Hyperons: Scaling, N* Resonances, and the $\Lambda(1405)$

Reinhard Schumacher

Carnegie Mellon University

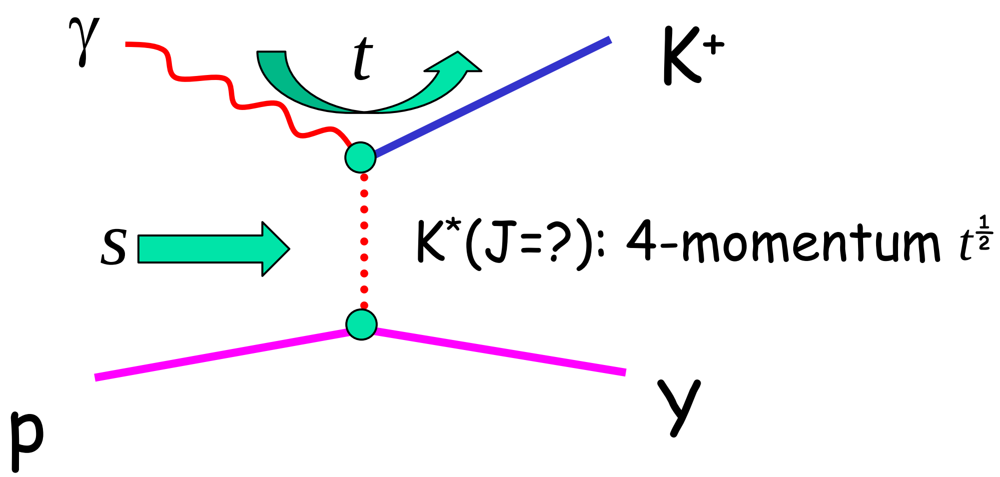
Overview

- "Scaling" of the reaction $\gamma + p \rightarrow K^{+} + \Lambda$
  - Regge scaling at small $-t$
  - Constituent-counting scaling at high $-t$

- N* Resonances seen in Scaled Cross Sections
  - Strong correlations at large angles → interferences
  - Connection to "missing resonance" searches

- Properties of the $\Lambda(1405)$
  - Lineshape reveals compound nature
  - Spin and parity measurement

Regge Scaling at Small -t

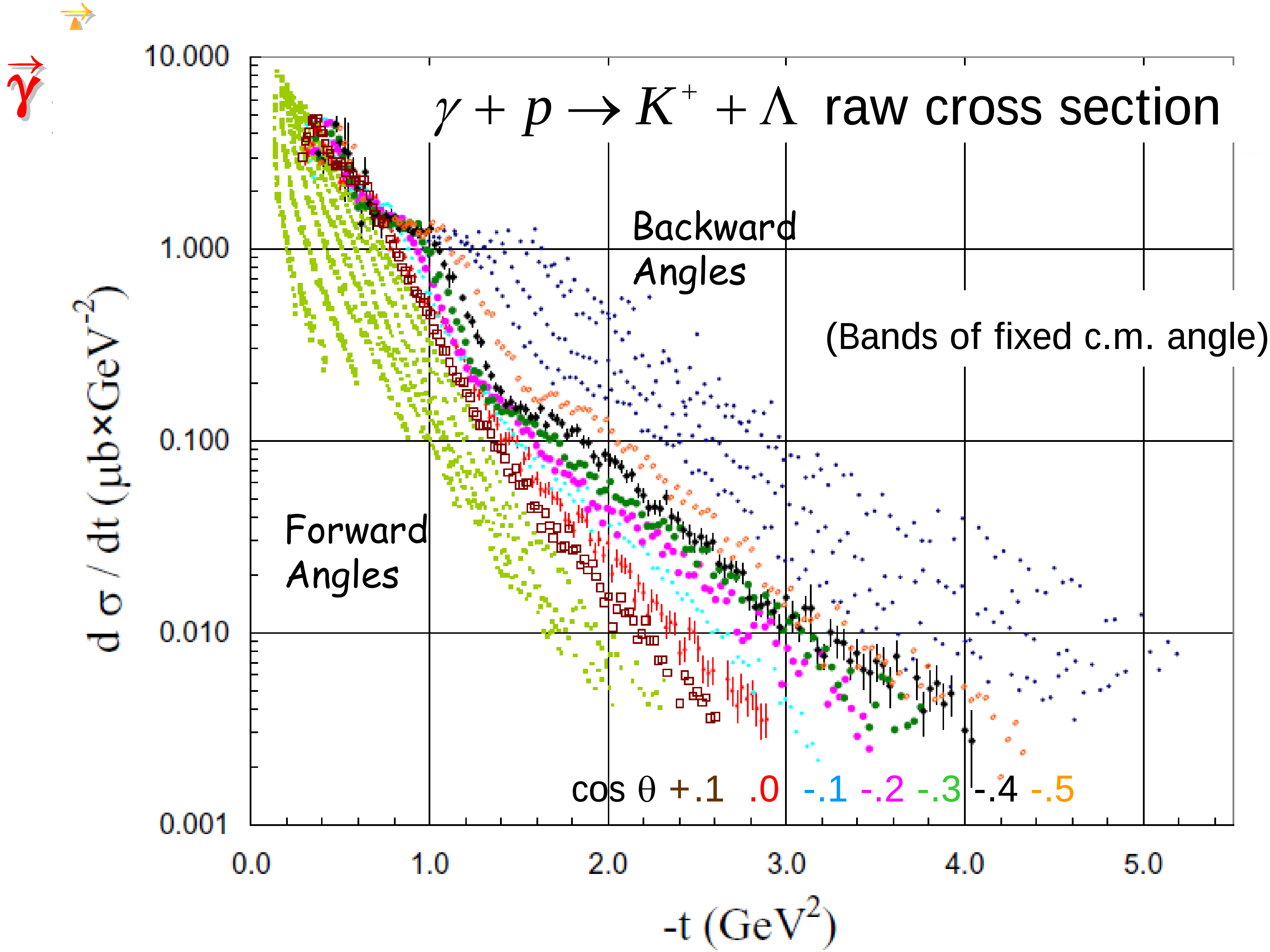


- How does dσ/dt vary with s and $-t$?

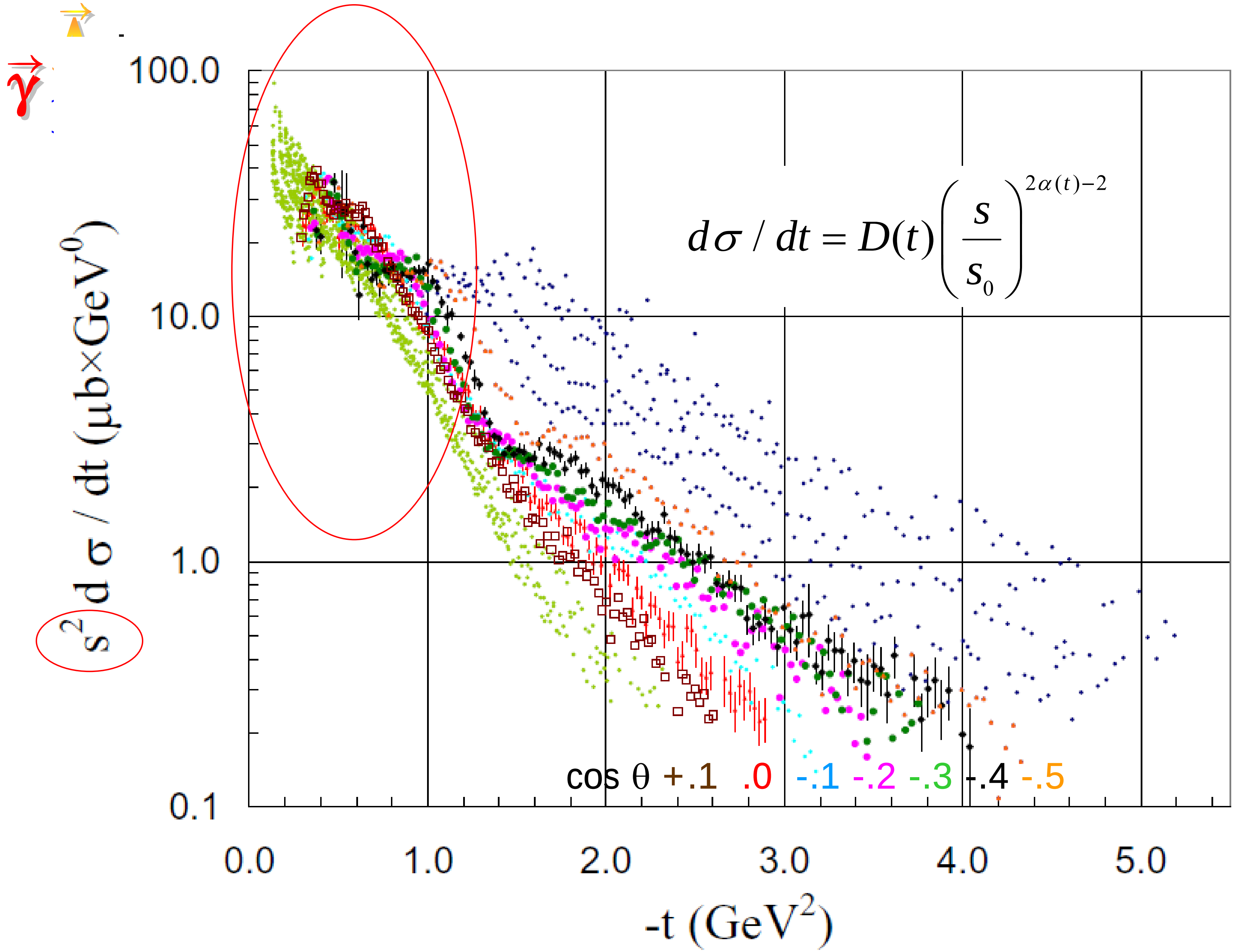
$$d\sigma / dt = D(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

$s = W^2$ invariant mass^2

$\alpha(t) = \alpha_{t=t_{min}} + \alpha' t$ Regge trajectory



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


100.0
10.0
1.0
0.1
0.0
1.0
2.0
3.0
4.0
5.0
$s^2 d\sigma / dt$ (μb×GeV^0)
-t (GeV^2)
$d\sigma / dt = D(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$
cos θ +.1 .0 -.1 -.2 -.3 -.4 -.5

Regge Scaling at Small $-t$

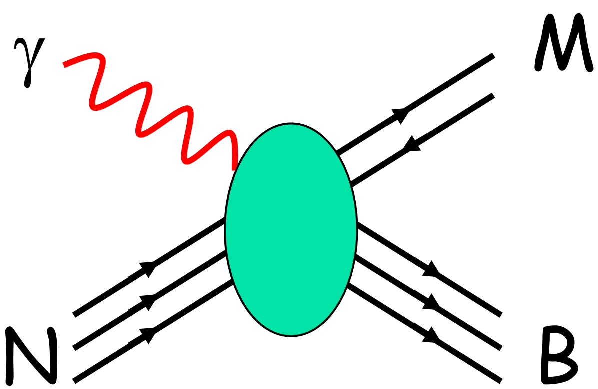
- Observation of approximate s^{-2} "Regge scaling" implies that

$$\alpha_{eff} = \alpha_{K^+} + \alpha_{K^*(892)} \approx 0, \text{ for } t \to 0$$

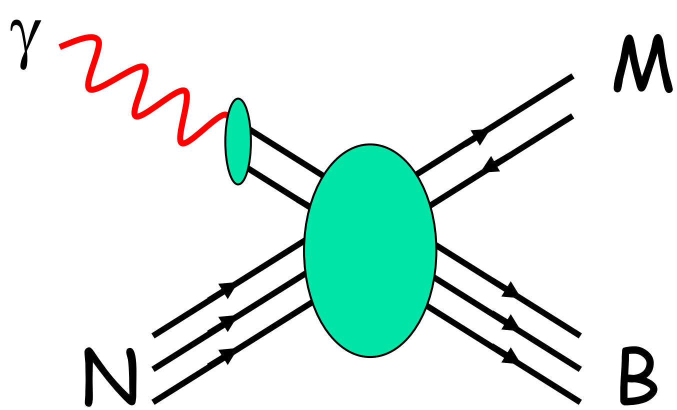
- Model calculation of $\alpha(t)$ remains as an open task…
- We move on to more dramatic phenomonology…

Constituent-Counting Scaling

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



$n=9$

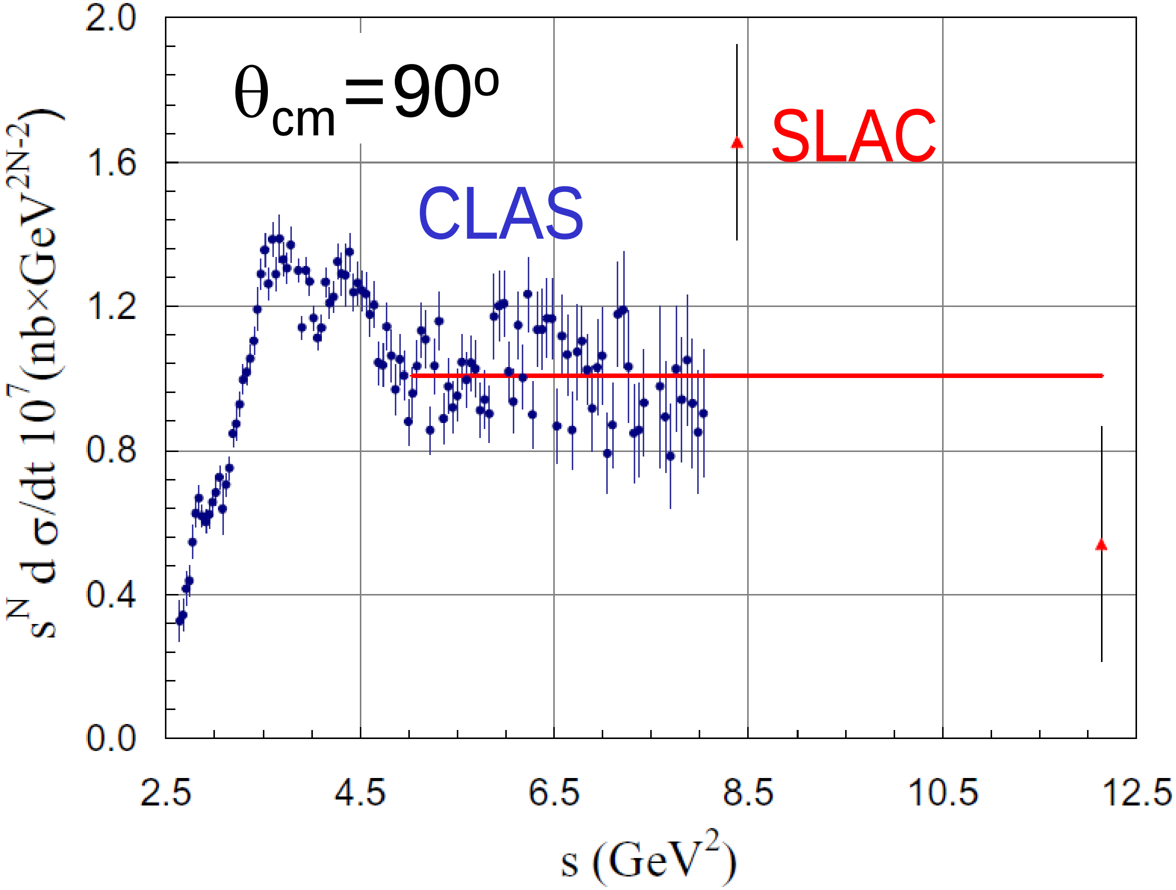


$n=10$

- Constituent counting rules for exclusive scattering
- "Valid" for $s \rightarrow \infty$ and t/s fixed
  - $t/s \sim \cos(\theta_{cm})$ as $s \rightarrow \infty$
- n = number of point-like constituents
- Follows from pQCD

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

Scaling Power Determination



- Optimize N in a fit of s^{-N} scaling
- Best fit:
  $N = 7.1 \pm 0.1$
- χ^2_ν = 92/60: fair fit
- Supports hypothesis of photon as a single bare elementary field
- Assume $N \equiv 7$ henceforth…

R.A. Sch. and M.M. Sargsian Phys. Rev. C**83** 025207 (2011). R. L. Anderson *et al.*, Phys. Rev. **D 14**, 679 (1976)

Scaling in Pion Production

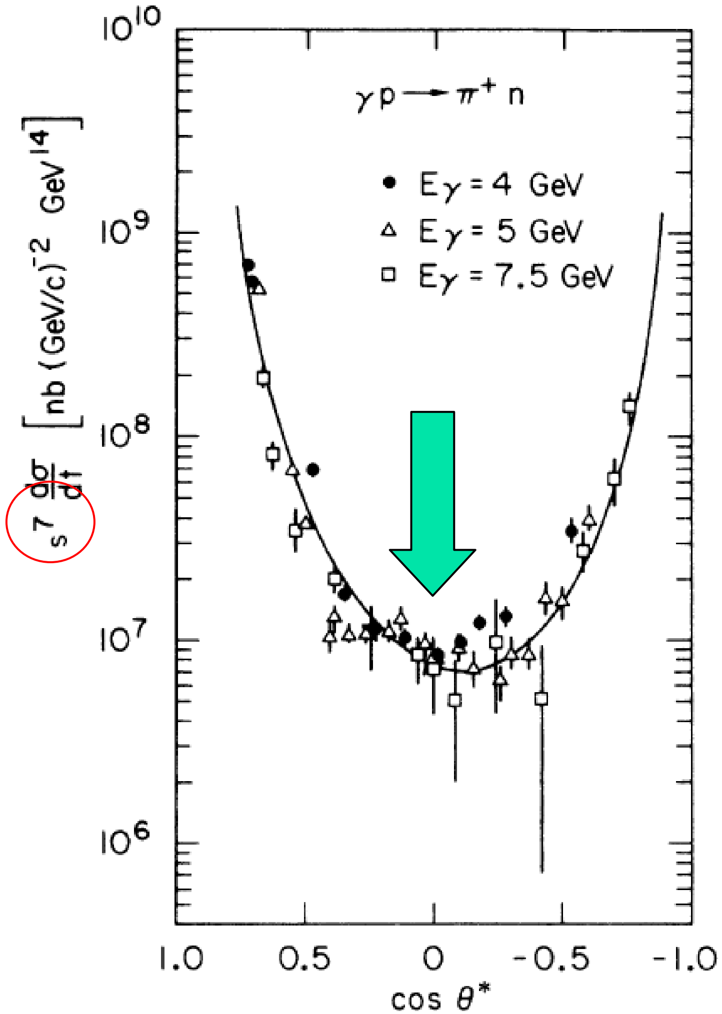
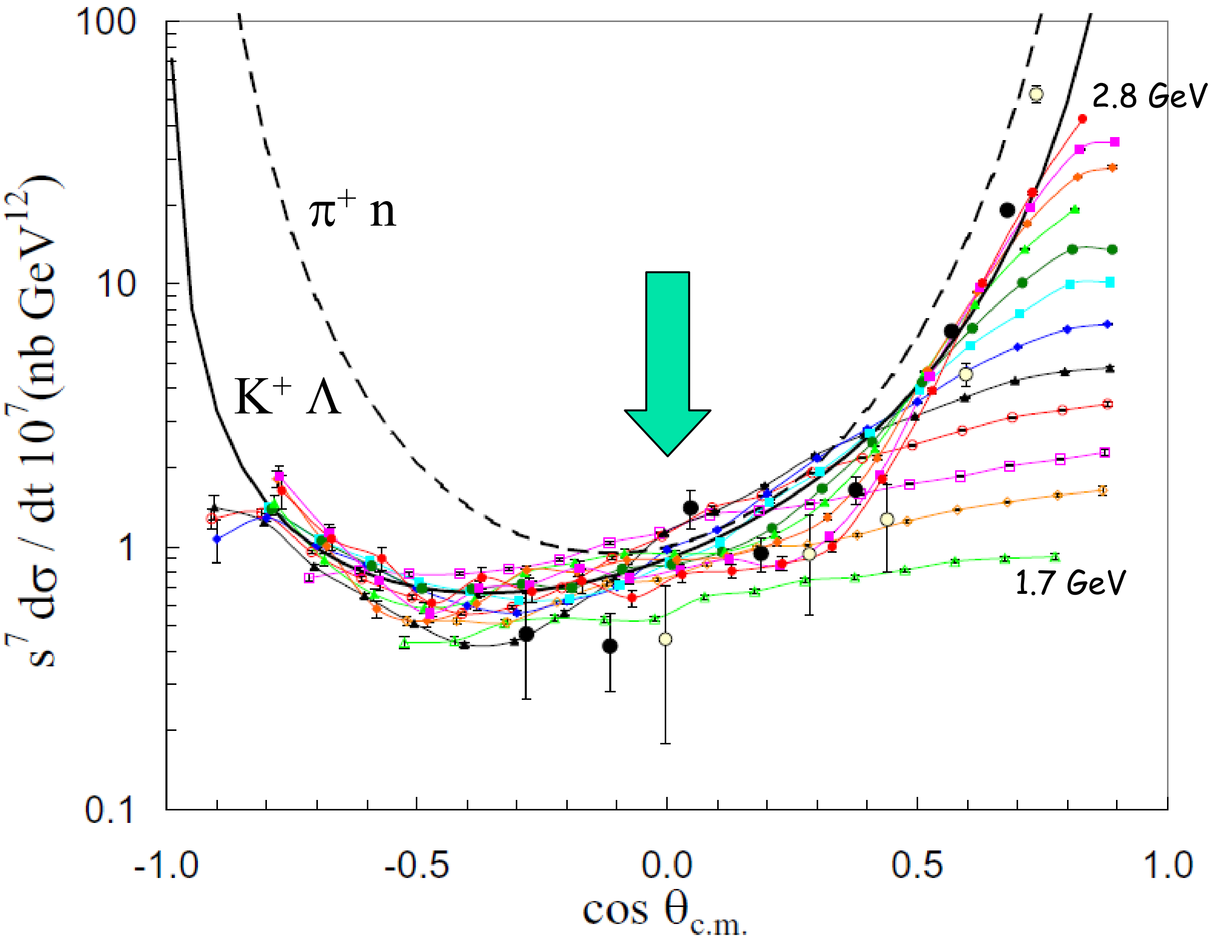


FIG. 6. $s^7 d\sigma/dt$ versus cosθ^* for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where ($z = \cos\theta^*$), which is an empirical fit to the angular distribution.

- "perturbative QCD" scaling at SLAC
- s^{-7} scaling found to "work" for $\gamma p \to \pi^+ n$, $\pi^0 p$, $\pi^- \Delta^{++}$, $\rho^0 p$, and maybe KY
- The curve is totally ad hoc
- Expect the best evidence for scaling near 90°

R. L. Anderson *et al.*, Phys. Rev. **D 14**, 679 (1976)

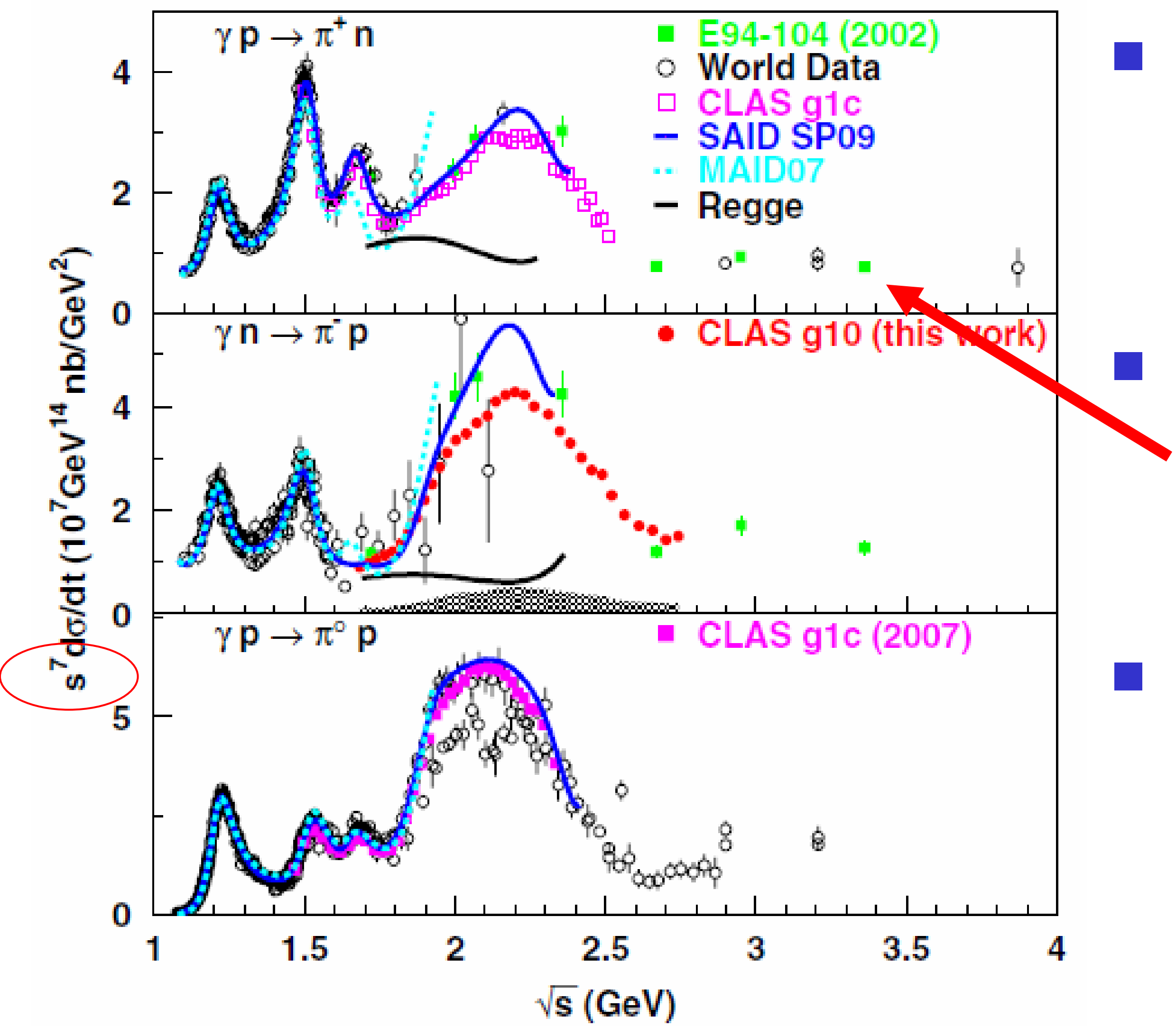
Evidence for s^{-7} Scaling…



- CLAS: 100 MeV wide bins in W
  - Green 1.7 GeV
  - Red 2.8 GeV
- SLAC:
  - Black 2.9 GeV
  - White 3.5 GeV
  - CLAS &SLAC show good agreement
- s^{-7} scaling happens for W > about 2.3 GeV
- Pions and Kaons scale to same value near 90°
  - Interesting: are the quark mass differ-ences irrelevant?

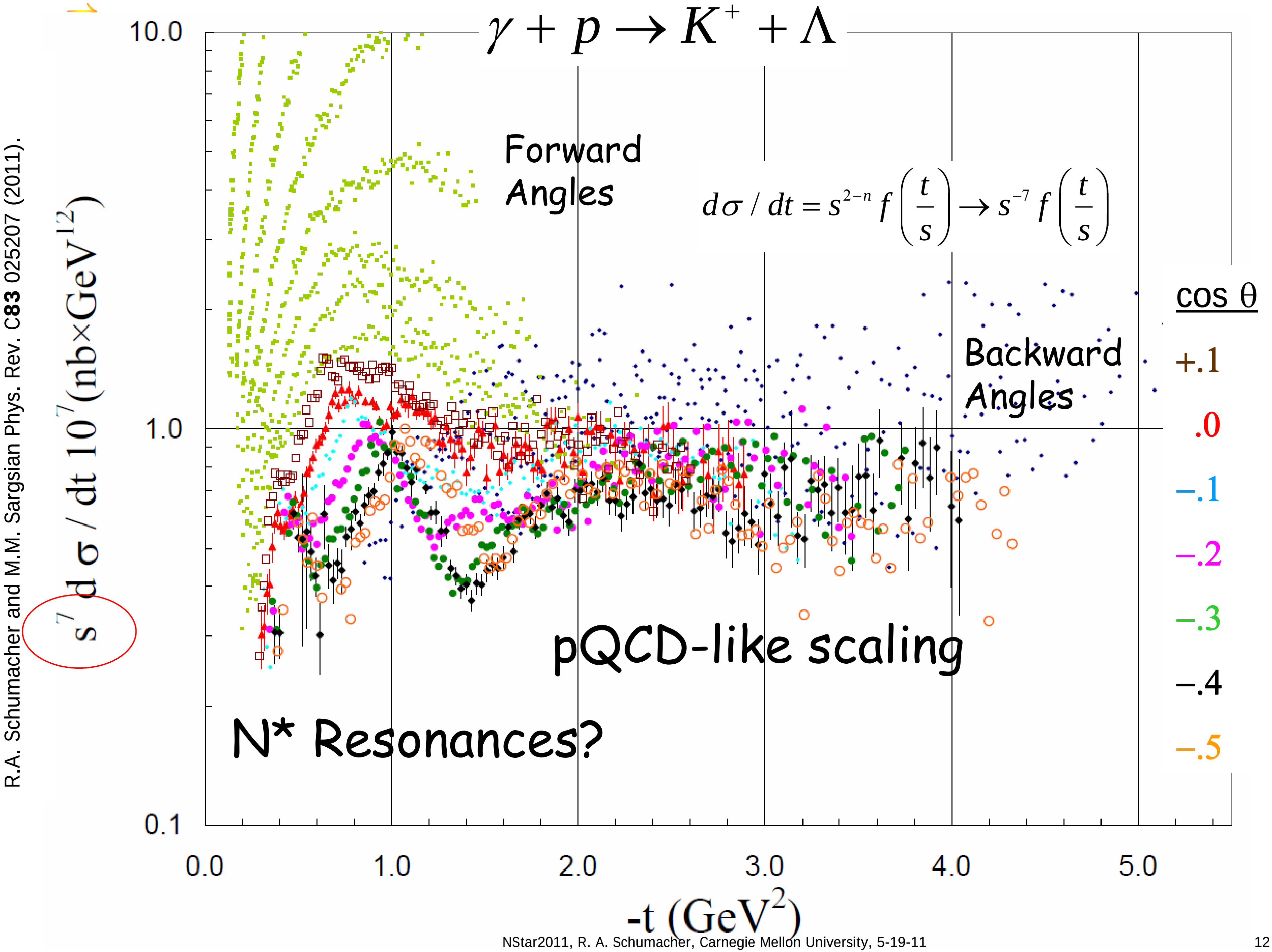
R. L. Anderson *et al.*, Phys. Rev. **D 14**, 679 (1976)

Scaling in Pion Production



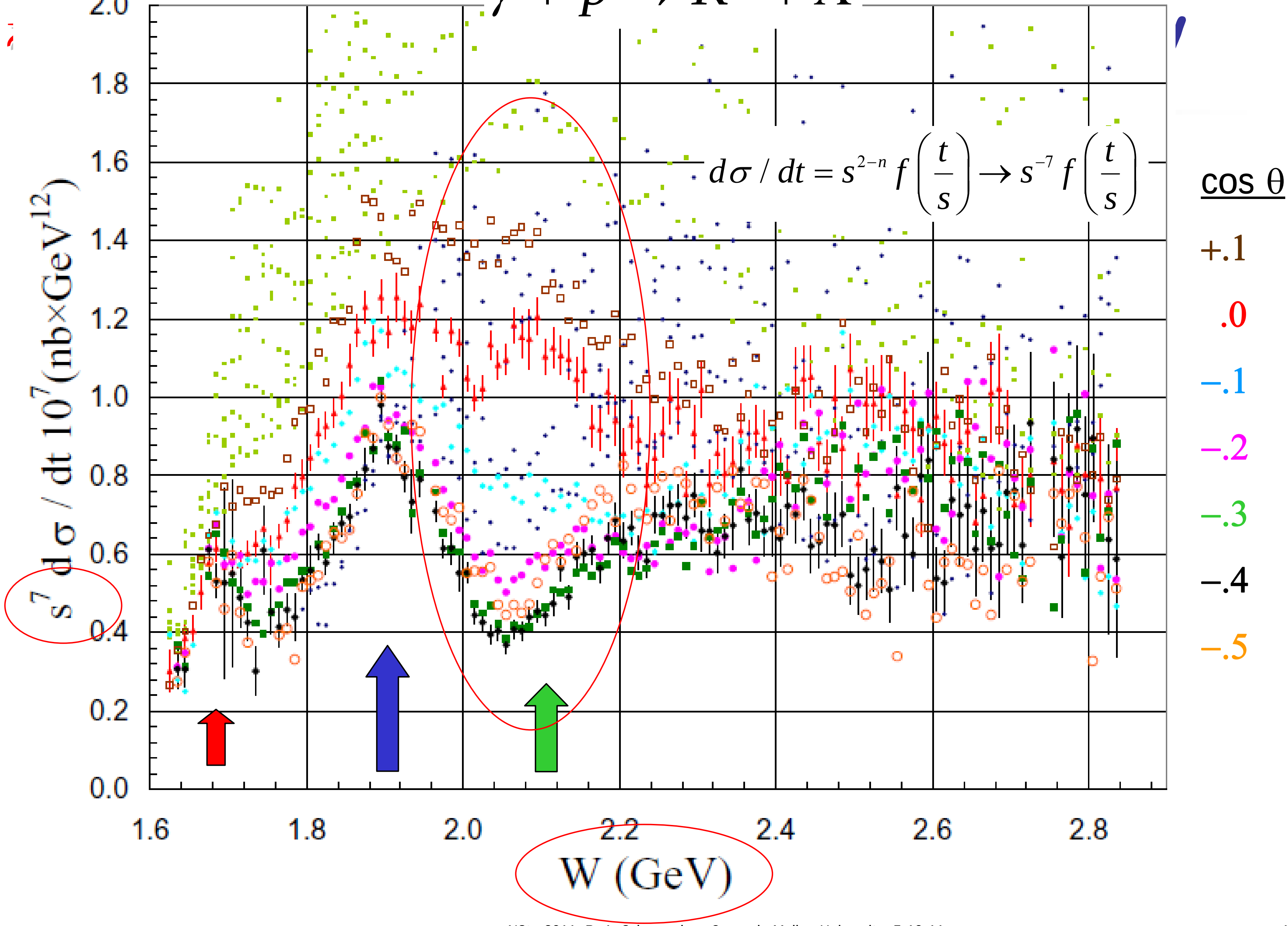
- Three pion channels at 90° vs. W
- pQCD scaling seen for W>2.6 GeV
- N* resonances seen below 2 GeV

W. Chen *et al.* (CLAS), PRL **103**, 012301 (2009)

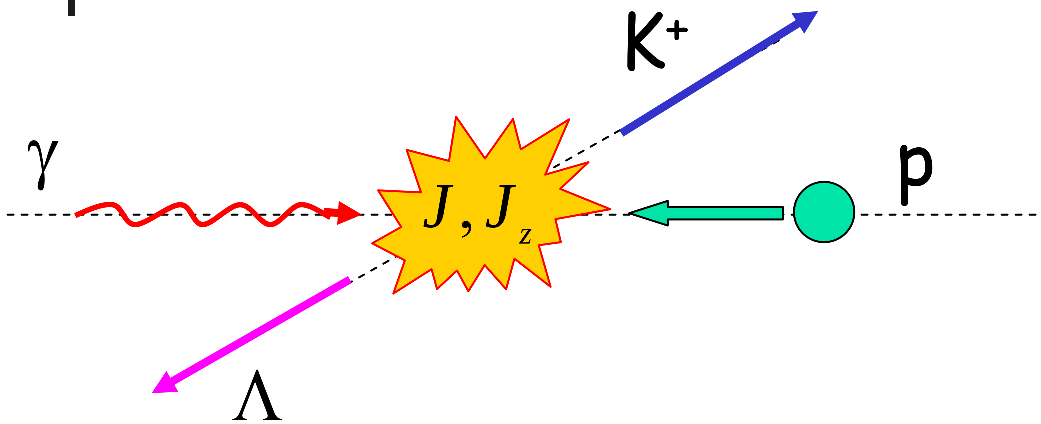


$\gamma + p \rightarrow K^+ + \Lambda$
R.A. Schumacher and M.M. Sargsian Phys. Rev. C83 025207 (2011).
$s^7\, d\sigma / dt\ 10^7 (nb \times GeV^{12})$
10.0
1.0
0.1
0.0
1.0
2.0
3.0
4.0
5.0
-t (GeV^2)
Forward Angles
$d\sigma / dt = s^{2-n} f\left(\frac{t}{s}\right) \rightarrow s^{-7} f\left(\frac{t}{s}\right)$
Backward Angles
cos θ
+.1
.0
−.1
−.2
−.3
−.4
−.5
pQCD-like scaling
N* Resonances?

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



Physics Model



- Quantize along beam axis
- Final state amplitude $\psi_L(J, J_z)$
- $\alpha_{\frac{1}{2},\pm\frac{1}{2}}$ nucleon spinors
- Y_{LM} spherical harmonic of final state

Example: J=3/2 resonance formed in J_z=+1/2 substate, decaying to P-wave

$$\psi_{L=1}\left(J=\frac{3}{2}, J_z=\frac{1}{2}\right) = \left\{\frac{1}{\sqrt{3}} Y_{1,1}\ \alpha_{\frac{1}{2},-\frac{1}{2}} + \frac{2}{\sqrt{3}} Y_{1,0}\ \alpha_{\frac{1}{2},+\frac{1}{2}}\right\} BW_{1/2}(m)$$

Similar expressions for

$$\psi_P\left(\frac{3}{2},\frac{3}{2}\right),\ \psi_D\left(\frac{3}{2},\frac{3}{2}\right),\ \psi_D\left(\frac{3}{2},\frac{1}{2}\right),\ \psi_S\left(\frac{1}{2},\frac{1}{2}\right)$$

Physics Model

$$BW_{J_z}(m) = \frac{\sqrt{m m_0 \Gamma_{J_z, \gamma p \to N^*} \Gamma_{N^* \to K\Lambda}(q)}}{m^2 - m_0^2 - i m_0 \Gamma_{tot}(q)}$$

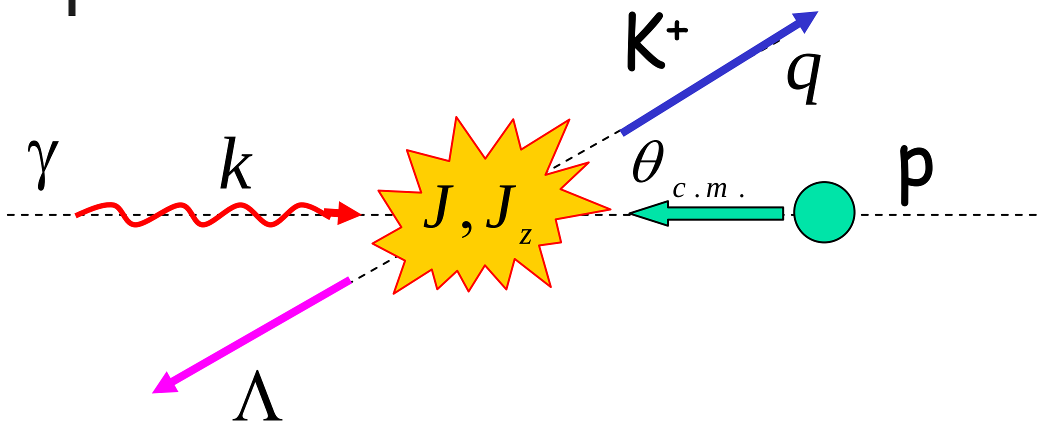
$$\Gamma_{tot}(q) = \Gamma_{N^* \to K\Lambda}(q) + \Gamma_S(q)$$

$$\Gamma_{N^* \to K\Lambda}(q) = \Gamma_0 \left(\frac{q}{q_0} \right)^{2L+1} \quad (L \in 0,1,2)$$

$$\Gamma_S(q) = \Gamma_{S_0} \left(\frac{q}{q_S} \right)^7$$

- Each resonance represented as a relativistic Breit-Wigner
- Phenomenological damping of high-mass tail to achieve s^{-7} scaling

Physics Model



- Compute coherent total amplitude
- Scale cross section
- Fit to optimize observed angular distributions

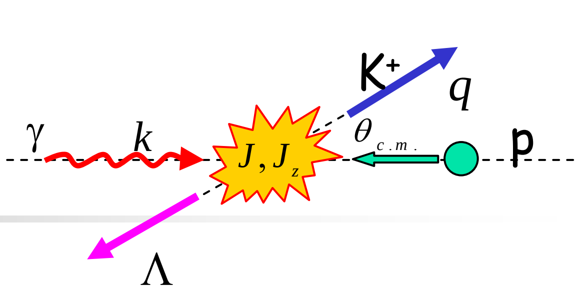
Total amplitude:

$$\left|A(m,\cos\theta_{c.m.})\right|^2 = \left|\psi_S\left(\frac{1}{2},\frac{1}{2}\right) + \psi_P\left(\frac{3}{2},\frac{1}{2}\right) + \psi_P\left(\frac{3}{2},\frac{3}{2}\right) + \psi_D\left(\frac{3}{2},\frac{1}{2}\right) + \psi_D\left(\frac{3}{2},\frac{3}{2}\right)\right|^2$$

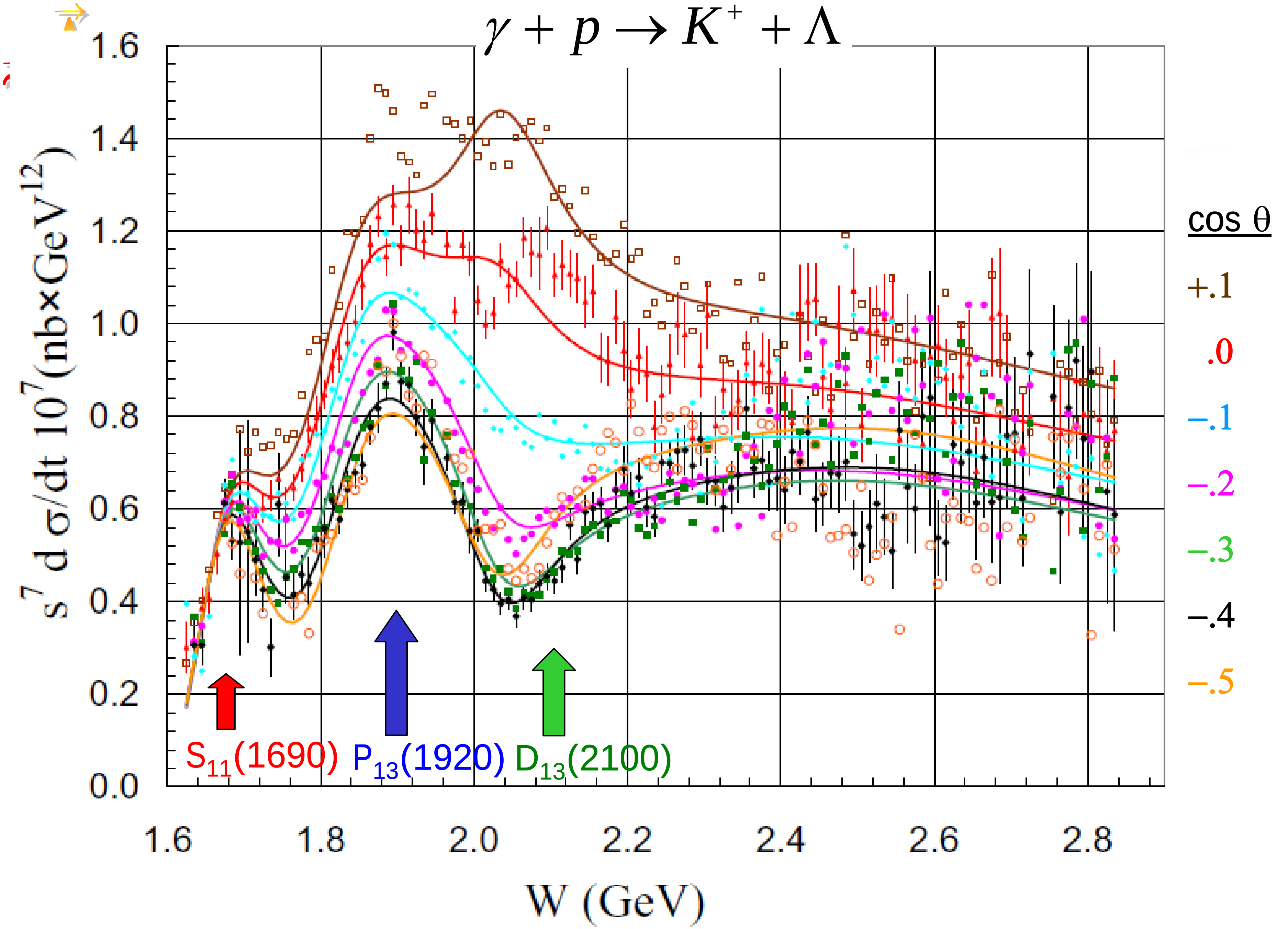
Cross section to fit:

$$s^7\frac{d\sigma}{dt} = s^7\frac{(hc)^2}{64\pi}\frac{1}{s}\frac{1}{k^2}\left|A(m,\cos\theta_{c.m.})\right|^2$$

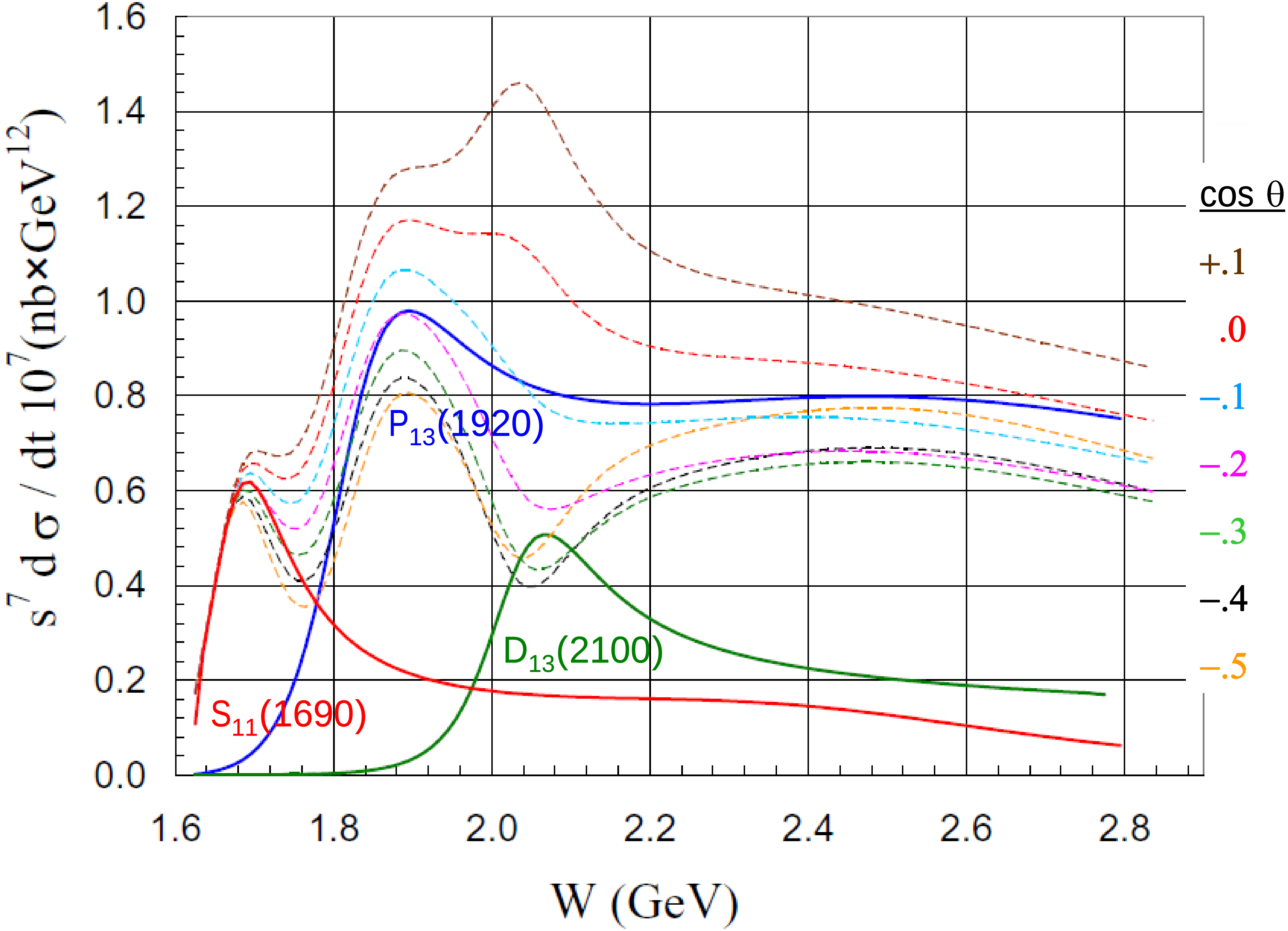
Physics Model



- Resonance combinations tested:
  - Low mass: S_{11}
  - Medium mass: S_{11}, P_{11}, P_{13}
  - High mass: S_{11}, P_{11}, P_{13}, D_{15}, D_{13}
- Free parameters:
  - Masses, widths, couplings
- Not included:
  - Additional near-threshold P_{11} or P_{13} waves
  - Spin observables were not fitted



NStar2011, R. A. Schum R.A. Schumacher and M.M. Sargsian Phys. Rev. C**83** 025207 (2011).



NStar2011, R. A. Schum R.A. Schumacher and M.M. Sargsian Phys. Rev. C**83** 025207 (2011).

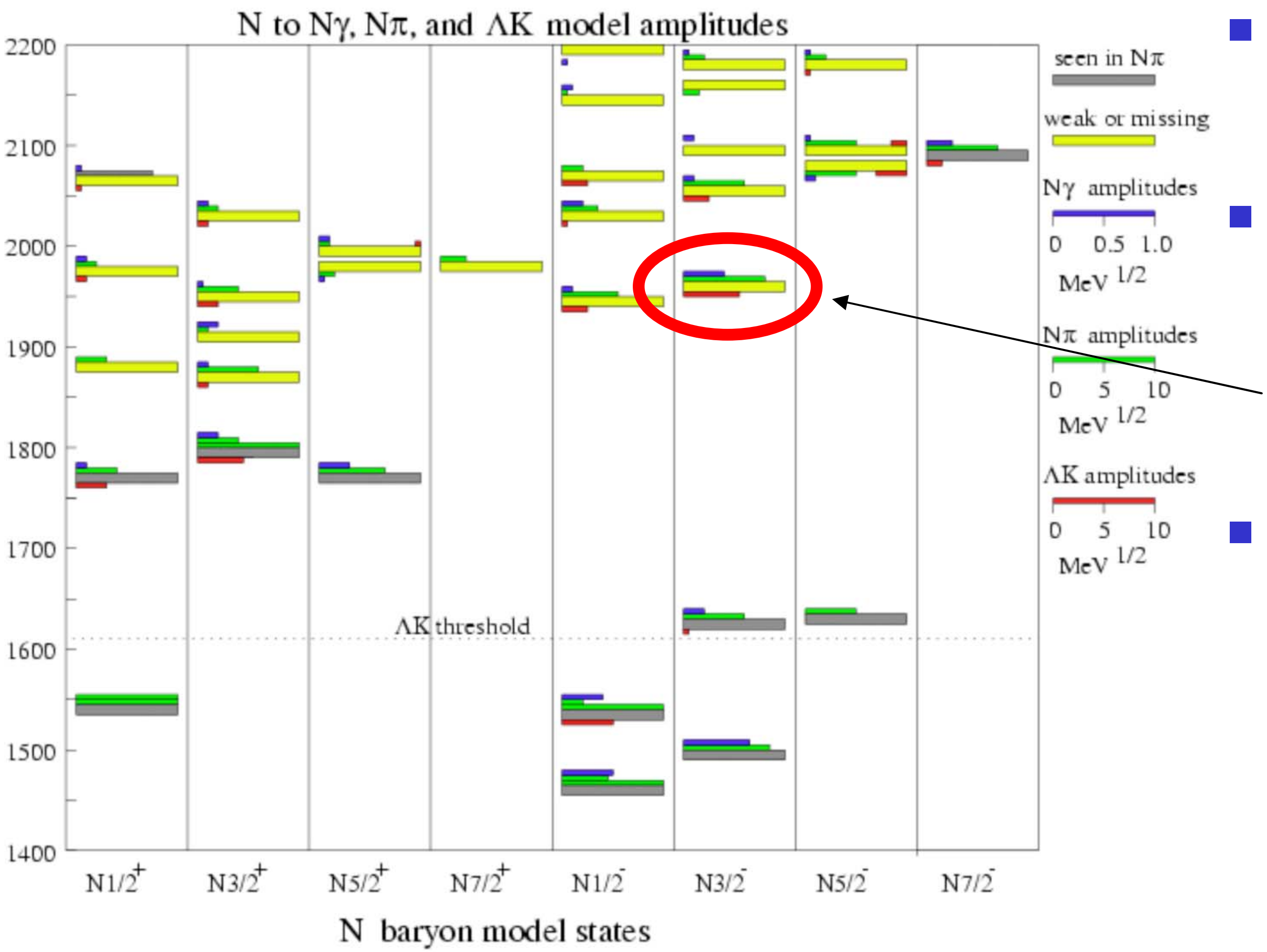
Model Results

Resonance &Decay	m_0 (GeV)	Γ_0 (MeV)	$\sqrt{\Gamma_{1/2,\gamma p\to N^*}}$ $(\mathrm{GeV})^{1/2}$ Phase	$\sqrt{\Gamma_{3/2,\gamma p\to N^*}}$ $(\mathrm{GeV})^{1/2}$ Phase
S_{11}	1690 ± 10	80 ± 20	$1.83 \pm .10$ $(-142 \pm 5)^\circ$	
P_{13}	1920 ± 10	440 ± 100	$1.93 \pm .10$ —	$1.67 \pm .07$ —
New → D_{13}	2100 ± 20	200 ± 50	$0.61 \pm .10$ $(45 \pm 5)^\circ$	$1.19 \pm .10$ $(45 \pm 5)^\circ$

$$\Gamma_S(q) = \Gamma_{S_0}\left(\frac{q}{q_S}\right)^7 \quad \begin{cases} \Gamma_{S_0} = 0.50 \quad \mathrm{GeV} \\ q_S = 0.77 \ \mathrm{GeV/c} \end{cases}$$

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

N* Baryons: Seen & "Missing"



- Relativised CQM
  - Classify oscillator-model states by I, J, P
- Possible observation of a "missing" N* state in $K^+\Lambda$
- There is a PDG "**" state N(2080) D_{13}
  - Weak evidence in $K\Lambda$
  - Mart & Bennhold: confused with the P_{13} at 1900MeV.

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

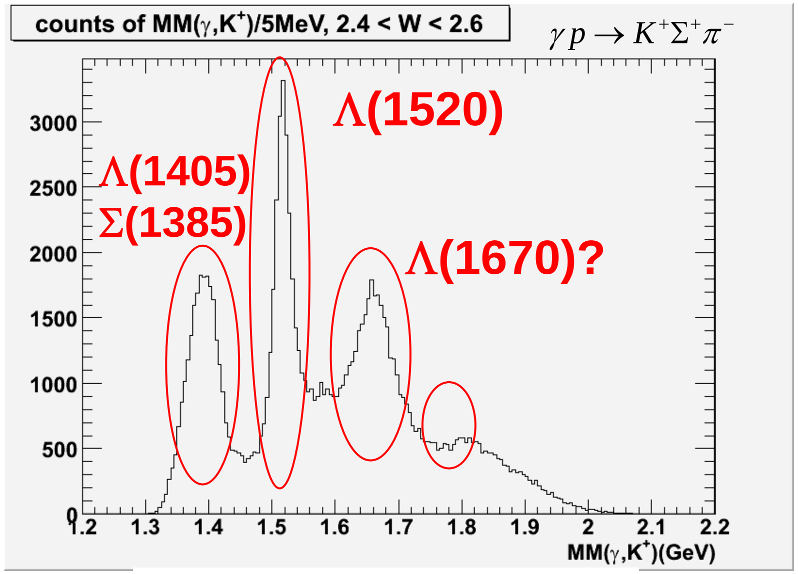
Next topic...

Λ(1405)

See talks by: K. Moriya photoproduction III-B
H. Lu electroproduction I-A

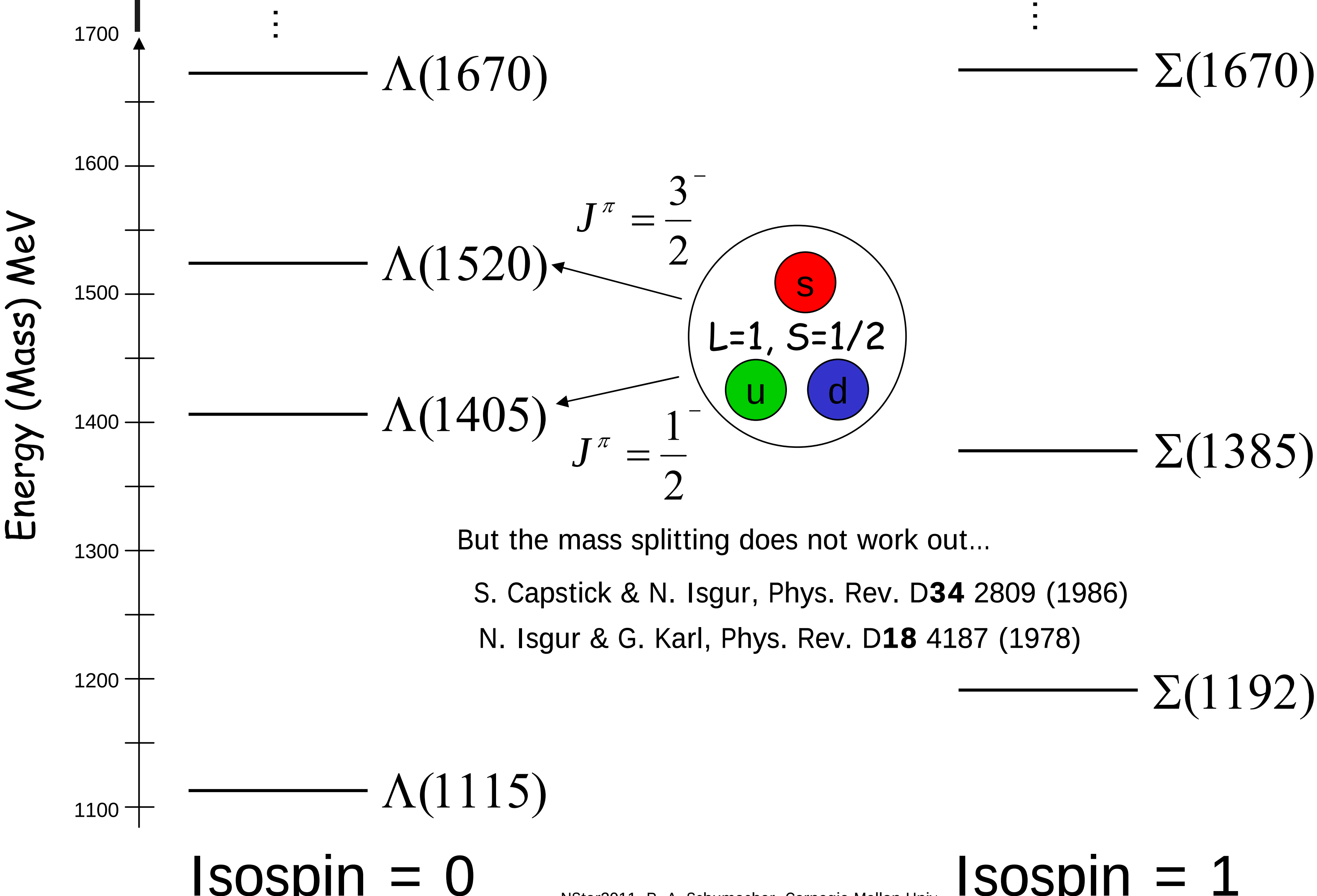
What "is" the Λ(1405)?

- 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)
  - Dynamically generated resonance, via unitary meson-baryon channel coupling



(γ,K) Missing Mass (GeV)

The Low-Mass S=-1 Hyperons

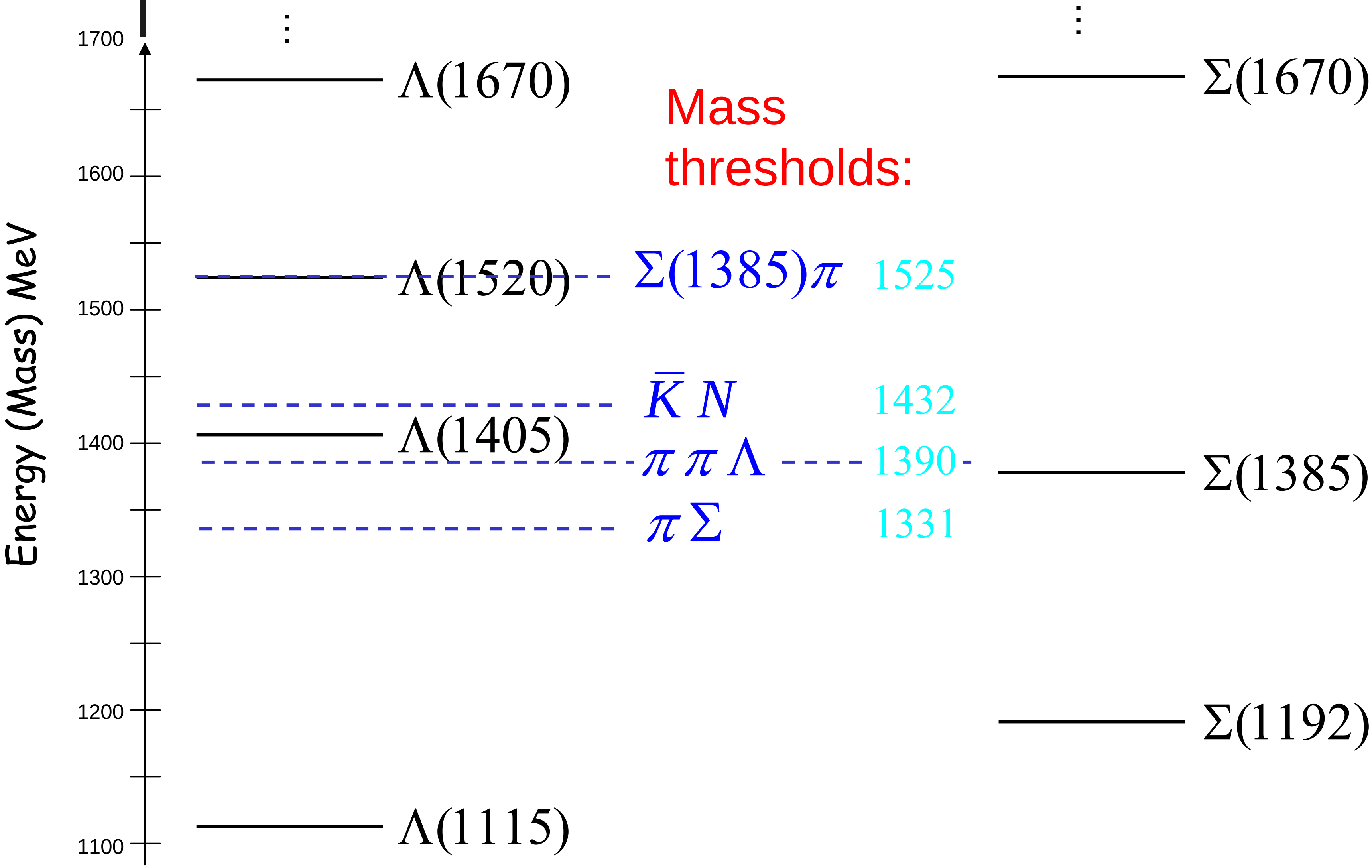


But the mass splitting does not work out…

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

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

The Low-Mass S=-1 Hyperons



Isospin = 0

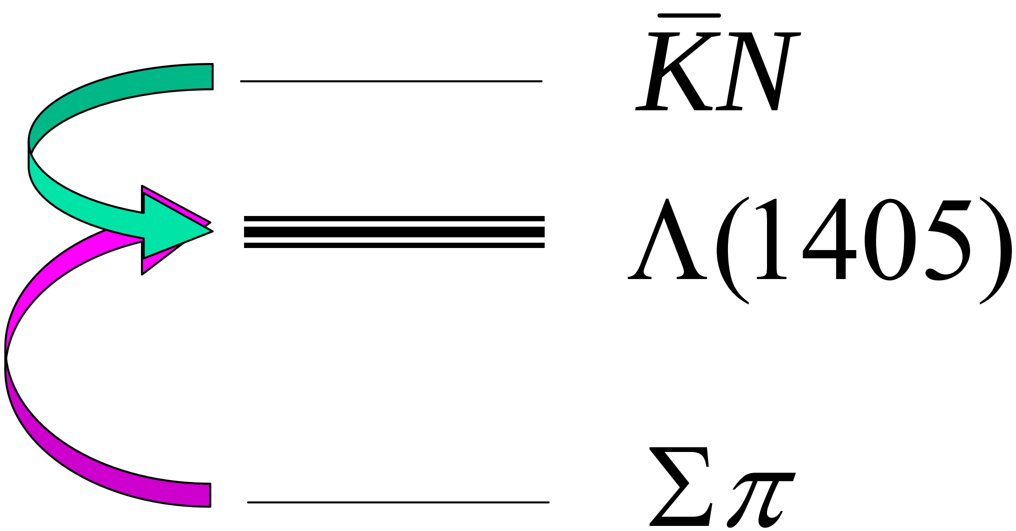
Isospin = 1

Dynamical State Generation

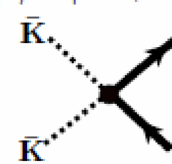
Do the "ground state" mesons and baryons attract strongly enough to form meson-baryon "molecular" bound states or unbound resonances?

Bound state

Resonance



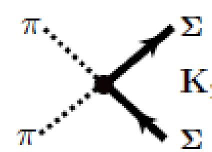
$|1\rangle = |\bar{K}N, I = 0\rangle$



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

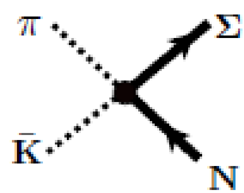
From chiral SU(3) effective field theory

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



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

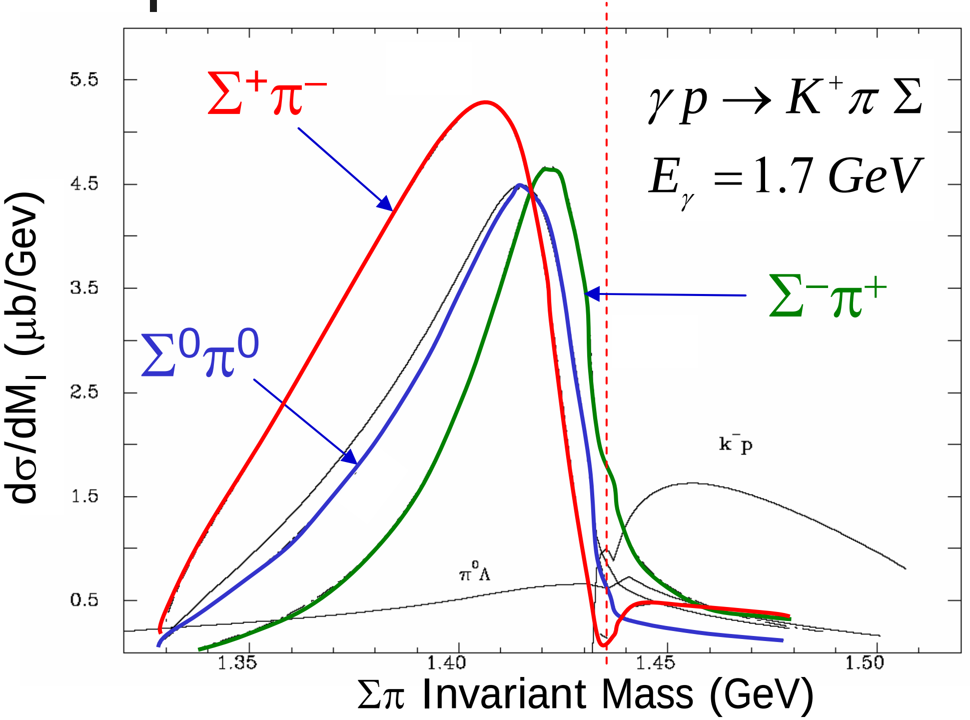
Channel Coupling:



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

Graphic: W. Weise

Chiral Unitary Models (example 1)



$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}\left|T^{(0)}\right|^2 + O\left(T^{(2)}\right)$$

- Mass distribution of the "Λ(1405)" predicted to depend on πΣ decay channel
- Model with I = 0 and I = 1 amplitudes
  - Chiral Lagrangian + Channel Coupling
  - I(π Σ) = {0,1} – not in an isospin eigenstate
    - Neglect I=2
  - Interference between I=0 and I=1 amplitudes modifies mass distributions
  - WT-type interaction: no energy or angle dependence
- Inspired CLAS experiment

J.C. Nacher, E. Oset, H. Toki, & A. Ramos, Phys. Lett. B **455**, 55 (1999).

Chiral Unitary Models (example 2)

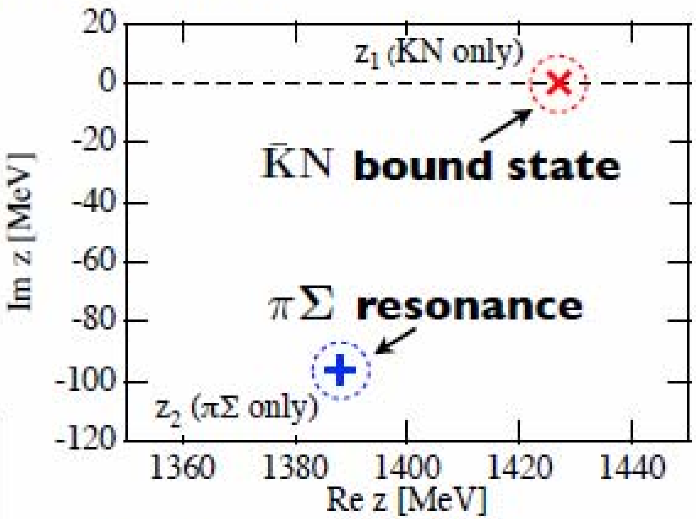
The TWO POLES scenario

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

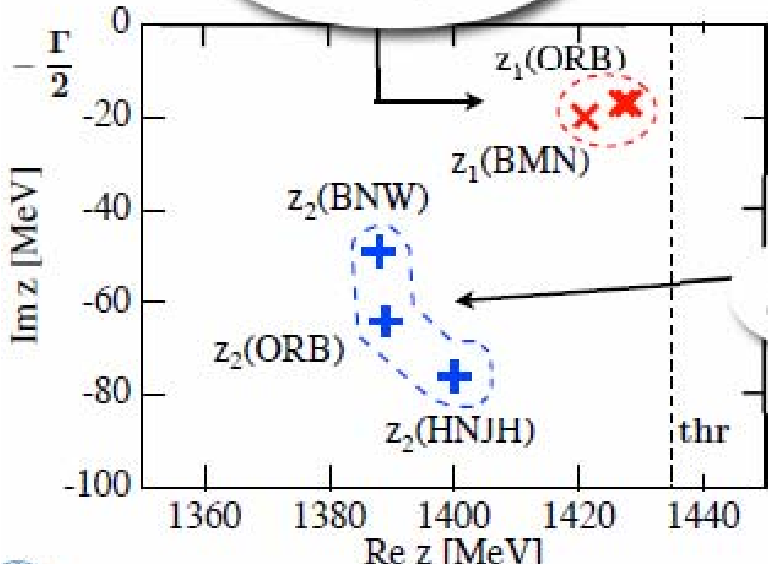
T. Hyodo, W.W., Phys. Rev. C77 (2008) 03524

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

starting point:
no channel coupling ▶

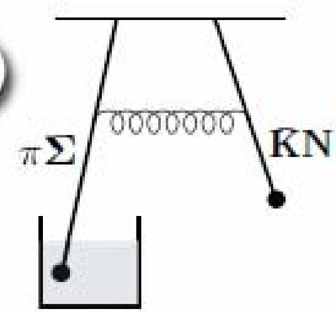


Pole I
(dominantly $\bar{K}N$)



◀ **channel coupling** at work

Pole II
(dominantly $\pi\Sigma$)



Graphic: W. Weise

Chiral Unitary Models (example 2)

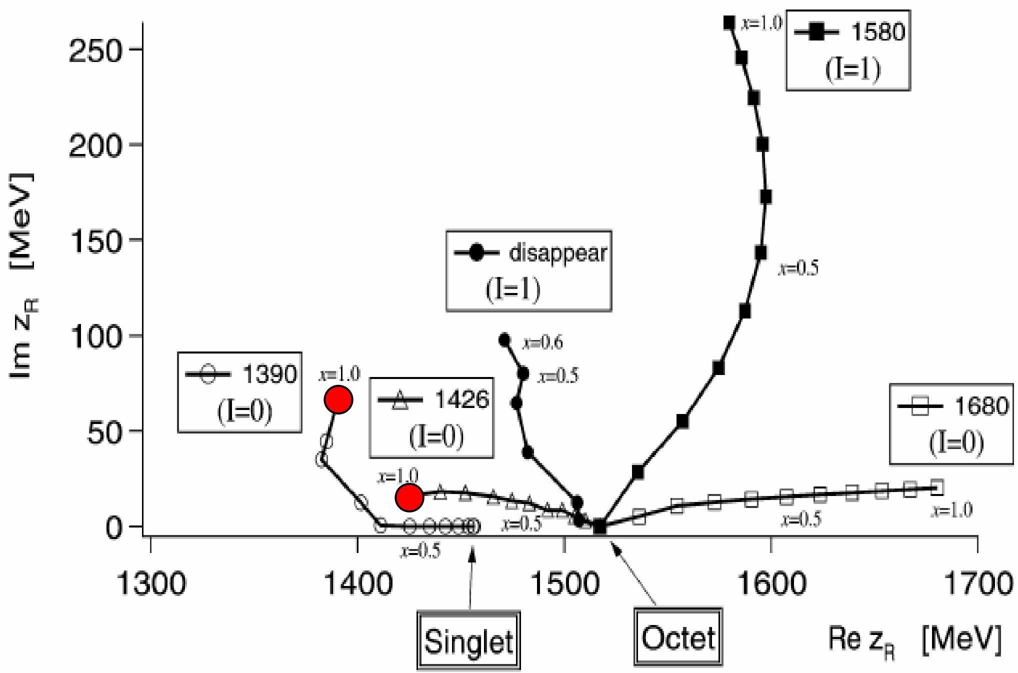
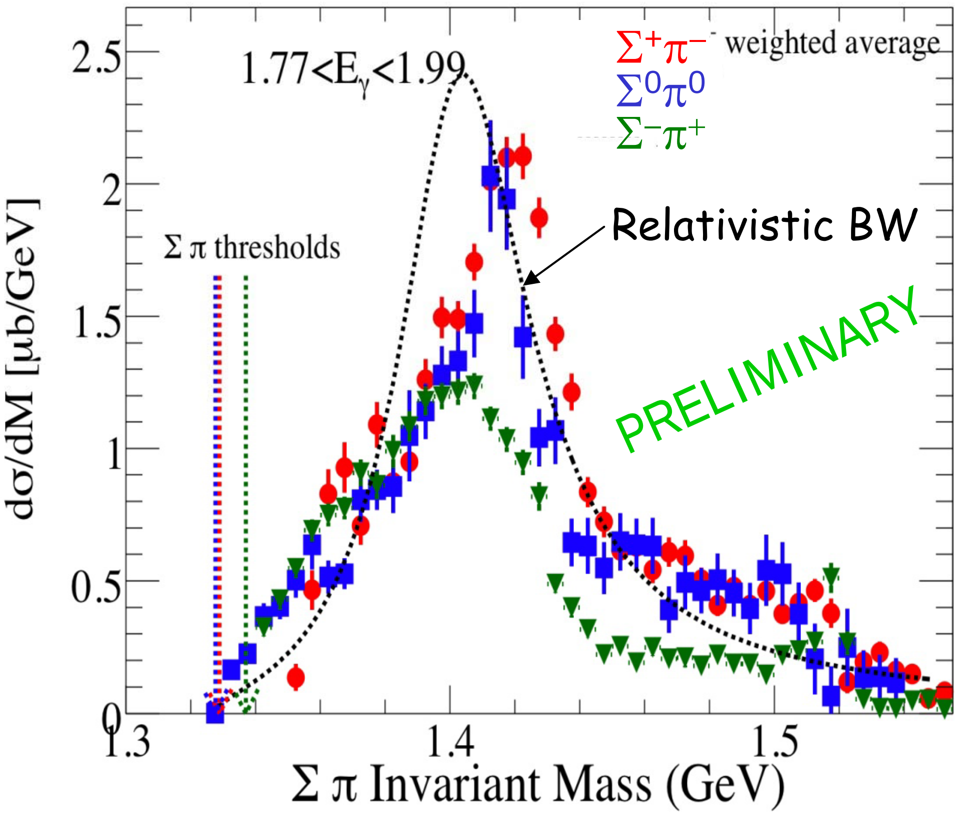


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

- 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)

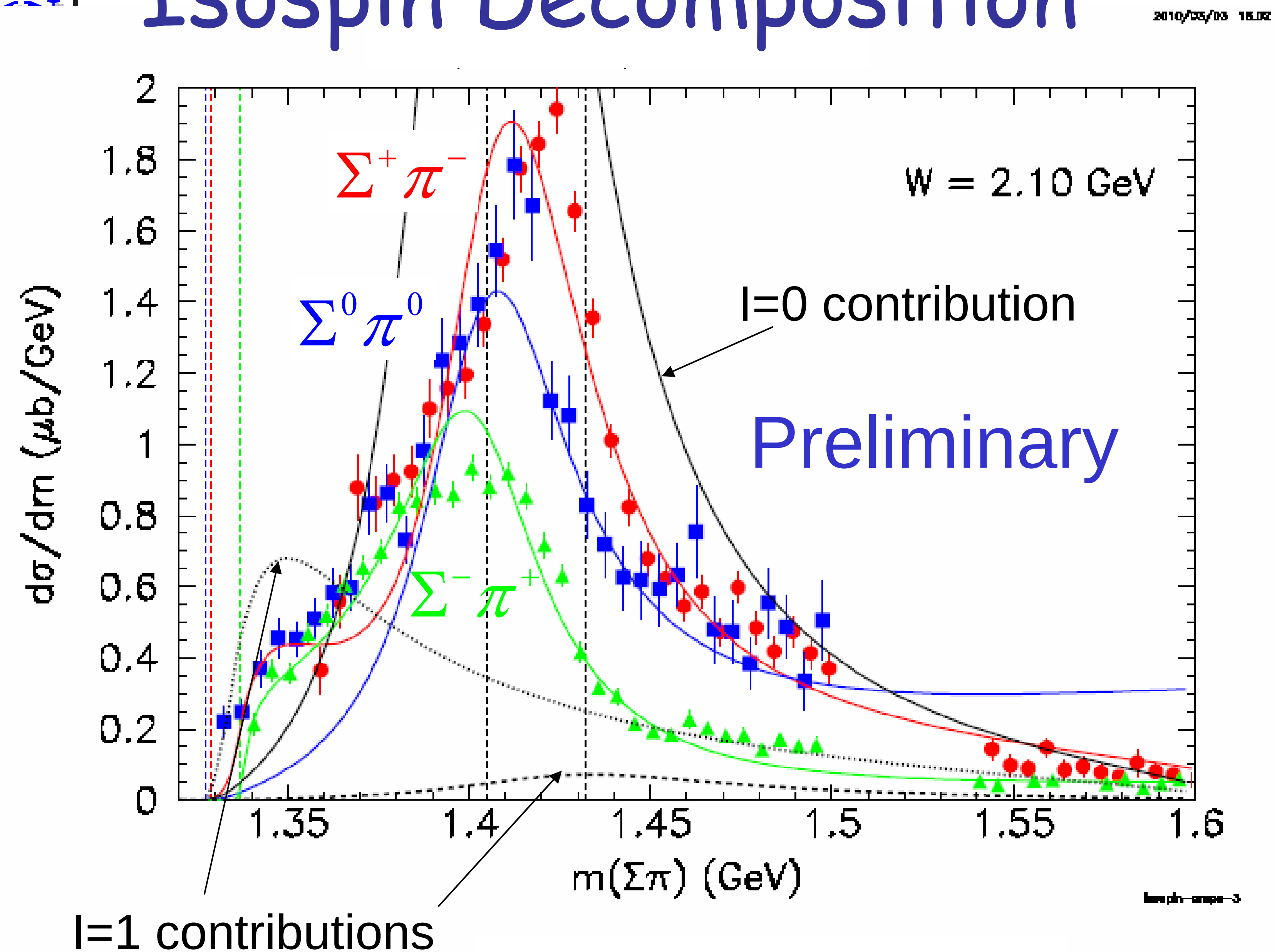
CLAS result for Λ(1405)



Note that "sign" of the charge asymmetry is opposite to Nacher *et al* prediction

- Decay-channel asymmetry of Λ(1405) lineshape confirmed
- Asymmetric among the three charge states → not a pure isospin I=0 process (decomposition in progress…)
- Subtracted back-grounds: Σ(1385), Λ(1520), K*(892)
- Direct Spin-parity measurement: $J^\pi = \frac{1}{2}^-$
- Details:
  - Kei Moriya Session IIIB

Isospin Decomposition



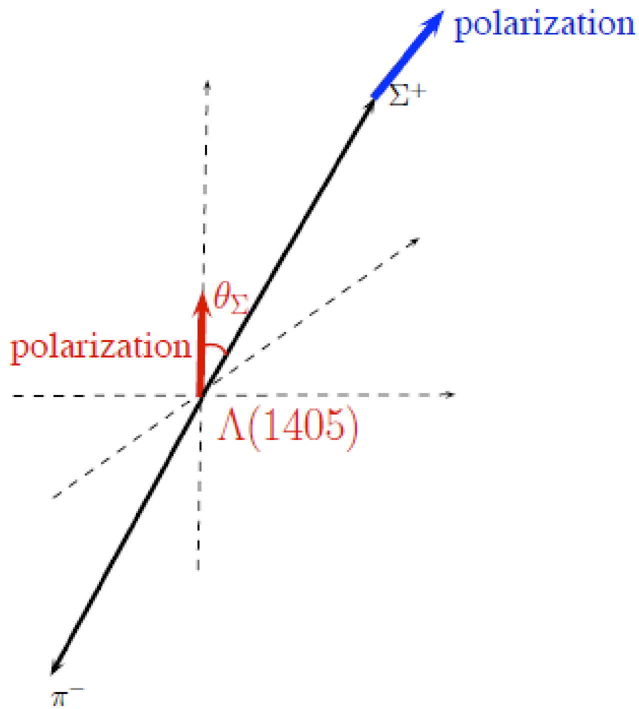
Parity and Spin of $\Lambda(1405)$

J^P of $\Lambda(1405)$

no previous **direct experimental evidence** for the spin and parity (PDG **assumes** $1/2^-$) "Note on the $\Lambda(1405)$" 1998 PDG, R.H. Dalitz

How do we measure these quantities?

- **spin** – measure distribution into $\Sigma\pi$
  - flat distribution is best evidence possible for $J = 1/2$
- **parity** – measure polarization of Σ from $\Lambda(1405)$
  - Polarization direction as a function of Σ decay angle will be determined by J^P of $\Lambda(1405)$

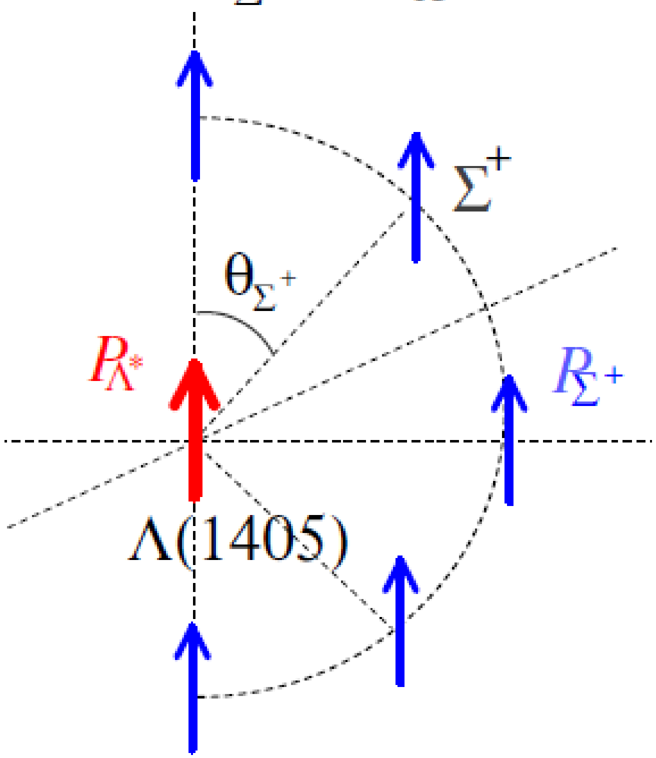


Kei Moriya, C.M.U. PhD thesis, CMU 2010

s-wave, p-wave Scenario

$L = 0$ (s-wave)

$\vec{P}_{\Sigma^+} = \vec{P}_{\Lambda^*}$

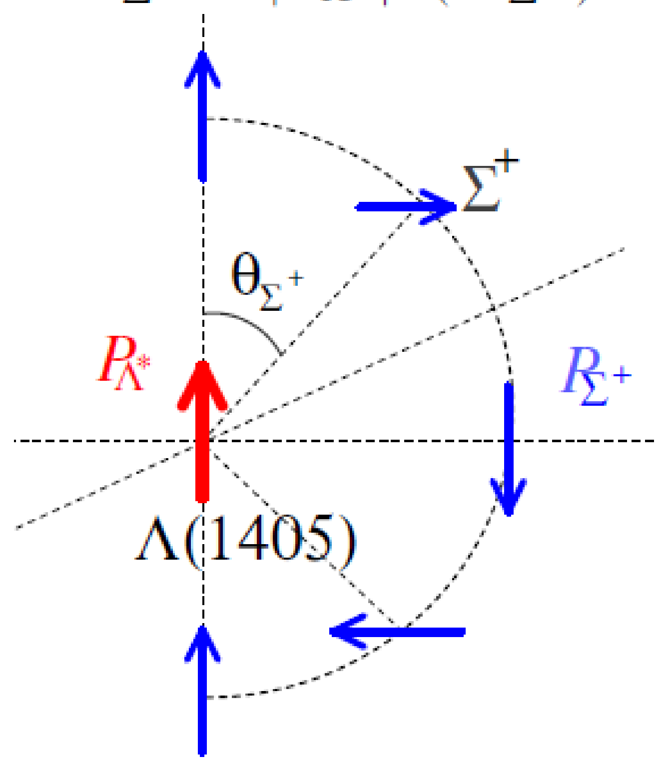


$\Lambda(1405) \rightarrow \Sigma\pi$ is s-wave

$\Leftrightarrow J^P = 1/2^-$

$L = 1$ (p-wave)

$\vec{P}_{\Sigma^+} = |\vec{P}_{\Lambda^*}|\hat{n}(2\theta_{\Sigma^+})$



$\Lambda(1405) \rightarrow \Sigma\pi$ is p-wave

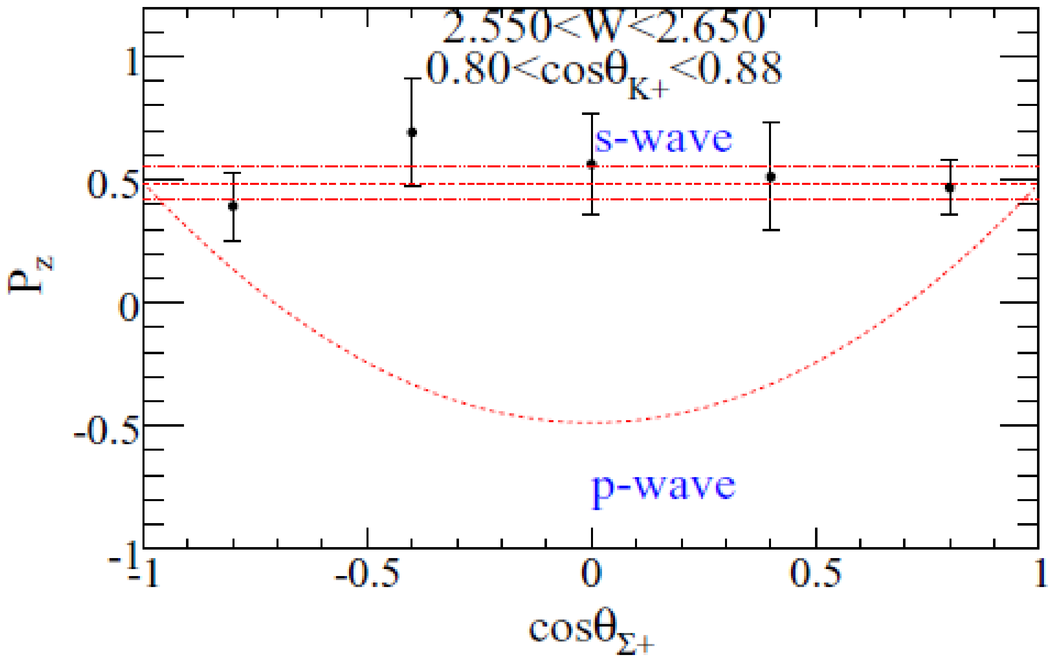
$\Leftrightarrow J^P = 1/2^+$

Kei Moriya, C.M.U. PhD thesis, CMU 2010

Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward K^+angles
- use reaction: $\Lambda(1405) \to \Sigma^+\pi^-$, $\Sigma^+ \to p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- bg is $\sim 10\%$ $\Sigma(1385)$



polarization does not change with Σ^+ angle (θ_{Σ^+})

$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured Σ^+ polarization **is** the $\Lambda(1405)$polarization

$\Rightarrow \Lambda(1405)$is produced with $\sim +40\%$ polarization

Kei Moriya, C. M. U. PhD thesis, CMU 2010

Conclusions

- Three phenomena in $K^+\Lambda$ photoproduction:
  - Regge scaling s^{-2} small $-t$ – confirmed
  - Constituent-counting s^{-N} – holds for N = 7
  - Evidence for N* production & interference
    - Present best fit has: $S_{11}(1690)$, $P_{13}(1920)$, $D_{13}(2100)$ ← new observation
    - PDG "**" $D_{13}(2080)$ "missing" state possibly seen
- $\Lambda(1405)$ – mass distributions in $\Sigma\,\pi$
  - Evidence for I=0, I=1 interference
  - Spin-Parity $J^P = \frac{1}{2}^-$ confirmed