Hyperon Photoproduction: What Has Been Learned at Jefferson Lab?

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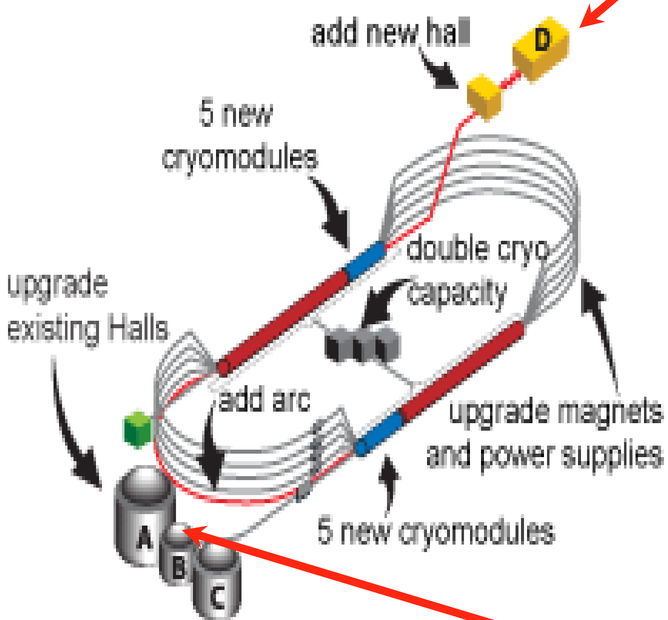
Users Group 2015

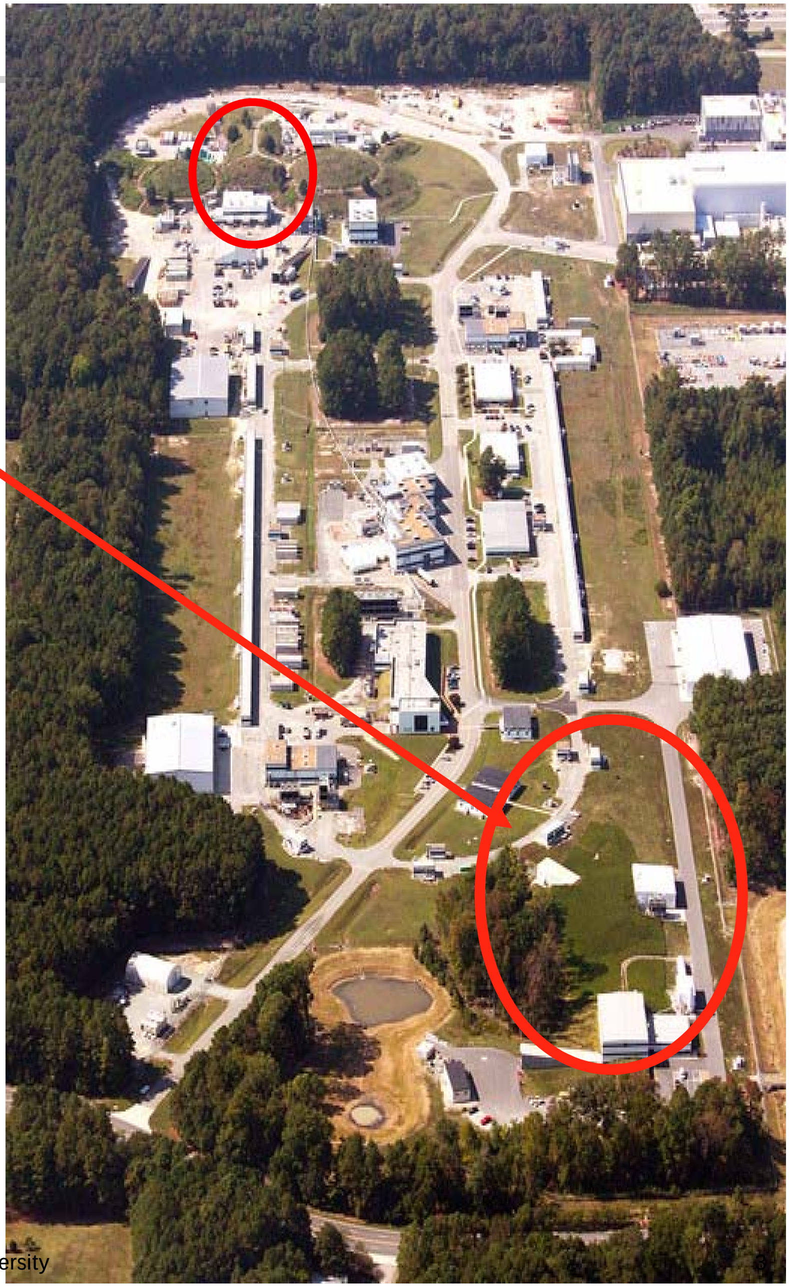
Outline /Overview

- Strangeness and the N* spectrum of states
  - Λ & Σ photo- and electro-production spin observables
- Dimensional scaling of $K\Lambda$ photoproduction
  - Constituent-counting rule supported
- 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
  - Support for chiral unitary models: 2-pole structure
- Strangeness suppression in exclusive electro-production
  - Low and high energy reactions similar behavior
- Outlook at GlueX and CLAS12

γ Y* K+ | Jefferson Lab

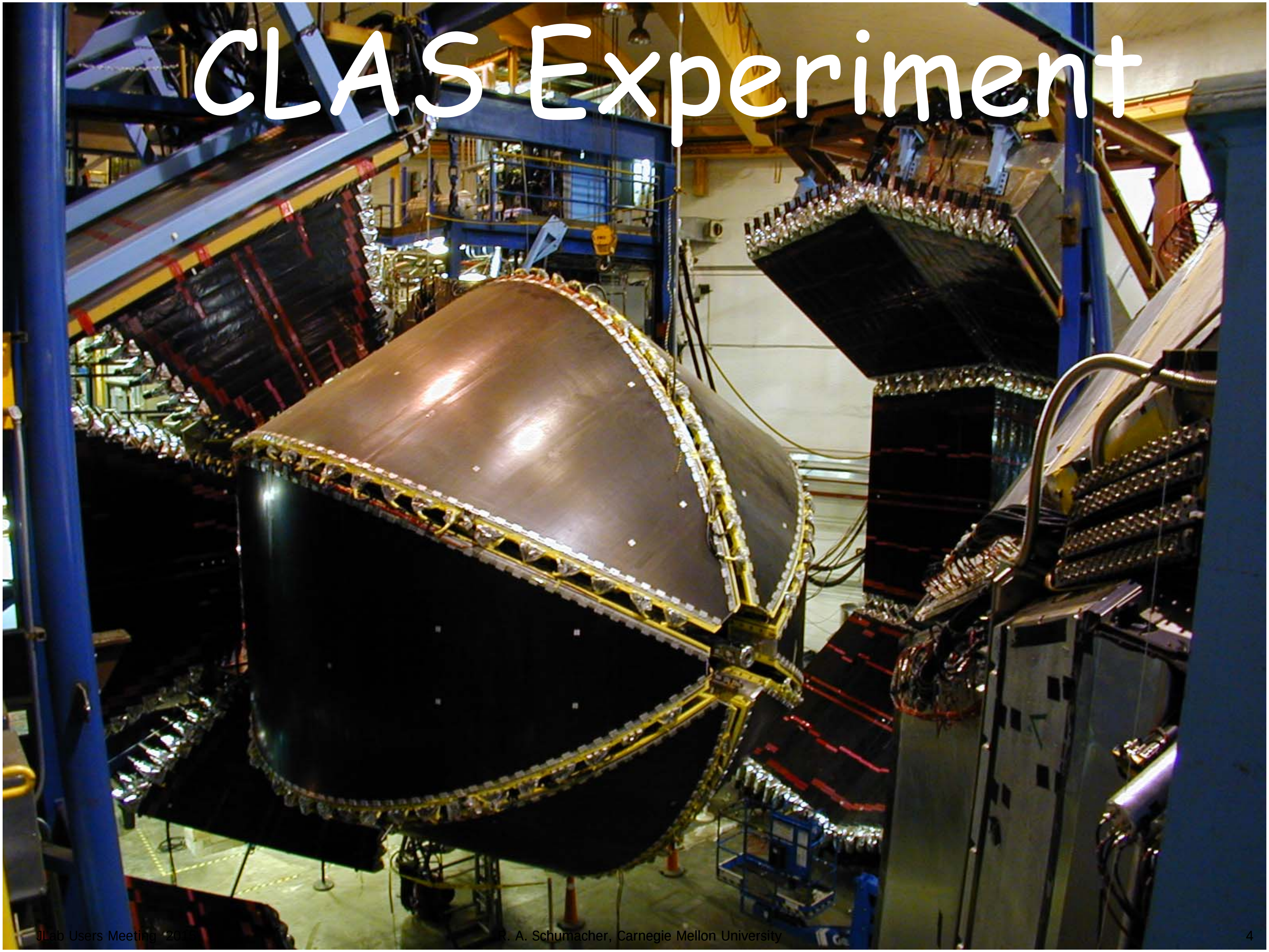
- Located in Newport News, Virginia
- Ran for ~14 yrs at 6 GeV in Halls A, B, C
- Upgrading to 12 GeV, new Hall D





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

CLAS Experiment



CLAS Experiment

- 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 from 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.

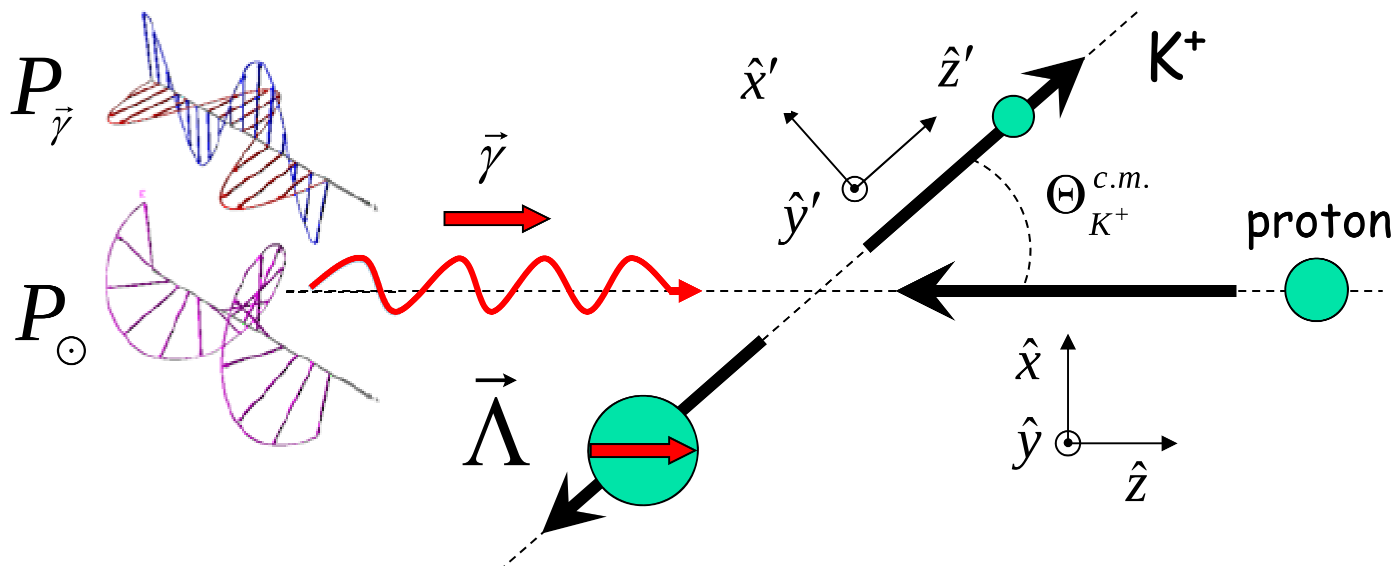
		all	πN	γN	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\sigma$
	$N(1440)\frac{1}{2}^+$	****	****	***★	(*)			***	★★★
	$N(1710)\frac{1}{2}^+$	***	***	***	**★	★★★	★★	*(*)	
	$N(1880)\frac{1}{2}^+$	★★	★	★		★★	★		
	$N(1535)\frac{1}{2}^-$	****	****	****	****			*	
S_{11}	$N(1650)\frac{1}{2}^-$	****	****	***	**★	***	**	**(*)	
	$N(1895)\frac{1}{2}^-$	★★	★	★★	★★	★★	★		
	$N(1720)\frac{3}{2}^+$	****	****	****	****	**	**	***	
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 $\Delta\eta$|	
	$\Delta(1905)\frac{5}{2}^+$	****	****	****			*★★	**(**)	
	$\Delta(1950)\frac{7}{2}^+$	****	****	***			*★★	**★	

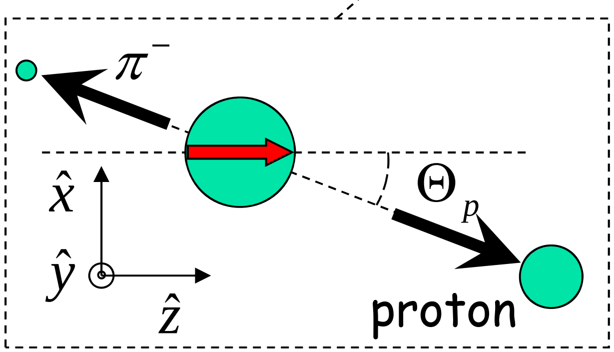
- What role has JLab strangeness physics in unraveling N* and Δ properties?
- Worldwide effort to determine resonance poles, branching fractions, helicity couplings, etc.
- <u>Bottom line</u>: "Stars" & new resonances added to world database

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

Define the Spin Observables

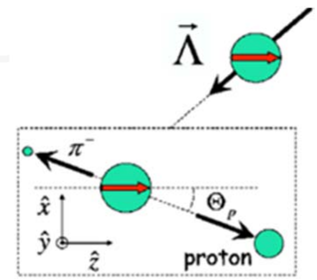
(for unpolarized nucleon)





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

γ Y^* K^+ 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
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$Td\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;y;-\}$	
$Pd\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{-;-;y\}$	
$Gd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*+b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$Hd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*-b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$Ed\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*+b_2b_4^*)$	$\{C;z;-\}$	
$Fd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*-b_2b_4^*)$	$\{C;x;-\}$	
$O_xd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*-b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_zd\sigma/dt$	$-2\ \mathrm{Im}(b_1b_4^*+b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_xd\sigma/dt$	$2\ \mathrm{Im}(b_1b_4^*-b_2b_3^*)$	$\{C;-;x'\}$	
$C_zd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*+b_2b_3^*)$	$\{C;-;z'\}$	
$T_xd\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*-b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_zd\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
$L_xd\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*+b_3b_4^*)$	$\{-;z;x'\}$	
$L_zd\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*+b_3b_4^*)$	$\{-;z;z'\}$	

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

γ Y^* K^+

Theory: Bonn Gatchina Model

(Just one of several models on the market)

- Coupled channels (K-matrix) framework
  - Input: from πN, $K N$ elastic; γN, πN inelastic to $\pi^{\pm 0} N$, ηN, $\eta' N$, $K^{\pm 0} Y$, $\pi \pi N$
    - 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)

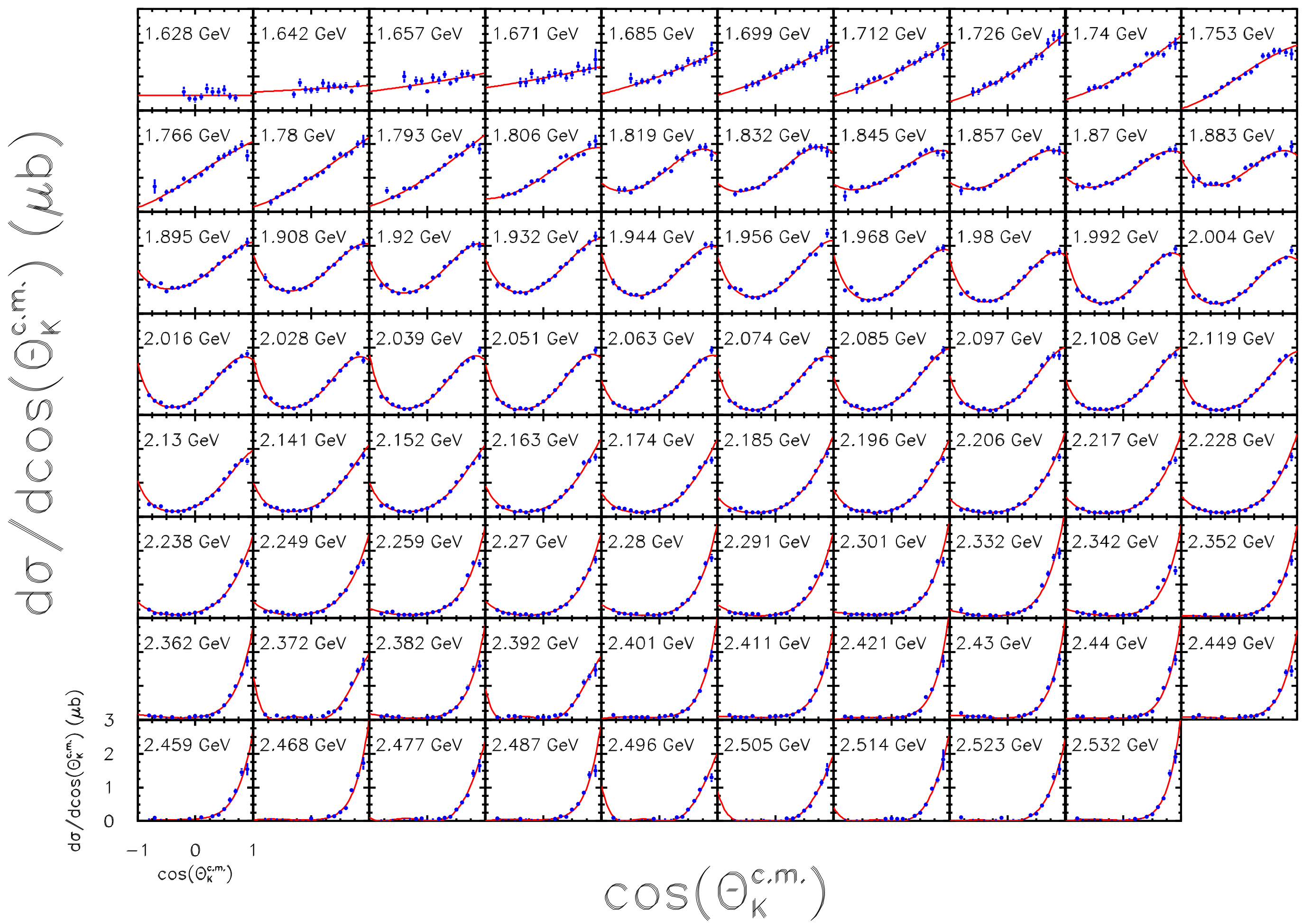
A.V. Anisovich *et al.*, Eur. Phys J. A **25** 427 (2005); Eur. Phys J. A **24,** 111 (2005);

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).

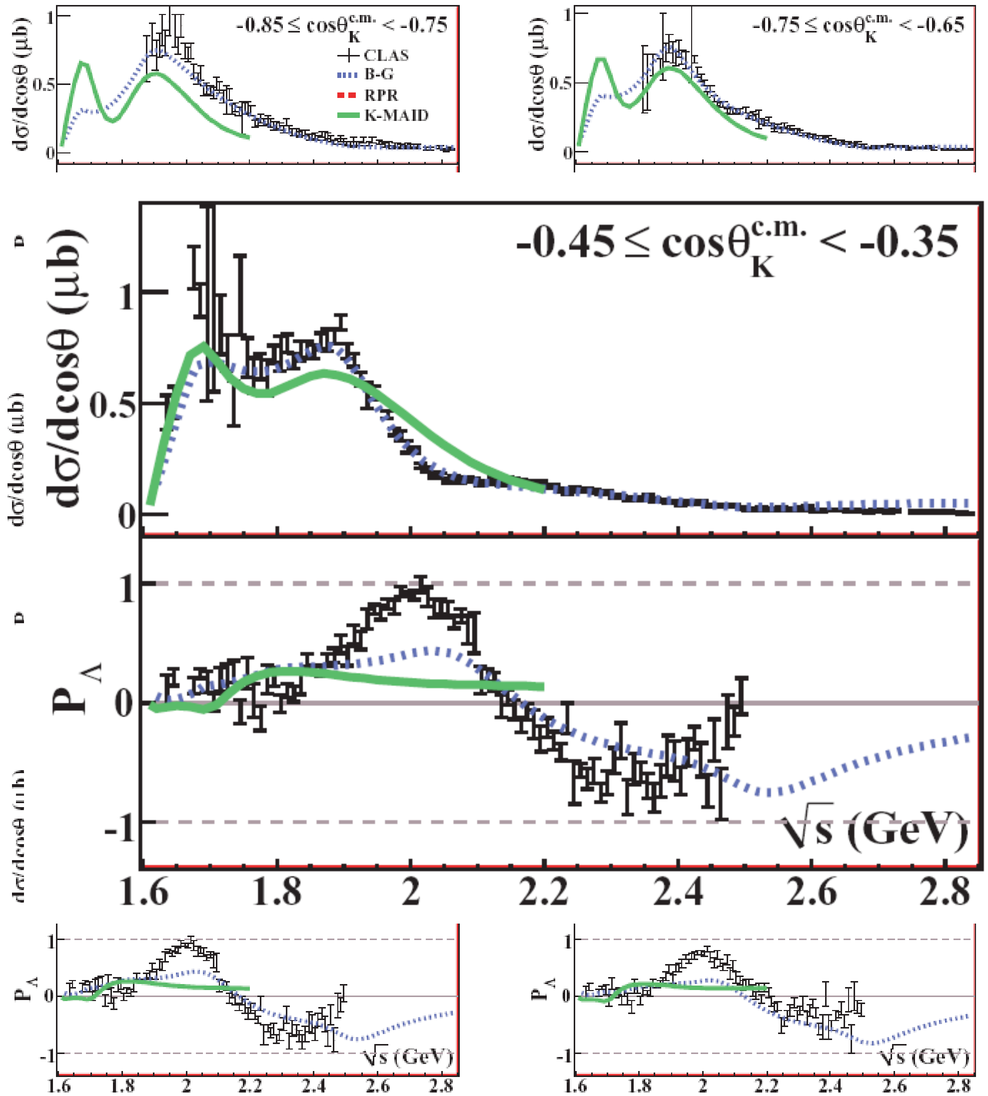
γp→K⁺Λ: cross section

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.

$\gamma p \rightarrow K^+ \vec{\Lambda}$: recoil polarization P



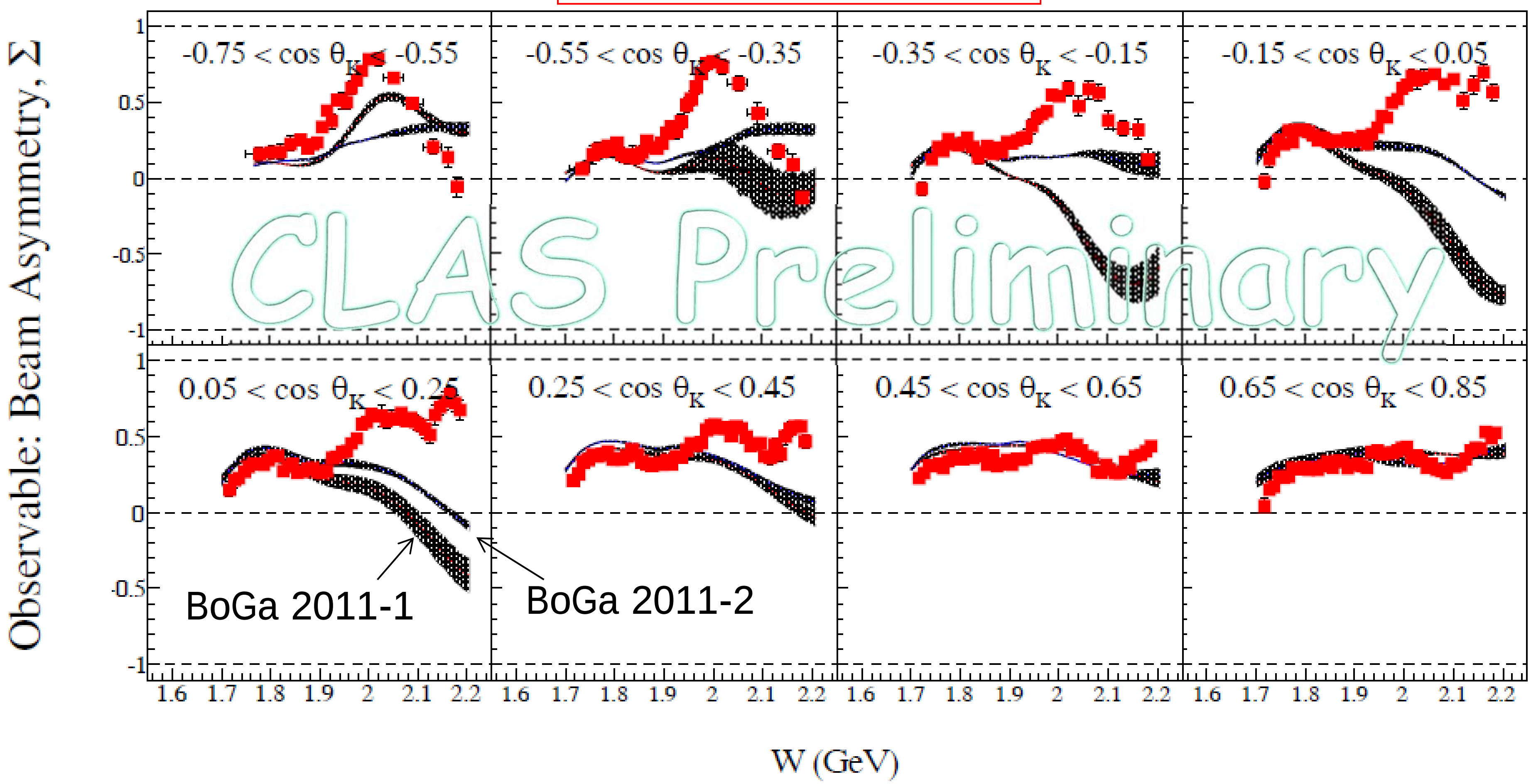
- Kaon-MAID model (green)
  - F.X. Lee *et al.*, Nucl. Phys. **A695**, 237 (2001).
  - Single-channel BW resonance fits
  - No longer up-to-date
- Bonn-Gatchina model (blue)
  - Multi-channel, unitary, BW resonance fit
  - Large suite of N* contributions
  - Was not predictive for recoil polarization

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

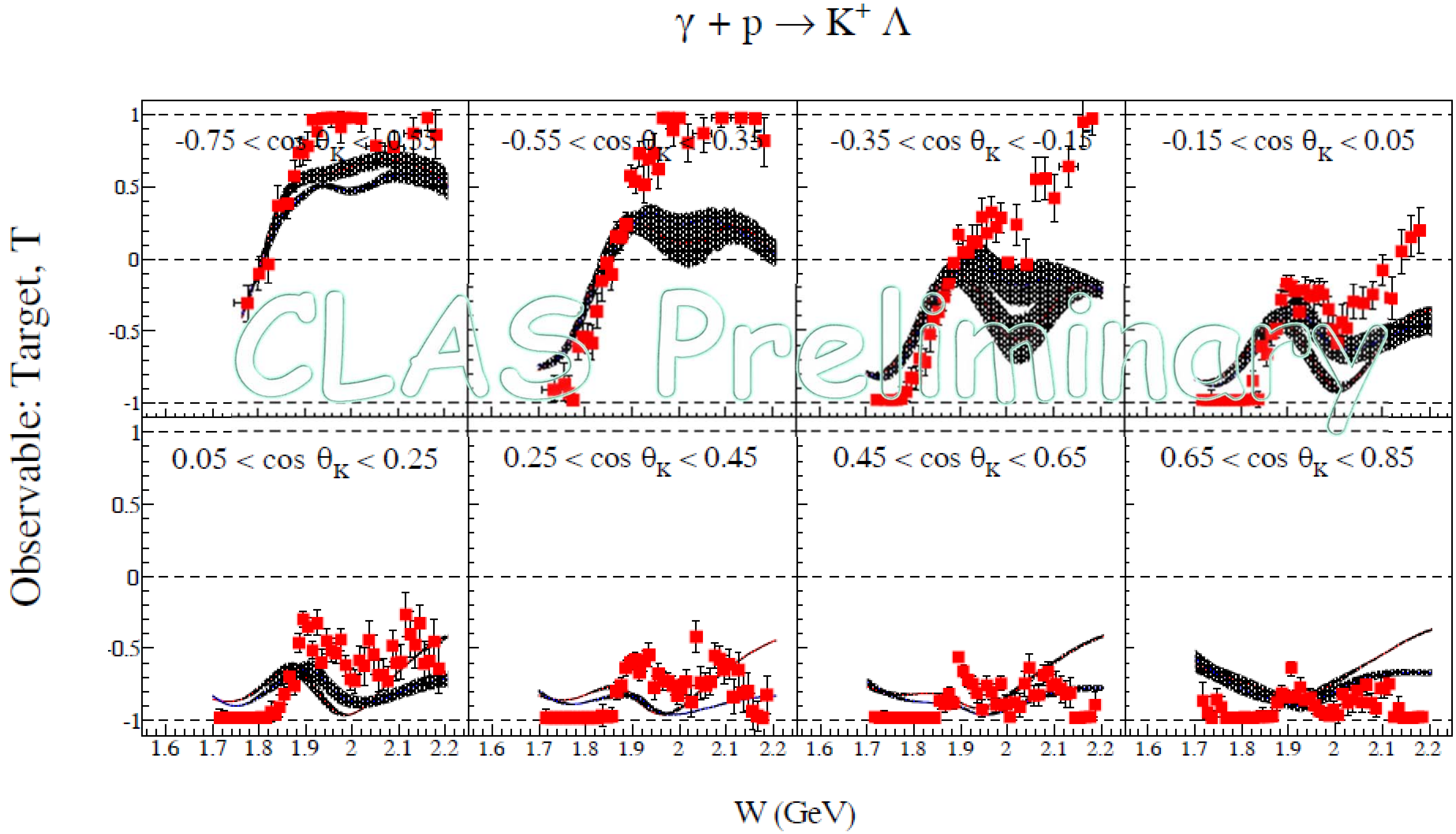
$$\frac{d\sigma}{d\Omega_{K^+}} = \frac{d\sigma}{d\Omega_{K^+}}\bigg|_{unpol.} \left\{1 + \Sigma P_\gamma \cos 2\phi\right\}$$



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

CLAS/Glasgow Preliminary

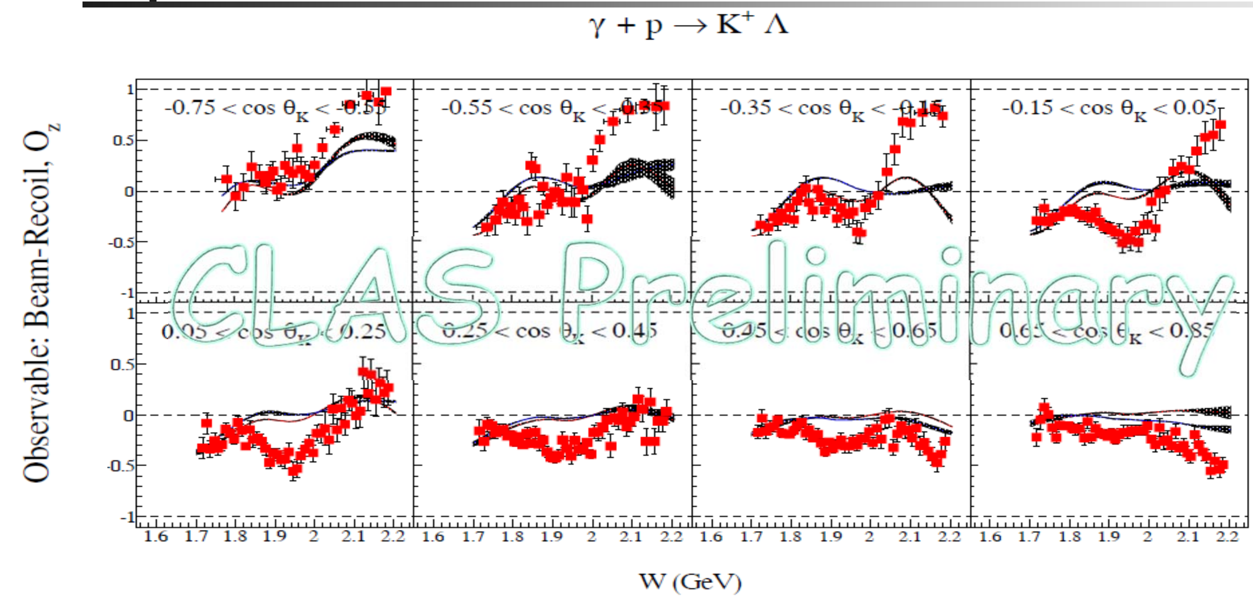
γp→K⁺Λ : target asymmetry T



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

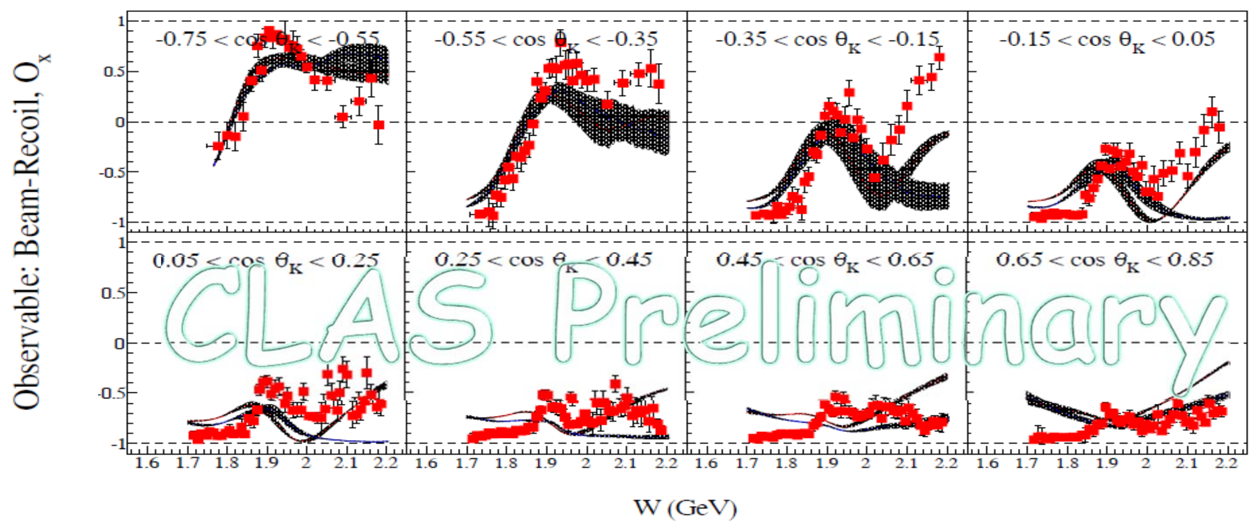
CLAS/Glasgow Preliminary

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



O_x

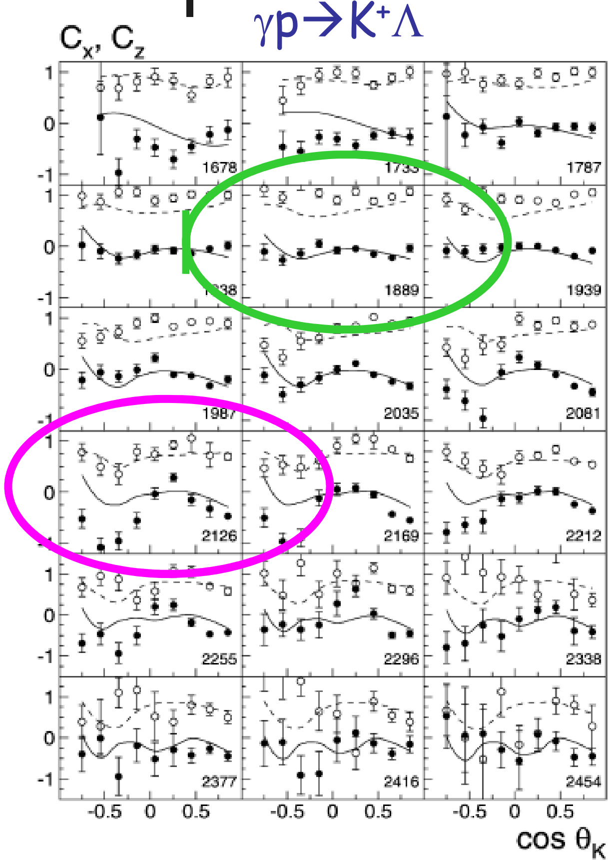
The Bonn-Gatchina model is not predictive at newly-measured kinematics



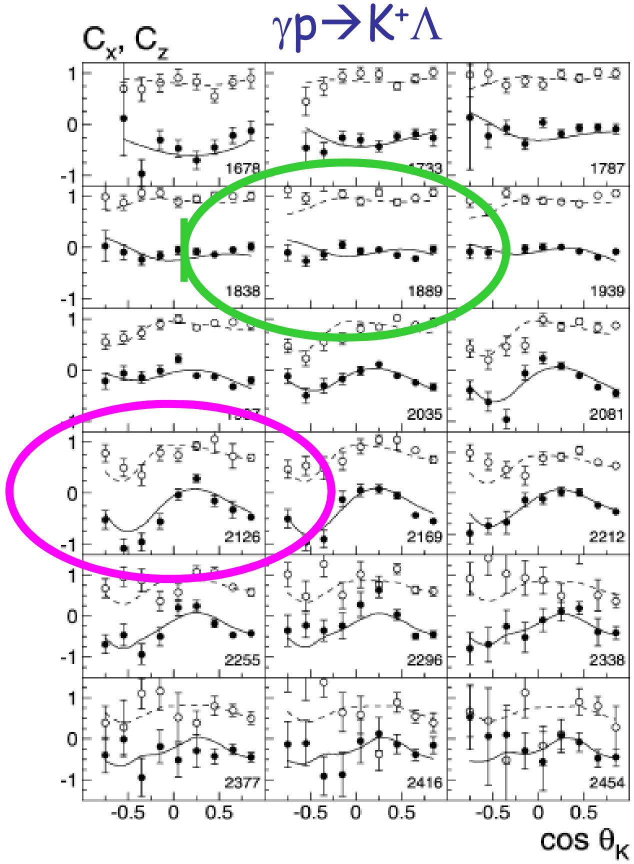
O_z

CLAS/Glasgow Preliminary

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

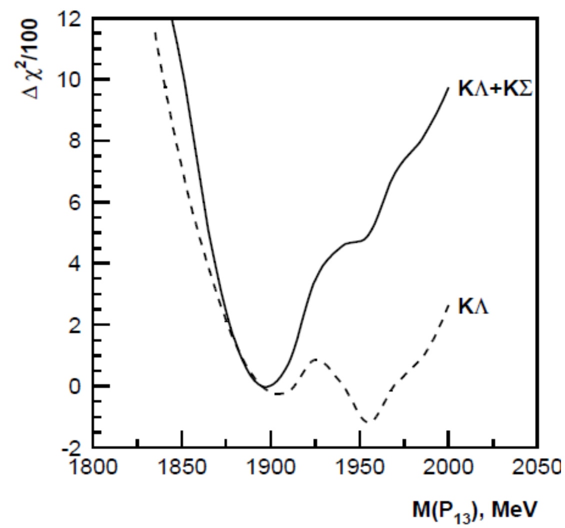


C_xC_z without N*(1900)P_{13}



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).

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
$p\pi^0$	✔	✓	✓	✓	✓	✓	✓	✓									g1, g8, g9
$n\pi^+$	✔	✓	✓	✓	✓	✓	✓	✓									g1, g8, g9
$p\eta$	✔	✓	✓	✓	✓	✓	✓	✓									g1, g11, g8, g9
$p\eta'$	✔	✓	✓	✓	✓	✓	✓	✓									g1, g11, g8, g9
$p\omega$	✔	✓	✓	✓	✓	✓	✓	✓									g11, g8, g9
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	g1, g8, g11
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	g1, g8, g11
$K^{0*}\Sigma^+$	✔										✓	✓			✓	✓	g1, g8, g11

Source: V. D. Burkert

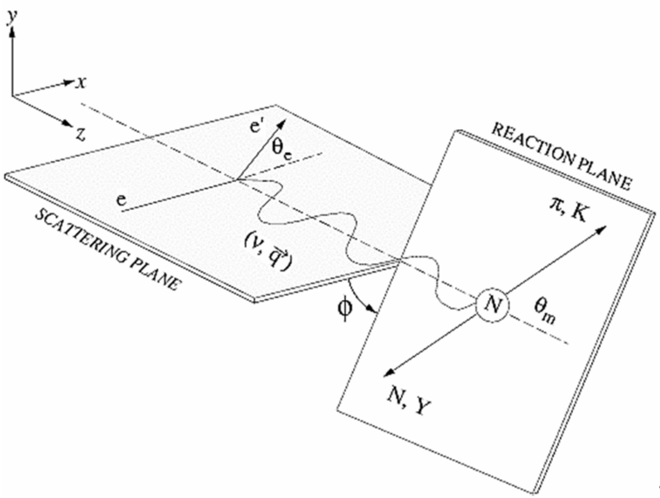
γ Y^* K^+ Lots more could be said…

- Omit results for Σ photoproduction
- Omit discussion of reactions on the neutron (deuteron), which accesses photon coupling isospin dependence.
- Overall goal: measure enough observ-ables for "complete" determination of amplitudes $\Rightarrow$ extract N* and Δ content

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

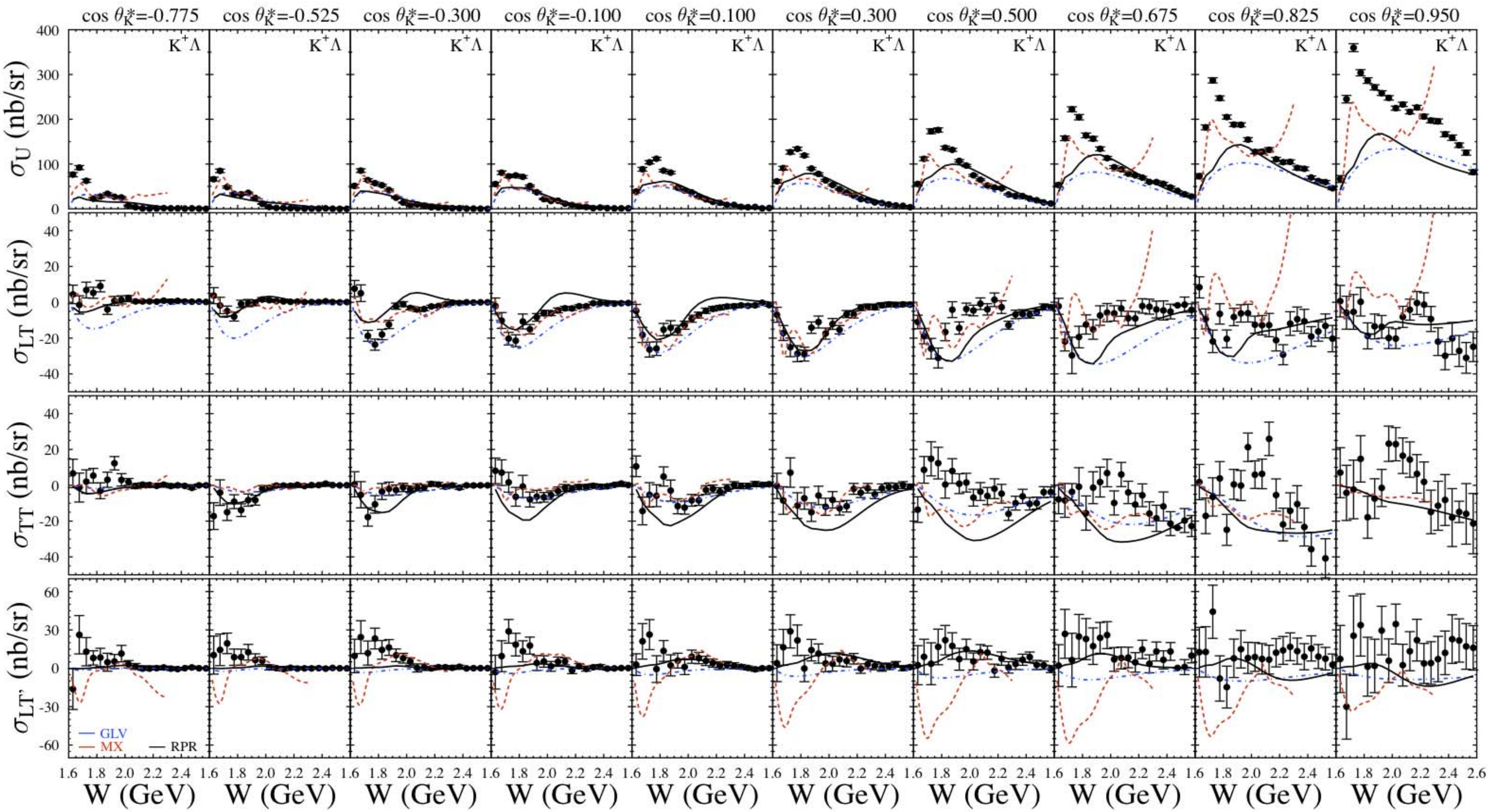
Helicity structure

σ_u "Unseparated"

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

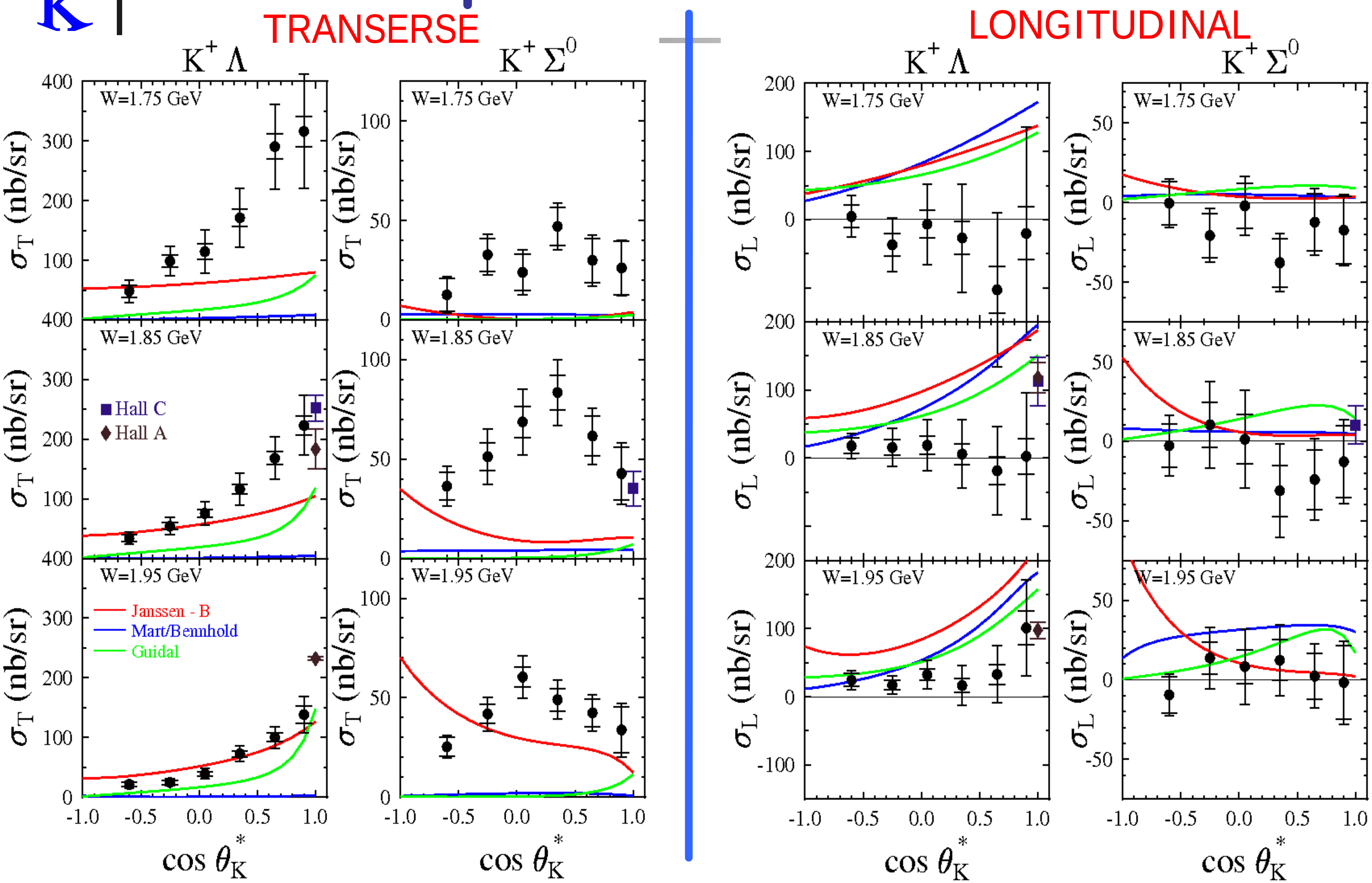
Transverse-longitudinal interference

$K^+\Lambda$ 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)]

L/T Separation



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

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 polariazation
  - *W=1.6-2.7 GeV, <Q^2>=1.9 GeV^2*
    [Gabrielyan *et al.*, PR C **90**, 035202 (2014)]

Publications:

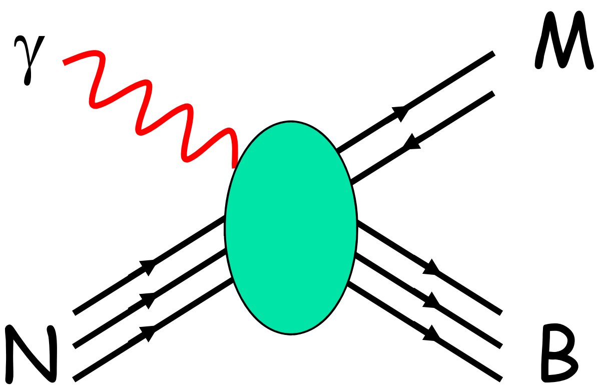
- $K^+\Lambda$ beam-recoil pol. transfer
  - *W=1.6-2.15 GeV, Q^2=0.3 – 1.5 GeV^2*
    [Carman *et al.*, PRL **90**, 131804 (2003)]
- $K^+\Lambda$ σ_L/σ_T ratio from pol. transfer data
  - *W=1.72-1.98 GeV, Q^2~0.7 GeV^2*
    [Raue & Carman, PR C **71**, 065209 (2005)]
- $K^+\Lambda$, $K^+\Sigma^0$ separated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

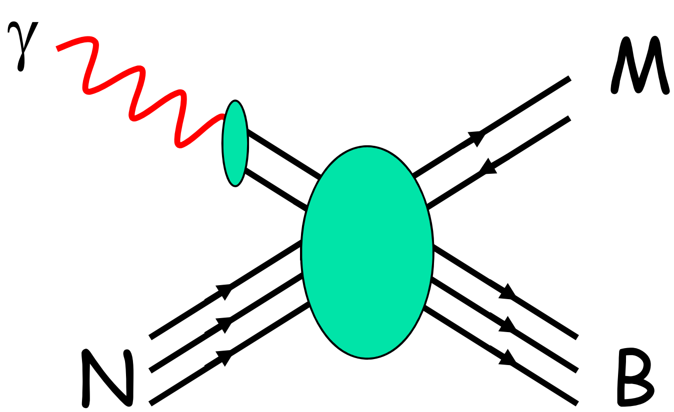
Publication: Scaling and Resonances in Elementary $K^{+}\Lambda$ Photo-production, R.A.Sch. and M.M. Sargsian Phys.Rev.C**83** 025207 (2011).

Constituent-Counting Scaling

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



n=9

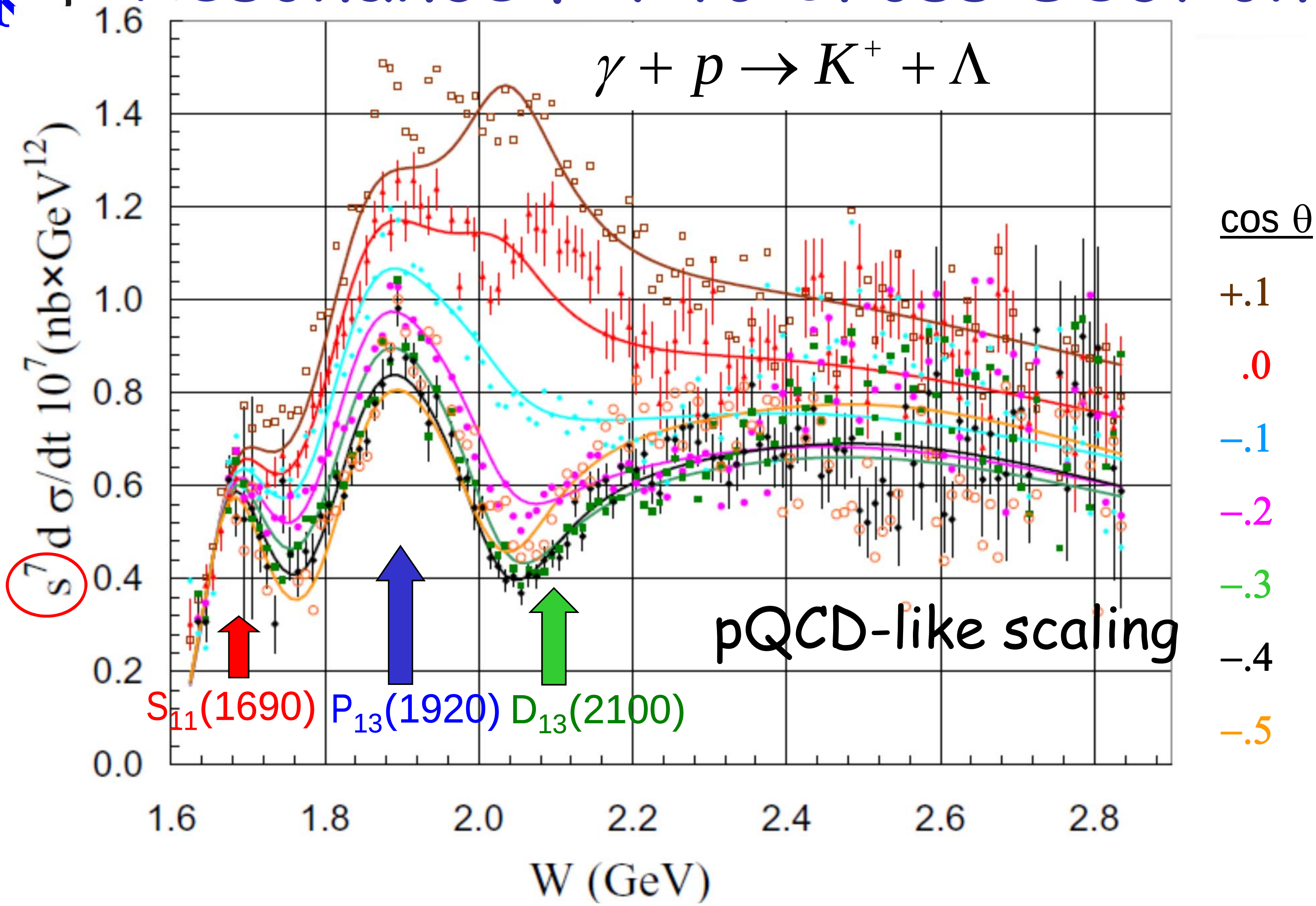


n=10

- 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 Cross Section

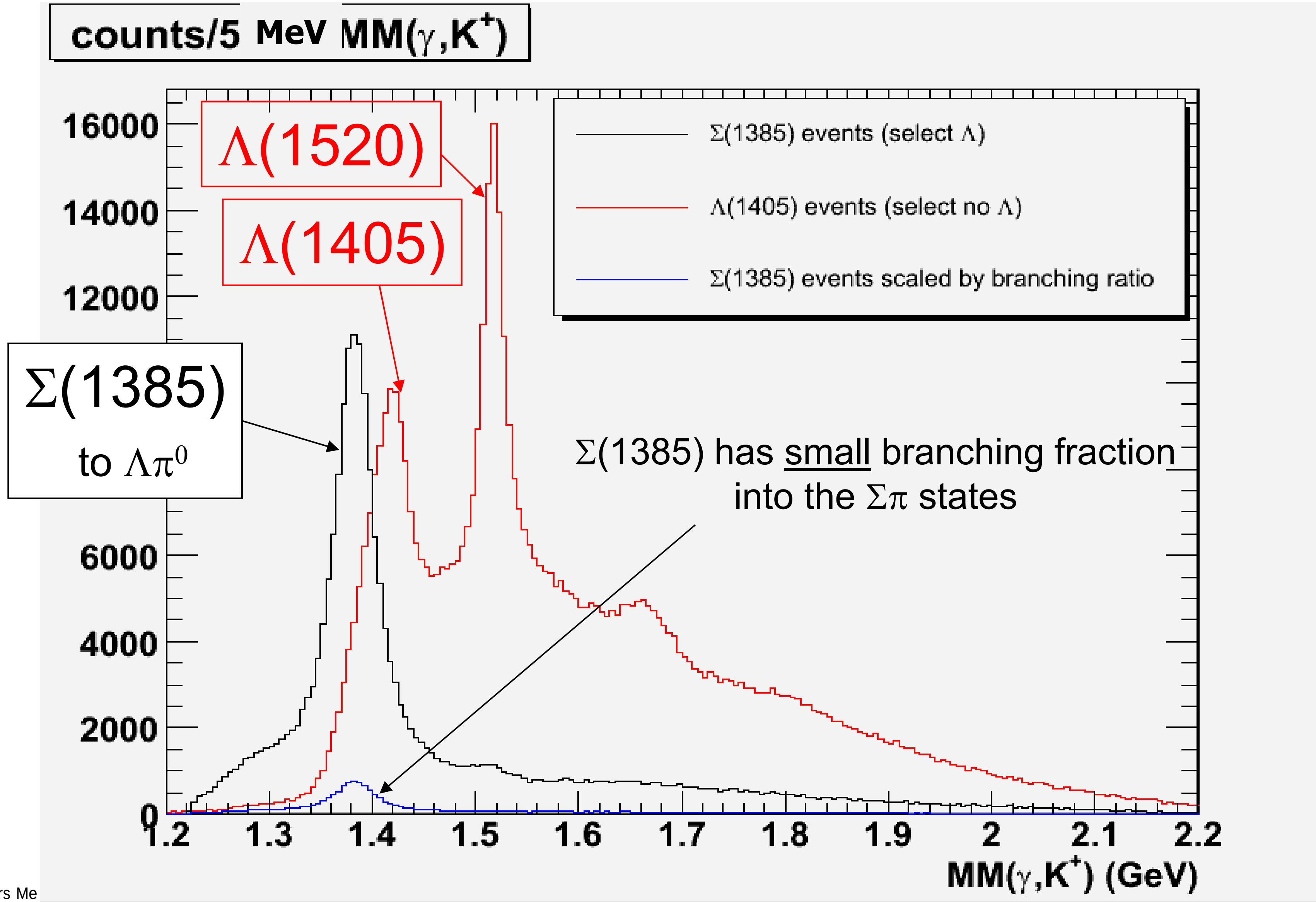


R.A. Schumacher and M.M. Sargsian Phys. Rev. C **83** 025207 (2011).

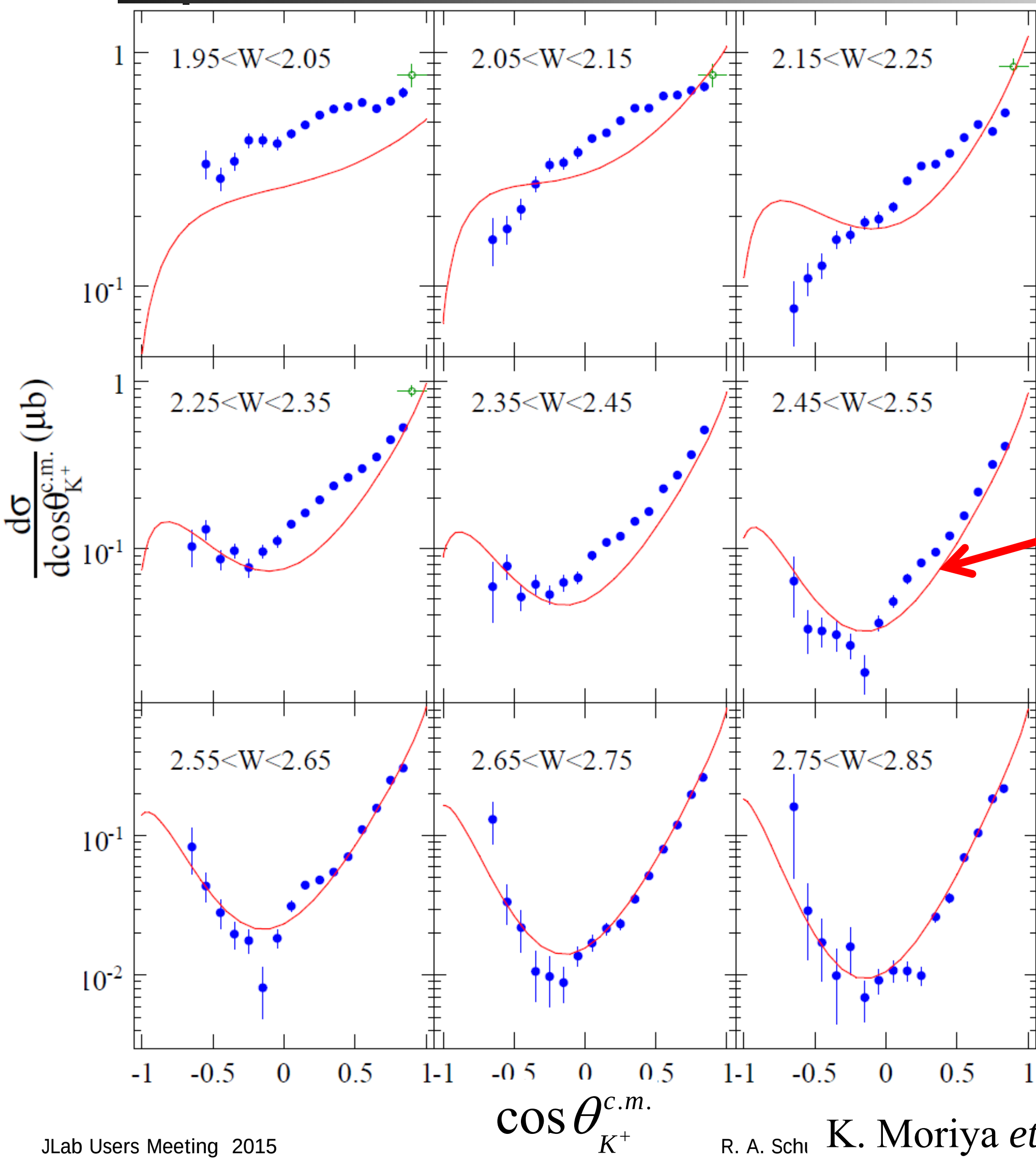
Excited Y* Cross Sections

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 $K^+\pi^+\pi^-(n)$



γ Y* K+ | Differential $\Sigma^0(1385)$ Cross Section

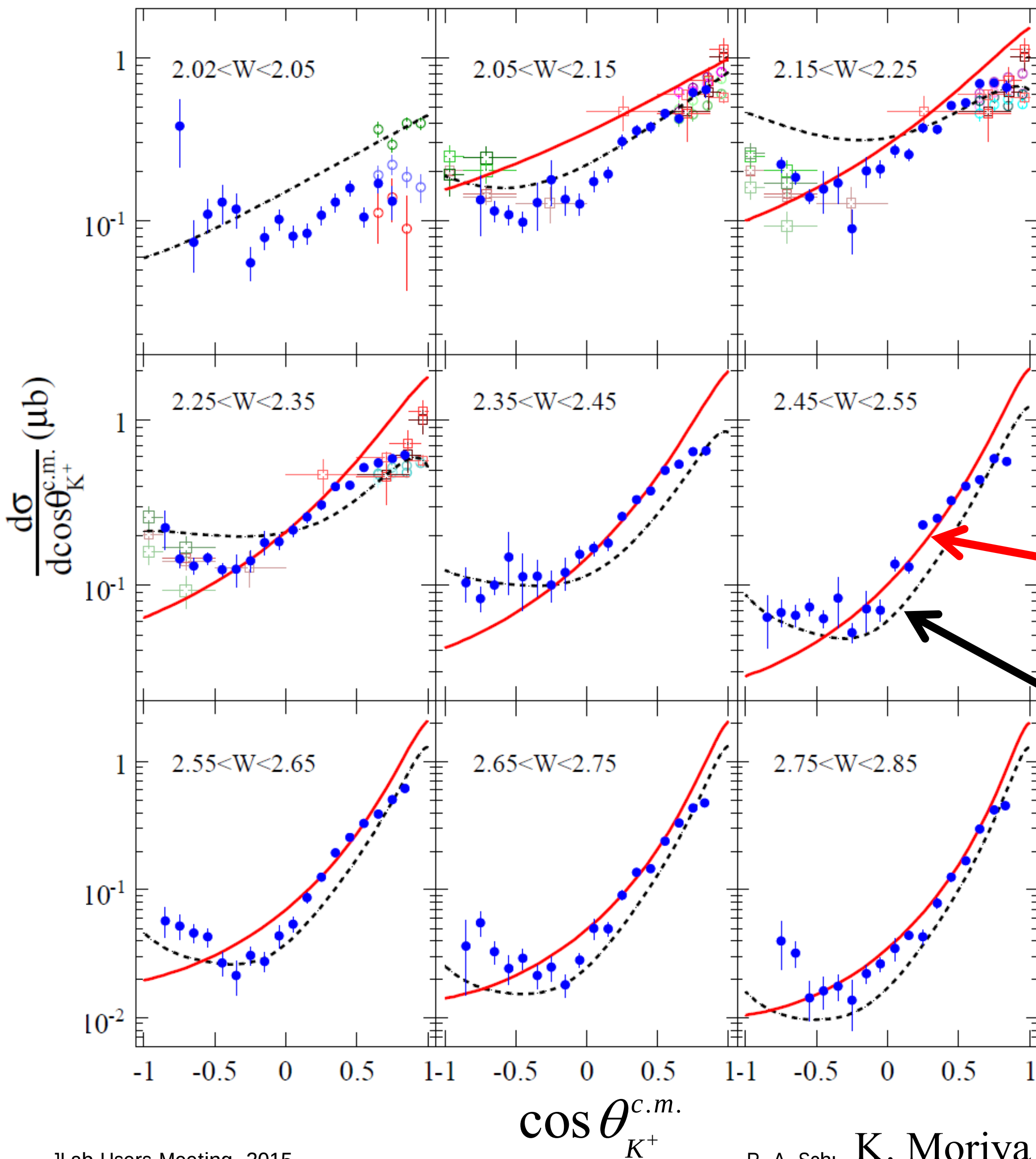


- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
- Experiment: see *t*-channel-like forward peaking & *u*-channel backward rise
  - Agreement with LEPS
- Theory by Oh et al.[1]: contact term dominant; included four high-mass N^* and Δ resonances
  - Prediction was fitted to preliminary CLAS total cross 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 $\Lambda(1520)$ Cross Section

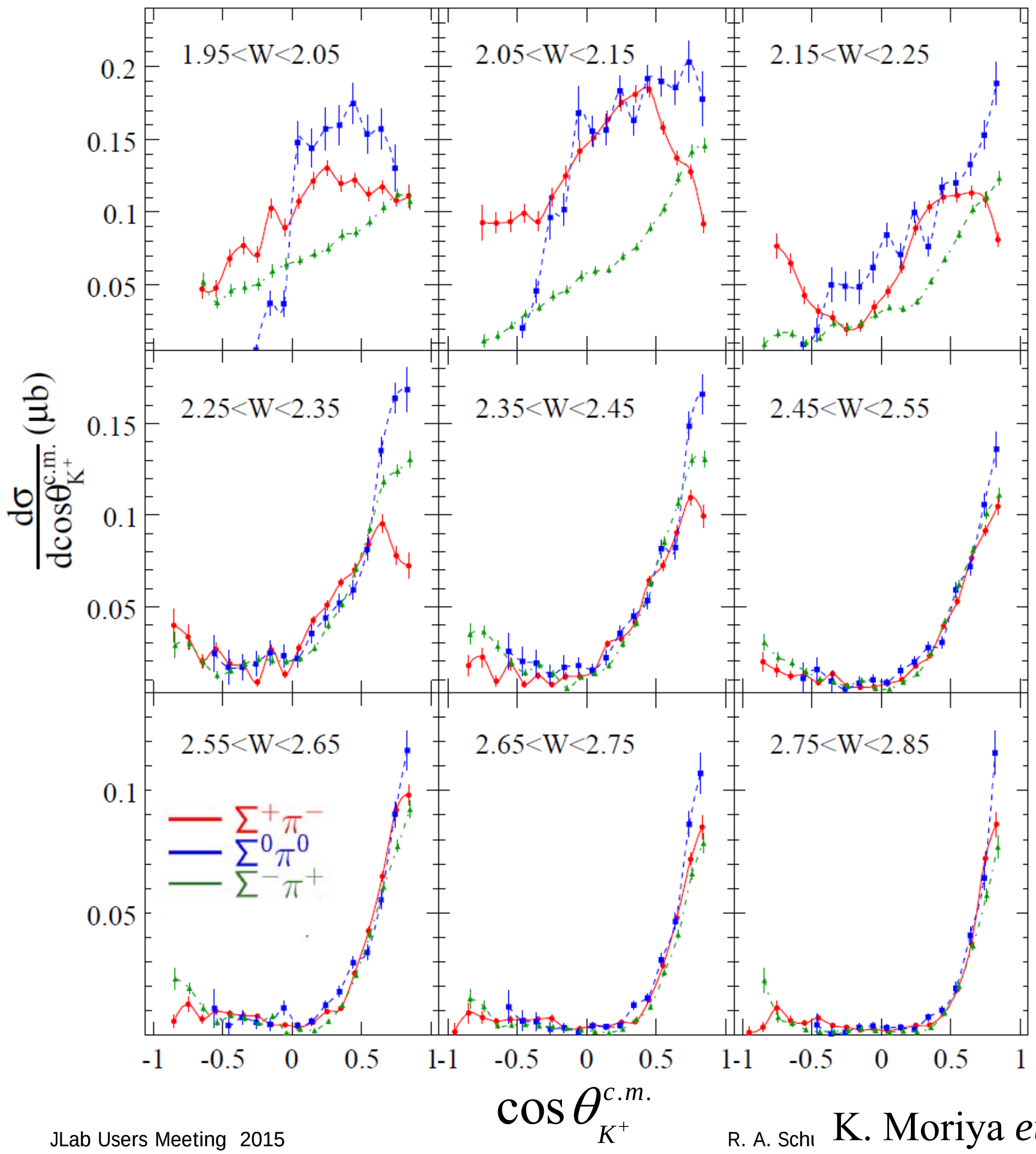


K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

- $\gamma + p \rightarrow K^+ + \Lambda(1520)$
- 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)

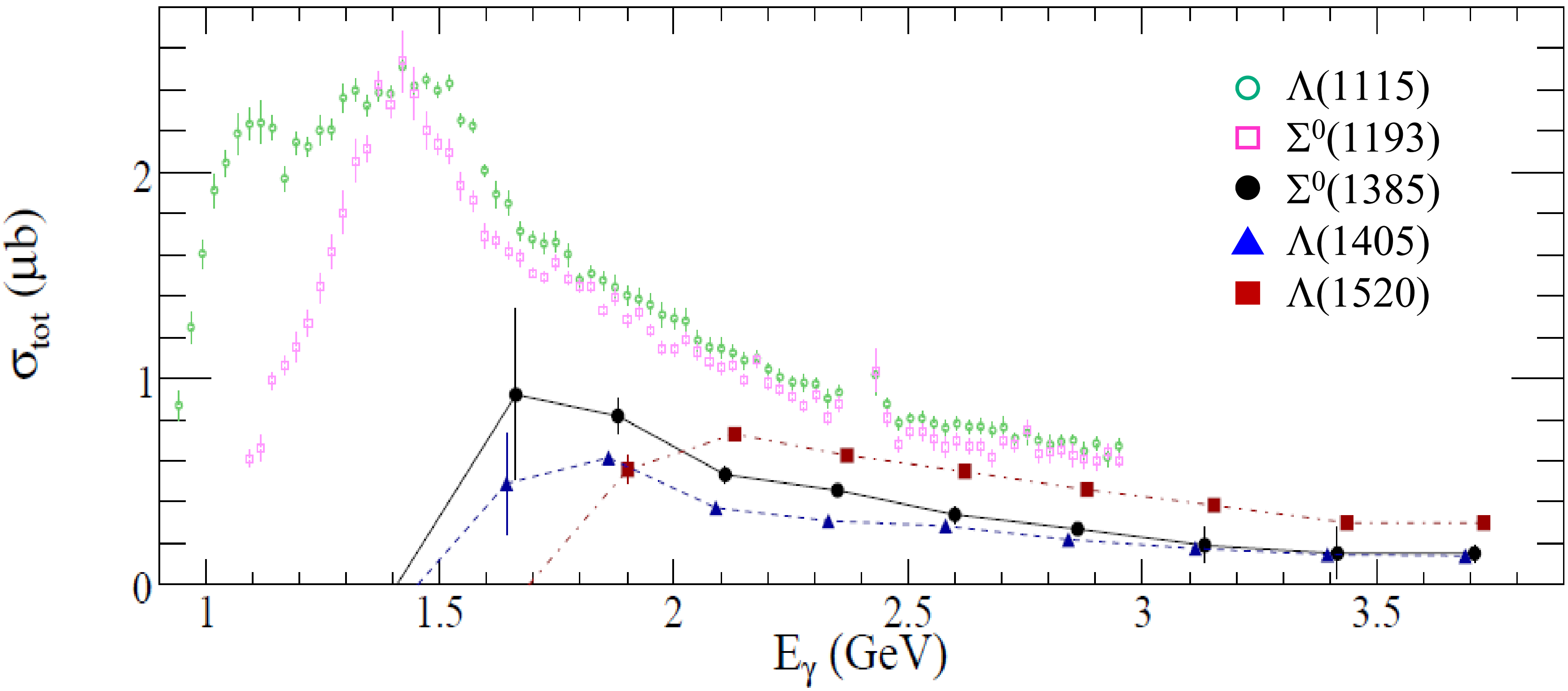
Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- 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]

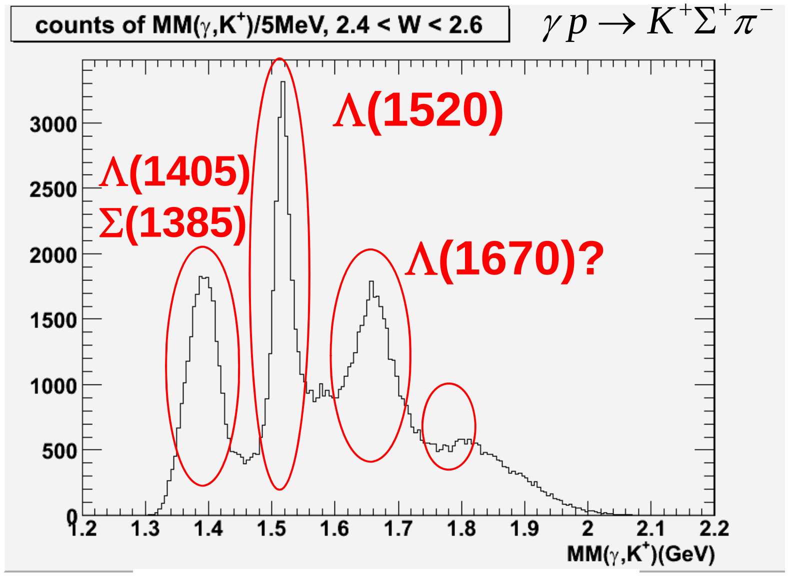
1. R. Bradford et al. (CLAS) Phys. Rev. **C 73**, 035202 (2006)
   K. Moriya *et al.* (CLAS), Phys. Rev. C **88**, 045201 (2013).

Λ(1405) Structure

Publications: Measurement of the Σπ 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 Σπ System near the Λ(1405), R. A. Sch. & K. Moriya, Nucl. Phys A **914**, 51 (2013) .

What "is" the $\Lambda(1405)$?

- 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, I=0, $J^{\pi} = \frac{1}{2}^{-}$
  - $\bar{K}N$ sub-threshold state
    - Recent first Lattice QCD result: J. Hall *et al.*, Phys Rev Lett **114**, 132002 (2015)
  - Signal may be an overlay of I=0 and I=1 states



(γ,K) Missing Mass (GeV)

Chiral Unitary Models

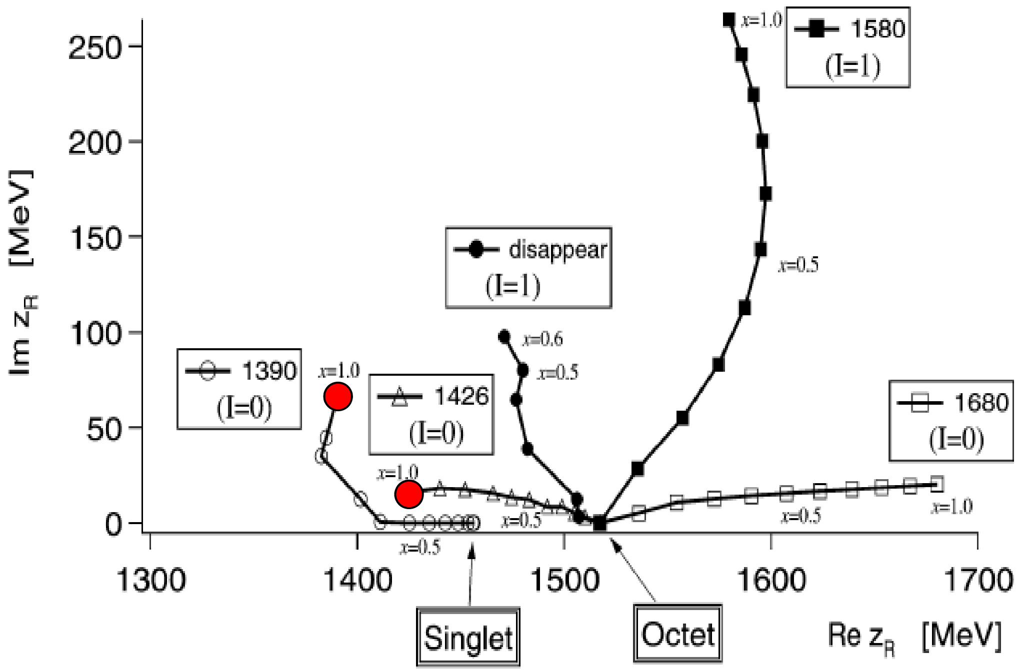
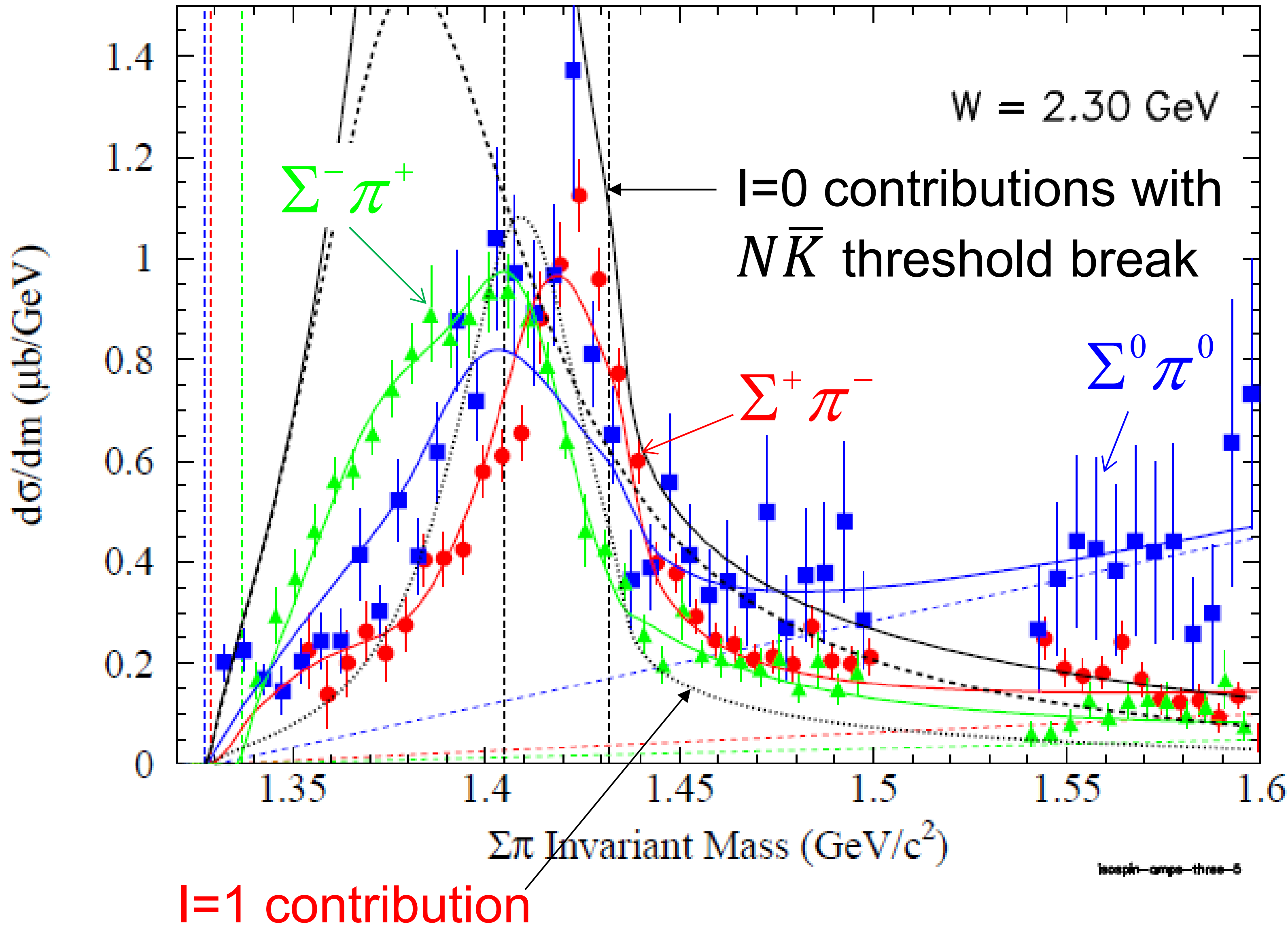


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

- 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 <u>two</u> $S = -1 \quad I = 0$ poles near 1405 MeV
  - ~1420 mostly $\bar{K}N$
  - ~1390 mostly $\pi\Sigma$
- Possible weak $I=1$ pole also predicted

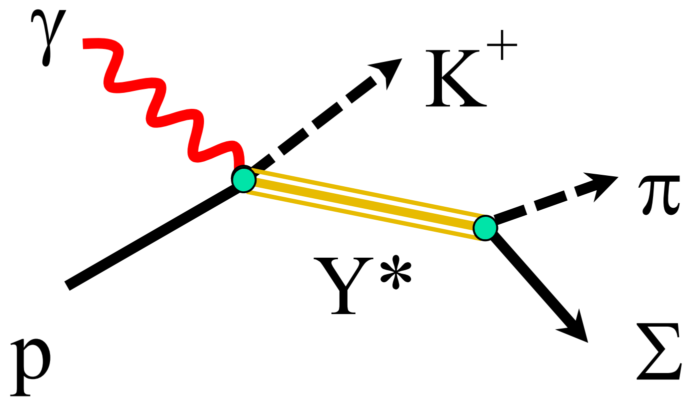
D. Jido, J.A. Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A **725,** 181 (2003)
J.A. Oller, U.-G. Meissner Phys. Lett B **500**, 263 (2001).

Example at W=2.30 GeV



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

Isospin Interference



Final Σπ state

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

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

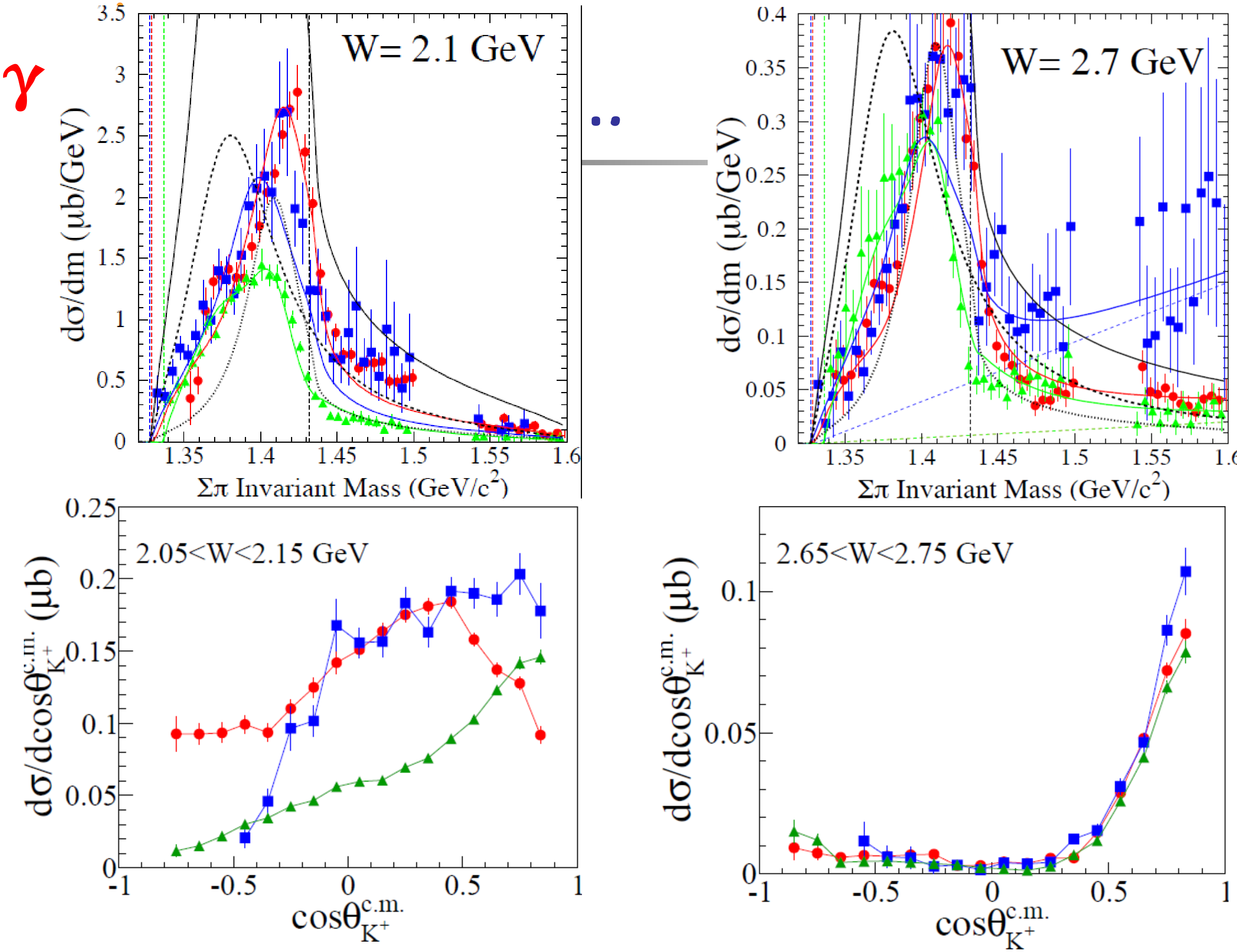
Three charge combinations:

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

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

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

γ



Line Shapes

Cross Sections

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

What "is" the I=1 piece?

- I=1 resonance? 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 !

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).

γ Y^* K^+

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 $m = \pm 3/2$ fraction

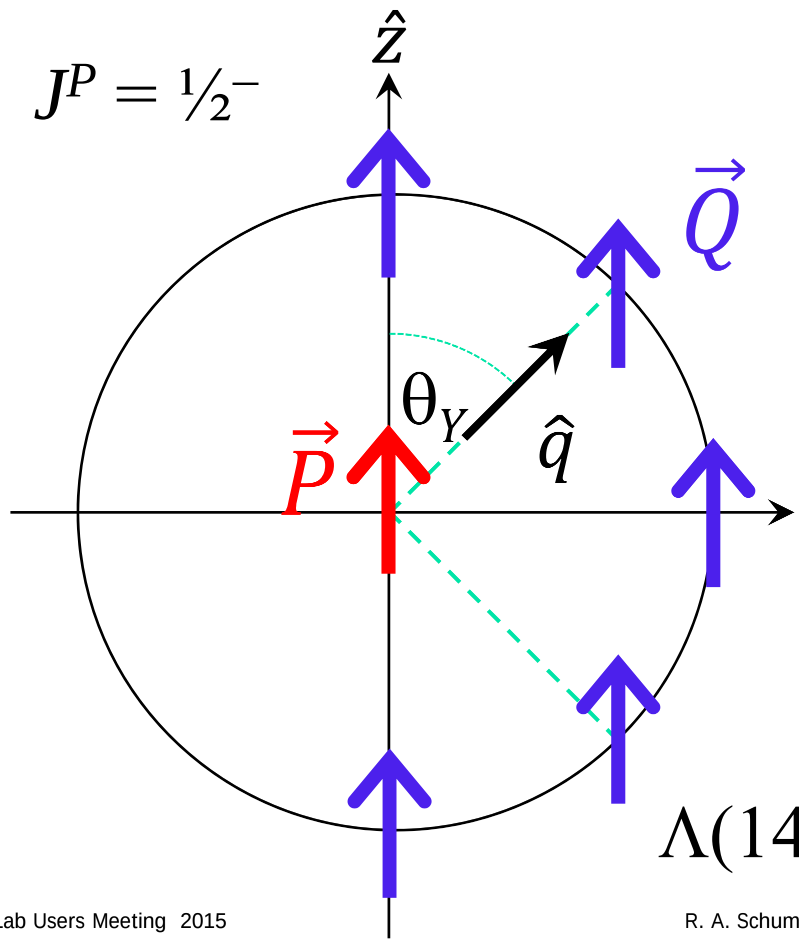
$$I(\theta_Y) \propto 1 + \frac{3(1-2p)}{2p+1}\cos^2\theta_Y$$

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

S-wave, P-wave Scenarios

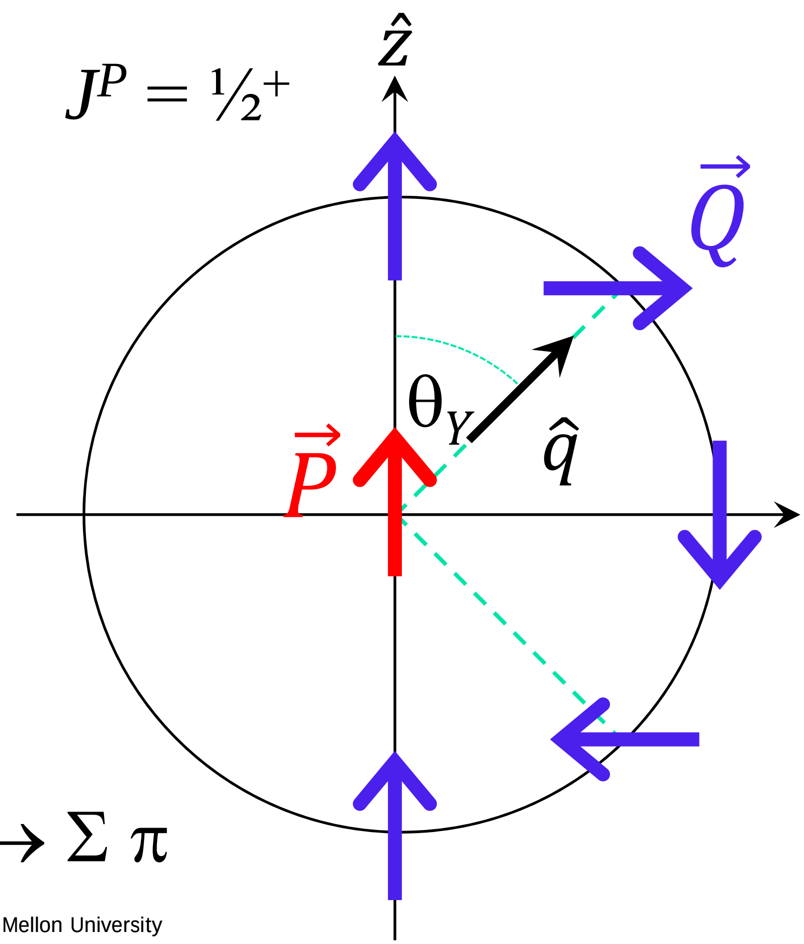
L=0 (s-wave)

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



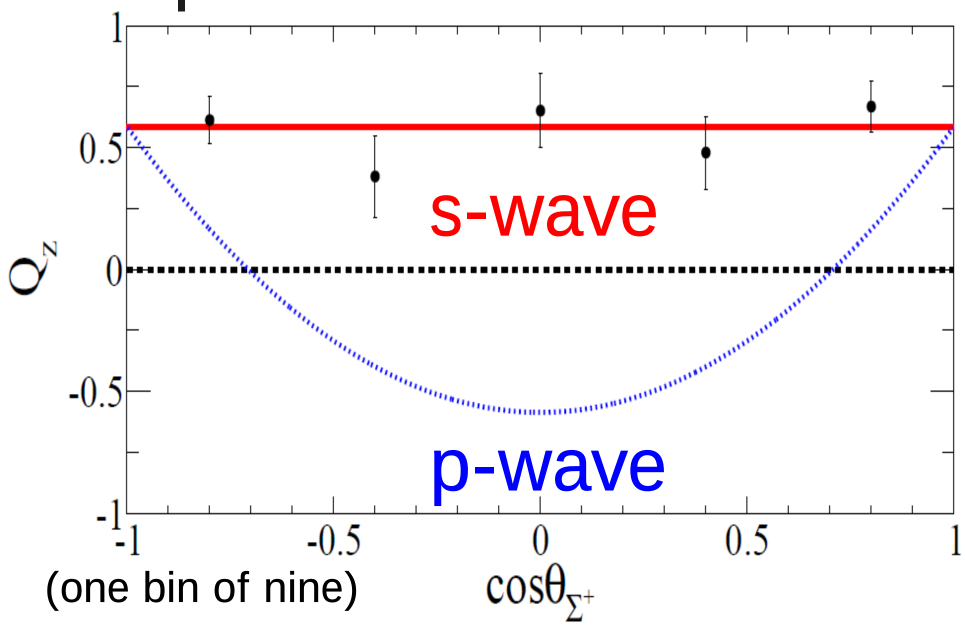
L=1 (p-wave)

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



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

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 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 = $"*negative*"

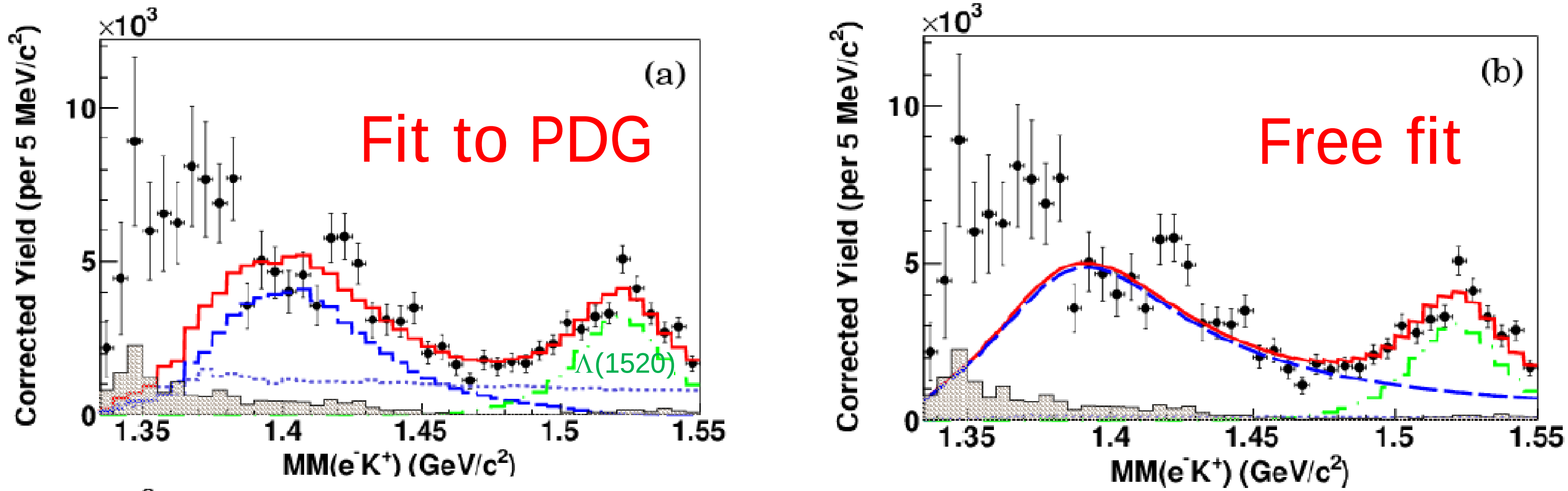
$J^P = ½^-$ confirms quark model expectation

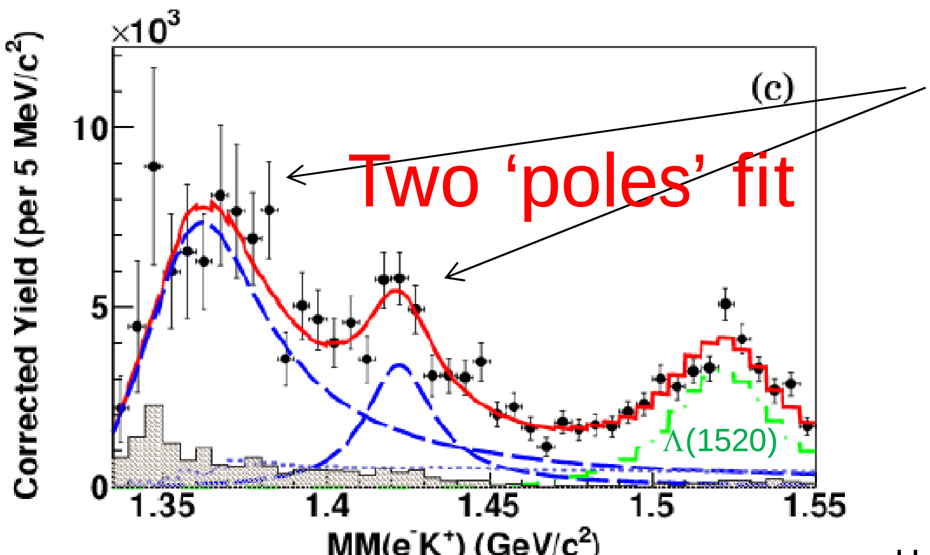
and $\Lambda(1405)$ is produced ~ +45% polarized

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)





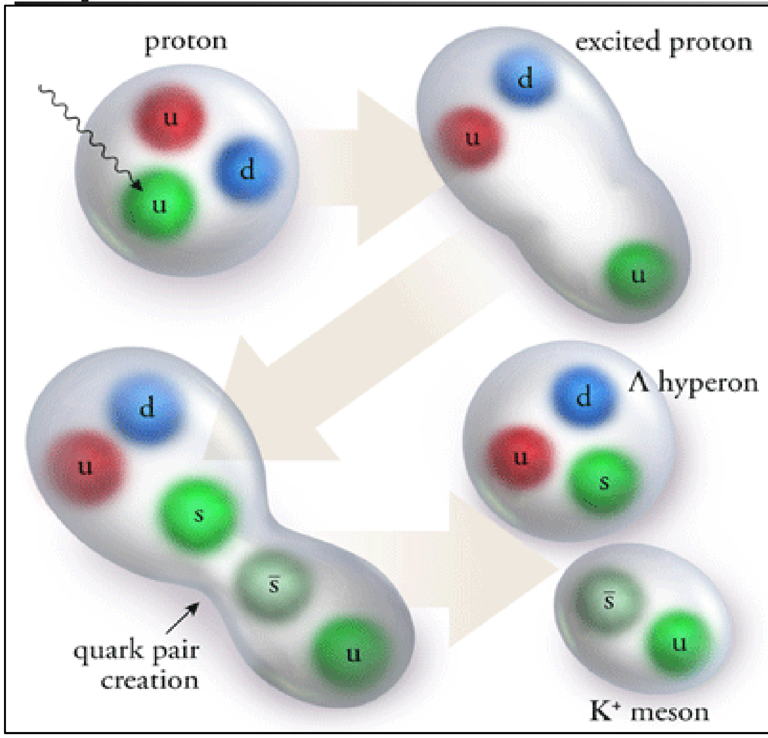
- Two-bump structure seen
- Possible evidence for two I=0 poles
- PDG Λ(1405) values fail utterly
- Calculation needed!

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

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

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

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



Ratio	$s\bar{s}\ /\ d\bar{d}$	$u\bar{u}\ /\ d\bar{d}$
$K^+\Lambda/\pi^+n$	0.19 ± 0.03	-
$K^+\Lambda/\pi^0p$ **"a"**	0.22 ± 0.07	-
$K^+\Lambda/\pi^0p$ **"b"**	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, ratios are proportional to the relative production rates of $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$

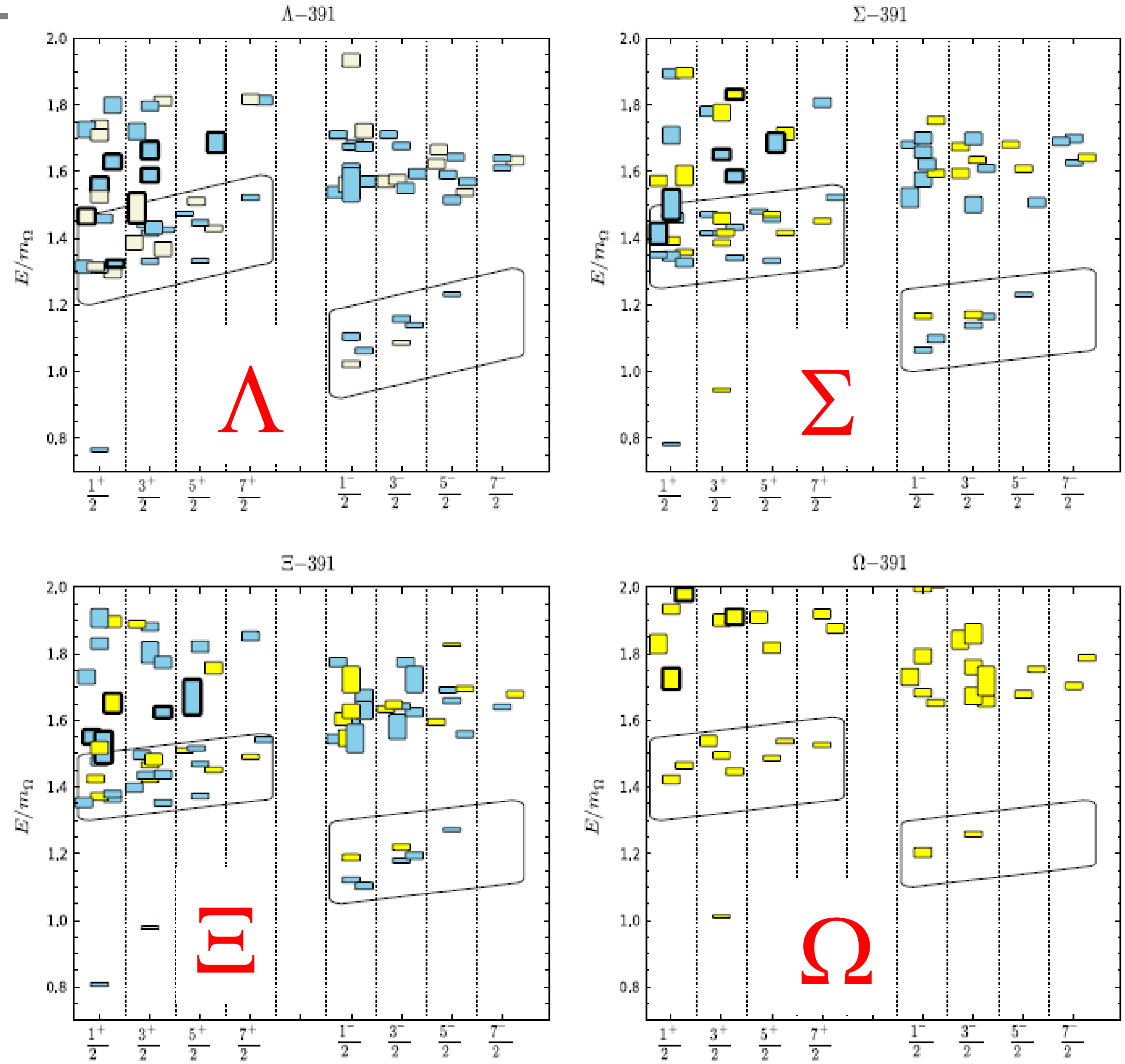
Physics conclusion:

- Ratio of $s\bar{s}$ pair creation relative to $u\bar{u}$ or $d\bar{d}$ is suppressed; $\approx 0.2 - 0.3$
- Consistent with high-energy results when 100's of particles are produced

The Future: Outlook at GlueX and CLAS12

Lattice QCD Predictions

- Lattice QCD now predicts rich baryon families
- Most states not identified by experiment yet

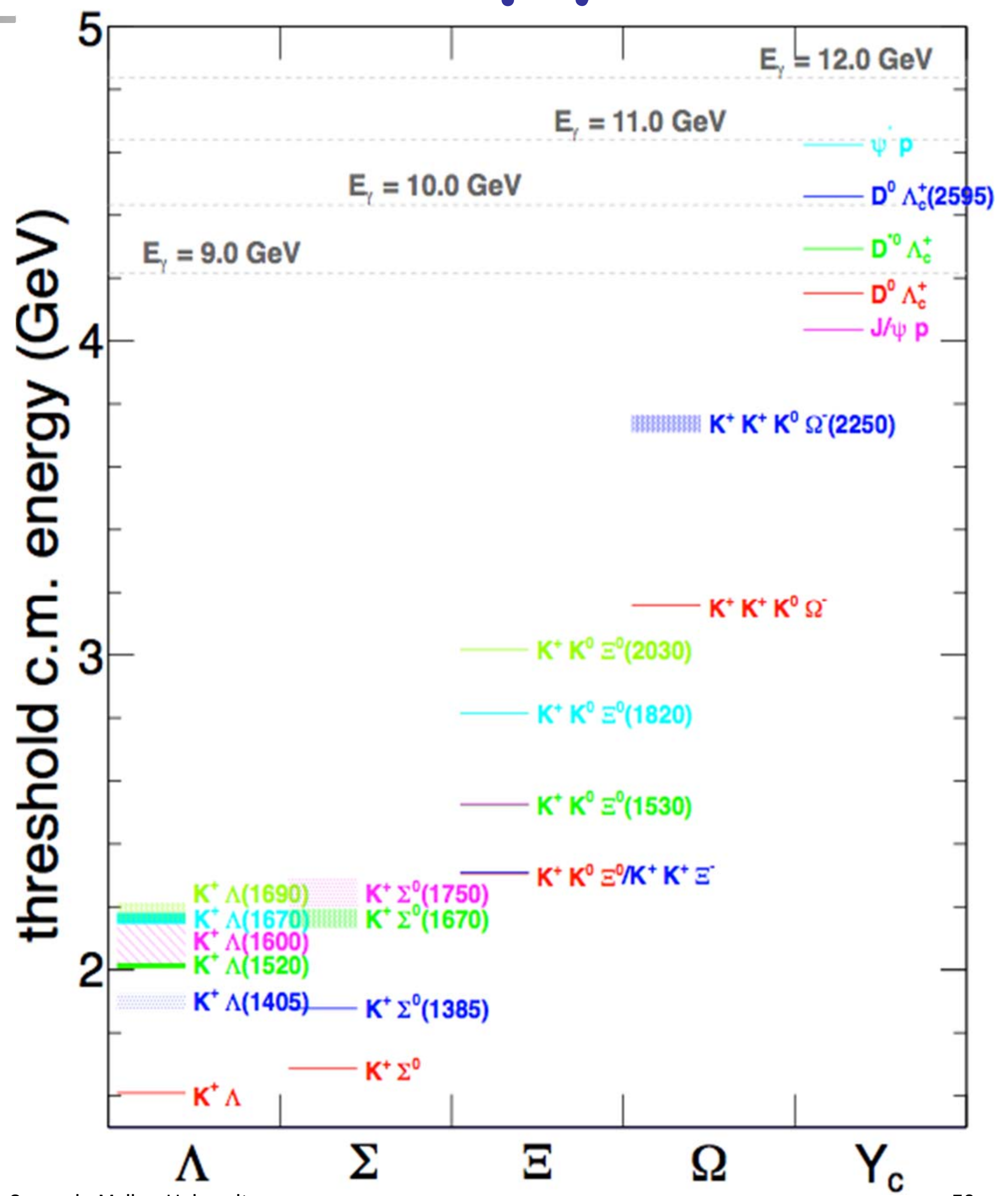


flavor singlet
flavor octet
flavor decouplet

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 remain undiscovered
- Charm threshold



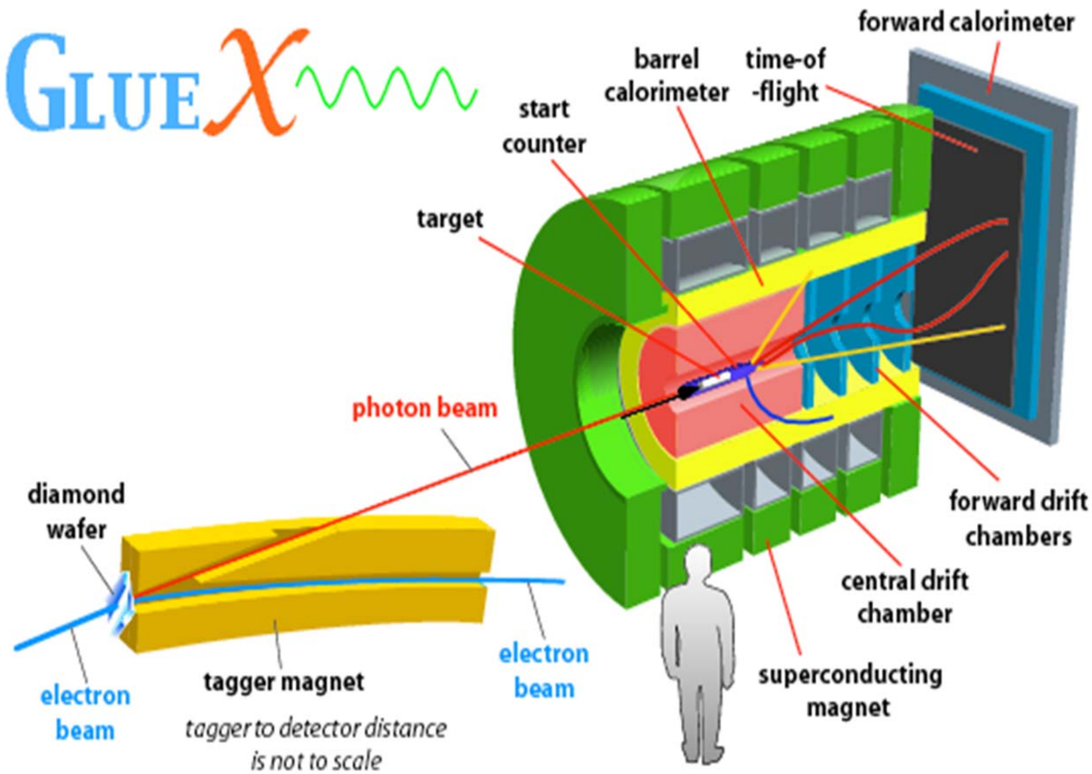
(K. Moriya, priv. comm.)

JLab Hall D/GlueX

- New hall, finished construction
- Commissioning in progress now
- Approved for 220 days of high statistics running

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

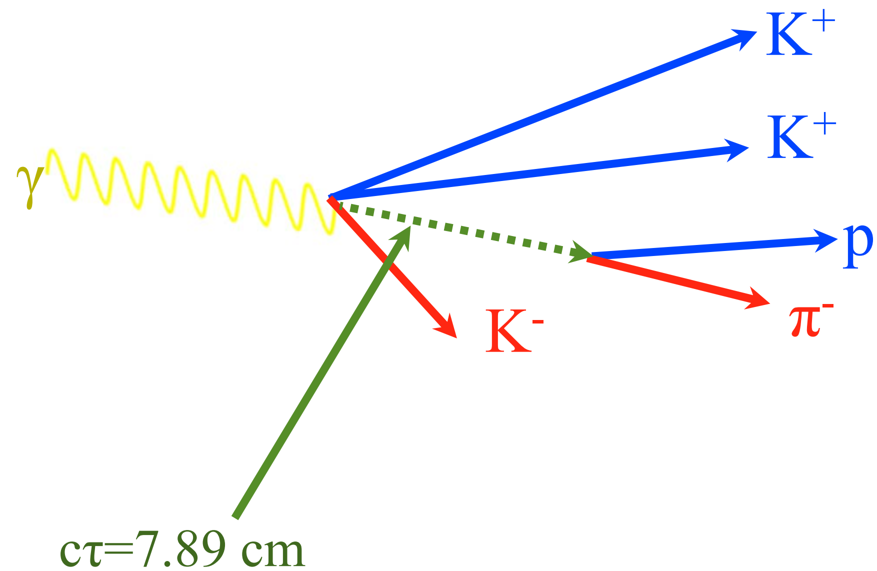


GlueX Study of $\Xi^-(1820)$

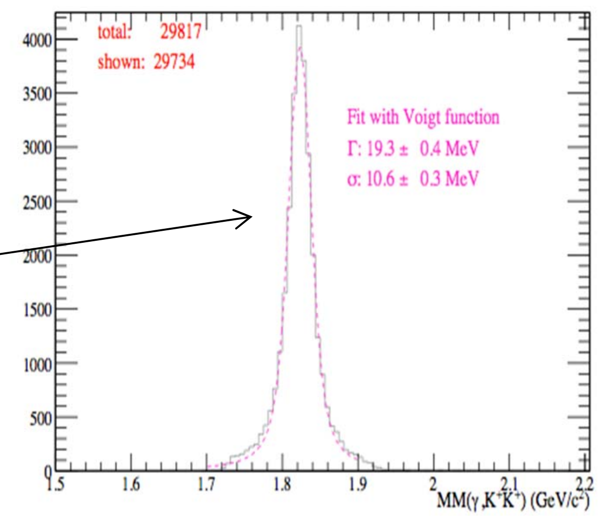
- Use simulated data to study

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

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



- 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.)

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

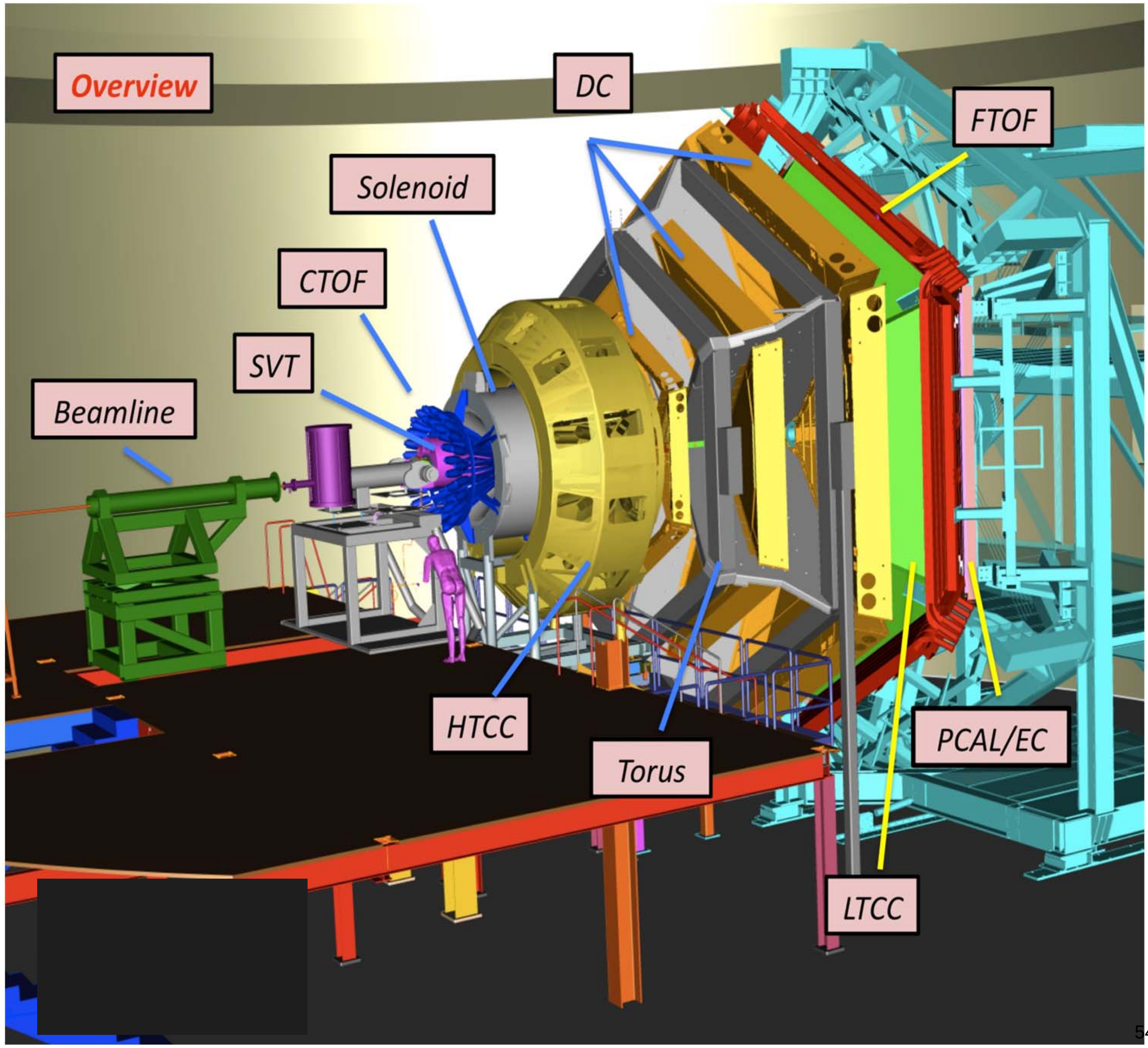
Central Detector (CD)
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

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.)

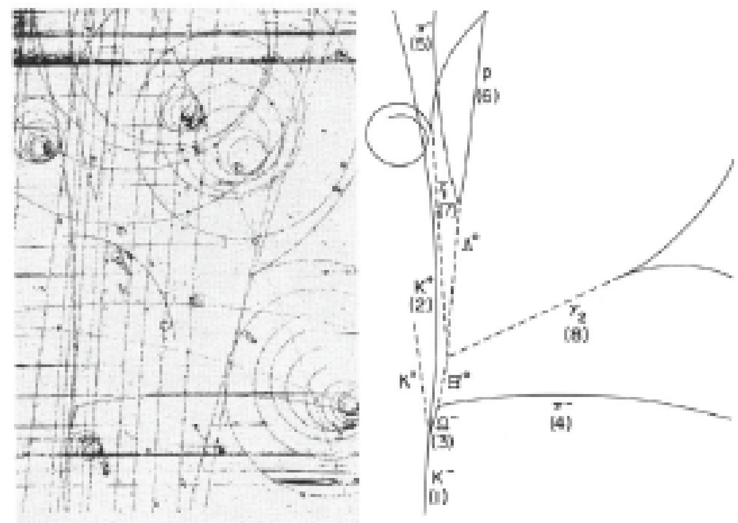
6/19/14



CLAS12: Very Strange Baryons

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

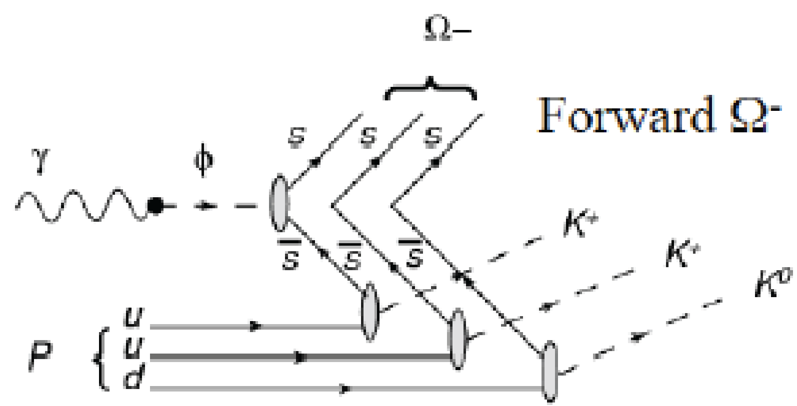
- Ω^- discovered in 1964: after 50 years, indication on J^P from Babar and others but full determination not yet achieved
- Ξ^* spectrum still poorly known: many states missing and spin/parity undetermined



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.)

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).
- Ξ photoproduction
  - g12 group, Goetz, Guo, et al.
- Hypernuclear electroproduction
  - Halls A & C, Nakamura, Hashimoto, Markowitz, Tang, et al.

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 demonstrated
- Direct J^P measurement for $\Lambda(1405)$ made: $\frac{1}{2}^-$
- Cross section scaling demonstrated and strangeness suppression seen
- JLab at 12 GeV with CLAS12 and GlueX will explore Y* and meson spectra

Supplemental Slides

CLAS Experiment

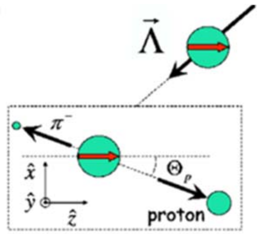
- Jefferson Lab, Newport News, VA, USA
- Photoproduction:
  - Targets: unpolarized LH_2, polarized p and HD
  - Beams: unpolarized, circular, linear, to ~5 GeV
  - Reconstructed $K^+ p \pi^- (\pi^0)$ or $K^+ \pi^+ \pi^- (n)$
  - 20×10^9 triggers → 1.41×10^6 $KY\pi$ events in g11a
- Electroproduction: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

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 | **KY**

recoil target γ | 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).

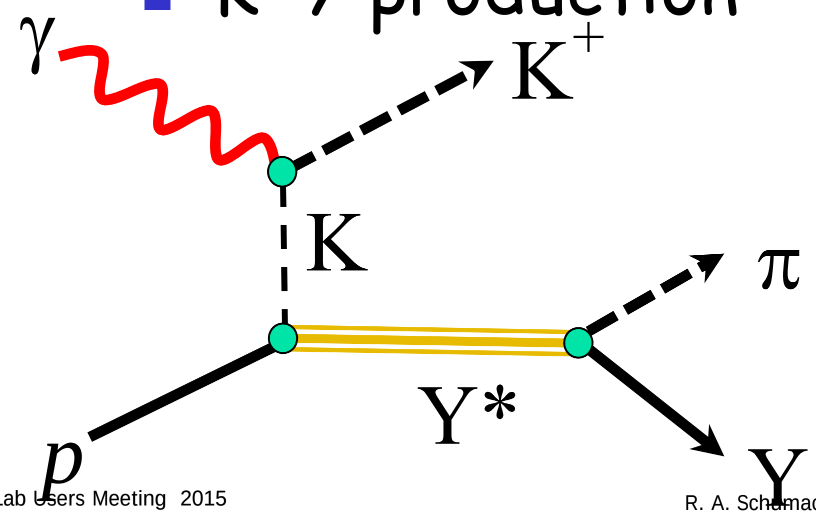
circ polarized photons | longitudinally polarized target

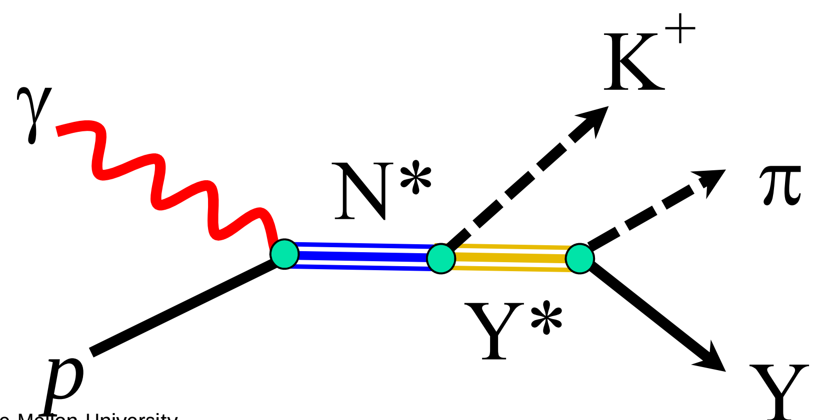
linearly polarized photons | transversely polarized target

Complete, and over-determined

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

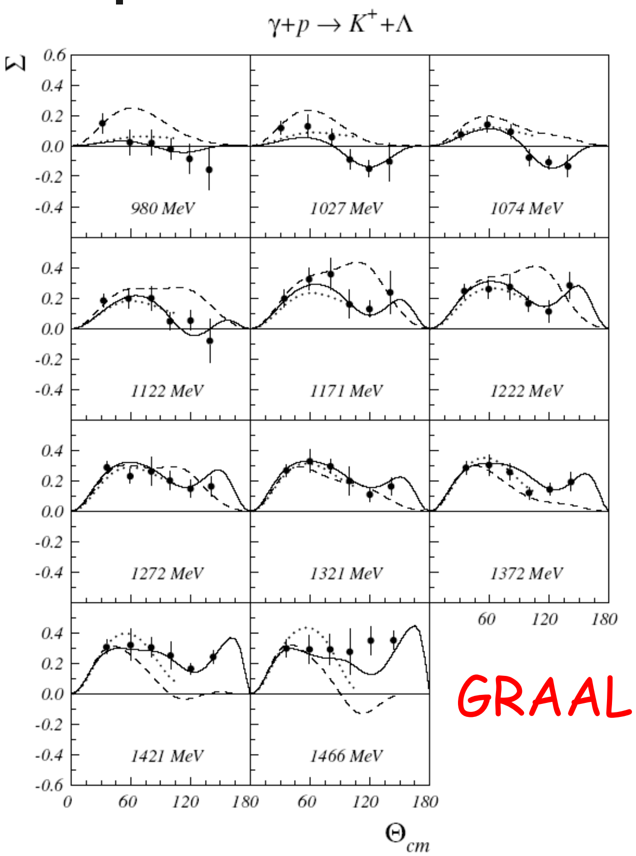


Fig. 14. Angular distributions of the beam asymmetries Σ for $\gamma p \rightarrow K^+\Lambda$ and γ-ray energies ranging from t 1500 MeV. Data are compared with the new solutions of the BCC (solid line), SAPCC (dashed line) and GRP models.

GRAAL

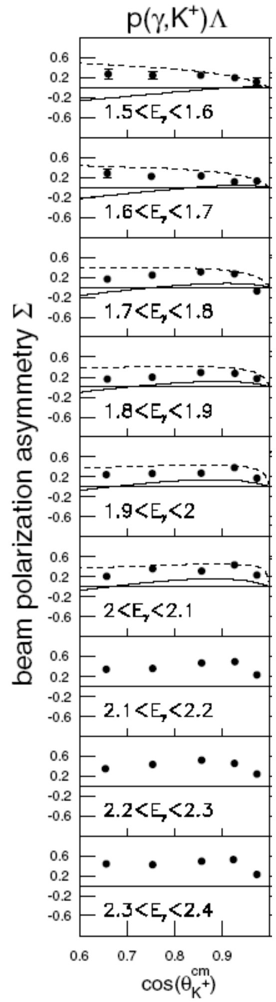


FIG. 3. Beam polarization asymmetries for the $p(\tilde{\gamma}, K^+)\Lambda$ (left) and $p(\tilde{\gamma}, K^+)\Sigma^0$ (right) reactions as a function of $\cos(\theta^{c.m.}_{K^+})$ for different photon-energy bins. The error bars are ... ons using ... Janssen ... rimental

LEPS

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

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).

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

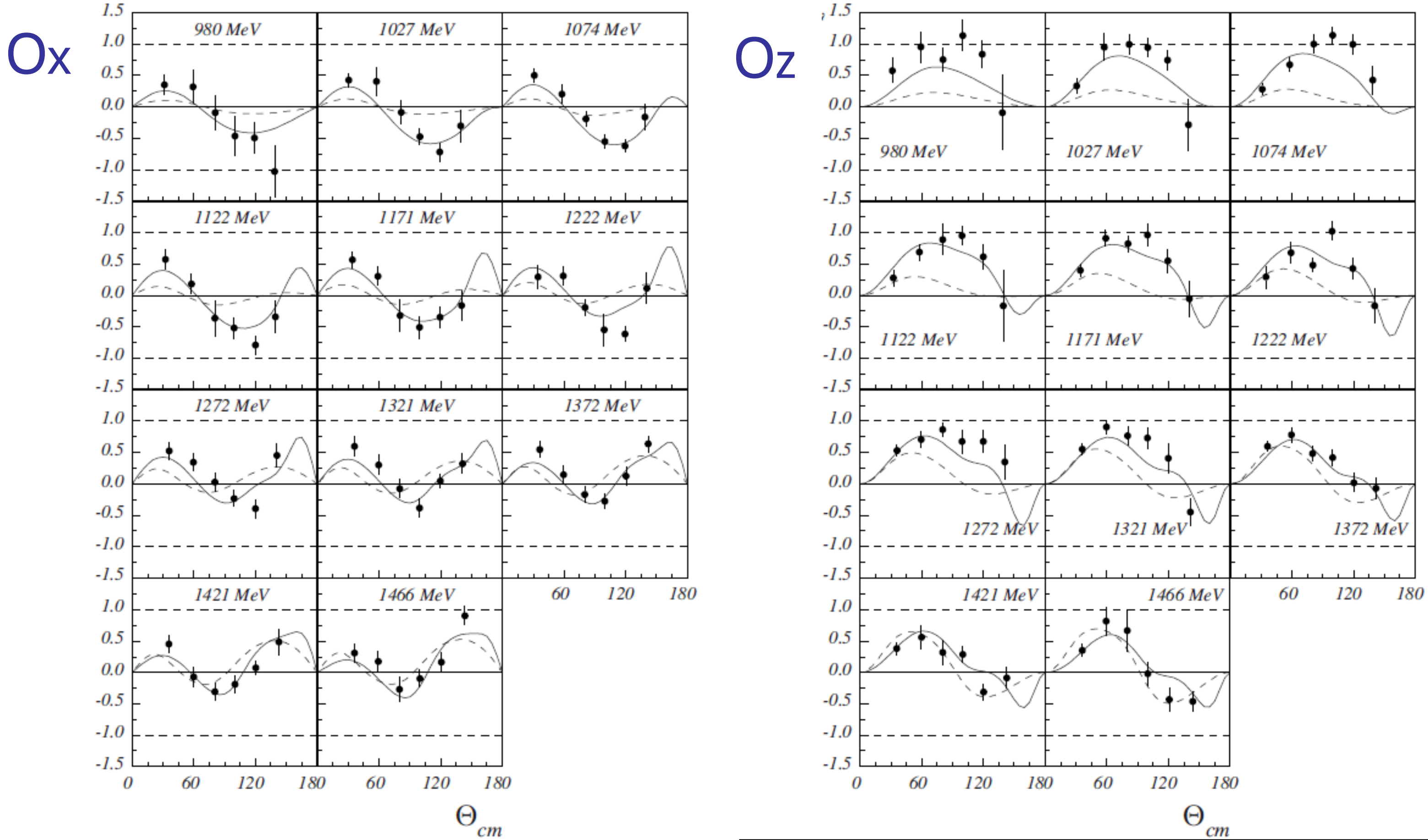
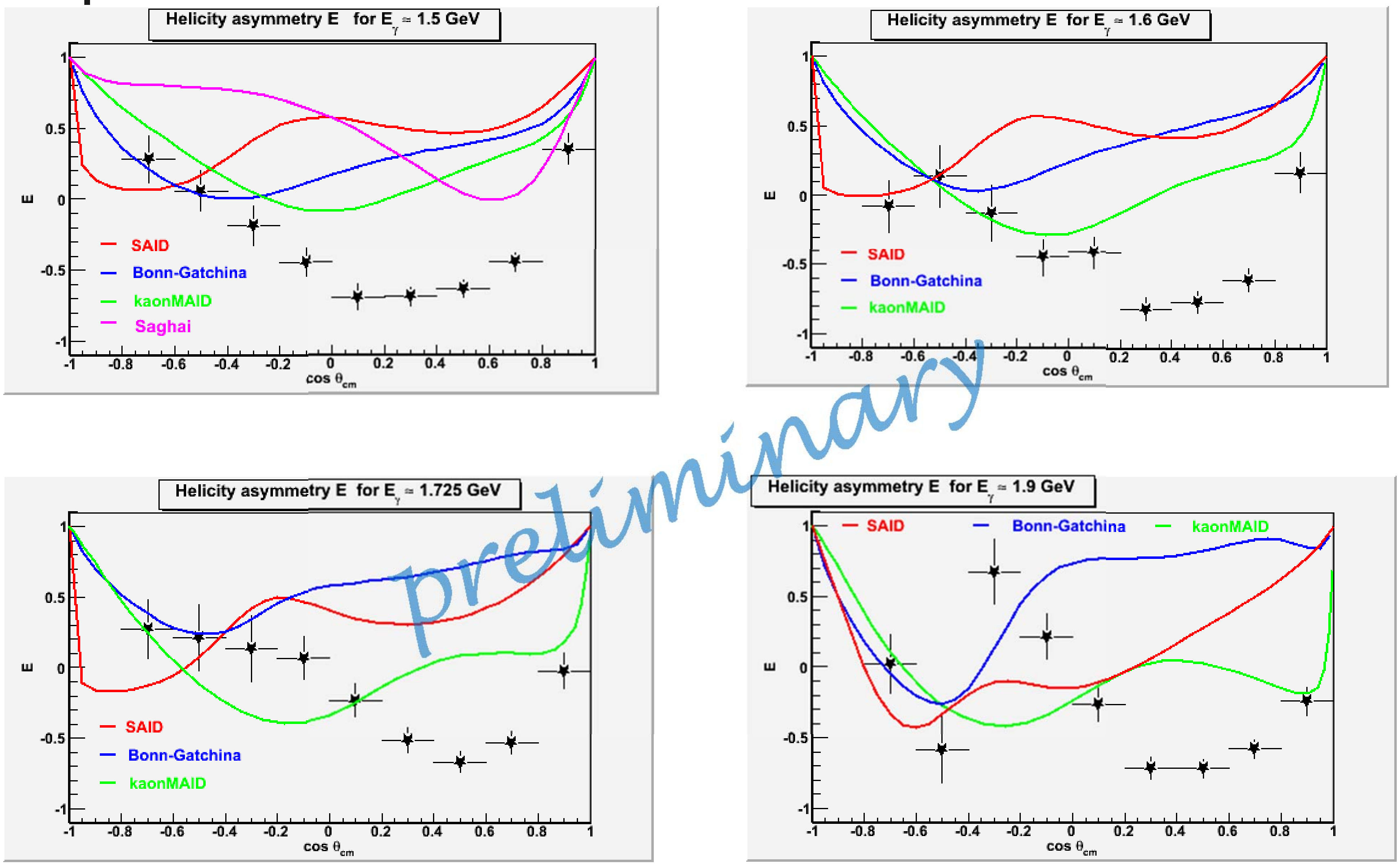


Fig. 9. Angular distributions of the beam-recoil observable O_x for photon energies E_γ ranging from 980 MeV to 1466 MeV. Error bars represent the quadratic sum of statistical and systematic errors. Data are compared with the predictions of the BG (solid line) and RPR (dashed line) models.

GRAAL data: fair agreement with BoGa and RPR models

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

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



L. Casey, Catholic U. / CLAS

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

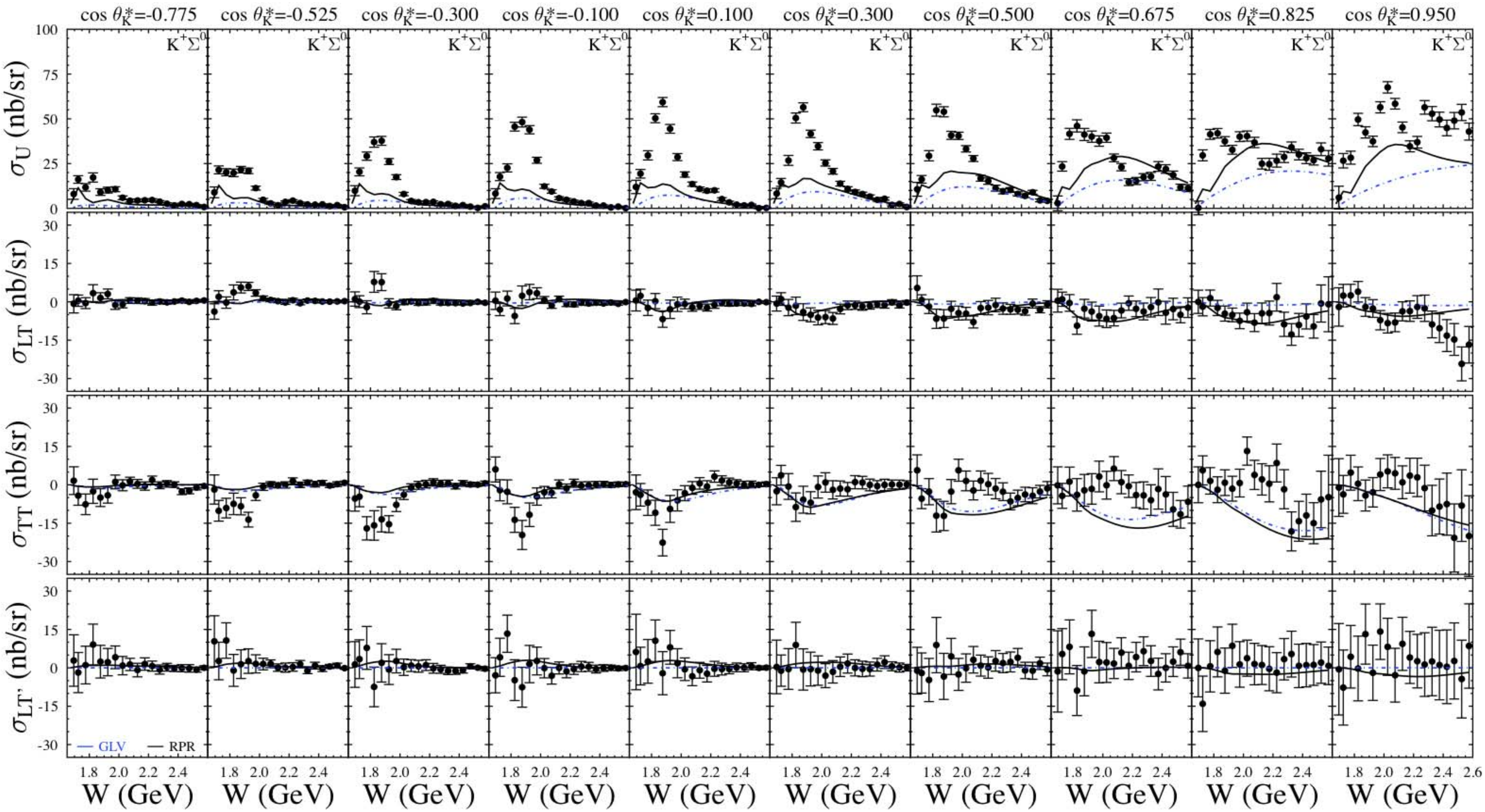
published, acquired, HD-ice

	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.

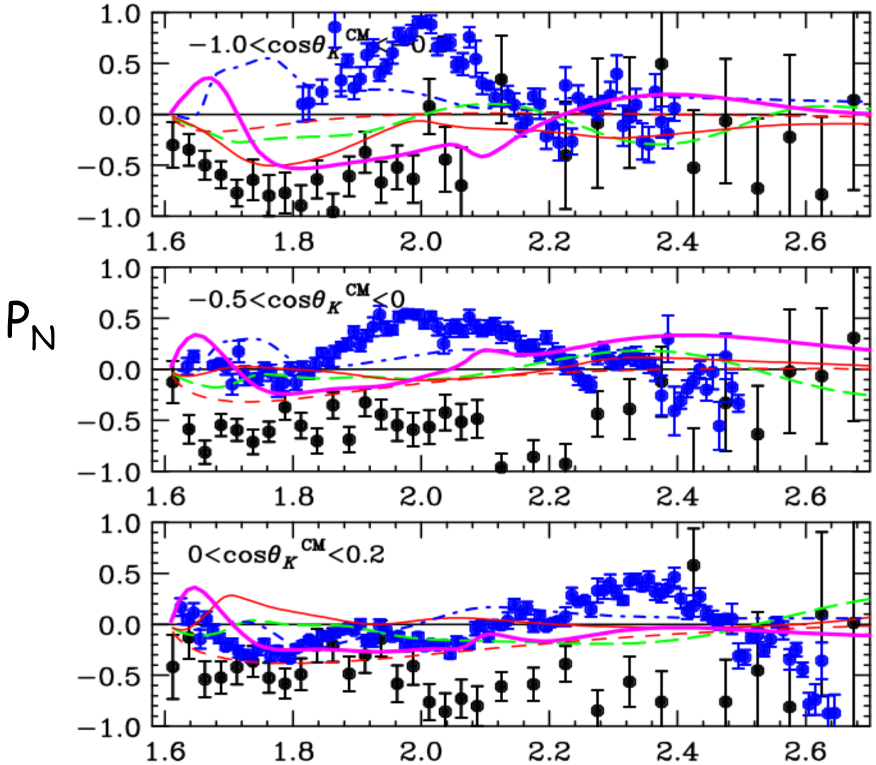
Source: V. D. Burkert

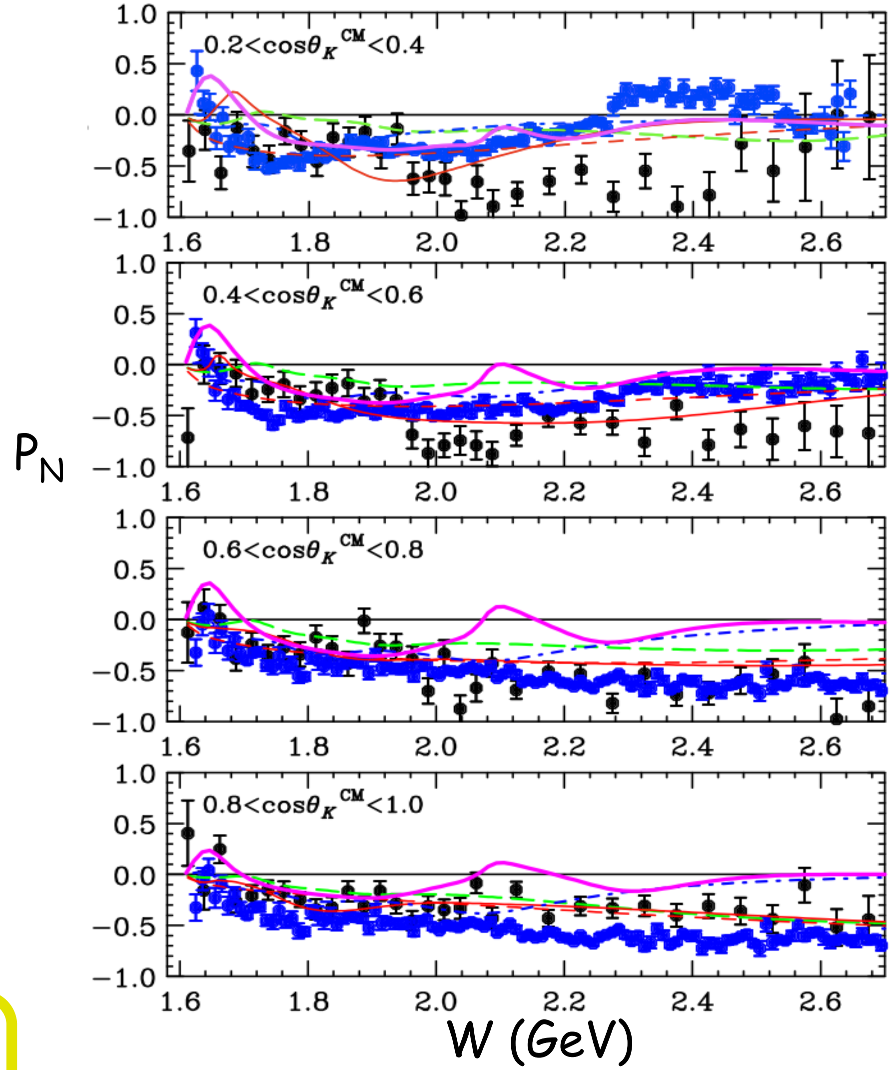
$K^+\Sigma^0$ Structure Functions



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

$\gamma\,Y^*\,K^+$ Recoil Polarization $\vec{e}p \rightarrow e'K^+\Lambda$





$\langle Q^2 \rangle \sim 1.9\ \mathrm{GeV}^2$

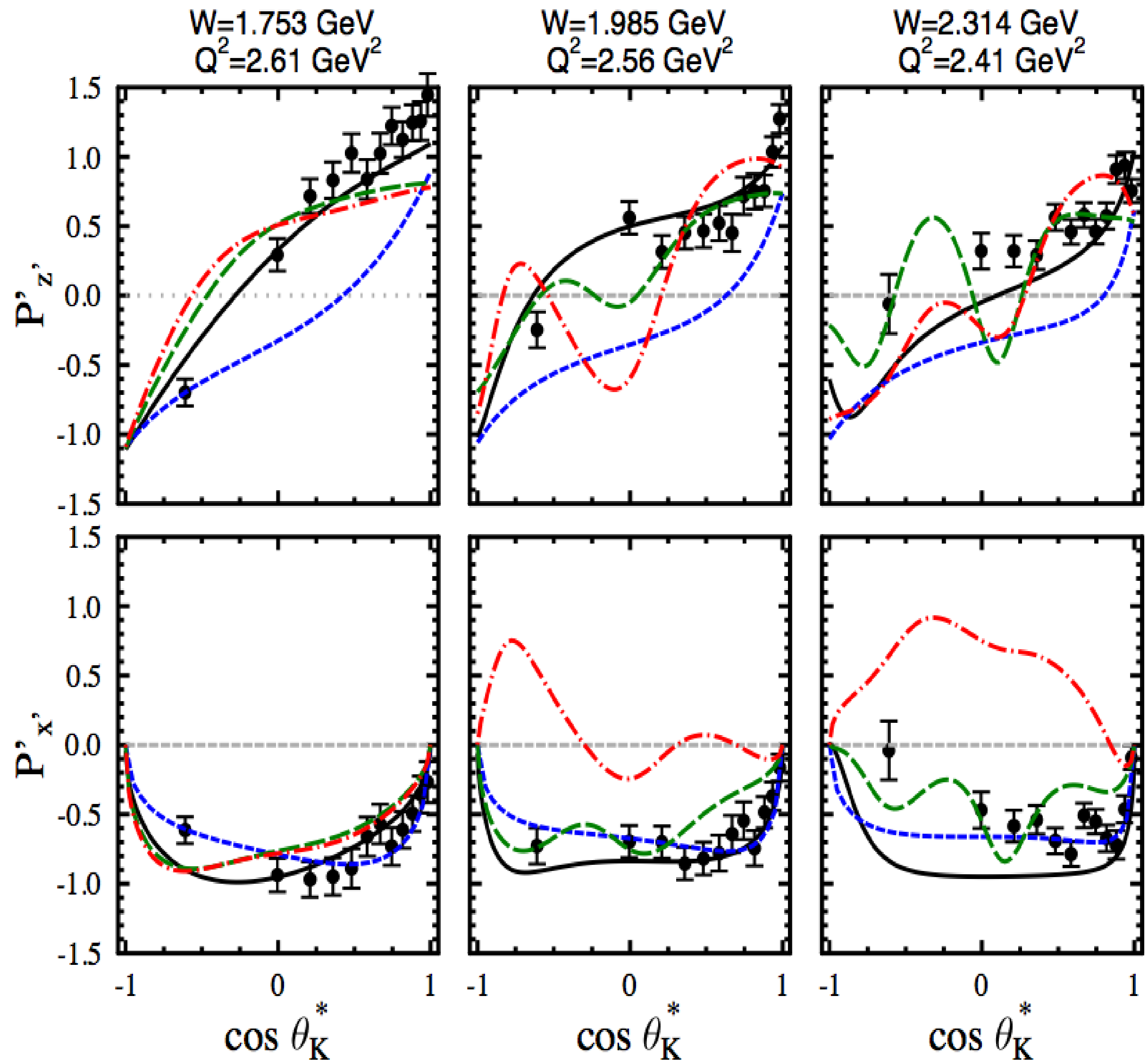
[Gabrielyan *et al.*, PR C **90**, 035202 (2014)]

Kaon-Maid *Maxwell* *RPR-2007*

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

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

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



5.754 GeV
Summed over Q^2, Φ

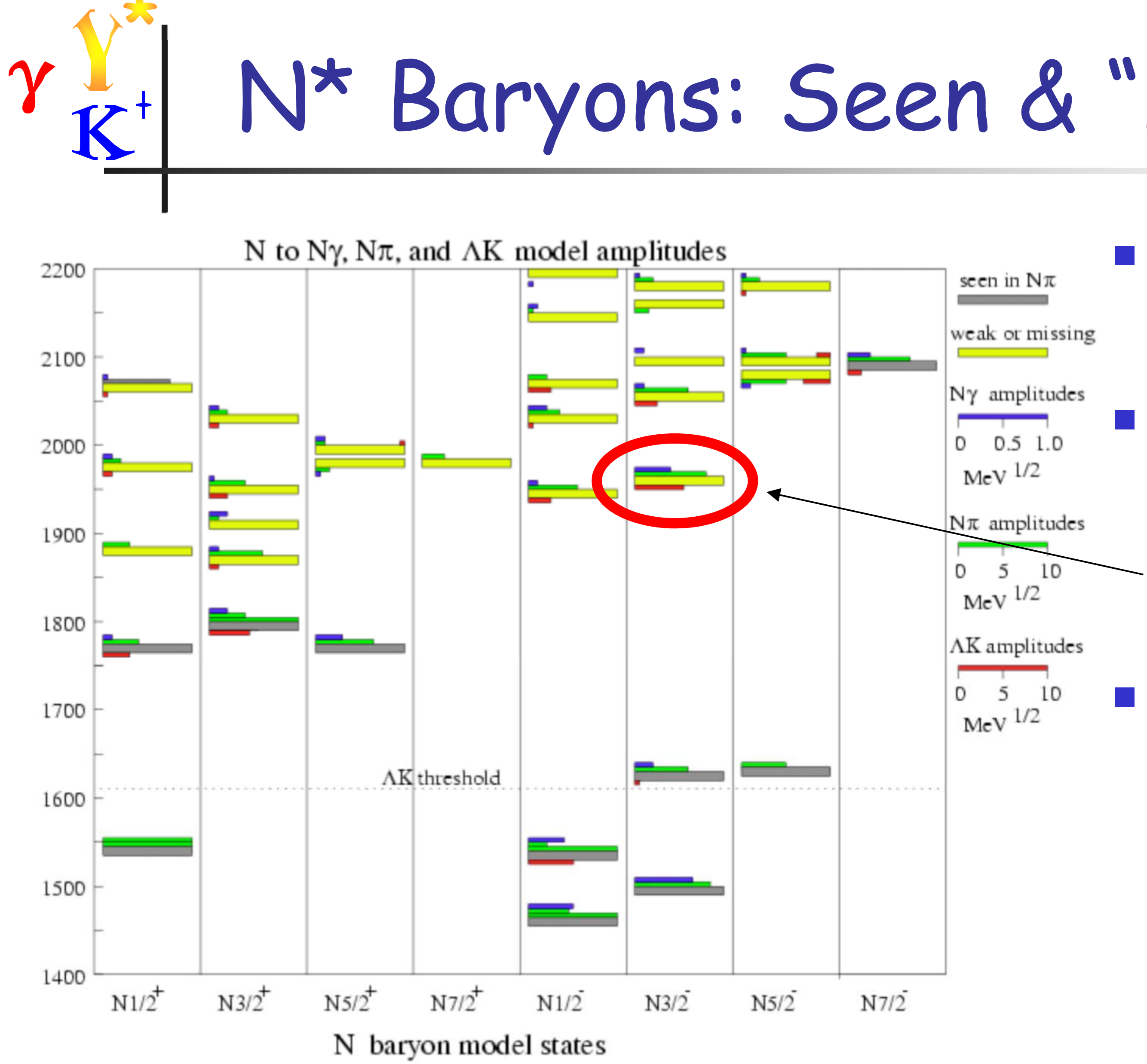
- Data not included in fits
- Rule out $P_{11}(1900)$ assignment
- $D_{13}(1900)$ not ruled out via P′ data but with S.F. data

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)]

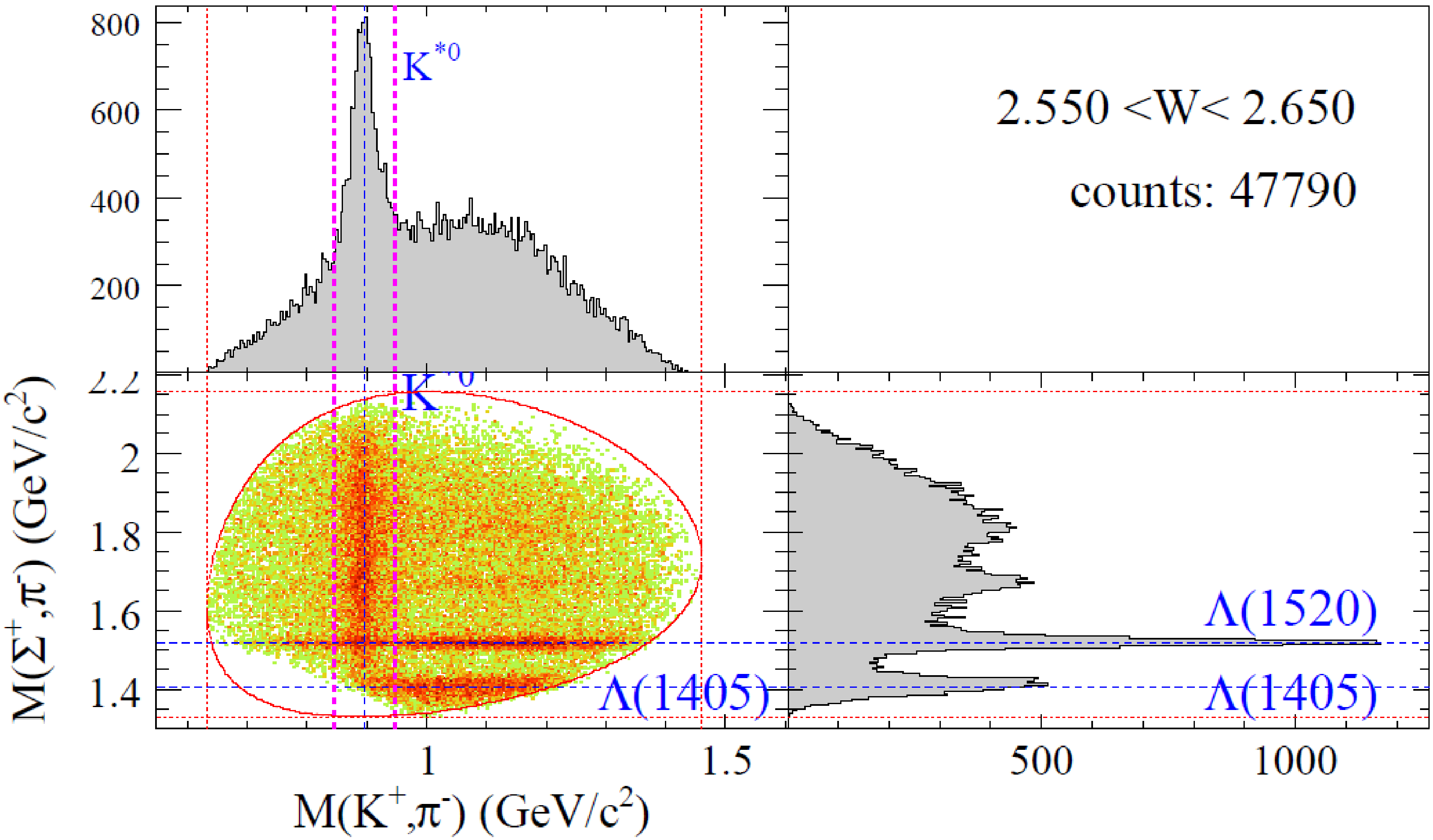
N* Baryons: Seen & "Missing"



- 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

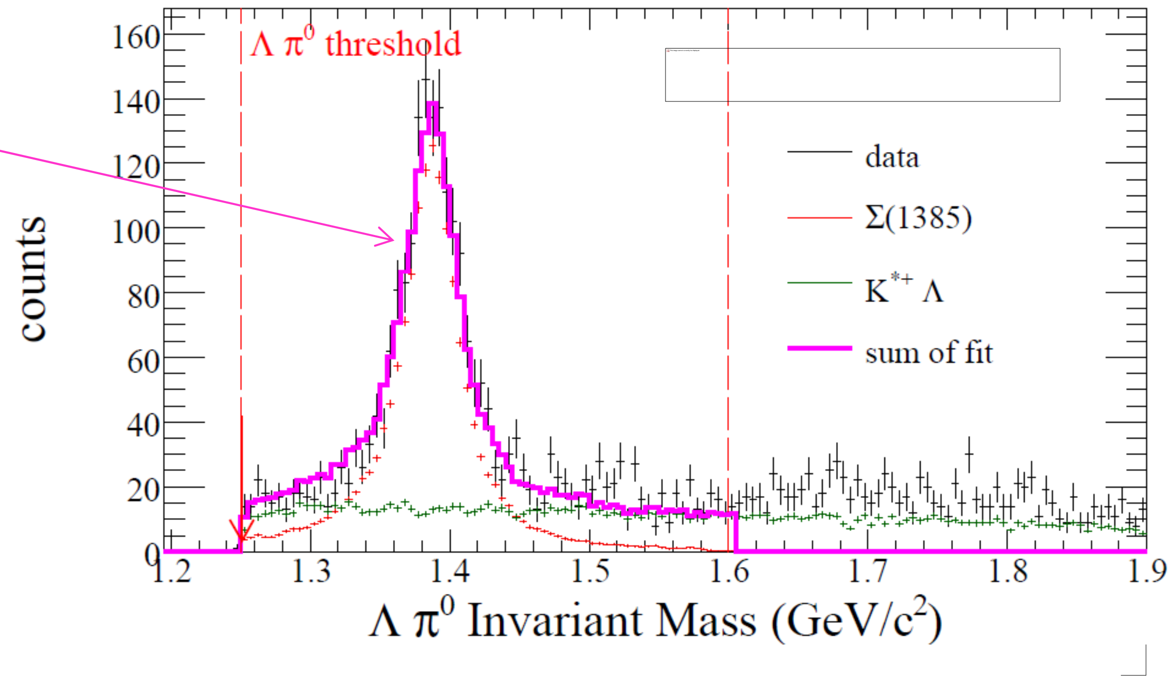


K* overlap must be subtracted in some W bins

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



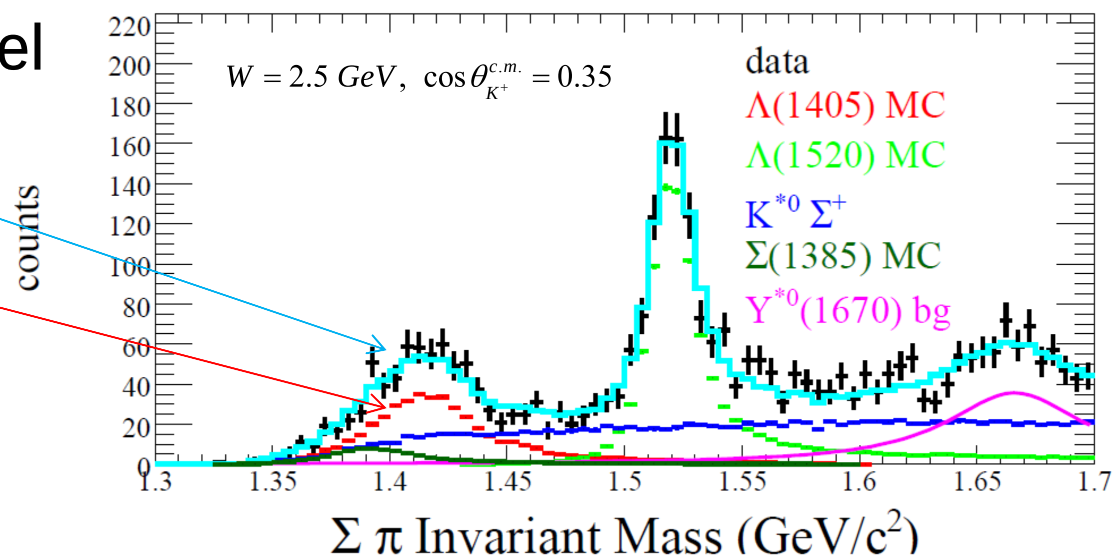
Yields for $\Lambda(1405)$ & $\Lambda(1520)$

- Reconstruct and select ground state $\Sigma^{\pm}$ states
- Remove $\Sigma^0(1385)\to\Sigma^{\pm}\pi^{\mp}$ (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

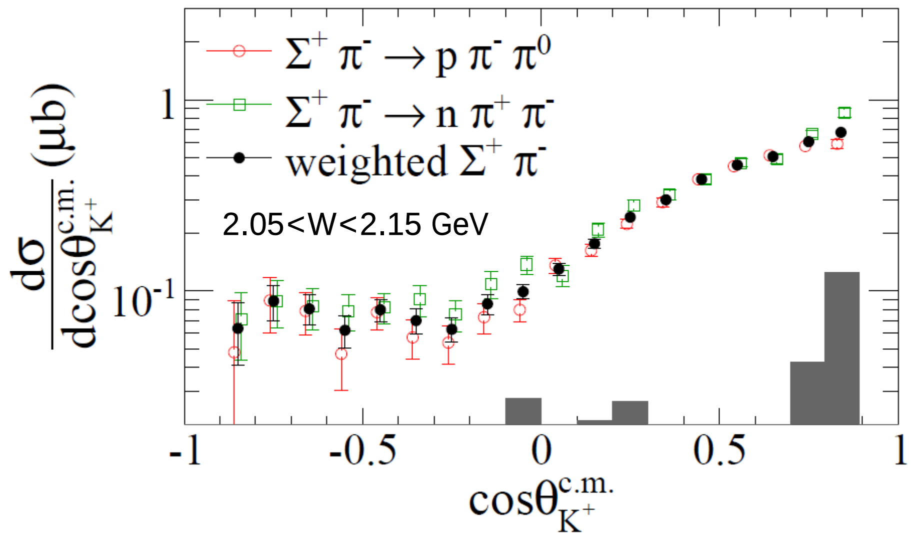
Fit to $\Sigma^+\pi^-$ channel

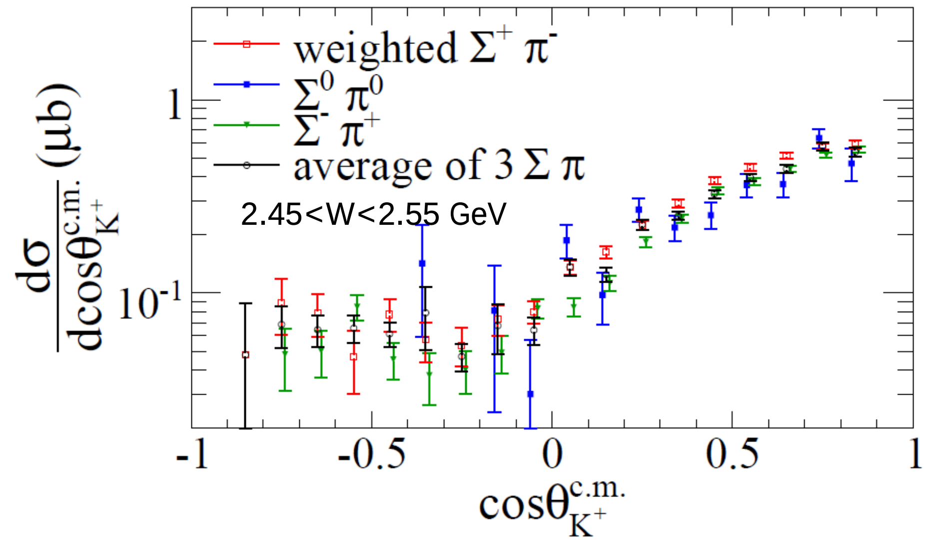
Total fit result

Iterated $\Lambda(1405)$ line shape



Differential Λ(1520) Cross Section



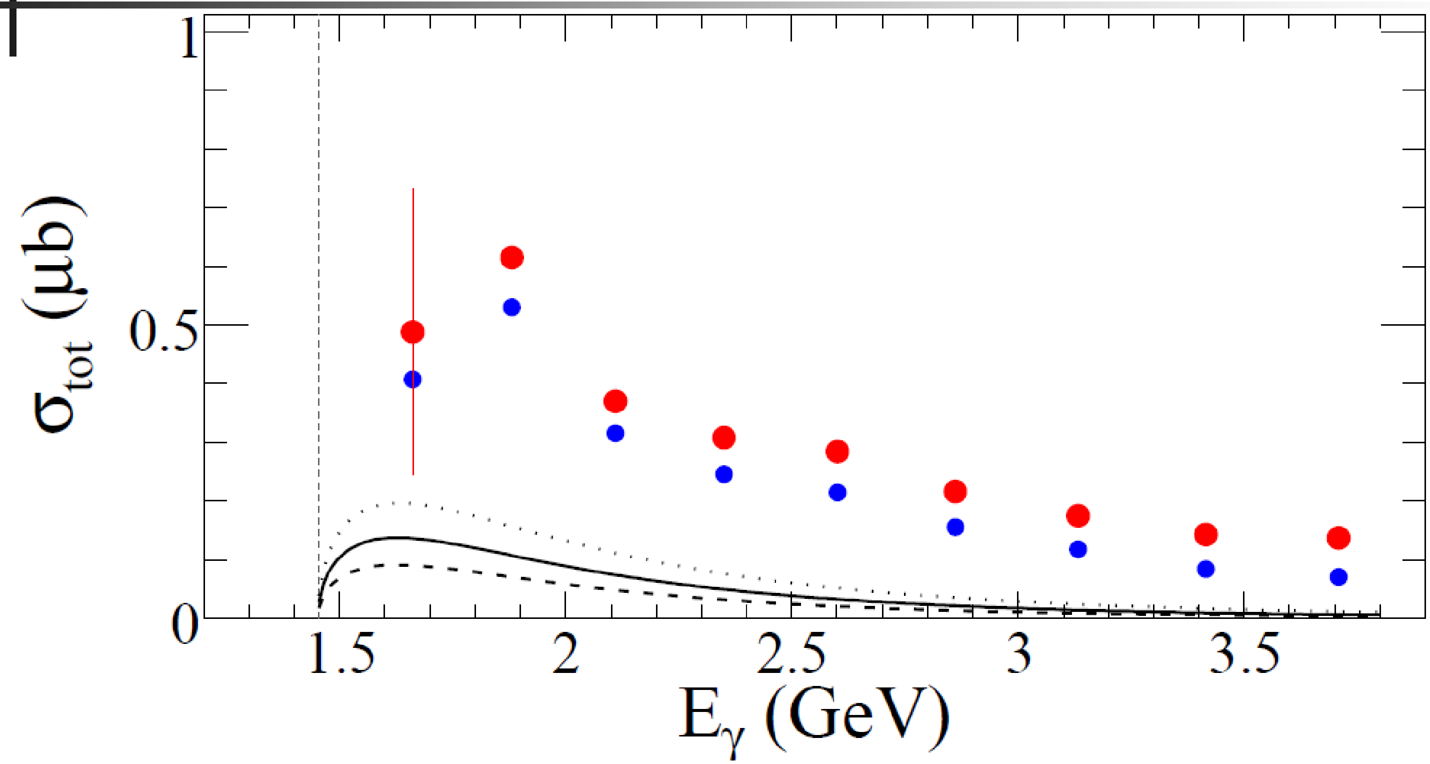


Agreement between $\Sigma^+\pi^-$ decay modes: tests acceptance consistency

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

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

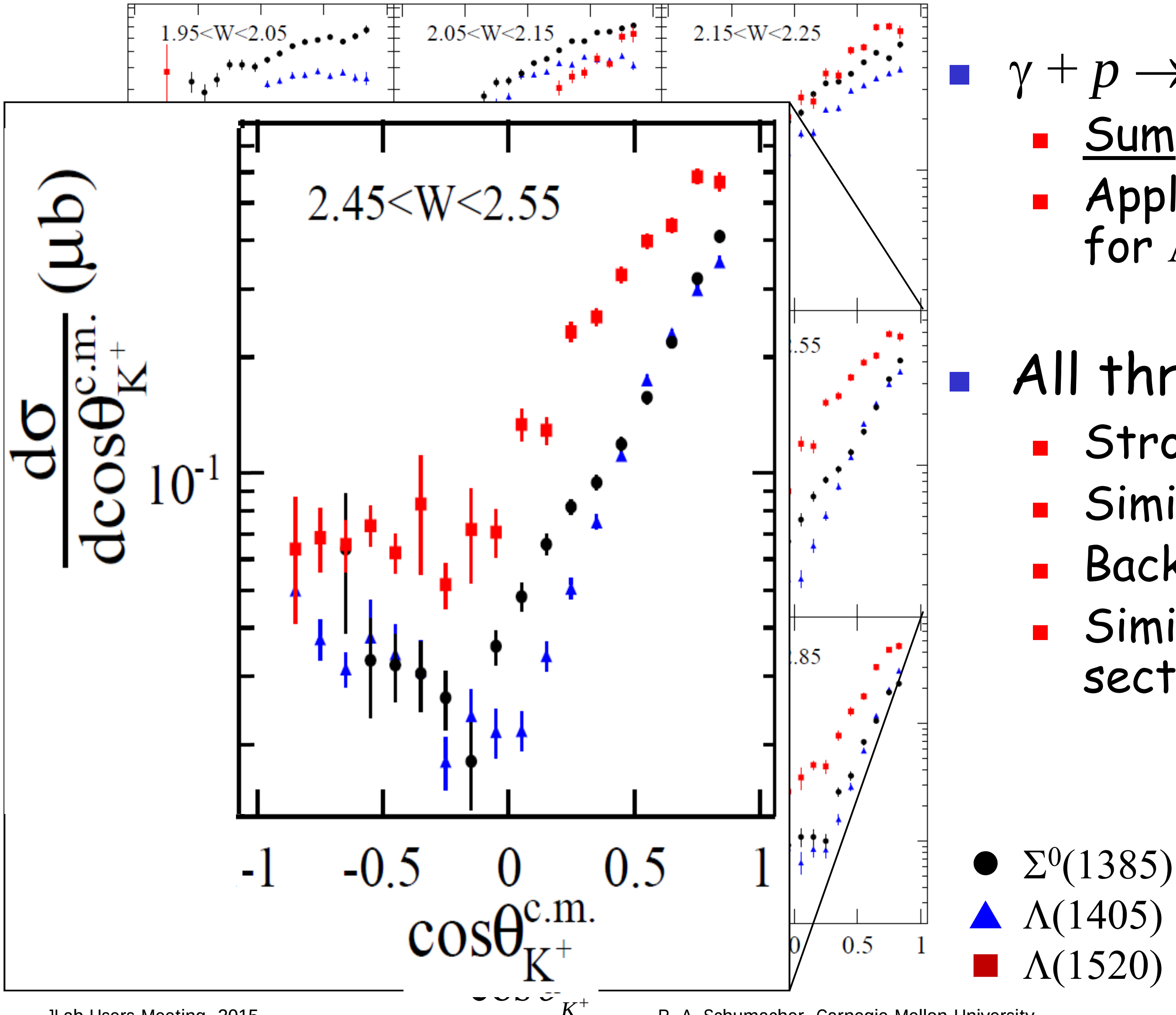
Total $\Lambda(1405)$ Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
  - 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)

Direct Y* Cross Section Comparison



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

Example at W=2.40 GeV

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