XIth Quark Confinement and the Hadron Spectrum

September 8-12, 2014
Saint-Petersburg State University, Russia

Electromagnetic Strangeness Production at Jefferson Lab Energies

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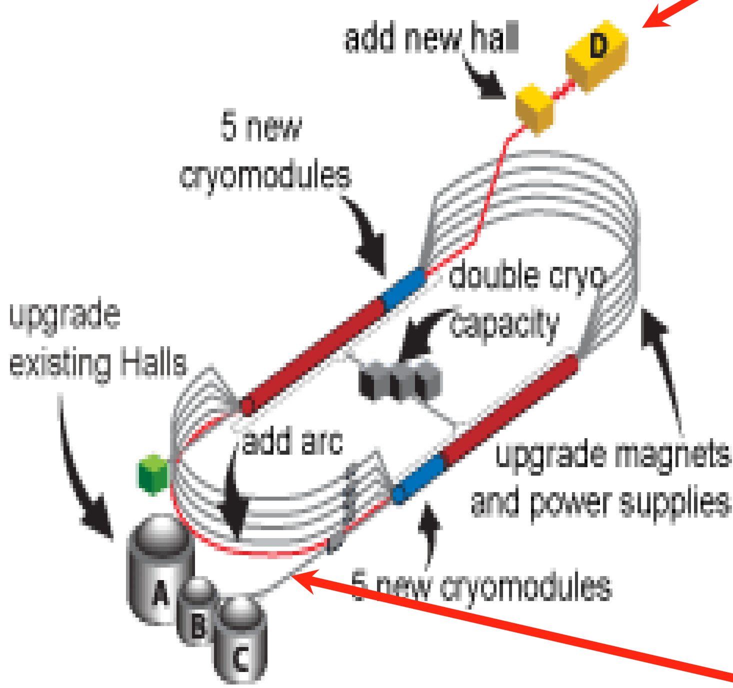
September 9, 2014, St.Petersburg, Russia

Outline /Overview

- Strangeness and the N* spectrum of states
  - Ground state photoproduction
  - Ground state electroproduction
- Excited Y* cross sections measured at CLAS
  - $\Sigma^0(1385)$ ($J^P = 3/2^+$); $\Lambda(1405)$ ($J^P = 1/2^-$); $\Lambda(1520)$ ($J^P = 3/2^-$)
- Dimensional scaling of $K\Lambda$ photoproduction
- The $\Lambda(1405)$ and chiral unitary models
  - line shapes
  - Spin & parity J^P of the $\Lambda(1405)$
  - First Electro-production of $\Lambda(1405)$
- K*Y production
- Outlook at GlueX and CLAS12

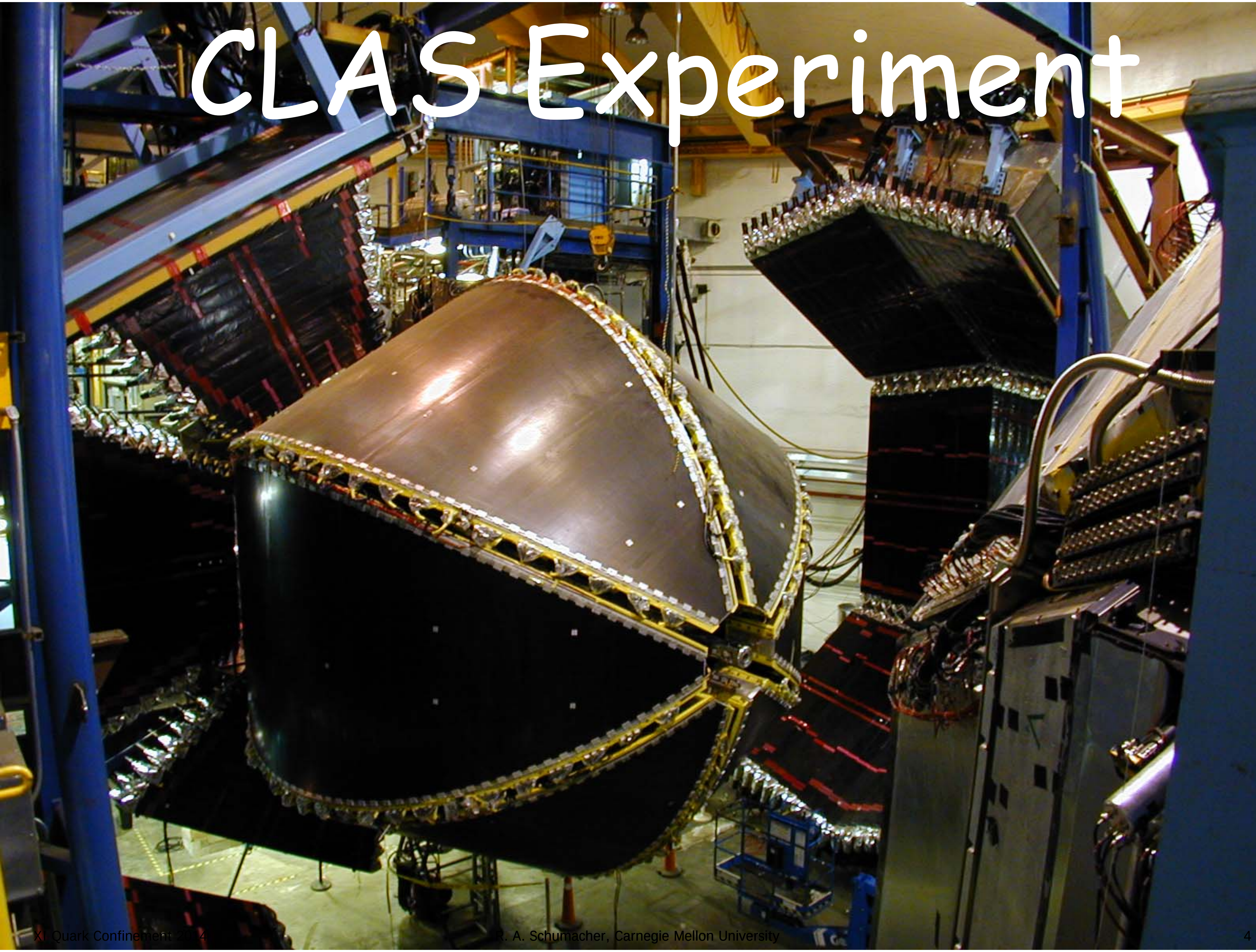
Jefferson Lab

- 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

CLAS Experiment



CLAS Experiment

- Jefferson Lab, Newport News, VA, USA
- Photoproduction:
  - Targets unpolarized LH_2, polarized p and HD
  - Beams unpolarized, circular, linear, to ~5 GeV
  - reconstructed $K^+p\pi^-(\pi^0)$ or $K^+\pi^+\pi^-(n)$
  - $20\text{x}10^9$ triggers → $1.41\text{x}10^6$ $KY\pi$ events in g11a
- Electroproduction:
  - Q^2 from ~0.5 to ~3 $(GeV/c)^2$
  - Rosenbluth and beam-helicity separations

Strangeness and the N* Spectrum of States - 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.

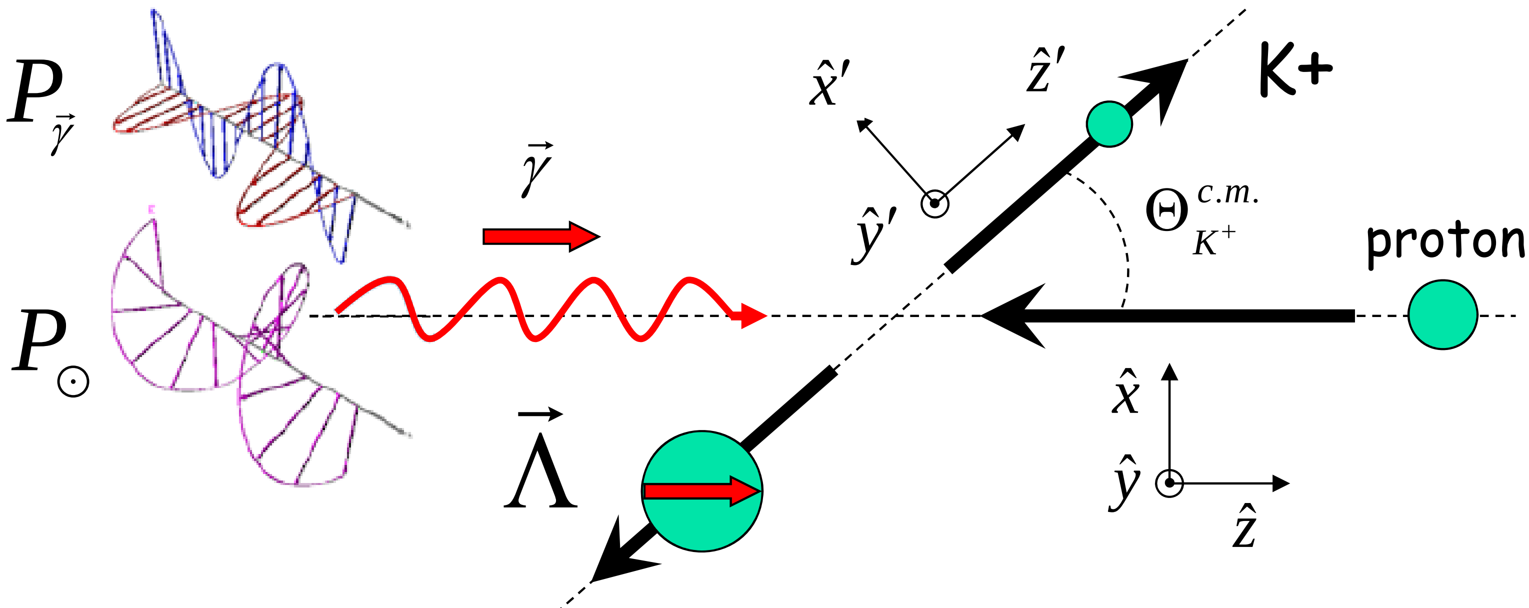
		all	πN	γN	Nη	ΛK	ΣK	Δπ	Nσ
	$N(1440)\frac{1}{2}^+$	****	****	***★	(*)			***	★★★
	$N(1710)\frac{1}{2}^+$	***	***	***	**★	★★★	★★	*(*)	
	$N(1880)\frac{1}{2}^+$	★★	★	★		★★	★		
	$N(1535)\frac{1}{2}^-$	****	****	****	****			*	
S_{11}	$N(1650)\frac{1}{2}^-$	****	****	***	*★★	***	**	**(*)	
	$N(1895)\frac{1}{2}^-$	★★	★	★★	★★	★★	★		
	$N(1720)\frac{3}{2}^+$	****	****	****	****	**	**	***	
P_{13}	$N(1900)\frac{3}{2}^+$	**★	**	★★★	★★	★★★	★★	★★	
	$N(1520)\frac{3}{2}^-$	****	****	****	***			****	
	$N(1700)\frac{3}{2}^-$	**★	**	**	*	*(*)	*	**★	
	$N(1875)\frac{3}{2}^-$	★★★	★	★★★		★★★	★★		★★★
D_{13}	$N(2150)\frac{3}{2}^-$	★★	★★	★★		★★		★★	
	$N(1680)\frac{5}{2}^+$	****	****	****	*			**(*)	★★
	$N(1860)\frac{5}{2}^+$	★	★	★					
	$N(2000)\frac{5}{2}^+$	*★★	*(*)	★★	★★	★★	★		
	$N(1675)\frac{5}{2}^-$	****	****	***(*)	*	*		***(*)	★
	$N(2060)\frac{5}{2}^-$	★★★	★★	★★★	★		★★		
	$N(1990)\frac{7}{2}^+$	**	*(*)	★★					
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 Δη|	
	$\Delta(1905)\frac{5}{2}^+$	****	****	****			*★★	**(**)	
	$\Delta(1950)\frac{7}{2}^+$	****	****	***			*★★	**★	

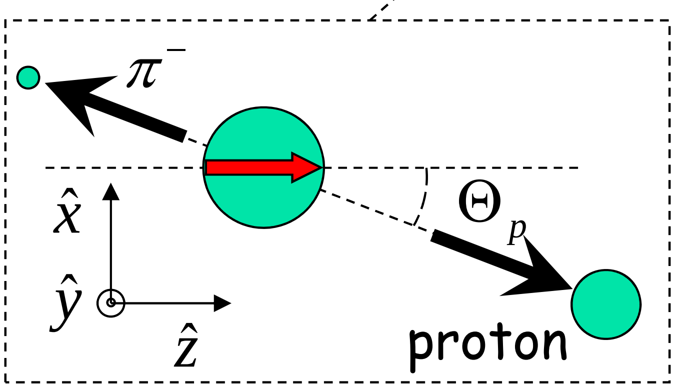
- How significant is strangeness physics in unraveling N* and Δ properties?
- It is part of a large effort to determine pole positions, branching fractions, helicity couplings, etc.
- Bottom line: "Stars" and resonances added to world database

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

Define the Spin Observables

(for target polarization zero)





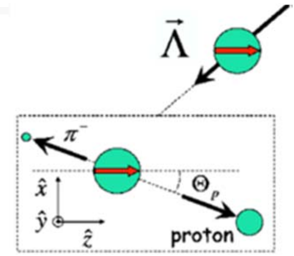
$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ \begin{array}{l} 1 - P_{\vec{\gamma}} \Sigma \cos 2\phi \\ \quad - \alpha \cos\theta_{x'} \sin 2\phi P_{\vec{\gamma}} O_{x'} - \alpha \cos\theta_{x'} P_{\odot} C_{x'} \\ \quad - \alpha \cos\theta_{z'} \sin 2\phi P_{\vec{\gamma}} O_{z'} - \alpha \cos\theta_{z'}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

Observables in Pseudoscalar Meson Photoproduction

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

Complete measurement from **8** carefully 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
$T_z d\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*+b_3b_4^*)$	$\{-;z;x'\}$	
$L_x d\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*+b_3b_4^*)$	$\{-;z;z'\}$	

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

circ polarized photons — longitudinally polarized target

linearly polarized photons — transversely polarized target

Complete, and over-determined

Theory: Bonn Gatchina Model

(Just one of several models on the market)

- Coupled channel (K-matrix) framework
  - Input from πN, KN elastic; γ, π induced inelastic to $\pi^{\pm\,0}N$, ηN, $\eta' N$, $K^{\pm\,0}Y$, $\pi\pi N$
    - Use ALL experimental channels, including the strangeness channels & measured spin obervables
  - Partial Wave Analysis
    - First extract each J and parity waves
    - Map to extract 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)

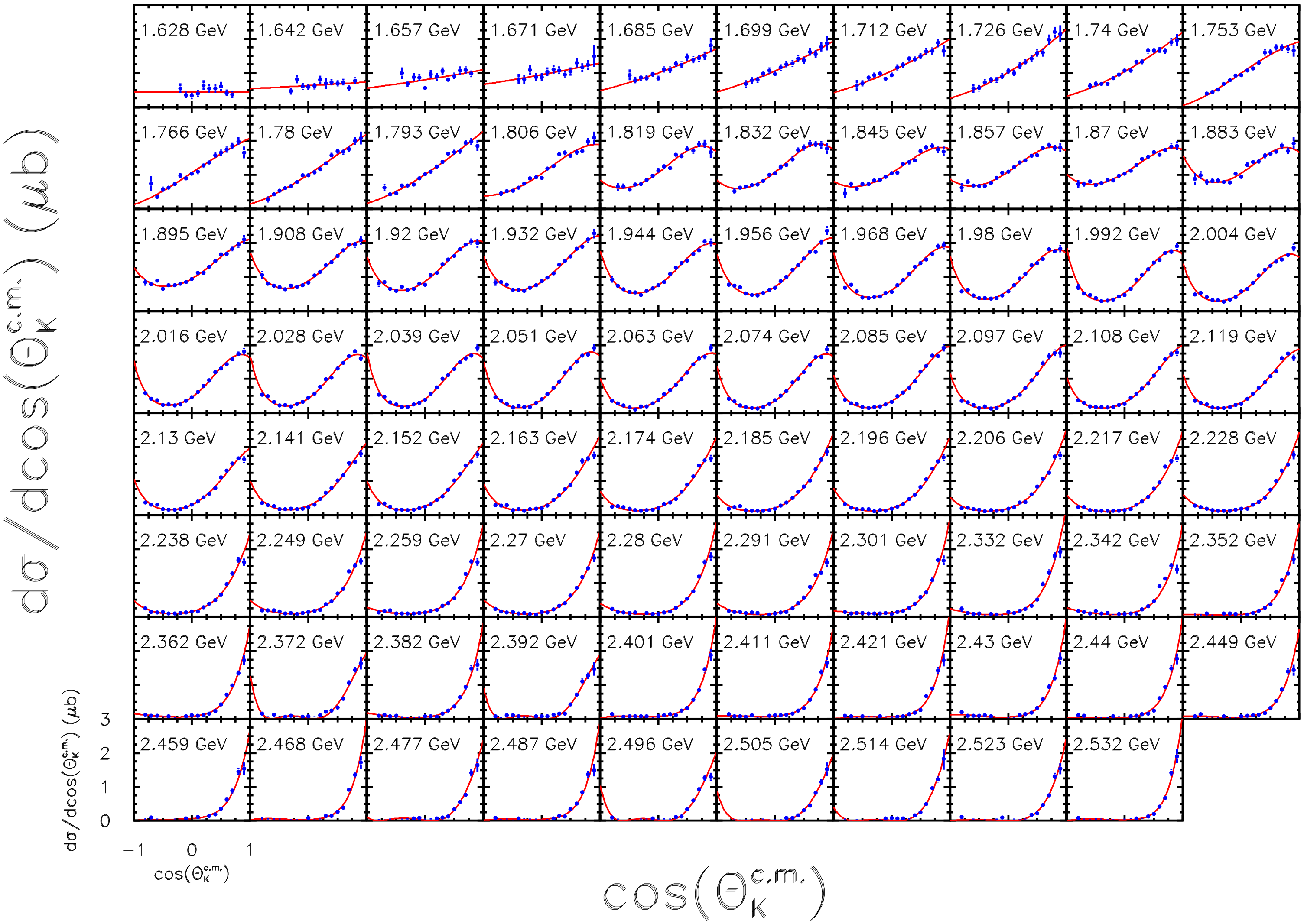
A.V. Anisovich *et al.*, Eur. Phys J. A **25** 427 (2005); Eur. Phys J. A **24,** 111 (2005);

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).

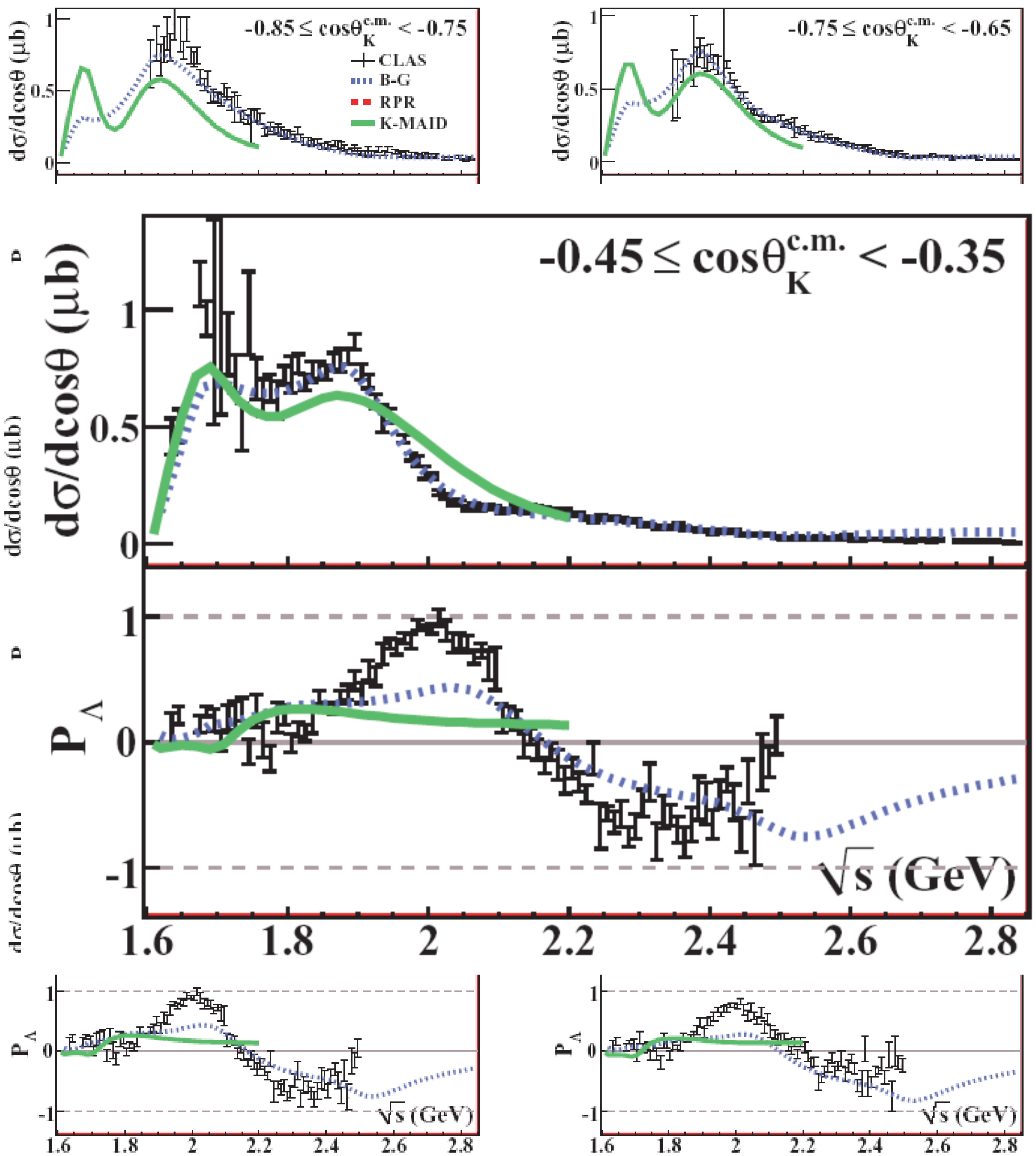
$\gamma p \rightarrow K^+\Lambda$: cross section

R. Bradford et al., Phys.Rev.C73, 035202 (2006)



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

$\gamma p \to K^+\Lambda$: 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

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

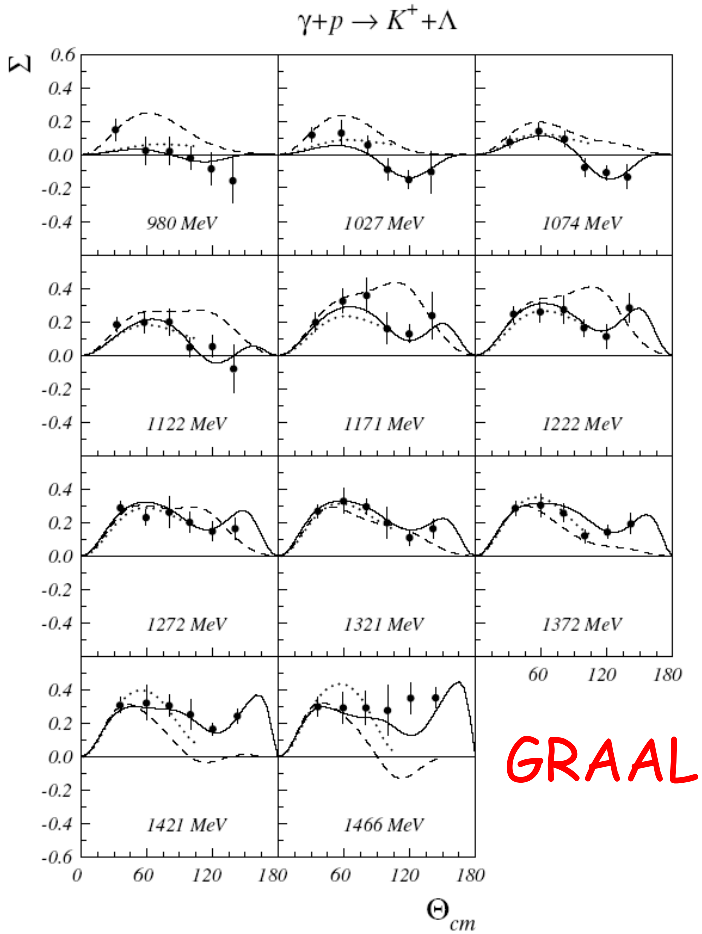


Fig. 14. Angular distributions of the beam asymmetries Σ for $\gamma p \rightarrow K^+\Lambda$ and γ-ray energies ranging from t 1500 MeV. Data are compared with the new solutions of the BCC (solid line), SAPCC (dashed line) and GRPI models.

GRAAL

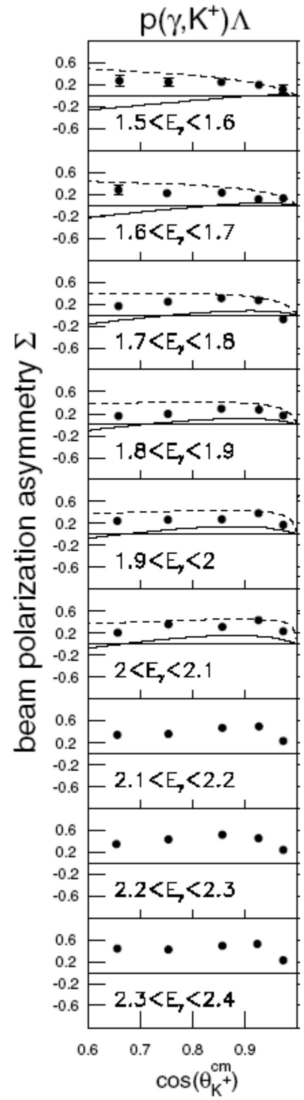


FIG. 3. Beam polarization asymmetries for the $p(\vec{\gamma}, K^+)\Lambda$ (left) and $p(\vec{\gamma}, K^+)\Sigma^0$ (right) reactions as a function of $\cos(\theta^{c.m.}_{K^+})$ for different photon-energy bins. The error bars are ... ons using ... Janssen ... rimental

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, $E_\gamma < 1.5$ GeV

LEPS $1.5 < E_\gamma < 2.4$ GeV

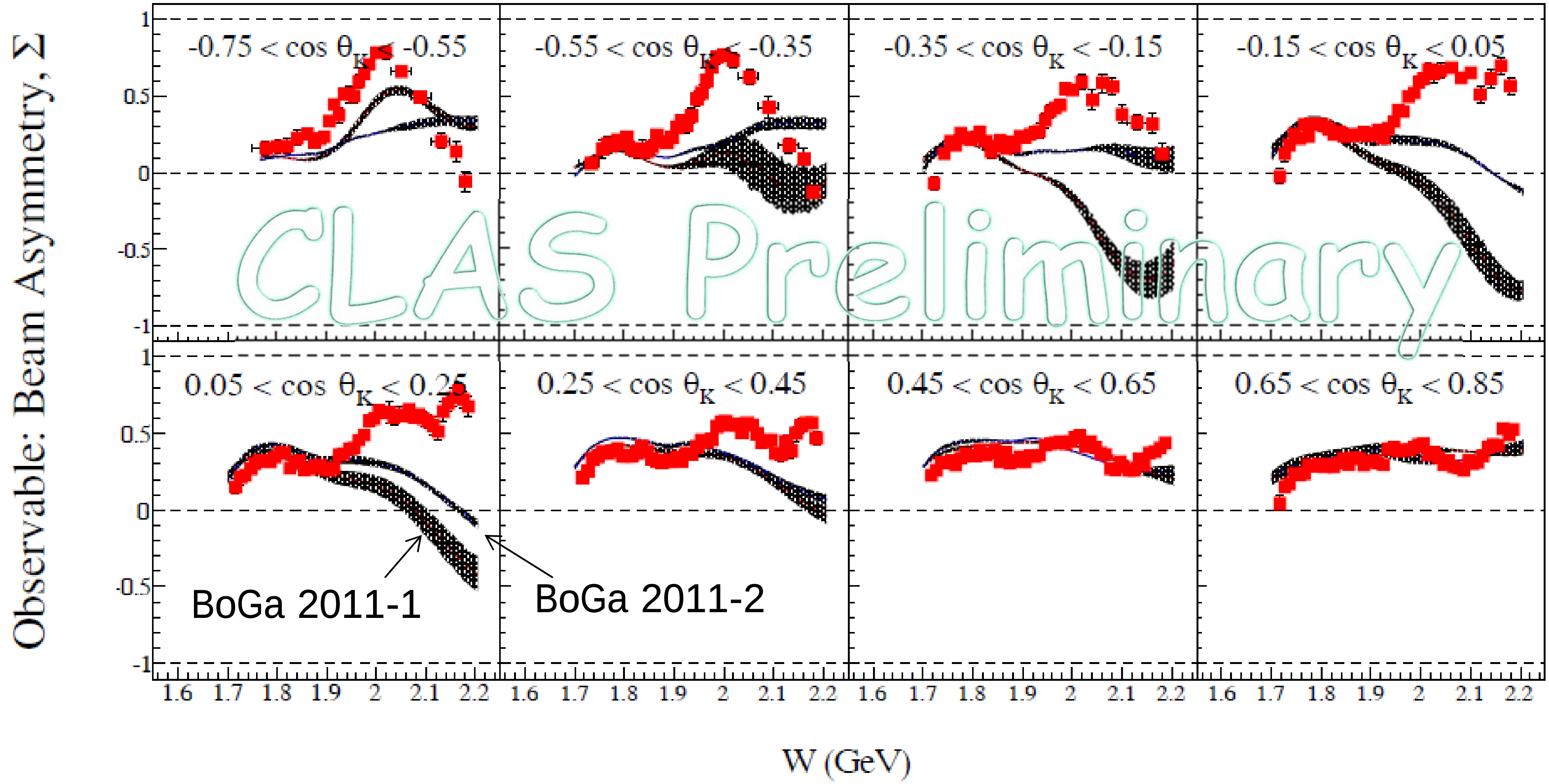
The trends are consistent: Σ is smooth and featureless at all energies and angles.

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).

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

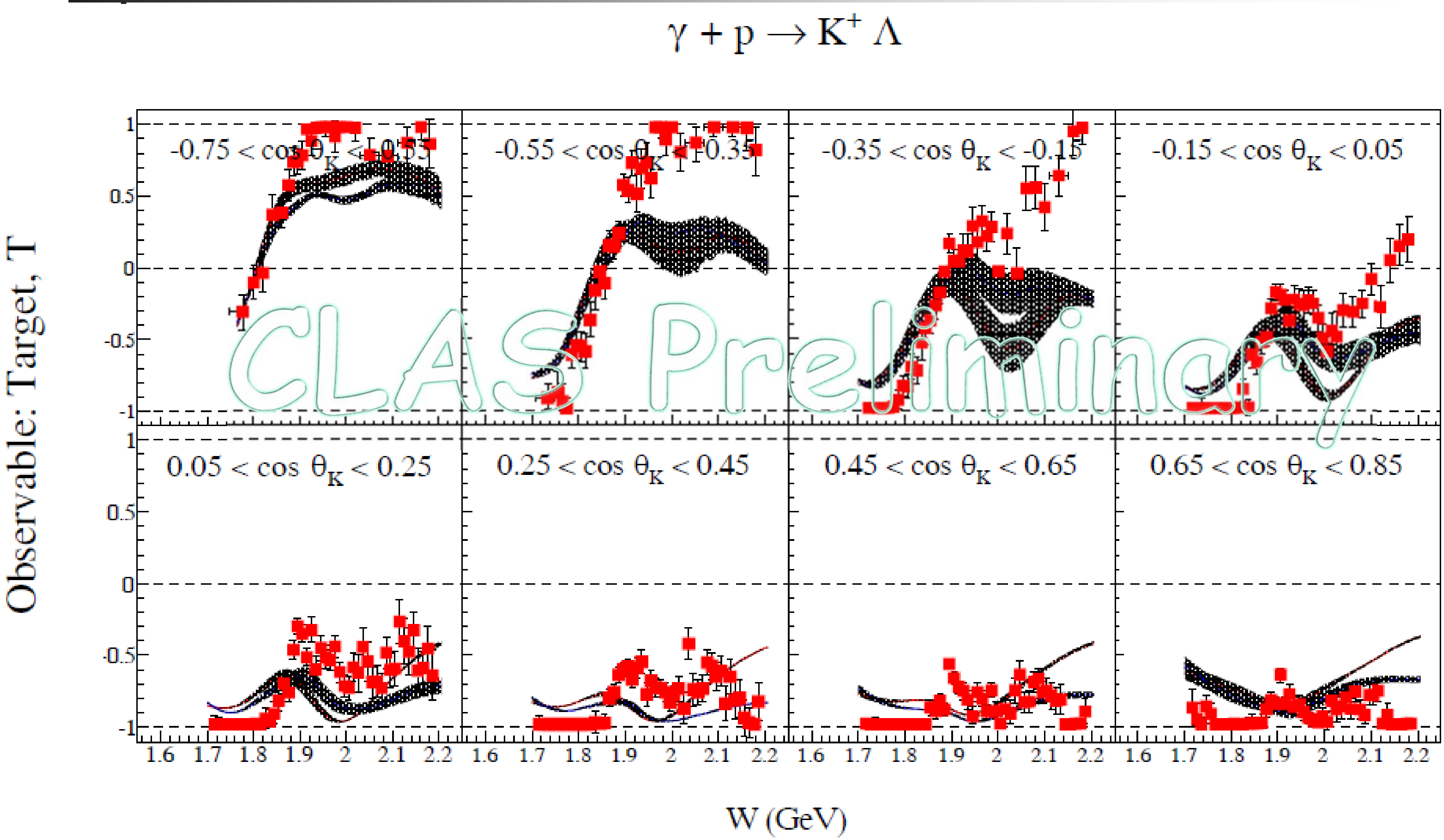
$$\frac{d\sigma}{d\Omega_{K^+}} = \left.\frac{d\sigma}{d\Omega_{K^+}}\right|_{unpol.} \left\{1 + \Sigma P_\gamma \cos 2\phi\right\}$$



Bonn-Gatchina model is <u>not</u> predictive in newly-measured kinematics

CLAS/Glasgow Preliminary

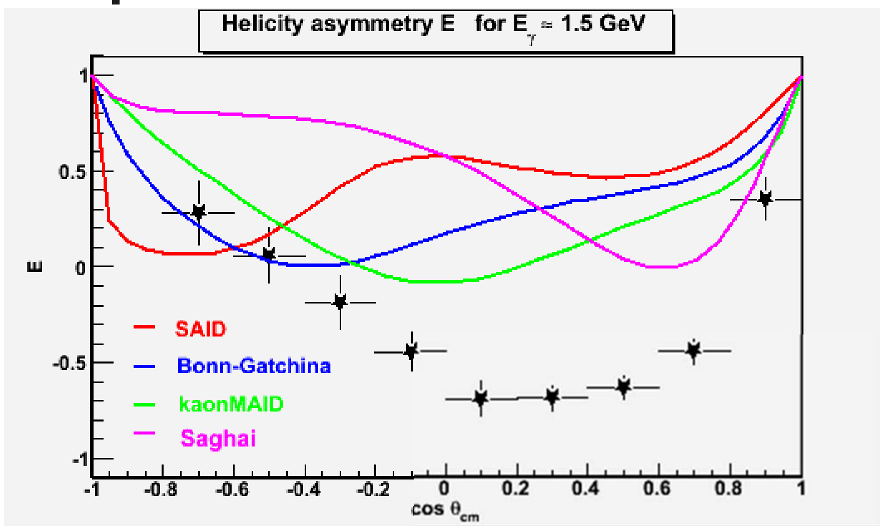
γp→K⁺Λ : target asymmetry T

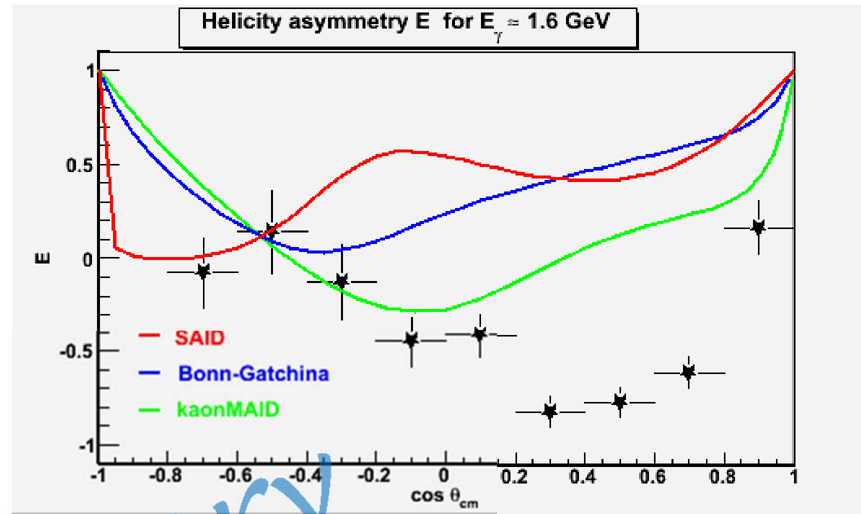


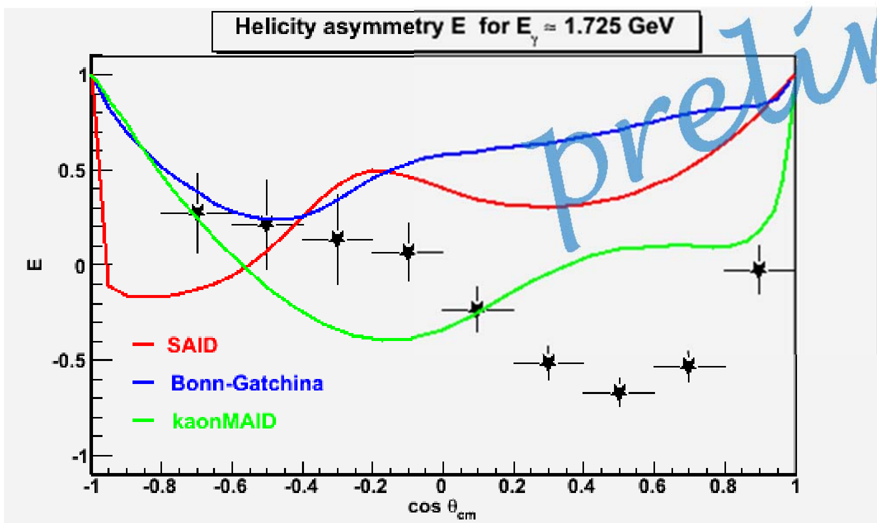
Bonn-Gatchina model is not predictive in newly-measured kinematics

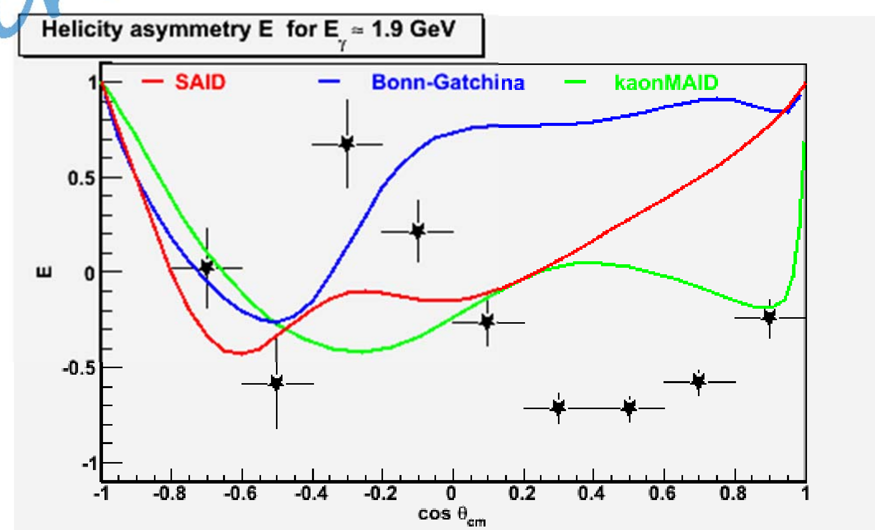
CLAS/Glasgow Preliminary

$\gamma p \rightarrow K^+\Lambda$: helicity asymmetry E



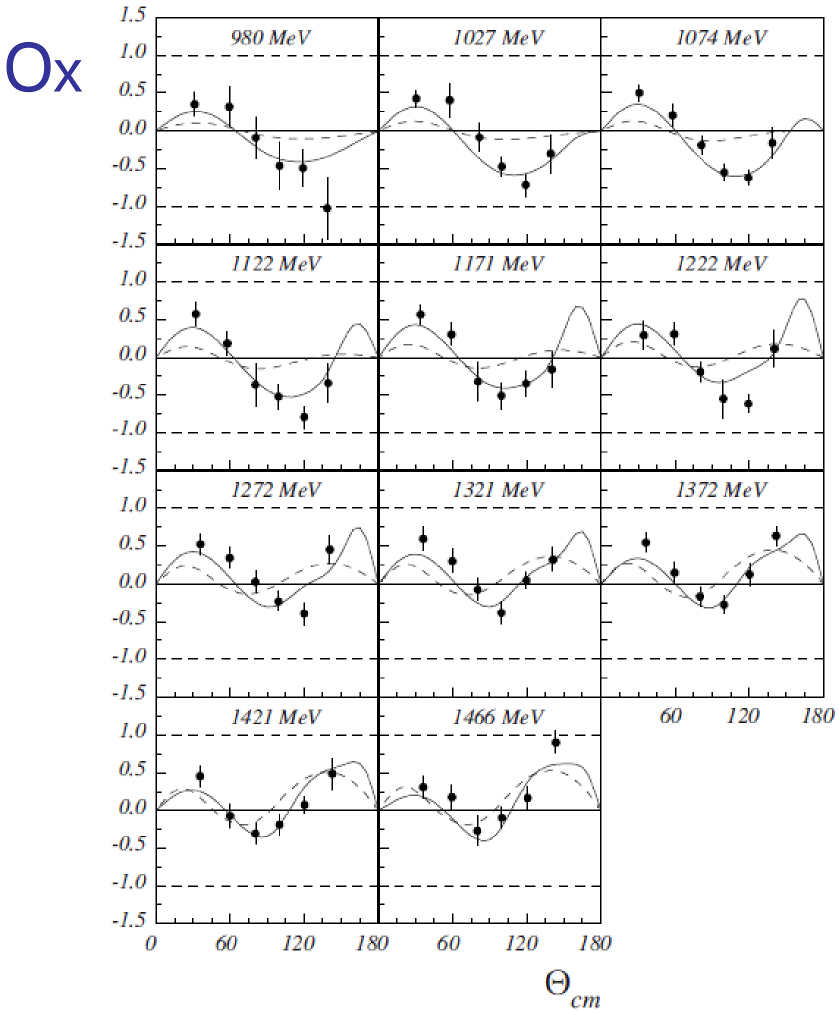






L. Casey, Catholic U.

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



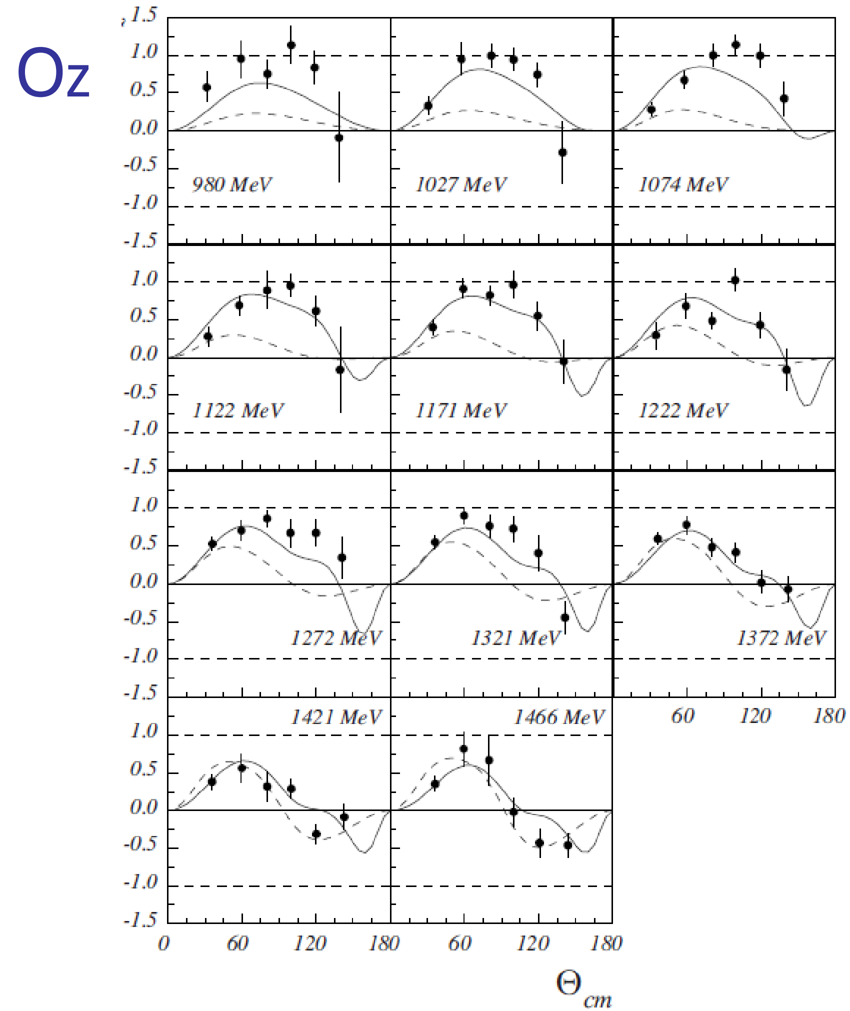


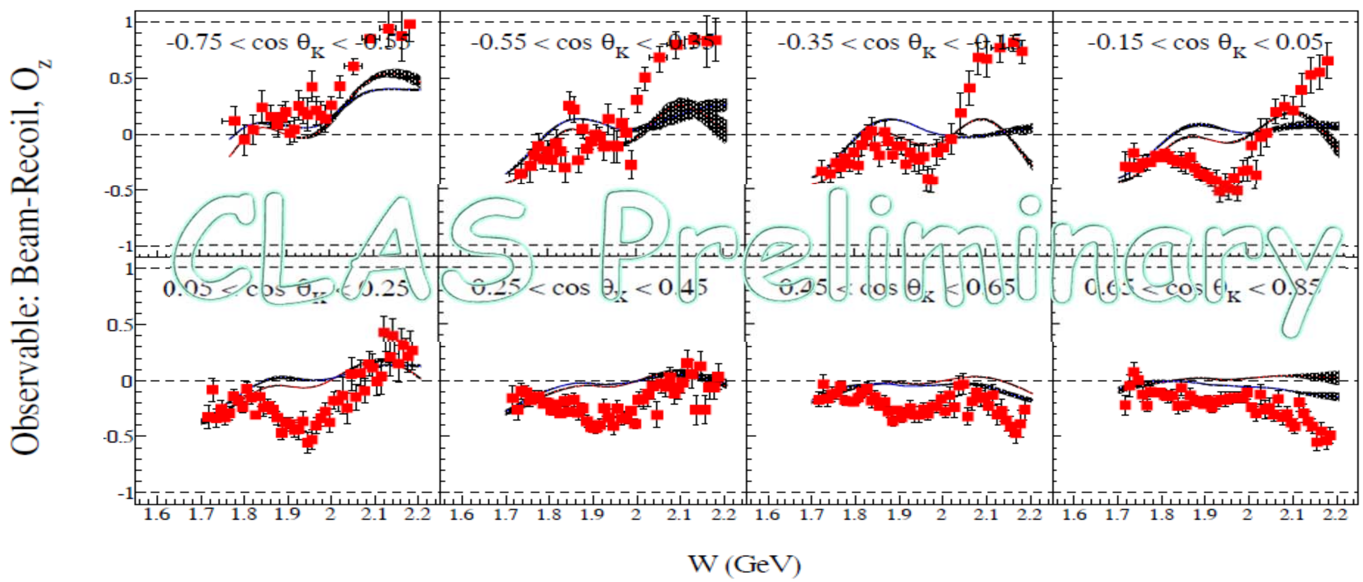
Fig. 9. Angular distributions of the beam-recoil observable O_x for photon energies E_γ ranging from 980 MeV to 1466 MeV. Error bars represent the quadratic sum of statistical and systematic errors. Data are compared with the predictions of the BG (solid line) and RPR (dashed line) models.

GRAAL data: fair agreement with BG and RPR models

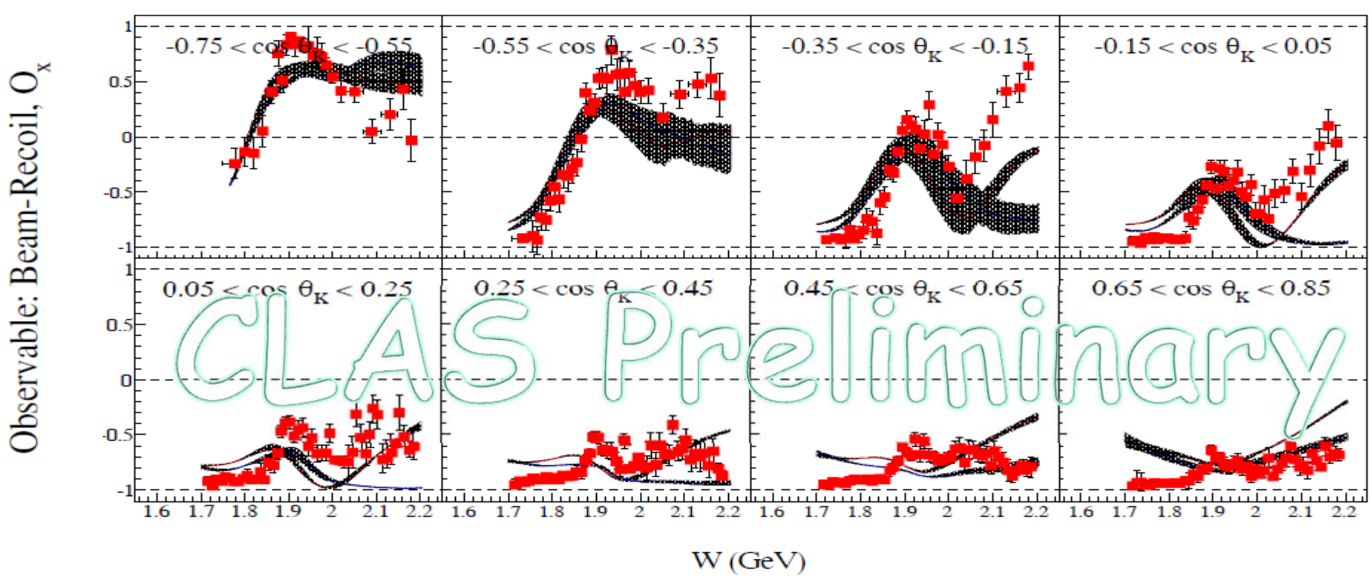
A. Lleres et al (GRAAL), Eur. Phys. J A 39, 149 (2009)

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

$\gamma + p \to K^+ \Lambda$



Ox

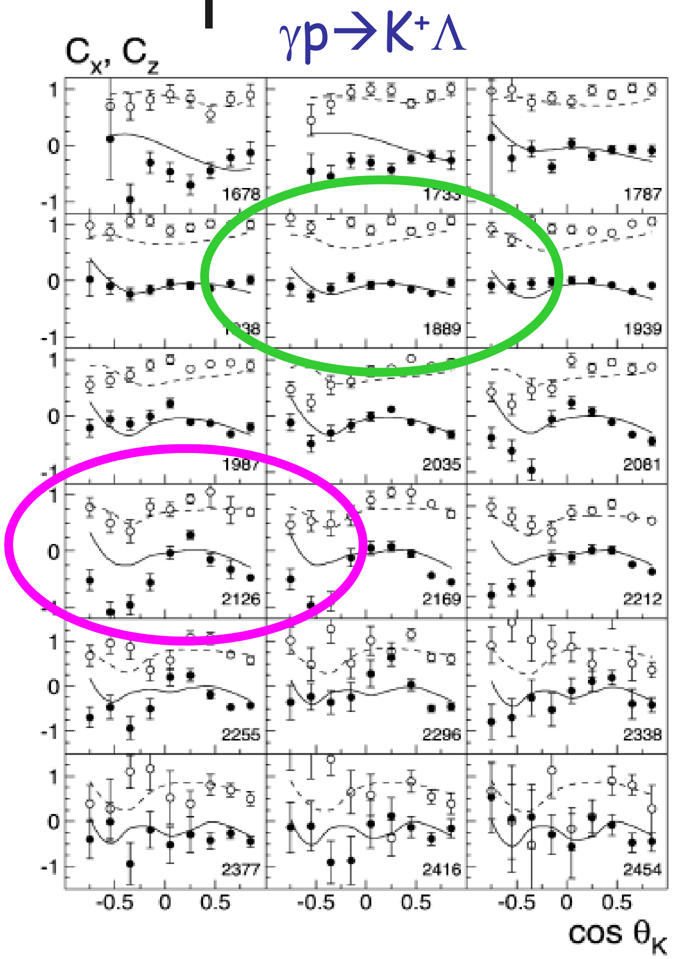


Oz

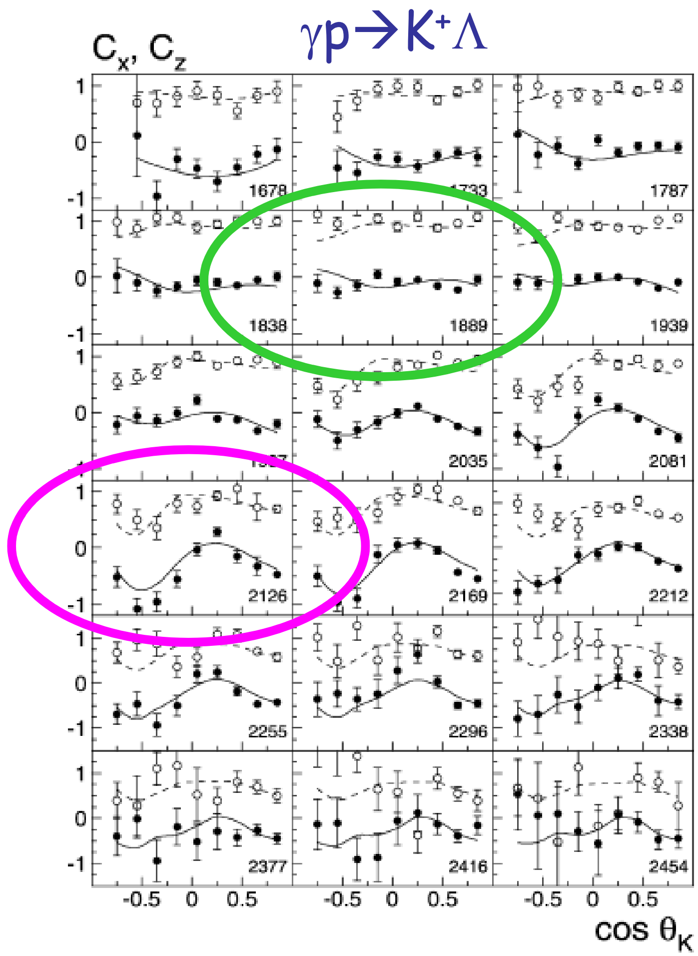
Bonn-Gatchina model is <u>not</u> predictive in newly-measured kinematics

CLAS/Glasgow Preliminary

$\gamma Y^* K^+$ | $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$ Beam-Recoil C_x and C_z

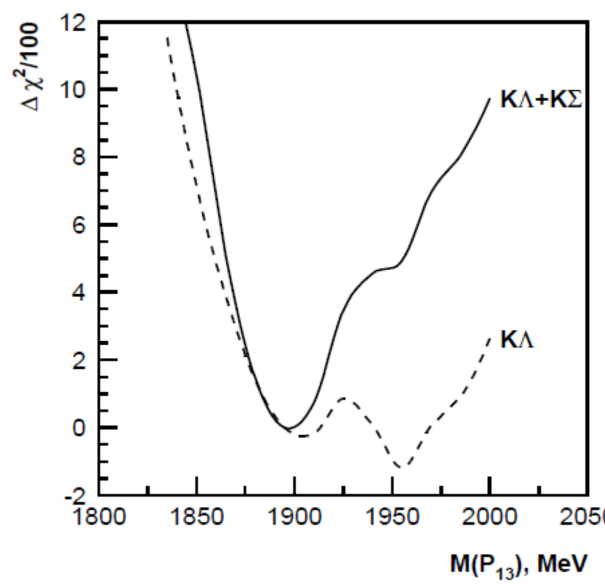


C_xC_z without N*(1900)P_{13}



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).

Lots more published…

- Omit results for Σ photoproduction
- Omit discussion of reactions on the neutron (deuteron), which teases isospin dependence apart.
- Overall goal: measure enough observables for "complete" amplitude determination ← extract N^* and Δ 's participating

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
$p\pi^0$	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)									g1, g8, g9
$n\pi^+$	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)									g1, g8, g9
$p\eta$	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)									g1, g11, g8, g9
$p\eta'$	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)									g1, g11, g8, g9
$p\omega$	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)									g11, g8, g9
$K^+\Lambda$	✔ (red)	✓ (black)	✓ (blue)	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (black)	✓ (black)	✓ (black)	✓ (black)	✔ (red)	✔ (red)	g1, g8, g11
$K^+\Sigma^0$	✔ (red)	✓ (black)	✓ (blue)	✔ (red)	✓ (black)	✓ (blue)	✓ (black)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (black)	✓ (black)	✓ (black)	✓ (black)	✔ (red)	✔ (red)	g1, g8, g11
$K^{0*}\Sigma^+$	✔ (red)										✓ (black)	✓ (black)			✓ (black)	✓ (black)	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
$p\pi^-$	✓ (red)	✓	✓ (blue)		✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)									g2, g10 (red), g13, g14 (blue)
$p\rho^-$	✓	✓	✓ (blue)		✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)									g2, g10, g13, g14 (blue)
$K^0\Lambda$	✓	✓	✓ (blue)	✓	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓	✓	✓	✓	g13, g14 (blue)
$K^0\Sigma^0$	✓	✓	✓ (blue)	✓	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)	✓	✓	✓	✓	g13, g14 (blue)
$K^+\Sigma^-$	✓ (red)	✓	✓ (blue)		✓ (blue)	✓ (blue)	✓ (blue)	✓ (blue)									g10, g13, g14 (blue)
$K^{0*}\Sigma^0$	✓	✓															g10, g13

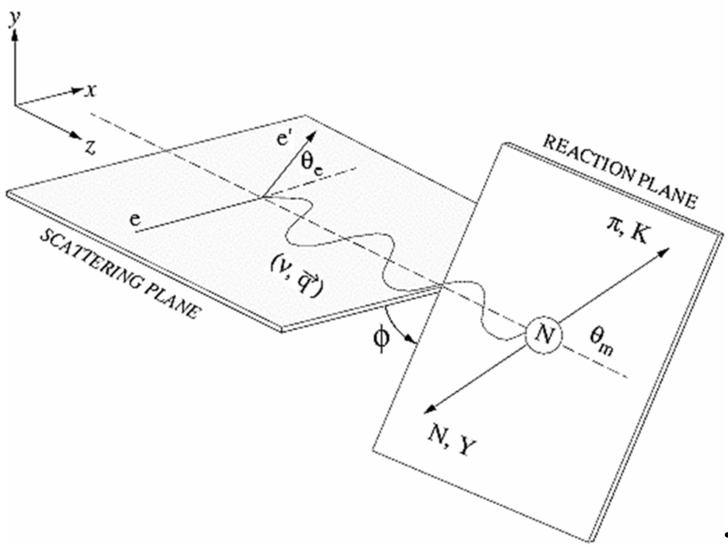
The combination of all of these measurements on proton and neutron targets represents an extremely powerful tool in the search for new baryon states.

Source: V. D. Burkert

Ground States
- Electroproduction

Structure Functions

For unpolarized target & polarized e⁻ beam:



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

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

CLAS ep Data Set Overview

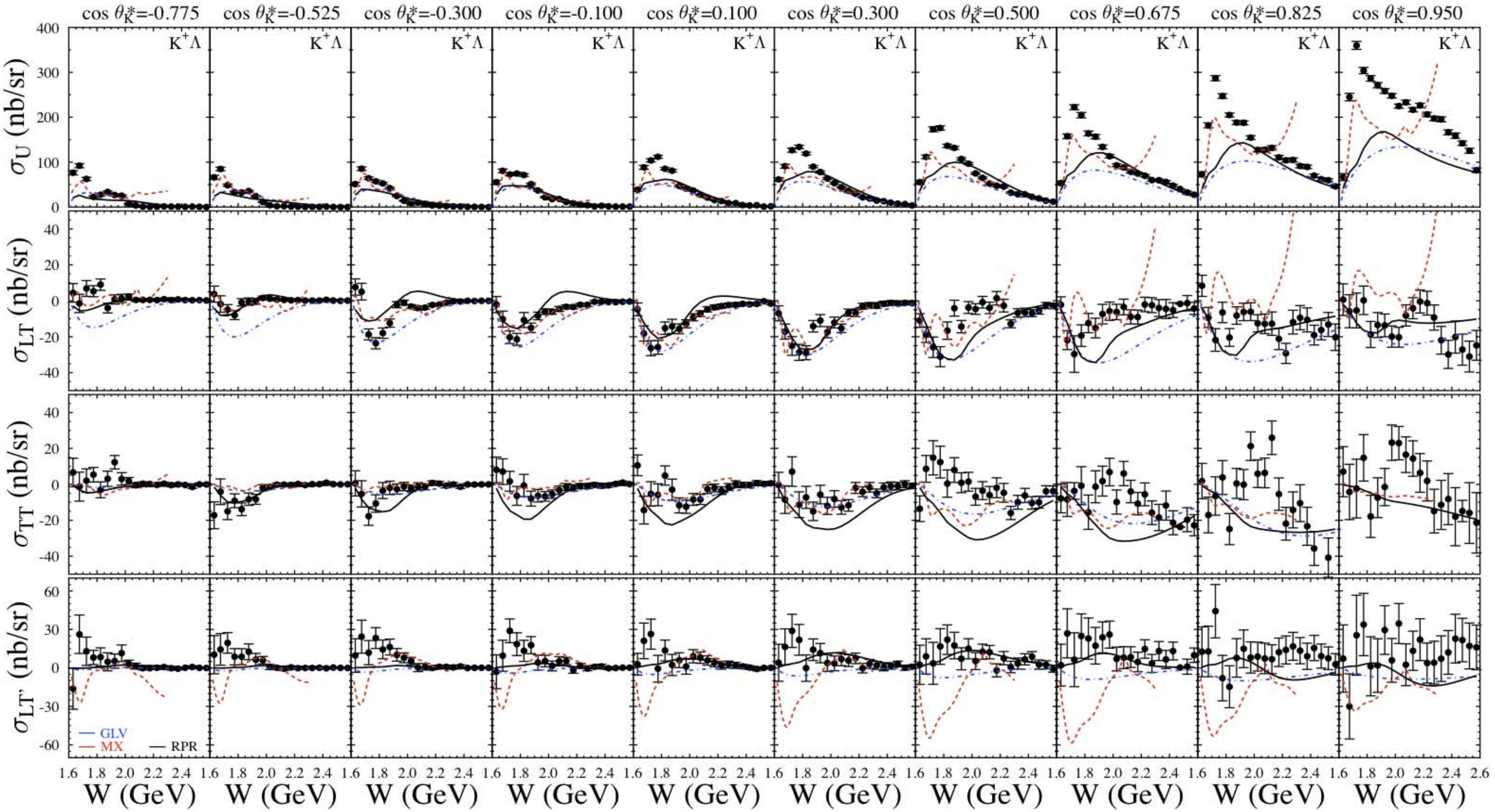
#	Run	E_b (GeV)	Trig.
1	e1c	2.567	900
2	e1c	4.056	370
3	e1c	4.247	620
4	e1c	4.462	420
5	e1d	4.817	300
6	e1-6	5.754	4500
7	e1f	5.499	5000
8	e1g	3.178	2500

- $K^+\Lambda$ recoil pol.
  - *W=1.6-2.7 GeV, <Q^2>=1.9 GeV^2*
    [Gabrielyan et al., arXiv:1406.4046 (2014)]

Publications:

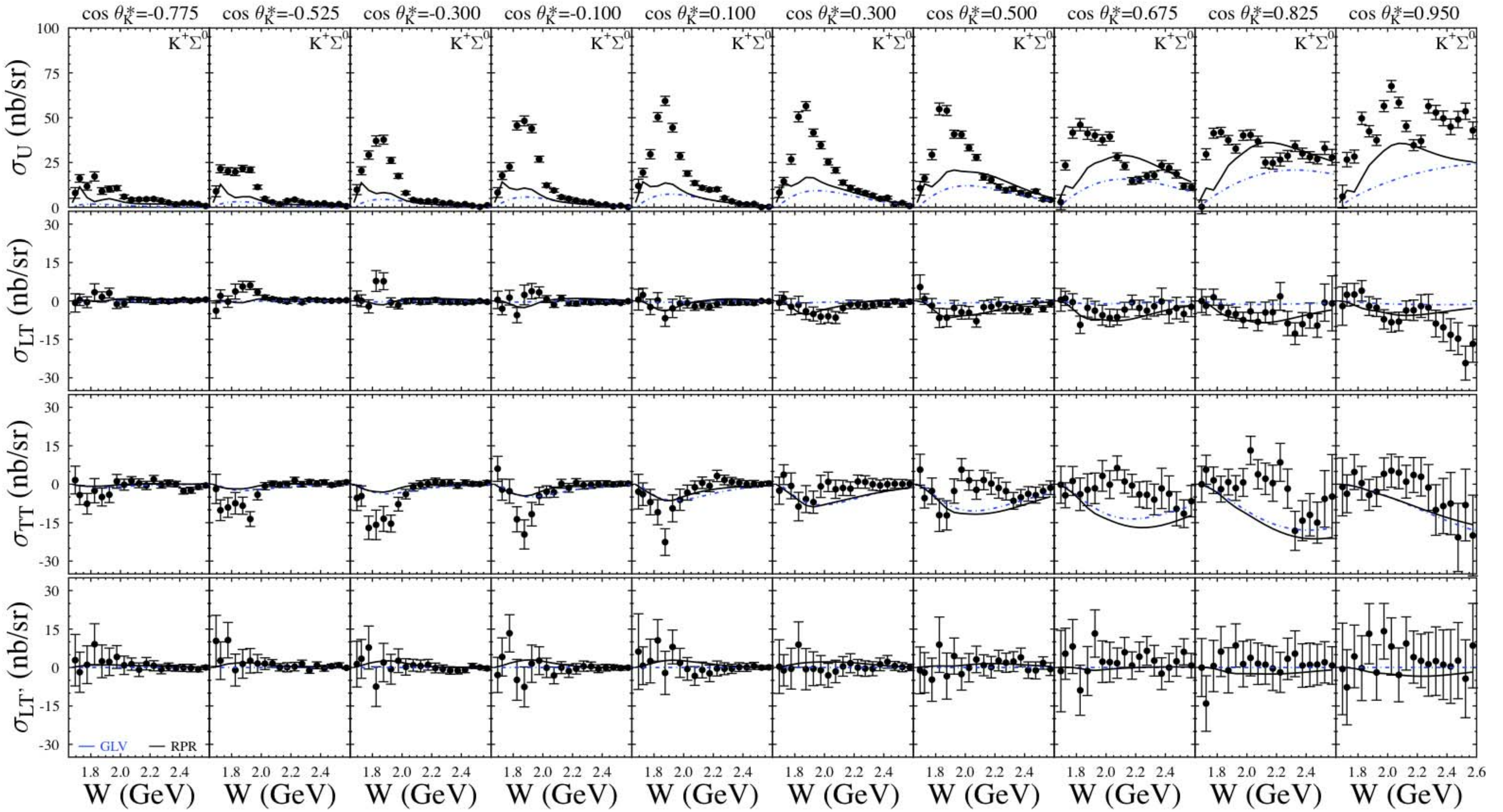
- $K^+\Lambda$ beam-recoil pol. transfer
  - *W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2*
    [Carman et al., PRL 90, 131804 (2003)]
- $K^+\Lambda$ σ_L/σ_T ratio from pol. transfer data
  - *W=1.72-1.98 GeV, Q^2~0.7 GeV^2*
    [Raue & Carman, PRC 71, 065209 (2005)]
- $K^+\Lambda$, $K^+\Sigma^0$ separated structure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

$\gamma_v^* Y^+$ | $K^+\Lambda$ 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)]*

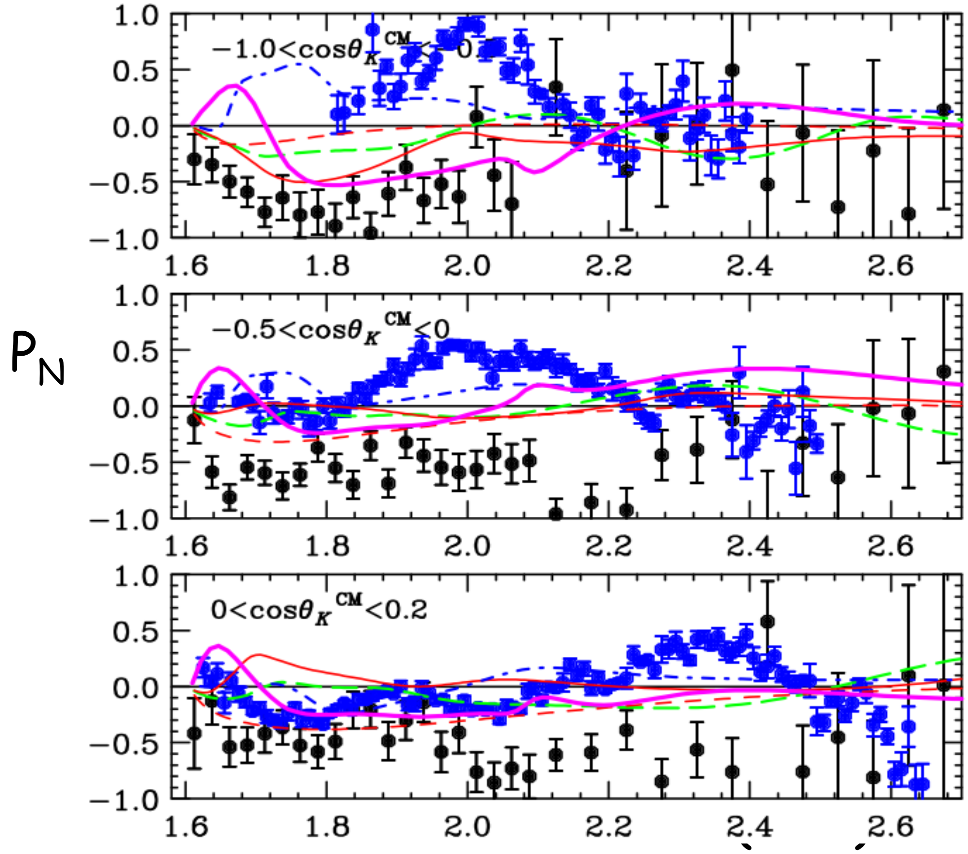
$\gamma\, Y^* \,|\, K^+$ $K^+\Sigma^0$ Structure Functions

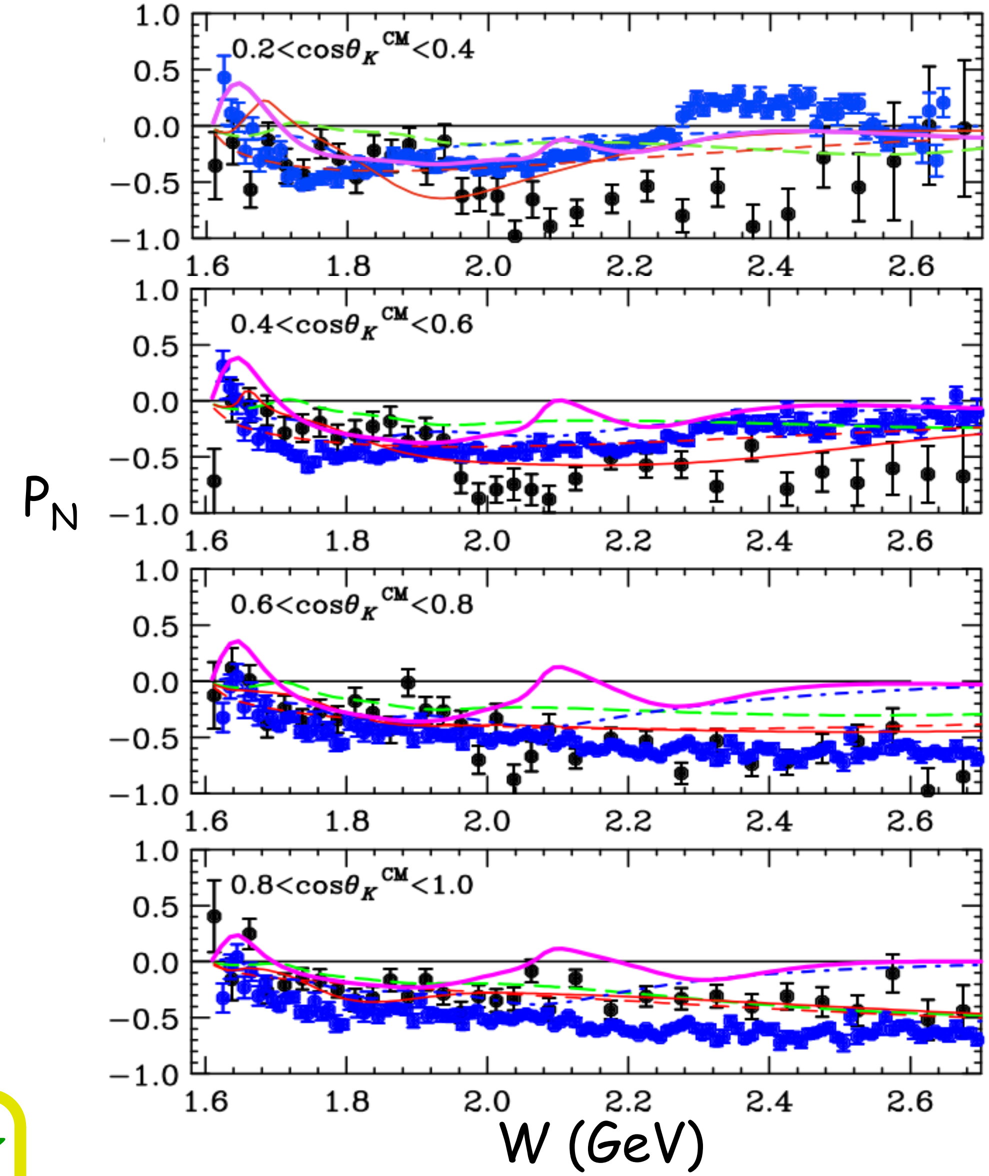


E = 5.5 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2

[Carman et al., PRC 87, 025204 (2013)]

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





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

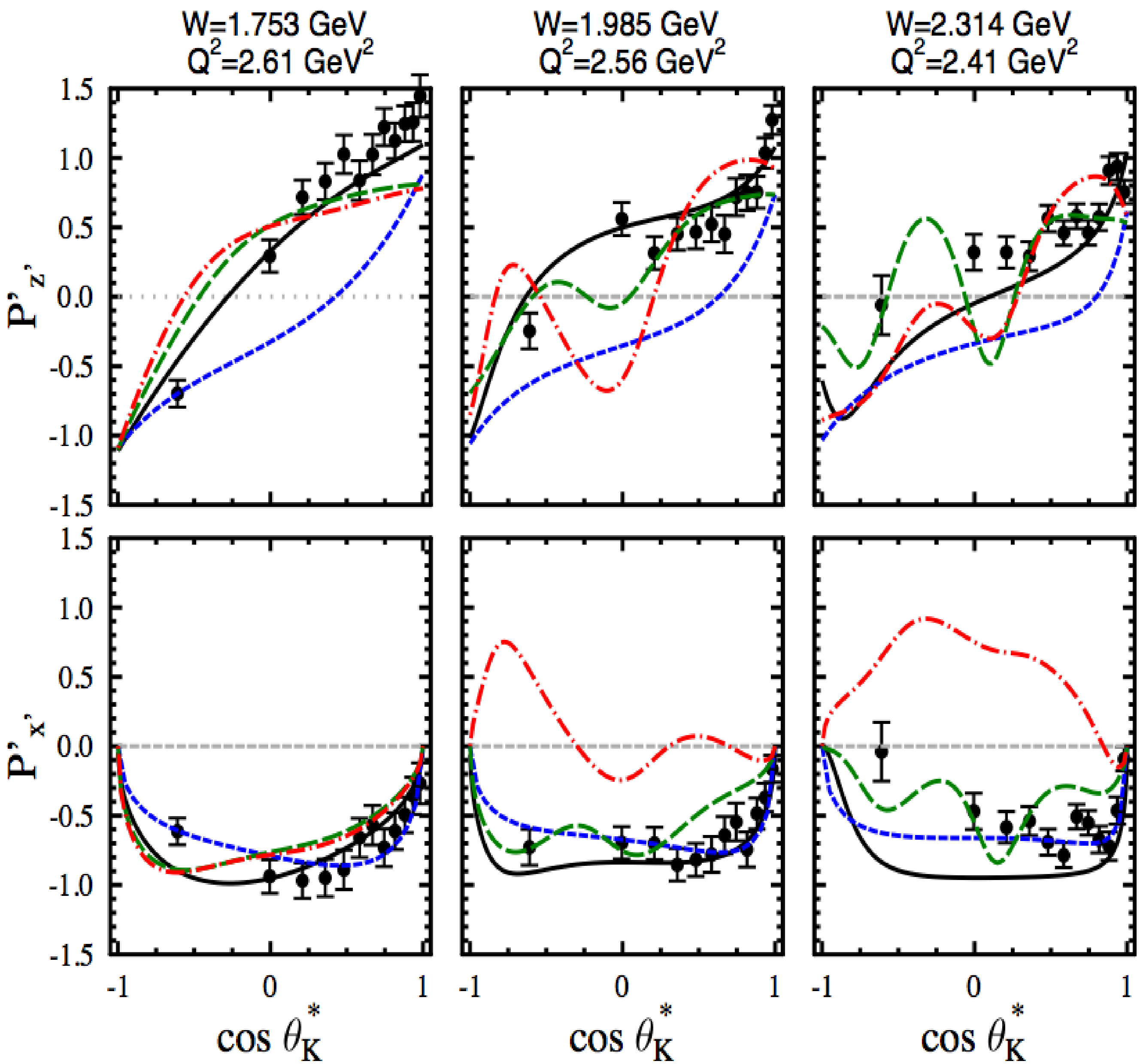
[Gabrielyan et al., arXiv:1406.4046, (2014)]

Kaon-Maid *Maxwell* *RPR-2007*

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

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

γ Y^* K^+ | Transfer Polarization $\vec{e}p \rightarrow e'K^+\vec{\Lambda}$



5.754 GeV
Summed over Q^2, Φ

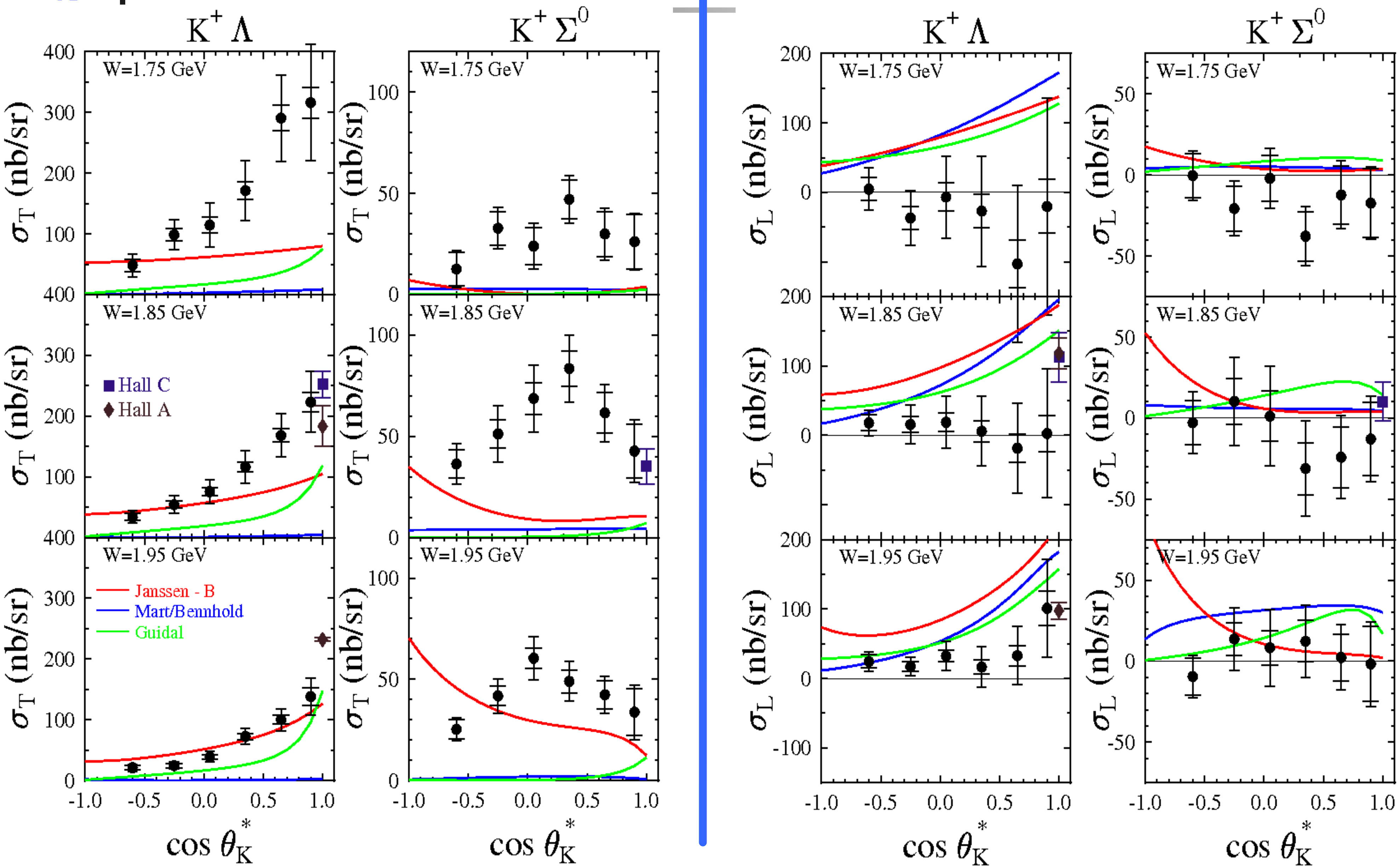
- Data not included in fits
- Rule out $P_{11}(1900)$ assignment
- $D_{13}(1900)$ not ruled out via P' data but with S.F. data

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)]

L/T Separation

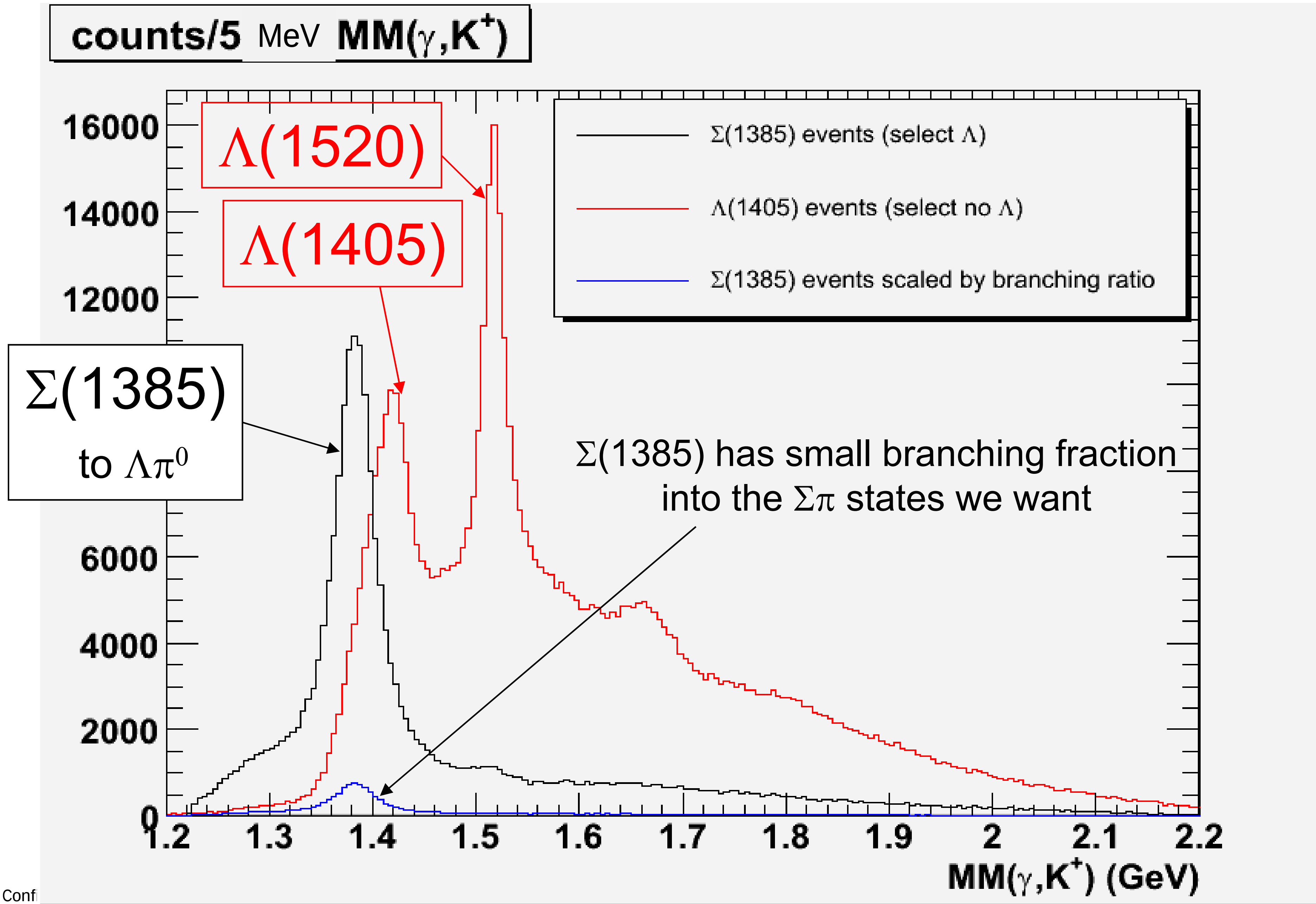


[Ambrozewicz et al., PRC 75, 045203 (2007)]

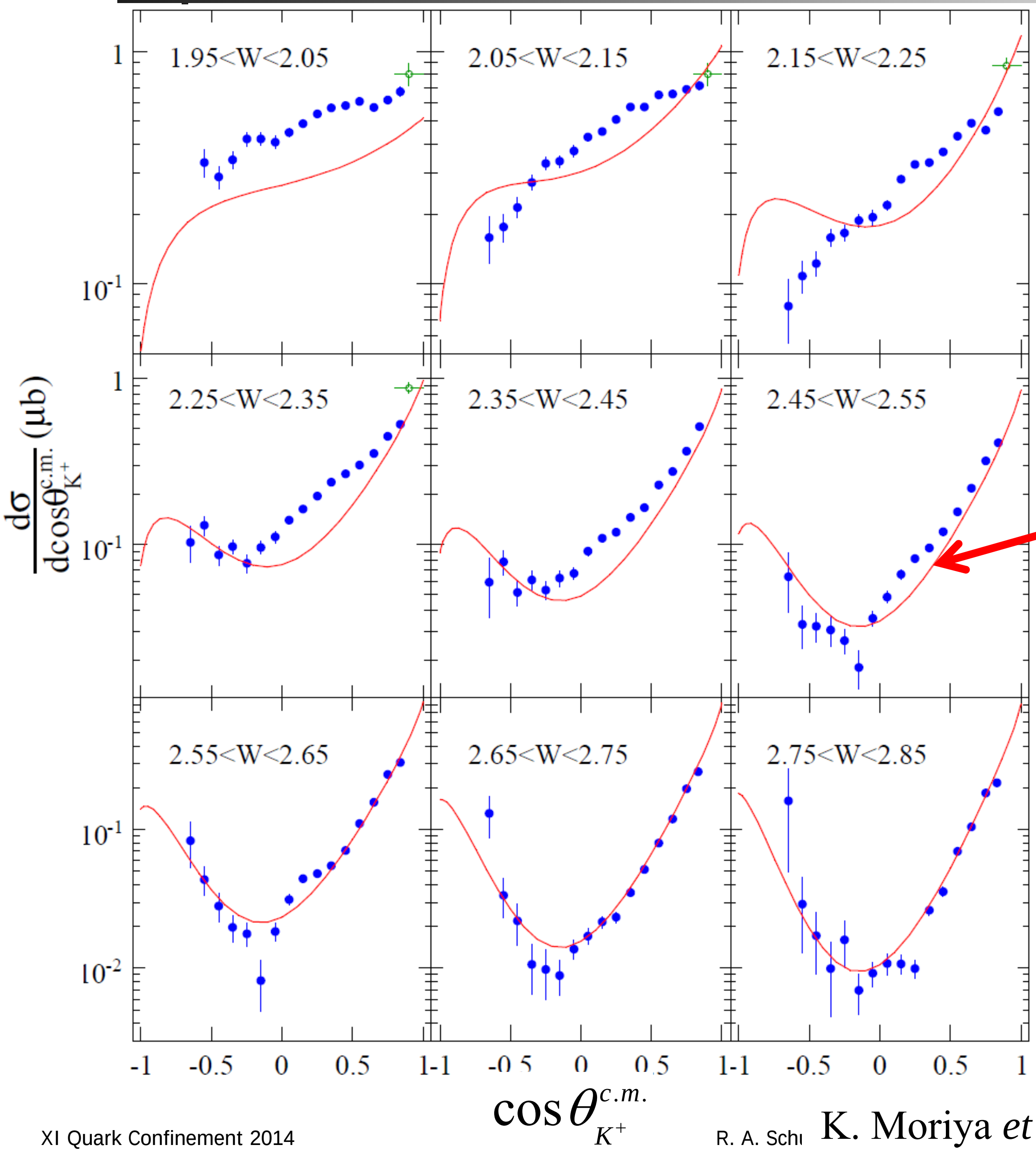
Excited Y* Cross Sections

Publication: Differential Photoproduction Cross Sections of Σ^0(1385), Λ(1405) and Λ(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

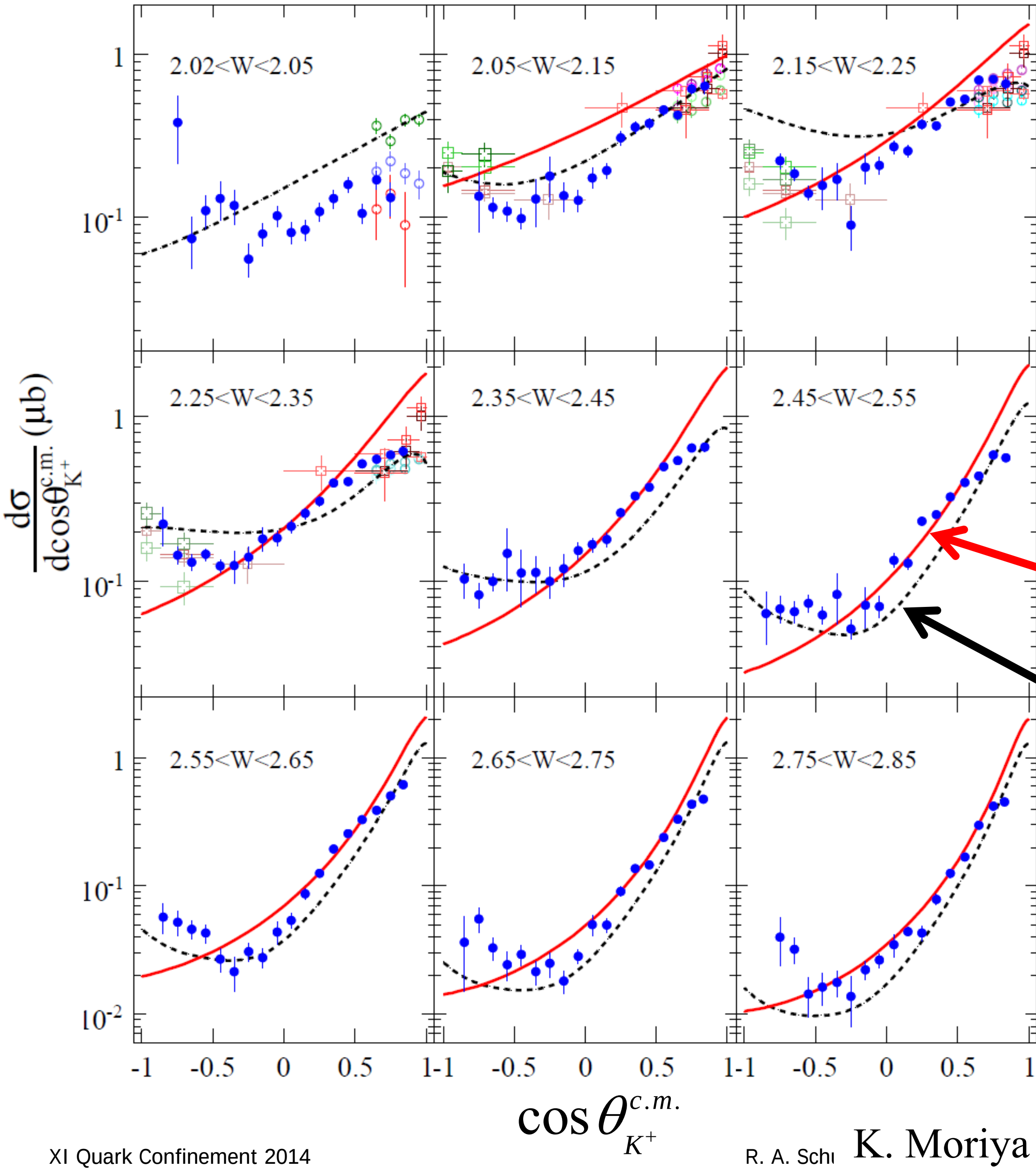


K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
- 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)

Differential Λ(1520) Cross Section

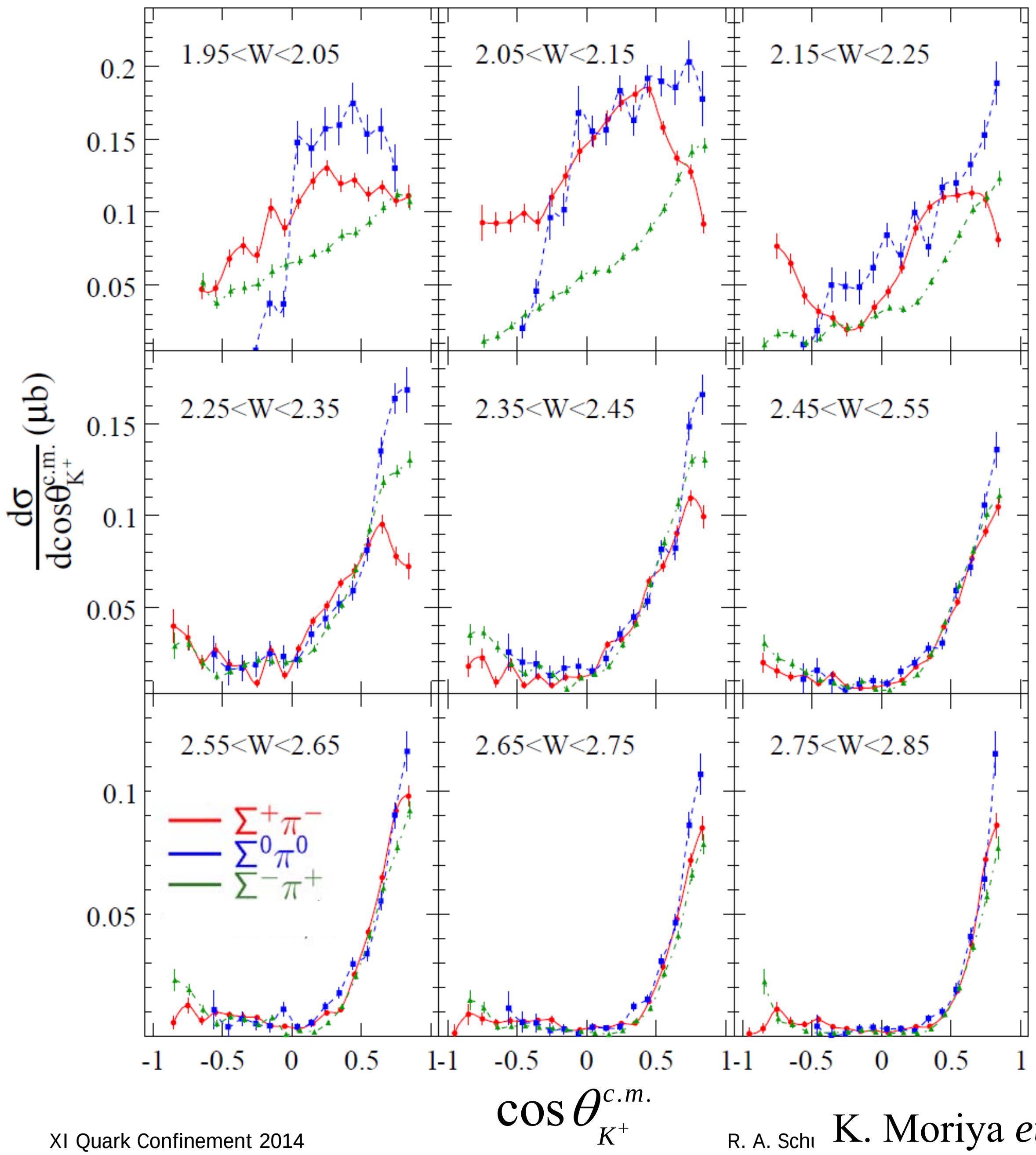


- $\gamma + p \rightarrow K^+ + \Lambda(1520)$
- Experiment: see t-channel-like forward peaking & u-channel backward rise
  - Agreement with LEPS[1,2]
- Theories:
  - Nam & Kao[3]: contact term dominant; no K^* or u-channel exchanges
  - He & Chen[4]: K^* and $N(2080)D_{13}$ $J^P=3/2^-$ added

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).

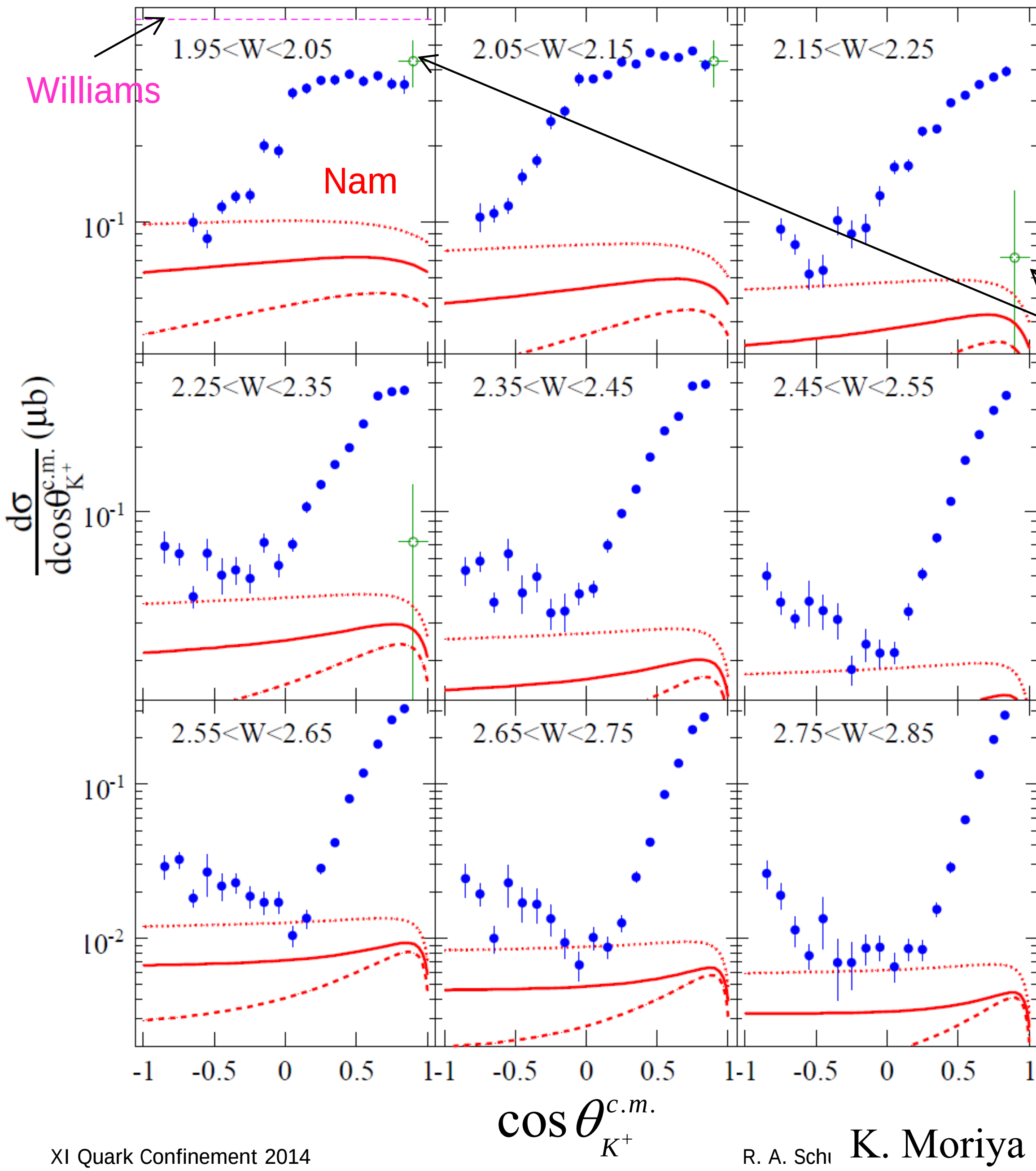
Differential Λ(1405) Cross Section



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

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

Differential Λ(1405) Cross Section

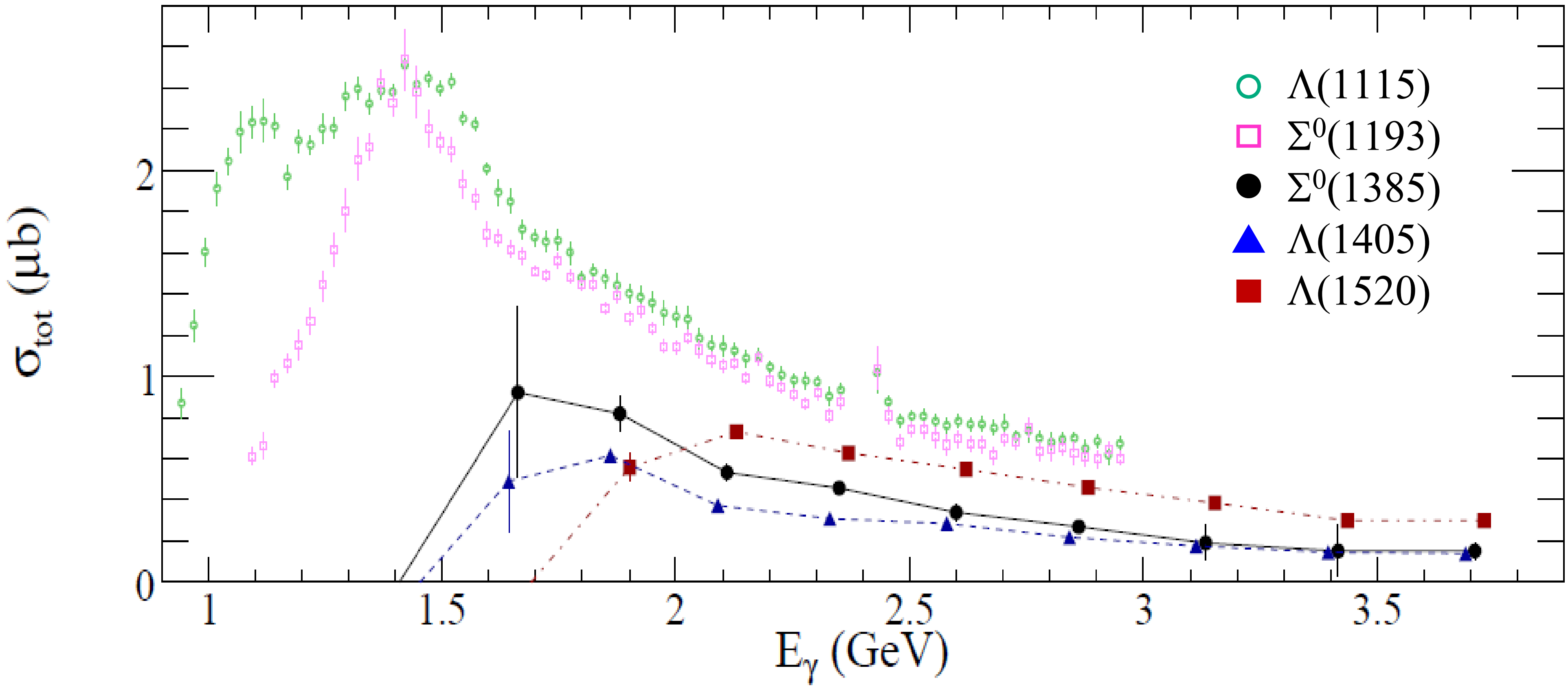


- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Sum three Σπ decay modes → "net" differential cross section
  - Mixed agreement with LEPS data[1]
- Theories:
  - Nam et al.[2]: s-channel Born term dominant ; K^* exchange for 3 values of $g_{K^*N\Lambda^*}$
  - Williams, Ji, Cotanch[3]: crossing and duality contraints; no N^*, estimated $g_{KN\Lambda^*}$

1. M. Niiyama et al. (LEPS) Phys Rev **C78**, 035202 (2008)
2. S.I. Nam et al., J. Kor. Phys. Soc. **59**, 2676 (2011)
3. R. Williams et al., Phys. Rev. **C43**, 452 (1991)

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)

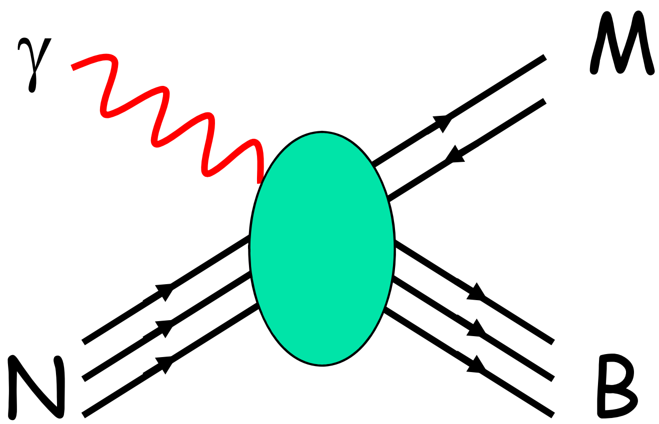
K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

Dimensional Scaling of $K\Lambda$

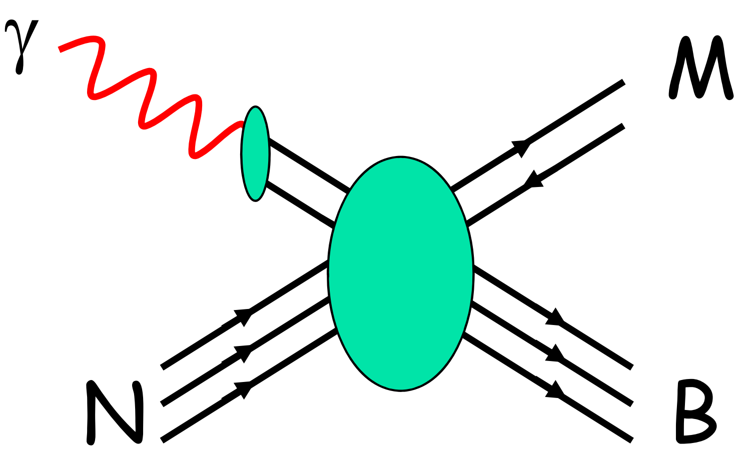
Publication: Scaling and Resonances in Elementary $K^{+}\Lambda$ Photoproduction, R.A. Schumacher and M.M. Sargsian Phys. Rev. C **83** 025207 (2011).

Constituent-Counting Scaling

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



n=9

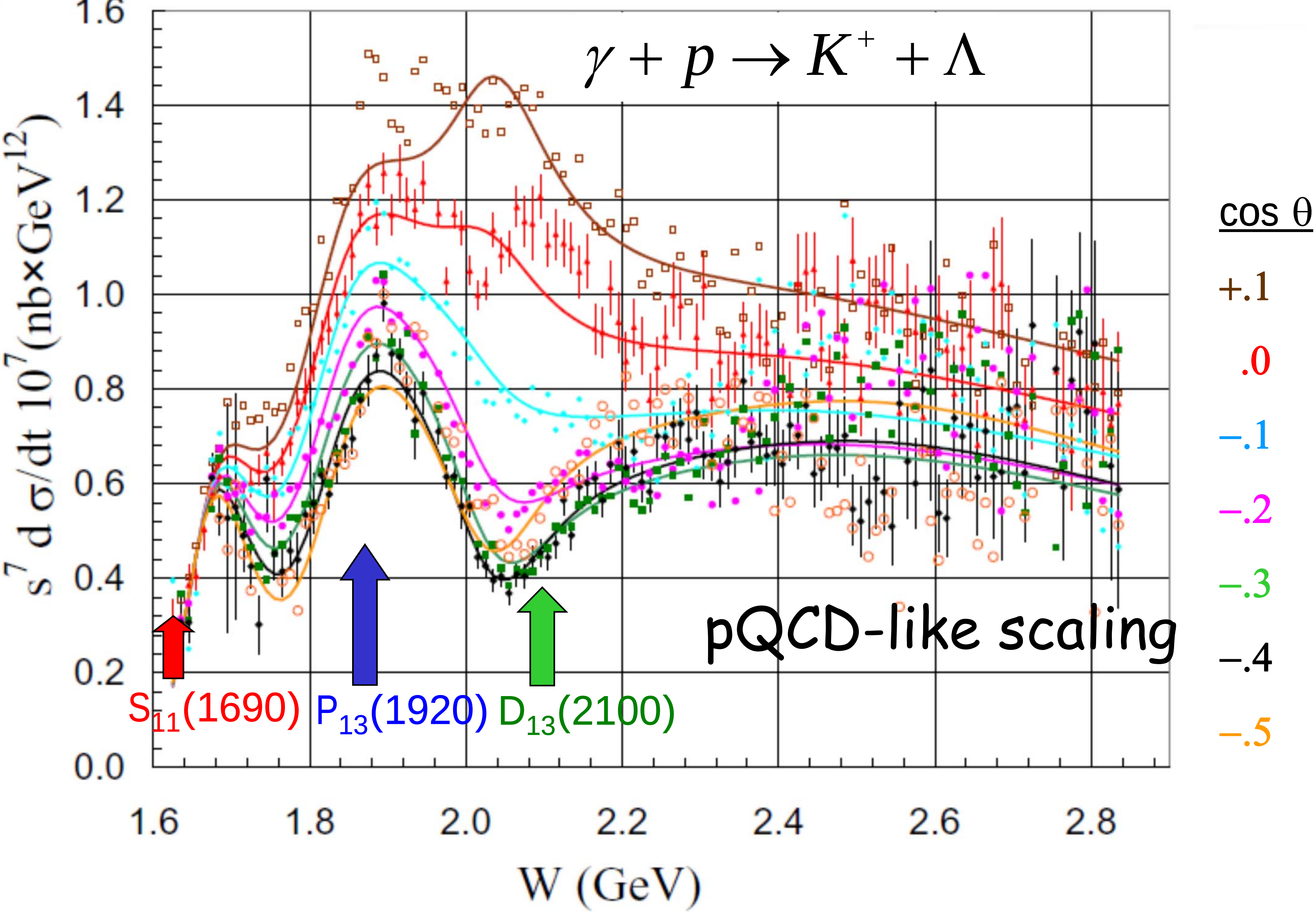


n=10

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

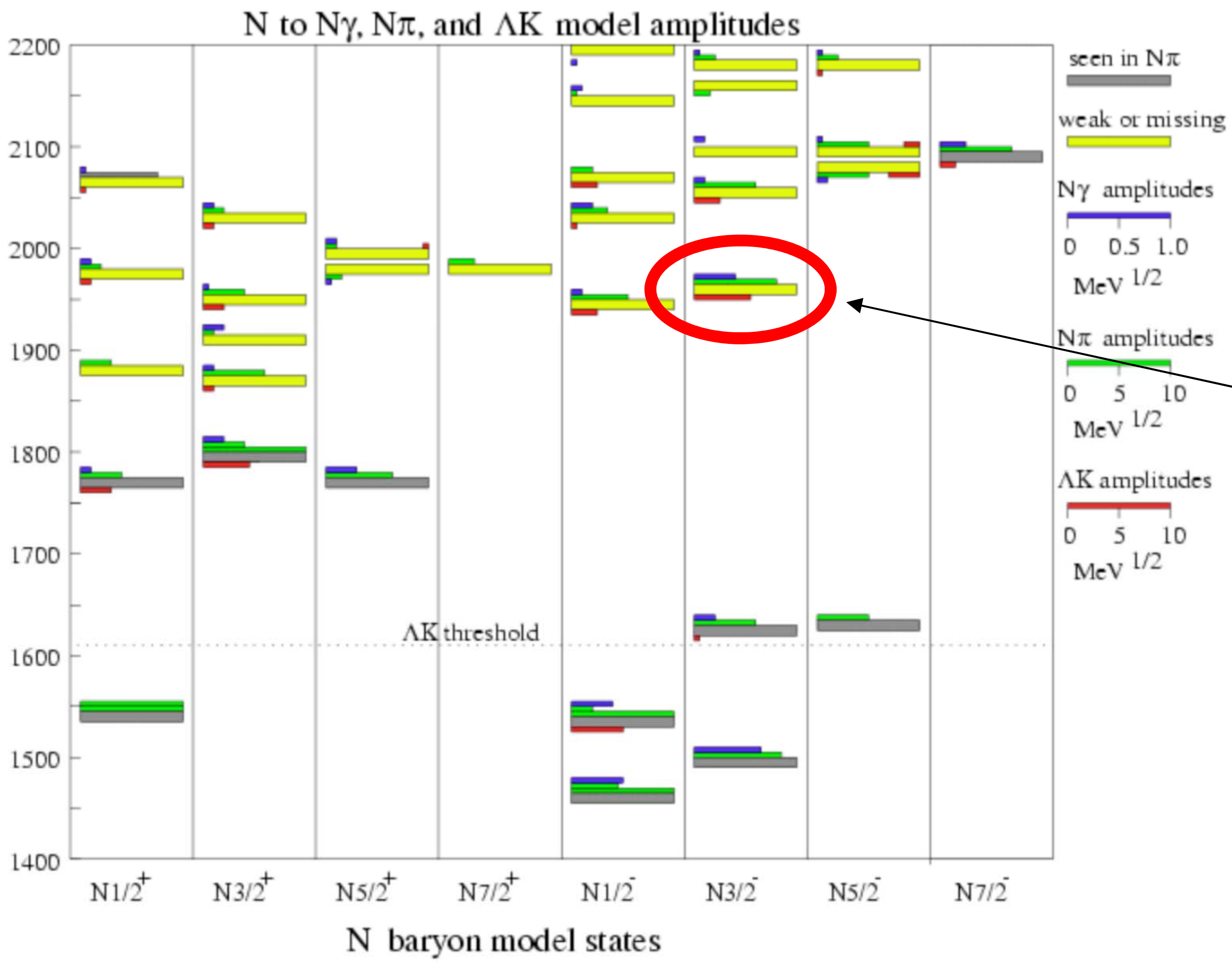
S. J. Brodsky and G. R. Farrar, PRL **31**, 1153 (1973)

Resonance Fit to Cross Section



R.A. Schumacher and M.M. Sargsian Phys. Rev. C **83** 025207 (2011)

N* Baryons: Seen & "Missing"



- Relativised 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).

Λ(1405) and Chiral Unitary Models

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

Chiral Unitary Models (example 1)

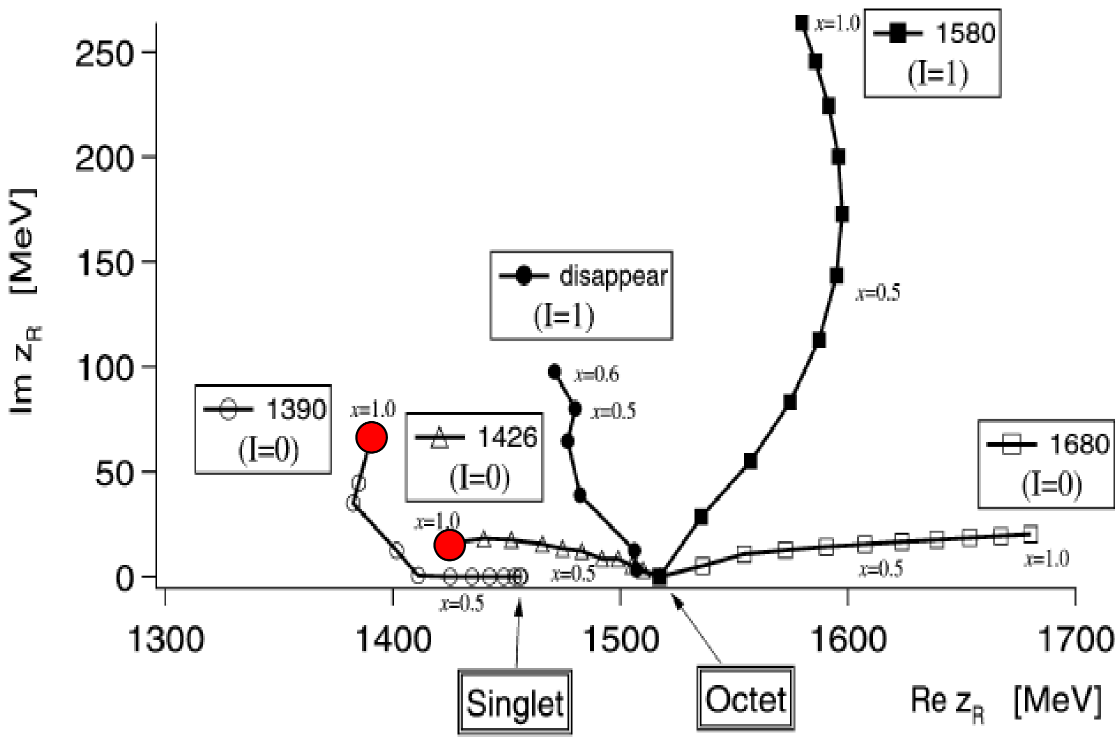
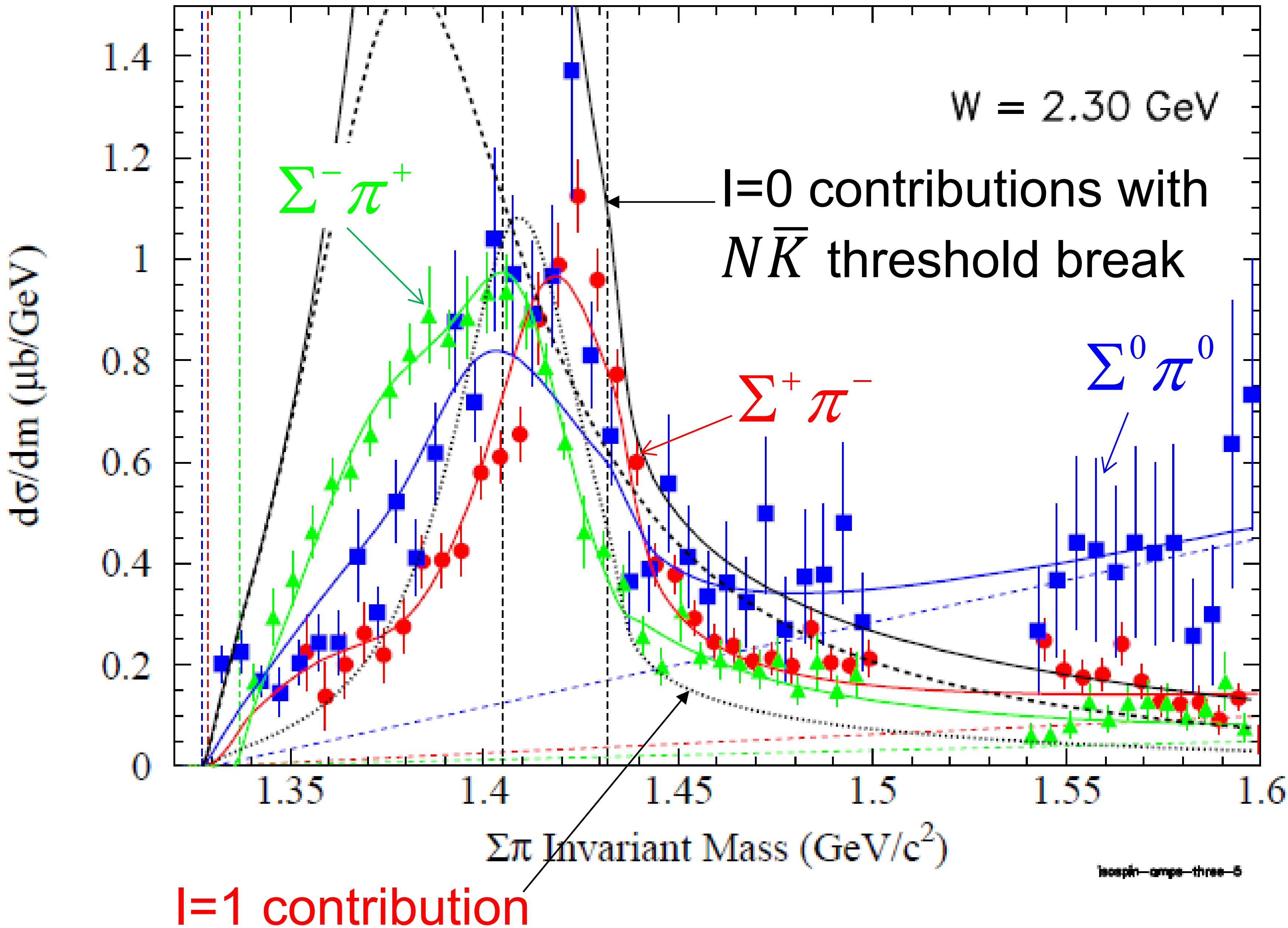


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

- 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 $\bar{K}N$
  - ~1390 mostly $\pi\Sigma$
- Possible weak I=1 pole also predicted

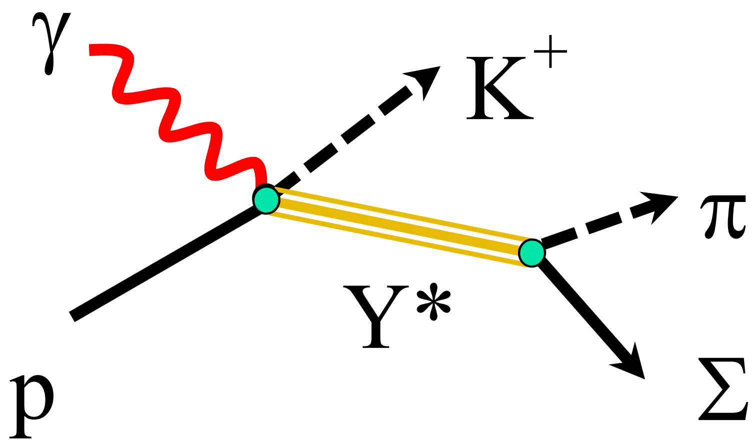
D. Jido, J.A. Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A **725,** 181 (2003)
J.A. Oller, U.-G. Meissner Phys. Lett B **500**, 263 (2001).

Example at W=2.30 GeV



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

Isospin Interference



Final Σπ state

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

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

Three charge combinations:

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

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

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

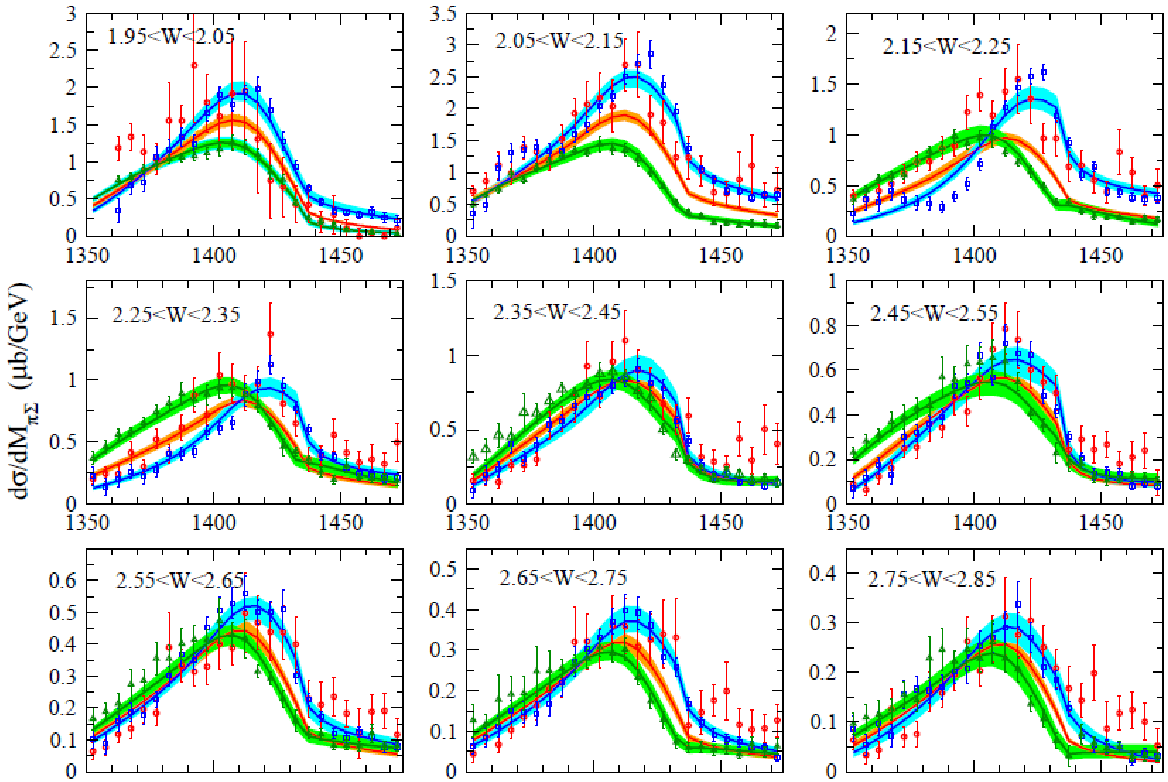
What "is" the I=1 piece?

- I=1 resonance? I=1 continuum amplitude?
- L. Roca and E. Oset paper[1]
  - Possible $I=1$ resonance in vicinity of $N\bar{K}$ threshold
- B.-S. Zou papers[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 !

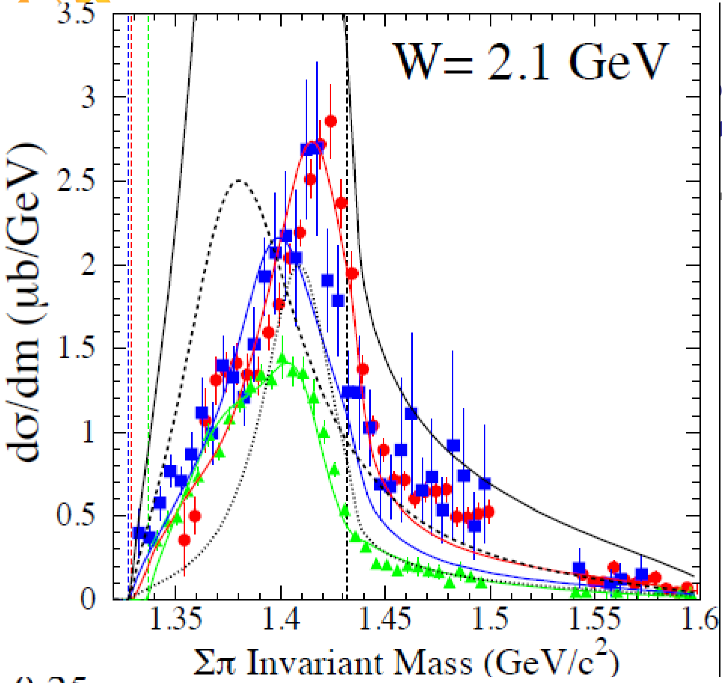
1. L. Roca, E. Oset "On the isospin 0 and 1 resonances from $\pi\Sigma$ photoproduction data" Phys. Rev. C **88** 055206 (2013).
2. Bing-Song Zou "Five-quark components in baryons", Nucl Phys A 835 199 (2010).

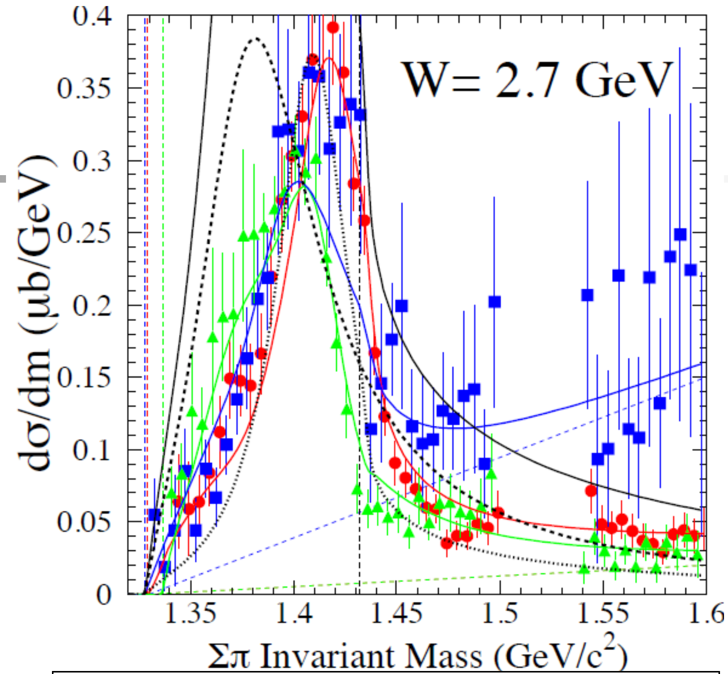
"Best" model calculation

- L. Roca and E. Oset ← best job so far
  - Possible I=1 resonance in vicinity of $N\bar{K}$ threshold

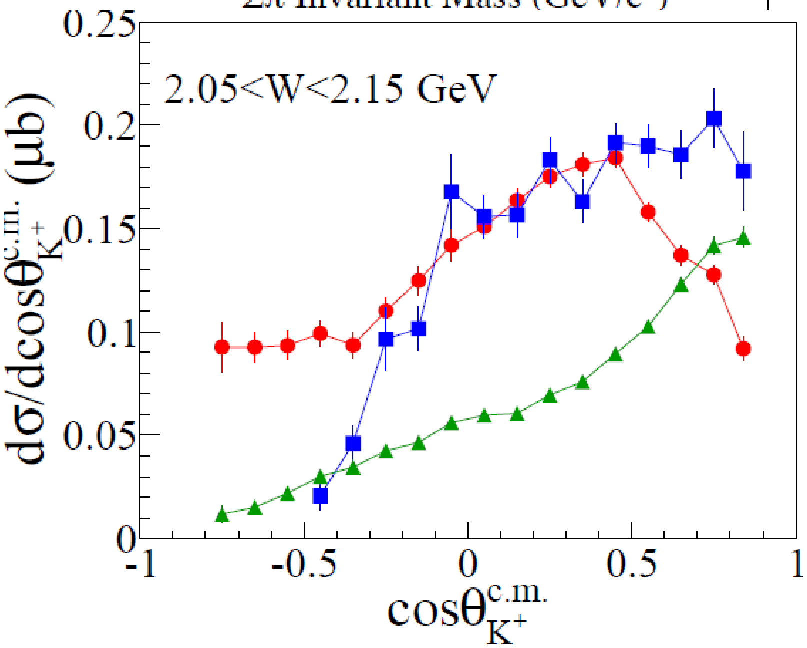


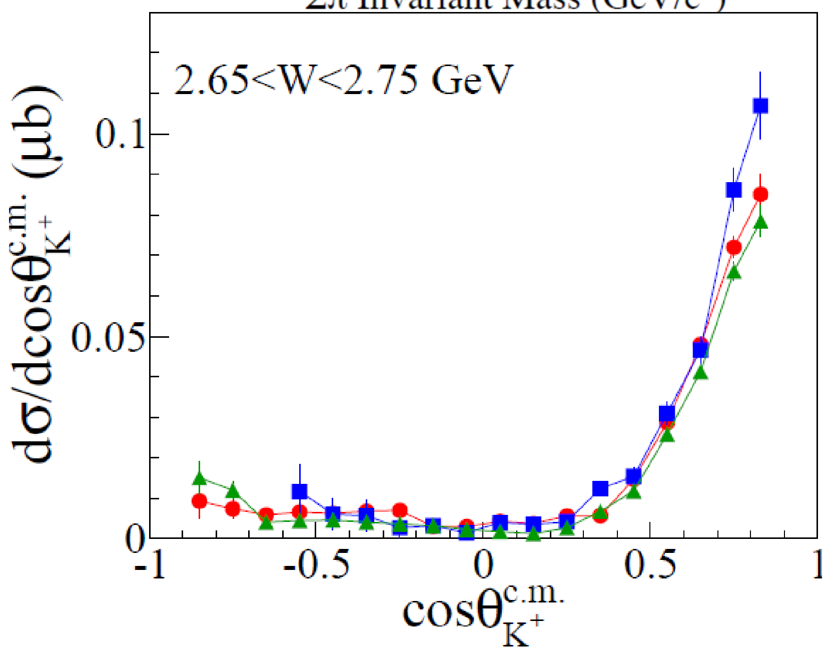
1. L. Roca, E. Oset "On the isospin 0 and 1 resonances from $\pi\Sigma$ photoproduction data" Phys. Rev. C **88** 055206 (2013).





Line Shapes





Cross Sections

- This effect is NOT seen for the $\Lambda(1520)$
- No model calculation has computed cross section and line shapes <u>together</u>.

Spin and Parity of $\Lambda(1405)$

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

Parity and Spin of $\Lambda(1405)$

- PDG assumes $J^P = \frac{1}{2}^-$ based on quark model
  - No direct experimental evidence for the parity
  - Cf. note by R. H. Dalitz, 1998 RPP
- 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 $m = \pm 3/2$ 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

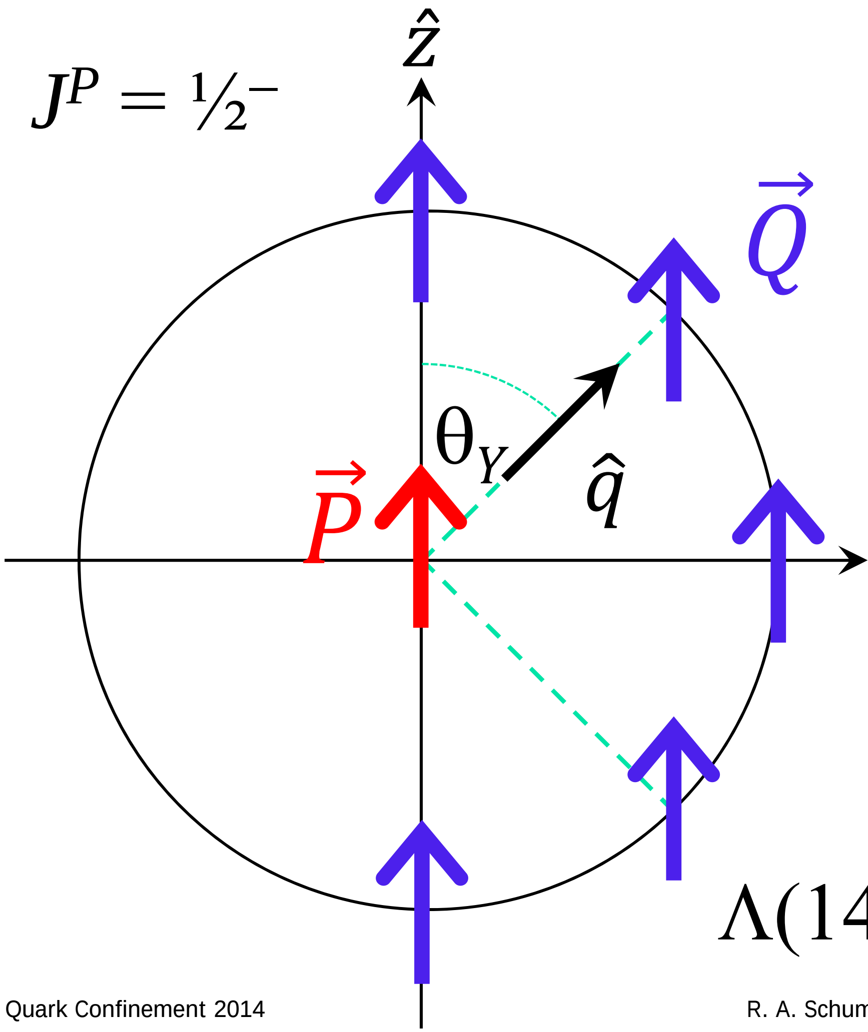
S-wave, P-wave Scenarios

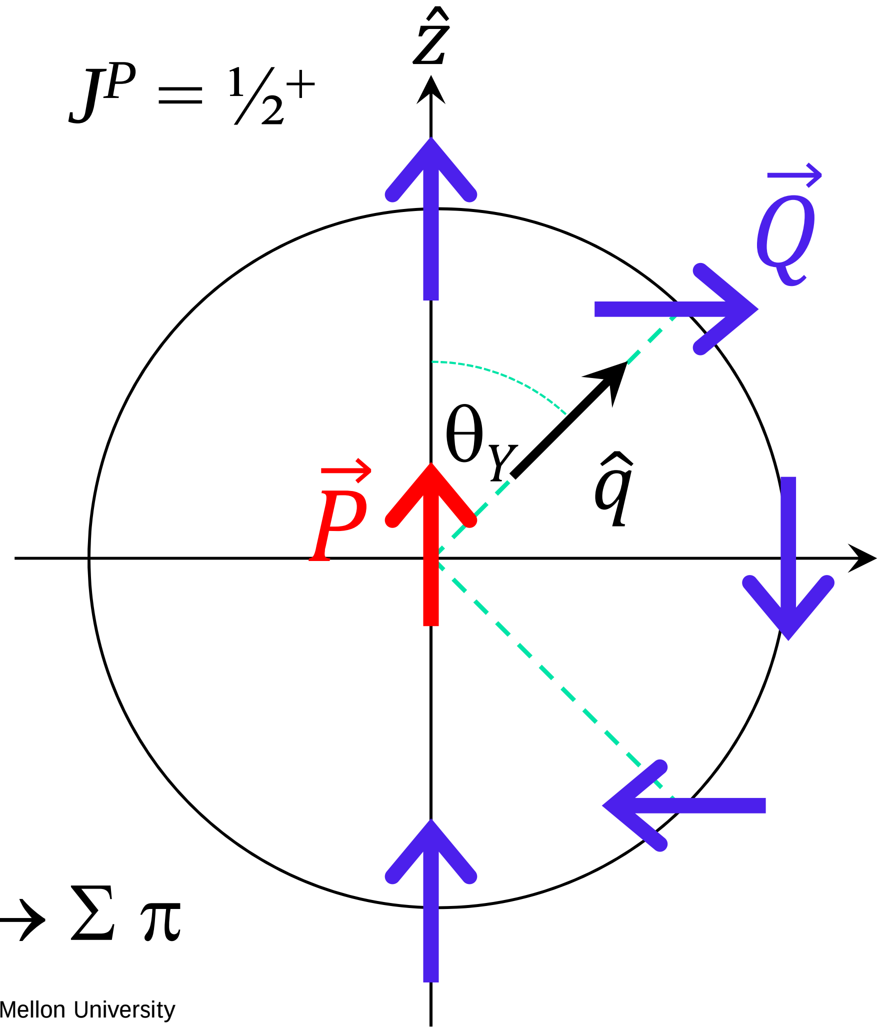
L=0 (s-wave)

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

L=1 (p-wave)

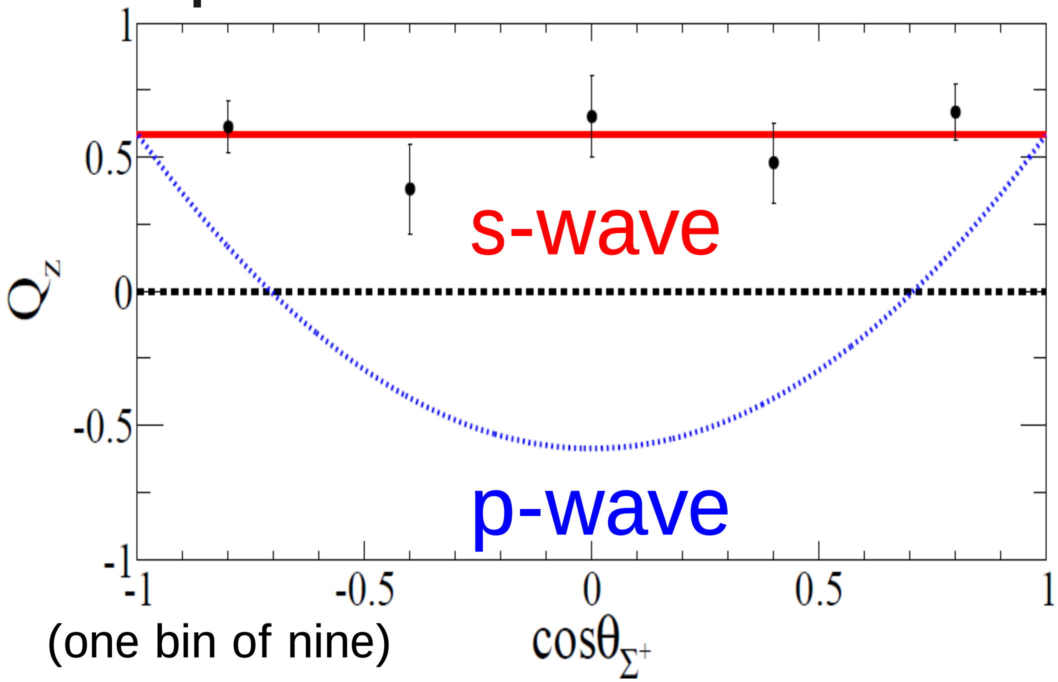
$\vec{Q} = -\vec{P} + 2(\vec{P}\cdot\hat{q})\hat{q}$





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

Parity and Spin of $\Lambda(1405)$



- Polarization axis is along $\hat{z} = \hat{\gamma} \times \hat{K}$
- Used W=2.55 to 2.85 GeV, $\cos\theta_K^{c.m.} > 0.6$
- Decay $\Lambda(1405) \to \Sigma^+ \pi^-$ is <u>isotropic</u> (p = 0.5) , so $J \to 1/2$
- Weak decay asymmetry for Σ^+ is $\alpha = -0.98$ (big!)
- Decay is s-wave, $\Rightarrow P = \text{"}negative\text{"}$

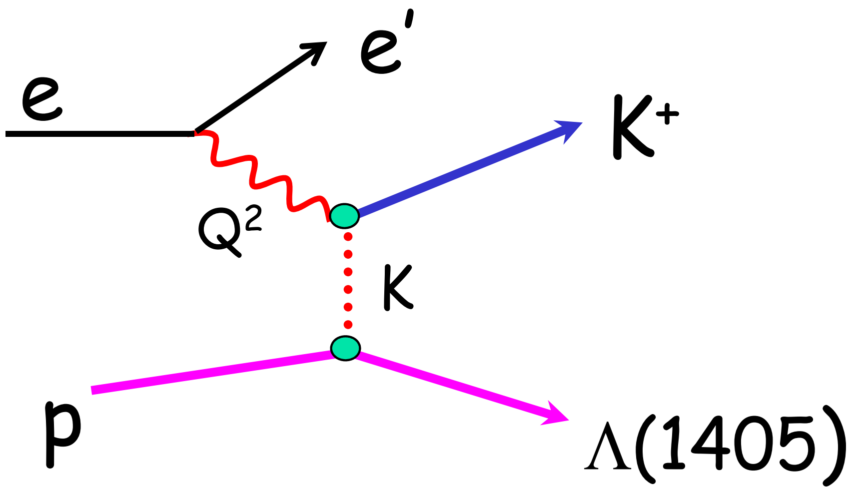
<u>$J^P = ½^-$ confirms quark model expectation</u>

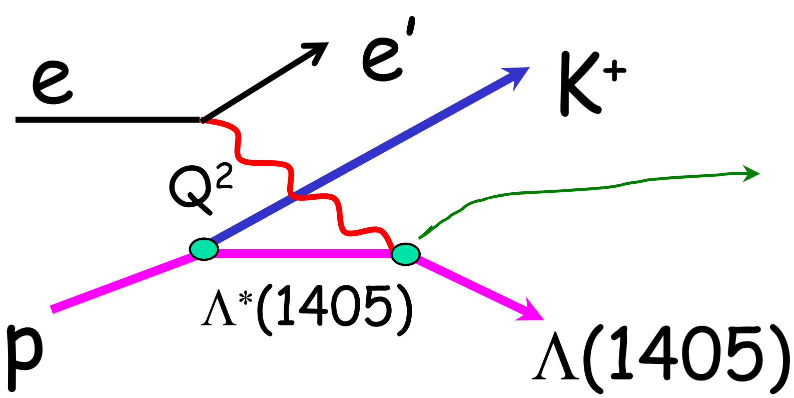
$\Lambda(1405)$ is produced ~ +45% polarized

Λ(1405) Electroproduction

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

Electroproduction of Λ(1405)

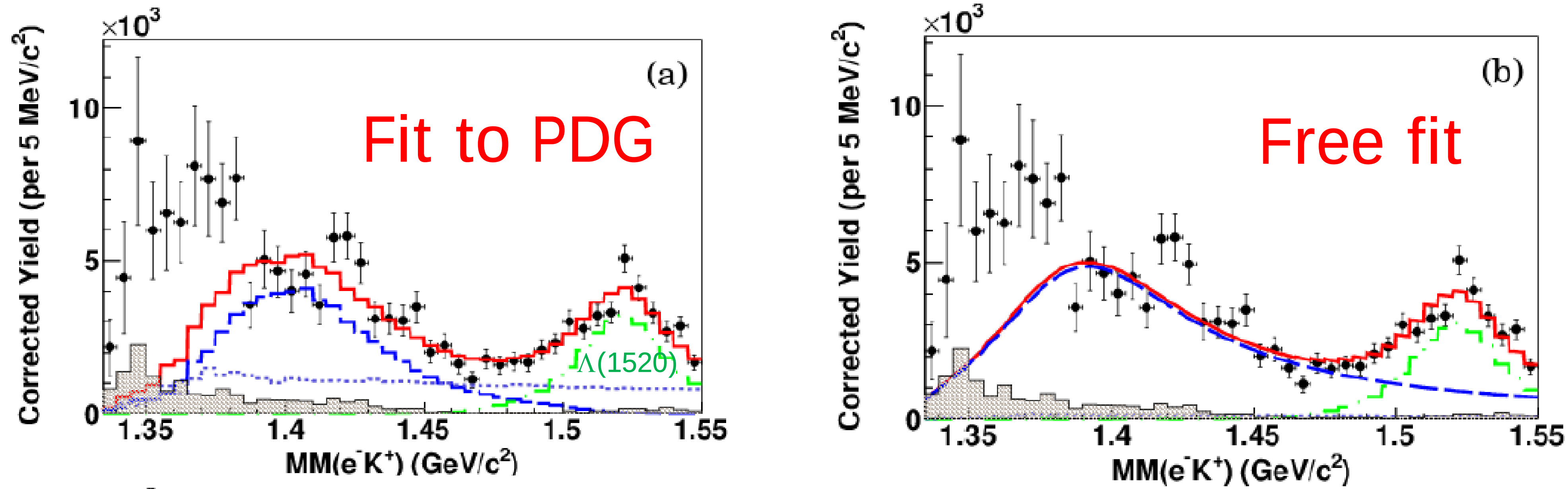


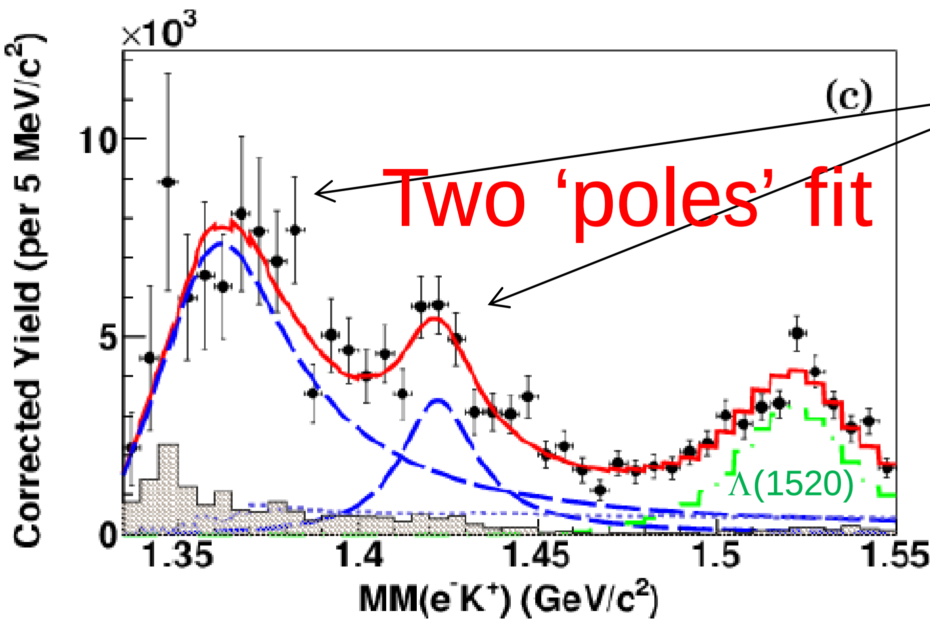


- Probe the pole "structure" for $Q^2 > 0$ via electro-magnetic form factors
- Theory: e.m. form factors computed; Λ(1405) is "larger" than the neutron
- Experiment: hard to isolate pure e.m. $\gamma\Lambda^*\Lambda$ vertex
- In CLAS $e\,p \rightarrow e'\,K^+\,p\,\pi^-\,(\pi^0)$, four particles detected
- CLAS acceptance:
  - $1.0 < Q^2 < 3.0$ GeV^2;
  - $1.5 < W < 3.5$ GeV.

cf: T. Sekihara, T. Hyodo, D. Jido, Phys Rev C83, 055202 (2011).

γ Y* K⁺ Electroproduction of Λ(1405)





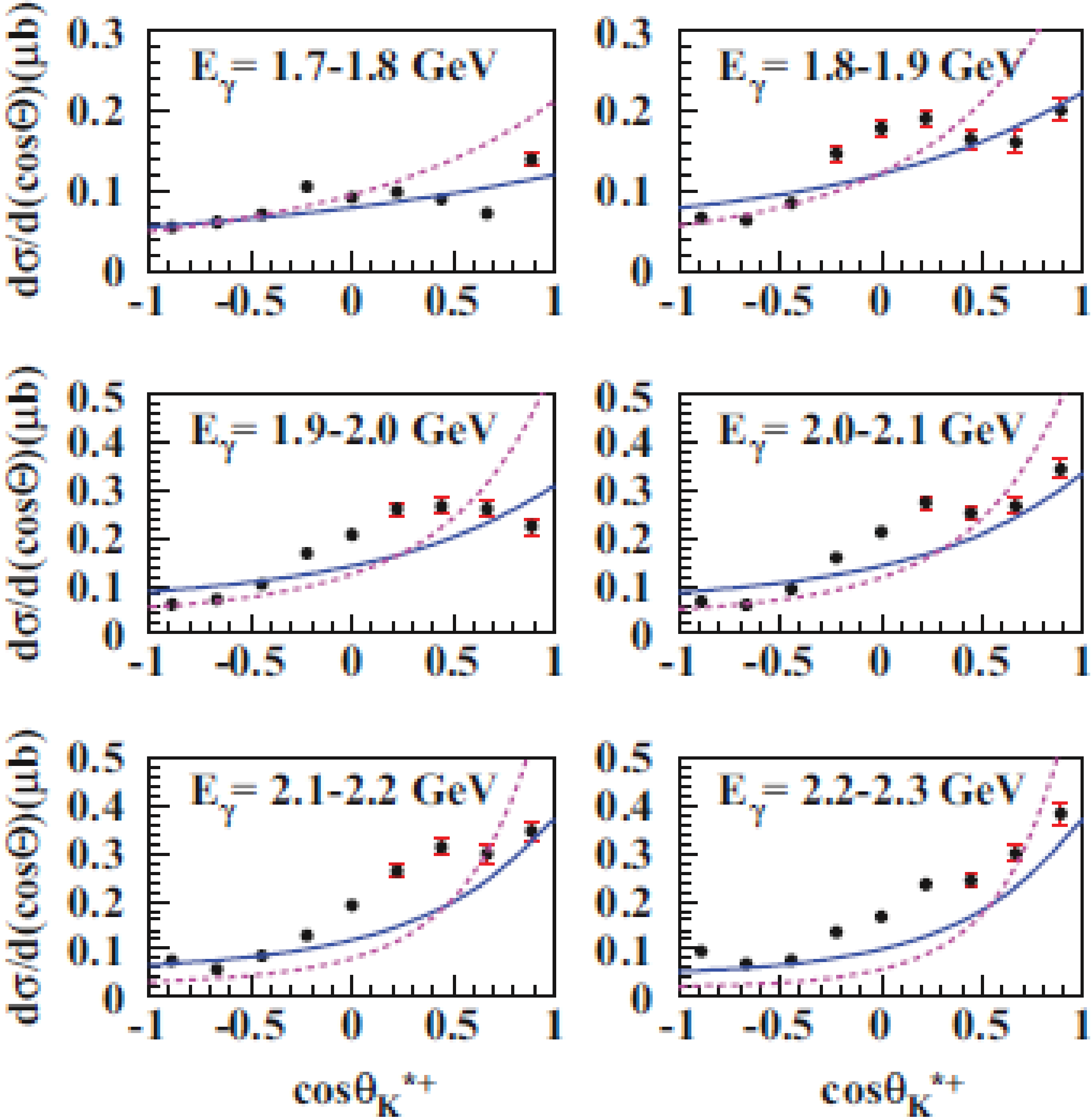
- Two-bump structure seen
- Possible evidence for two I=0 poles
- PDG Λ(1405) values fail utterly
- Calculation needed!

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

K^* Production

Publication: Cross Sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma\, p \rightarrow K^{*+}\,\Sigma^0$ Reactions, W. Tang *et al*. (CLAS) Phys. Rev. C **87**, 065204 (2013).

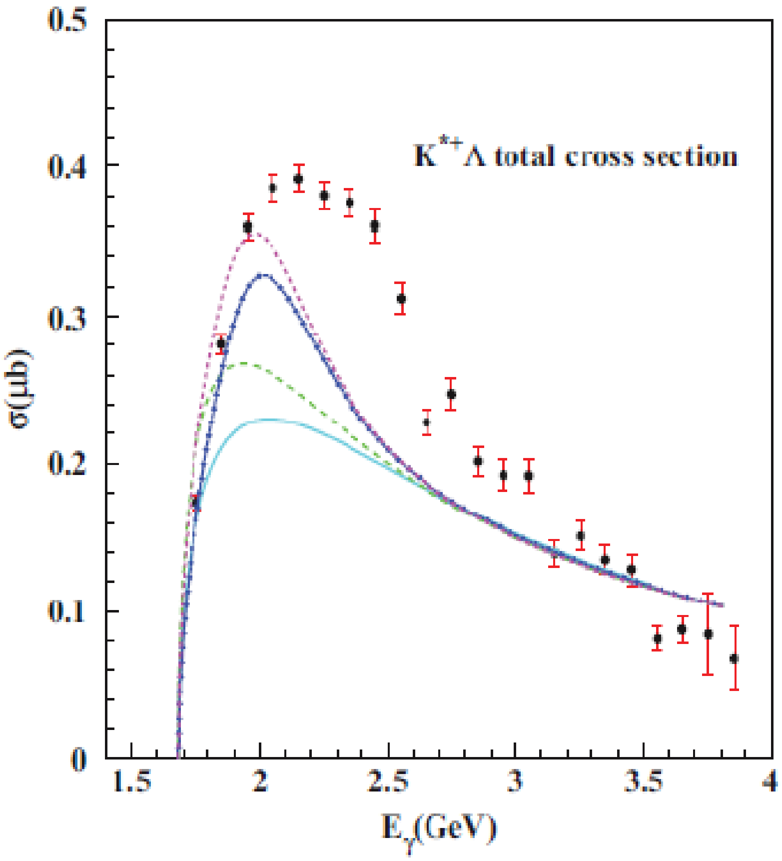
$K^{*+}\Lambda$, $K^{*+,0}\Sigma^{0,+}$ photoproduction



- N* searches with coupling to K^*Y
- Search for κ-meson interaction
- 1.7 to 3.9 GeV

$K^{*+}\Lambda$, $K^{*+0}\Sigma^{0+}$ photoproduction

Comparison with theory



Cyan: Oh and Kim (O-K)
Isobar Model
Blue: Kim, Nam, Oh, Kim (KNOK)
Regge Model
Dotted curves include additional s-channel N* with M<2.2 GeV and L<3.

Clearly, the currently available theoretical models cannot reproduce the data. This suggests that higher-mass and higher-L resonances are needed.

- Models include known high-mass resonances

$K^{*+}\Lambda$, $K^{*+0}\Sigma^{0+}$ photoproduction

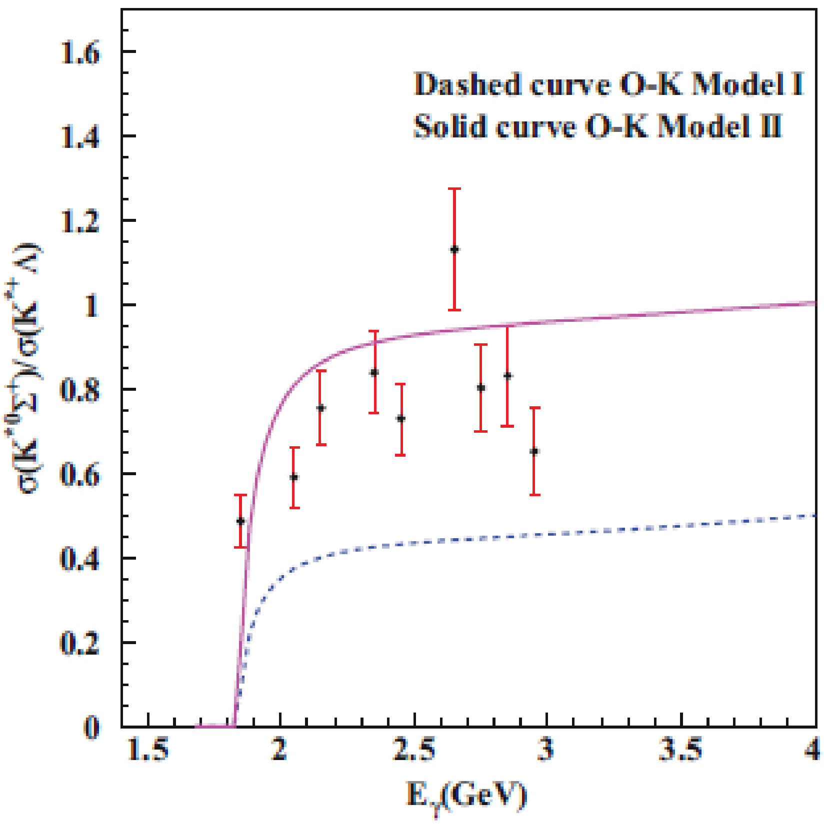


FIG. 12. (Color online) Total cross section ratio of the reactions $\gamma p \to K^{*0}\Sigma^+$ to $\gamma p \to K^{*+}\Lambda$. The ratio uses the present data in the denominator and data from Ref. [5] in the numerator. The dashed and solid curves are theoretical calculations from Oh and Kim [4] models I and II, respectively.

- Suggestion of κ-meson exchange

Solid: mostly t-channel κ-meson

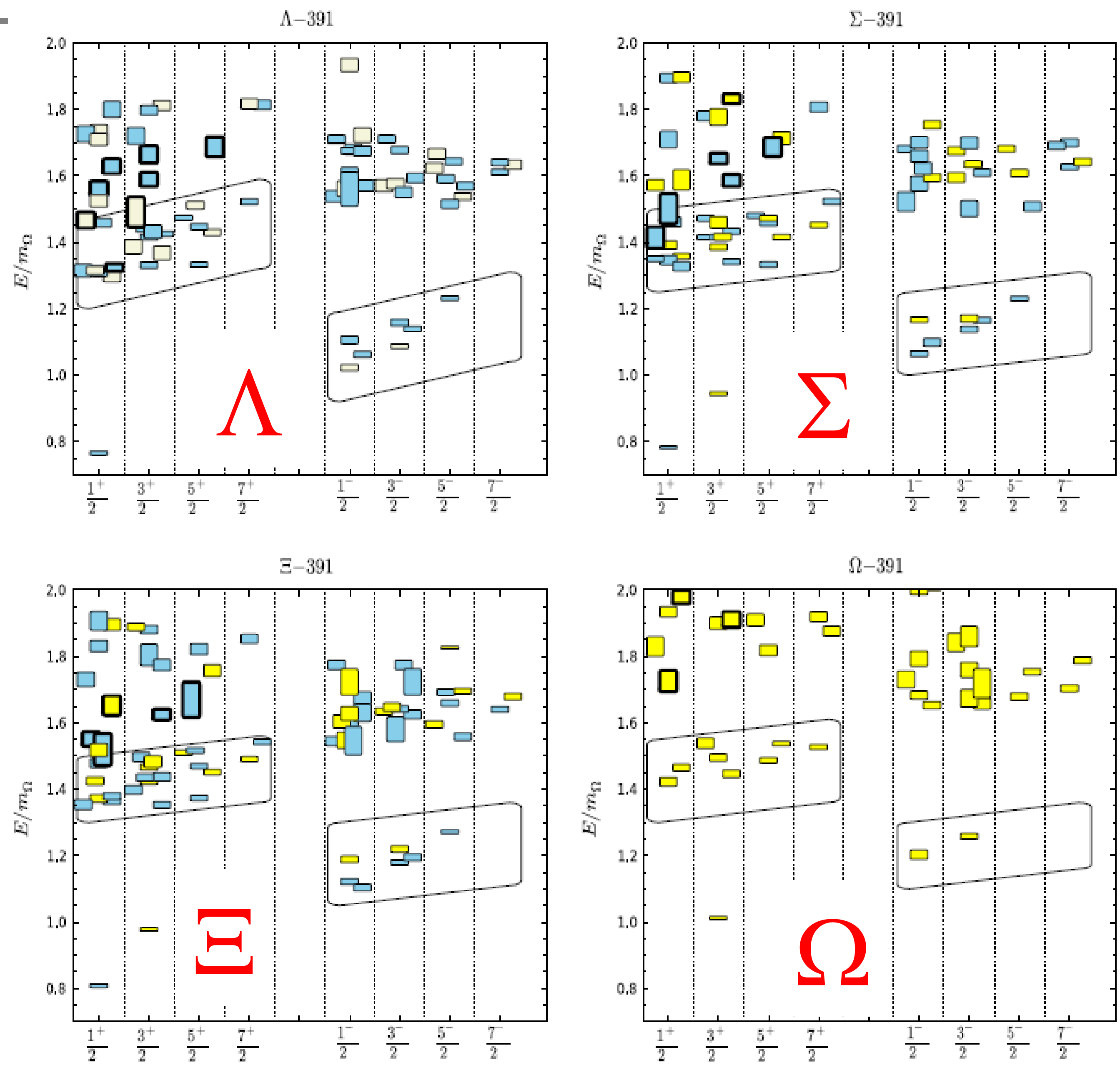
Dotted: very little κ-meson

There is scarce evidence for the strange scalar called the kappa (κ), which is the octet partner of the $a_0(980)$ and $f_0(980)$ mesons. The CLAS data support an earlier claim by LEPS that also measured $K^{*0}\Sigma^+$ photoproduction.

The Future: Outlook at GlueX and CLAS12

Lattice QCD Predictions

- Lattice QCD predicts baryon spectra
- Most states not identified by experiment yet



flavor singlet

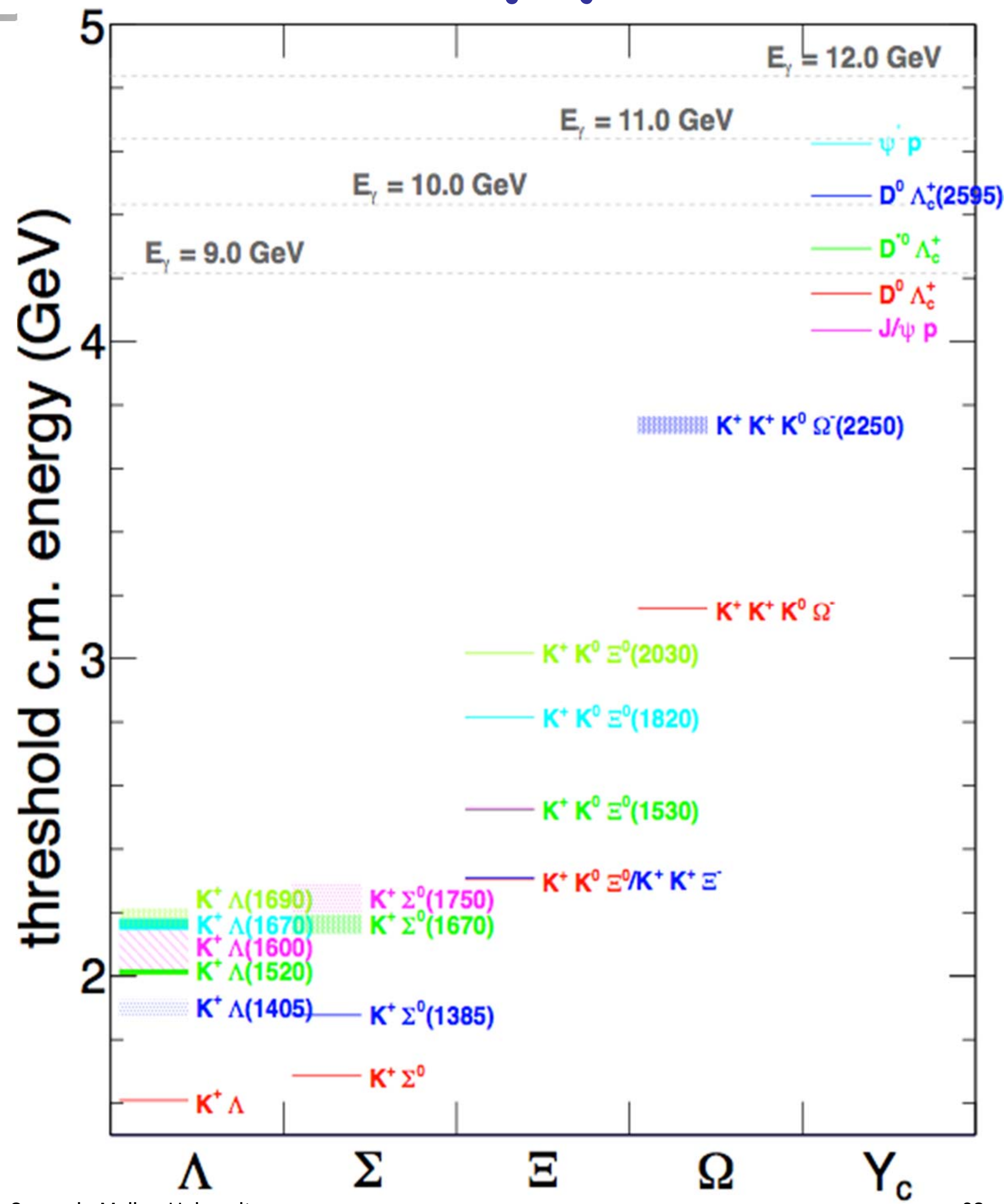
flavor octet

flavor decouplet

R. Edwards *et al.*, PRD 87, 054506 (2013)

Baryon Spectroscopy

- JLab at 12 GeV will surpass many Y* thresholds
- S = -1, -2, -3
  - Many Λ^*, Σ^*, Ξ^*, Ω^* states reamin undiscovered
- Charm threshold



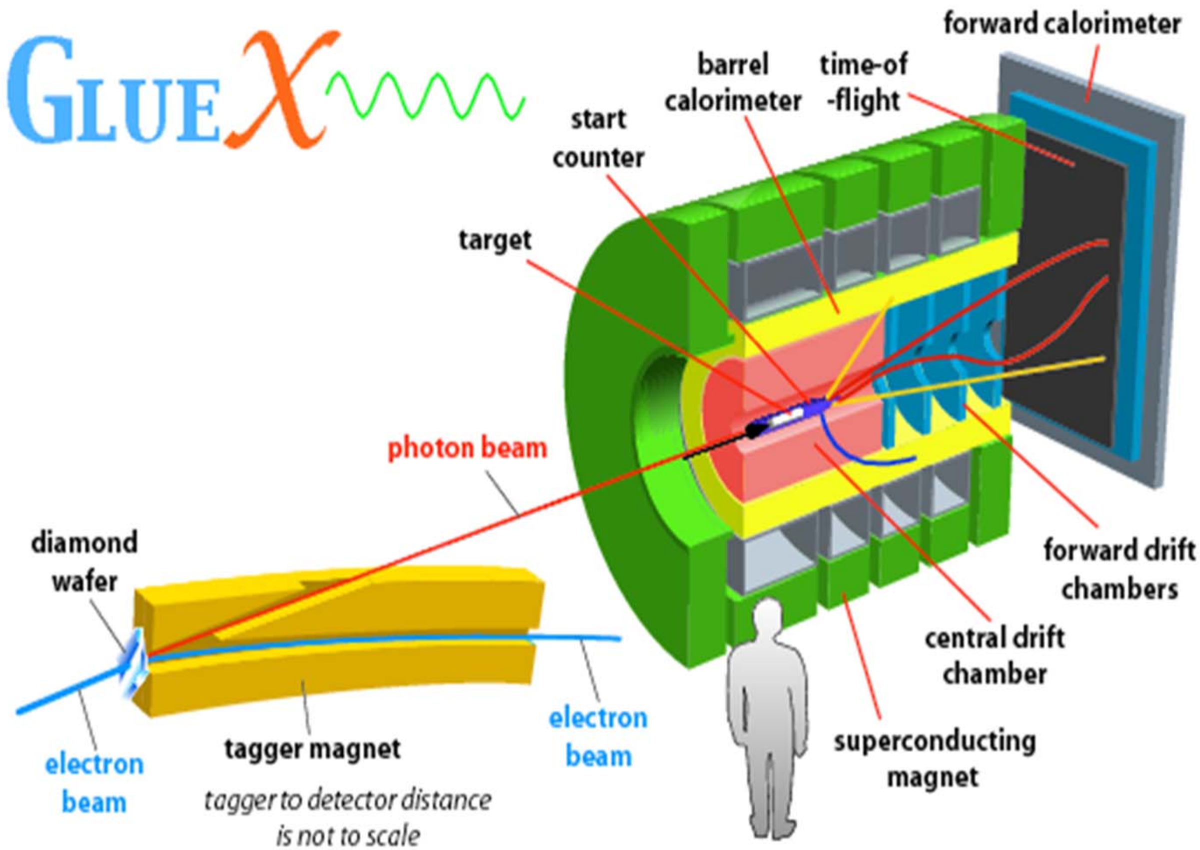
K. Moriya, priv. comm.

Hall D/GlueX

- New hall, finished construction
- Approved for 120 PAC days of commissioning, 220 days of high statistics running

Hall D/GlueX

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

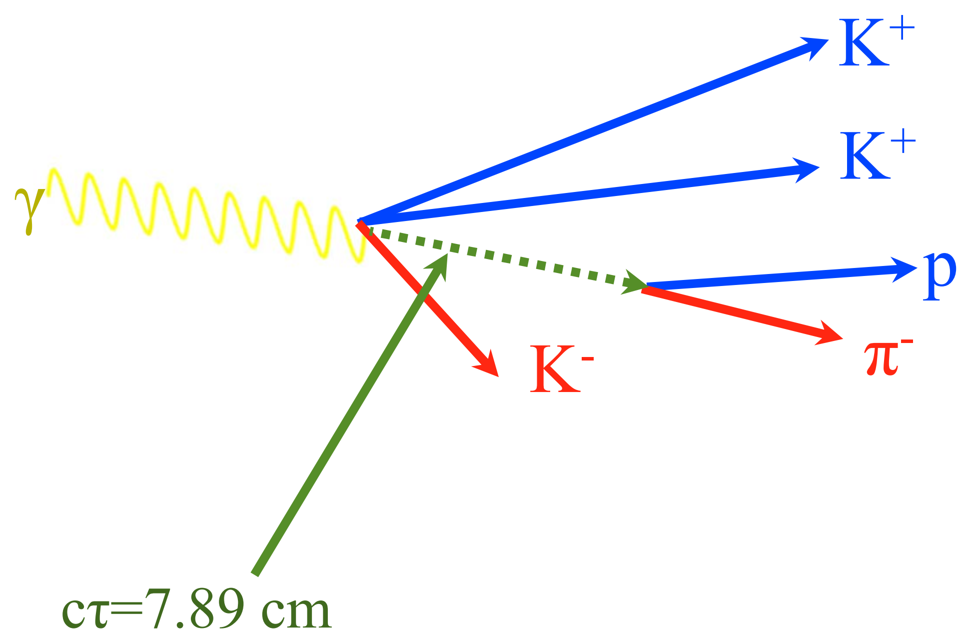


GlueX Study of $\Xi^-(1820)$

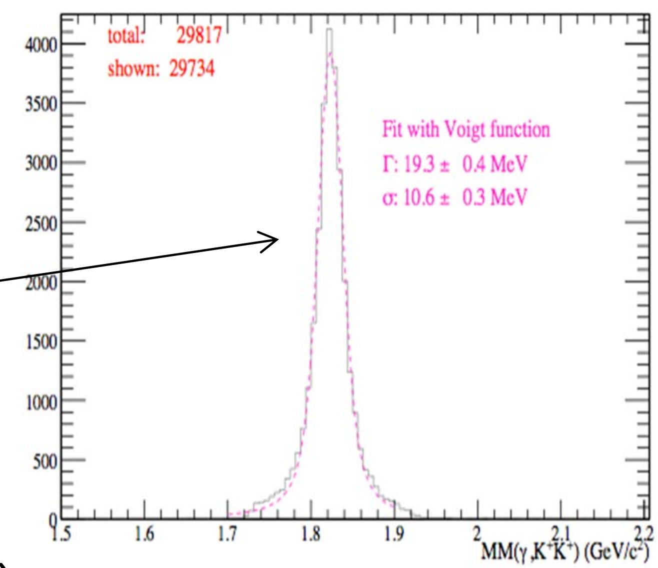
- Use simulated data to study

$$\gamma + p \rightarrow K^+ + K^+ + \Xi^-(1820)$$

$$\Xi^-(1820) \rightarrow \Lambda + K^-$$



- Final state is 5 charged particles, K^+, K^+, K^-, p, π^-
- Can GlueX reconstruct this?
- reconstruction efficiency
  - 10 MeV mass resolution
  - Secondary vertex resolution: ~1 cm along beam line (z-direction)



(K. Moriya, priv. comm.)

Hall B / CLAS12

See talk by M. Battaglieri

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

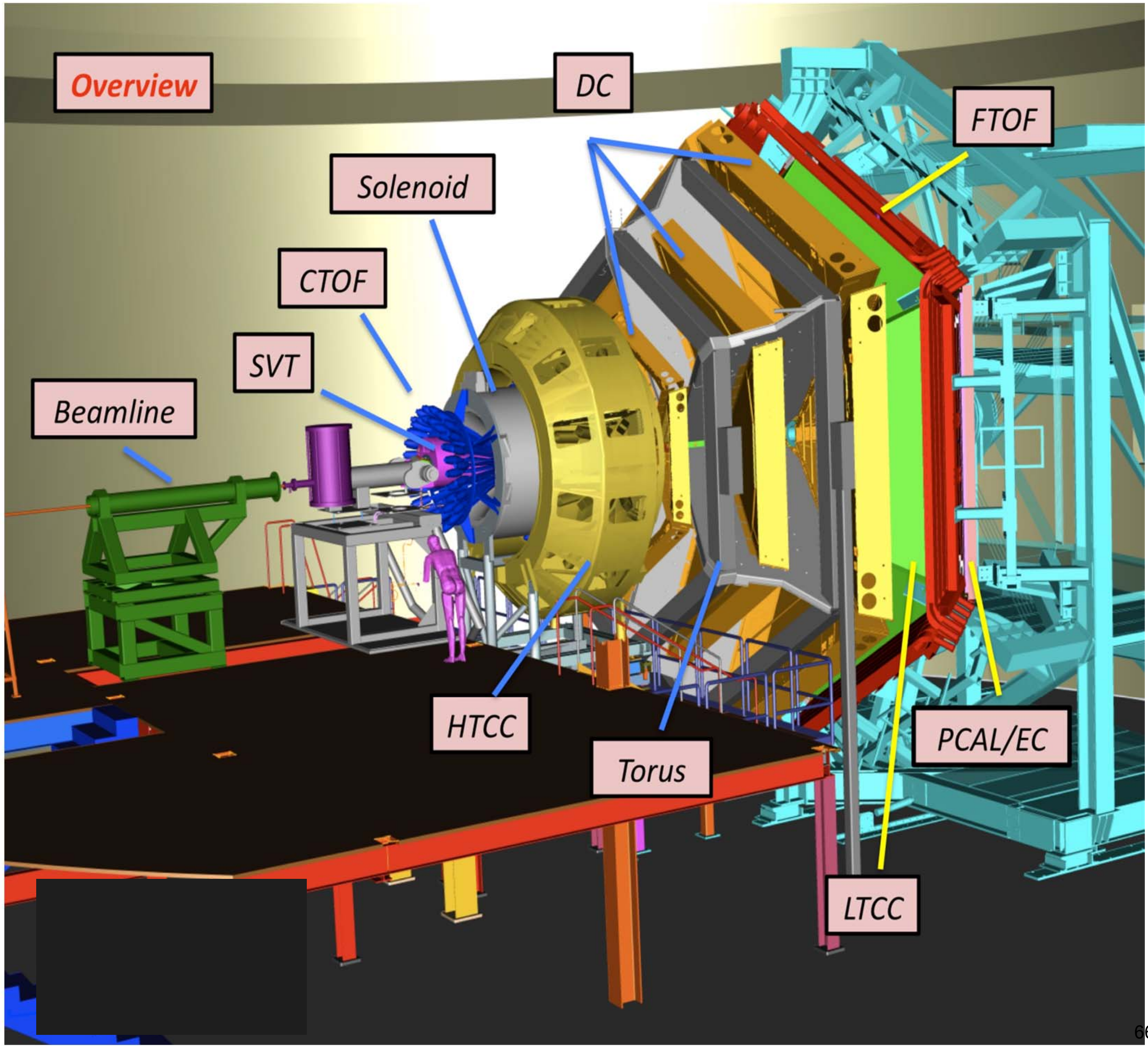
Beamline

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

Upgrades to the baseline

Under construction

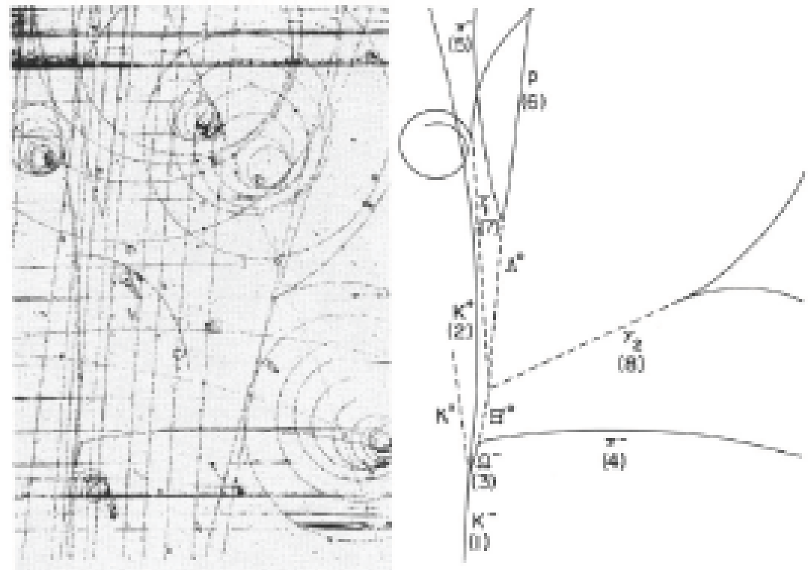
- MicroMegas
- Central Neutron Detector
- Forward Tagger
- RICH detector (1 sector)
- Polarized target (long.)



CLAS12: Very Strange Baryons

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

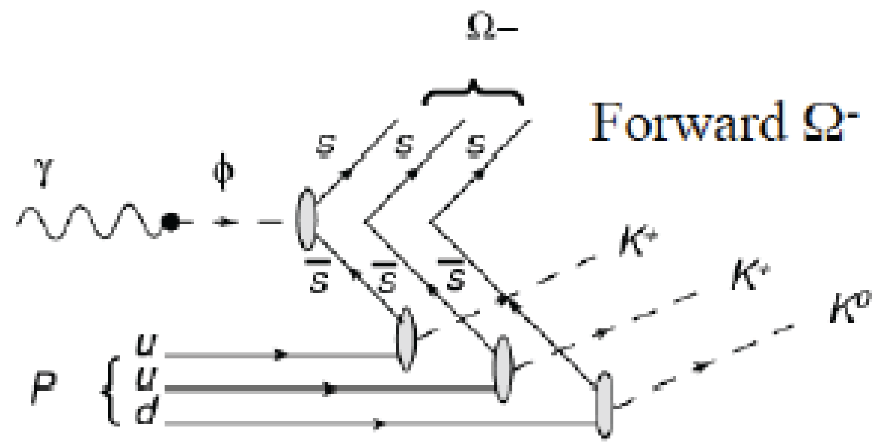
- Ω^- discovered in 1964: after 50 years, indication on J^P from Babar and others but full determination not yet achieved
- Ξ^* spectrum still poorly known: many states missing and spin/parity undetermined



V. E. Barnes et al., Phys. Rev. Lett. 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.

Summary/Conclusions

- Hyperon photo- and electro-production used to pin down N* spectrum above 1.6 GeV
- New interference phenomena in $\Lambda(1405)$ cross section(s) and line shapes demonstrated
- First direct J^P measurement for $\Lambda(1405)$: $\frac{1}{2}^-$
- JLab program at 12 GeV in CLAS12 and GlueX will explore Y* and meson spectra