Differential Photoproduction Cross Sections for the $\Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$

γ K^+ Y^*

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Baryons2013

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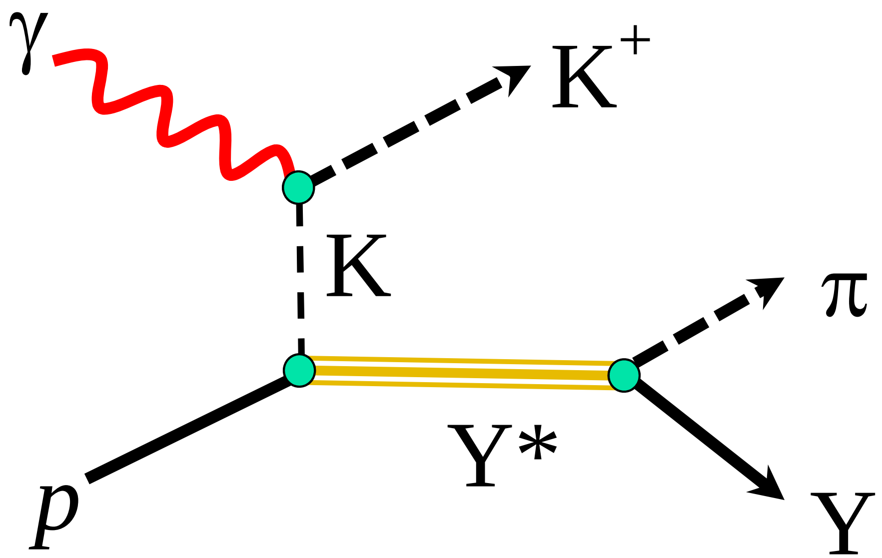
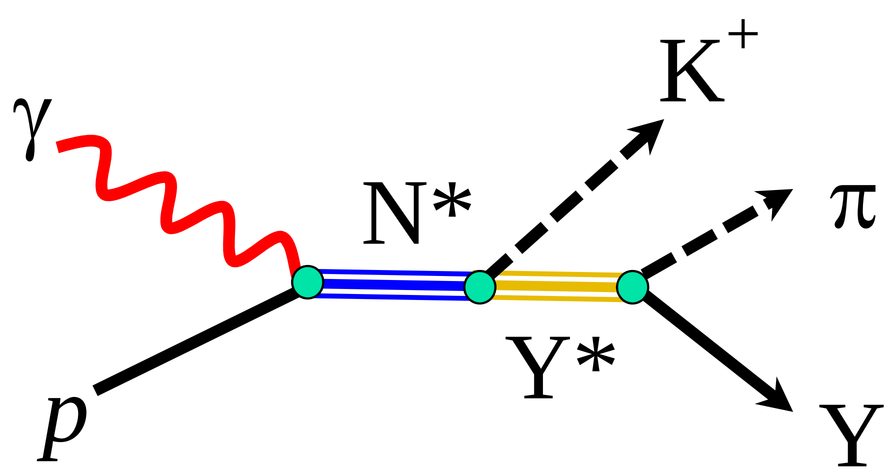
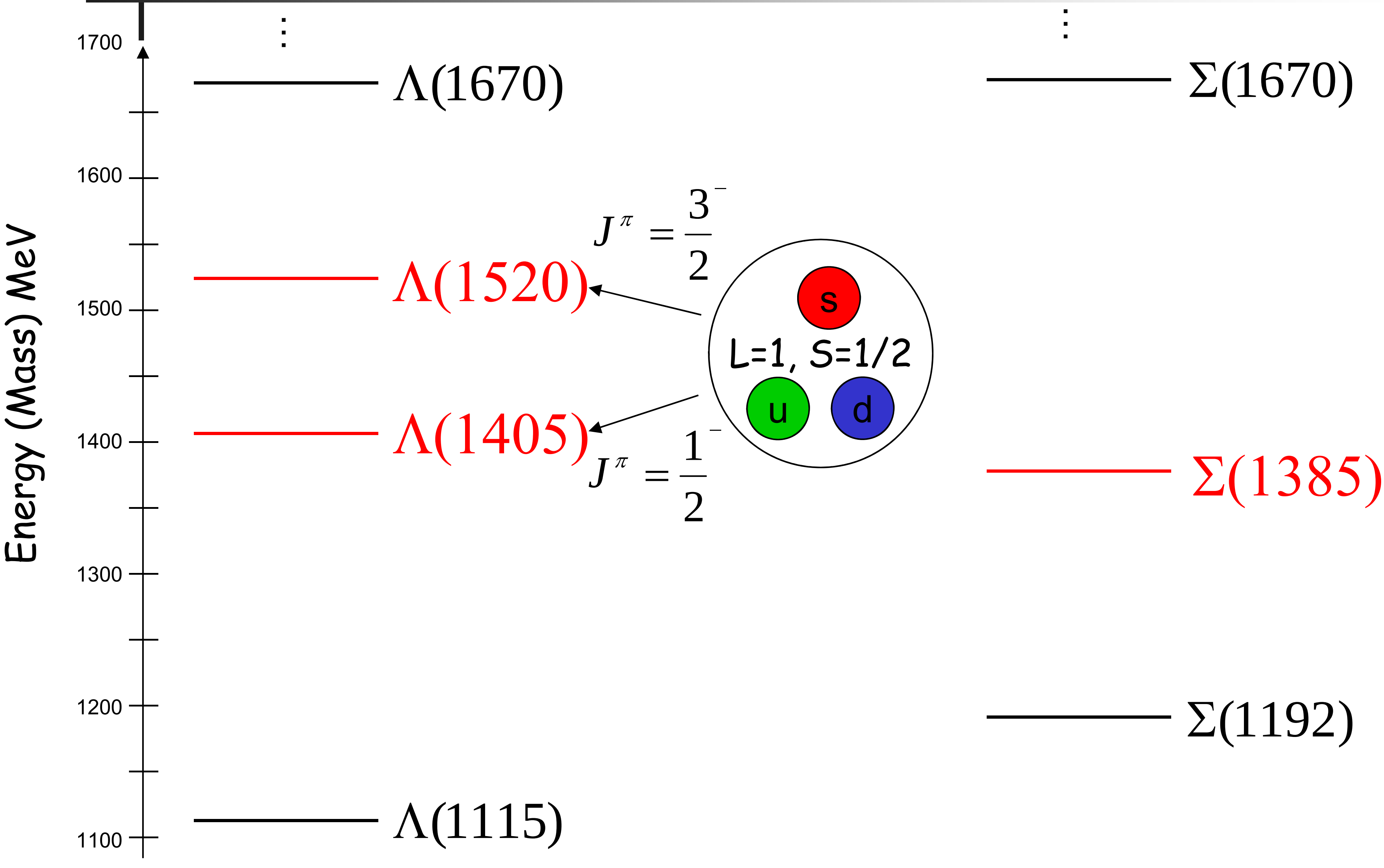
Outline / Overview

- Excited hyperon spectra 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
- Compare to best current models



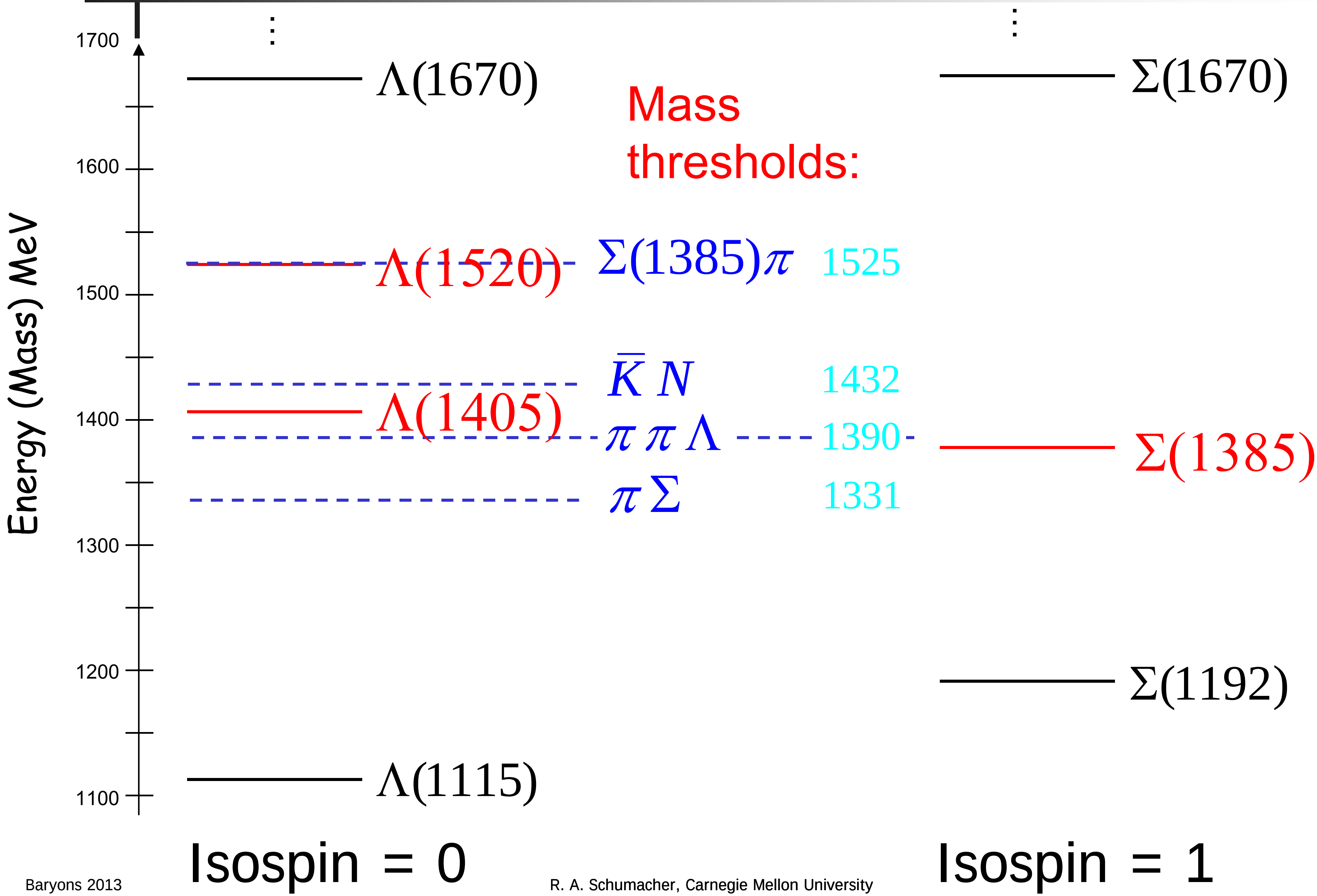


The Low-Mass S=-1 Hyperons



Isospin = 0 Isospin = 1

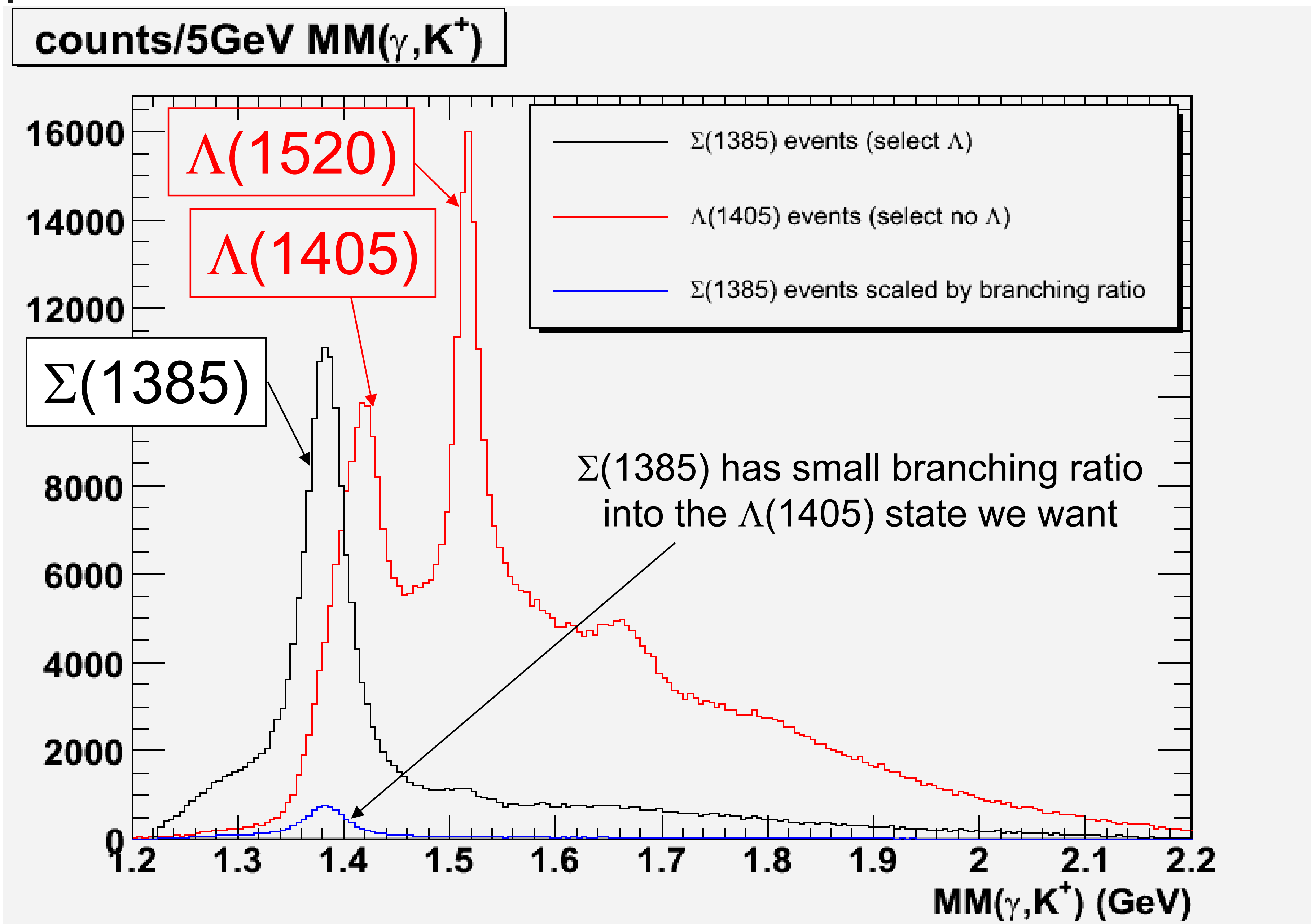
The Low-Mass S=-1 Hyperons



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

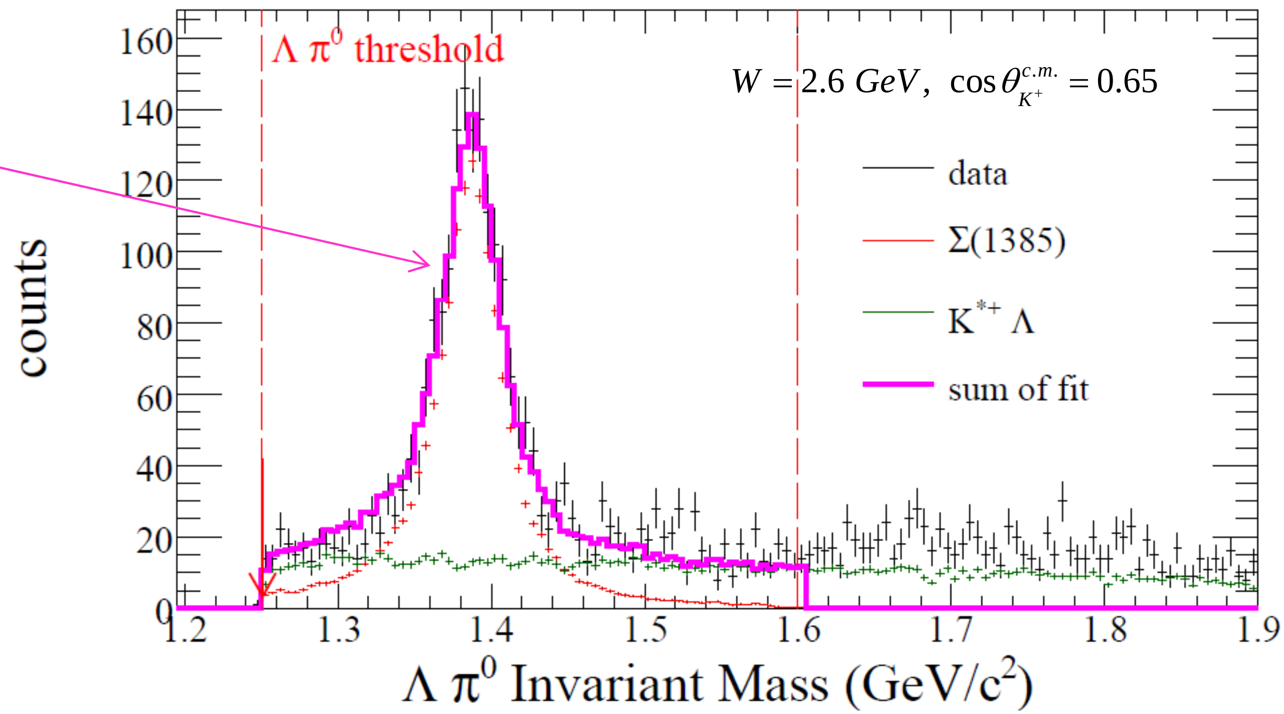
Detect $K^+ p\pi^-(\pi^0)$ or $K^+\pi^+\pi^-(n)$



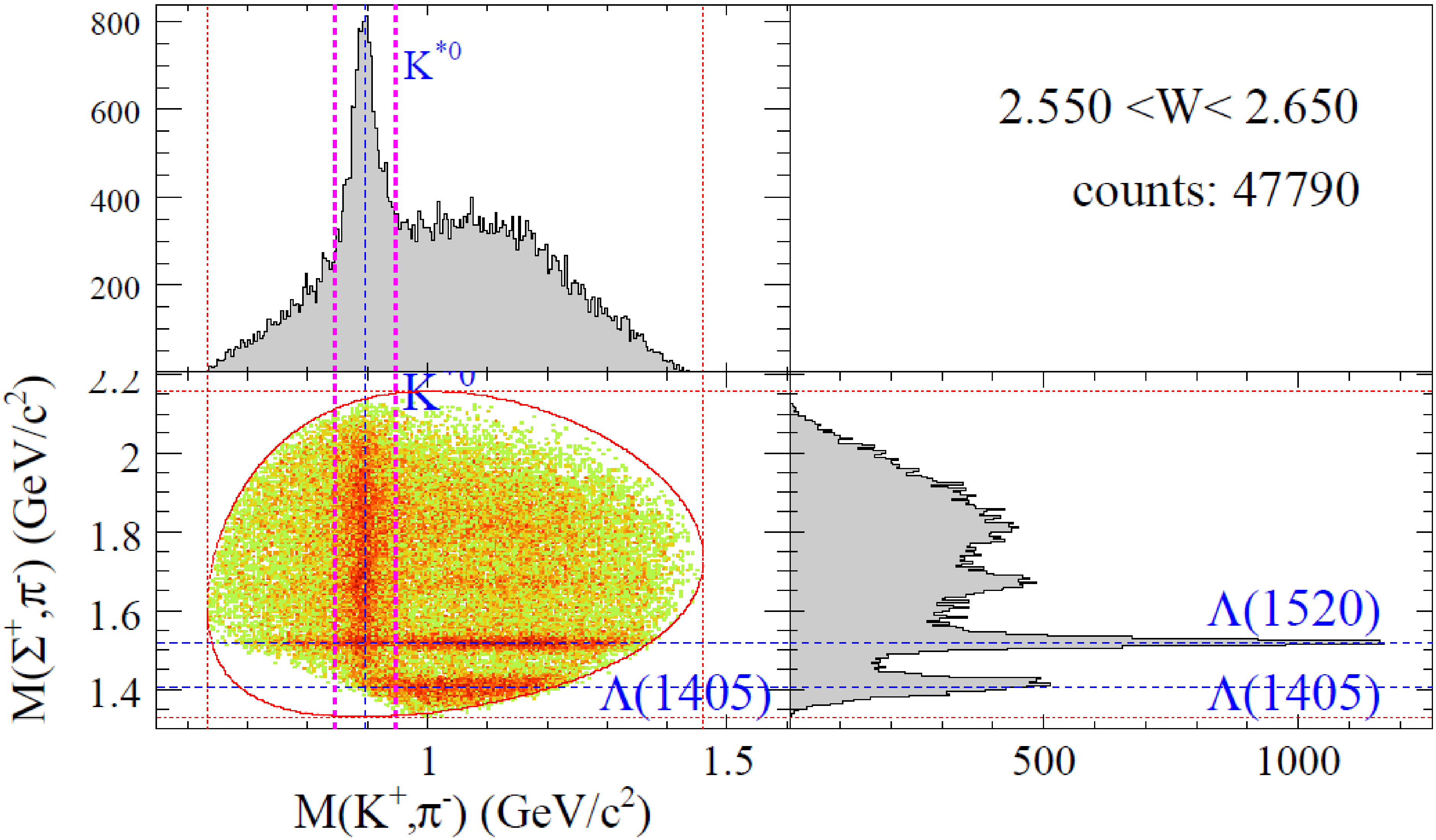
Yields for $\Sigma^0(1385)$

- 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



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



Note K* overlap: must be subtracted in some W bins

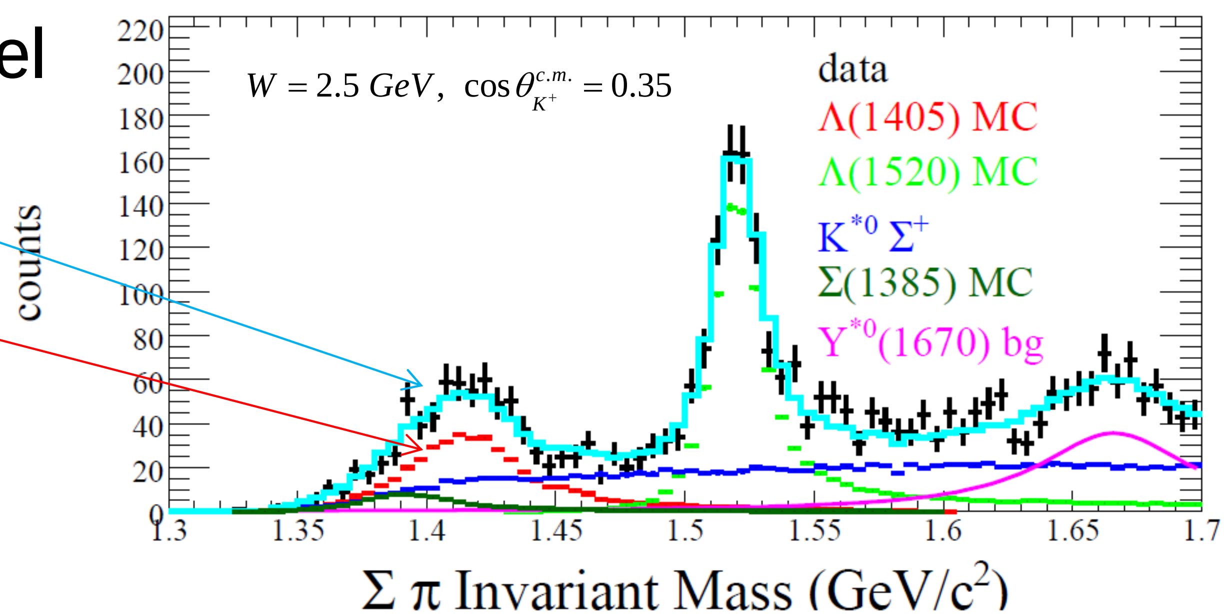
Yields for $\Lambda(1405)$ & $\Lambda(1520)$

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

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

Total fit result

Iterated $\Lambda(1405)$ line shape

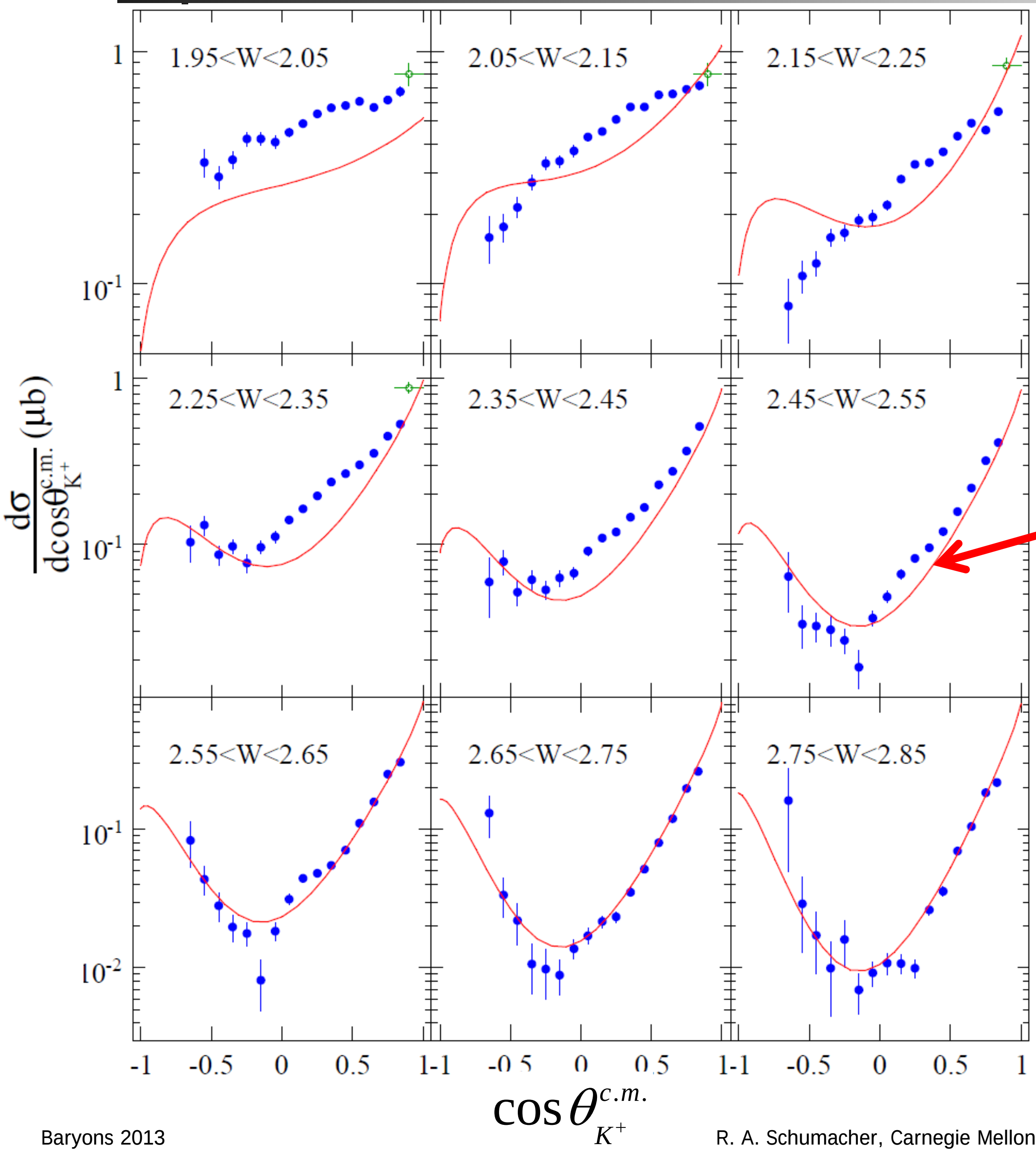


Systematics

Source	Value (%)
ΔTOF cuts	2–6
Confidence level on kinematic fit	3–12
Selection of intermediate hyperons	2–3
Target density	0.11
Target length	0.125
Photon normalization	7.3
Live-time correction	3
Photon transmission efficiency	0.5
$\Sigma^0(1385) \to \Sigma\pi, \Lambda\pi$	1.5
$\Lambda \to p\pi^-$	0.5
$\Sigma^+ \to p\pi^0, n\pi^+$	0.30
$\Sigma^- \to n\pi^-$	0.005
Total	11.6

- Global systematic uncertainty: 11.6%
- Dominated by photon normalization uncertainty

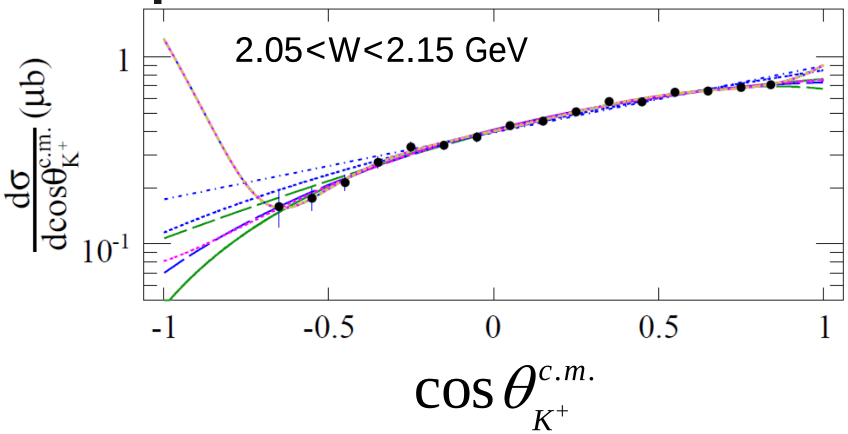
Differential $\Sigma^0(1385)$ Cross Section

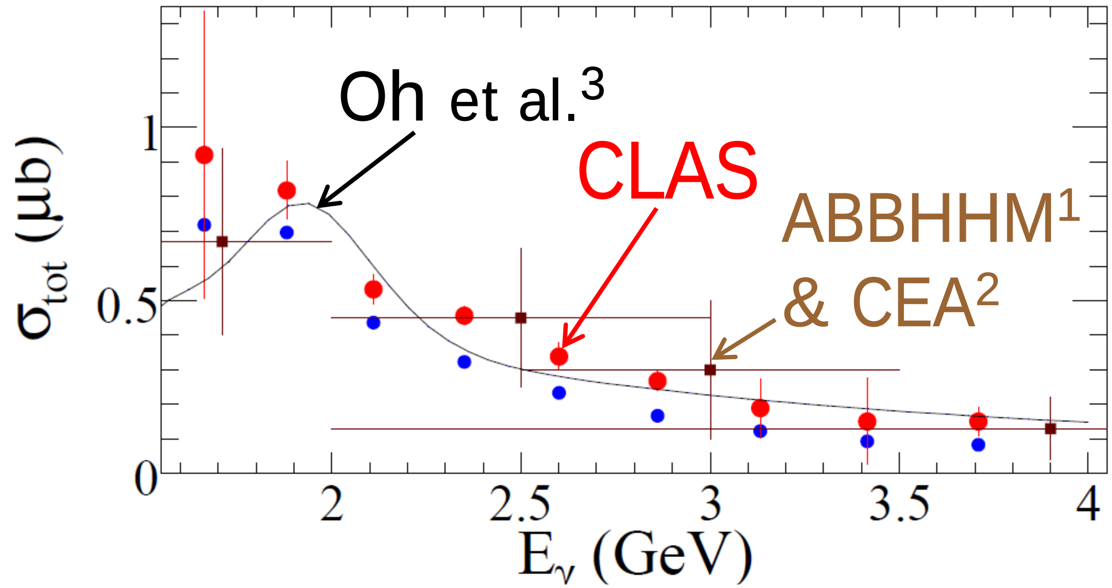


- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
- Experiment: see *t*-channel-like forward peaking & *u*-channel backward rise
  - Agreement with LEPS
- Theory by Oh et al.[1]: contact term dominant; included four high-mass N^* and Δ resonances
  - Model prediction was fitted to preliminary CLAS total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

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

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



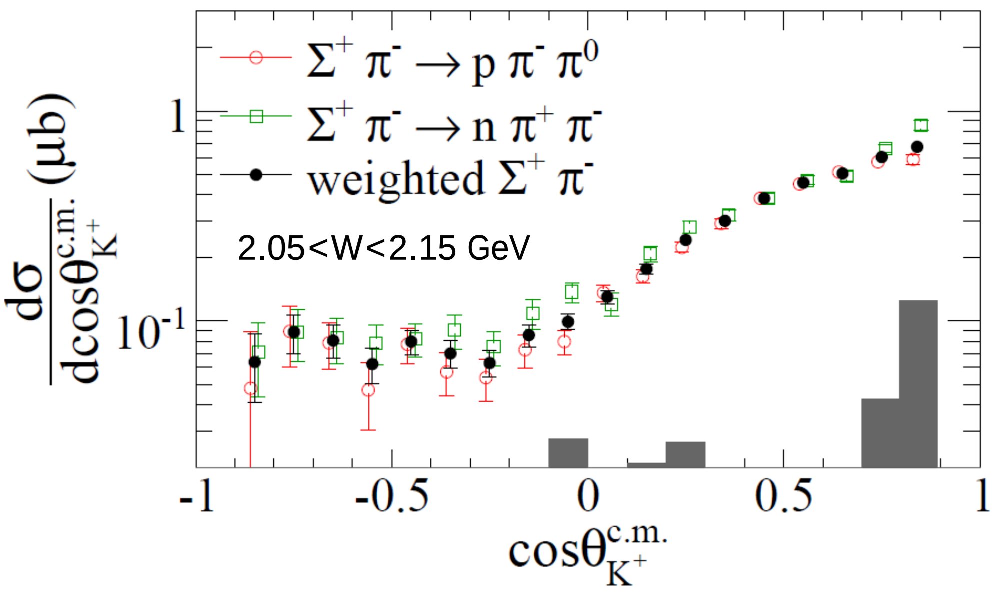


- Extrapolation to all kaon angles
- Average of many similar polynomials
  - e.g. $f(z) = \left|\sum_{l=0}^{L} c_l P_l(z)\right|^2$

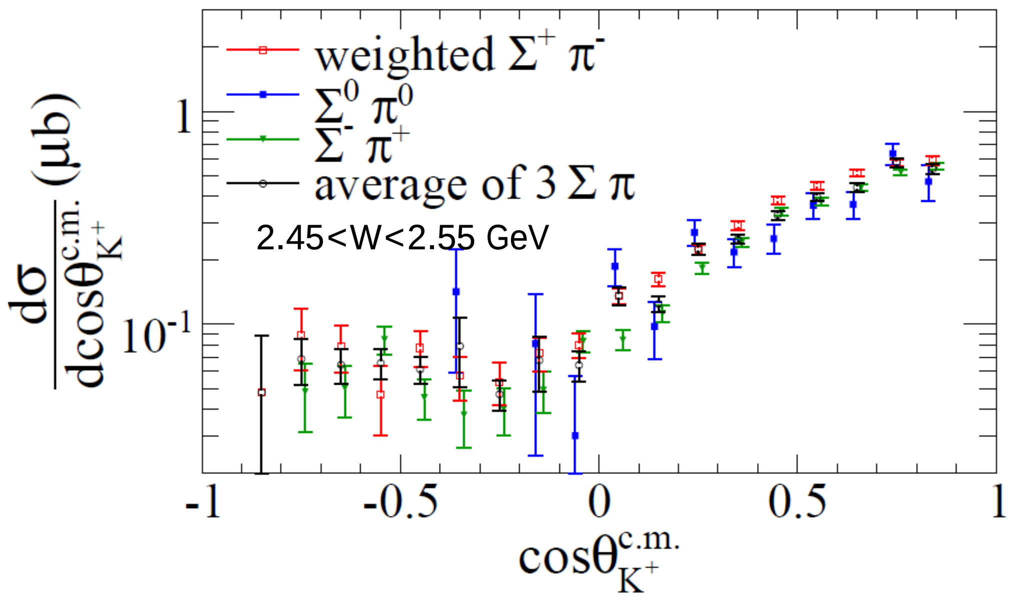
- $\gamma + p \rightarrow K^+ + \Sigma^0(1385)$
  - Blue: measured
  - Red: extrapolated total
- Agrees with ABBHHM[1] & CEA[2]
- Oh's[3] "bump" at W=2.1 GeV (E_γ=1.9 GeV) due to N^*'s

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



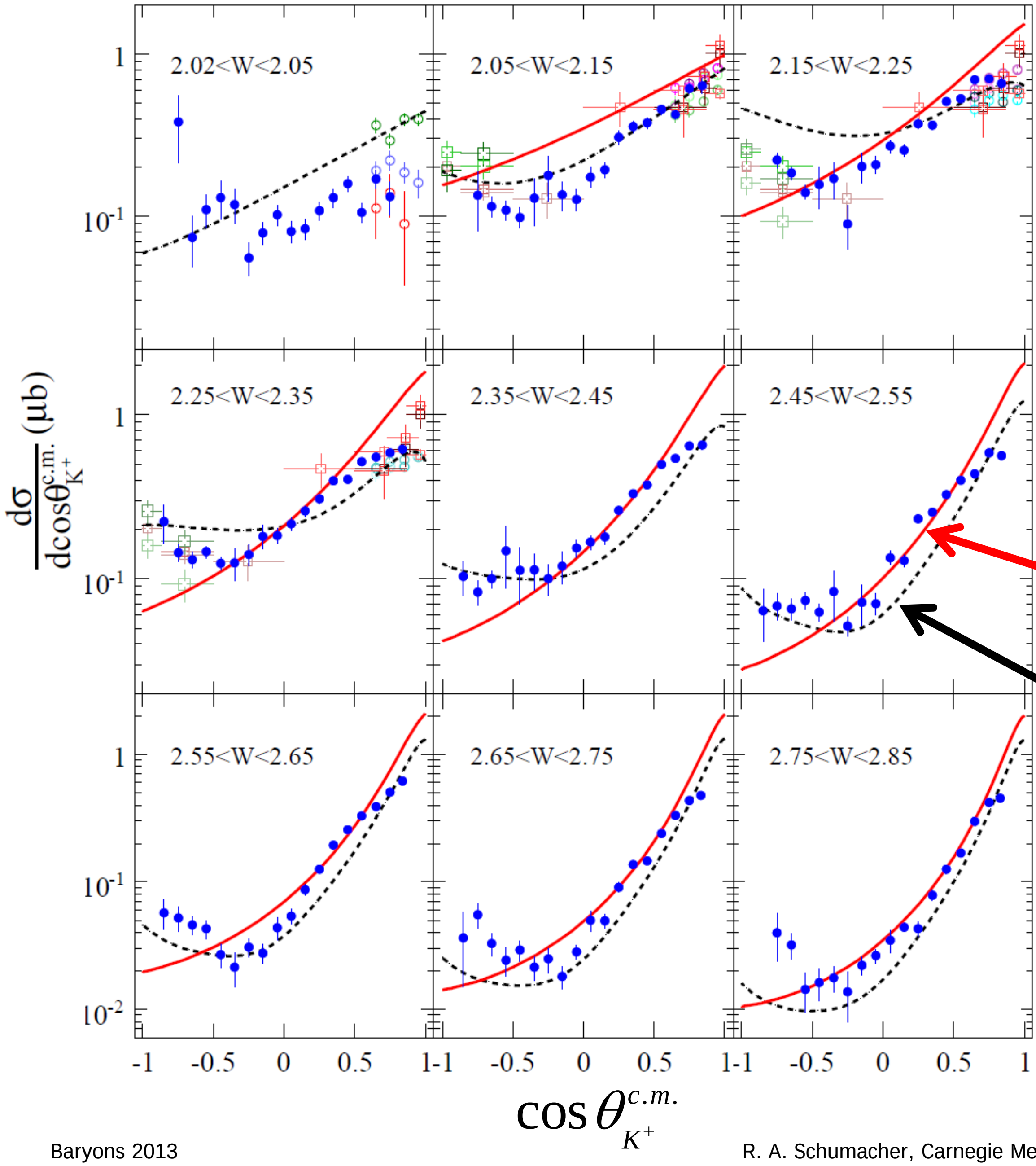
Agreement between $\Sigma^+\pi^-$ decay modes: tests acceptance consistency



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

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

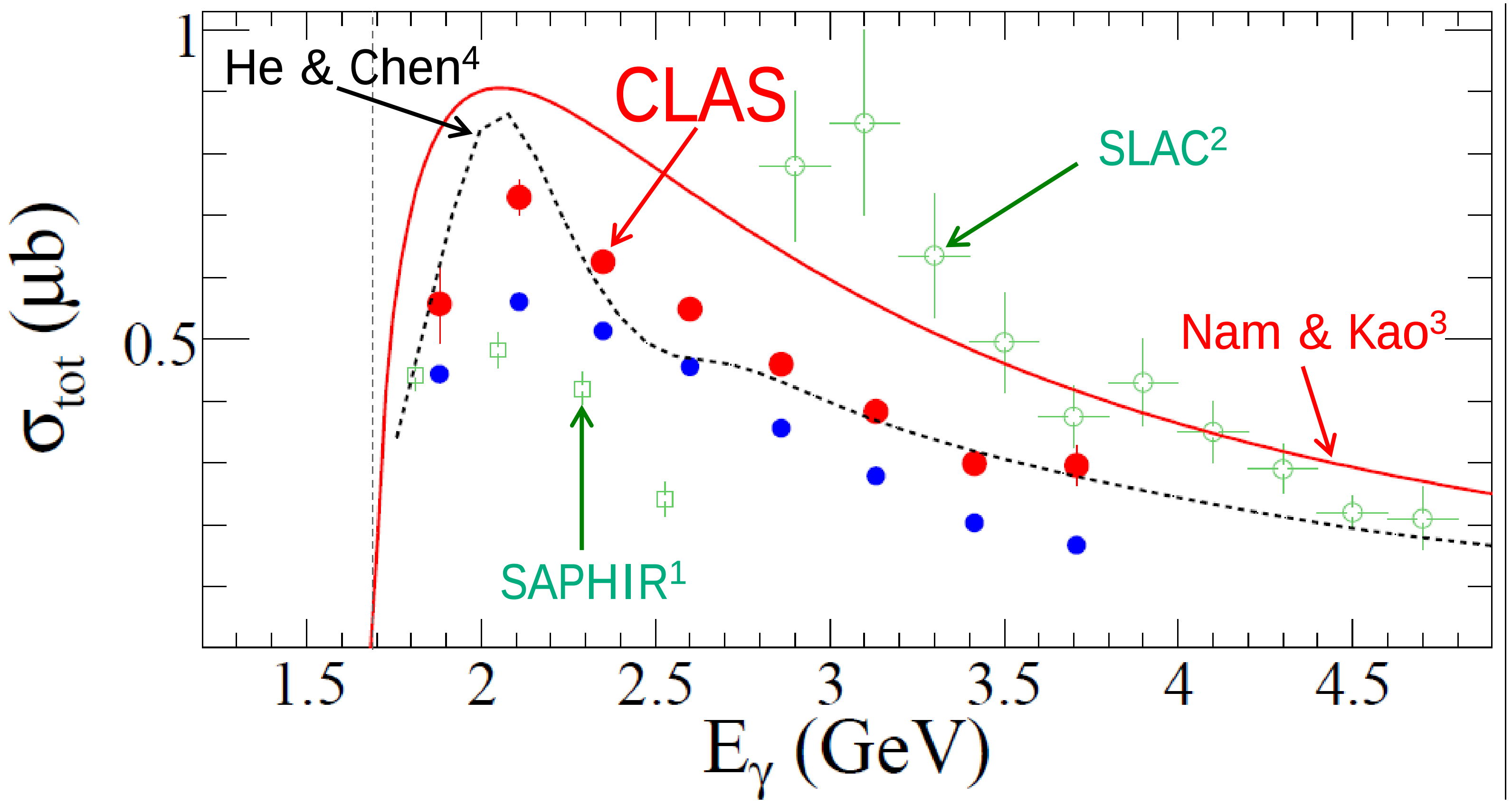
Differential Λ(1520) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1520)$
- Experiment: see t-channel-like forward peaking & u-channel backward rise
  - Agreement with LEPS[1,2]
- Theories:
  - Nam et al.[3]: contact term dominant; no K^* or u-channel exchanges
  - He and 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. Cao, Phys. Rev. **C 81**, 055206 (2010)
4. J. He & X.R. Chen, Phys. Rev. **C 86**, 035204 (2012)

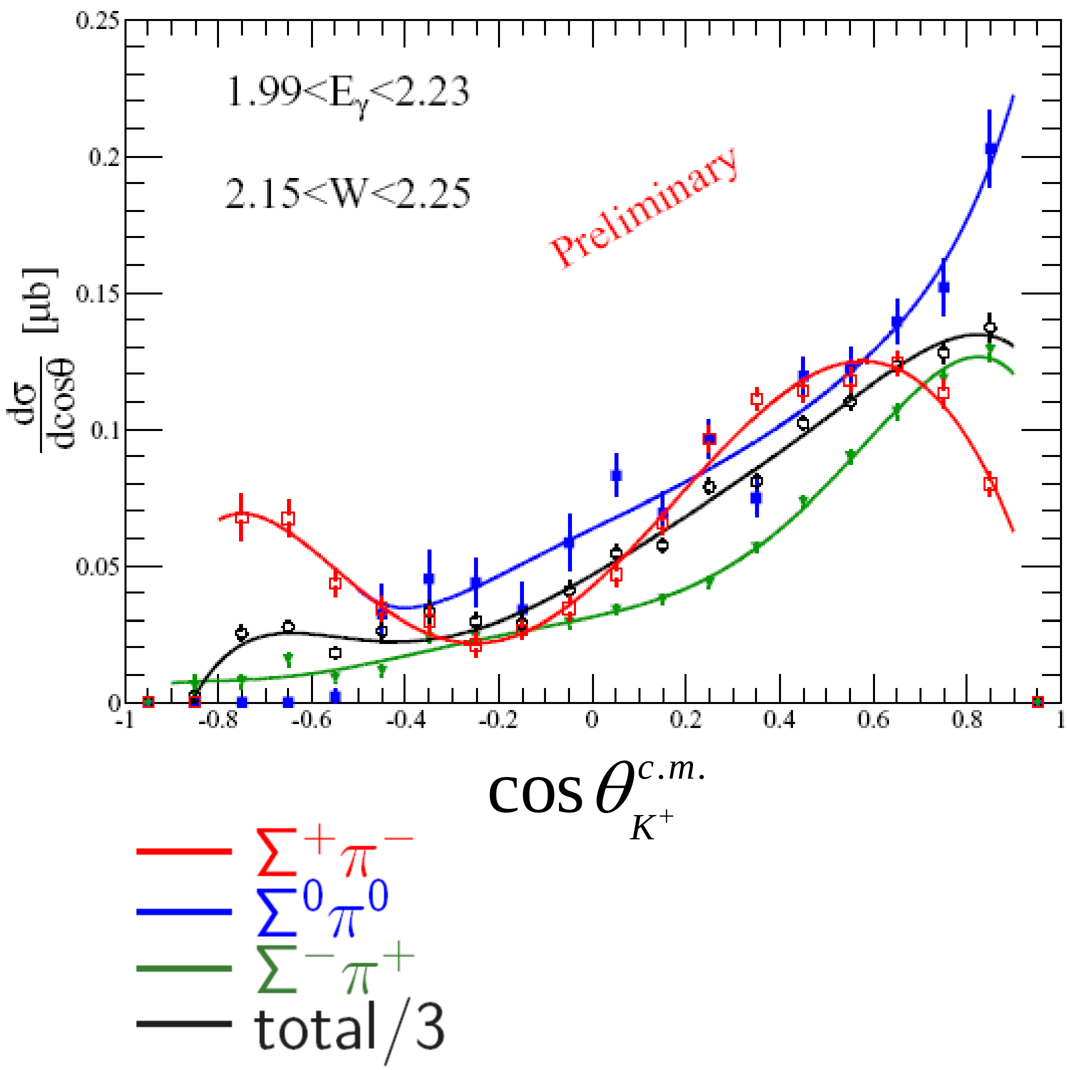
Total Λ(1520) Cross Section



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

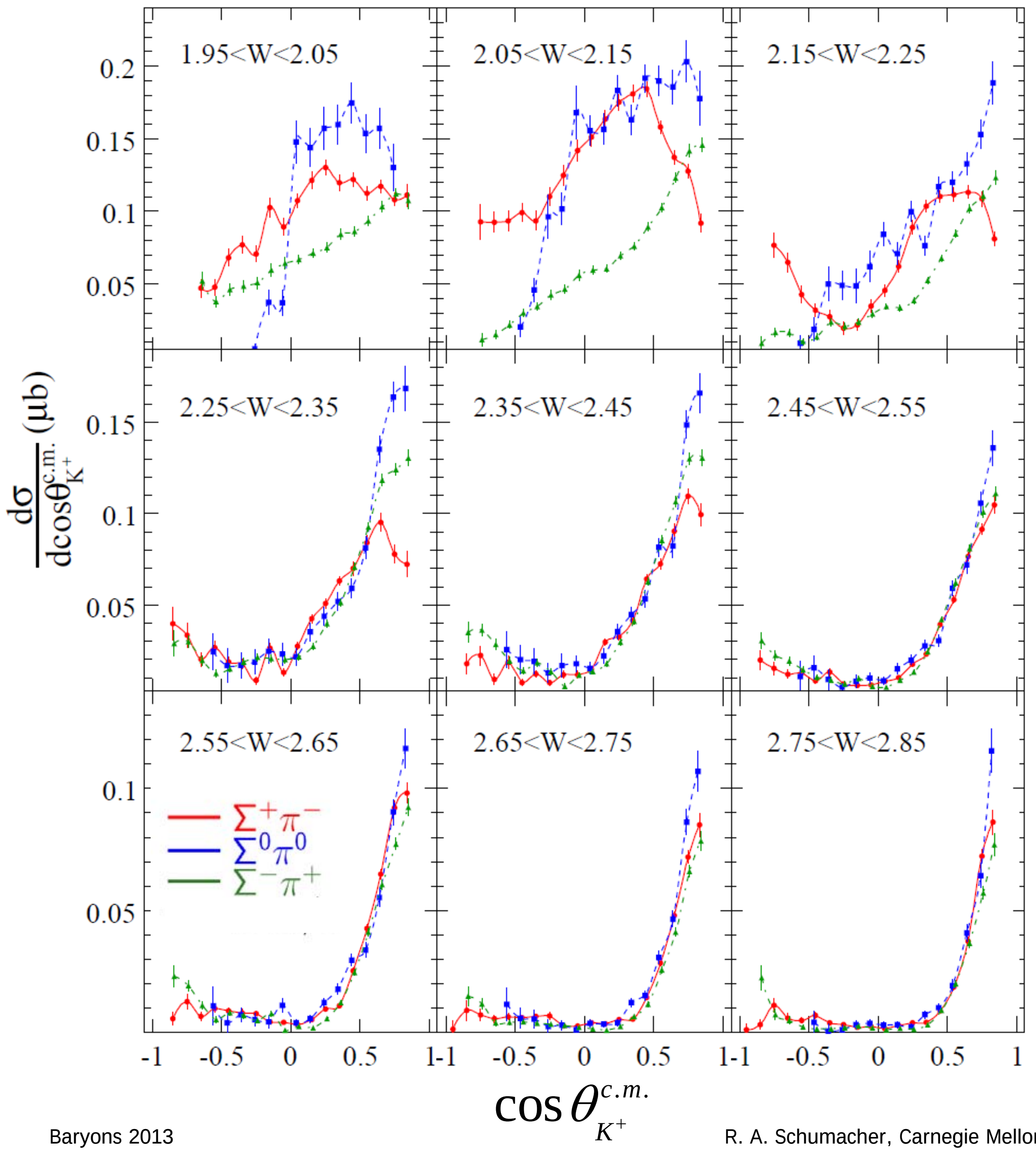
1. F. Wieland et al. (SAPHIR) Eur.Phys.J. **A47**, 47 (2011)
2. D. Barber et al. (SLAC/LAMP2) Z. Phys. **C7**, 17 (1980)
3. S.I. Nam & C.W. Kao, Phys. Rev. **C 81**, 055206 (2010)
4. J. He & X.R. Chen, Phys. Rev. **C 86**, 035204 (2012)

Differential Λ(1405) Cross Section



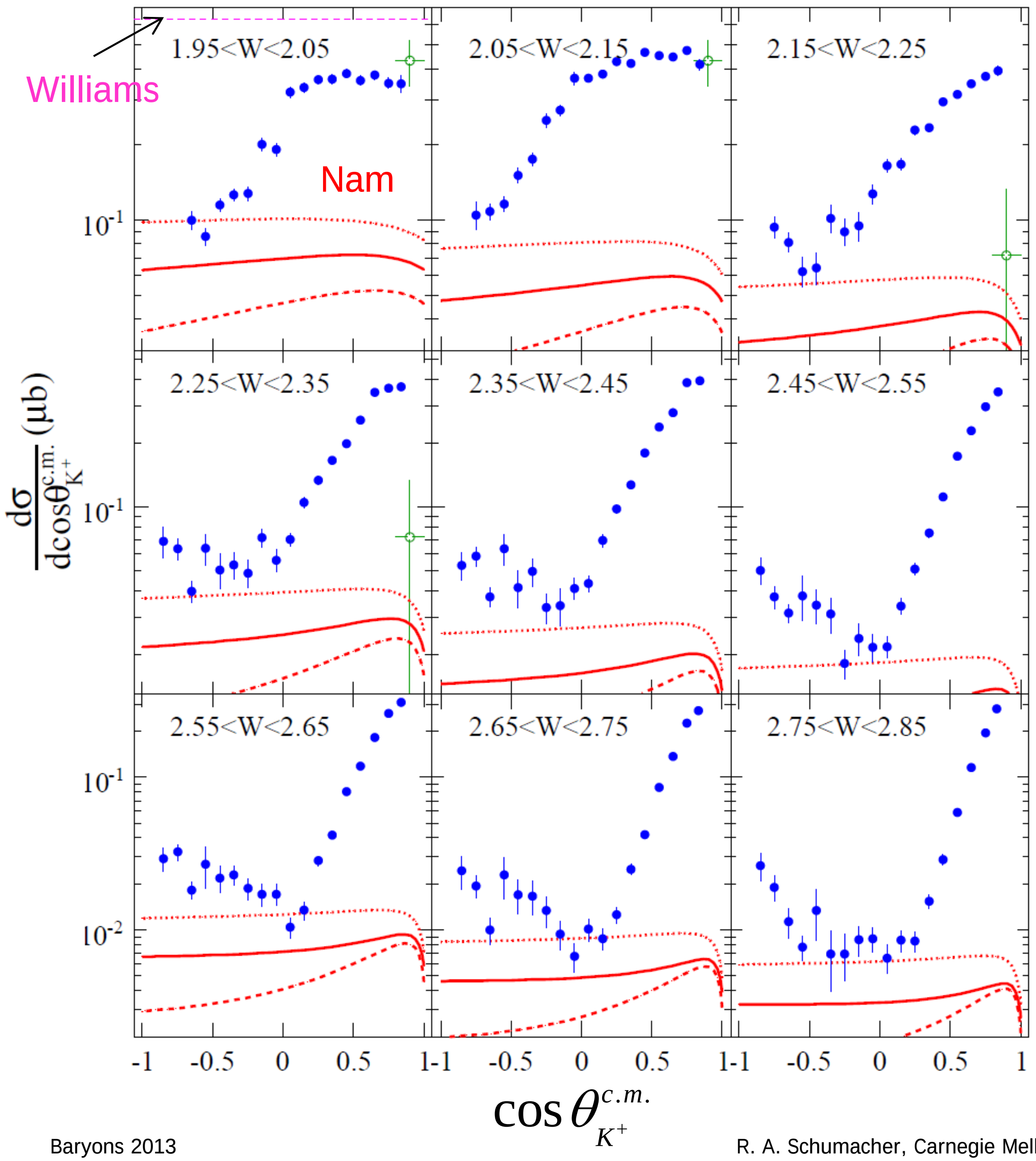
- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Experiment: each Σ π channel yields a different cross section (! Not expected !)
- Indication of isospin interference in Λ(1405) mass region
  - Threshold < $m_{\Sigma\pi}$ < 1.50 GeV

Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Experiment: first-ever measurements
- See *t*-channel-like forward peaking & *u*-channel backward rise at high W
  - Same as other hyperons
- See very different behavior at low W
  - Charge channels differ
- Channels merge together at high W

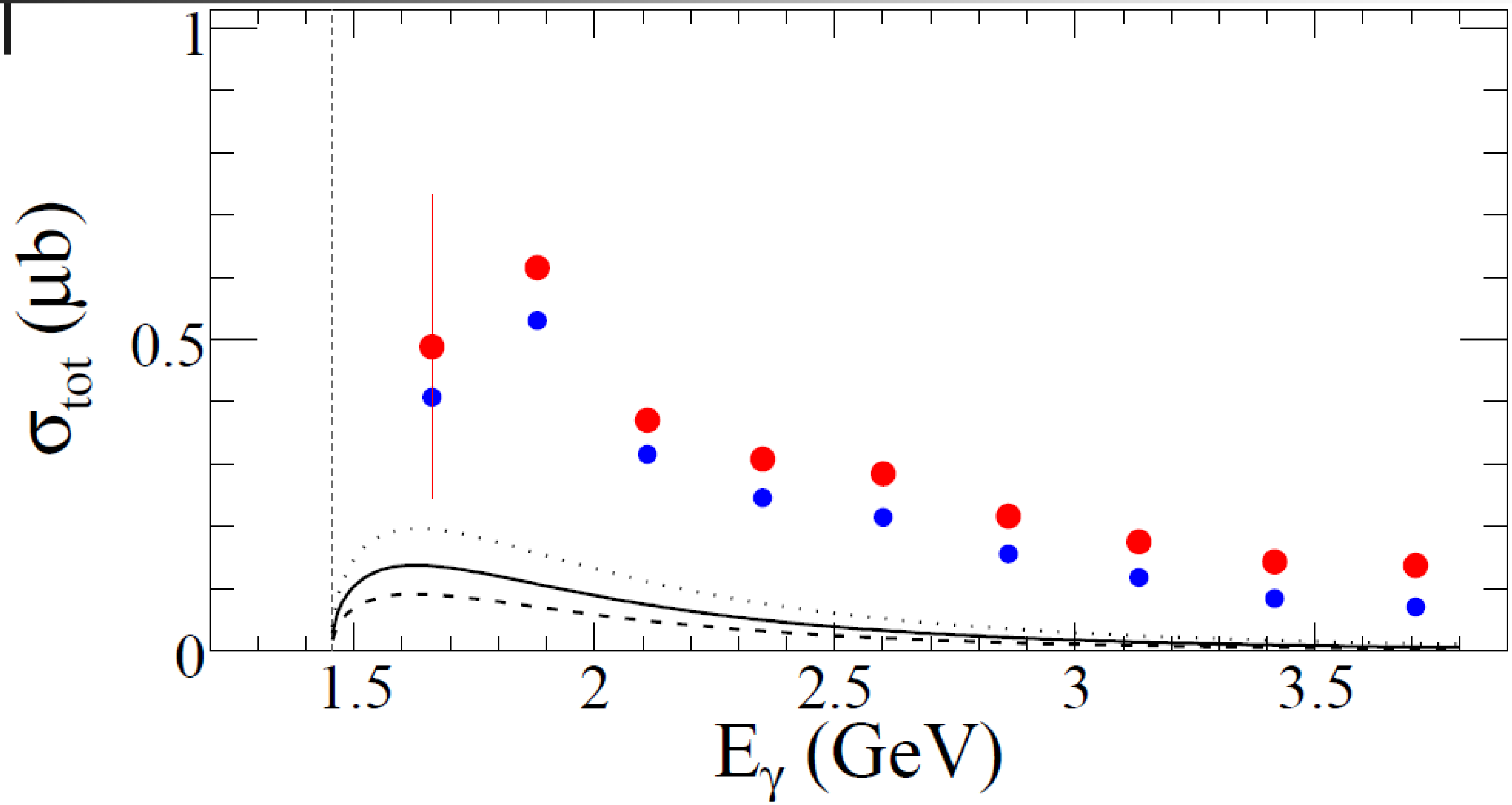
Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Sum three Σπ decay modes → "total" 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)

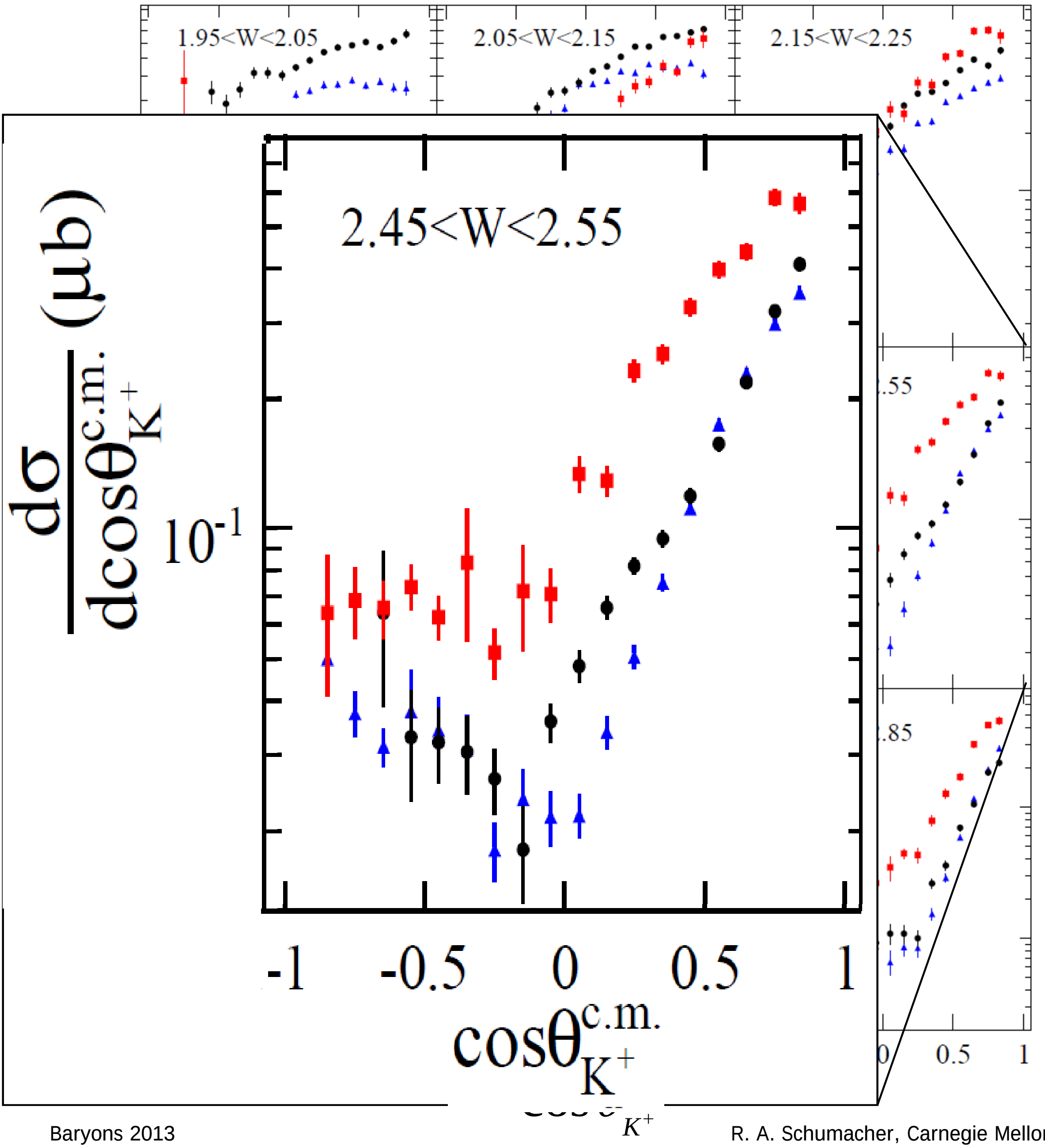
Total Λ(1405) Cross Section



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

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

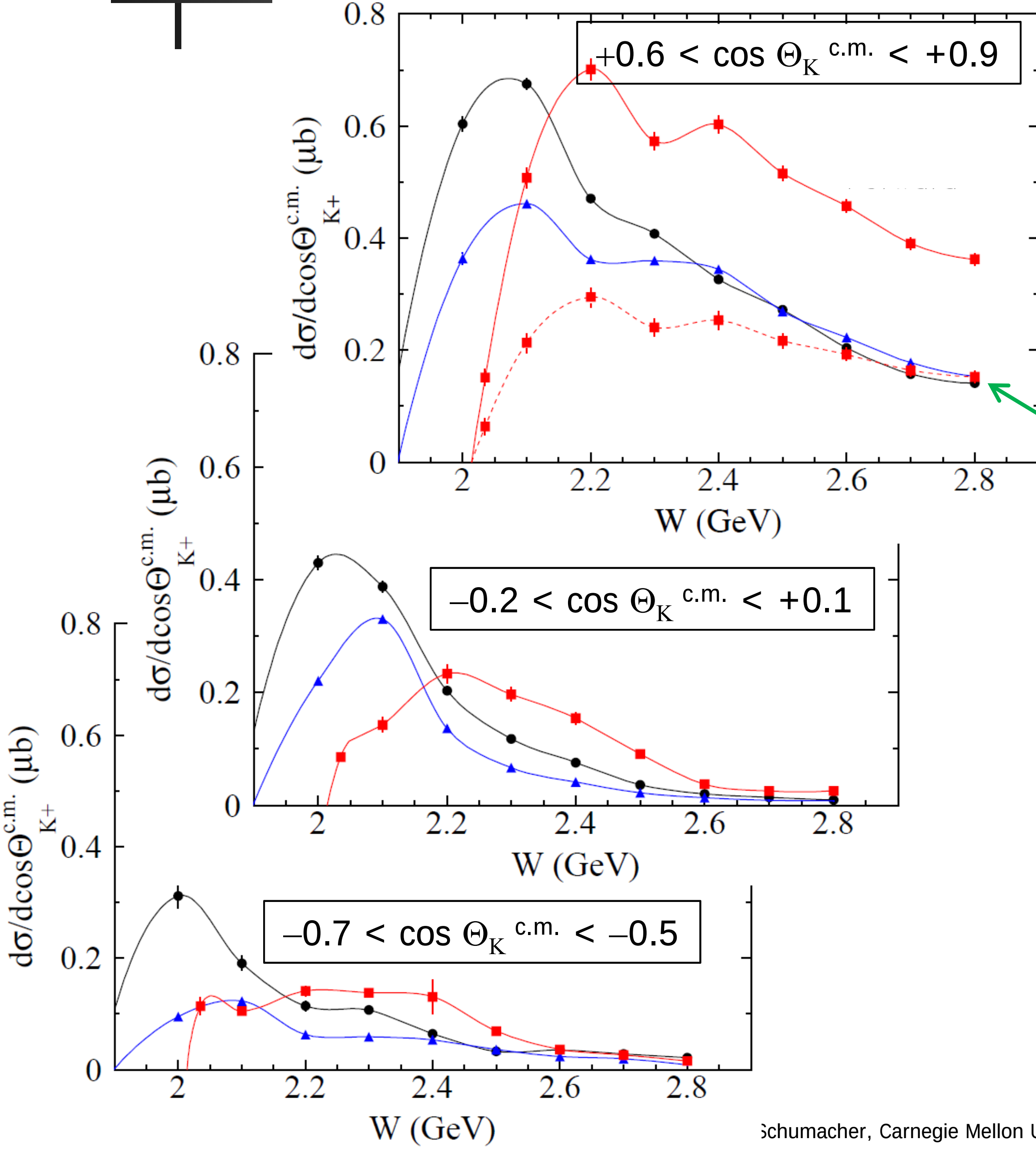
Direct Y* Cross Section Comparison



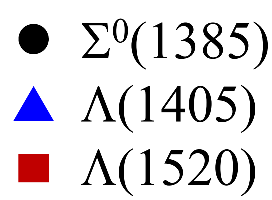
- $\gamma + p \rightarrow K^+ + Y^*$
  - Sum $\Lambda(1405)$ channels
  - Apply branching fractions for $\Lambda(1520)$, $\Sigma(1385)$
- All three hyperons have
  - Strong forward peaking
  - Similar t-slopes
  - Back-angle rises
  - Similar-size cross sections

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

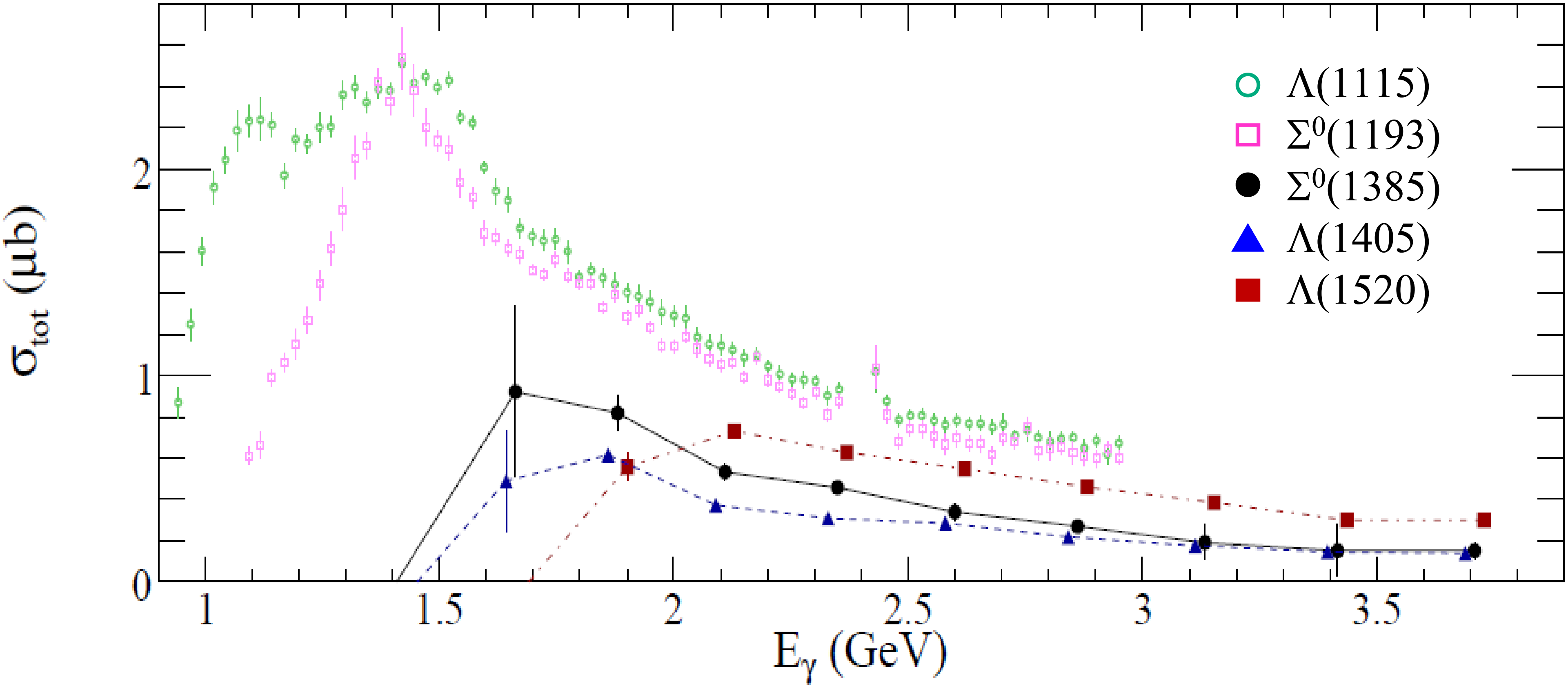
Direct Y* Cross Section Comparison



- $\gamma + p \rightarrow K^+ + Y^*$
  - (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



γ Y^* K^+ Total Cross Section Comparison



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

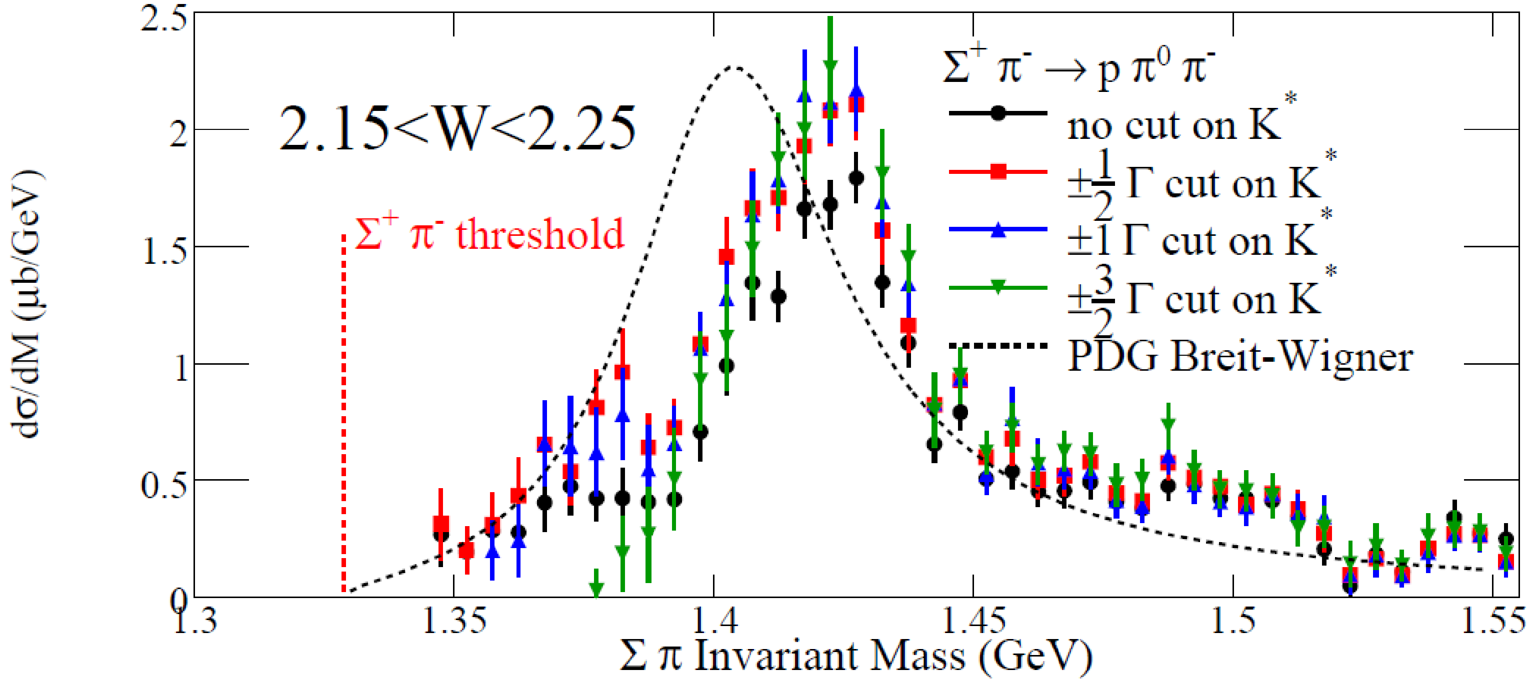
1. R. Bradford et al. (CLAS) Phys. Rev. **C 73**, 035202 (2006)

Summary/Conclusions

- First comprehensive Y^* cross sections for the first three excited hyperons from CLAS
- Similar t-channel dominated production at high W
- Predictions are in poor-to-fair agreement
- In the $\Lambda(1405)$ case, isospin interference is clearly evident at lower W
- Publications: Differential Photoproduction Cross Section of the $\Sigma^0(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$, K. Moriya, R. A. Schumacher *et al.* (CLAS Collaboration) submitted to Phys. Rev. C; arXiv:1305.6776 [nucl-ex]
  - Also: Measurement of the $\Sigma\pi$ Photoproduction Line Shapes Near the $\Lambda(1405)$ K. Moriya, R. A. Schumacher *et al.*, Phys. Rev. C 87, 035206 (2013)

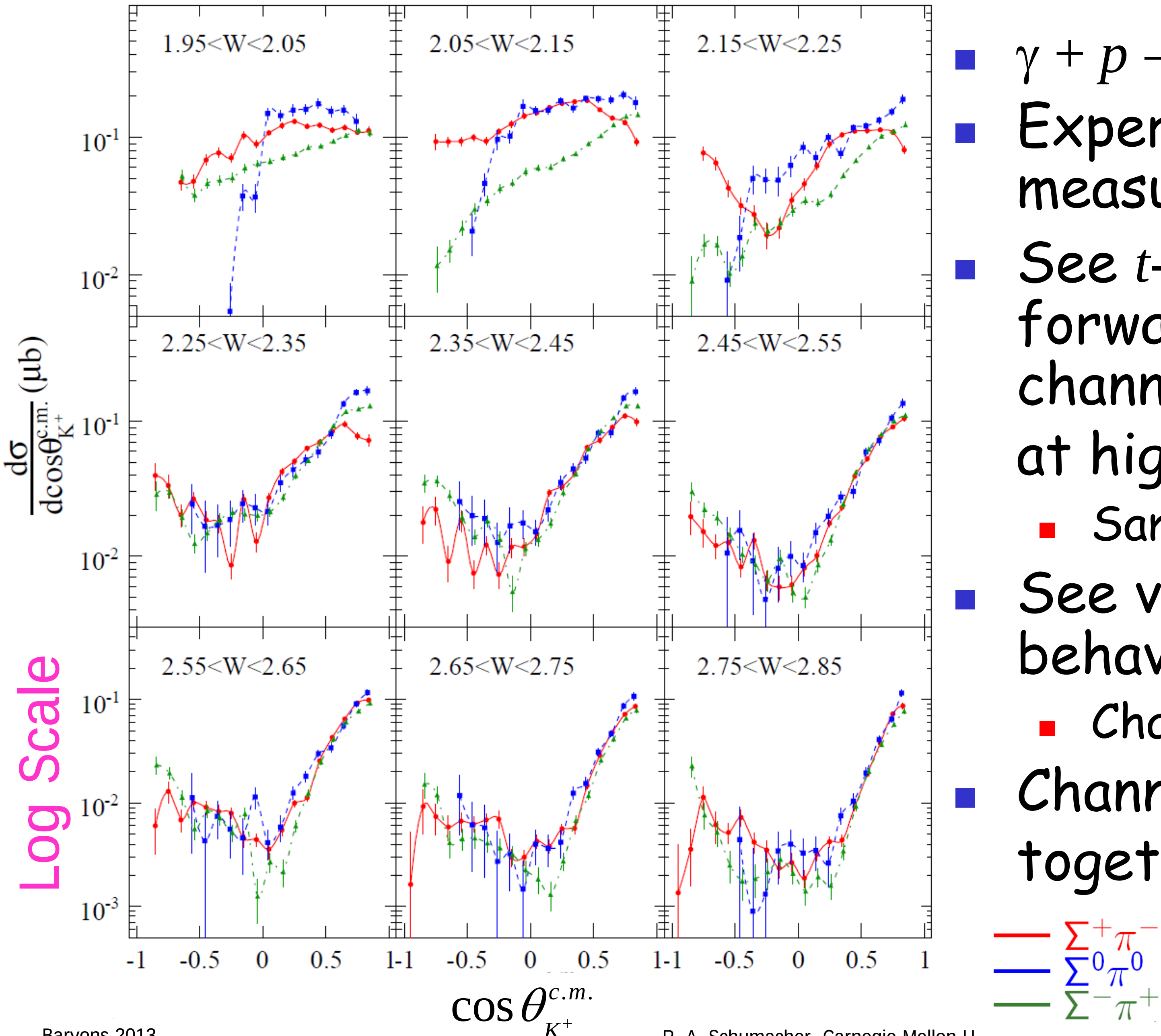
Supplemental Slides

Removing the K* Incoherently



- $\Sigma^+ \pi^-$ line shape data for <u>worst case</u> overlap at W=2.2 GeV
- No significant change in result, despite very "wide" K* removal: no coherence seen
- Method tested on the $\Sigma^0(1385) \rightarrow \Sigma\pi$ channel

Differential Λ(1405) Cross Section



- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- Experiment: first-ever measurements
- See t-channel-like forward peaking & u-channel backward rise at high W
  - Same as other hyperons
- See very different behavior at low W
  - Charge channels differ
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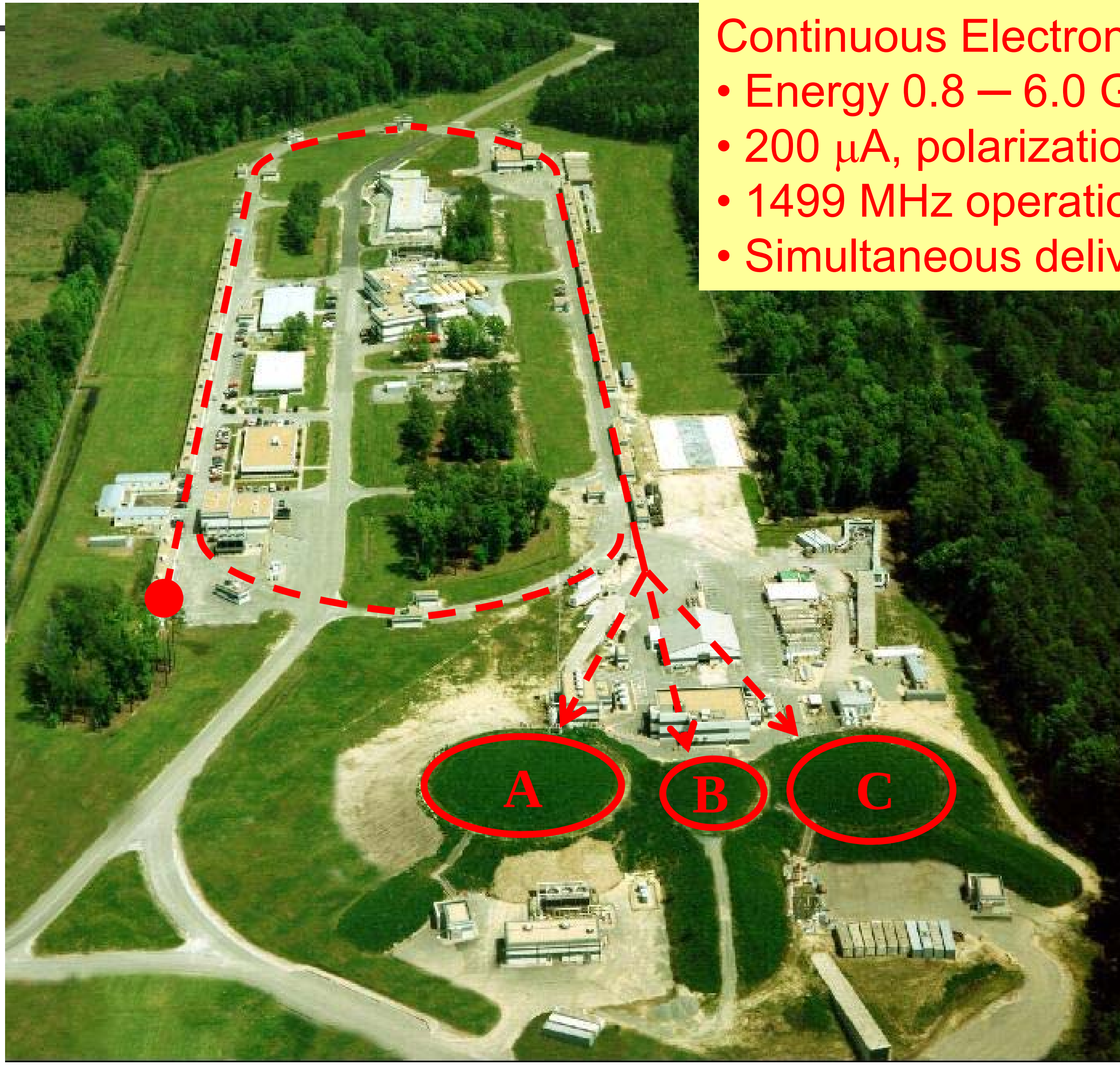
CEBAF accelerator at JLab



Continuous Electron Beam
- Energy 0.8 – 6.0 GeV
- 200 μA, polarization 75%
- 1499 MHz operation
- Simultaneous delivery 3 halls

What is CLAS?

- Most versatile detector system at Jefferson Lab
- Beams of up to 6 GeV real photon and electrons (→virtual photons) on hydrogen or light nuclear targets
- Detect multiple particles per “event”
- ~200 physicists from
  ~35 institutions from
  ~8 countries

The CLAS Detector in Hall B

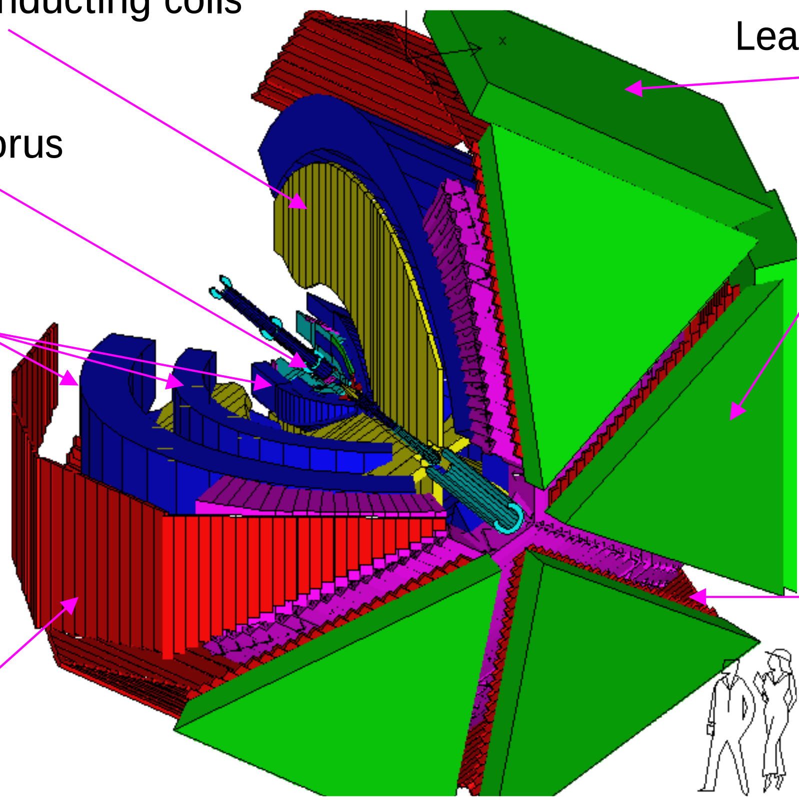
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Liquid H_2 target +
γ start counter; e minitorus

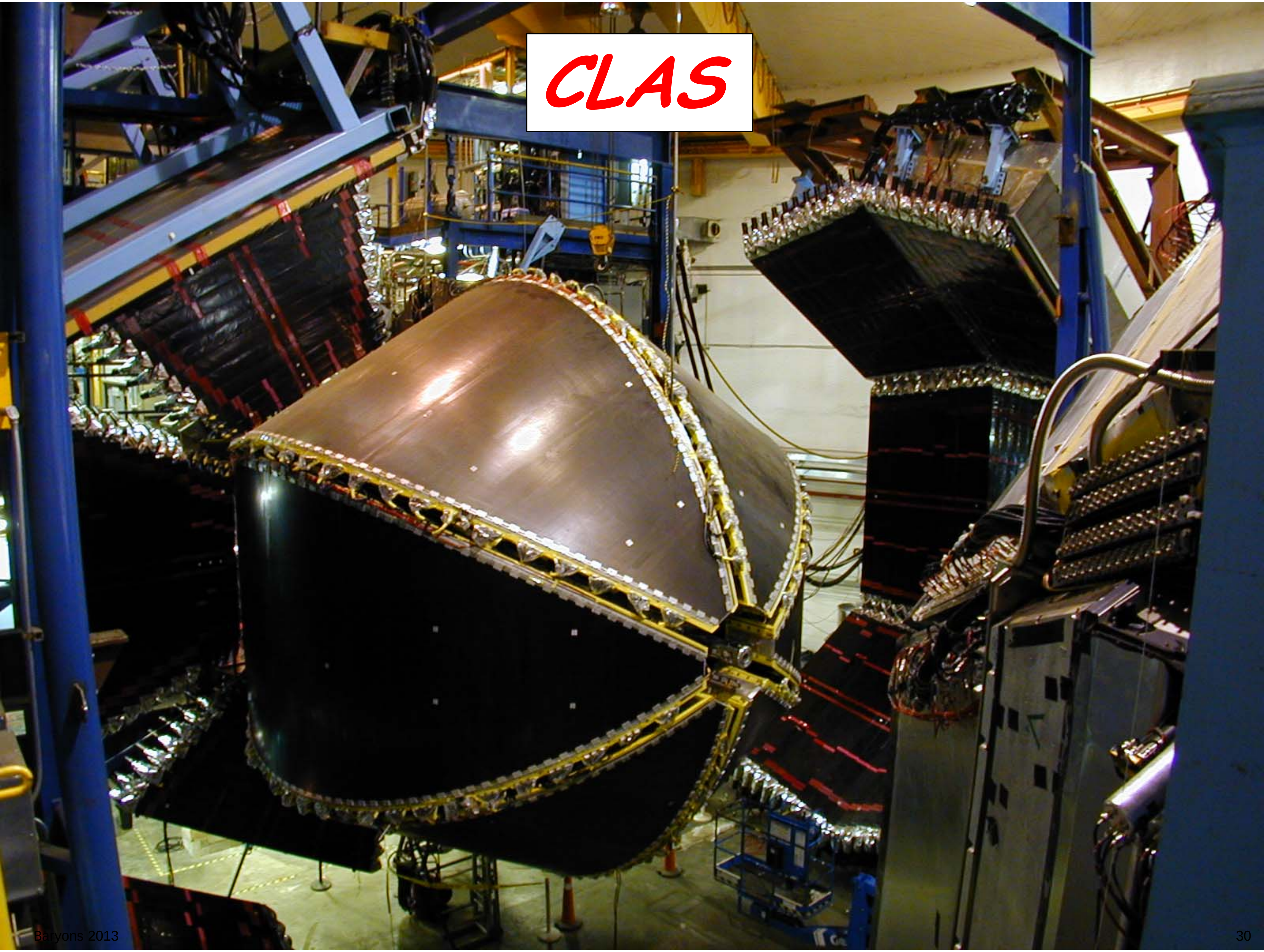
Drift chambers
argon/CO_2 gas, 35,000 cells



Gas Cherenkov counters
e/π separation, 256 PMTs

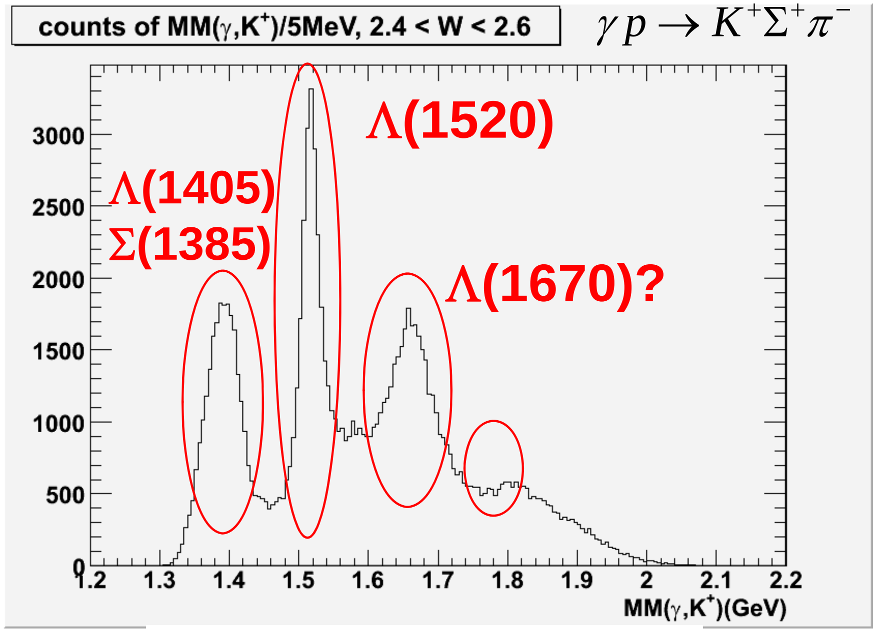
Time-of-flight counters
plastic scintillators, 684 photomultipliers

CLAS



What "is" the Λ(1405)?

- Structure – an issue since its discovery
  - SU(3) singlet 3q state
    I=0, $J^\pi = \frac{1}{2}^-$
  - $\bar{K}N$ sub-threshold bound state
  - Gluonic $J^\pi = \frac{1}{2}^+$ hybrid (udsg)
    - O. Kittel & G.R.Farrar hep-ph/0010186
  - 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).



(γ,K) Missing Mass (GeV)

Nature of the $\Lambda(1405)$?

- 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).
  - E. Oset and A. Ramos, Nucl. Phys. A **635**, 99 (1998).
  - Very many others…
- Quark model genuine three quark state
  - C. G. Wohl, Phys. Lett. B **667** 1182 (2008) RPP…. But statement is deleted in (2012) RPP.
  - S. Capstick & N. Isgur, Phys. Rev. D**34** 2809 (1986).
- $\bar{K}N$ sub-threshold bound state
  - Y. Akaishi & T. Yamazaki, Phys Rev 65, 044005 (2002).

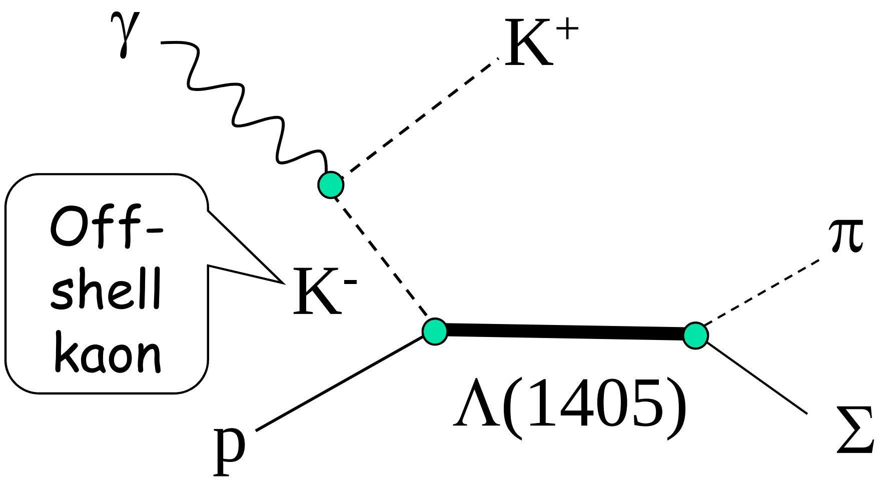
Nature of the $\Lambda(1405)$? (2)

- Two-pole, I=0, S=-1, solution to the chiral unitary scattering problem $\pi\Sigma$ … $\bar{K}N$ … MB …
  - J.A. Oller, U.-G. Meissner Phys. Lett B **500**, 263 (2001).
  - D. Jido, J.A. Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A **725**, 181 (2003).

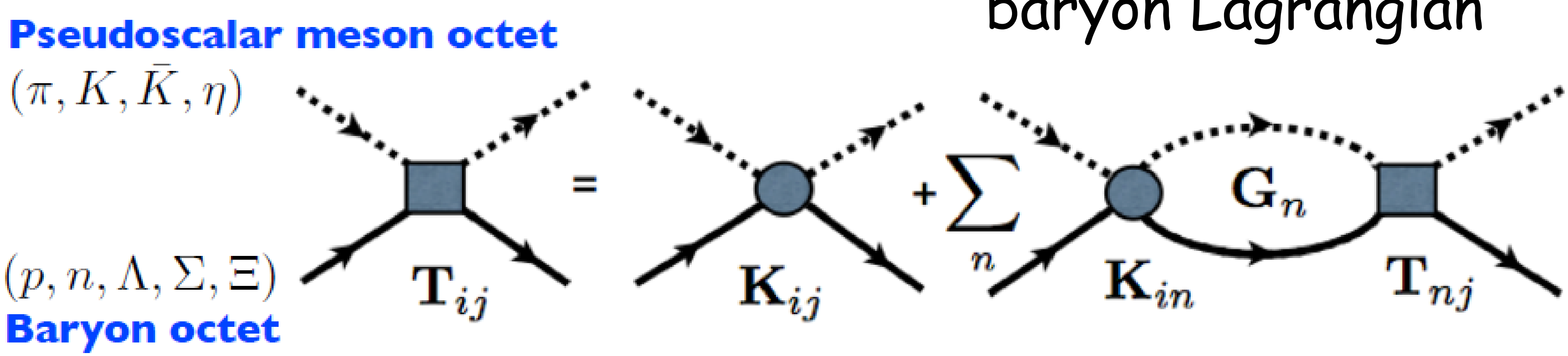
- 5-quark cluster model: $|B\rangle = c_1|qqq\rangle + c_2|qq\,qq\,\bar{q}\rangle$
  - B. Zou, Nucl. Phys. A **835**, 199 (2010). Predicts extra $\frac{1}{2}^-$ baryon nonet with a Σ^* at 1380

- Hybrids: udsg, udcg with “active” glue
  - O. Kittel & G. Farrar, hep-ph/0010186(2000); /0580815(2005)

Chiral Unitary Approach



- Chiral perturbation theory fails in the presence of strong threshold effects
- K_{ij} kernel from chiral SU(3) effective meson-baryon Lagrangian



$$\mathbf{T} = \mathbf{K} + \mathbf{K}\,\mathbf{G}\,\mathbf{T} = (1 - \mathbf{K}\,\mathbf{G})^{-1}\,\mathbf{K}$$

Leading s-wave I=0 interaction: “Weinberg-Tomozawa” driving term

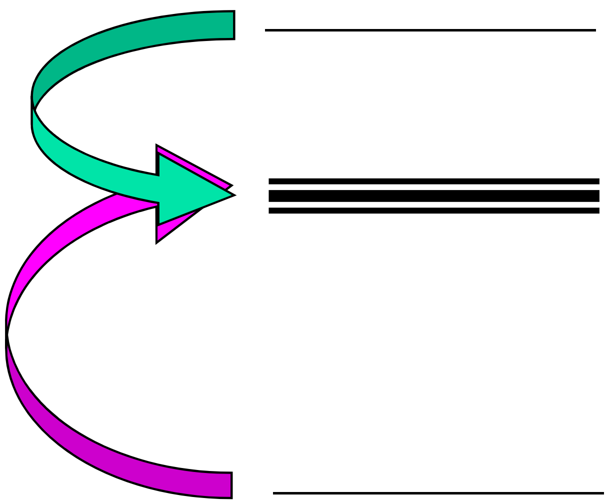
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A 594, 325 (1995)

Dynamical State Generation

Do the "ground state" mesons and baryons attract strongly enough to form meson-baryon "molecular" bound states or unbound resonances?

Bound state

Resonance

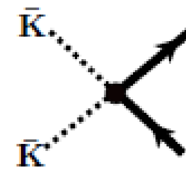


$\bar{K}N$

$\Lambda(1405)$

$\Sigma\pi$

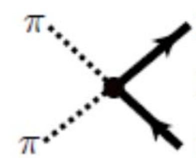
$|1\rangle = |\bar{K}N, I = 0\rangle$



$$K_{11} = \frac{3}{2f^2}(\sqrt{s} - M_N)$$

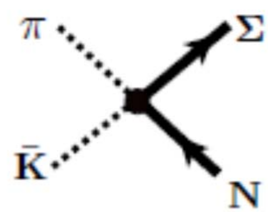
From chiral SU(3) effective field theory

$|2\rangle = |\pi\Sigma, I = 0\rangle$



$$K_{22} = \frac{2}{f^2}(\sqrt{s} - M_\Sigma)$$

Channel Coupling:



$$K_{12} = \frac{-1}{2f^2}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_N + M_\Sigma}{2}\right)$$

Graphic: W. Weise

Chiral Unitary Models (example 1)

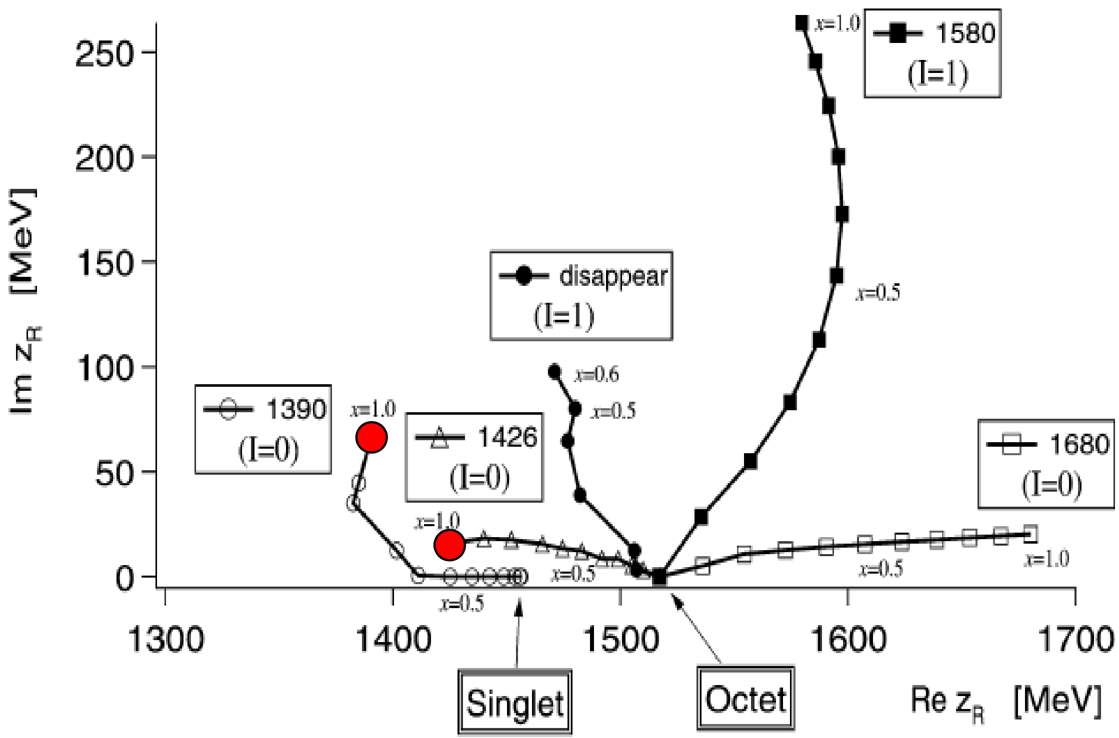


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

- 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).

Chiral Unitary Models (example 2)

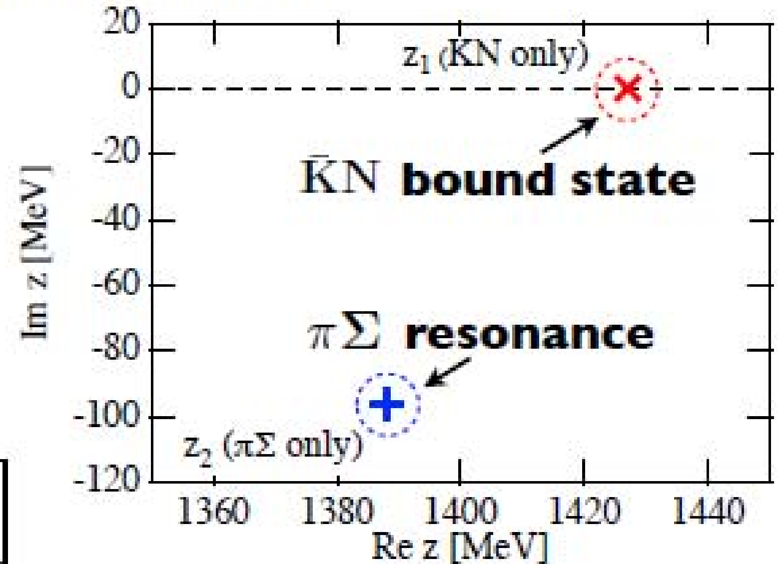
The TWO POLES scenario

D. Jido et al.
Nucl. Phys. A725 (2003) 181

T. Hyodo, W.W., Phys. Rev. C77 (2008) 03524

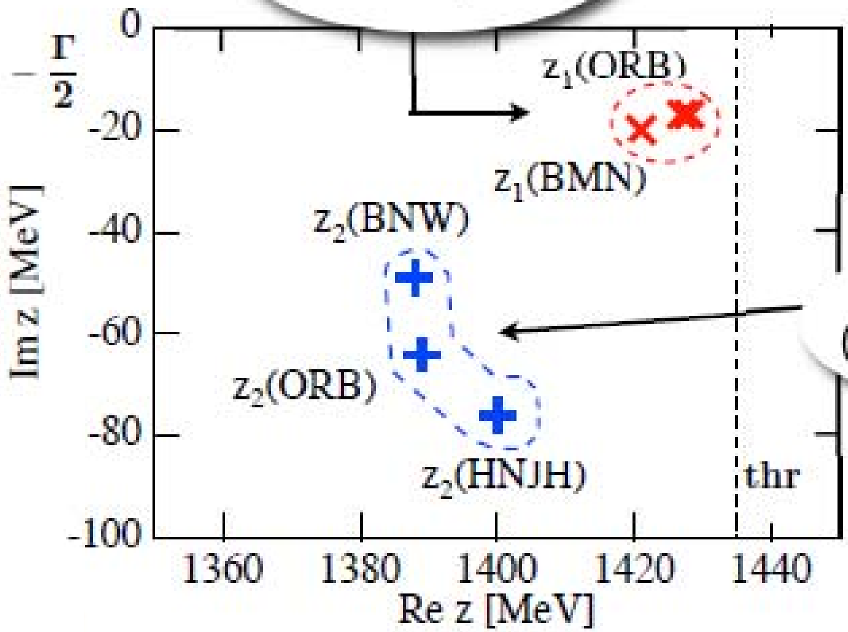
- Singularities of $\bar{K}N$ amplitude in the complex energy plane

starting point:
no channel coupling ▶

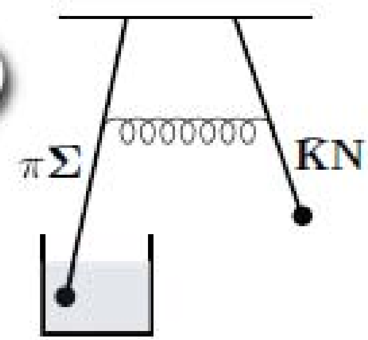


◀ **channel coupling** at work

Pole I
(dominantly $\bar{K}N$)



Pole II
(dominantly $\pi\Sigma$)



Graphic: W. Weise

Getting the three final states:

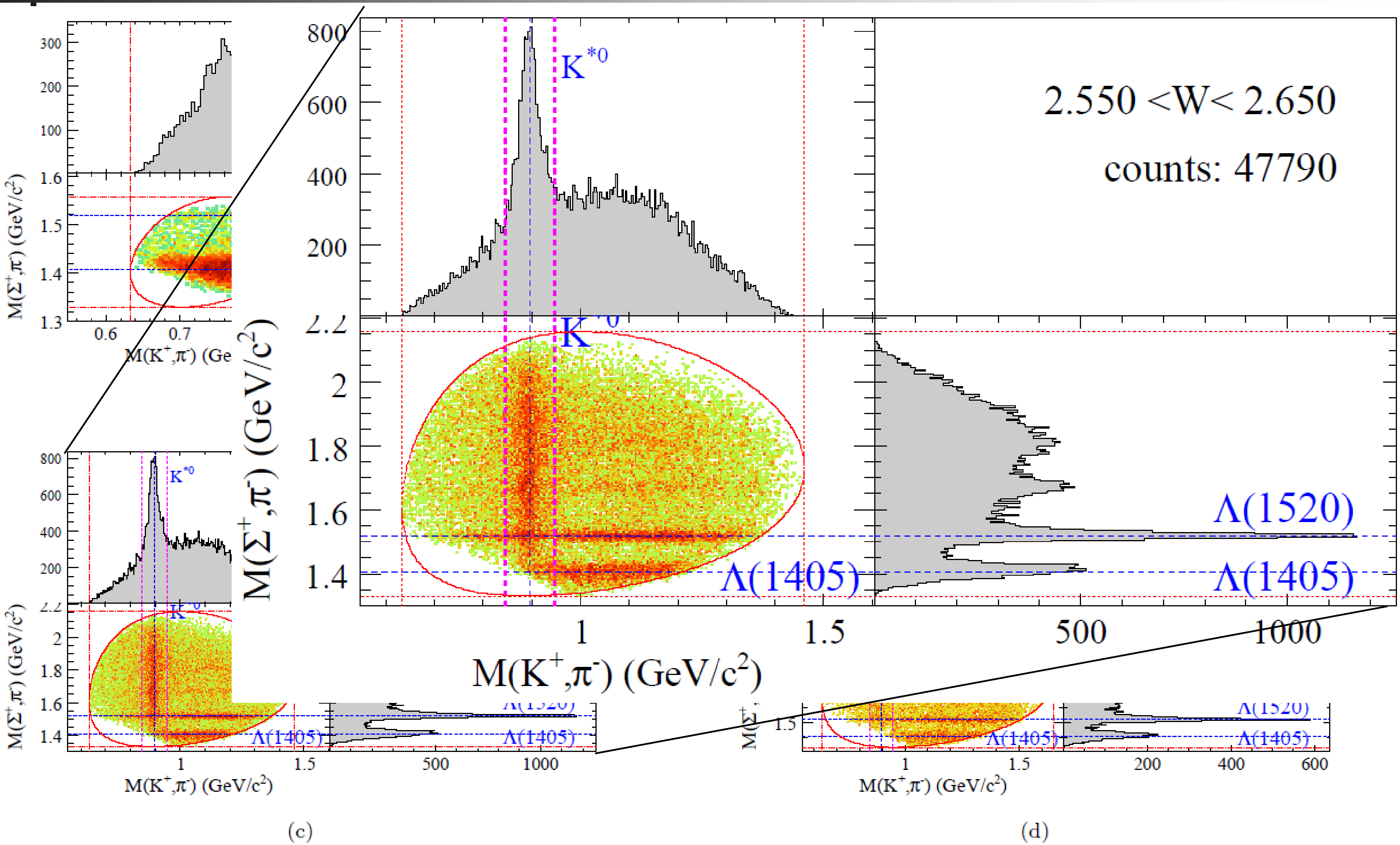
$\gamma + p \rightarrow K^{+} + \Lambda(1405)$ — CLAS Events

				CLAS Events
33%	$\Sigma^{-}\pi^{+}$	$\rightarrow \pi^{-}(n)\,\pi^{+}$		338k
33%	$\Sigma^{+}\pi^{-}$	$\rightarrow p(\pi^{0})\,\pi^{-}$	52%	440k
		$\rightarrow \pi^{+}(n)\,\pi^{-}$	48%	316k
33%	$\Sigma^{0}\pi^{0}$	$\rightarrow \Lambda(\gamma\,\pi^{0})$		76k

$\gamma + p \rightarrow K^{*+,0} + \Sigma^{0,+}$ Subtracted incoherently bin by bin using Monte Carlo model

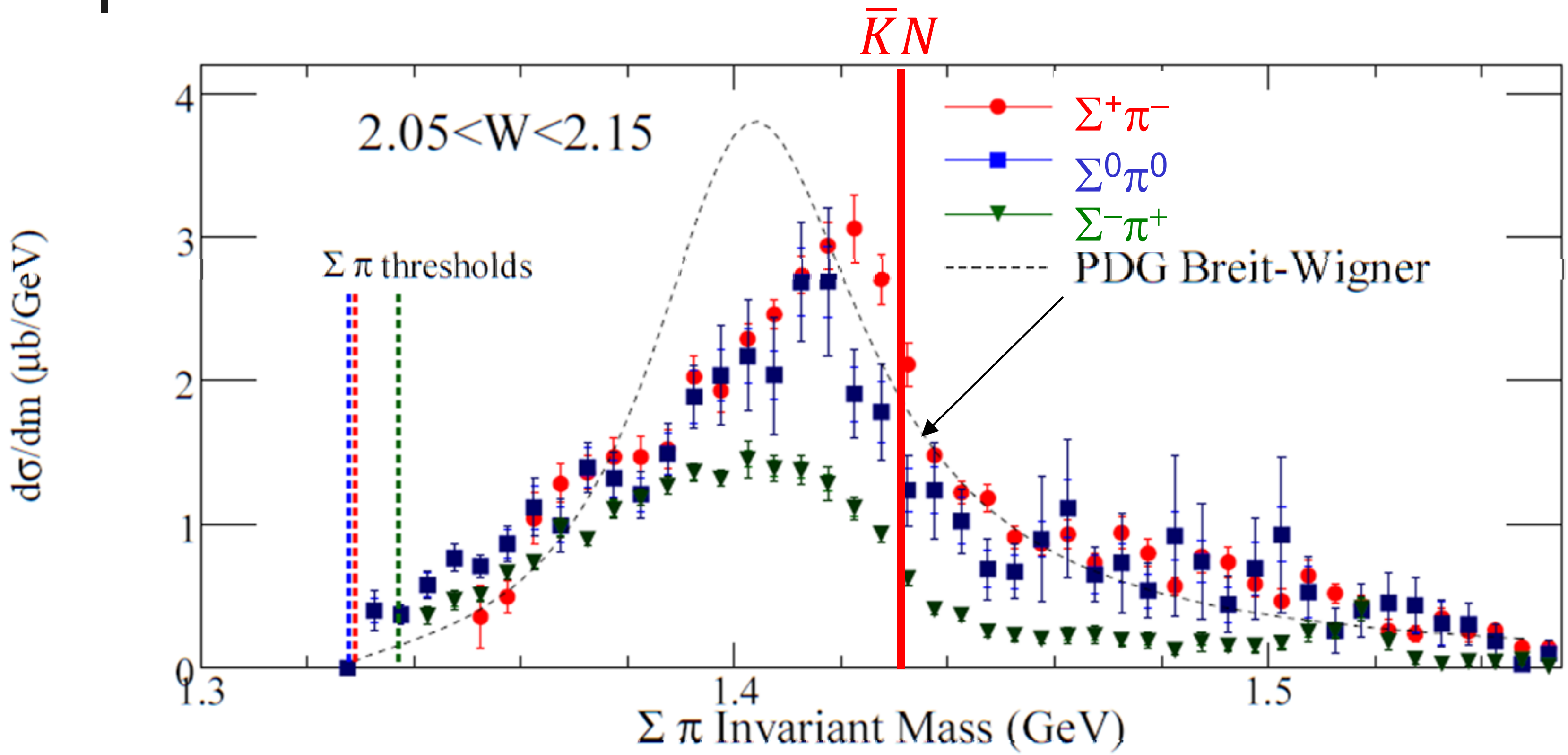
Quark model expectation: equally-strong decays to each of three $\Sigma\pi$ states, with Breit-Wigner mass distributions

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



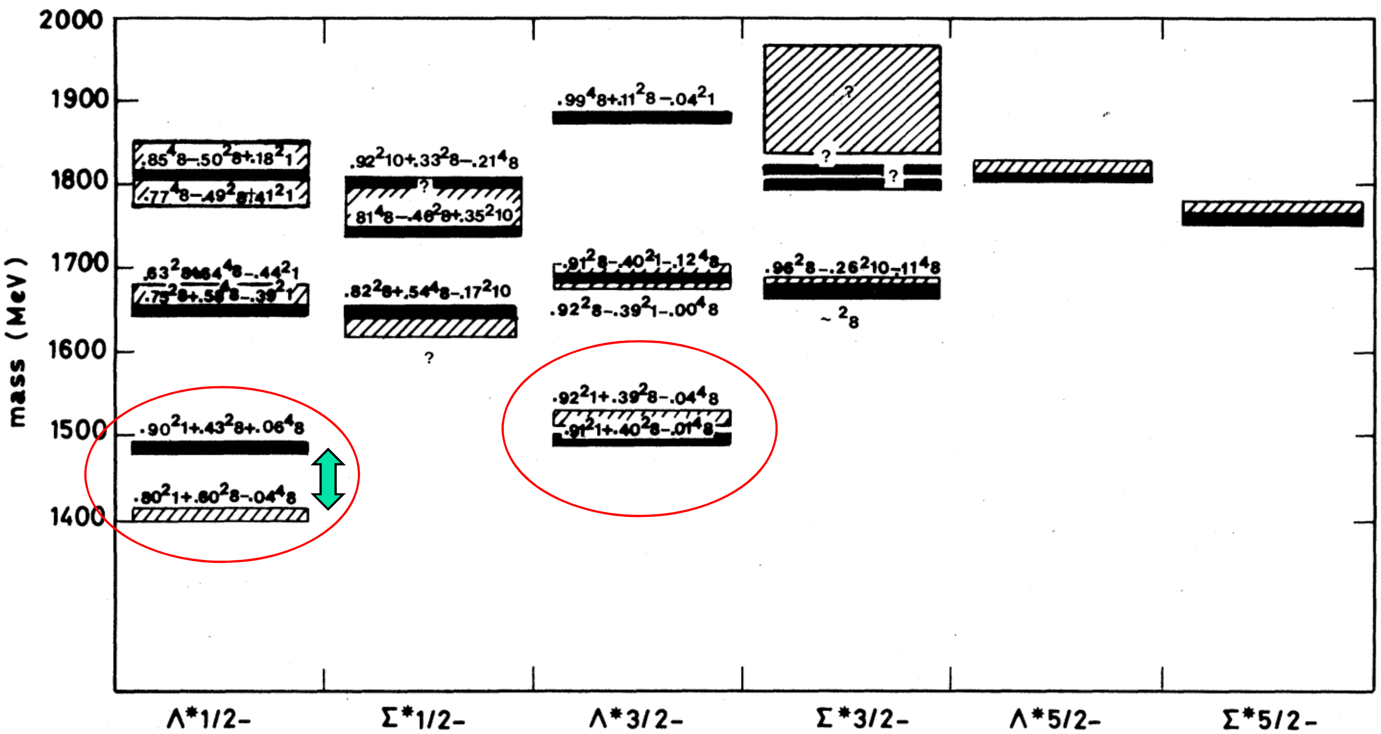
Note K* overlap: must be subtracted in some W bins

CLAS Result for Σπ Line Shape



- Decay-channel asymmetry of Λ(1405) line shape confirmed
- Line shapes are not Breit-Wigner and depend on charge
- Subtracted backgrounds: Σ^0(1385), Λ(1520), K^*(892)

Constituent Quark Model



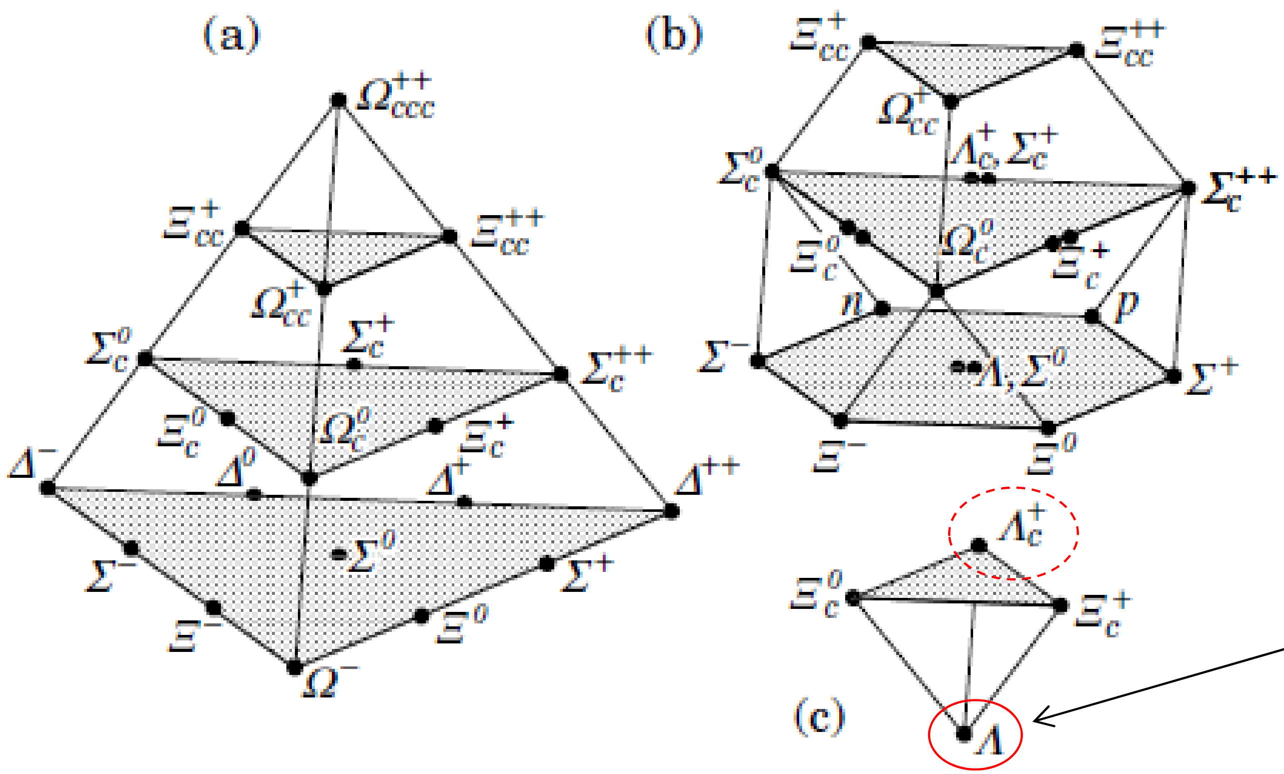
- QM is not "fund-amental" QCD, but a good classification scheme
- Harmonic oscillator basis
- Spin-dependent hyperfine quark-quark interaction

- P-wave baryons well-described *except* for the Λ(1405)
  - ½ ⁻ and 3/2 ⁻ states should be almost degenerate at ~1490 MeV
  - ~80 MeV discrepancy in mass
- Discrepancy may be due to
  - $\overline{K}N$ threshold nearby, or
  - neglect of higher Fock space components: $qqq \rightarrow qqq\,q\bar{q}$

S. Capstick & N. Isgur, Phys. Rev. D**34** 2809 (1986)

N. Isgur & G. Karl, Phys. Rev. D**18** 4187 (1978)

Strange/Charm Analogs



- Flavor SU(4) multiplets for u, d, s, c baryons
  - (a) 20′-plet with SU(3) decuplet at lowest level
  - (b) 20′-plet with SU(3) octet at lowest level
  - (c) $\Lambda(1405)$ is part of $\overline{4}$-plet of $\frac{1}{2}^-$ baryons

C. G. Wohl, Phys. Lett. B **667** 1182 (2008) PDG.

Strange/Charm Analogs

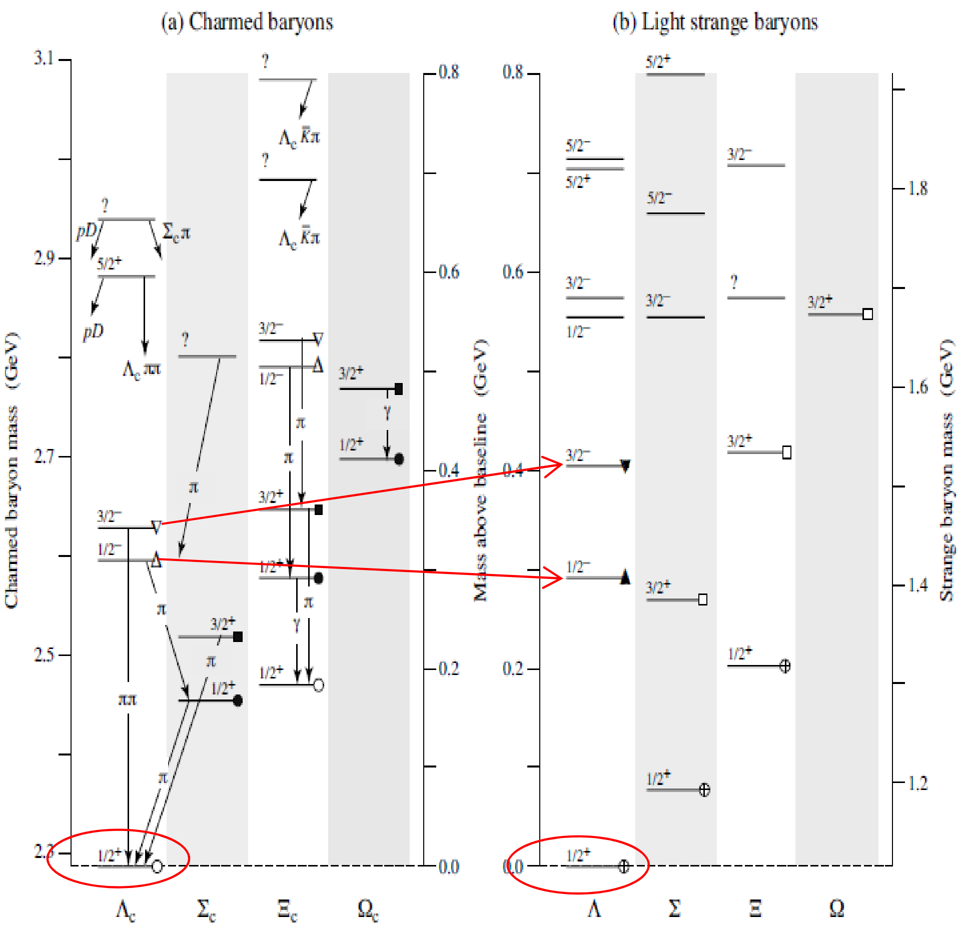


Fig. 1. (a) The known charmed baryons, and (b) the lightest "4-star" strange baryons. Note that there are two $J^P = 1/2^+$ Ξ_c states, and that the lightest Ω_c does not have $J = 3/2$. The $J^P = 1/2^+$ states, all tabbed with a circle, belong to the SU(4) multiplet that includes the nucleon; states with a circle with the same *fill* belong to the same SU(3) multiplet within that SU(4) multiplet. Similar remarks apply to the other states: same shape of tab, same SU(4) multiplet; same fill of that shape, same SU(3) multiplet. The $J^P = 1/2^-$ and $3/2^-$ states tabbed with triangles complete two SU(4) $\bar{4}$ multiplets.

- Charm and Strange baryons spectra look similar
- Excited states Λ_c*(2593) $1/2^-$ and Λ_c*(2625) $3/2^-$ map to excited states Λ(1405) and Λ(1520)
- Suggests Λ(1405) is a "true 3-quark state"…
- …but Λ_c* has no thresholds nearby

C. G. Wohl, Phys. Lett. B **667** 1182 (2008) PDG.