Scaling and Resonances in $K^+\Lambda$ Photoproduction

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4-28-2011, Anaheim, CA

GHP2011

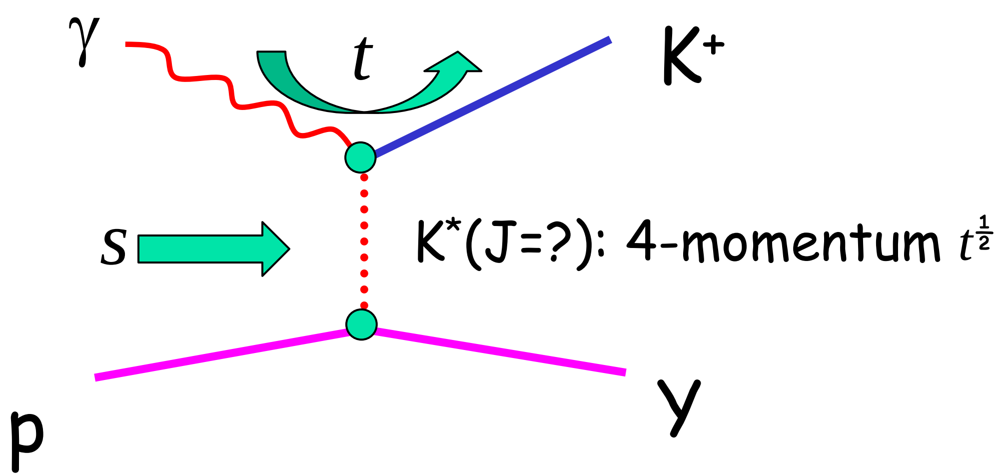
Overview

- "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

- Feasible due to recent CLAS published results
  - M. McCracken *et al.* Phys. Rev. C **81**, 025201 (2010).

Regge Scaling at Small $-t$



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

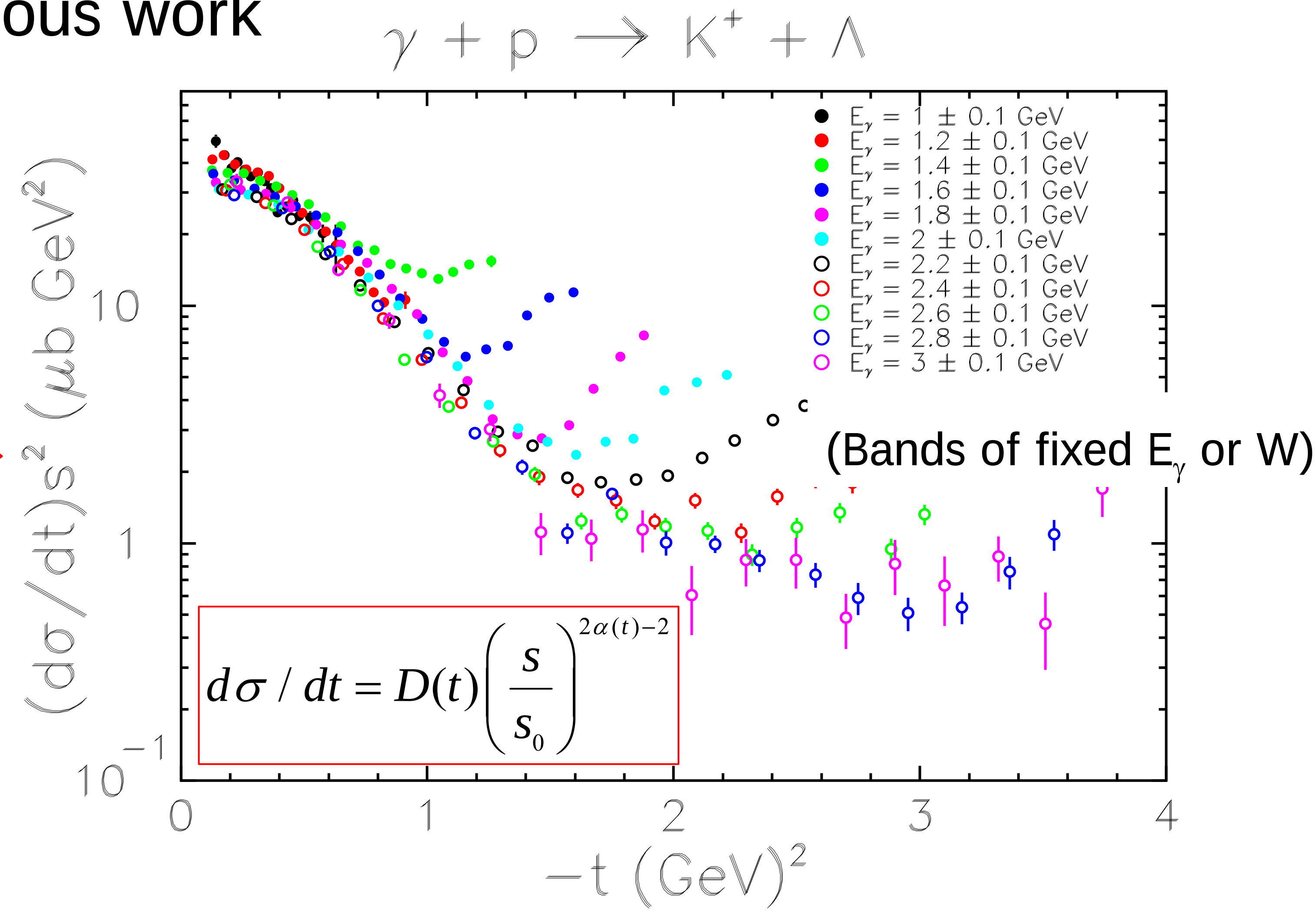
$$d\sigma / dt = D(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

$s = W^2$ invariant mass

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

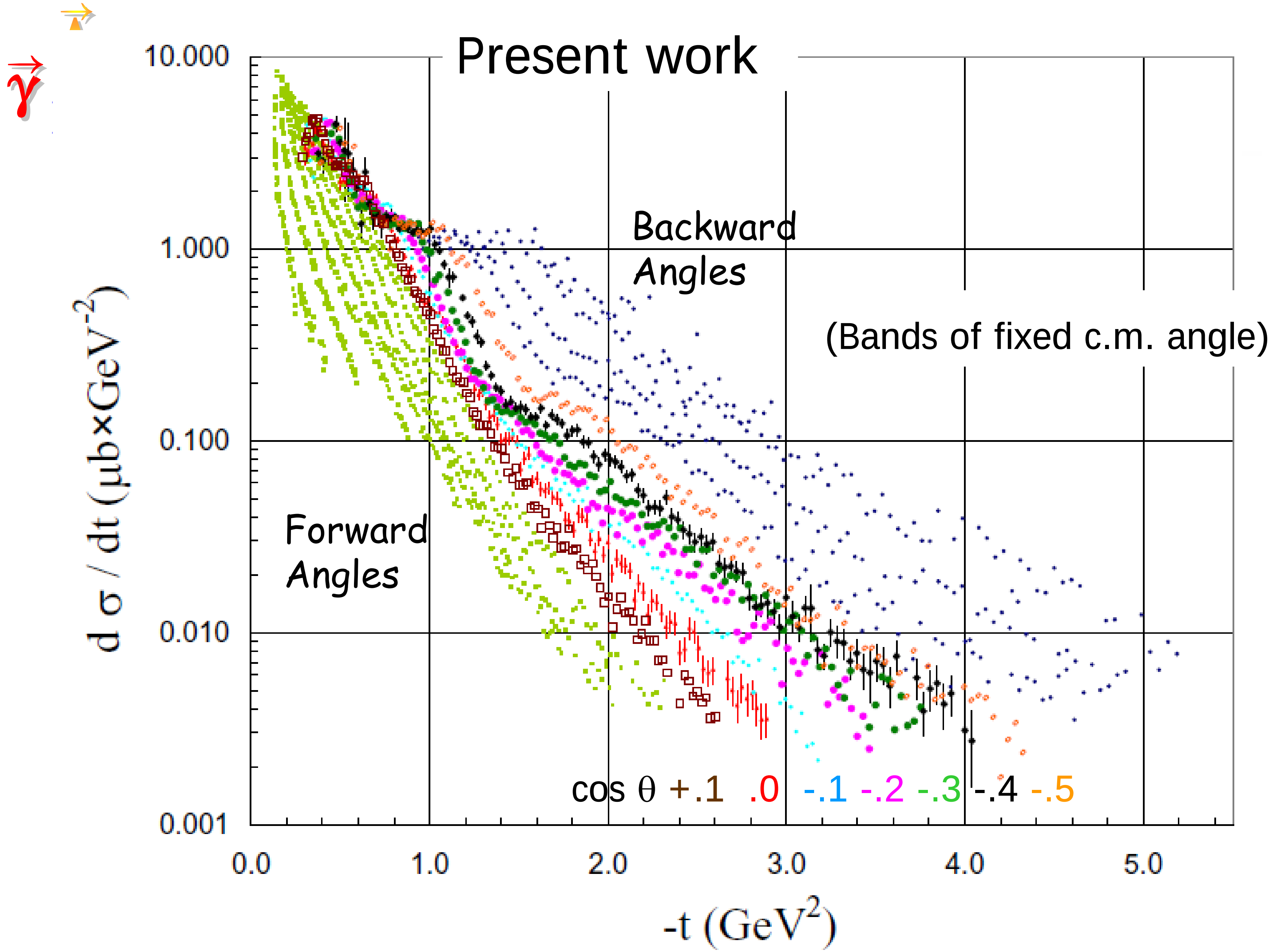
Regge Scaling at Small $-t$

Previous work

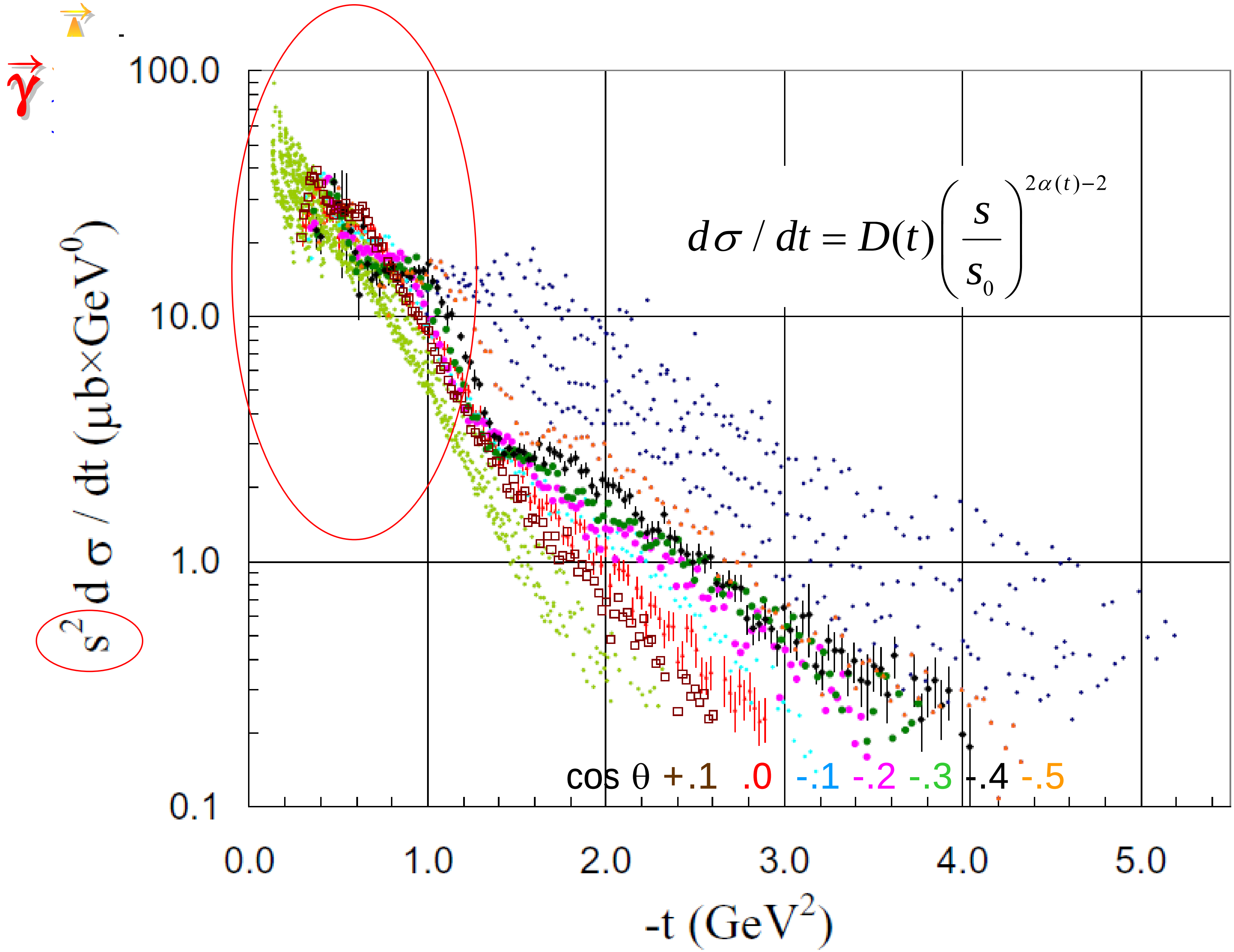


$$d\sigma / dt = D(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

Jefferson Lab / CL R. Bradford *et al.* Phys. Rev. C**73** 035202 (2006)



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



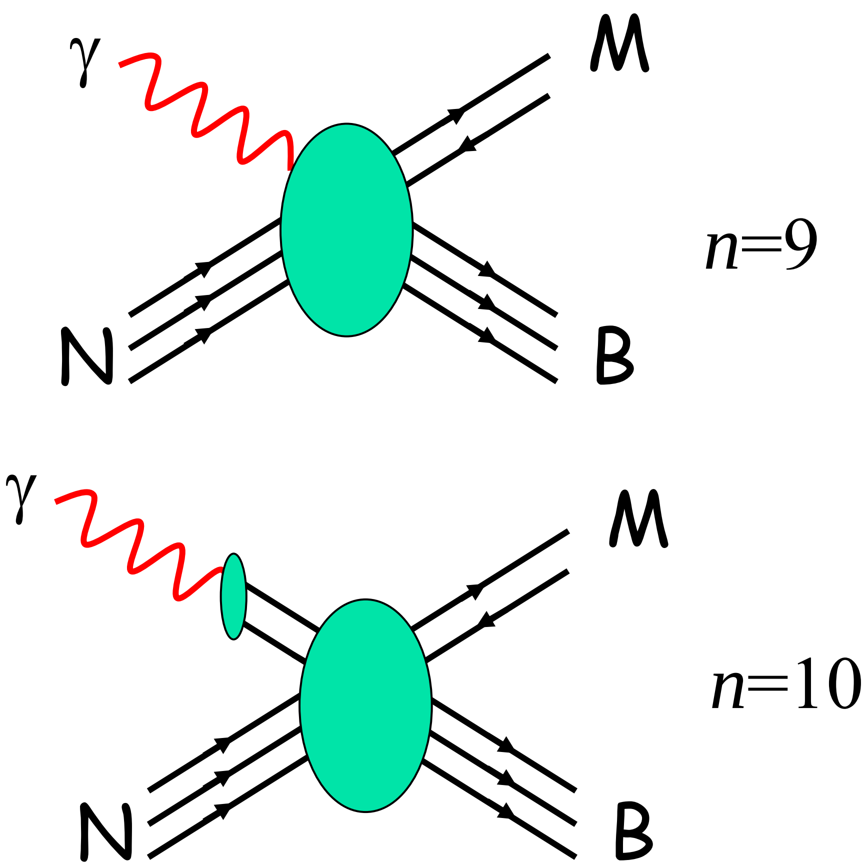
100.0
10.0
1.0
0.1
s² d σ / dt (μb×GeV⁰)
0.0
1.0
2.0
3.0
4.0
5.0
-t (GeV²)
$d\sigma / dt = D(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$
cos θ +.1 .0 -.1 -.2 -.3 -.4 -.5

Regge Scaling at Small $-t$

- New and previous CLAS $K^+\Lambda$ results are in good agreement
- Observation of approximate s^{-2} "Regge scaling" is confirmed
  - Implies that $\alpha_{eff} = \alpha_{K^+} + \alpha_{K*(892)} \approx 0, t \to 0$
- Model calculation of $\alpha(t)$ remains as an open task…

Constituent-Counting Scaling

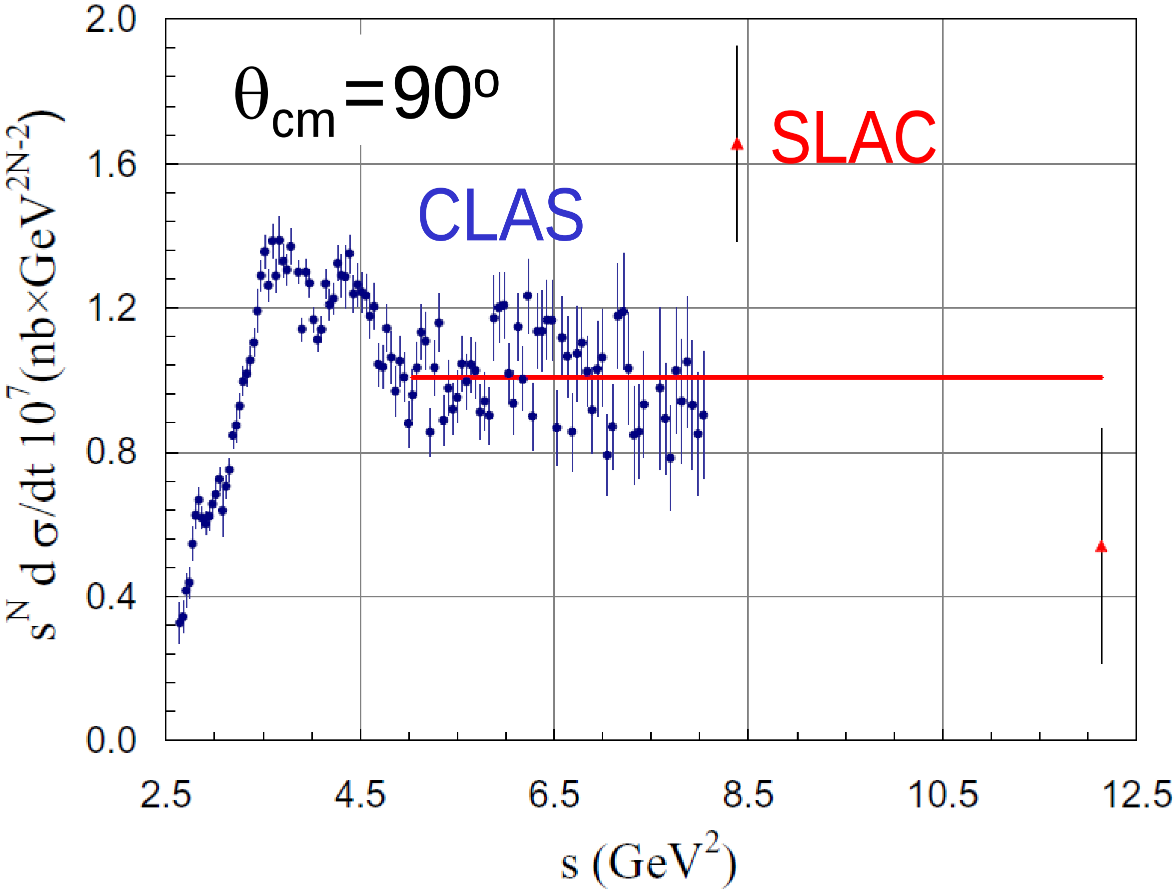
$$\frac{d\sigma}{dt} = f\left(\frac{t}{s}\right)s^{2-n}$$



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

Scaling in Pion Production

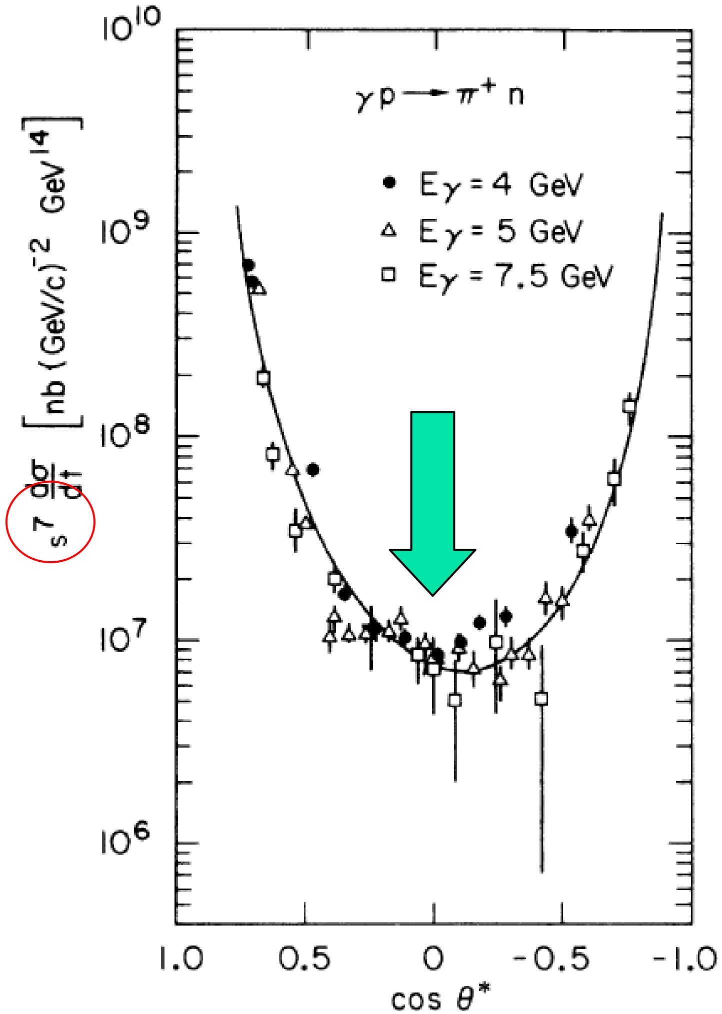
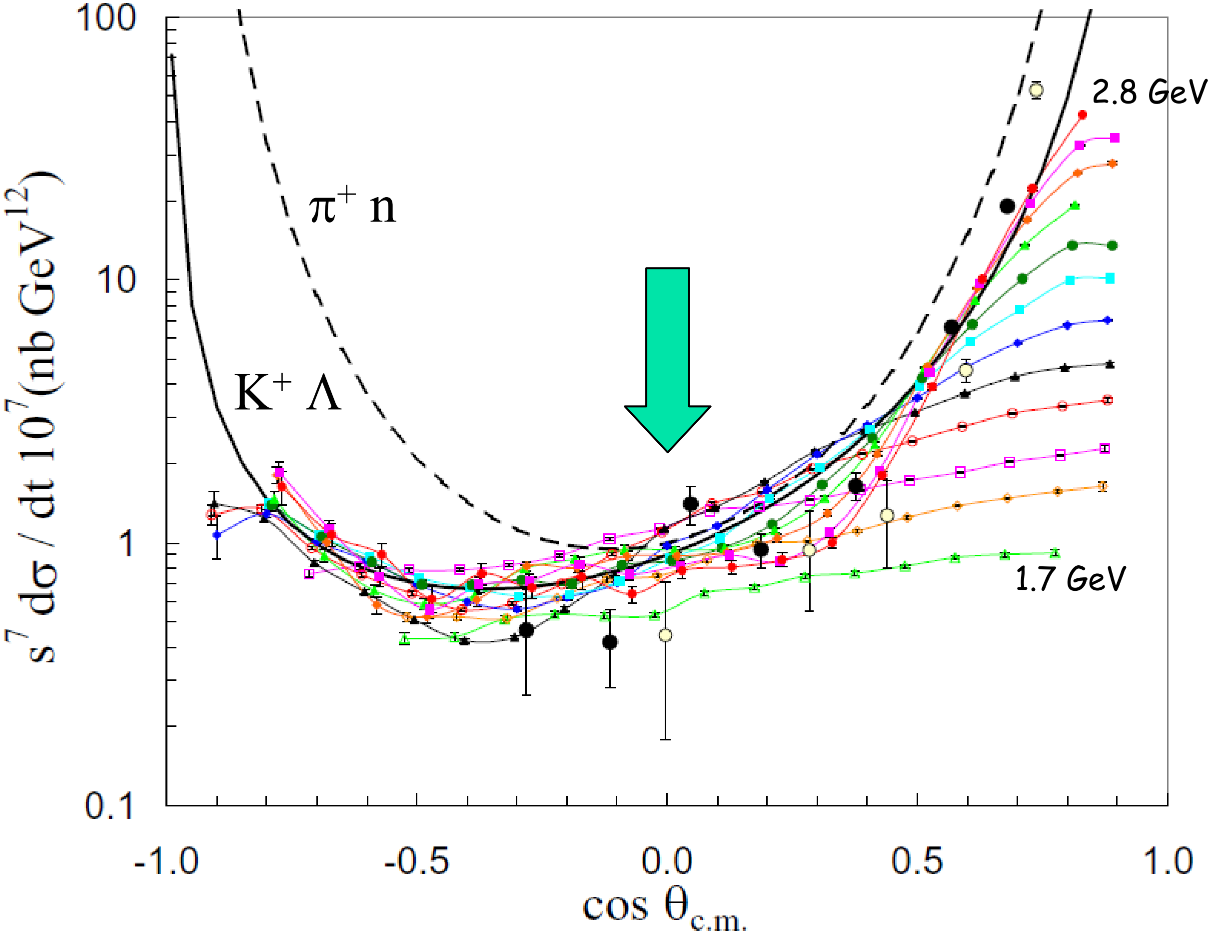


FIG. 6. $s^7 d\sigma/dt$ versus cosθ^* for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where ($z = \cos\theta^*$), which is an empirical fit to the angular distribution.

- "perturbative QCD" scaling at SLAC
- s^{-7} scaling found to "work" for $\gamma p \rightarrow \pi^+ n$, $\pi^0 p$, $\pi^- \Delta^{++}$, $\rho^0 p$, 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)

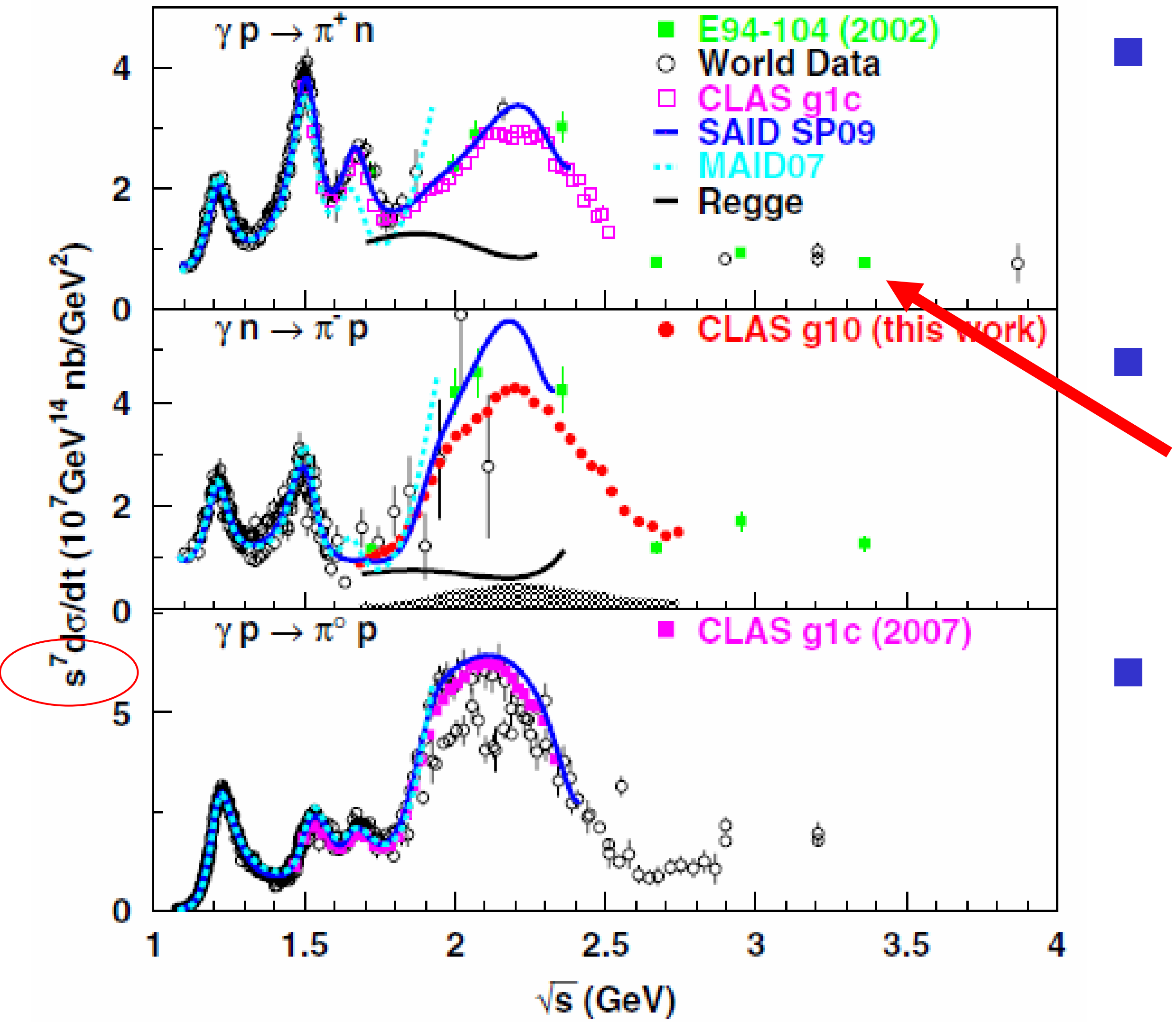
Evidence for s^{-7} Scaling…



- 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?

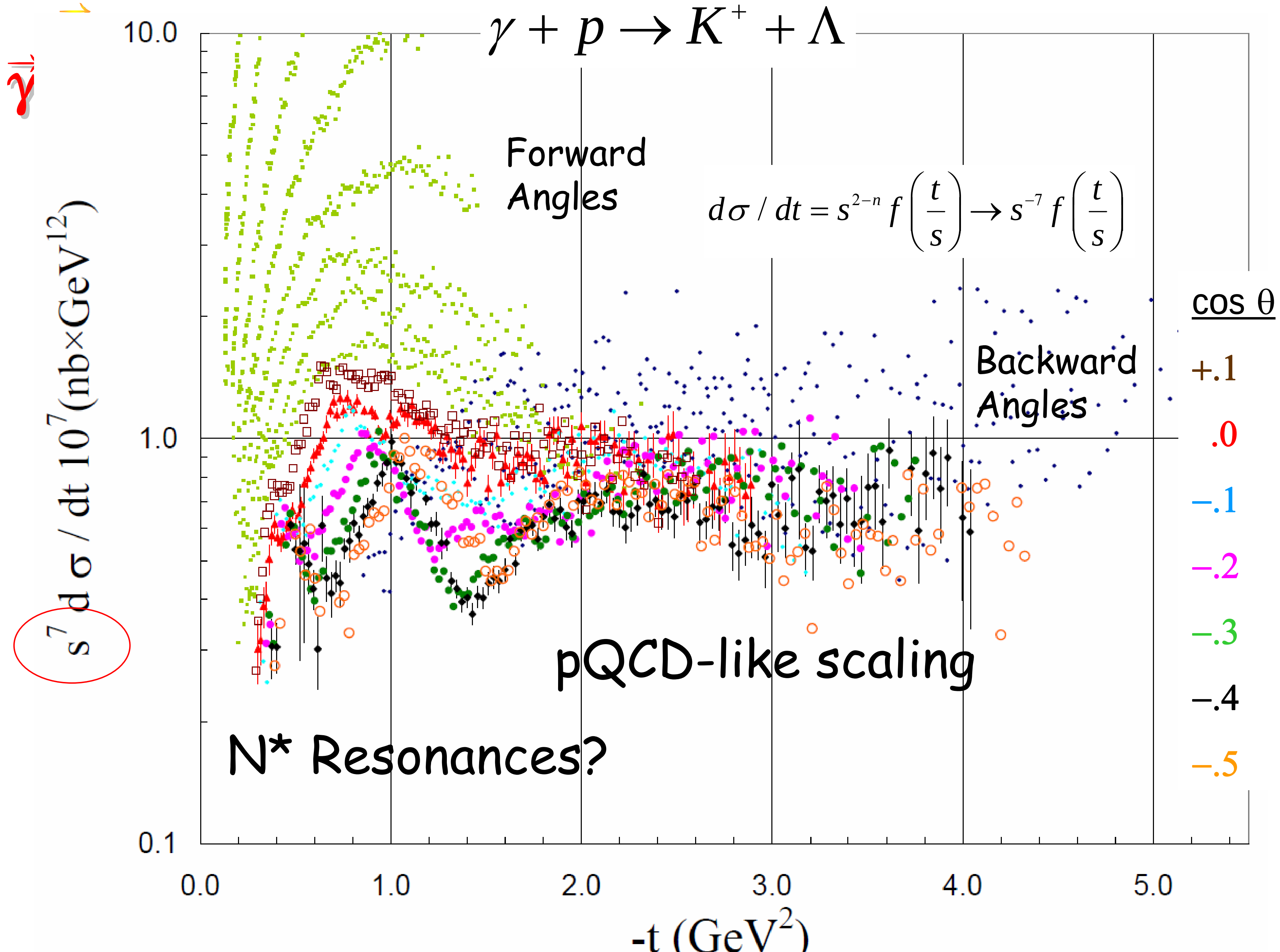
R. L. Anderson *et al.*, Phys. Rev. **D 14**, 679 (1976)

Scaling in Pion Production

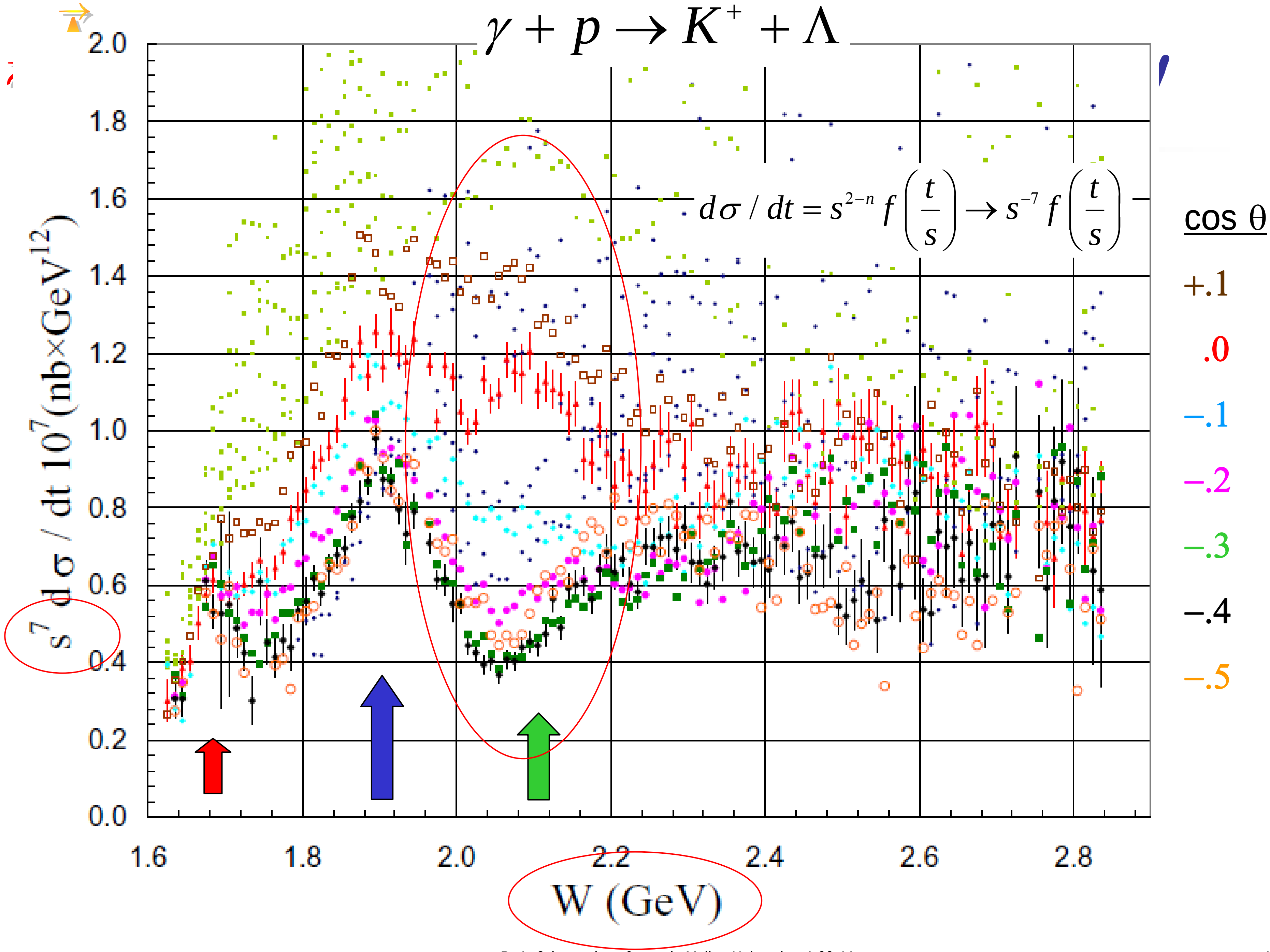


- Three pion channels at 90° vs. W
- pQCD scaling seen for W>2.6 GeV
- N* resonances seen below 2 GeV

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



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

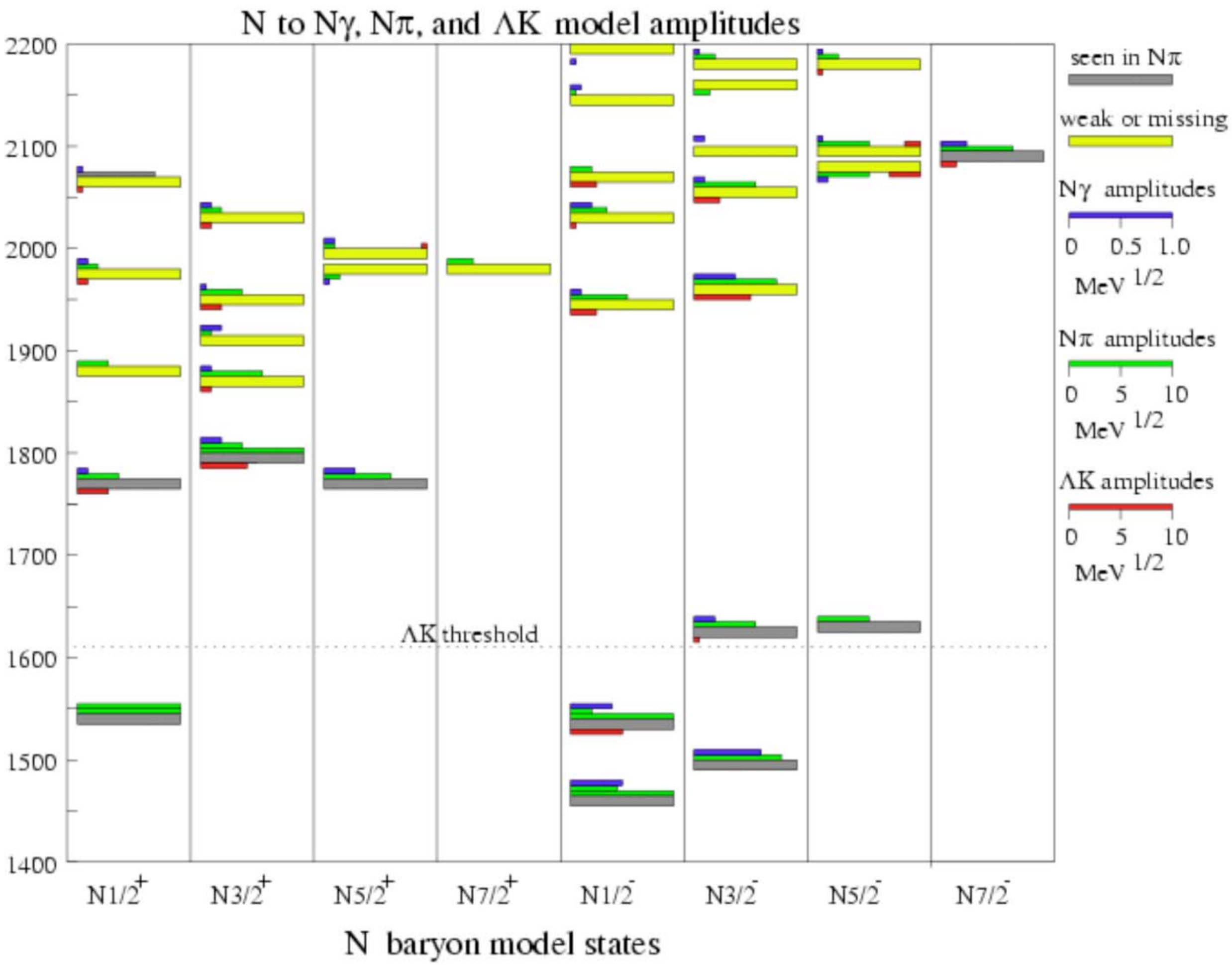


$\gamma + p \rightarrow K^{+} + \Lambda$
$d\sigma / dt = s^{2-n} f\left(\frac{t}{s}\right) \rightarrow s^{-7} f\left(\frac{t}{s}\right)$
cos θ
+.1
.0
−.1
−.2
−.3
−.4
−.5
$s^7 \, d\sigma / dt \; 10^7 (\mathrm{nb} \times \mathrm{GeV}^{12})$
W (GeV)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.6
1.8
2.0
2.2
2.4
2.6
2.8

Resonances in $K^+\Lambda$ Production

- Scaled cross section enhances visibility of resonances near 1.7, 1.9, & 2.1 GeV
- Strong interference signal near 2.1 GeV
- Model the cross section using S, P, D - wave resonances with relativistic-BW amplitudes

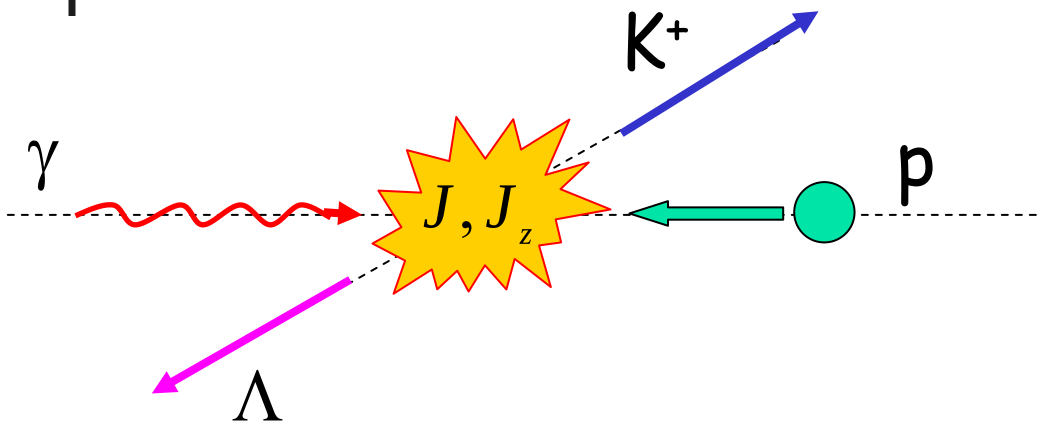
N* Baryons: Seen & "Missing"



- Relativised CQM
  - Classify oscillator-model states by I, J, P
- Only low-mass states in each band seen in πN 3*, 4* status
- Where are the higher masses?
  - πN couplings shrink
  - KY coupling are significant

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

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

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

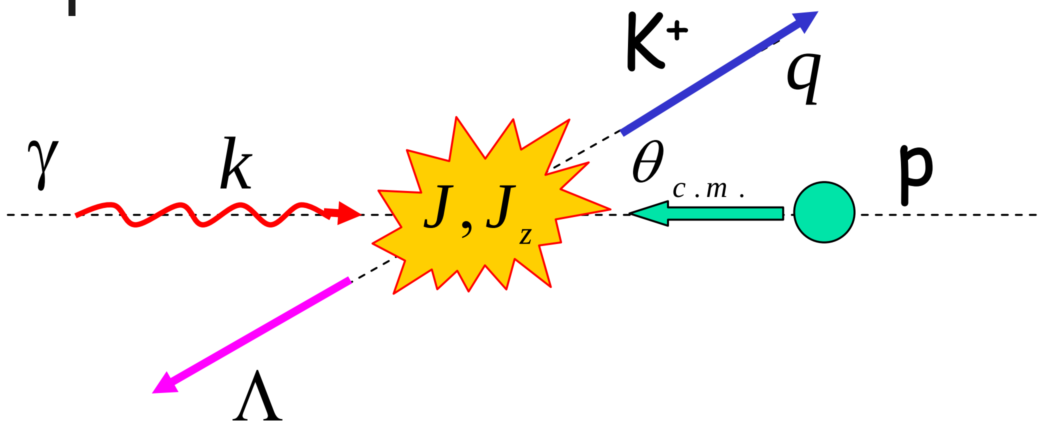
$$\Gamma_{tot}(q) = \Gamma_{N^* \to K\Lambda}(q) + \Gamma_S(q)$$

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

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

- 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

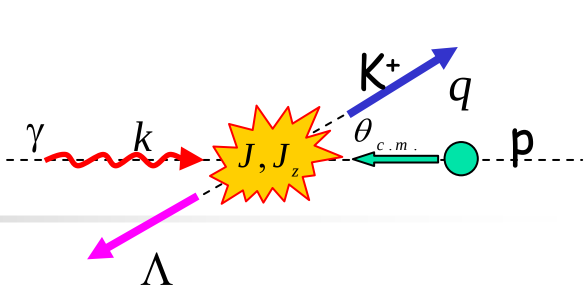
Total amplitude:

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

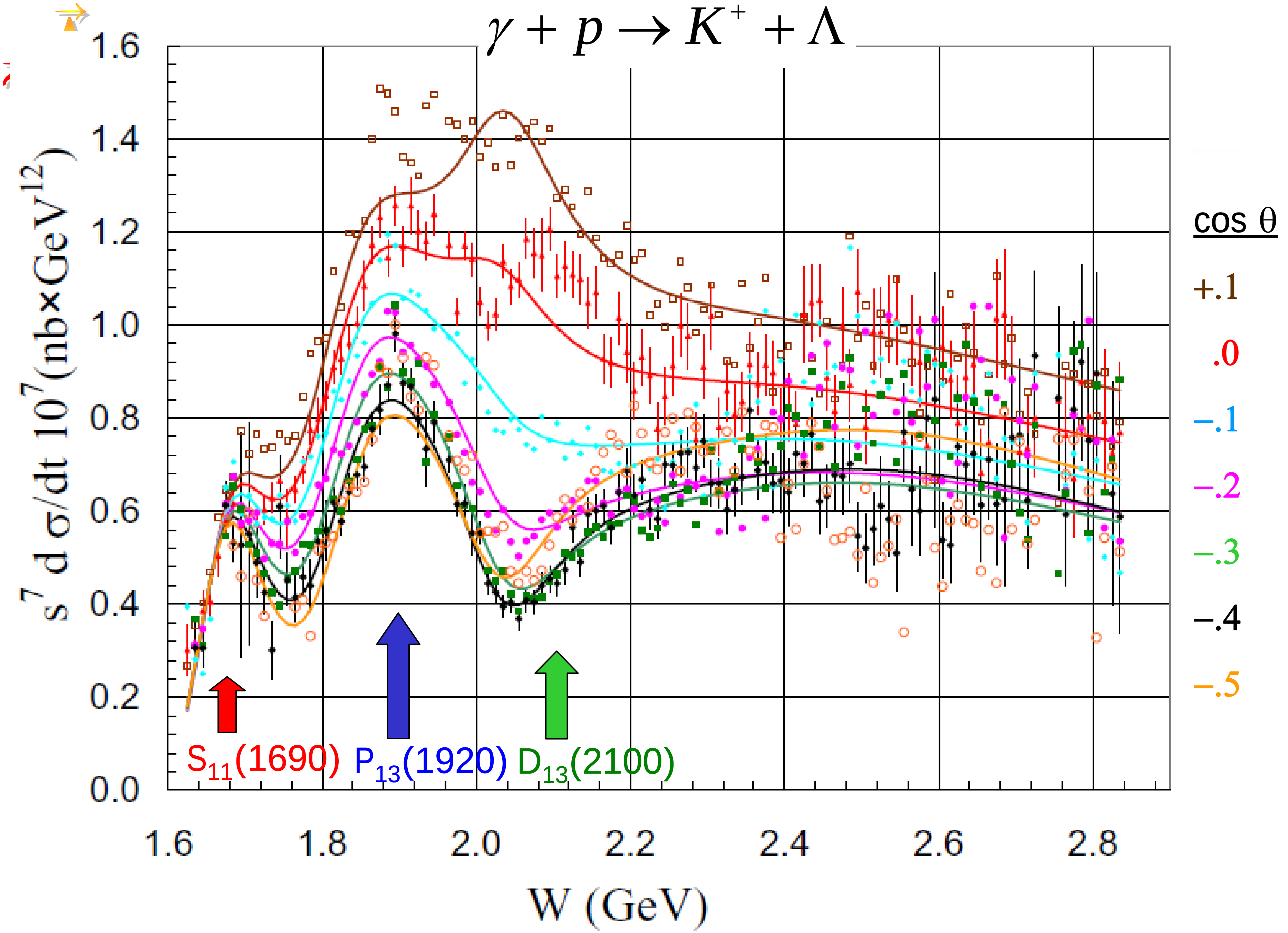
Cross section to fit:

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

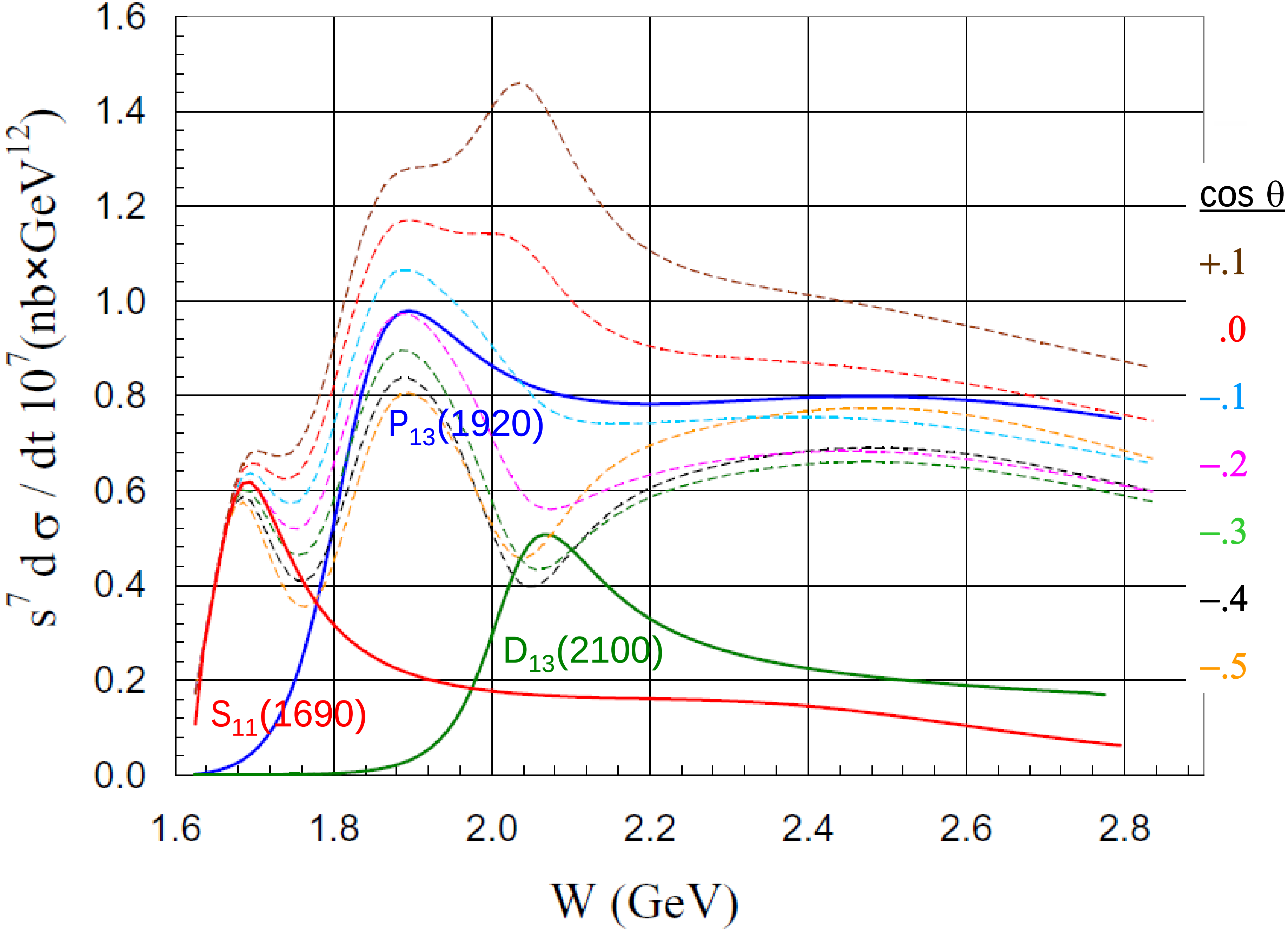
Physics Model



- 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



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



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

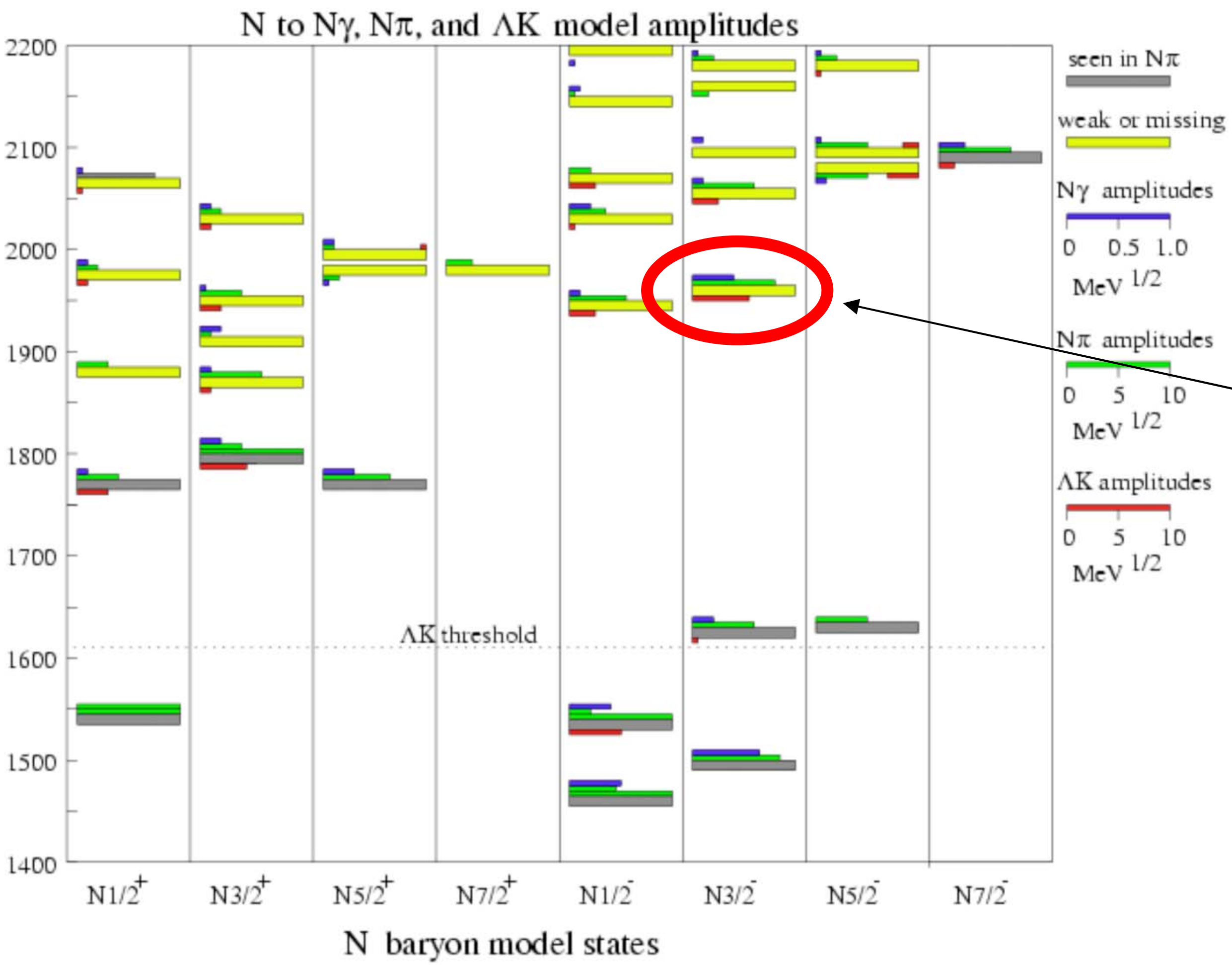
Model Results

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	$0.61 \pm .10$	$1.19 \pm .10$
			$(45 \pm 5)^\circ$	$(45 \pm 5)^\circ$

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

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).

Conclusions

- We see three phenomena in $K^+\Lambda$ photoproduction:
  - Regge scaling s^{-2} small $-t$ – confirmed
  - Constituent-counting s^{-N} – holds for N = 7
    - Photon is a "single elementary field"
  - Evidence for N* production & interference
    - Angular distributions tested included: $S_{11}P_{11}P_{11}$, $S_{11}P_{11}S_{11}$, $S_{11}P_{13}D_{13}$,…
    - Present best fit has: $S_{11}(1690)$ $P_{13}(1920)$ $D_{13}(2100)$
    - PDG lists a "**" $D_{13}(2080)$; a "missing" state possibly seen
- For full details, see:

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

Supplemental Slides

Scaling in pion production

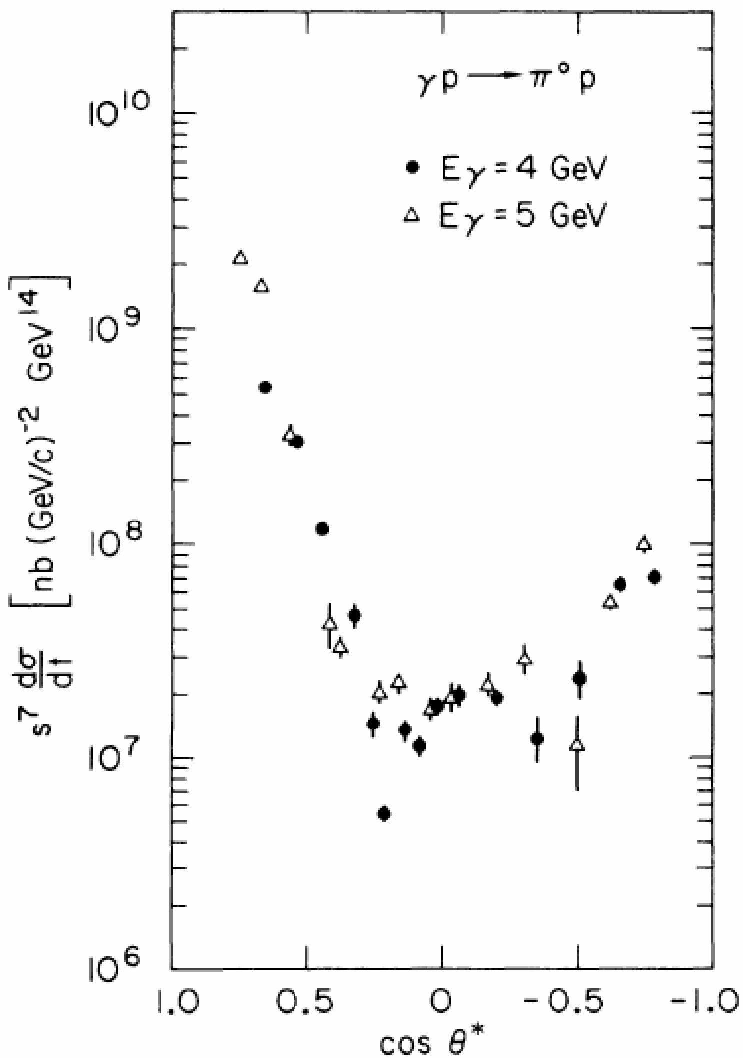


FIG. 9. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \rightarrow \pi^0 p$.

- pQCD scaling at SLAC

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

Scaling in pion production

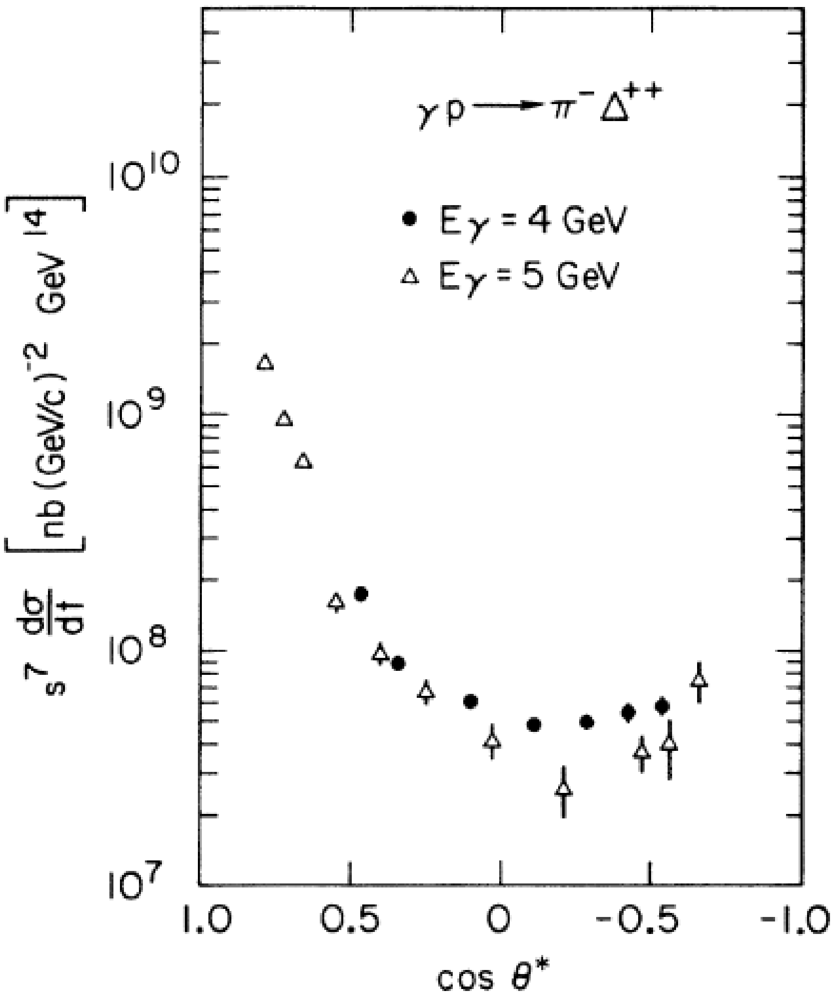


FIG. 12. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^- \Delta^{++}$.

- pQCD scaling at SLAC

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