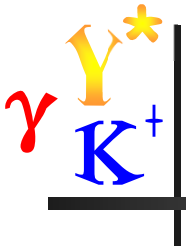


Photoproduction of Strangeness (Excited States)

Reinhard Schumacher

Carnegie Mellon University

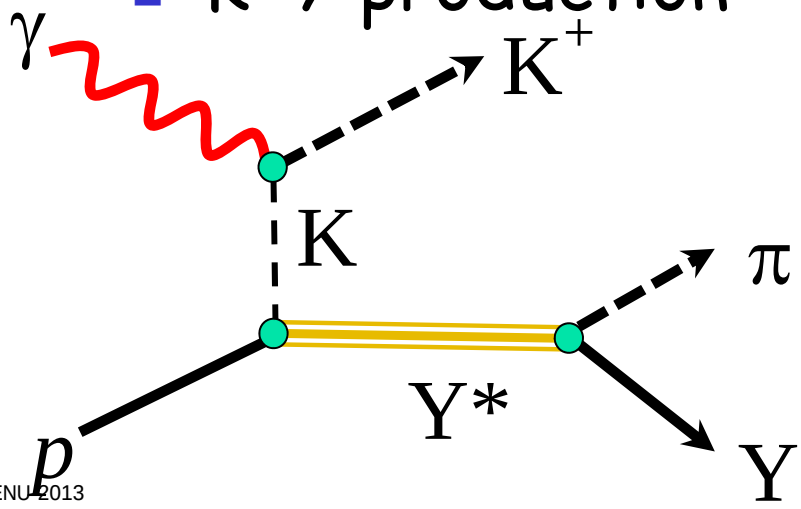
& Kei Moriya, PhD

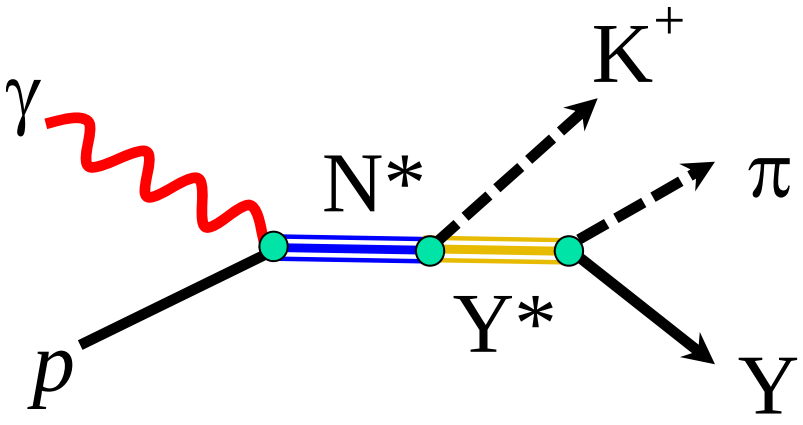
for the CLAS Collaboration

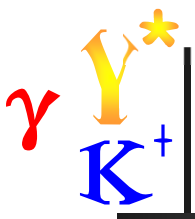
October 1, 2013, Rome, Italy

Outline /Overview

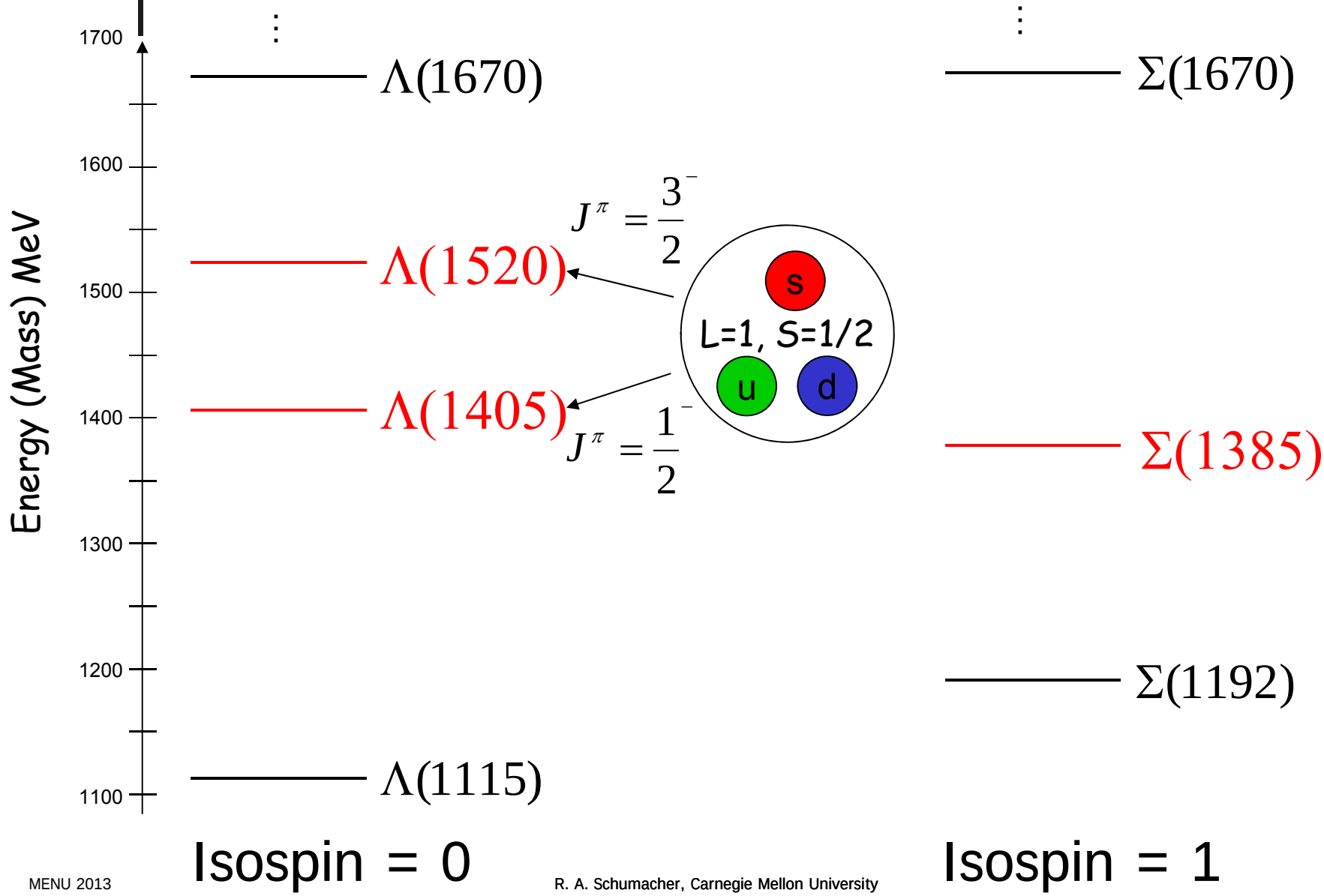
- Excited Y* cross sections measured at CLAS
  - $\Sigma^0(1385)$ ($J^P = 3/2^+$) in $\Lambda\pi^0$ channel
  - $\Lambda(1405)$ ($J^P = 1/2^-$) in 3 $\Sigma\pi$ channels
  - $\Lambda(1520)$ ($J^P = 3/2^-$) in 3 $\Sigma\pi$ channels
- Isospin interference in $\Lambda(1405)$: line shapes
- Spin & parity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

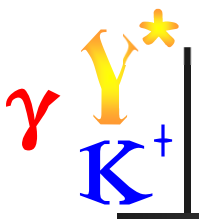




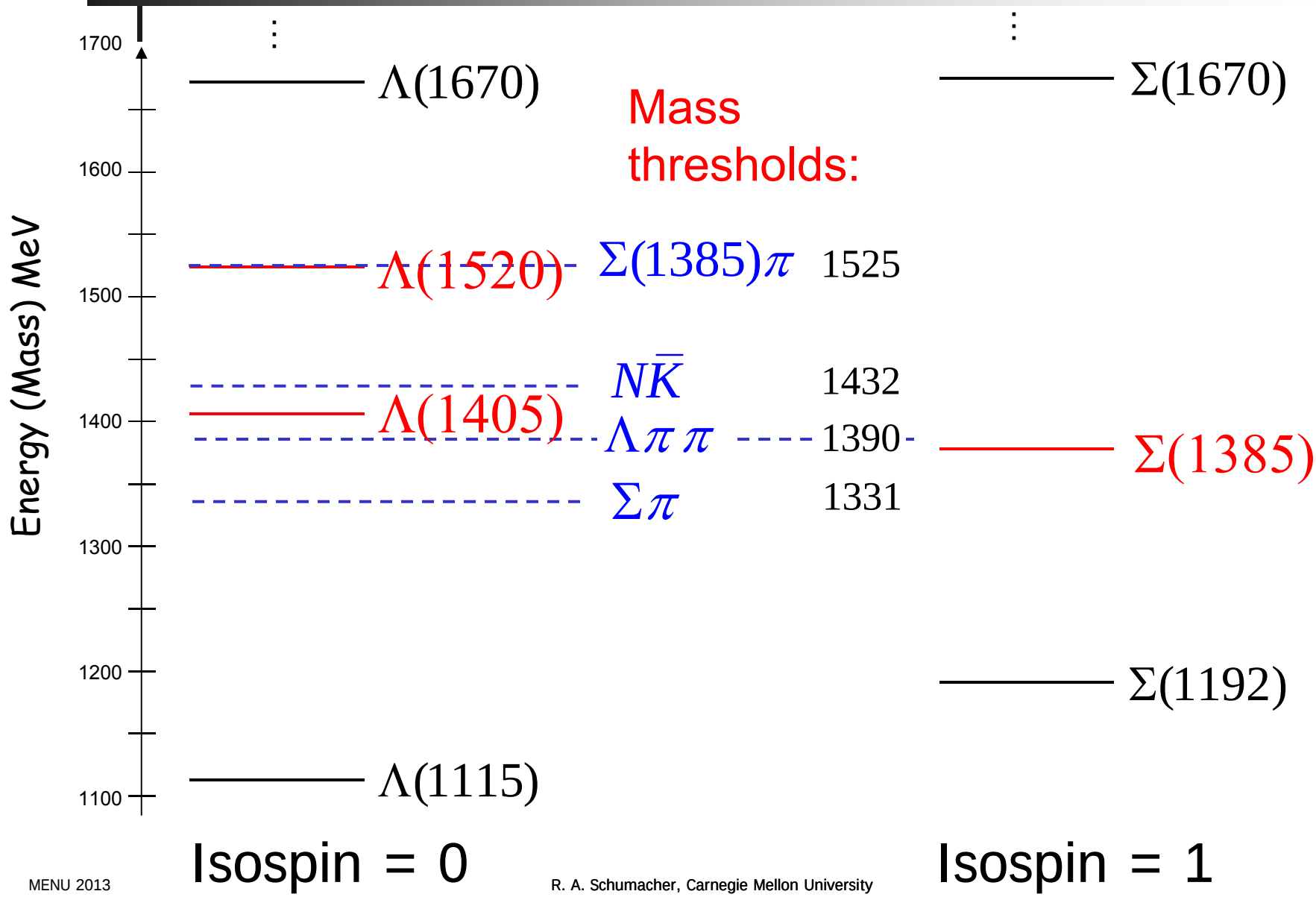


The Low-Mass S=-1 Hyperons





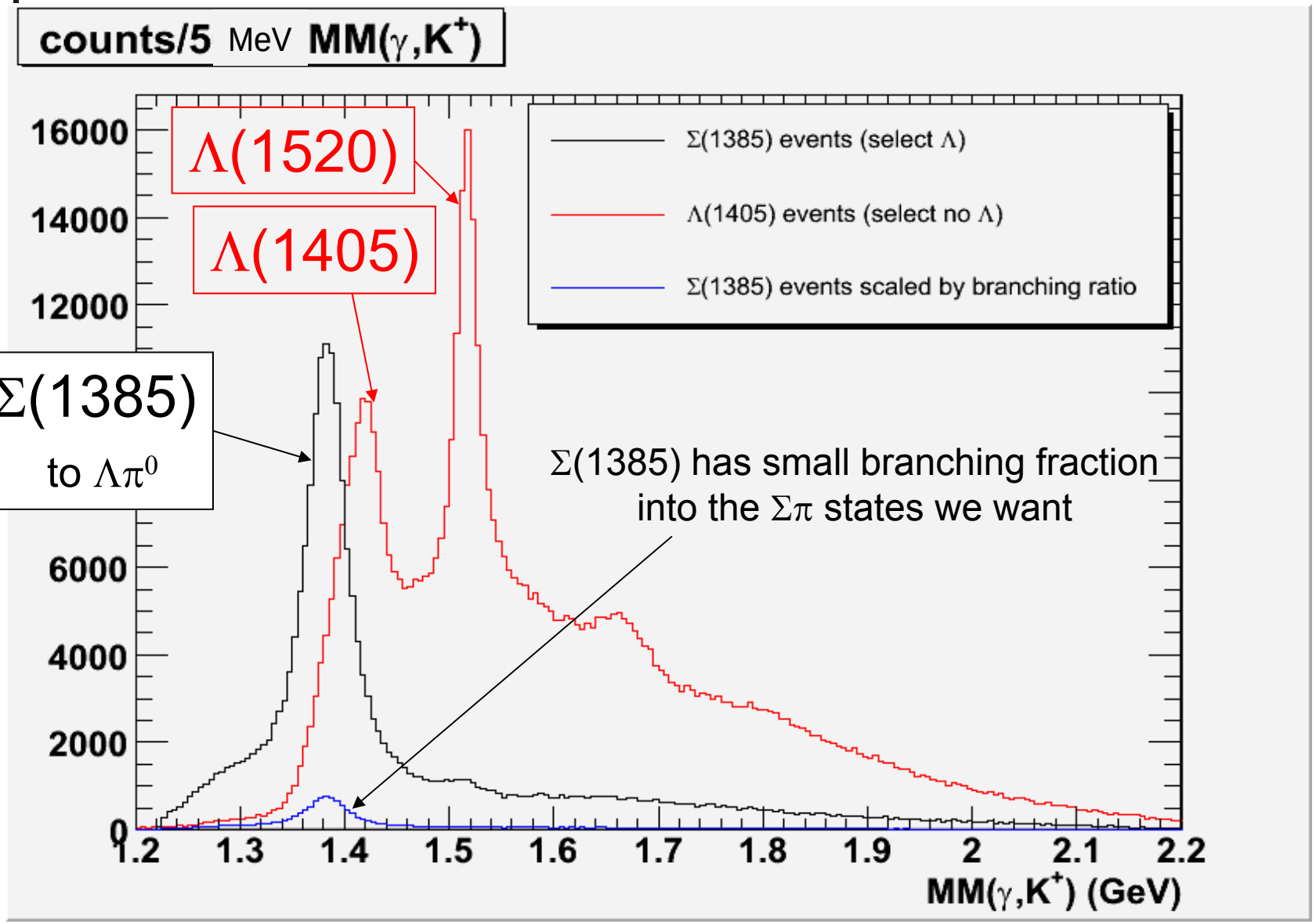
The Low-Mass S=-1 Hyperons

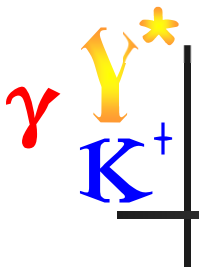


CLAS Experiment

- Jefferson Lab, Newport News, VA, USA
- PhD work of Kei Moriya, currently at Indiana University
- g11a data set, 2004
  - unpolarized LH_2 target
  - unpolarized tagged photon beam: 0.8 to 3.8 GeV
  - reconstructed $K^+p\pi^-(\pi^0)$ or $K^+\pi^+\pi^-(n)$
  - 20×10^9 triggers → 1.41×10^6 $KY\pi$ events

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

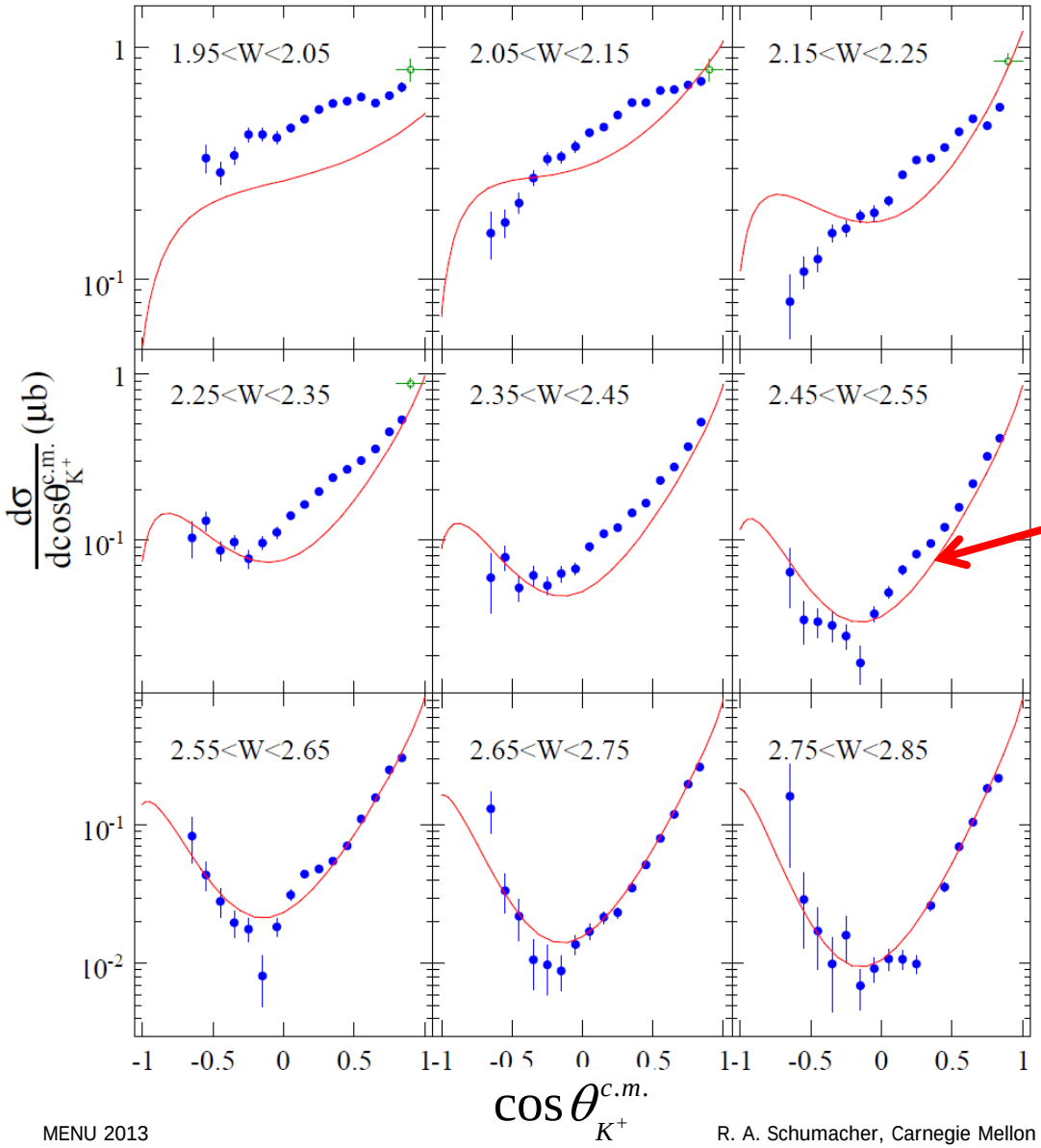




Cross Sections

New Publication: Differential Photoproduction Cross Sections of $\Sigma^0(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$, K. Moriya, R. A. Sch. *et al.* (CLAS Collaboration), accepted by Phys. Rev. C; arXiv:1305.6776 [nucl-ex]

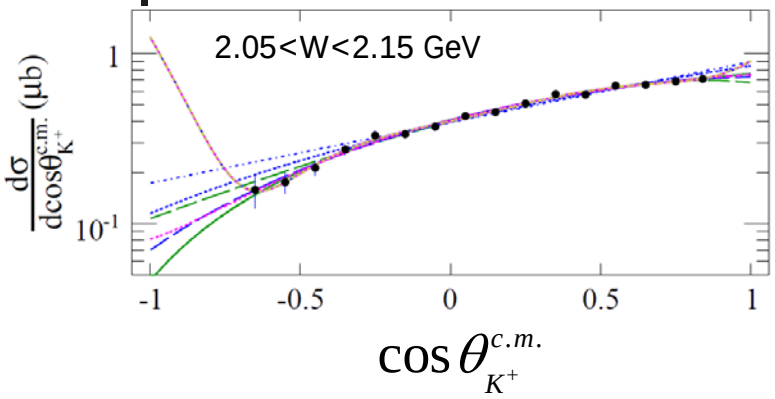
Differential $\Sigma^0(1385)$ Cross Section

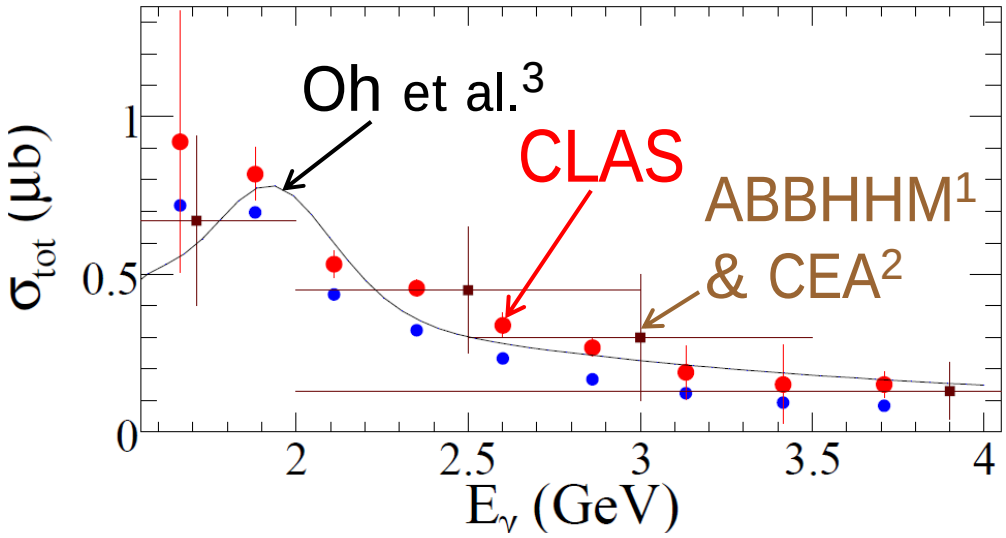


- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
- Experiment: see *t*-channel-like forward peaking & *u*-channel backward rise
  - Agreement with LEPS
- Theory by Oh et al.[1]: contact term dominant; included four high-mass *N** and Δ resonances
  - Prediction was fitted to preliminary CLAS total cross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

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

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



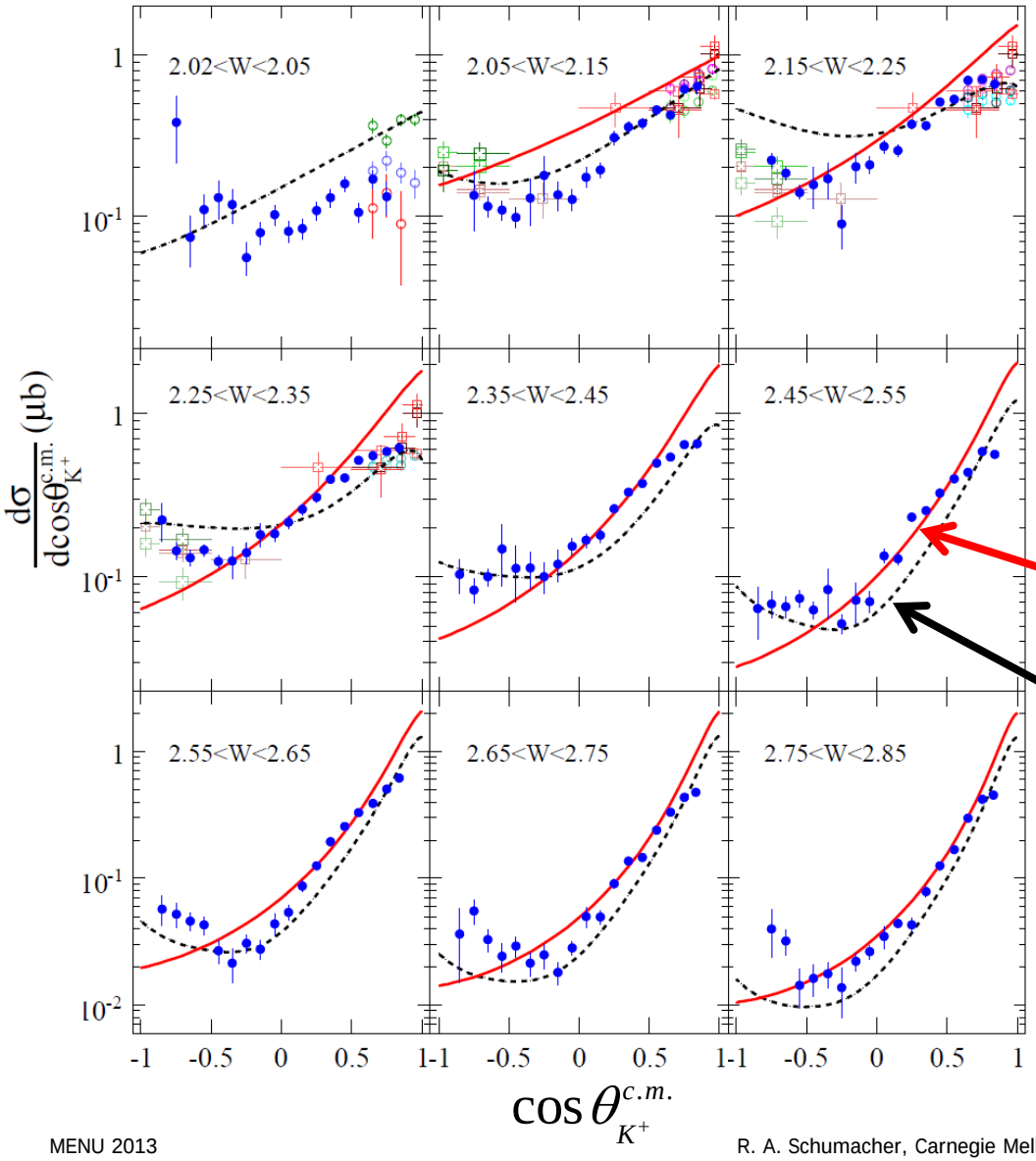


- Extrapolation to all kaon angles
- Average of many similar polynomials
  - e.g. $f(z) = \left| \sum_{l=0}^{L} c_l P_l(z) \right|^2$

- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
  - Blue: measured
  - Red: extrapolated total
- Agrees with ABBHHM[1] & CEA[2]
- Oh's[3] "bump" at W=2.1 GeV (E_γ=1.9 GeV) due to N^*'s

1. R. Erbe et al. (ABBHHM) Phys Rev. 188, 2060 (1969)
2. H. Crouch et al. (CEA) Phys Rev 156, 1426 (1967)
3. Y. Oh, C. M. Ko, K. Nakayama, Phys. Rev. **C 77**, 045204 (2008)

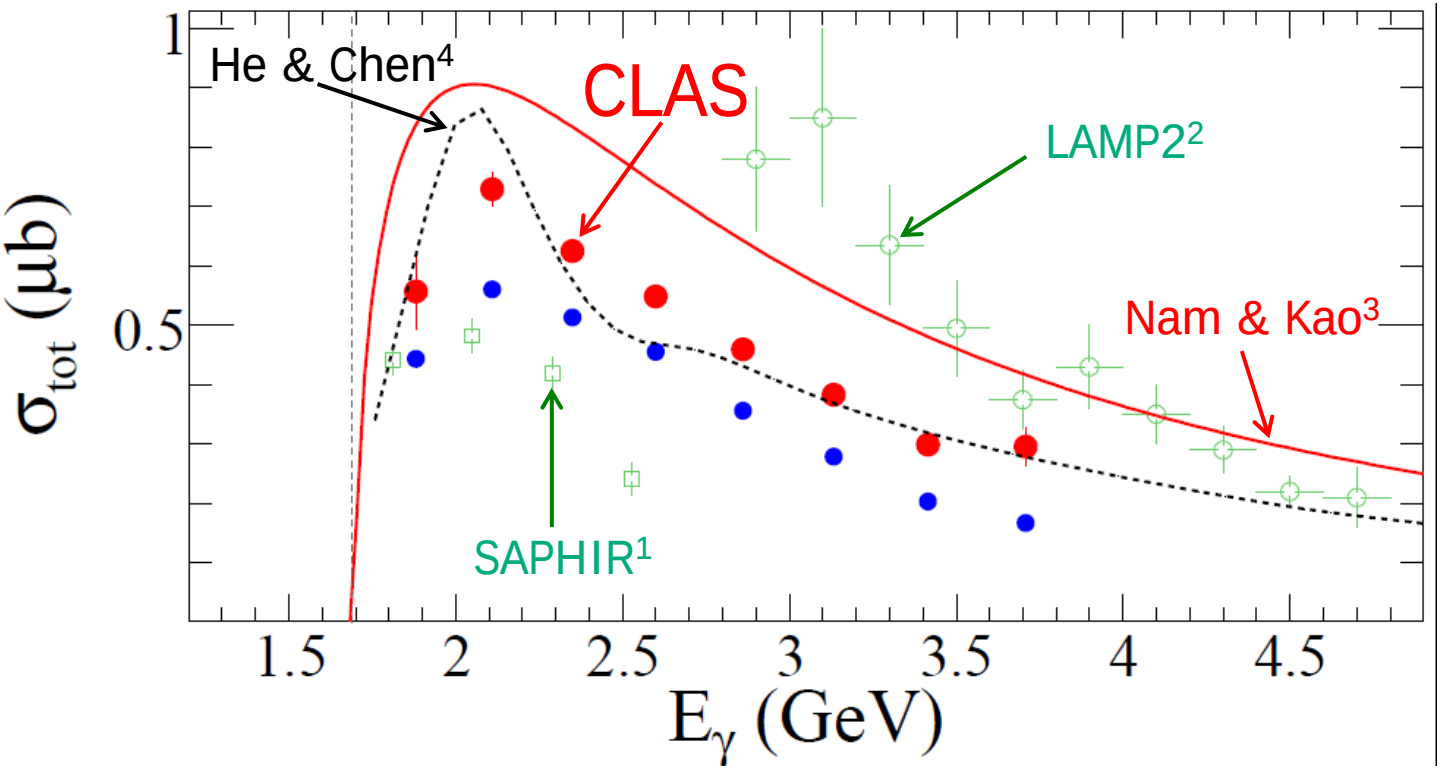
Differential Λ(1520) Cross Section



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

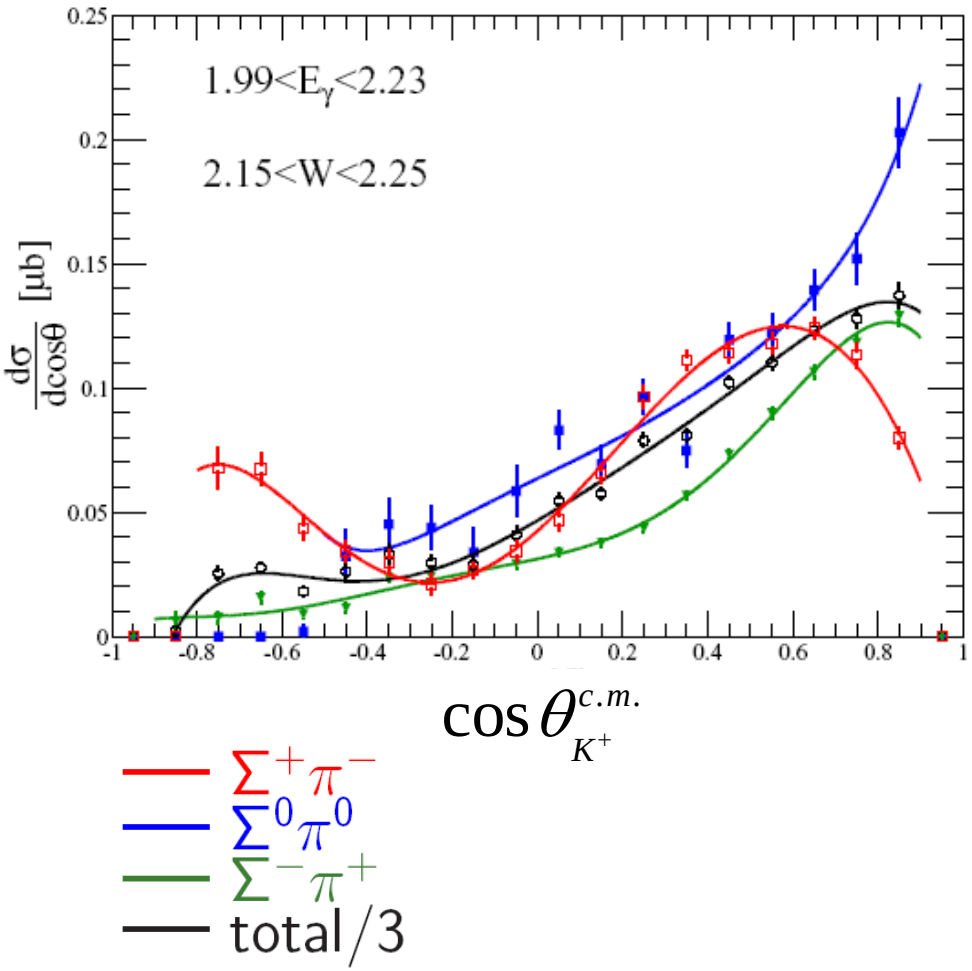
Total Λ(1520) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1520)$
  - Blue: measured Red: extrapolated total
- CLAS midway between SAPHIR[1] and LAMP2[2] results
- He & Chen[4] "bump" at W=2.1 GeV (E_γ=1.9 GeV) from $N(2080)\ D_{13}\ J^P = 3/2^-$

1. F. Wieland et al. (SAPHIR) Eur.Phys.J. **A47**, 47 (2011)
2. D. Barber et al. (LAMP2) Z. Phys. **C7**, 17 (1980)
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)

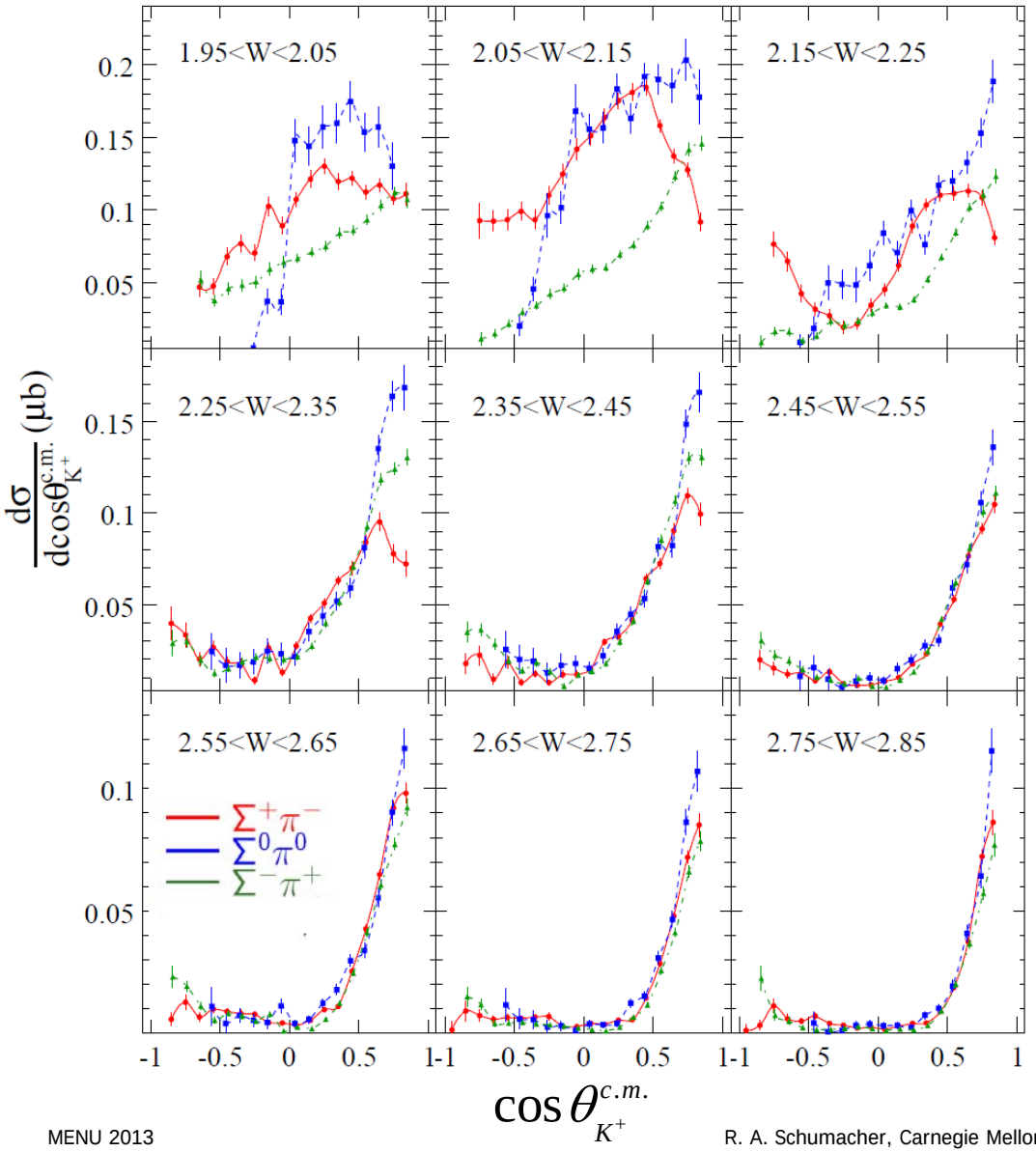
Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Experiment: each $\Sigma\pi$ channel yields a different cross section (! Not expected[1] !)
- Indication of isospin interference in Λ(1405) mass region
  - threshold < $m_{\Sigma\pi}$ < 1.50 GeV

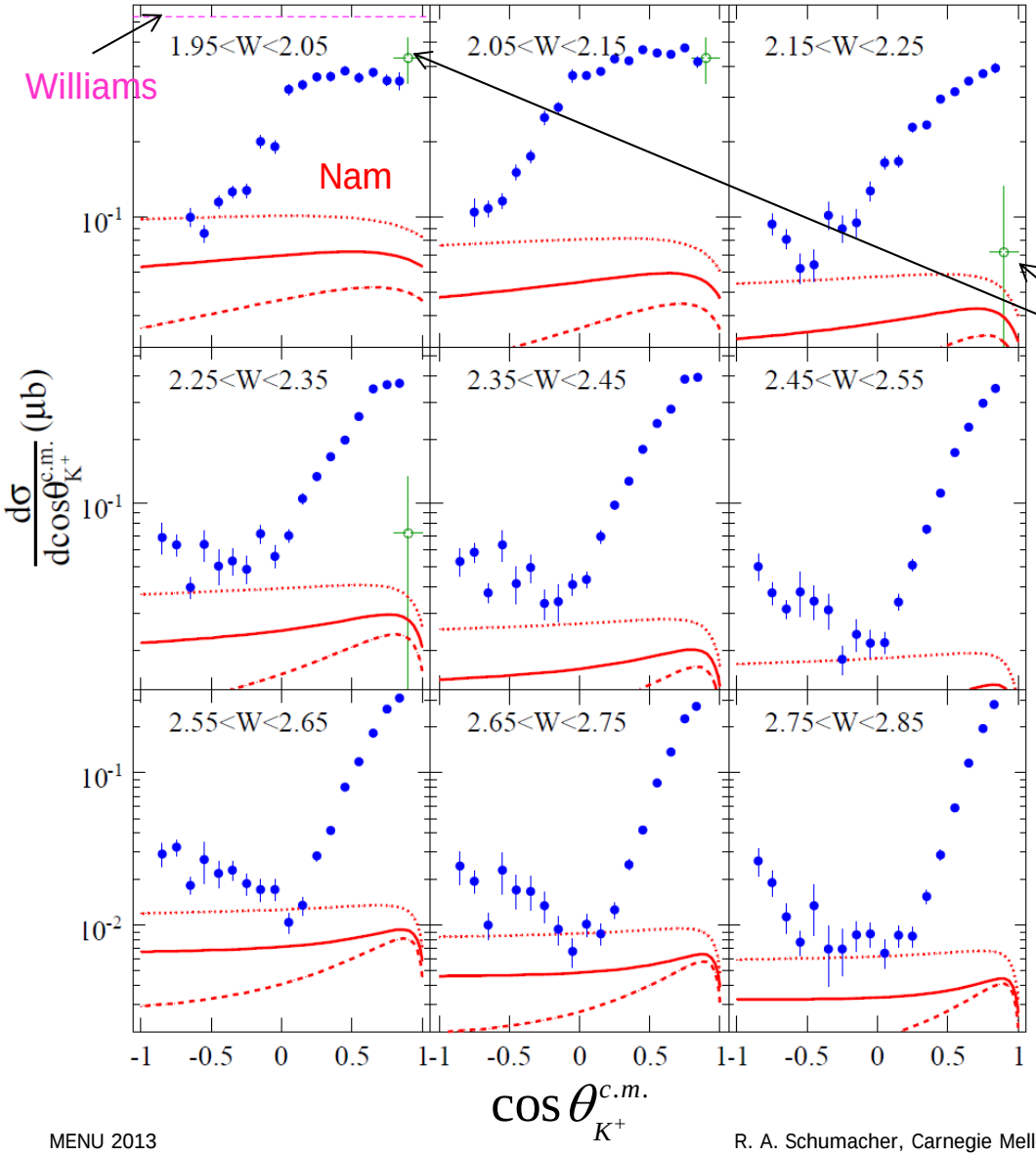
1. K. Moriya, R. A. Schumacher *et al.*, arXiv:1305.6776 [nucl-ex]

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

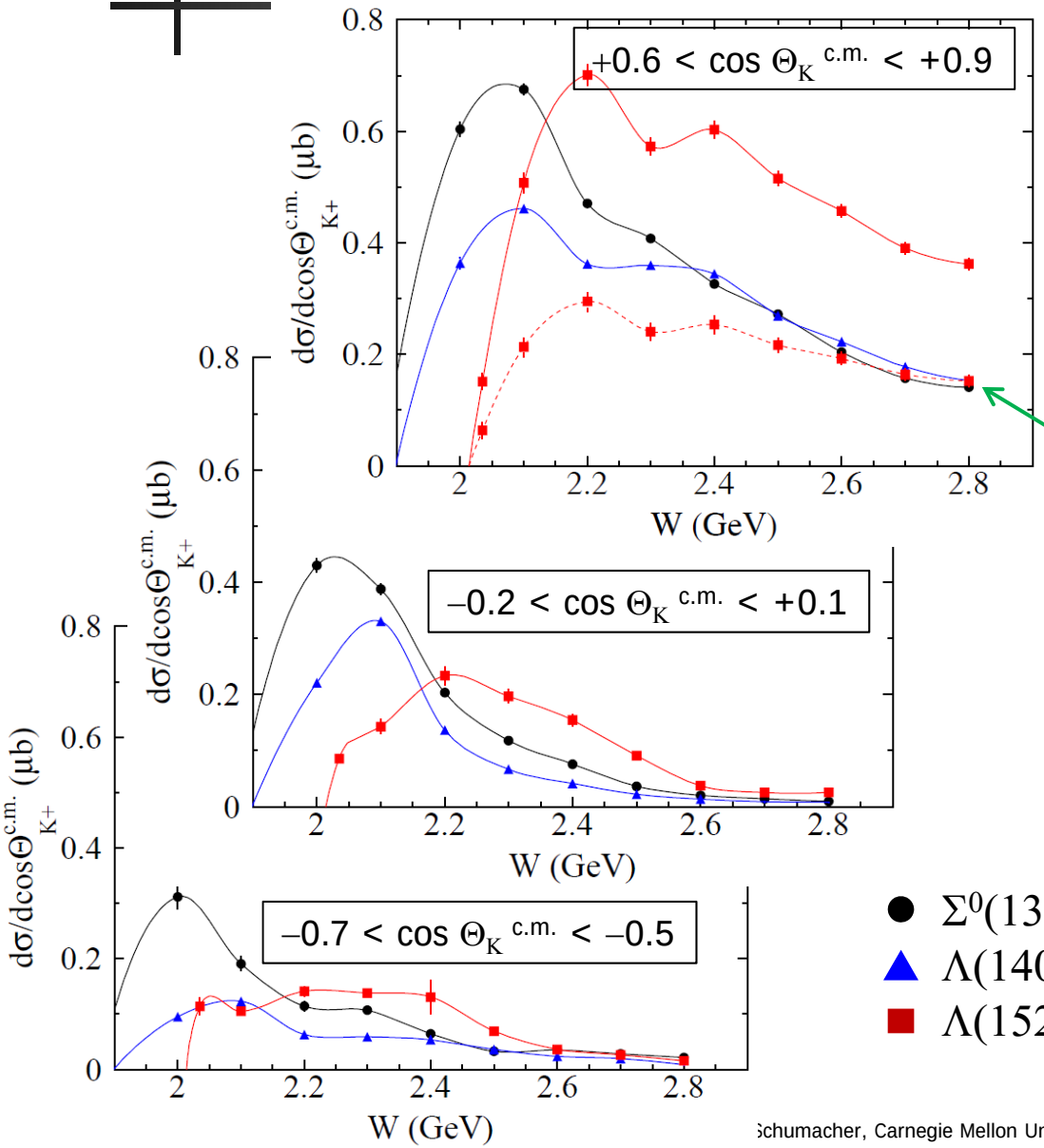
Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Sum three $\Sigma\pi$ 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 $g_{KN\Lambda^*}$

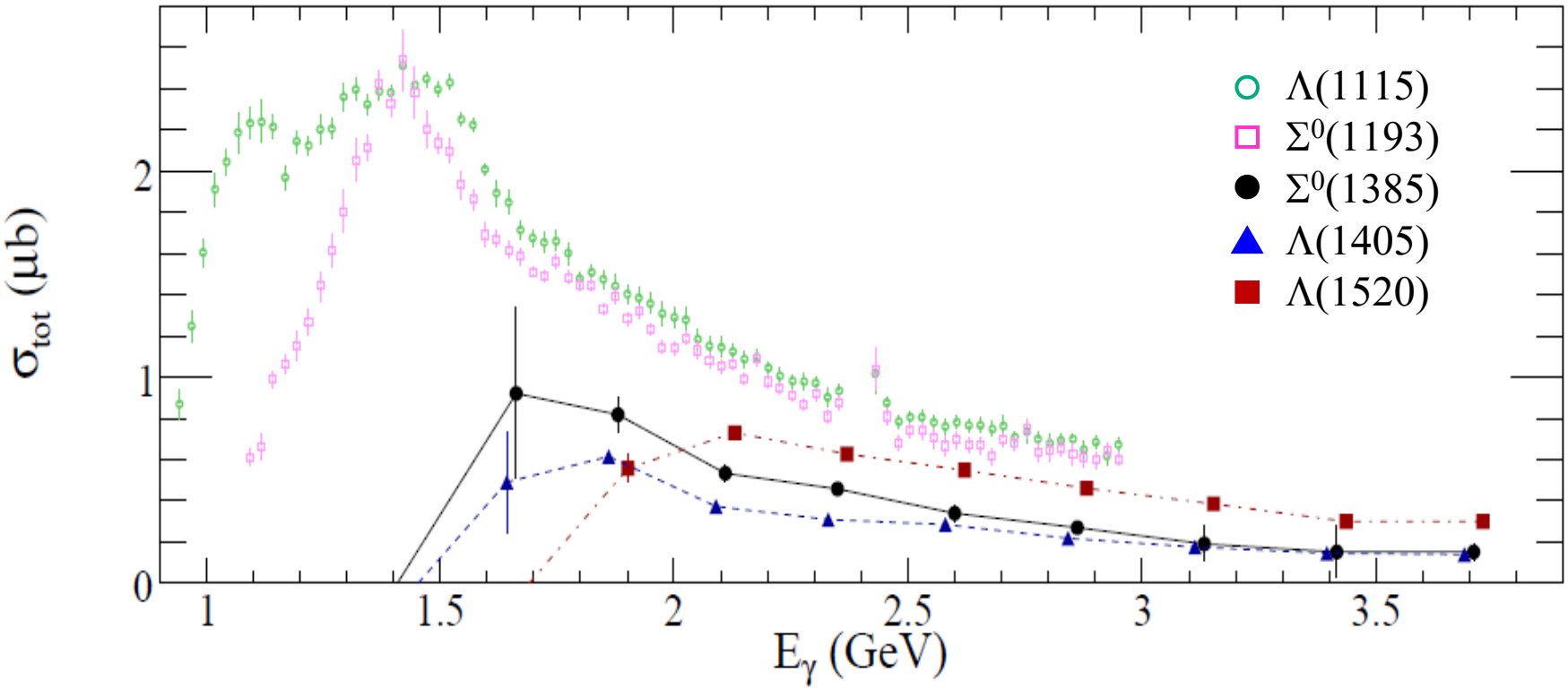
1. M. Niiyama et al. (LEPS) Phys Rev **C78**, 035202 (2008)
2. S.I. Nam et al., J. Kor. Phys. Soc. **59**, 2676 (2011)
3. R. Williams et al., Phys. Rev. **C43**, 452 (1991)

Direct Y* Cross Section Comparison



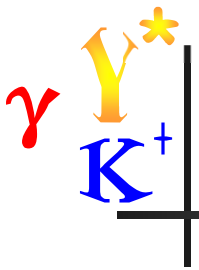
- $\gamma + p \rightarrow K^+ + Y^*$
  - (showing spline fits)
- All three have
  - Near- threshold peaking
  - Similar size cross sections
  - $\Sigma\pi$-fraction (42%) of $\Lambda(1520)$ has same cross section as $\Lambda(1405)$ at high W!
- Λ^*'s have a hint of second peak/plateau

Total Cross Section 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]

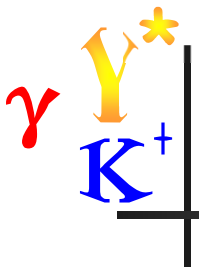
1. R. Bradford et al. (CLAS) Phys. Rev. **C 73**, 035202 (2006)



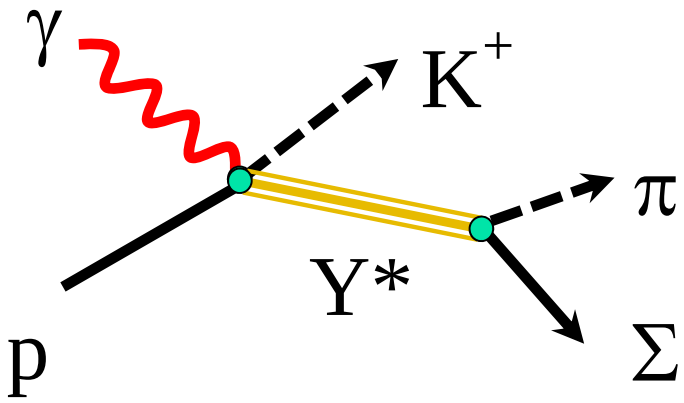
Line Shapes

Recent Publications: Measurement of the $\Sigma\pi$ Photo-production Line Shapes Near the $\Lambda(1405)$, K. Moriya, R. A. Sch. *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)



Isospin Interference



Final $\Sigma\pi$ state

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

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

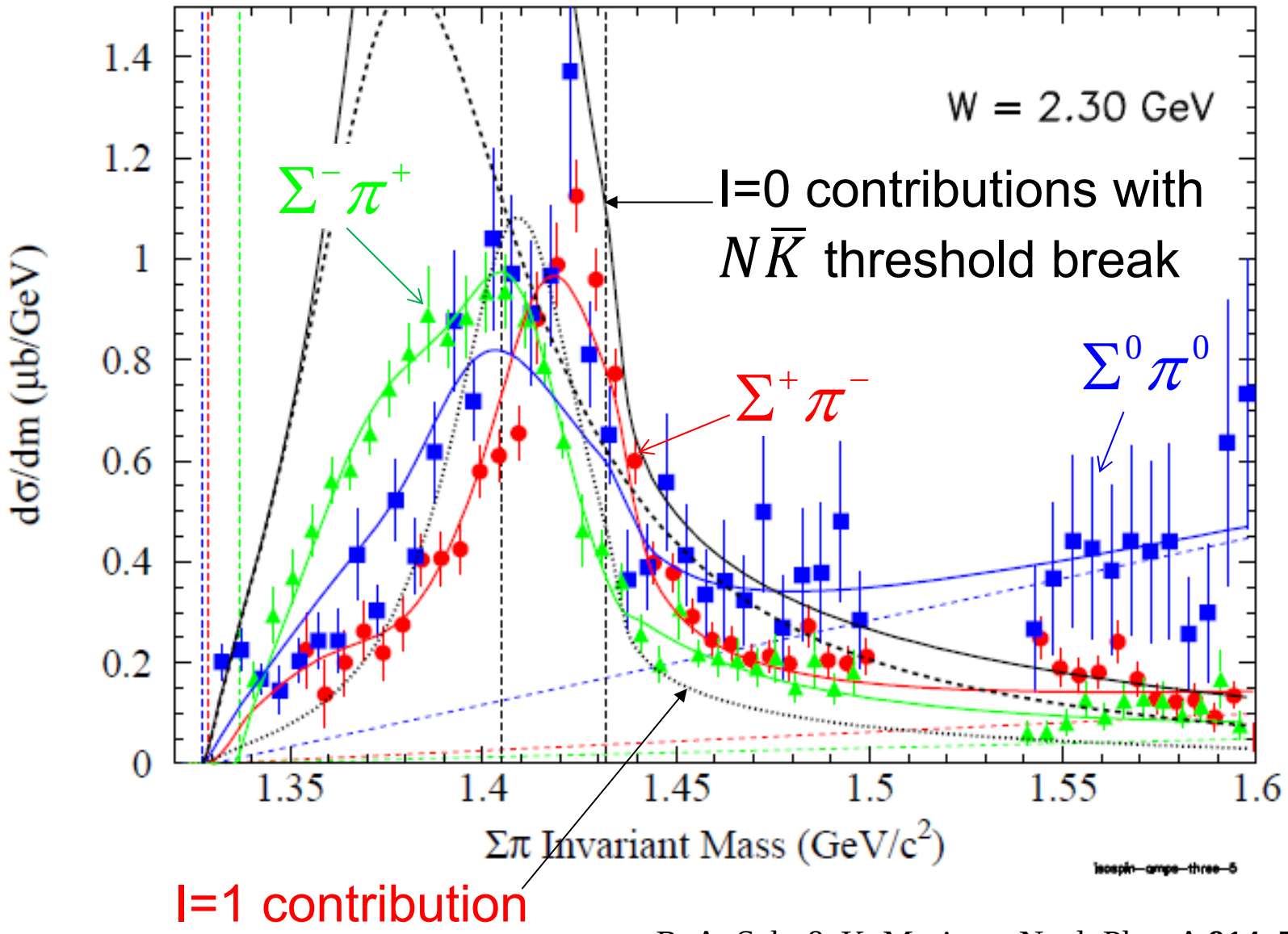
Three charge combinations:

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

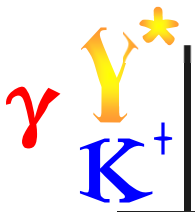
$$|T_{\pi^0\Sigma^0}|^2 = \frac{1}{3}|t_0|^2,$$

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

Example at W=2.30 GeV



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



Σπ Isospin Decomposition

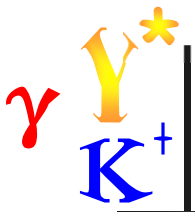
Table 2: Results using two $I = 0$ and one $I = 1$ Breit-Wigner line shapes and fitting to all final charge states simultaneously. The uncertainties reflect the stability of repeated fits with varying initial values. "N/A" means no free parameter was allowed.

Amplitude	Centroid m_R (MeV)	Width Γ_0 (MeV)	Phase $\Delta\Phi_I$ (radians)	Flatté γ Factor
$I = 0$ (low mass)	1338 ± 10	44 ± 10	N/A	0.94 ± 0.20
$I = 0$ (high mass)	1384 ± 10	76 ± 10	1.8 ± 0.4	N/A
$I = 1$	1367 ± 20	54 ± 10	2.2 ± 0.4	1.19 ± 0.20

Coupling to $\bar{K}N$

- One I=0 centroid moves to $\Sigma\pi$ threshold
- Flatté channel coupling; pulls peak to ~1405MeV
- Single I=1 amplitude treated as resonant

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



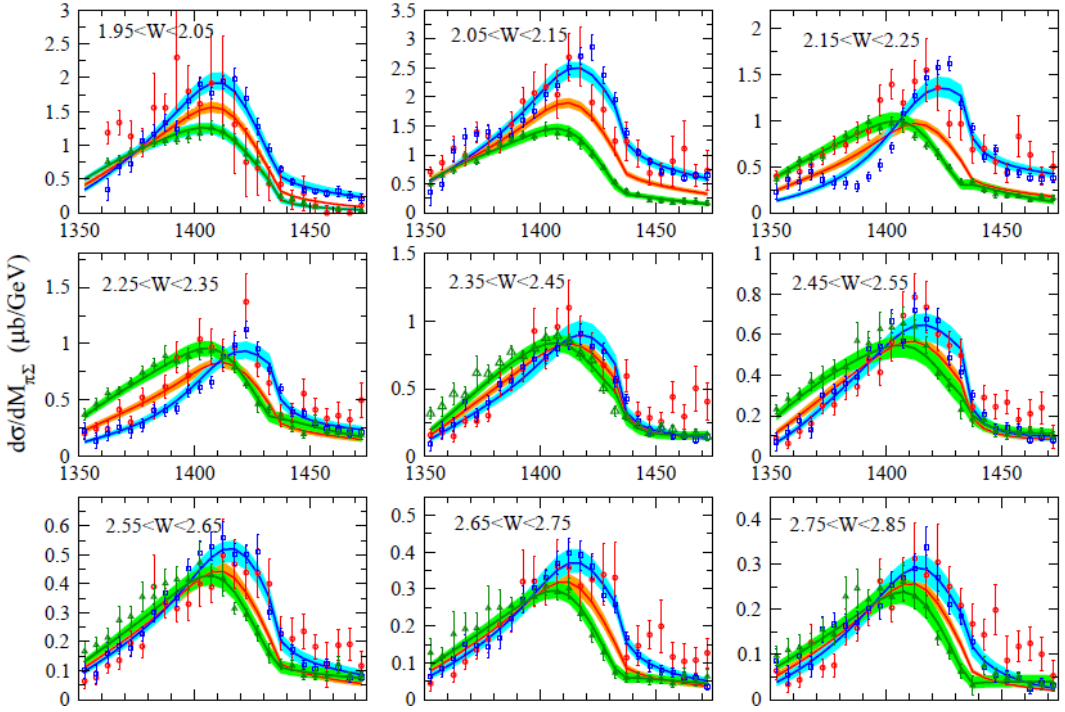
What "is" the I=1 piece?

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

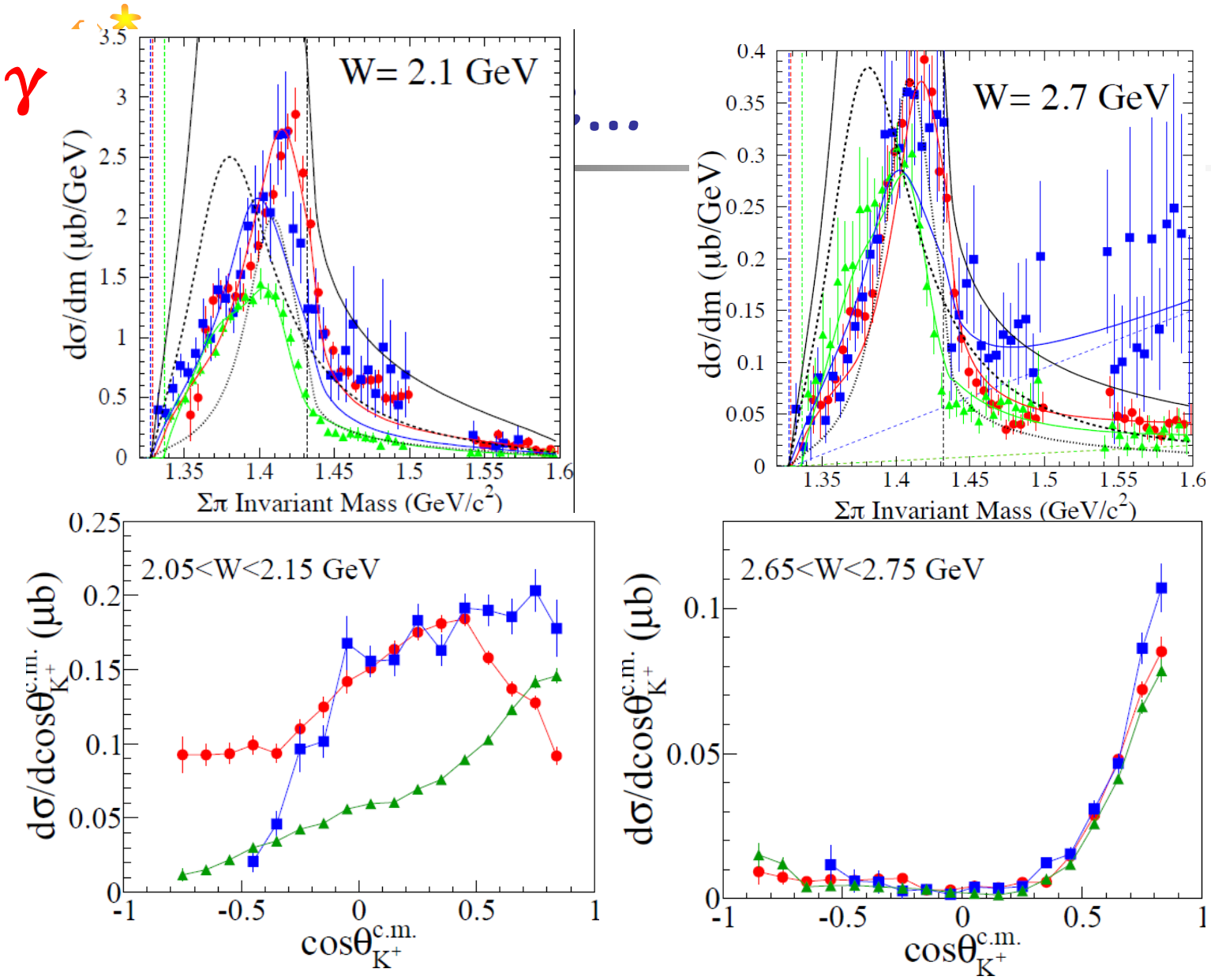
1. L. Roca, E. Oset "On the isospin 0 and 1 resonances from πΣ photoproduction data" arXiv:1307.5752 [nucl-th]
2. Bing-Song Zou "Five-quark components in baryons", Nucl Phys A 835 199 (2010).

"Best" model calculation

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



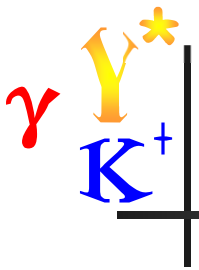
L. Roca, E. Oset "On the isospin 0 and 1 resonances from πΣ photoproduction data" arXiv:1307.5752 [nucl-th]



Line Shapes

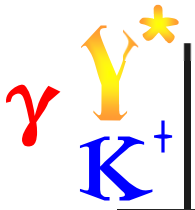
Cross Sections

- 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 $\Lambda(1405)$

Upcoming Publication: CLAS, to be submitted soon ...



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

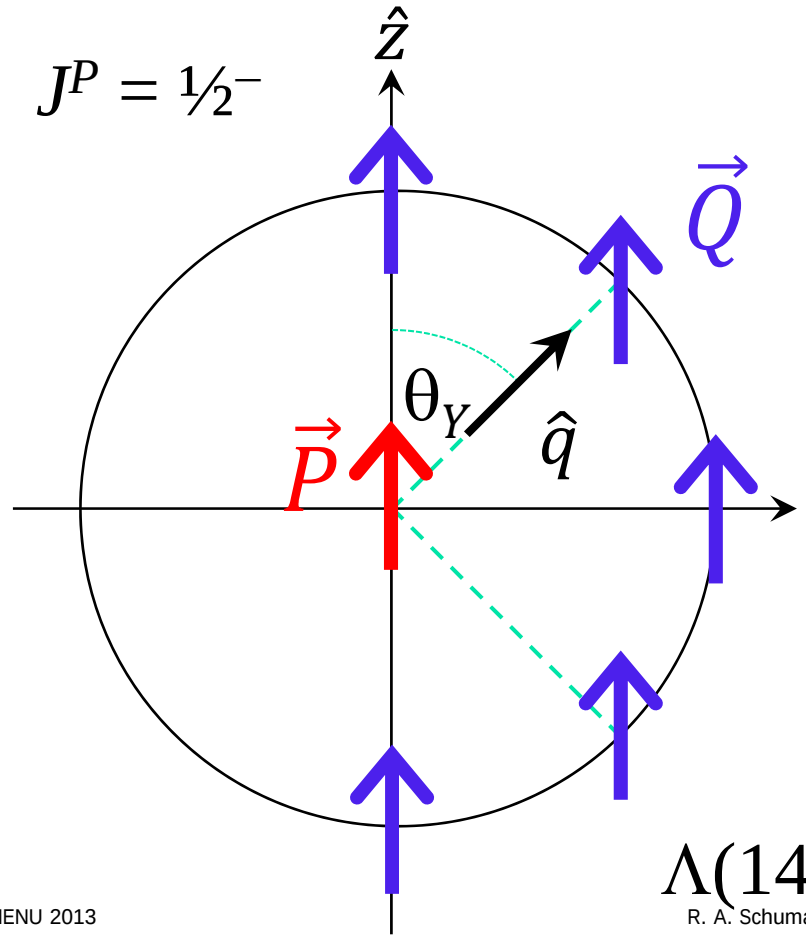
S-wave, P-wave Scenarios

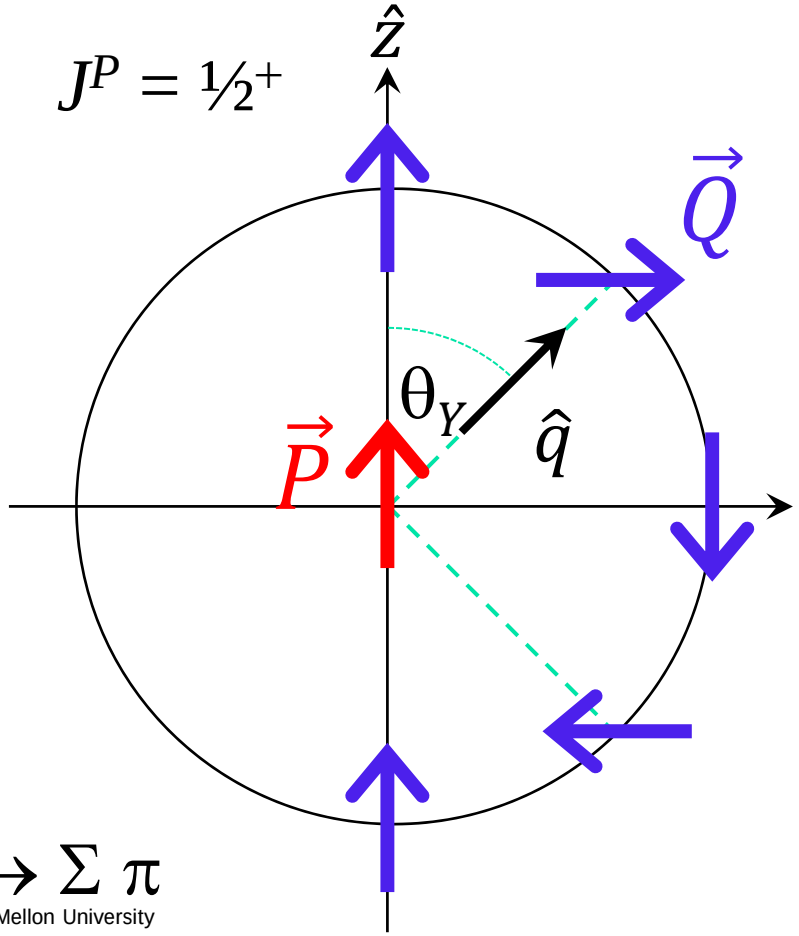
L=0 (s-wave)

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

L=1 (p-wave)

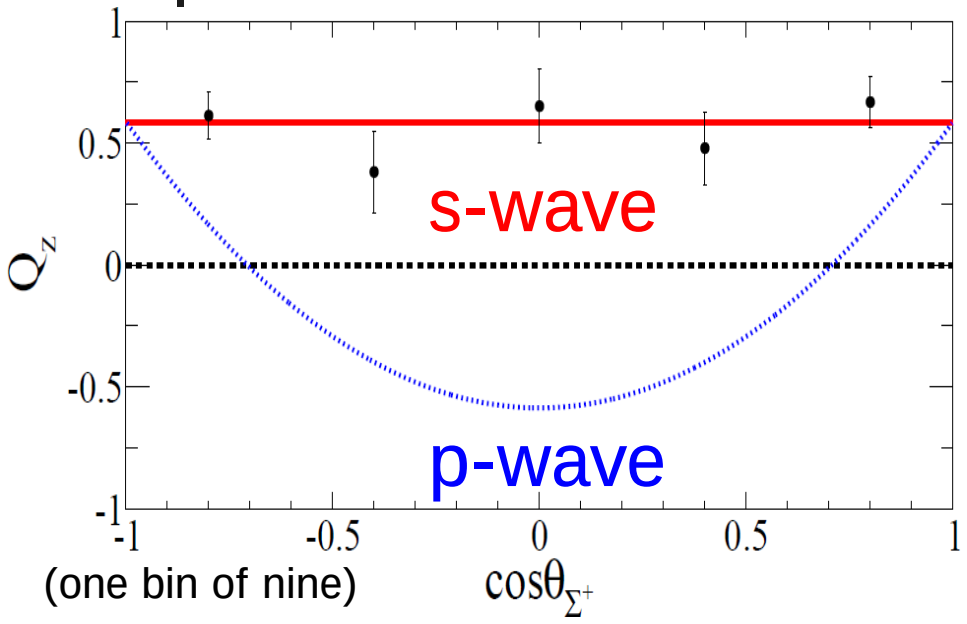
$\vec{Q} = -\vec{P} + 2(\vec{P} \cdot \hat{q})\hat{q}$





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

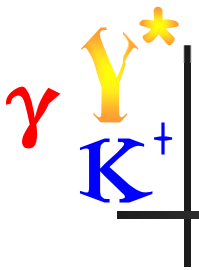
Parity and Spin of $\Lambda(1405)$



- 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 $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$ is isotropic (p = 0.5) , so $J \rightarrow 1/2$
- Weak decay asymmetry for Σ^+ is $\alpha = -0.98$ (big!)
- Decay is s-wave, $\Rightarrow P = "negative"$

$J^P = ½^-$ is confirmed for the first time

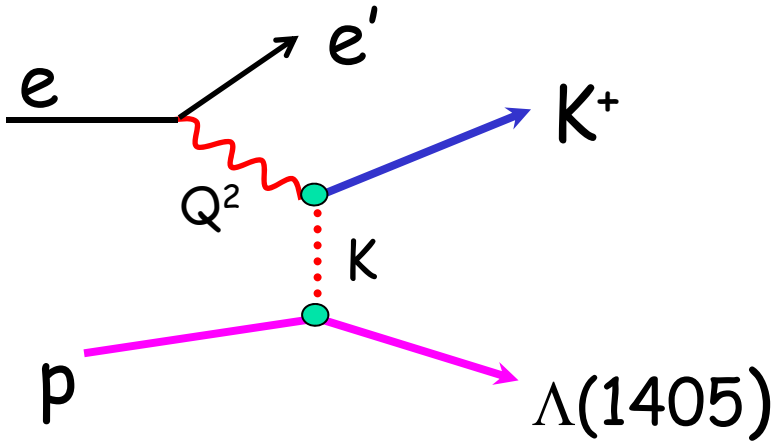
$\Lambda(1405)$ is produced ~ +45% polarized



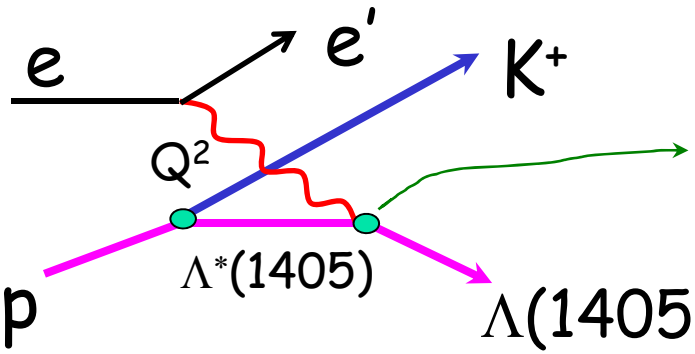
Strangeness Electroproduction

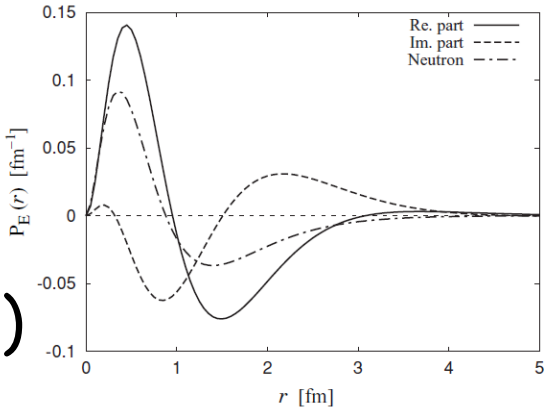
Publication: First Observation of the Λ(1405) Line Shape in Electroproduction, H. Lu *et al.* (CLAS Collaboration), submitted to Phys. Rev. C; arXiv:1307.4411 [nucl-ex]

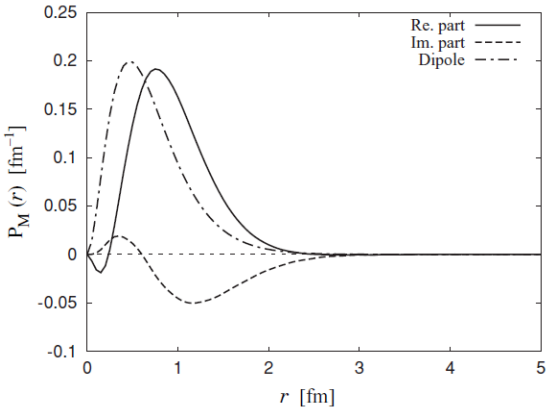
Electroproduction of Λ(1405)



- 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

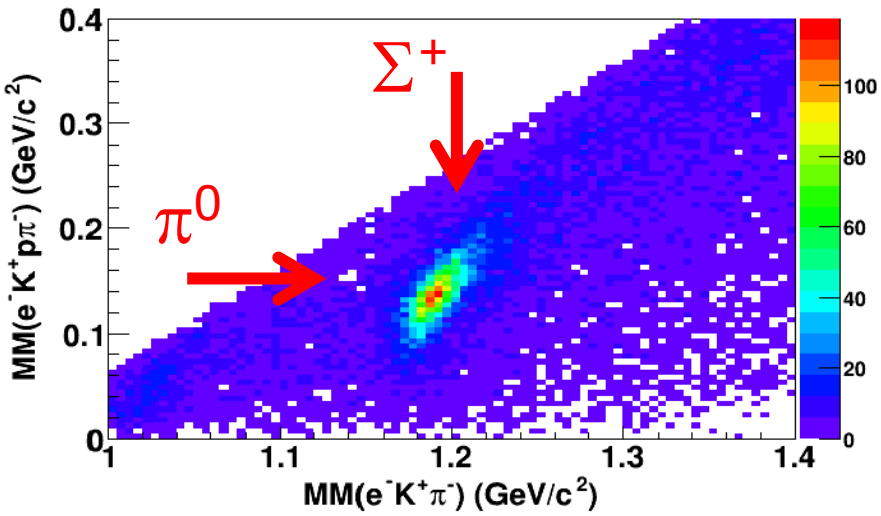


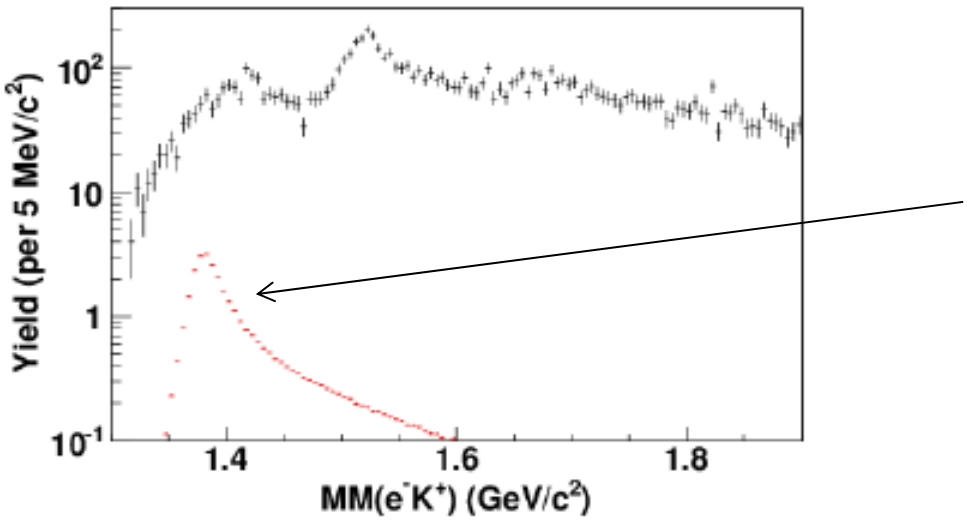




T. Sekihara, T. Hyodo, D. Jido, Phys Rev C83, 055202 (2011).

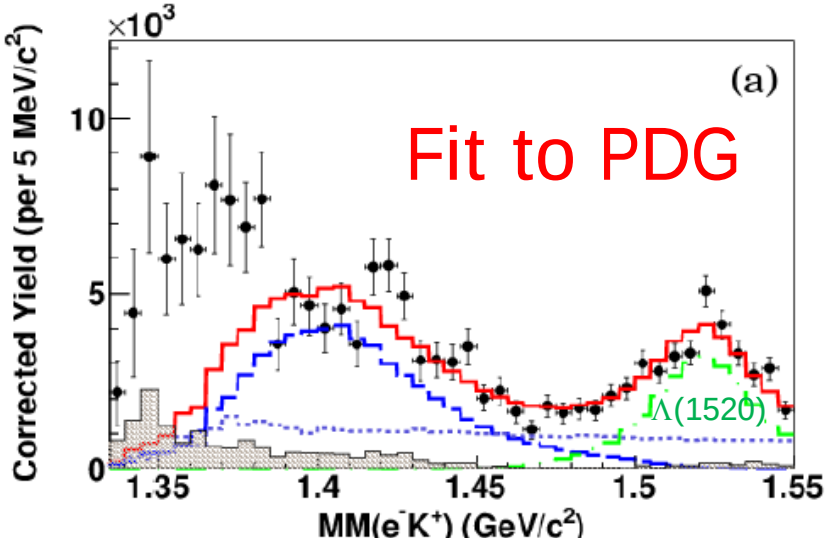
Electroproduction of $\Lambda(1405)$

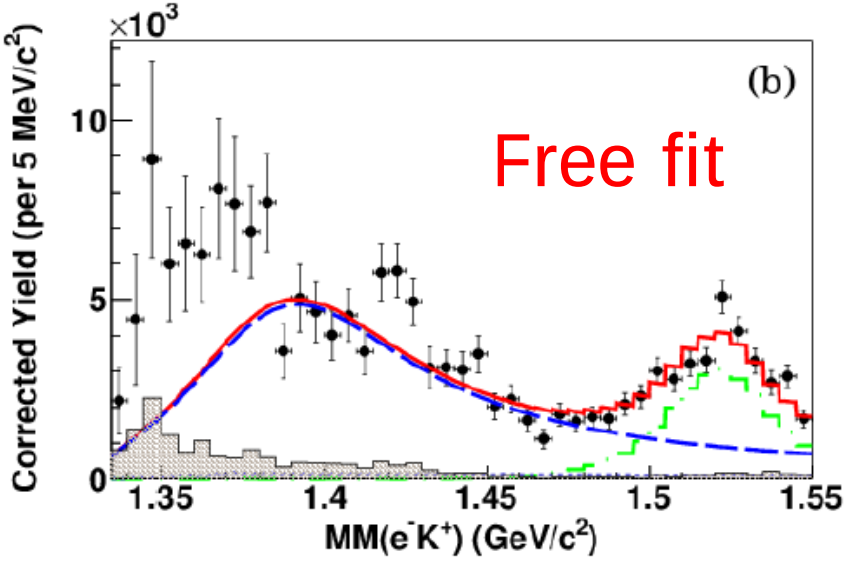


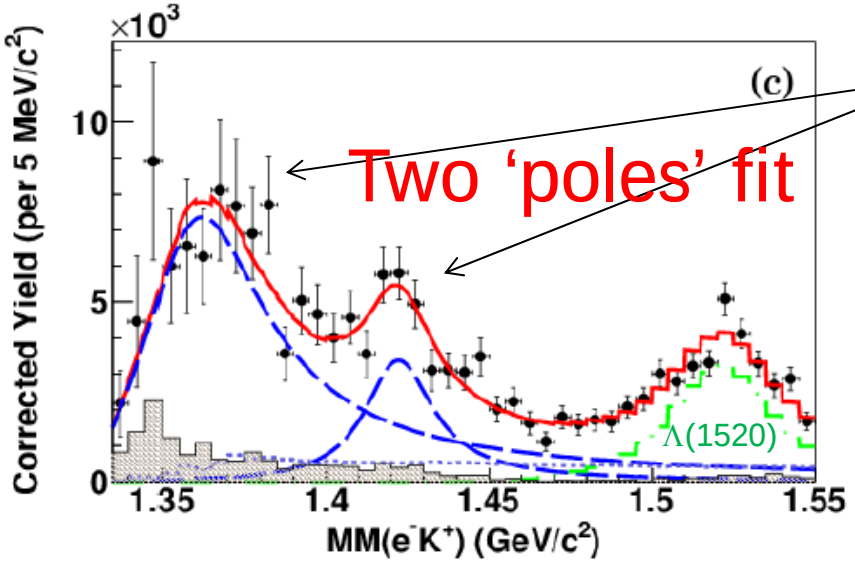


- 5.5 GeV electron beam
- e p → e′ K^+ p π^- (π^0), four particles detected
- CLAS acceptance: $1.0 < Q^2 < 3.0$ GeV^2; $1.5 < W < 3.5$ GeV.
- Dominant backgrounds: non-resonant $K^+ \Sigma^+ \pi^-$ resonant $K^{*0} \Sigma^+$
- $\Sigma(1385)$ found negligible
- Monte Carlo for signal and background channels acceptances

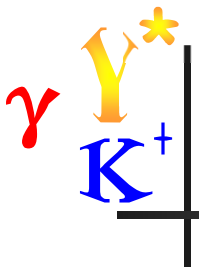
$\gamma p \to K^+ Y^*$ Electroproduction of $\Lambda(1405)$





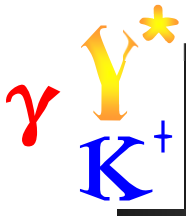


- Two-bump structure seen
- Possible evidence for two I=0 poles
- PDG $\Lambda(1405)$ values fail utterly
- Calculation needed!

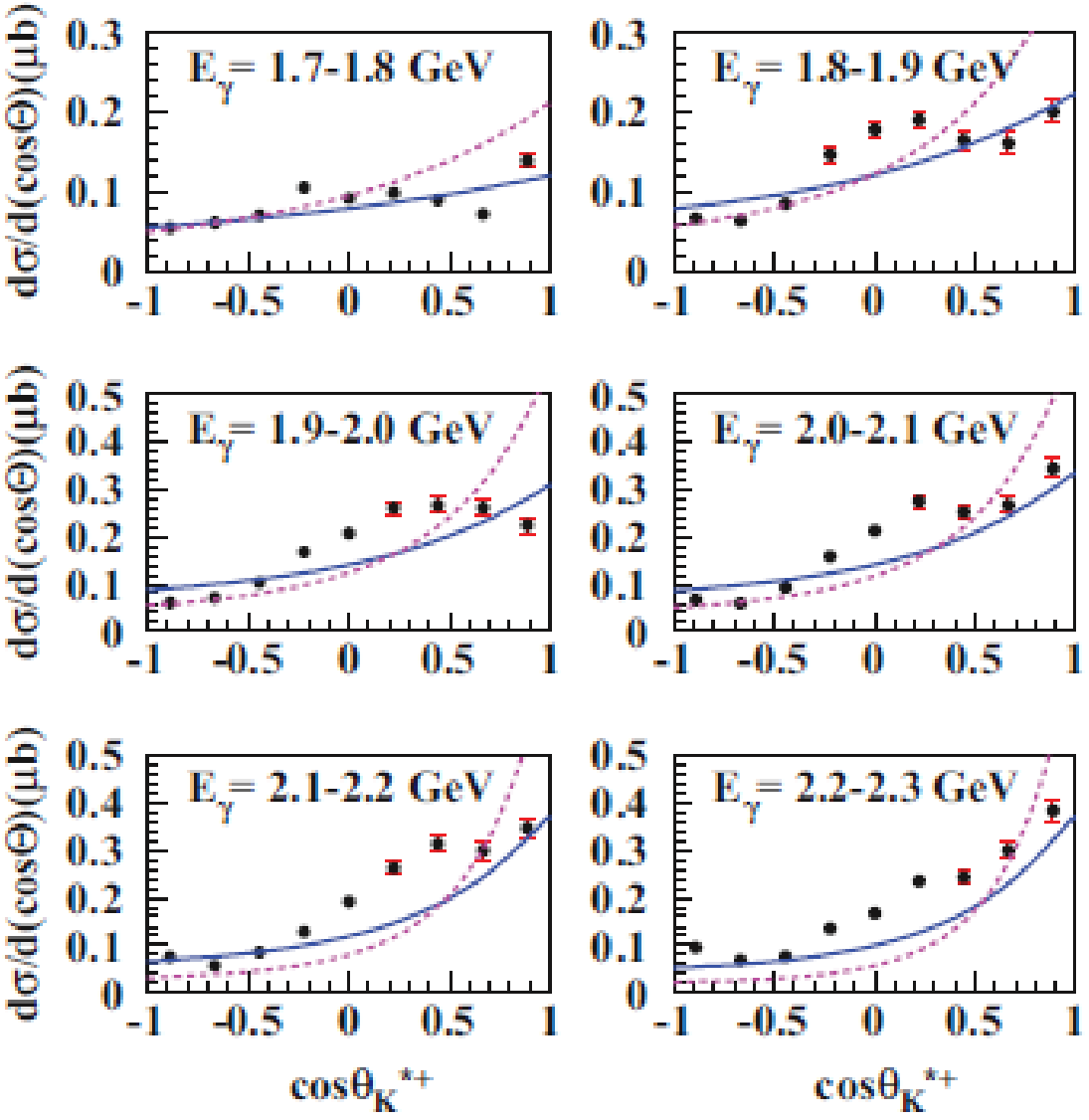


K* Production

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



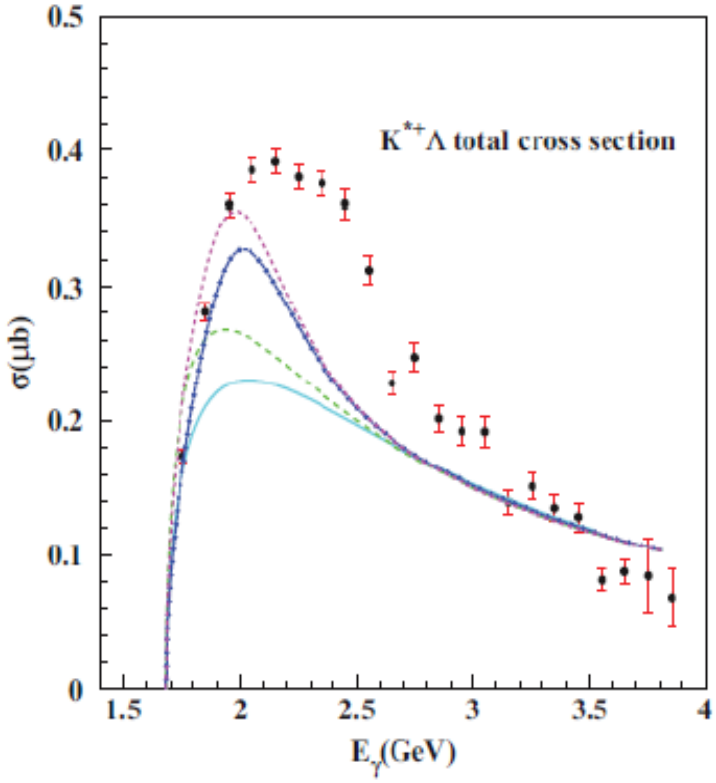
$K^{*+}\Lambda$, $K^{*+,0}\Sigma^{0,+}$ photoproduction



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

$\gamma p \to K^{*+}\Lambda$, $K^{*+0}\Sigma^{0+}$ 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

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

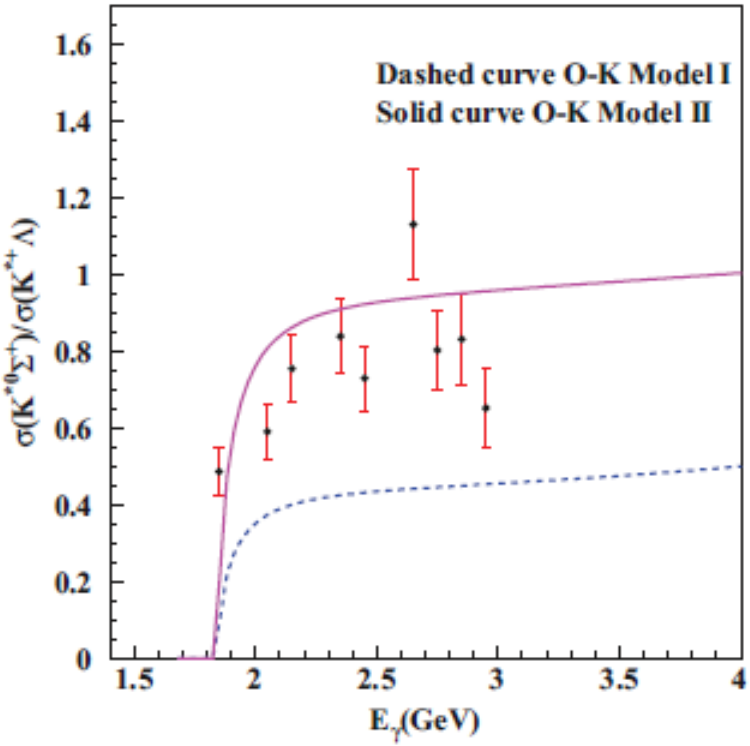
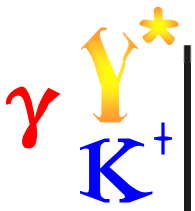


FIG. 12. (Color online) Total cross section ratio of the reactions $\gamma p \to K^{*0}\Sigma^+$ to $\gamma p \to K^{*+}\Lambda$. The ratio uses the present data in the denominator and data from Ref. [5] in the numerator. The dashed and solid curves are theoretical calculations from Oh and Kim [4] models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



Summary/Conclusions

- First comprehensive $\gamma p \to \mathrm{K}^{+}\mathrm{Y}^{*}$ cross sections for the first three excited hyperons, all current models show (fixable?) deficiencies
- New interference phenomena in $\Lambda(1405)$ cross section(s) and line shapes demonstrated
- First direct J^P measurement for $\Lambda(1405)$: $\frac{1}{2}^{-}$
- First look at $\Lambda(1405)$ electroproduction: supports a possible two-bump/pole structure
- First K*+Y cross sections shown