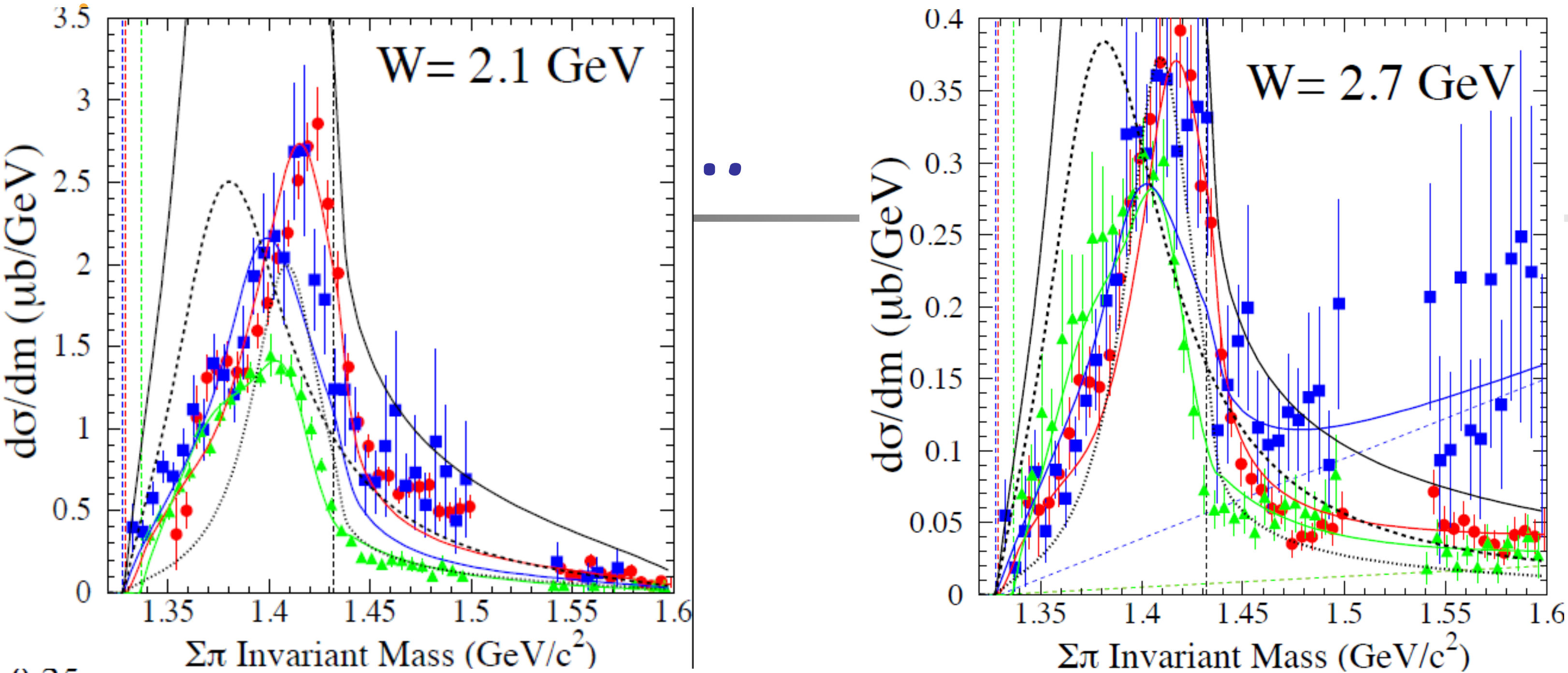
Total Λ(1405) Cross Section



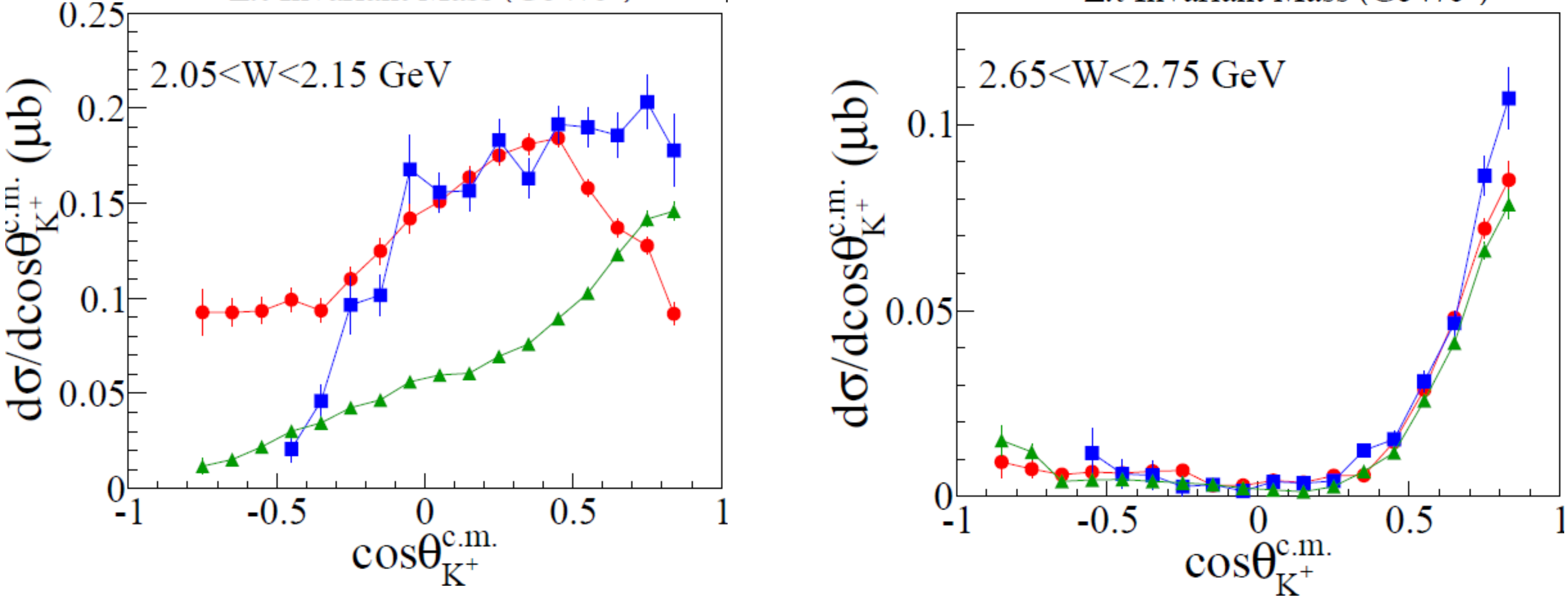
- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
  - Blue: measured; Red: extrapolated total
- Model[1]: s-channel Born term dominant; K^* exchange for 3 values of $g_{K^*N\Lambda^*}$

1. S.I. Nam et al., J. Kor. Phys. Soc. **59**, 2676 (2011)

γ



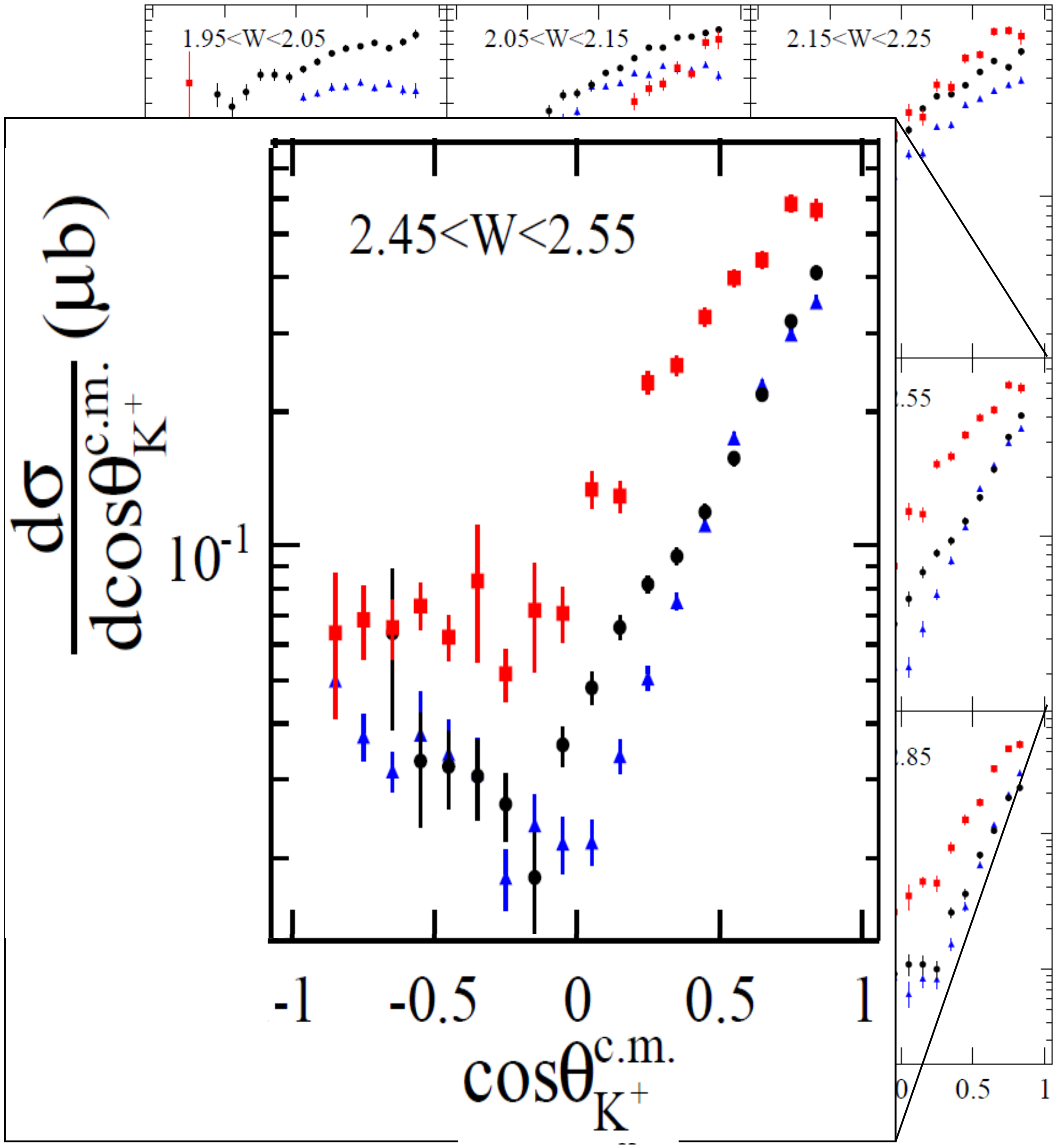
Line Shapes



Cross Sections

- Charge-dependence is NOT seen for the Λ(1520).
- No model calculation has computed cross section and line shapes together.

Direct Y* Cross Section Comparison



- $\gamma + p \rightarrow K^+ + Y^*$
  - Sum $\Lambda(1405)$ channels
  - Apply branching fractions for $\Lambda(1520)$, $\Sigma(1385)$
- All three hyperons have
  - Strong forward peaking
  - Similar t-slopes
  - Back-angle rises
  - Similar-size cross sections

● $\Sigma^0(1385)$
▲ $\Lambda(1405)$
■ $\Lambda(1520)$

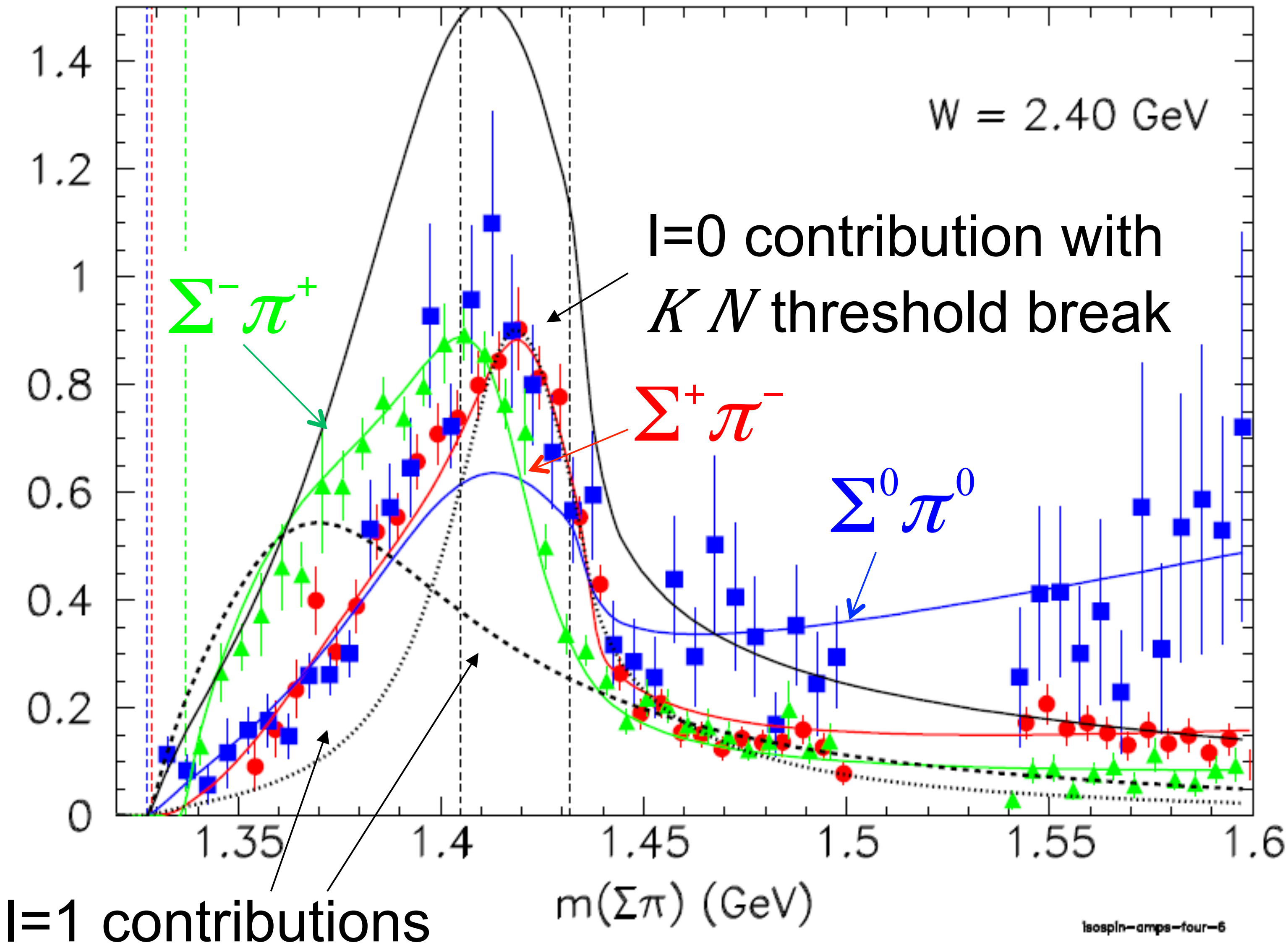
Parity and Spin of $\Lambda(1405)$

- How does one measure these things?
  - Find a reaction wherein Λ^* is created polarized
  - Decay angular distribution to $\Sigma\,\pi$ relates to J
    - $J = 1/2$: *flat* distribution is the best possible evidence
    - $J = 3/2$: "smile or frown" distribution, where p is the $m=\pm3/2$ fraction

$$I(\theta_Y) \propto 1 + \frac{3(1-2p)}{2p+1}\cos^2\theta_Y$$

  - Parity given by polarization transfer to daughter
  - No model dependence: pure kinematics

Example at W=2.40 GeV

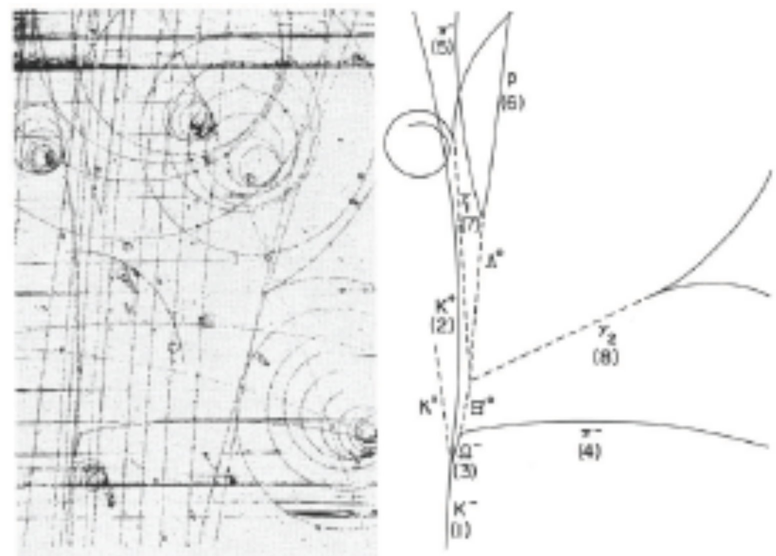


K. Moriya, R. A. Sch. *et al.* (CLAS), Phys. Rev. C 87, 035206 (2013)

CLAS12: Very Strange Baryons

Study of the Ω^- and Ξ^* are among the main goals of the CLAS12 spectroscopy program:

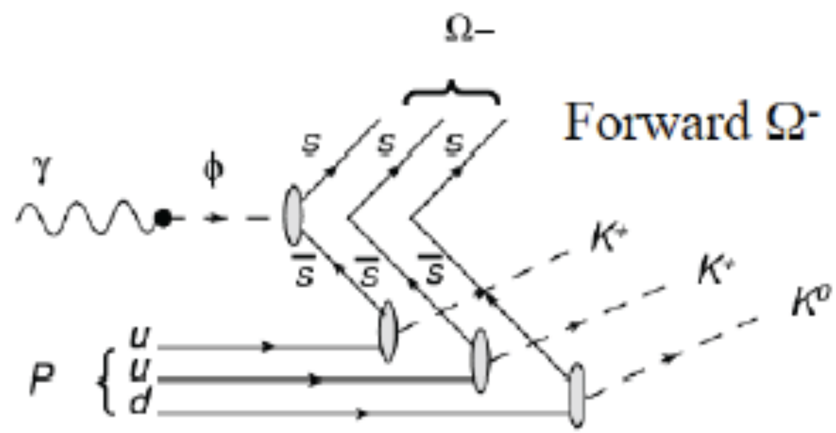
- Ω^- discovered in 1964: after 50 years, indication on J^P from Babar and others but full determination not yet achieved
- Ξ^* spectrum still poorly known: many states missing and spin/parity undetermined



V. E. Barnes et al., Phys. Rev. Let. 12 (1964) 204

Photoproduction mechanism implies creation of three s quarks

- Models indicate $\sigma(\Omega^-)$ ~0.3-2 nb at E~7GeV
- Expected production rates in CLAS12:
  - Ω^- : 90 /h
  - Ξ-(1690)/Ξ-(1820): 0.2/0.9 k/h
- Ω^- : measurement of the cross section and investigation of production mechanisms
- Ξ^*: spin/parity determination, cross section and production mechanism, measurement of doublets mass splitting

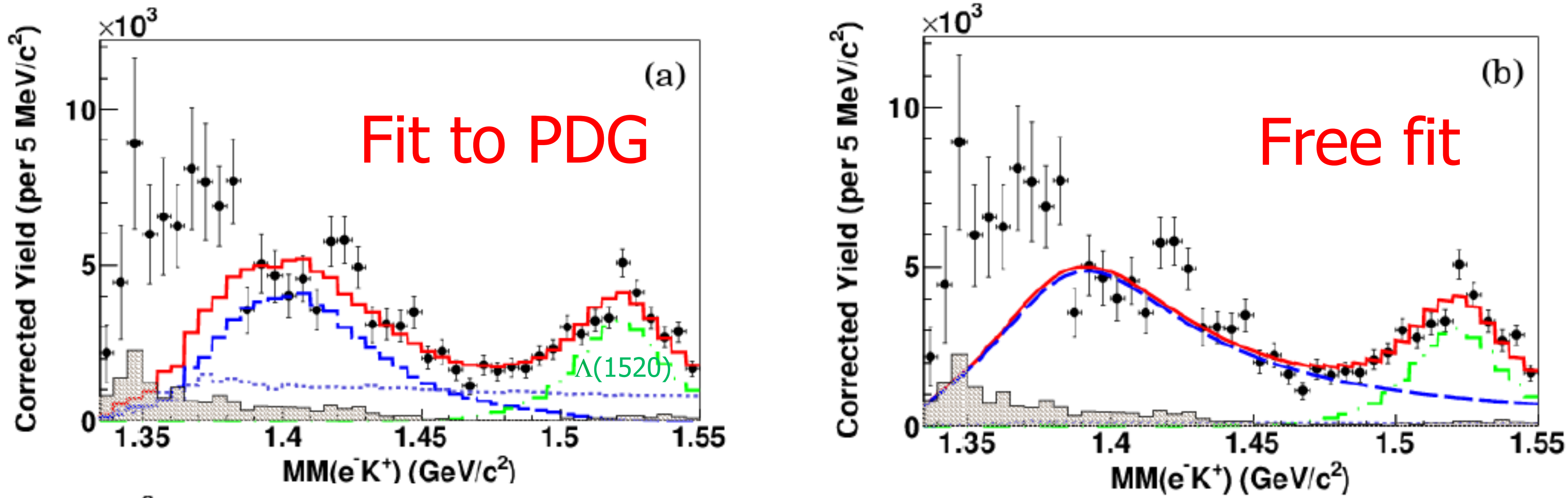


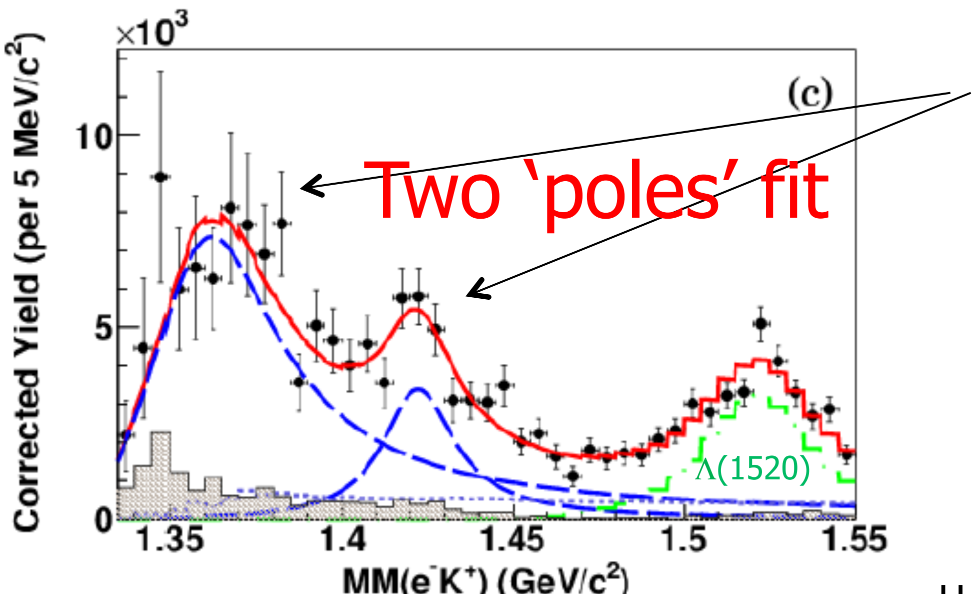
(R. deVita, priv. comm.)

$\Lambda(1405)$ Electroproduction

Publication: First Observation of the $\Lambda(1405)$ Line Shape in Electroproduction, H. Lu *et al.* (CLAS Collaboration), Phys. Rev. C **88**, 045202 (2013).

Electroproduction of Λ(1405)





- Two-bump structure seen
- Possible evidence for two I=0 poles
- PDG Λ(1405) values fail utterly
- Calculation needed!

H. Lu *et al.* (CLAS), Phys. Rev. C **88**, 045202 (2013).